**High temperature structures tropical forest *Drosophila* communities: evidence from physiological and population level measures**

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JC and OTL both contributed to the development of ideas. JC designed and conducted the experimental work. JC analyzed the results and led the writing of the manuscript. OTL contributed to the writing.

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**Abstract:**

Tropical insects are challenged by global warming, presumably altering their distribution and the related ecosystem functions. Multiple abiotic factors and biotic factors can influence species response to climate change. The importance of high temperature in influencing species’ distribution at the warmer boundaries is still controversial. Therefore, to precisely estimate the real magnitude of the impact of warming on tropical species, the correlation between species’ thermal physiology and realized distribution needs to be examined in the first place. Reproductive success is key to long-term population growth. Physiological response to the sublethal condition is tightly linked with survival during a short period of extreme weather. We examined the relationships between these lab-measured thermal traits and the altitudinal distribution of Drosophila species in the Australian rainforest mountains. Our findings reveal that the tropical lowland community is already structured by high temperature as the dominant *Drosophila* species share higher tolerance to heat with respect to both reproduction and physiology. In contrast, upland species do not show stronger cold tolerance. These results provide the foundation for elucidating the role of temperature in structuring the biological community on tropical mountains and imply the vulnerability of upland tropical insects to future warming.

**Introduction**

Temperature is one of the fundamental environmental factors deciding species’ ranges and abundance (Hoffmann and Blows 1994). Insects are directly challenged by warming because their reproduction, survival, growth, and behavior are dictated by the environmental temperature (Huey and Kingsolver 1989; Huey and Stevenson 1979). Warming-induced directional shifts in species’ distribution (Moritz et al. 2008; Parmesan et al. 1999) and phenology (Peñuelas and Filella 2001; Renner and Zohner 2018) have been documented. The resulting change of insects’ ecological functions imposes direct environmental and economic threats (Deutsch et al. 2018; Logan, Régnière, and Powell 2003; Pecl et al. 2017).

Thermal tolerance, which is derived from either laboratory measures or observed distribution, has been used in species distribution models to evaluate species’ sensitivity to climate change (Kearney and Porter 2009). The impact of warming to tropical species is still much debated, from least to most concern among major biotas (Corlett 2011). Tropic species on average have narrower range than temperate species (Khaliq et al. 2014) and have been living near their upper thermal limits suggested by laboratory measurements (Deutsch et al. 2008; Diamond et al. 2012; Huey et al. 2009). Tropical species are thus predicted to face particular difficulty to tolerate or adapt to the projected warming in their current location (Bonebrake and Deutsch 2012; Deutsch et al. 2008; Kellermann et al. 2012), and to track the relatively large shift of their “climate envelope”, the projected suitable climate zone that moves toward higher latitude or altitude (Colwell et al. 2008; Sheldon, Yang, and Tewksbury 2011).

However, it is uncertain whether thermal tolerance is the key predictor of distribution in the warmer margins. The observation that species occupying the cooler environment have similar upper thermal limits with tropical species poses doubt on the importance of high temperature in structuring tropical communities (Huey et al. 2009; MacLean et al. 2019; Nowrouzi et al. 2018; Overgaard, Kearney, and Hoffmann 2014). Instead, other abiotic factors (e.g. precipitation) and biotic interactions may become the determining factors in the tropics (Engelbrecht et al. 2007; Jankowski et al. 2013; Louthan, Doak, and Angert 2015). Indeed, asymmetry has been observed in the relative role of high and low temperatures in determining species’ distribution. Physical constraints by the low temperature are thought to have a more profound role in setting the limit of distribution range (Bishop et al. 2017; Ettinger, Ford, and Hillerislambers 2011; Kimura 2004; de La Vega and Schilman 2018; Overgaard et al. 2014). Large comparative studies suggest that heat tolerance varies less than cold tolerance (Hoffmann 2010; Kellermann et al. 2012; Sunday et al. 2019). Organisms in the warmer environment are thought to experience less physical constrain but higher level of biotic interactions (Roslin et al. 2017), which predominantly drive ecological limits at the warm boundaries (O’Brien et al. 2017). This asymmetry is supported by the observed smaller change at the species’ warm boundaries than cold boundaries in response to warming (Chen et al. 2011; Sunday, Bates, and Dulvy 2012), undermining the gloom prediction for the tropical species in response to warming.

