Similarities in butterfly emergence dates among populations suggest local adaptation to climate

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Abstract

Phenology shifts are the most widely cited examples of the biological impact of climate change, yet there are few assessments of potential effects on the fitness of individual organisms or the persistence of populations. Despite extensive evidence of climate-driven advances in phenological events over recent decades, comparable patterns across species’ geographic ranges have seldom been described. Even fewer studies have quantified concurrent spatial gradients and temporal trends between phenology and climate. Here we analyse a large data set (~129 000 phenology measures) over 37 years across the UK to provide the first phylogenetic comparative analysis of the relative roles of plasticity and local adaptation in generating spatial and temporal patterns in butterfly mean flight dates. Although populations of all species exhibit a plastic response to temperature, with adult emergence dates earlier in warmer years by an average of 6.4 days per °C, among-population differences are significantly lower on average, at 4.3 days per °C. Emergence dates of most species are more synchronised over their geographic range than is predicted by their relationship between mean flight date and temperature over time, suggesting local adaptation. Biological traits of species only weakly explained the variation in differences between space-time and time-temperature phenological responses, suggesting that multiple mechanisms may operate to maintain local adaptation. As niche models assume constant relationships between occurrence and environmental conditions across a species’ entire range, an important implication of the temperature-mediated local adaptation detected here is that populations of insects are much more sensitive to future climate changes than current projections suggest.

Keywords: butterfly monitoring scheme, climate change, life history, local adaptation, phenology, plasticity, temperature, traits

Received 23 December 2014 and accepted 30 January 2015

Introduction

Evidence is accumulating that climate change is already affecting wildlife across the globe and across ecosystems (Parmesan et al., 2013; Settele et al., 2014). Phenological responses have been particularly well documented, revealing a general trend that spring events in the northern hemisphere have become earlier for several species groups (Parmesan, 2007). Such changes have the potential to disrupt the synchrony of ecological interactions (Thackeray et al., 2010) or lead to maladaptive changes with implications for population persistence (Van Dyck et al., 2015).

Populations can persist under a changing environment if they have dispersal capacity to track a shifting optimum through space, or can persist in situ by evolving to the new local conditions, or possess sufficient phenotypic plasticity to track a shifting optima (Chevin et al., 2010). The combination of rapid climate change and habitat fragmentation due to human activity may prevent many species from tracking the climate to which they are currently adapted through dispersal (Jump & Peñuelas, 2005). The evolutionary potential of populations and relative contribution of local adaptation and phenotypic plasticity to geographic variation are therefore key factors in understanding the limits to population persistence (Chevin et al., 2010). For instance, populations that differ in phenology due to temperature-driven local adaptation are expected to be subject to directional selection if the climate changes and population persistence will depend on the degree to which absolute fitness is reduced and the capacity of the population for adaptive evolution. In comparison, if populations are able to track the optimum via plasticity, mean population fitness may not be affected (Phillimore et al., 2010).
Evidence for local adaptation among populations has traditionally been derived from labour intensive and logistically challenging reciprocal transplant experiments and is only available for a taxonomically biased handful of species (Hereford, 2009). The application of recently developed statistical techniques that decompose spatiotemporal phenological data into contributions of phenotypic plasticity and local adaptation with respect to an environmental gradient provides a relatively straightforward alternative (Phillimore et al., 2010). Applying this approach to monitoring data allows local adaptation to be estimated for a suite of species with differing life-history characteristics.

Standardised monitoring of butterflies has operated in the UK for over three decades and has revealed temperature-related changes in abundance (Roy et al., 2001) and population dynamics (Oliver et al., 2012). Changes in flight dates of UK butterflies have been remarkably consistent, with almost all species showing a marked advance in the timing of adult emergence with increasing temperature (Roy & Sparks, 2000). To date, there have been few multi-species analyses of spatial variation in insect phenology apart from the demonstration that aphid flight times (Zhou et al., 1995) and butterfly sighting dates (Roy & Asher, 2003) are related to geographic gradients in temperature. Even fewer studies have assessed spatial and temporal trends simultaneously (Kharouba et al., 2013), yet this is key to accurate estimates of the survival of species, either within a region or globally, under future climates (Hodgson et al., 2011). For if the observed relationship between phenology and temperature in a species is closely matched over space and time (consistent with phenotypic plasticity determining both patterns), it is reasonable to assume that the development rates and fitness of individuals will respond to climate warming in similar and predictable ways throughout its current and potential geographical ranges. In contrast, if a species contains subsets of genotypes, each adapted to function optimally under different local climates any future responses will be harder to predict (Visser, 2008) and selection may impact negatively on demography (Chevin et al., 2010).

