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The Well-Temperatured Biologist

(American Society of Naturalists Presidential Address)[*]

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Online enhancements: audio files.

ABSTRACT: Temperature provides a powerful theme for exploring environmental adaptation at all levels of biological organization, from molecular kinetics to organismal fitness to global biogeography. First, the thermodynamic properties that underlie biochemical kinetics and protein stability determine the overall thermal sensitivity of rate processes. Consequently, a single quantitative framework can assess variation in thermal sensitivity of ectotherms in terms of single amino acid substitutions, quantitative genetics, and interspecific differences. Thermodynamic considerations predict that higher optimal temperatures will result in greater maximal fitness at the optimum, a pattern seen both in interspecific comparisons and in within-population genotypic variation. Second, the temperature-size rule (increased developmental temperature causes decreased adult body size) is a common pattern of phenotypic plasticity in ectotherms. Mechanistic models can correctly predict the rule in some taxa, but lab and field studies show that rapid evolution can weaken or even break the rule. Third, phenotypic and evolutionary models for thermal sensitivity can be combined to explore potential fitness consequences of climate warming for terrestrial ectotherms. Recent analyses suggest that climate change will have greater negative fitness consequences for tropical than for temperate ectotherms, because many tropical species have relatively narrow thermal breadths and smaller thermal safety margins.

Keywords: Bach, body size, climate change, physiological adaptation, temperature, *The Well-Tempered Clavier*.

Prelude and Theme

The year 2009 is the 150th anniversary of Charles Darwin's great masterpiece, *On the Origin of Species* (Darwin 1859), and there has been a wealth of conferences, meetings, and other activities celebrating this important milestone. You may not be aware that we are also celebrating the 300th anniversary of one of Johann Sebastian Bach's first masterpieces, the Passacaglia and Fugue in C Minor (BWV 582).[1]

Like many of Bach's great organ works, the Passacaglia was composed during his years at Weimar (1708–1717). This was his first real position as chamber musician and court organist; in his previous post, he was listed as "lackey Bach" (perhaps the equivalent of a graduate student today). It was also the first time he had command of an excellent organ, and Bach was widely admired as a virtuoso organist (Geck 2006).

The Passacaglia is structured around a recurring 16-bar theme in the bass (an audio file is available in the online edition of the *American Naturalist*). Keep in mind that the modern pianoforte (and electronic amplification) did not exist in the early eighteenth century. The organ was the only instrument of the period with the volume and sustained power to fill a cathedral and the only one capable of producing thunderous, ground-shaking bass, and Bach used these qualities to wonderful effect. But the brilliance of the Passacaglia is the way Bach used the theme and its 20 variations to explore the full spectrum of musical styles and colors of the period, to reflect a whole world of music in a single piece. Some of Bach's later masterpieces in this vein—the Goldberg Variations, the Chaconne in D Minor—similarly illustrate how musical diversity can emerge from a simple, fecund theme.

Most of us are not geniuses like Bach or Darwin. But the idea of using a single theme to explore the entire scope of music, biology, or any other field is a powerful one, and many of us use it in our own research and careers. For some this may involve focusing on a single taxon; for others it may involve a particular biological process or methodological approach. In this essay, I want to discuss

[1] Very few of Bach's works were published during his lifetime, and most of his compositions, including the Passacaglia, are impossible to date precisely. Based on historical and stylistic evidence, most Bach scholars agree that the Passacaglia was written during Bach's early years at Weimar.

temperature, a recurring theme that has fascinated me during my career.

The role of temperature in biology is certainly not a new idea. In the very first issue of the *American Naturalist* in 1867, E. D. Cope described the fossil reptiles of New Jersey from the Cretaceous period, including what was apparently the first report of a large bipedal dinosaur (Cope 1867). Following on the ideas of Richard Owen, Cope interpreted this find as a highly active, warm-blooded predator: "He no doubt had the usual activity and vivacity which distinguishes the warm-blooded from the cold-blooded vertebrates. We can, then, with some basis of probability imagine our monster carrying his eighteen feet of length on a leap, at least thirty feet through the air, with hind feet ready to strike his prey with fatal grasp" (p. 29). Cope clearly had in mind that large size and high body temperature are important for performance and evolutionary success; this and similar observations contributed to what later became known as Cope's rule (Cope 1896).

In this essay, I will explore temperature as a theme for understanding adaptation to environmental variation. There are several reasons why temperature is a powerful organizing theme for exploring the full scope of biology. First, temperature affects nearly all biological rate processes, from molecular and biochemical kinetics through population dynamics and rates of molecular evolution to macroevolutionary rates of diversification and extinction. Second, we can readily measure temperature in organisms and their environments at a wide range of temporal and spatial scales, from individual molecules to the globe. Indeed, temperature and electromagnetic radiation (both manifestations of the same physical processes) are now routinely monitored across the globe in real time at increasingly small spatial scales. Third, we have well-developed theoretical frameworks for understanding thermal biology at a variety of levels, including molecular kinetics and enzyme stability, mass/energy flux balances of organisms and their environments, and evolutionary models for describing plasticity, selection, and adaptation in response to temperature variation. These data and models provide powerful tools for understanding the integrative biology of temperature.

Bach's Passacaglia provided 20 variations on his theme; here I will develop three main variations on temperature, drawing from the work of many colleagues and collaborators. (For an excellent, more comprehensive review of thermal adaptation, see Angilletta 2009.) First, we will consider variation and evolution of thermal sensitivity. Here we will focus on the biochemical and genetic bases for thermal sensitivity and a larger-scale evolutionary pattern that emerges from these bases. Second, we will consider the important connections between temperature and body size. We will focus on a general pattern about phenotypic plasticity in size—the temperature-size rule—and on the rapid evolution of size and reaction norms. Third, we will consider the consequences of climate change at a global scale. Here we will emphasize the emergence of novel climatic conditions in some regions and how differences in the thermal biology of temperate and tropic species may determine the biological winners and losers that will result from global climate change.

Variations

The Mechanisms of Thermal Sensitivity

Temperature affects biochemical rates by altering the kinetic and free energies of biochemical reactions. For enzyme-mediated reactions, there are two components to the temperature dependence of reaction rates. First, increasing temperature increases the catalytic rate for an enzyme in its active state by increasing the kinetic energy of the system, as described by the Eyring (1935) model. The quantitative effect of temperature predicted by the Eyring model is best described using an Arrhenius plot, relating the inverse of (absolute) temperature (T) to the reaction rate (Arrhenius 1889). The second component is the probability that the enzyme is in its active state. In general, this probability is maximal at some intermediate temperature and declines at higher and lower temperatures as a result of both reversible and irreversible enzyme inactivation (Privalov 1979; Schoolfield et al. 1981; Ratkowsky et al. 2005). These two factors combine to give the thermal sensitivity of reaction rates a characteristic shape (Licht 1967; fig. 1, *top*). At low temperatures, reaction rates increase linearly to geometrically with increasing temperature, reach a maximum at some "optimal" temperature, and then decrease rapidly at temperatures above the optimum. As a result, thermal sensitivity of reaction rates is strongly asymmetric at temperatures below versus above the optimum.