Unlike the flat latitudinal temperature gradient in the tropics, tropical mountains provide the natural gradient to test the sensitivity of tropical species to temperature (Corlett 2011). Rainforest in the Wet Tropics bioregion in north-eastern Australia has high biodiversity values especially for its high degree of endemism in its cool, moist upland refugia (Williams, Bolitho, and Fox 2003). Species composition significantly changes along the altitude gradient on those tropical mountains (Williams et al. 2003). Although temperature varies markedly with rising altitude by physical rules, it remains unclear whether temperature directly drives the species’ abundance patterns in this region. To validate the causal effect of temperature, there remains a need for data from groups of ecologically similar, related species (Calosi et al. 2010) to reveal the relationship between species’ thermal physiology and biogeography. The generality of this relationship is essential to realistically estimate the magnitude of the impact of warming on tropical species.

Frugivore flies are sensitive to temperature on the organismal level (Batista, Rocha, and Klaczko 2018), while their population size is additionally regulated by humidity, food availability, competition, and natural enemies (e.g. parasitoid wasps) (Fletcher 1973; Krebs and Barker 1991; Mitsui et al. 2007). The relative abundance of frugivore flies can be easily surveyed through baiting (Jeffs et al. 2020). Multiple laboratory measurements of their thermal performance have been largely developed in the past two decades (Hoffmann, Sørensen, and Loeschcke 2003): Reproduction indicates a long-term response of the population-level performance within communities; Physiological response to sublethal condition links more tightly with organisms’ capacity to survive during a short period of extreme climatic conditions (Overgaard et al. 2014). By comparing thermal traits and realized distribution, this model system can be used to answer whether the temperature is the driver of distribution in the tropics and what mechanisms are involved.

Here, we study the effect of high temperature and low temperature on species turnover of *Drosophila* communities along the altitude gradients. We hypothesized that low temperature constrains species’ distribution at tropical highland; in contrast, higher abundance toward tropical lowland is not a result of high temperature. Therefore, species which are found predominantly at high altitude (compared with themselves) are predicted to have the stronger cold tolerance; while the heat tolerances are similar among all the species and/or do not correlate with their distribution types. To test the hypotheses, we first demonstrated the species turnover patterns along the altitude gradients and studied the relationship between the species’ abundance pattern and thermal tolerance based on different performance. Our findings revealed that on the contrary to the predictions, heat tolerance, rather than cold tolerance, is correlated with distribution type. Physiological tolerance and reproductive tolerance agree with each other in predicting distribution. These results suggest that high temperature already constrains the upland *Drosophila* species on Australian tropical mountains, thus implying their vulnerability to future warming.

**Methods**

1. Study system

Field data were collected, and laboratory cultures were initiated, from rainforest sites spanning elevations of from 59 – 916 m at Paluma Range (S18° 59.031' E146° 14.096') and Kirrama Range (S18° 12.134' E145° 53.102'), Queensland, Australia. Mean temperatures at study sites ranged from 21°C to 26°C.

*Drosophila* isofemale cultures were established in 2017 and 2018 from pupae collected from both high- and low-altitude sites. Cultures had been maintained at 24°C and 12/12 L/D cycle at the Biology Centre, Czech Academy of Sciences since collection and transferred and maintained at 25°C and 12/12 L/D cycle at the Department of Zoology, the University of Oxford, UK, since December 2018. Theywere maintained for approximately 15 to 30 non-overlapping generations in Czech Republic and additional approximately four to seven non-overlapping generations in Oxford before they were used to construct mass bred lines (see below).

1. Field distribution survey

*Drosophila* pupae were sampled using bottle traps baited with fermented banana from 11th March – 12th April 2016. Details were described in Jeffs et al. 2020. Relative abundance was surveyed for three sites representing the highest, lowest, and most central points of each of the two mountains. 182 pupae were sampled at each site. 716 pupae were successfully identified to species by DNA metabarcoding (Jeffs et al. 2020), with 86 – 134 pupae at each site. *D. serrata* (1 individual) and *D. immigrans* (4 individuals) were excluded from the distribution analysis due to infrequent occurrence.