Here, we present the first test of local adaptation for a whole faunal group within a region. We use the largest and longest-running data set on insect populations, the UK’s Butterfly Monitoring Scheme (UKBMS), to quantify changes in butterfly flight dates over a 37 year period (1976–2012) at 1622 sites. We test the hypothesis that within- and among-population slopes between mean flight dates and temperature are equivalent, implying that any geographic covariation is solely due to plasticity. We analyse differences in trends in phenology–temperature relationships in relation to species’ ecological traits in order to infer potential mechanisms that explain local adaptation.

Materials and methods

Data sources

Daily counts of butterflies were obtained from the UKBMS. The methodology of this scheme is described in detail by Pollar & Yates (1993) and is summarised only briefly here. At each site, ideally a fixed route is walked in each of 26 recording weeks from 1 April to 29 September, provided weather conditions meet set criteria and volunteers are able to do a transect walk. All butterflies seen within fixed limits are recorded. The raw data used for this study are counts and days of counts, numbered from 1 April for the period 1976–2012. Data were available from 1622 sites distributed across the UK (Fig. S1). Average monthly temperatures from 1975 to 2012 for 5-km² grid cells of the British Ordnance Survey national grid were obtained from the UK Climate Projections 2009 data set (http://ukclimateprojections.metoffice.gov.uk/).

Calculation of phenology measures

The timing of each flight period was measured as the (weighted) mean date of counts, as described by Brakefield (1987), and gives an estimation of the date of mean abundance in the adult flight period (van Strien et al., 2008). The day of the butterfly counts was used as the unit of time, providing a more precise measure of phenology than previous analyses of butterfly transect schemes, which used recording weeks (e.g., Roy & Sparks, 2000). We restrict our analyses to site-year-species combinations where there is sufficient data to estimate an annual index abundance for a flight period (Rothery & Roy, 2001) and therefore provide a robust measure of mean flight dates.

Most butterfly species in the UK have a single generation per year, allowing phenological measures to be derived from a distinct flight period. Two univoltine species, A. io and Gonepteryx rhamni, overwinter as adults. Individuals of these species appear throughout the winter months, but mainly in March–April, partly before the monitoring season begins. The subsequent single generation emerges in the summer months, and we restrict analyses to this prehibernation period for these two species.

A number of species show a more complex pattern of adult emergences. We excluded multivoltine species with a flight period that is characterised by two or more overlapping generations that can not readily be separated (e.g. Pararge aegeria, Coenonympha pamphilus, A. urticae, Leptidea sinapis, Polygonia c-album). Several other multivoltine species have a distinct first generation in the spring that is followed by one or more, often overlapping, generations throughout the summer and early autumn. For most species, this makes it impossible to identify distinct generations for second and subsequent generations, so phenology measures were calculated for the spring generation only. Finally, we excluded species whose populations in the UK mainly comprise migrant individuals.
(e.g. Vanessa atalanta, Vanessa cardui, Colias croceus). In total, 31 species were analysed.

**Statistical analysis**

**Identifying the most important temperature period for each species’ phenology.** For each UKBMS monitoring site, monthly temperatures were obtained from the 5 km grid cell containing the site centroid. Three-monthly running means were then calculated by taking a mean of the temperature of each month and its preceding and following month. We used these running means to identify for each species the three-month period whose mean temperature had the greatest effect on flight date UK-wide. To do this, we fitted 12 separate regression models with the UK-wide mean flight date in each year as the response variable and mean temperature from one of the 12 three-monthly periods as an explanatory variable. We included periods that come after the flight period of the species to test that spurious relationships were not apparent. We selected the model with the strongest relationship (as measured by t-value) between temperature and mean flight date (Table 1). The same or adjacent month was selected using the magnitude of the effect (coefficient between temperature and mean flight date) as an alternative criterion (Table S1) and gave similar results (Fig. S2). For example, for Callophrys rubi period 3 (March) had the largest, most statistically significant (negative) coefficient, indicating that warmer mean monthly temperatures between February and April had the greatest effect on shifting the butterfly mean flight date to earlier in the year. The t-values and coefficients of the relationships between mean flight dates and all 12 three-monthly periods tested are given in the Supplementary Materials (Table S1). We adopt this data-driven approach to negate incomplete knowledge of the biology of butterfly species; the detailed autecological information needed to identify key stages of development is only available for a few species.