Remarkably, most biological rate processes at the whole-organism level, including rates of locomotion, growth, development, and fitness, exhibit the same basic form of thermal sensitivity as biochemical reaction rates (fig. 1, *bottom*; Huey and Stevenson 1979; Angilletta 2009). As a result, models for the thermal sensitivity of biochemical reaction rates can be readily adapted to model the thermal sensitivity of organismal performance and fitness (Ratkowsky et al. 2005). This common overall shape provides a useful means of identifying important patterns, or "modes," of variation in thermal performance curves (TPCs) for organismal performance or fitness among genotypes, populations, or species (Huey and Kingsolver 1989; Izem and Kingsolver 2005). Imagine a set of genotypes that vary in their TPCs in three distinct directions,
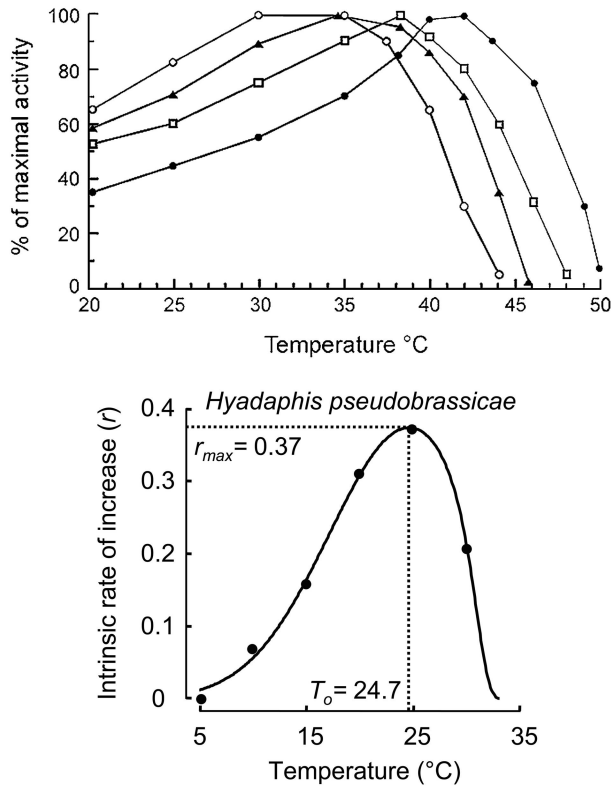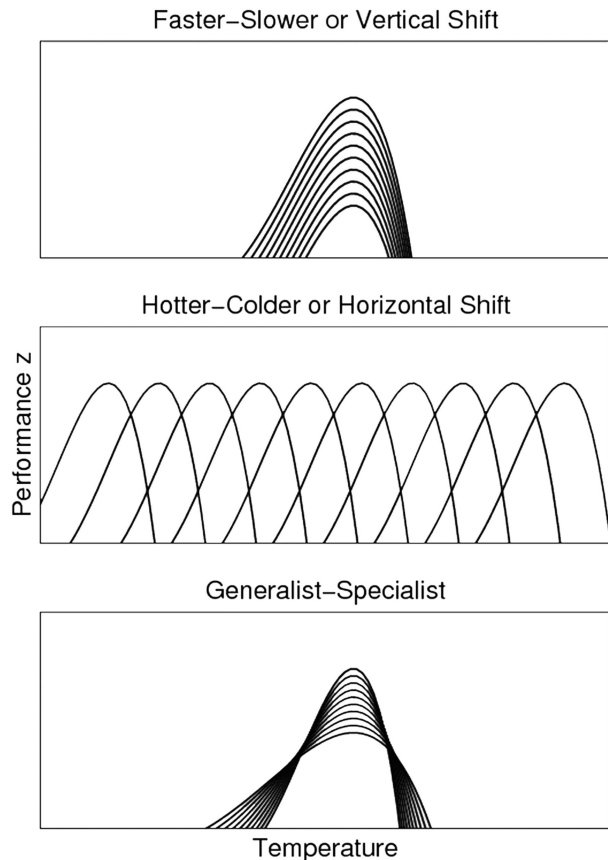
Figure 1: Thermal sensitivity of enzyme reaction rates and organismal fitness. *Top*, ATPase activity (percent of maximum) for lizard species; adapted from Licht (1967). *Bottom*, fitness (intrinsic rate of increase, *r*) for an aphid; adapted from figure 2 of Frazier et al. (2006).

resented only 7% of genetic variation; the vast majority of genetic variation in growth rate is temperature specific. These and similar results in other systems suggest that there is abundant genetic variation for thermal sensitivity of performance and fitness in many populations (Gilchrist 1996).

This approach is useful for understanding patterns of variation at the level of phenotypes and quantitative genetics but provides little insight into the underlying genetic bases for variation in reaction norms. How do specific allelic differences or amino acid substitutions alter the position and shape of thermal reaction norms? Studies of evolutionary adaptation in microbial systems can help address this question. For example, alkaline hot springs generate steep and stable spatial gradients of environmental temperatures to which microbial communities must adapt. Cyanobacteria are photoautotrophic bacteria that commonly occur in such hot springs over a range of temperatures from ∼40°C to more than 73°C, the thermal maximum for photosynthetic life (Brock 1967; Castenholz

or modes (fig. 2). "Vertical shift" (faster-slower) represents variation in the overall height of the TPCs, or variation in overall performance across all temperatures (fig. 2, *top*). "Horizontal shift" (hotter-cooler) represents variation in the position of the curve along the temperature axis, or variation in the location of the thermal maximum (fig. 2, *middle*). This mode reflects trade-offs between performance at higher and lower temperatures. "Generalist-specialist" represents variation in the width of the TPCs and the trade-off between thermal breadth (σ_t) and maximal performance (P_{max}) at the optimal temperature (fig. 2, *bottom*). A natural question is, How is genetic variation in TPCs within a population or species distributed among these three modes? Recent statistical methods allow us to address this question (Izem and Kingsolver 2005). For example, analyses of TPCs for larval growth rates of the small cabbage white butterfly (*Pieris rapae*) reveal that generalist-specialist trade-offs accounted for 43% of the total genetic variation in TPCs; variation in optimal temperature (horizontal shift) accounted for another 21%. In contrast, variation in overall growth rate (vertical shift) rep-

Figure 2: Modes of variation in thermal performance curves; adapted from figure 1 of Izem and Kingsolver (2005).