1. Preparation of experimental animals

To revive genetic variation, we constructed mass bred lines (MBLs) by combining four isofemale lines of each *Drosophila* species (except for *D. pandora*, where only three isofemale lines were available). The four lines were selected from different mountains and different altitude if possible (Detailed arrangement was shown in supplementary table 1). Each population cage was initiated using two independently-reared MBLs of the same species. Cages were maintained at 25°C and 12/12 L/D cycle for more than four generations before the experiment. Therefore, thermal traits should not have been influenced by maternal effect, acclimation, or isofemale line effect. MBLs of eight Australian *Drosophila* species and one laboratory strain (wild typeDah) of *D. melanogaster* were used for laboratory measurement of thermal performance. *D. melanogaster* does not occur naturally at the study sites, was measured together with the focal species as a benchmark for future comparisons.

Fly eggs collected from the population cage were reared under low-density (less than 100 eggs per vial) at 25°C and 12/12 L/D cycle. Within 12 hours of emergence, virgin females and males were separately kept at 25°C and 12/12 L/D cycle. We additionally mixed five females and five males in each of two vials to monitor their reproductive activity every day. As different species have different development times and sexual maturation times, eggs of different species were collected from cages on different days so that their first day of egg-laying was synchronized. Two days after sexual maturation, half of the adults were subjected to fecundity measurement and the other half, which were siblings, were subjected to physiological measurement.

1. Fecundity measurement

Two virgin females were paired with two virgin males on a 4ml *Drosophila* medium (Percentage concentration (weight/volume): 8% corn flour, 4% yeast, 5% sugar, 1% agar, and 1.67% methyl-4-hydroxybenzoate.). They were randomly subjected to water baths set at one of the seven constant temperature (14°C, 17°C, 20°C, 23°C, 26°C, 29°C, 32°C) and 12/12 L/D cycle. Vials were submerged in water baths. The water level was kept above the area that flies could freely move. The temperature and humidity of each water bath were monitored in two additional empty tubes. The level of humidity was similar to field condition, ranging between 80% - 95%. The observed temperature showed ±0.5°C fluctuation around the mean temperature, which was used as the corrected temperature in analysis (Supplementary table 2 [both centre and corner logs]).

As fecundity changed through time and this trend of change was influenced by temperature (Supplementary figure 1), the offspring numbers were measured for the 1st – 2nd day and the 7th – 8th day and they were combined to reflect relative fecundity. After eight-day temperature treatments, all flies were kept at 25°C for another four days to examine the recovery of reproduction. Surviving flies were recorded at the beginning and end of each period. Vials containing eggs produced during the testing periods were maintained at their corresponding temperature for development. Vials were examined daily for emergence. The first emergence dates were recorded for different temperatures and the numbers of F1 adults were frozen after 5-7 days and counted later. For each species and each temperature treatment, eight replicates were evenly split between two blocks. The detailed schedule is shown in supplementary figure 2.

1. Physiological measurement

Critical temperatures (CTmin and CTmax), half lethal temperature (LT50cold and LT50heat), heat stress survival, knockdown (heat coma and chill coma) time, recovery time, etc. have been common practice to compare relative resistance to heat stress and cold stress (Gibert et al. 2001; Hoffmann et al. 2003). Critical temperature becomes more popular for its direct association of climate data. However, the absolute value of CTmin and CTmax is significantly influenced by the rate of temperature change (Terblanche et al. 2007), making it difficult to compare between studies. Knockdown time and recovery time are simpler measure which also serve the purpose of comparing thermal tolerance. Variation has been observed among species and geographic ranges (Gibert et al. 2001; Hoffmann, Anderson, and Hallas 2002), and knockdown/recovery time were correlated with other measurement, such as critical temperature (Andersen et al. 2015).