**Comparing effects of temperature change on species’ phenology over space and time.** To compare the relative effect of temperature change over time vs. temperature change over space, we followed the method of Phillimore et al. (2010). Local monitoring sites were aggregated into ‘populations’ by overlaying a 50 km grid (N-S/E-W orientation) onto the UK map. We also repeated the analysis at two further scales, with overlaying a 100 km grid, finding the results similar: using individual site location (e.g. no aggregation) and by overlaying with a 100 km grid (N-S/E-W orientation) onto the UK map. We also repeated the analysis at two further scales, with overlaying a 50 km grid (N-S/E-W orientation) onto the UK map. To compare the relative effect of temperature change on species’ phenology over space and time, we used published molecular data to create phylogenies of British butterflies. We used Geneious (Drummond et al., 2006) to search GenBank for nucleotide sequences from the mitochondorial cytochrome oxidase subunit I (COI) gene. We were able to find sequences for 54/62 British species; for a further five species, we included the sequence of a congener (see Fig. S5 legend). Sequences ranging from 406 to 1450 bp long were aligned by eye in Se-Al (http://tree.bio.ed.ac.uk/software/seal/). Technical details for developing the phylogenies of British butterflies are included within the supplementary material.

**Comparing trends across species.** We used a phylogenetic meta-analysis (Hadfield & Nakagawa, 2010) to estimate the phylogenetic signal in interspecific variation in the within-population slope (an estimate of plasticity) and Δb (an estimate of local adaptation) and to test for fixed effect predictors of these values. We implemented this using the MCMCglmm R library (Hadfield, 2010) fitting phylogeny as a random effect (Eqn 1).

\[ y_i = \mu + \beta x_i + a_i + e_i + m_i \]  