1969). Recent studies with the cyanobacterium genus *Synechococcus* at Hunter Hot Springs (Oregon) nicely illustrate the process (Peary and Castenholz 1964; Miller and Castenholz 2000). Optimal temperatures (T_o) for clonal growth rate range from 40° to 65°C among different clonal genotypes (fig. 3); maximal growth rates tend to increase with increasing T_o up to ~60°C but decline at even higher T_o (see below). These phenotypic differences enable different clonal genotypes to adapt to different positions and temperatures along the thermal gradient (Miller and Castenholz 2000). The carbon-fixing gene *rbcL* encodes the large subunit of Rubisco, an autotrophic enzyme that is essential to growth in *Synechococcus* and other cyanobacteria. Adaptive evolution of *rbcL* appears to have occurred during the diversification of *Synechococcus* at high temperatures (Miller 2003). About 40 amino acid replacements have occurred in the hot springs clade (fig. 3); 10 such replacements have occurred since the evolutionary divergence of the (OH) lineage with the highest thermal tolerances. Many of these 10 amino acid substitutions are clustered near the active site for Rubisco, the photosynthetic enzyme encoded by *rbcL* (Miller 2003; fig. 3, *bottom*). Recent analyses suggest greater thermal stability for Rubisco from the most thermotolerant lineages of *Synecho-*
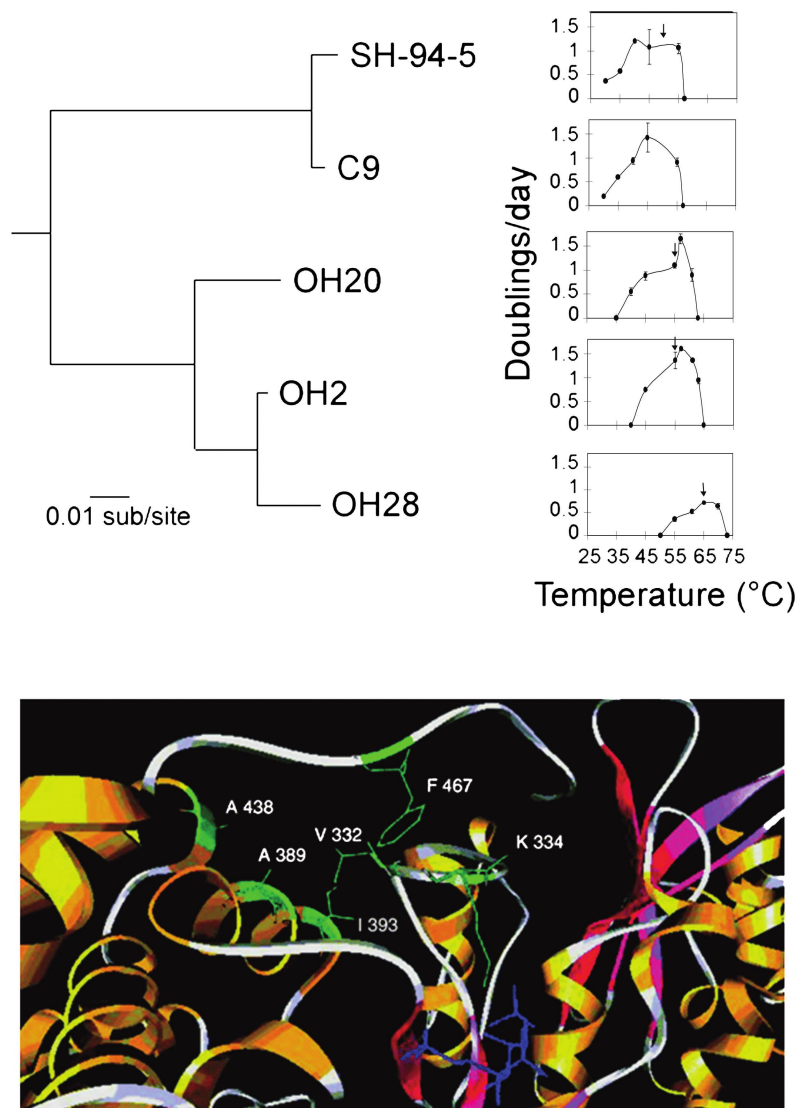

Figure 3: Thermotolerance in hot springs cyanobacteria *Synechococcus*. *Top*, phylogenetic pattern of thermotolerance in clones of *Synechococcus*; adapted from figure 2 of Miller and Castenholz (2000). *Bottom*, large subunit of Rubisco. The clustering of amino acid substitutions in the most thermotolerant (OH) lineage of *Synechococcus* are indicated; adapted from figure 5 of Miller (2003).

coccus (S. R. Miller, unpublished results). These studies illustrate how amino acid substitutions in key enzymes can affect thermal stability and thermal tolerance during adaptation, resulting in the evolution of thermal reaction norms even under these extreme conditions (Miller 2003).

What is the effect of a single mutation on the shape and position of the thermal reaction norm for fitness? Recent studies of thermal adaptation in G4 bacteriophage yield one answer (Knies et al. 2006). G4 has a circular DNA genome consisting of 11 genes and a rapid generation time of ~30 min. Knies et al. (2006) took advantage of an earlier study (Holder and Bull 2001) in which phage were adapted to high temperatures (44°C) over 100 transfer cycles, starting with a single ancestral phage genotype adapted to 37°C. Phage genotypes were sampled at several different time points during the experiment (including the ancestor and the end point), and the thermal reaction norm for fitness (clonal growth rate) was determined for each genotype (Knies et al. 2006). Sequencing the entire genome for each genotype identified 10 mutations that were fixed during adaptation; these mutations collectively increased optimal temperature, thermal breadth, and maximal fitness during adaptation (fig. 4). Of particular interest is the change from transfer 20 to transfer 50, in which a single mutation in a gene encoding a structural coat protein was fixed. This single substitution increases both the breadth and the height of the thermal reaction norm, resulting in increased fitness at higher temperatures (fig. 4). This same substitution also occurs in natural variants of G4 (Rokyta et al. 2006) and confers greater fitness at higher temperatures in those genetic backgrounds as well (Knies et al. 2006). These studies demonstrate how genomic and phenotypic analyses can be combined to understand evolutionary adaptation of thermal reaction norms.