How to assess Drosophila heat tolerance: Unifying static and dynamic tolerance assays to predict heat distribution limits

knockdown time has linear relationship with testing temperature (static). They accord well with distribution ecotypes. Knockdown time at 40C capture the variance and produce time scale which is easy to measure logistically. (Jørgensen et al., 2019)

Relative tolerance to extreme cold temperature was measured by individuals’ knockdown time at 5°C and the time for recovery of mobility after a 30-minute exposure to 5°C. Constant temperature for cold stress are often chosen around 0°C (Gibert et al. 2001). As tropical species often have significantly lower cold resistance (Gibert et al. 2001), 5°C was used instead to increase the variation among the tested species (pilot results not shown). Heat stress is chosen to be 40°C, following common practice (Hoffmann et al. 2003). After being knocked down by heat (40°C), most flies did not survive. In this case, only knockdown time was used to evaluate tolerance to the extremely high temperature.

Measures of CTmin, LTe50 and LTi50 proved to be the best predictors to describe the variation in realized latitudinal distributions. there was only a weak correlation between the entrance into coma (CTmin) and the recovery from chill coma (CCRT) (Anderson, 2015)

Virgin adult flies were kept in groups at 25°C and 12/12 L/D cycle for 9-10 days before randomly-selected individuals were allocated separately in empty flat-bottom 3ml insect tubes. An observation rack was divided into 3X3 grids and each grid held seven tubes containing the same species. Nine species were assigned in random order to one grid. The observation rack was moved immediately into the incubator, representing the start of the heat or cold treatment. Every tube was examined once every minute and the flies that lost or recovered their motor ability were recorded. For each sex, three identical blocks of the above procedures were repeated.

1. Data analysis

All statistics were performed with R statistical software (version 3.6.0 ). All analysis code is available in ??GITHUB or SUPP??. *D. melanogaster* and *D. simulans* were not included in analyses involving field distribution, because their distribution patterns were unavailable.

*Distribution*. To calculate the abundance-weighted central altitude (hIndex) of distribution, the relative location of each sample was assigned 0, 0.5, and 1 if it was collected at low-, middle- and high-altitude sites. In addition, intra-specific abundance patterns were assessed by logistic regression of detection probability with altitude. For each species, pupal identity was labeled as 1 if the pupa was identified as the focal species and 0 if it was identified as any other species. Their identity was fitted against the altitude as the fixed effect and the transect as the random effect in generalized linear mix-effect model (varying intercept, varying slope) using the *lmer* package. These two ways of describing distribution patterns were compared using a Spearman’s rank test.

It is important to note that the abundance patterns we focus here is to compare the abundance of a species with itself along the altitude, rather than to compare the abundance of multiple species in a given location. By this definition, an upland-biased species may have higher absolute value of population size than the lowland-biased species in the lowland.

*Thermal performance curve*. A multi-level, non-linear piecewise model was fitted under the Bayesian framework using MCMC sampling within the *rstan* package in R. Total offspring numbers were calculated by combining the offspring numbers on day 1-2 and day 7-8. The average daily fecundity per female was calculated, then square root transformed. Square-rooted daily fecundity was modeled with the Briere2 function (Briere et al. 1999):

Y = a \* T \* (T - RTmin) \* (RTmax - T)^(1/b) (RTmin < T < RTmax),

Y = 0 (T <= RTmin or R >= RTmax),

where T is the temperature, *RTmin* and *RTmax* is the minimum and maximum temperature for the species to reproduce, *a* is a scaling factor and *b* is a shape factor of the curve. *a*, *b*, *RTmin*, and *RTmax* of the nine species were assumed to share normal distribution respectively. Square rooted daily fecundity was modeled using a normal distribution with temperature-dependent standard deviation. Assuming temperature dependency of standard deviation generated better fitting than assuming the same standard deviation across temperature treatments, as judged by leave-one-out cross-validation. It was because when the temperature was equal or close to *RTmin* and *RTmax*, the standard deviation should be zero or close to zero. A normal distribution is not ideal to model the transformed count data, which are all positive. However, modeling offspring counts with Poisson, zero-inflated Poisson, negative binomial, lognormal distribution did not produce converged results, potentially due to the piecewise nature of the thermal performance function. Diagnostics were performed and the model performance is acceptable (supplementary figure 3). Non-informative priors were chosen for all parameters. The values of *a* were bounded to be positive. The values of *b* were bounded to be larger than 0.8 to ensure that the thermal performance curve has a steeper slope on the right side. The values of *RTmin* were bounded to be lower than 17°C and the values of *RTmax* were bounded between 26°C - 35°C according to experience.