<table>
<thead>
<tr>
<th>Species</th>
<th>Mean flight date</th>
<th>Month</th>
<th>n (sites)</th>
<th>n (site/year)</th>
<th>R²</th>
<th>Within-population slope</th>
<th>Among-population slope</th>
<th>Slope difference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Group (a): Univoltine species: one flight period in each year</strong></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Thymelicus sylvestris</td>
<td>21st June</td>
<td>May</td>
<td>1033</td>
<td>6211</td>
<td>0.25</td>
<td>-6.41 (−8.29; −4.74)</td>
<td>-4.06 (−5.10; −3.17)</td>
<td>2.38 (0.35; 4.21)</td>
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<td>Hesperia comma</td>
<td>18th July</td>
<td>July</td>
<td>58</td>
<td>553</td>
<td>0.21</td>
<td>-4.35 (−5.75; −3.14)</td>
<td>2.26 (−5.88; 10.79)</td>
<td>6.53 (−1.62; 15.46)</td>
</tr>
<tr>
<td>Ochloides sylvanus</td>
<td>5th June</td>
<td>May</td>
<td>1140</td>
<td>8126</td>
<td>0.16</td>
<td>-6.76 (−8.18; −5.52)</td>
<td>-0.15 (−1.90; 1.30)</td>
<td>6.63 (4.70; 8.56)</td>
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<td>Eretria tages</td>
<td>26th April</td>
<td>March</td>
<td>449</td>
<td>2785</td>
<td>0.26</td>
<td>-5.68 (−6.71; −4.70)</td>
<td>-1.79 (−3.56; 0.02)</td>
<td>3.88 (1.86; 5.87)</td>
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<tr>
<td>Pyrgus malvae</td>
<td>22nd April</td>
<td>March</td>
<td>344</td>
<td>2041</td>
<td>0.10</td>
<td>-6.00 (−7.11; −4.57)</td>
<td>-1.44 (−13.82; 9.68)</td>
<td>4.51 (−7.70; 16.14)</td>
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<td>Anthocharis cardamines</td>
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<td>March</td>
<td>1209</td>
<td>7422</td>
<td>0.39</td>
<td>-7.21 (−8.35; −6.09)</td>
<td>-5.23 (−6.75; −3.78)</td>
<td>2.04 (0.24; 3.92)</td>
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<td>23rd April</td>
<td>March</td>
<td>514</td>
<td>2784</td>
<td>0.19</td>
<td>-5.42 (−6.11; −4.59)</td>
<td>3.66 (1.31; 6.63)</td>
<td>9.12 (6.42; 11.85)</td>
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<tr>
<td>Polyommatus coridon</td>
<td>10th July</td>
<td>June</td>
<td>233</td>
<td>1765</td>
<td>0.18</td>
<td>-5.22 (−6.53; −3.78)</td>
<td>-2.67 (−6.75; 1.01)</td>
<td>2.47 (−1.36; 6.97)</td>
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<td>Linenitis camilla</td>
<td>15th June</td>
<td>May</td>
<td>278</td>
<td>1745</td>
<td>0.21</td>
<td>-7.83 (−8.60; −8.86)</td>
<td>-12.68 (−25.73; 5.73)</td>
<td>-4.85 (−19.12; 12.4)</td>
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<td>Boloria selene</td>
<td>21st May</td>
<td>May</td>
<td>227</td>
<td>1228</td>
<td>0.29</td>
<td>-6.25 (−8.19; −4.30)</td>
<td>-6.26 (−8.11; −4.08)</td>
<td>-0.03 (−2.63; 2.71)</td>
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<tr>
<td>Boloria euphrosyne</td>
<td>26th April</td>
<td>March</td>
<td>157</td>
<td>872</td>
<td>0.23</td>
<td>-6.96 (−8.15; −5.71)</td>
<td>-5.02 (−9.11; −0.74)</td>
<td>1.9 (−2.23; 6.24)</td>
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<tr>
<td>Argynnis adippe</td>
<td>17th June</td>
<td>May</td>
<td>62</td>
<td>478</td>
<td>0.12</td>
<td>-6.22 (−8.51; −4.69)</td>
<td>-7.04 (−19.11; 4.66)</td>
<td>-0.89 (−12.39; 11.59)</td>
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<tr>
<td>Argynnis aglaja</td>
<td>19th June</td>
<td>June</td>
<td>447</td>
<td>2312</td>
<td>0.09</td>
<td>-6.42 (−6.08; −3.04)</td>
<td>-1.79 (−3.22; −0.32)</td>
<td>2.77 (0.61; 4.86)</td>
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<td>Argynnis paphia</td>
<td>20th June</td>
<td>May</td>
<td>519</td>
<td>2670</td>
<td>0.19</td>
<td>-5.53 (−7.21; −3.84)</td>
<td>-7.53 (−10.18; −4.88)</td>
<td>-2.01 (−5.19; 0.94)</td>
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<tr>
<td>Euphydryas aurinia</td>
<td>3rd May</td>
<td>April</td>
<td>87</td>
<td>474</td>
<td>0.38</td>
<td>-6.97 (−9.35; −5.15)</td>
<td>-8.24 (−13.55; −2.69)</td>
<td>-1.26 (−7.05; 4.78)</td>
</tr>
<tr>
<td>Melanargia galathea</td>
<td>13th June</td>
<td>May</td>
<td>721</td>
<td>4866</td>
<td>0.37</td>
<td>-6.92 (−8.13; −7.58)</td>
<td>-4.72 (−7.38; −2.33)</td>
<td>2.21 (−0.60; 4.87)</td>
</tr>
<tr>
<td>Hipparchia semele</td>
<td>6th July</td>
<td>May</td>
<td>231</td>
<td>1310</td>
<td>0.05</td>
<td>-3.74 (−3.51; −2.37)</td>
<td>1.20 (−1.40; 3.54)</td>