Is Hotter Better? An Evolutionary Pattern

The examples described above suggest that the different modes of variation in thermal reaction norms may change in concert rather than individually. The "hotter-is-better" hypothesis suggests a specific type of concerted change. Hotter-is-better proposes that genotypes or species with relatively high optimal temperatures (T_o) also have relatively high maximal performance or fitness (r_{max}) at the optimum (Hamilton 1973; Bennett 1987). This is based on the thermodynamic argument that reaction rates of active enzymes increase with absolute temperatures, such that maximum reaction rates for species adapted to hot temperatures will be higher than those for species adapted to cold temperatures (measured at the optimal temperature for each; Frazier et al. 2006; Kingsolver and Huey 2008). As a result, the maximum potential fitnesses of
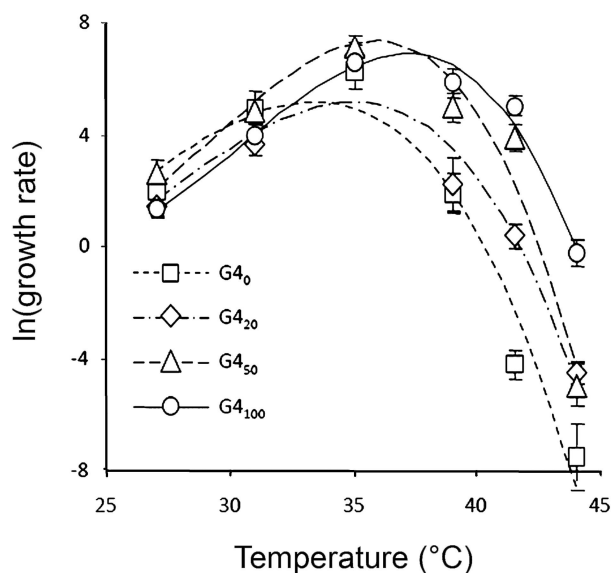

Figure 4: Thermal sensitivity of fitness for G4 phage during evolutionary adaptation to high temperatures (44°C). Mean curves for four time points (0, 20, 50, and 100 transfers) during adaptation are indicated; adapted from figure 3 of Knies et al. (2006).

adapted organisms will be greater in a warmer than in a cooler world.

Eppley's (1972) studies of thermal reaction norms for growth rate in algal species provided the first quantitative evidence supporting hotter-is-better. Several recent studies have further bolstered the idea. A comparative analysis of thermal reaction norms for fitness (the intrinsic rate of increase, r) with insect species from diverse orders demonstrated that evolutionary increases in T_o were positively associated with evolutionary increases in r_{max}, as predicted by hotter-is-better (Frazier et al. 2006; fig. 5, *top*). An analysis of natural variants in populations of G4 phage yielded a similar result (Knies et al. 2009; fig. 5, *bottom*). This suggests that the effect can operate at the level of genotypic variation within populations as well as for interspecific variation within taxonomic groups.

More than 20 comparative (Angilletta et al. 2010) and quantitative genetic (Gilchrist 1996; Kingsolver et al. 2004) studies have now addressed the hotter-is-better hypothesis in a variety of study systems. Support for hotter-is-better is quite mixed for some aspects of performance, such as locomotion, photosynthesis, and parasitism. Interestingly, support for hotter-is-better is much stronger from studies that consider fitness or traits, such as growth and development rates, that are often closely associated with fitness (Angilletta et al. 2010). Indeed, of the seven studies to date that consider fitness itself, only one does not significantly support hotter-is-better, and that is the *Synechococcus*
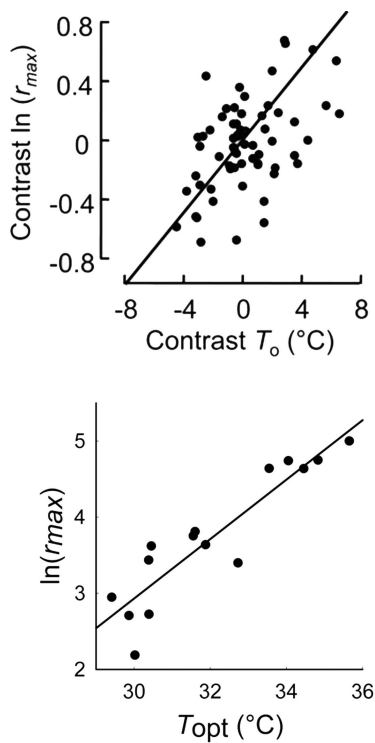
Figure 5: Hotter is better: the relation between optimal temperature (T_o) and maximum fitness (r_{max}). *Top*, comparative data (independent contrasts) for insect species; adapted from figure 3 of Frazier et al. (2006). *Bottom*, data for G4 phage clonal genotypes; adapted from figure 5 of Knies et al. (2009).

study considered above (fig. 3). This exception is largely due to the reduced r_{max} in *Synechococcus* genotypes with the highest optimal temperature (65°C), which approaches the upper thermal limit (73°C) for photosynthetic life itself (Brock 1967; Castenholz 1969); clearly, hotter-is-better cannot apply at these extreme limiting conditions.

Further evidence is needed to determine the generality of the hotter-is-better hypothesis for different taxa and for different aspects of performance. But the evidence now at hand strongly supports the hypothesis as it applies to fitness. The potential ecological and evolutionary consequences of this pattern—that maximal fitness is greater for systems adapted to warmer conditions—are intriguing and largely unexplored (Kingsolver and Huey 2008).

Size, Temperature, and the Temperature-Size Rule

Body size affects nearly all aspects of an organism's morphology, physiology, performance, and fitness (Peters 1983; Bonner 2006). As a consequence, phenotypic selection and microevolution of size have been abundantly documented (Hendry and Kinnison 1999; Kingsolver et al.

2001). One interesting pattern is that many studies show consistent directional selection for increasing body size (Kingsolver and Pfennig 2004): larger individuals tend to have greater survival, greater fecundity, and greater mating success. In contrast, evidence of stabilizing or balancing selection on size in natural populations is largely lacking (Kingsolver and Pfennig 2007; fig. 6).