Median of the posterior distribution of *a*, *b*, *RTmin*, and *RTmax* were used as the model parameters to construct the thermal performance curve.

The model parameters were also estimated by the maximum likelihood method using the *bbmle* package. Total offspring numbers were modeled by Poisson distribution. This method was not multi-level; therefore, the shapes of curves of different species varied more than when assuming shared distributions of model parameters. Besides, this method behaved badly in estimating the uncertainty of the parameter estimation. Nevertheless, the ranks of the *RTmax* (rho = 0.88, p = 0.003, Spearman’s rank test) and *RTmin* (rho = 0.97, p = 0.00016, Spearman’s rank test) estimated by both methods are highly correlated.

*Reproduction-related traits*: The posterior distributions of *RTmin*, *RTmax*, and *RTopt* (6000 samples of each parameter of each species) were modeled by hIndex as the fixed effect and species identity as the random effect in the linear mix-effect model. Fecundity of 29°C and 17°C, recovered fecundity after 29°C and 14°C were used as direct measurements of their performance in the high and low temperatures. The offspring numbers were modeled by hIndex and experimental block as fix effects and species as a random effect in the generalized linear mix-effect model (family = “negative binomial”). Diagnostics of the models were conducted. Data points with extreme leverage value were excluded and the model was fitted again to test if the statistical significance still holds.

*Physiological tolerance*. The six measurements of physiological tolerance were modeled by hIndex, block, and tube position as fixed effects, species as a random effect in the linear mix-effect model.

*Correlation analysis*. The pairwise correlation among thermal traits was evaluated by Spearman’s rank test in *Hmisc* package. Traits included RTmin, RTmax, RTopt, median knockdown time to hot of female (FKDHEAT), median knockdown time to hot of male (MKDHEAT), median knockdown time to cold of female (FKDCOLD), median knockdown time to cold of male (MKDCOLD), median recovery time from cold of female (FRCCOLD), median recovery time from cold of male (MKDCOLD).

**Results**

The nine *Drosophila* species shown in figure 1a accounted for 99% of samples. Abundance patterns across the altitude gradient differed among species. The regression coefficient evaluated how detection probability change along with altitude (supplementary figure 4). Values of the regression coefficients correlated tightly with the weighted central altitude (hIndex) of distribution (rho = 0.98, p-value < 0.001, Spearman’s rank test). For simplification, the hIndex was used to represent the distribution pattern in the following analysis.

*D. bipectinate* and *D. pandora* were categorized as lowland-biased species with high confidence. *D. pseudoananassae* was most likely to bias towards lowland. *D. rubida* and *D. sulfurigaster* showed no significant change with altitude. *D. birchii* was most likely to bias towards highland. *D. palidifrons* and *D. pseudotakahashii* were significantly enriched in high altitudes. The only six samples of *D. bunnanda* were all found at low altitude, which might explain the peculiar value of its estimated coefficient (coefficient = -69, not shown in figure 1b) and its large standard error (se = 21603). Another larger-scale study also confirm that it was found predominantly at lowland (Schiffer and McEvey 2006). Therefore, *D. bunnanda* was categorized as lowland-biased species. As shown by supplemental figure XX, species that are closely related did not share the same distribution type.

Thermal performance curves of daily fecundity per female vary in the range, optimal temperature, height, and shape among species (figure 2). Table 1 shows estimates of the parameters of the Briere’s function for each species. *D. bunnanda* and *D. birchii* are closely related, but have completely opposite distribution types. The lowland-biased species *D. bunnanda* have higher minimal temperature, optimal temperature and maximal temperature than the upland-biased *D. birchii*, corresponding to their distribution types. In contrast, *D. sulfurigaster* always outperforms its upland-biased relative, *D. palidifrons.* The temperature for optimal reproductive performance (RTopt) did not correlate with their distribution patterns (coefficient = 0.068, 95% ci = -1.93 – 2.07). “hotter better” and “jack for all, master for none” hypotheses are not supported.