<td>5.04 (2.43; 7.93)</td>
</tr>
<tr>
<td>Pyronia tithonus</td>
<td>2nd July</td>
<td>June</td>
<td>1142</td>
<td>8391</td>
<td>0.45</td>
<td>-6.13 (−6.96; −5.33)</td>
<td>-3.39 (−4.41; −2.37)</td>
<td>2.77 (1.46; 4.05)</td>
</tr>
<tr>
<td>Maniola jurtina</td>
<td>29th June</td>
<td>May</td>
<td>1361</td>
<td>9876</td>
<td>0.13</td>
<td>-4.54 (−5.93; −3.01)</td>
<td>-1.04 (−1.89; −0.10)</td>
<td>3.51 (1.84; 5.28)</td>
</tr>
<tr>
<td>Aphantopus hyperantus</td>
<td>13th June</td>
<td>May</td>
<td>1202</td>
<td>7546</td>
<td>0.37</td>
<td>-6.52 (−7.38; −5.64)</td>
<td>-2.02 (−2.79; −1.42)</td>
<td>4.51 (3.42; 5.58)</td>
</tr>
<tr>
<td><strong>Group (b): Univoltine species: two flight periods per year but only one generation (adults overwintering, summer generation analysed)</strong></td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Gonepteryx rhamni</td>
<td>11th July</td>
<td>July</td>
<td>877</td>
<td>5720</td>
<td>0.30</td>
<td>-8.31 (−9.95; −6.77)</td>
<td>-5.72 (−7.78; −3.45)</td>
<td>2.65 (−0.17; 5.27)</td>
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<tr>
<td>Aglais io</td>
<td>8th July</td>
<td>May</td>
<td>1253</td>
<td>8273</td>
<td>0.53</td>
<td>-7.60 (−9.71; −5.68)</td>
<td>-8.82 (−9.66; −7.9)</td>
<td>-1.18 (−3.38; 0.82)</td>
</tr>
<tr>
<td><strong>Group (c): Multivoltine species: two or more flight periods per year representing different generations (1st generation analysed)</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Pieris rapae</td>
<td>20th April</td>
<td>April</td>
<td>1190</td>
<td>7325</td>
<td>0.31</td>
<td>-9.07 (−10.74; −7.32)</td>
<td>-3.72 (−4.71; −2.8)</td>
<td>5.38 (3.35; 7.37)</td>
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<td>Pieris napi</td>
<td>18th April</td>
<td>April</td>
<td>1214</td>
<td>7986</td>
<td>0.41</td>
<td>-8.21 (−9.78; −6.90)</td>
<td>-5.18 (−5.89; −4.61)</td>
<td>3.01 (1.41; 4.54)</td>
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<tr>
<td>Pieris brassicae</td>
<td>25th April</td>
<td>April</td>
<td>1195</td>
<td>7239</td>
<td>0.29</td>
<td>-8.10 (−9.51; −6.91)</td>
<td>5.45 (−6.39; −4.34)</td>
<td>2.67 (0.84; 4.23)</td>
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<td>Lycæa philæas</td>
<td>25th April</td>
<td>March</td>
<td>887</td>
<td>3739</td>
<td>0.31</td>
<td>-6.73 (−7.75; −5.65)</td>
<td>-4.35 (−5.61; −2.99)</td>
<td>2.40 (0.78; 4.06)</td>
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<tr>
<td>Cupido minimus</td>
<td>8th May</td>
<td>March</td>
<td>169</td>
<td>938</td>
<td>0.28</td>
<td>-4.98 (−6.32; −3.70)</td>
<td>-4.65 (−7.14; −2.07)</td>
<td>0.32 (−2.6; 3.04)</td>
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<td>Aricia agestis</td>
<td>1st May</td>
<td>March</td>
<td>411</td>
<td>2005</td>
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<td>-6.23 (−7.30; −5.09)</td>
<td>-5.68 (−8.44; −3.08)</td>
<td>0.56 (−2.15; 3.6)</td>
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<td>Polyommatus icarus</td>
<td>10th June</td>
<td>April</td>
<td>1104</td>
<td>6529</td>
<td>0.55</td>
<td>-7.04 (−8.52; −5.21)</td>
<td>-12.92 (−14.55; −11.2)</td>
<td>-5.90 (−8.25; −3.66)</td>
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<tr>
<td>Calastrina argiolus</td>
<td>12th May</td>
<td>March</td>
<td>908</td>
<td>4246</td>
<td>0.18</td>
<td>-5.89 (−6.86; −4.83)</td>
<td>-3.62 (−6.43; −0.54)</td>
<td>2.17 (−0.91; 5.36)</td>
</tr>
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<td>Lasiommata megera</td>
<td>27th May</td>
<td>March</td>
<td>420</td>
<td>1981</td>
<td>0.39</td>
<td>-7.33 (−8.09; −6.57)</td>
<td>-6.14 (−7.71; −4.57)</td>
<td>1.18 (−0.54; 2.88)</td>
</tr>
</tbody>
</table>
The trait, $y$ (estimate of either plasticity or local adaptation), of species $i$ is given by the grand mean ($\mu$), plus the influence of any fixed effects ($b_i$), deviations due to phylogeny ($a_i$), species-specific residual ($e_i$) and measurement error ($m_i$). $a$ and $e$ are assumed to follow normal distributions, and their variances ($\sigma_a^2$ and $\sigma_e^2$) are estimated in the model. The model incorporates uncertainty in our estimates of the species-specific measurement error variance (i.e. the variance in the relevant posterior distribution) plasticity and local adaptation. The distribution of $m$ was given by:

$$m \sim N(0, M)$$

where $M$ is a $N \times N$ matrix with the measurement error variances on the off-diagonal. In addition, we incorporated uncertainty in the phylogenetic hypothesis, by estimating all mixed model fixed and random effects from 1000 trees sampled from the posterior distribution. This meant that the resulting posterior distribution incorporated both model and phylogeny uncertainty (Pagel & Lutzoni, 2002). Phylogenetic heritability was estimated as:

$$H^2 = \sigma^2_e / (\sigma^2_a + \sigma^2_e).$$

The biological traits we tested as predictors of the within-population slope and $\Delta b$ were as follows: the seral stage of host plant(s) (early/mid/late succession grasses or trees/shrub); larval development duration (days); degree of multivoltinism (single-brooded, single plus partial second brooded, double-brooded, multi-brooded); hibernation stage (egg, larva, pupa, adult); mobility (sum of binary states for nine attributes including ex-habitat vagrants, garden records, urban central business district records, at-sea records, mass movements, range expansions, overseas migration from continent to Europe, regular reversed long distance migration, over-ocean (Atlantic) migration). The seral stage of host plants was categories following Thomas (2007); all other traits were derived from Dennis et al. (2004).

**Results**

For all 31 butterfly species analysed, annual fluctuations in mean flight date were strongly related to temperature, with advanced timing in warmer years (Table 1; range of $-3.7$ to $-9.1$ days $\degree C^{-1}$). The temperature variable most correlated with mean flight date for every species was mean temperature averaged over a three-month period prior to the overall average flight date. In all cases, the magnitude and statistical significance of this response was only slightly reduced in preceding and subsequent three-month periods (Table S1), due to the intercorrelation in temperatures between months.

Most (28 of 31) species also had a negative relationship between mean flight date and temperature over space, with later flight dates in cooler parts of their range (Table 1). Among-population temperature-phenology slopes ranged from $+3.7$ days $\degree C^{-1}$ in *Callophrys rubi* to $-12.9$ days $\degree C^{-1}$ in *Polyommatus icarus*.

For all species combined, temperature-related changes in flight periods were greater over time than space (Fig. 2; mean phylogenetically corrected difference $= 2.38$ (95% CIs: 0.76–3.90) days $\degree C^{-1}$) and this slope difference was individually significant (95% confidence intervals do not span zero) for 14 species (Table 1). Thus, the emergence dates of most species
are more synchronised over their geographic range than is predicted by their relationship between mean flight date and temperature over time (i.e. 26 of 31 species fall below the unity line in Fig. 2). Responses to a 1 °C variation in temperature were almost invariably greater over time than over space. For example, populations of *Ochlodes sylvanus* have appeared on average 1 week earlier per 1 °C increase in May temperatures over the last three decades (within-population slope). In contrast, populations of this species appear across the country at approximately the same time each year (among-population slope approximately zero; Table 1).

Within the data set analysed, the absolute temperature range of species is typically higher over space (among-populations) than over time (within populations), although the interquartile range is more similar and marginally higher over time (Table S2). The mean absolute range values are among-populations = 6.4 °C vs. within-populations = 3.5 °C; whereas the mean interquartile ranges are 0.9 °C vs. 1.2 °C, respectively.

Our analysis of species’ traits does not identify a strong link between species’ life-history characteristics and the degree of local adaptation, as measured by the difference in the within- and among-population relationships between appearance dates and temperature (Fig 3, Table S3). The one significant relationship detected was between the temperature–phenology trend over time (within populations, a measure of the strength of the relationship over time) and the mean timing of appearance, with flight dates of early season species tending to respond more markedly to year-to-year temperature differences. We find a significant phylogenetic signal, $H^2 = 0.75$ (95% CI: 0.25–0.94) in temperature–phenology relationships over time (within-population slopes) suggesting that responses are predictable on the basis of relatedness among species. As for the slope difference $\Delta b$, we did not detect a significant phylogenetic signal ($h^2 = 0.06$, 95% CI = 0.01–0.90).

**Discussion**

We provide the first evidence from a multi-species analysis of structured monitoring data that geographic relationships between phenology (mean butterfly flight dates) and temperature are not readily predicted from relationships over time. This confirms similar patterns found for sparser, less structured phenology estimates derived from museum specimens (Kharouba et al., 2013). The key features of our analyses being data to estimate phenology based on repeated counts from fixed locations over 37 years, with data points per species being three orders of magnitude greater; ~3000 data points per species in our analyses vs. ~2 per species in Kharouba et al. (2013). We found that flight periods were earlier in years when the weather was warm prior to and during emergence, confirming the strong relationship previously demonstrated for butterflies (Roy & Sparks, 2000). However, emergence dates of most species are more synchronised over their geographic range than is predicted by their relationship between mean flight date and temperature over time, suggestive of local adaptation to temperature.