The magnitude and directionality of phenotypic selection on size are quite strong, compared with those on other traits. The (variance-standardized) directional selection gradient β is a useful standard metric that quantifies the strength of selection relative to the phenotypic variance of a trait (Lande and Arnold 1983). From a summary of field studies (Kingsolver and Pfennig 2004), the median strength (β) and magnitude ($|\beta|$) of directional selection on size were 0.15 and 0.18, respectively; 79% of estimates of β were greater than 0 (fig. 6). For other morphological traits not related to size, the median strength (β) and magnitude ($|\beta|$) of directional selection were 0.02 and 0.16, respectively, and β was distributed symmetrically around 0 (fig. 6). Another important class of traits is phenology, the seasonal timing of key life-history events (e.g., dates of bud burst, flowering, and first reproduction). Phenological traits are increasingly important in the context of recent and future climate change; several studies have detected shifts in phenological events toward earlier dates
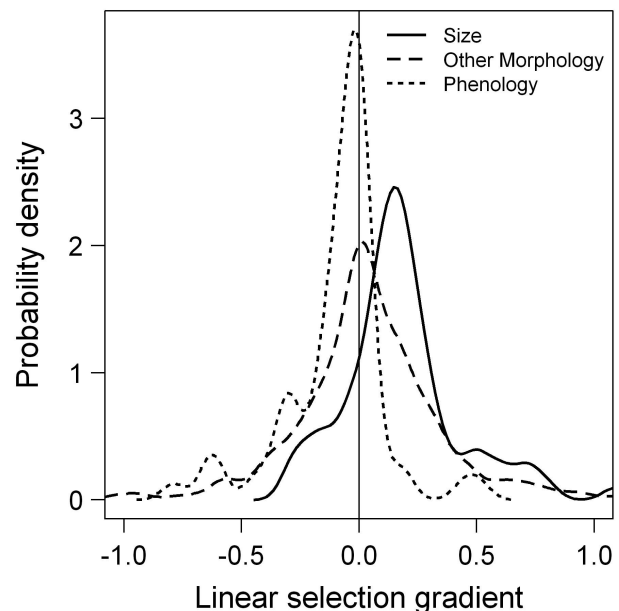
Figure 6: Probability density of estimates of the strength of directional selection (linear selection gradient β) in natural populations for three types of phenotypic traits: size, phenology, and other morphological traits; data from Kingsolver et al. (2001).

in diverse groups (Root et al. 2003; Parmesan 2006, 2007), and selection and evolution for earlier phenology have been widely predicted (Bradshaw and Holzapfel 2001, 2006). What are the patterns of directional selection on phenological traits in the wild? The available evidence is limited (65 estimates from 10 studies; Kingsolver et al. 2001), but the median strength (β) and magnitude ($|\beta|$) of directional selection on phenological timing were -0.05 and 0.06, respectively. The distribution of β was shifted significantly toward negative values (72% of β values were <0; fig. 6). These limited data suggest that the typical magnitude of directional selection on phenology is considerably smaller than that on size or other morphological traits. However, there is some evidence suggesting consistent directional selection for earlier seasonal timing in systems studied to date (Bradshaw and Holzapfel 2006). This analysis considers selection estimates reported over the time period 1984–1998; it would be instructive to see whether this pattern has changed in the past decade.

Body size and temperature also interact in a fundamental way: in most ectotherms, higher temperatures during development result in smaller final (adult) body size. This pattern, termed the temperature-size rule (TSR), is one of the most widespread forms of phenotypic plasticity, occurring in nearly 80% of ectothermic organisms in diverse taxa (Atkinson 1994). In evolutionary terms, the TSR indicates a negative slope for the thermal reaction norm that relates rearing temperature to adult body size. Both mechanistic and adaptive models have been proposed to account for the TSR, but a general explanation remains elusive (Angilletta et al. 2004). For holometabolous insects, a detailed physiological model correctly predicts the TSR from the thermal sensitivity of key growth and endocrine processes (Davidowitz and Nijhout 2004; Nijhout and Davidowitz 2009).

Reversals of the rule—where higher rearing temperatures generate larger final body sizes—may be particularly instructive for understanding the causes and generality of the TSR. Curiously, to my knowledge such reversals have so far been reported only in several orders of insects. For example, Walters and Hassall (2006) showed that reversal of the TSR in a temperate grasshopper matches predictions from an optimal life-history model (Walters and Hassall 2006). In addition, the TSR can sometimes be reversed by other environmental factors. For example, tobacco hornworms (*Manduca sexta*) follow the TSR when feeding on tobacco or on artificial diets but show a reversal of TSR when feeding on a novel, low-quality host plant (Diamond and Kingsolver 2010).

How rapidly can thermal reaction norms for size evolve? Laboratory (family) selection on reaction norm slope in *Drosophila* was able to eliminate or accentuate the TSR in only 20 generations (Scheiner and Lyman 1991). Two stud-

ies of insect colonization events suggest that thermal reaction norms can also evolve rapidly in nature. The small cabbage white butterfly (*P. rapae*) is native to Europe and northern Africa and occurs in a variety of open habitats and on a range of larval host plants in the family Brassicaceae, especially *Brassica*. *Pieris rapae* was introduced to eastern North America near the city of Québec in 1860, perhaps by Irish immigrants fleeing the potato famine (Guppy and Shepard 2001). It rapidly expanded its range to the south and west, reaching the southeastern United States by the 1870s and the west coast of the United States and southern Canada by ~1900 (Scudder 1887; Guppy and Shepard 2001). Populations of *P. rapae* from within its native range in England follow the TSR (Baker 1968). However, there is significant geographic differentiation in thermal reaction norms among North American populations of *P. rapae* (Kingsolver et al. 2007). For example, northwestern U.S. (Washington) populations follow the TSR for adult body mass, whereas southeastern U.S. (North Carolina) populations show a reversal of the TSR, in which mean mass at cooler rearing temperatures is smaller than that at warmer temperatures. There are both parental and genetic contributions to this pattern (Kingsolver et al. 2007). These population differences have likely evolved in the 100–150 years since the colonization of North America by *P. rapae* from Europe (Scudder 1887).

Drosophila subobscura provides an elegant example of rapid, repeatable evolution after colonization. In its native range across Europe, *D. subobscura* exhibits a strong geographic cline in size (e.g., wing length and area), with larger size at higher latitudes (Prevosti 1955). This size cline occurs even when animals from different populations are reared under common thermal conditions, demonstrating a genetic basis for the geographic clines. European populations also follow the TSR, with larger size at cooler rearing temperatures (Gilchrist and Huey 2004). In separate introductions, *D. subobscura* was introduced independently into both South America (by 1978) and North America (by 1982) and rapidly expanded its geographic range on each continent. Studies in the mid-1980s showed that there was no significant geographic differentiation in size among populations reared under the same temperature conditions within either North or South America (Pegueroles et al. 1995). However, by 2000, population divergence had generated size clines in both North and South America that paralleled the European cline (Huey et al. 2000; Gilchrist et al. 2004). Substantial evolutionary increases in size for higher-latitude populations in North and South America were particularly important in establishing these clines. Recent analyses by George Gilchrist and colleagues indicate that plasticity of size has also changed during this evolutionary process: the slopes of the thermal reaction norms for size are smaller in the New

World than those in Europe (G. W. Gilchrist and R. B. Huey, unpublished results). It is unclear whether these evolutionary changes are the result of reduced genetic variation for plasticity due to genetic bottlenecks during founding, direct selection on thermal reaction norms, or a correlated evolutionary response to selection on size at particular temperatures (Gomulkiewicz and Kirkpatrick 1992).