Values of RTmin had no relationship with the species distribution patterns (coefficient = 0.024, 95% ci = -2.47 – 2.52). Similarly, upland-biased species did not show higher fecundity at the stressfully-low temperature, 17°C (p = 0.788). For example, *D. palidifron* has the highest RTmin and lowest reproductive success at 17°C, while it is found predominantly at high altitude. When exposed to acute sublethal low temperature (5°C), except for *D. simulans* and *D. melanogaster*, the other *Drosophila* species all show similarly weak resistance (male: p = 0.18; female: p = 0.53). All species recovered their fecundity after eight-day exposure to 14°C. This recovered fecundity showed a minor but not significant increase (coefficient = 0.35, p = 0.105) for the upland-biased species. They also spent a longer time to recover from the chill coma (male: p = 0.054; female: p = 0.029), which is presumably disadvantaged in the upland environment. Species that had lower RTmins did not show any advantage in the short-term cold resistance or cold recovery (spearman’s rank rho = XXX, table 2).

Species whose distribution were biased towards lowland show higher RTmax (coefficient = -2.52, 95% ci = -3.68 - 1.36, p = 0.00125). Reproductive performance at 29°C decrease with hIndex (coefficient = -5.09, p < 0.0001). After exposure to 29°C for eight days, neither of the two highland-biased species could reproduce when transferred back to mild temperature. Five out of the six non-biased and lowland-biased species resumed reproduction. Heat tolerance, measured by knockdown time at high temperature, was lower among species whose distribution were biased towards high latitude (male: coefficient = -9.1, p = 0.0013; female: coefficient = -5.4, p = 0.056). Species which had higher RTmax also stayed active for longer in the extreme high temperature (spearman’s rank rho = XXX, table 2).

Values of RTmin have more variation among species than the RTmax, as predicted by the “climate variability hypothesis”. Heat tolerance was not found to have a trade-off relationship with cold tolerance: RTmin and RTmax were not significantly correlated (supplementary figure 6); (on the contrary) Species that resisted heat for longer also showed stronger tolerance to cold, indicated by longer resistance to chill coma and shorter recovery time.

Thermal breadth:

Tbr was calculated as the temperature range where performance was above an 80% threshold (Huey et al., 2012; Huey and Stevenson, 1979) and as such Tbr can be used as a measure of the flatness of the TPC. (Kellermann, 2019)

[GUT FEELING: By this method, then of course “jack for all” hypothesis holds. Because this is using percentage]

Choice of TPC curve:

>Try out the new TPC fitting package in R [I have tried “rTPC”. There is no way to build hierarchy in the modeling strategy as I did with my customerized rstan. I could learn from the functions in their library (but I can’t find the original paper of some)]

>Check what functions did others used:

Three studies examined TPCs in fecundity (Condon et al., 2014; Cooper et al., 2010; Klepsatel et al., 2013)

TPCs in egg-to-adult viability (Cohet et al., 1980; Petavy et al., 2001; Schou et al., 2017),

two studies examined TPCs in both fecundity and egg-to-adult viability (Clemson et al., 2016; Overgaard et al., 2014).

2019 kellermann: The full model for activity included developmental temperature (scaled) as a quadratic fixed effect, test temperature (scaled) as a linear fixed effect, as well as the interactions between the two fixed effects. [This is not the performance at the vairous temperature. This is the performance of adults which used to develop at the various temperature] [Quadratic function – not good! Negative values, symmetric]

2013 Kingslover: RG model vs. Deustch’s model (To evaluate whether the simulation results are sensitive to the specific model used for thermal performance)

urn:x-wiley:02698463:media:fec12145:fec12145-math-0001(eqn 1)

For each species, we used a Gaussian function to model *R*0 as a function of temperature (*T*). [So this is also a symmetric function]

urn:x-wiley:02698463:media:fec12145:fec12145-math-0002(eqn 2)

Similarly, we used an asymptotic function to model *G*−1 as a function of temperature:

urn:x-wiley:02698463:media:fec12145:fec12145-math-0003(eqn 3)

>Phylogenetic correction: [EMAILED KELLERMANN, NO ANSWER]

Literature:

In the present study, we employed a suite of

analytical approaches to analyze phylogenetic signal. Although

these analytical methods are related in their aims, their different

assumptions may potentially lead to different conclusions and

we therefore based our conclusions on the consensus findings

(Cooper et al. 2010).