The difference between spatial and temporal phenology responses may relate to one or more of the latitudinal gradients reported in butterfly populations, such as in morphology, resource use, life-history patterns, physiology, biochemistry and behaviour (Nylin, 2009). For example, it is notable that the most extreme exception to the general pattern in Fig. 2, *Callophrys rubi* is the only polyphagous species analysed to switch its principal larval foodplant over its latitudinal range in Great Britain (Thomas, 2007). Having restricted our analyses to a single generation for species with variable voltinism, the other potential mechanisms underpinning local adaptation can broadly be classed into three nonexclusive types: (i) Developmental compensation – for example, pupation can occur at a lower weight, at the cost of producing smaller adults, when temperatures are cool, especially where other cues are in...
operation such as resource availability or a day-length trigger for metamorphosis (Dennis & Shreeve, 1989; Van Dyck et al., 2015). Complete phenotypic plasticity in development with respect to temperature would lead to similar phenology–temperature relationships across time and space. (ii) Behavioural compensation for cooler temperatures by thermo-regulating as adults or larvae (Weiss et al., 1988), or by occupying warmer or cooler niches, respectively, within ecosystems in regions, seasons or years when air temperatures are lower or higher (Thomas, 1993; Thomas et al., 1999, 2001; Roy & Thomas, 2003; Oliver et al., 2009, 2012). Note that this latter behavioural mechanism could plausibly arise via the action of another plastic trait. (iii) Physiological or morphological adaptations by local populations to regional climates, whereby each genotype has evolved to function optimally under the range of environmental conditions that it has historically experienced in a region (Nylin & Gotthard, 1998).

If complete phenotypic plasticity and the same reaction norms existed in populations across species’ ranges, as postulated by the two explanations involving compensation (developmental and behavioural), then any phenology–temperature relationship should be similar across space and time. For example, not only do many UK butterflies shift to inhabit warmer, narrower niches within sites at higher (cooler) latitudes (Thomas, 1993; Thomas et al., 1999, 2001; Roy & Thomas, 2003; Oliver et al., 2009), but a similar temporal shift also occurs within individual sites, with females distributing eggs during warm years on foodplants growing in spots that (in our examples) would normally be too cool for exploitation, or compensating for cold weather by concentrating the population into the warmest available microhabitats (Thomas et al., 1994, 2001; Roy & Thomas, 2003). Similarly, phenology has been shown to be affected by habitat (Pollard & Greatorex-Davies, 1997; Altermatt, 2012) and microclimate (Wallisdevries & Van Swaay, 2006). The fact that we find a consistently stronger phenological response per 1 °C change over time compared with space (Fig. 2) suggests that compensation with respect to temperature is not the sole influence on local phenology. We would, however, expect such a pattern if local butterfly populations can function optimally within a range of temperatures experienced at each site.

The difference between spatial and temporal relationships found here might also arise if additional phenological cues elicit a plastic phenological response spatially but not temporally, for example photoperiod. Although photoperiod has a key role for insect development and phenology in seasonal environments (Nylin & Gotthard, 1998), it is not likely to explain the patterns we observe here. There are few examples of a photoperiod cue operating on the timing of butterfly emergence, and this cue appears to be more important for determining when insects enter diapause (Bradshaw & Holzapfel, 2007). Moreover, we find strong trends in emergence dates

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**Fig. 3** Relationship between butterfly traits and a) species’ within-population phenology–temperature slopes (an estimate of plasticity in flight date; top panels) and slope differences \( \Delta b \) (an estimate of local adaptation; bottom panels). Traits are as follows (panels left to right): larval development duration (days); degree of multivoltinism (single-brooded, single plus partial second brooded, double-brooded, multi-brooded); hibernation stage (egg, larva, pupa, adult); mobility (sum of ranked scores for nine variables); mean flight date (weighted mean of adult abundance by week). Mean flight date was derived directly from monitoring data; all other traits were derived from Dennis et al. (2004).
within populations over time, despite photoperiod being fixed at locations. Evidence for local adaptation is found for species with both relatively narrow and large latitudinal (and climatic) ranges in the UK (Table S2).

One explanation for the patterns in phenology–temperature patterns in butterflies is that countergradient local adaptation, whereby development is faster in colder areas (Conover & Schultz, 1995), may be prevalent in Lepidoptera. The adaptive explanation for such a countergradient in development rates is a trade-off between a cost to the butterfly of emerging too early – perhaps in the form of exposure to late frosts for spring-flying species – vs. the advantage of emerging early to maximise the growth and reproduction achieved during the summer months. Fitness costs of high growth rates (Conover & Present, 1990), such as increased exposure to predators, increase risk of desiccation, etc., may also lead to delays in development in warmer locations. These trade-offs may give rise to geographic variation in the optimum average emergence date. Countergradient local adaptation may also be driven by host plants that themselves show a countergradient trend. However, in general trophic generalism makes it unlikely that patterns in butterfly phenology are driven by host-plant availability, even though countergradients have been reported in plants (Eckhart et al., 2004). For the butterfly species analysed here, host availability per se is not likely to be limiting (Quinn et al., 1998) and, where investigated, butterfly phenology appears to be better predicted by temperature than by flowering times of host plants (Phillimore et al., 2012). Host-plant quality is a key factor in the persistence of butterfly populations, however, and can vary with abiotic factors such as altitude, geology and climate. As such, variability in host-plant use may be a mechanism causing spatial patterns in butterfly emergence dates. Some butterfly species are known to exploit differing food plants across their geographic range, and this can change through climatic conditions (Pateman et al., 2012; Bridle et al., 2014).