These two studies illustrate how selection and evolution in the field can weaken or even the reverse the TSR over short time frames of tens to hundreds of generations. Although physiological and developmental mechanisms may underlie the TSR and contribute to the prevalence of this pattern, it is clear that natural selection may act on variation in these mechanisms (and their thermal sensitivity) to alter and reverse the TSR quite rapidly. In this sense, thermal reaction norms provide a useful framework for exploring the interplay of mechanism and selection in the evolution of phenotypic plasticity (Angilletta and Dunham 2003; Angilletta 2009).

Thermal Sensitivity and the Impacts of Climate Change

Global climate change is here and will continue. One important lesson from recent observations and future predictions is that the rate and magnitude of climate warming are likely smaller in the tropics than at middle and higher latitudes (IPCC 2007). There is increasing evidence that plant and animal populations are already responding to climate warming in the past few decades, primarily through shifts in latitudinal range boundaries and in phenological timing (Parmesan et al. 1999; Bradshaw and Holzapfel 2001; Parmesan 2006). As a result, some recent analyses have predicted that the ecological impacts of climate change are likely to be smaller in the tropics than at higher latitudes (Root et al. 2003; Parmesan 2007). How can an understanding of thermal biology inform this discussion (Tewksbury et al. 2008)?

One important issue is that climate is defined in terms of specific diurnal and seasonal patterns of temperature, precipitation, and solar radiative conditions. The correlative structures of temperature and precipitation across diurnal, seasonal, and annual timescales frequently determine the distribution and abundance of species that occur in a geographic region (Kingsolver 2001; Helmuth et al. 2005). Ecological niche models depend critically on the correlations among different seasonal components of temperature and precipitation for modeling range boundaries and for predicting responses to climate change (Pearson and Dawson 2003).

One important challenge for forecasting the ecological impacts of climate change is that the correlative structure of climate may change in different regions during the mean annual global increase in temperature anticipated in the next 50–100 years, producing novel climate states with no current analogues and the disappearance of some extant climates. Williams et al. (2007) used global circulation models to model the distribution of such novel and disappearing climates in 2100 AD (Williams et al. 2007). Although the largest mean annual and winter temperature increases will be at higher latitudes, novel and disappearing climates will occur primarily in the tropics, especially in northern South America, central Africa, and parts of southeastern Asia (Williams et al. 2007). As a result, organisms in these tropical regions may experience climatic conditions unlike any they have experienced in their recent evolutionary histories. In a related analysis, Battisti and Naylor (2009) used observational data and climate model predictions to explore future patterns of high summer temperatures in different geographic regions. Their results suggest that record high summer temperatures will occur primarily in tropical and low-latitude regions by the end of the twenty-first century (Battisti and Naylor 2009).

The ecological impacts of climate change for a population or species will depend on both the magnitude and pattern of climate change and the thermal sensitivity of the organisms in question (Helmuth et al. 2005; Tewksbury et al. 2008). Following A. R. Wallace, Janzen (1967) predicted that tropical ectotherms will be thermal specialists, compared with higher-latitude relatives, because they evolved in relatively constant, aseasonal thermal environments. This predicted difference in thermal breadth between tropical and temperate species has been confirmed in several different groups of terrestrial ectotherms (Angilletta 2009).

Several recent analyses have explored the consequences of this difference, combining climate change scenarios with data on thermal sensitivity of ectotherms to predict the performance and fitness consequences of climate warming (Deutsch et al. 2008; Huey et al. 2009; fig. 7). Using data and models for 43 insect species across a range of latitudes, Deutsch et al. (2008) explored the predicted fitness consequences of climate warming. Their analysis suggests that predicted climate warming during the next century will increase mean fitness of species at temperate and higher latitudes but decrease mean fitness for tropical and low-latitude species (fig. 7). These results are due to two main factors. First, as predicted by Janzen (1967), tropical species have narrower thermal tolerances and thus are more sensitive to a given change in environmental temperature (fig. 7A, 7B). Second and more surprisingly, most tropical species are currently living at environmental temperatures very close to their optimal temperatures, such that even small increases in environmental temperature may have strong negative impacts on fitness. In contrast, species at higher latitudes are currently living at environmental tem-
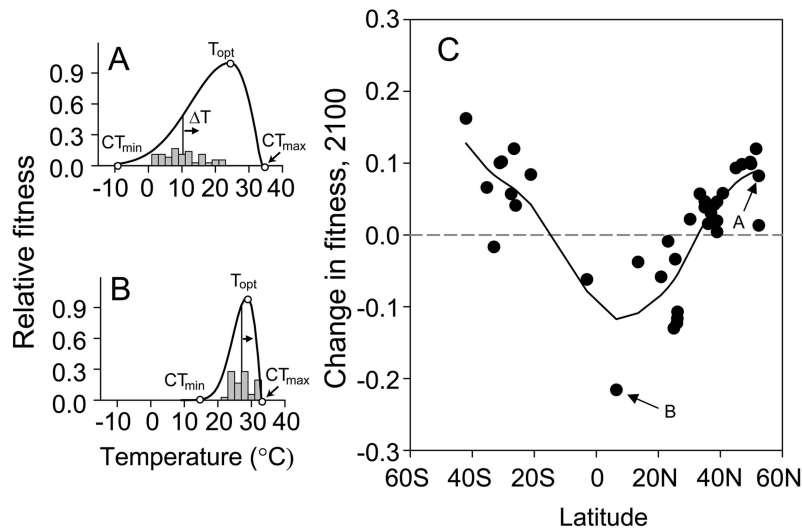
Figure 7: *A*, *B*, Thermal sensitivity of relative fitness (r) for a temperate (*A*) and a tropical (*B*) insect species. The optimal temperature (T_{opt}) and range of current environmental temperatures (*histogram*) are indicated for each. *C*, Predicted changes in fitness resulting from climate change in 2010 AD. Predictions for the two species in *A* and *B* are indicated. Adapted from figure 1 of Deutsch et al. (2008).

peratures cooler than their optimal temperatures, such that climate warming may enhance fitness (Deutsch et al. 2008; fig. 7). Huey et al. (2009) found similar results for tropical forest lizards, using analyses of the thermal sensitivity of locomotion and tolerance. Importantly, tropical forest lizards have surprisingly low optimal and critical thermal maximum temperatures, lower than those for many temperate-zone desert lizards (Huey et al. 2009). The general pattern emerging from these and related studies is that climate warming may have greater negative fitness consequences for tropical than for temperate ectotherms, even if the magnitude of warming is smaller in the tropics than in temperate regions.

Why do higher-latitude ectotherms have optimal temperatures that are higher than the environmental conditions in which they generally occur? Several factors may contribute to this pattern. First, there is greater variation in environmental temperatures at higher latitudes. Because TPCs are asymmetric, there are strong negative consequences of experiencing environmental temperatures above the optimal temperature. As a result, in variable environments the optimal temperature should be above the mean environmental (or operative) temperature (Ruel and Ayres 1999; Martin and Huey 2008). Second, if hotter-is-better applies, fitness may be maximized when optimal temperature is above the environmental temperature, even in a constant environment (Kingsolver and Huey 2008; Knies et al. 2009). Third, the appropriate measure of "average" fitness in a variable thermal environment depends on how temperature affects different components of fitness

within and between generations. As a result, decreases in survival at temperatures above the optimal temperature may weigh disproportionately in overall fitness (Lynch and Gabriel 1987; Gilchrist 1995). However, present models for the evolution of thermal sensitivity that incorporate these factors still do not fully account for the "high" optimal temperatures of temperate organisms (G. W. Gilchrist, unpublished results; J. G. Kingsolver, J. J. Tewksbury, C. A. Deutsch, and R. B. Huey, unpublished results). More work on the thermal safety margins of higher-latitude organisms is needed (Deutsch et al. 2008).

Climate Change: Adaptation or Extinction?

These recent analyses predict that climate warming will reduce mean fitness of many tropical ectotherms as environmental temperatures exceed the optimal temperatures for these species. Three possible outcomes of these predicted changes are migration into cooler regions, population or species extinction, and evolutionary adaptation. The effectiveness of migration will be limited by the shallow latitudinal temperature gradient in the tropics and by opportunities for elevational shifts in many systems (Colwell et al. 2008; Chen et al. 2009). As documented above ("The Mechanisms of Thermal Sensitivity"), there is abundant evidence (albeit primarily in temperate systems) from both experimental and comparative studies of genetic variation and of rapid evolution of thermal sensitivity in response to changing environmental temperatures. Will

tropical ectotherms adapt evolutionarily to climate warming in the coming decades?

Theoretical models suggest that the answer will depend on the interplay between ecological, environmental, and evolutionary factors (Lynch and Lande 1993). Consider a population at a mean environmental temperature θ (with stochastic variance σ_e) that is increasing at some constant linear rate k. Within this population, there is genetic and phenotypic variation in thermal performance curves for fitness, defined by optimal temperature T_o and thermal breadth σ_t. Suppose that at time 0 the population is perfectly adapted to environmental conditions, such that the mean optimal temperature T_o in the population matches the mean environmental temperature θ. As environmental temperatures increase over time, the mean T_o in the population begins to lag ($\lambda = \theta - T_o$) behind the changing mean environmental temperature θ, reducing the mean fitness of the population.

Deterministic and stochastic models of this scenario show several possible outcomes (Huey and Kingsolver 1993; Lynch and Lande 1993; Bürger and Lynch 1995; Gomulkiewicz and Holt 1995). One possibility is that the lag between the population mean phenotype (T_o) and the environmental temperature will continue to increase until the mean population fitness declines to 0 and the population becomes extinct. Alternatively, selection can generate evolutionary increases in the mean T_o. In time, the balance between continuing environment change and evolutionary adaptation approaches a steady state at which the lag λ between mean environmental temperature and mean population phenotype is constant; in this case, evolutionary adaptation can prevent extinction. For any particular population, there is a critical rate of climate change k_c that determines whether the population will become extinct or adapt (Lynch and Lande 1993).

Theoretical analyses identify several major factors that will increase the critical rate of climate change k_c and enable adaptation to reduce the likelihood of extinction (Huey and Kingsolver 1993; Lynch and Lande 1993; Bürger and Lynch 1995; Gomulkiewicz and Holt 1995). First, shorter generation times can facilitate more rapid evolution, reducing the lag λ and increasing k_c. Increasing genetic variation in thermal sensitivity has similar effects. Second, greater maximal fitness under optimal conditions (e.g., R_{max} or r_{max}) can speed evolution and can prevent the mean population fitness from declining below replacement rate as selection occurs, making adaptation more likely. Similarly, larger population size can reduce demographic stochasticity and reduce the likelihood of extinction. Third, stochastic environmental variation (σ_e) generally increases the lag and decreases the critical rate of climate change.

The effects and evolution of thermal breadth σ_t on re-

sponses to sustained climate warming are interesting and complex (Huey and Kingsolver 1993; Bürger and Lynch 1995). Increased thermal breadth σ_t initially reduces the fitness consequences of climate change, allowing the population to accommodate to new conditions. But by reducing the strength of selection, increased σ_t will also increase the steady state lag of the population and can thus increase the likelihood of extinction. Increased thermal breadth may also increase the genetic variance in T_o maintained in the population by altering the mutation-selection balance. The combined effects of these factors are complex, but for reasonable rates of climate change, an intermediate thermal breadth generally increases the likelihood of adaptation and decreases the risk of extinction (Huey and Kingsolver 1993; Bürger and Lynch 1995).

What are the lessons from these models for understanding the likelihood of adaptation or extinction of tropical ectotherms in response to climate warming? Using available information on mean rates of climate warming, thermal sensitivities, and maximal fitness, one can predict that adaptive evolution in many tropical insects has the potential to reduce the likelihood of extinction due to the direct thermal effects of climate warming, assuming that current population sizes are not too small. This is due to the short generation times (1 year or less) and high maximal reproductive potential of many tropical insects. Interestingly, the relatively narrow thermal breadths of tropical species may increase rather than decrease the possibility of adaptive escape from extinction. These tentative predictions assume that there is sufficient genetic variation in thermal sensitivity, about which very little is known for tropical insects (or other tropical ectotherms). Unfortunately, the potential role of adaptive evolution for tropical lizards may be much more limited, because of their longer generation times and much smaller maximal clutch sizes. In both cases, a key issue is whether selection will reduce the mean fitness of a population below replacement rate during the early stages of climate change; at that point, sufficient adaptive evolution to prevent extinction can occur only under quite restrictive conditions (Gomulkiewicz and Holt 1995; Holt et al. 2003, 2004).