Our finding of substantial phylogenetic signal for the temporal slope, which we take to be a measure of phenological plasticity, is consistent with earlier work on the phenological signal of phenological responses of plants to temperature in Thoreau’s woods (Willis et al., 2008). Both results reveal a role for phylogenetic climatic niche conservatism. An implication of our finding of high phylogenetic signal in phenological plasticity is that we may be able to predict the phenological plasticity of species outside this study, provided that they are closely related to species we included here (Davis et al., 2010). The slope difference (degree of local adaptation) in comparison was found not to be phylogenetically heritable – although the credible interval was broad – suggesting that close relatives are not more likely to become locally adapted in either a countergradient or co-gradient way.

Understanding these gradients and how they maintain population responses, including flight dates and population stability (Thomas et al., 1994; Oliver et al., 2010), are key to our ability to predict the impacts of climate change (Pau et al., 2011). If local adaptation to temperature occurs widely, as suggested here, this has implications for the conservation of butterflies by introduction from one locality to aid range expansion (Høgh-Guldberg et al., 2008) or where extinction has occurred. Butterflies moved from a cooler to a warmer locality may emerge too early in the season to interact with local resources, as occurred when Maculinea arion was introduced from Sweden to UK sites where mean temperatures were >2 °C cooler than the source (D. J. Simcox pers comm.). More importantly, a locally adapted butterfly may be unable to cope with predicted rapid climate warming, even if that increase remains well within the climate envelope of the species as a whole (Pelini et al., 2009; Van Dyck et al., 2015). Strong directional selection may be expected under such scenarios, and we recommend field studies to confirm this prediction.

Niche (bioclimate) models are a primary tool for identifying the risks of climate change and informing future conservation policy for biodiversity, and specifically butterflies (Settele et al., 2008). Such models assume constant relationships between occurrence and environmental conditions across a species’ entire range. The evidence for widespread local adaptation reported here, combined with low dispersal ability of many species, suggests that the vulnerability of UK butterflies to projected warming may be critically underestimated. Common garden experiments and reciprocal transplants (Hereford, 2009) are a priority to confirm the extent of local adaptation suggested by correlative models.

A fuller assessment of the extent of local adaptations within populations and greater understanding of the underlying mechanisms are essential for more accurate projections of the impacts of climate warming on biodiversity and the ecosystem services it supports (Visser, 2008).

Acknowledgements

We are indebted to all the UKBMS volunteers for collecting and submitting transect data. We thank Stephen Freeman, Nick Isaac, Jarrod Hadfield, Dan Nussey and Peter Rothery for helpful advice on the analysis approach used. The UKBMS is funded
by a multiagency consortium led by JNCC and including Defra, NRW, FC, NE, NERC and SNH. The analyses were partly funded by the Biodiversa project CLIMIT within the FP6 of the European Commission, and the CEH National Capability funding from the Natural Environmental Research Council (Project NEC04932).

Author contributions

DR designed the study; MB, TB, BB CH, RD collected and processed data; TO and AP designed and performed the analysis; DR, TO, AP and JT wrote the manuscript.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Data S1. Developing a phylogeny of British butterflies (technical details).

Table S1. Species’ t-values and co-efficients from regressions of mean flight date and three-monthly mean temperatures.

Table S2. Temperature range (within- and between-populations) of data analysed for each species.

Table S3. Results from phylogenetic MCMCglmm analysis.

Figure S1. Locations of the 1622 United Kingdom Butterfly Monitoring Scheme transects used for the analysis.

Figure S2. Expected shift in mean flight date for a 1 °C increase in mean temperature in both the spatial (x-axis) and temporal dimension (y-axis) for the 30 species analysed.

Figure S3. Expected shift in mean flight date for a 1 °C increase in mean temperature in both the spatial (x-axis) and temporal dimension (y-axis) for the 30 species analysed.

Figure S4. Plots of flight date on temperature for each species.

Figure S5. The maximum clade credibility mtDNA COI gene tree for British butterflies obtained using Beast [11] with branch lengths proportional to time.