Recapitulation

Toward the end of his time at Weimar, Bach began work on a masterpiece that was quite different from the Passacaglia: *The Well-Tempered Clavier*. *The Well-Tempered Clavier* addressed a major musical challenge whose solution we now take for granted: how to tune a keyboard (Schweitzer 1966). Before the eighteenth century, keyboard instruments were tuned according to "natural-temperament," the system based on the natural harmonics that emerge from dividing a vibrating string at simple intervals

(one-half, one-quarter, etc.). This system, known in the West since at least the ancient Greeks, was thought to reflect the natural order of music—the harmony of the gods (or in more recent religious traditions, God). But if natural temperament is used to tune a keyboard, the result is that intervals in some keys sound badly out of tune, restricting keyboard music to a handful of keys. During the late seventeenth and early eighteenth centuries, musicians experimented with a variety of unnatural, "well-tempered" systems of tuning, which eventually led to our current system of "equal temperament" (12 equally spaced intervals in an octave). While this solution may seem obvious in retrospect, most keyboard tuners will likely agree that equal-tempered tuning is neither simple nor intuitive. In *The Well-Tempered Clavier, Part 1* (1722), Bach explored the full range of keys inherent in Western music; it is a collection of preludes and fugues in both major and minor keys, for each of the 12 tones in the diatonic scale. The first piece in the *Well-Tempered Clavier*, the lovely Prelude in C Major, is among the most famous; this prelude may be familiar to many as the background for a nineteenth-century setting of "Ave Maria" by Gounod (an audio file is available in the online edition of the *American Naturalist*). The exact tuning system that Bach had in mind is still unclear, but *The Well-Tempered Clavier* was the first systematic exploration of all the possible keys in Western music. By moving beyond the "divine harmony" of natural temperament, *The Well-Tempered Clavier* helped to reveal the real diversity of music that is possible and that other composers have explored throughout the past 3 centuries. More than a century later, during Darwin's life, a comparable shift in perspective was required to move beyond the limitations of special creation and the fixity of species, to reveal the true history and diversity of life on earth (Darwin 1859; Ruse 1979).

For the well-temperatured biologist, temperature provides a unifying theme for understanding adaptation to environmental variation across all levels of biology. The variations I have explored here provide several useful lessons. First, the thermal sensitivity of biochemical reaction rates can be readily modeled from the basic thermodynamic principles that underlie enzyme kinetics and enzyme stability. The thermal sensitivity of biological rates of performance and fitness at the whole-organism level—the thermal performance curve—exhibits the same shape and asymmetry as that of enzyme reaction rates. We can readily decompose genetic variation in thermal performance curves in terms of variation in optimal temperature, thermal breadth, and other features, and we can quantify the effects of single mutations and amino acid substitutions for the shape and position of these performance curves. One general prediction that emerges from these thermodynamic considerations is the hotter-is-better hypothesis,

which predicts that increased optimal temperature allows greater maximum performance or fitness at the optimum. The implications of this pattern—that greater maximal fitness is possible in a warmer world—have not been fully explored.

Second, size is special. There is positive directional selection favoring increased size in many natural populations, and phenotypic selection on size is considerably stronger than selection on seasonal timing (phenology) or on other morphological traits. The temperature-size rule, whereby increased developmental temperature decreases adult body size, is one of the most common forms of phenotypic plasticity in a wide range of taxa. Mechanistic models can explain the existence of the temperature-size rule in some groups on the basis of the thermal sensitivity of underlying growth and endocrine processes. But recent field studies demonstrate that the temperature-size rule can be weakened or even reversed as a result of rapid evolution in natural populations. The interplay of mechanism and adaptive evolution in generating and reversing the temperature-size rule deserves further study.

Third, several recent analyses of thermal sensitivity and responses to climate change predict that the negative fitness consequences of climate warming will be much greater for tropical ectotherms than for temperate and higher-latitude ectotherms. This is predicted despite the fact that the magnitude of climate warming will be smaller in the tropics than at higher latitudes. The greater negative impacts of climate warming in the tropics result from three factors: novel and disappearing climates will be more frequent in the tropics, tropical ectotherms have narrower thermal breadths than temperate ectotherms, and the difference between current environmental temperatures and optimal temperatures (the thermal "safety margin") is much smaller for tropical than for temperate ectotherms. The importance of this last factor has not been widely appreciated, but it may be critical to understanding the biological consequences of climate change for ectotherms. Current models for the evolution of thermal sensitivity do not fully account for the large thermal safety margins of most higher-latitude ectotherms. Evolutionary models for the response to sustained, directional climate change suggest that adaptive evolution of thermal performance curves may ameliorate the fitness consequences of climate warming and reduce the risks of extinction in some tropical insects. However, given current and predicted rates of climate warming, adaptive evolution may contribute little to reducing extinction risks in most tropical lizards, because of their longer generation times and smaller clutch sizes. Further modeling and analysis of thermal safety margins and the building of more-realistic models of evolutionary responses to climate change are needed to give greater confidence to these tentative predictions.

Note Added in Proof

A recent paper (Kellermann et al. 2009) indicates that narrowly distributed tropical species of *Drosophila* have low genetic variation in desiccation and cold tolerance, compared with more widespread temperate species of *Drosophila*.

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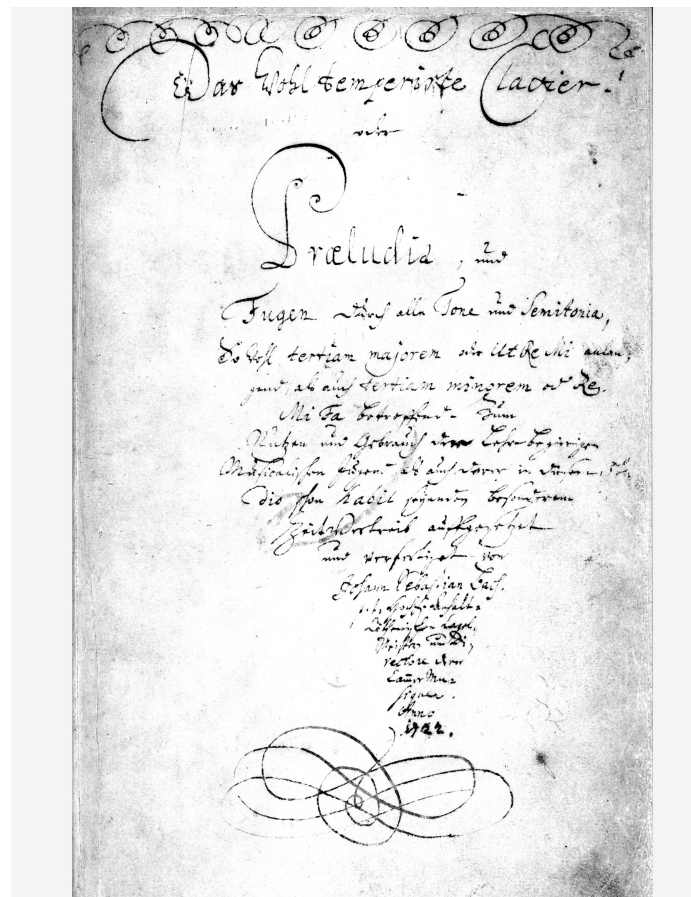
Title page for J. S. Bach's *The Well-Tempered Clavier*, Part I (1722).