To examine the proportion of trait variation that could be entirely

attributed to climatic variables, we controlled for phylogenetic

effects using two independent methods of analysis. This was done

by computing phylogenetic independent contrasts (PIC) and the

SLOUCH model (SLOUCH, described below). These approaches

were calculated in ape and SLOUCH (Hansen et al. 2008),

respectively.

**Discussions**

[Summary] We show the distinctive abundance patterns of Drosophila species along the altitude gradient on tropical mountains in Australia. Furthermore, we found the distribution patterns are significantly associated with heat tolerance, independent of the species’ evolutionary history. On the contrast, species that were found predominantly at upland do not have advantage in cold tolerance than others. Combined, these results indicate an asymmetric role of thermal factors in influencing species distribution, with daily high temperature has already constrained the populations of the upland species in the tropical lowland.

[Interpretation] The strong correlation between abundance patterns and thermal tolerance does not downplay the role of biotic competition in affecting distribution. Firstly, suppression of population size by biotic factors will also create the a biased abundance patterns. Secondly, temperature changes the fitness difference among species through influencing organisms’ reproduction and competitive effect on others, which drives the thermally maladapted species to a lower level or even extirpated. Therefore, the realized distribution pattern is often under combined regulation by temperature and competition. The most likely interpretation of the observed geographic structure of thermal traits in this study is that heat-tolerating species survive in the warm lowland, free from the competition of the upland species which already have low performance due to high temperature. When moving upwards, they are outcompeted by the upland species even though they could have survived in such cool environment if by themselves.

[Implication] Combined with the temperature data, the thermal performance results implied the importance of extreme and/or stressful temperature rather than mean temperature in structuring distribution. The mean temperature during the survey season in the lowland is around 26°C, which all the species are around its peak reproductive performance. In addition to difference in mean temperature, highland and lowland sites significantly differ in the number of days and the daily duration that the temperature reached above 28°C (supplementary figure xxx). The lowland-biased and upland-biased species show significant distinction in their reproduction and recovery from our stressful testing temperature, 29°C. Saxon et al. showed that brief exposure to stressful thermal environment has similar fitness costs to continuously stressful conditions (Saxon, O’Brien, and Bridle 2018). These results stress the necessity to consider daily temperature variation and extreme temperature event in research studying the relationship between the environmental factors and distribution and future projection (Kingsolver, Diamond, and Buckley 2013).

Buckley, Lauren B., and Raymond B. Huey. "How extreme temperatures impact organisms and the evolution of their thermal tolerance." *Integrative and comparative biology* 56.1 (2016): 98-109.

Thermal extremes can drive organisms in temperate and tropical sites to have similar thermal tolerances despite major differences in mean temperatures

[Bigger context] On the contrary to our results, high temperature is not usually regarded as the limiting factor to local distribution patterns. Climate factors are generally viewed as drivers operating at the continental or regional scale, while at the local scales, biological variables are thought to become increasingly important (Hortal et al. 2010). Heat tolerance traits has less variation (Hoffmann 2010), especially in studies of local scales rather than continental scales (Nowrouzi et al. 2018; Overgaard et al. 2014).

[Bigger context] Tolerance-competition has been widely used to explain species turnover along environmental gradients [CITATION]. However, compared with cold tolerance [CITATION], the heat tolerance – competition trade-off and its influence on distribution is not widely recognized [CITATION]. The ones that occupy the warm area is often regarded as better competitor… The lack of study may be partly explained by the bias in geographic coverage. ANY POSITIVE STUDY? [1. PNG birds’ cold tolerance can’t explain upper distribution (Freeman 2016)]

[] Recent studies focusing on the tropic area have SOME POSITIVE RESULTS… Our study included most of the Drosophila species in the community, offering a systematic examination on the relationship between heat tolerance and distribution in the local scale. Our study’s meaning to the field: driving factors of distribution are not the same across geographic areas.

1. thermal performance of sperm activity is closely associated with the long-term abundance patterns in variable thermal environment among two sister Drosophila species occurring at the tropics.
2. Species’ northern and southern range limits are related to their tolerance of low and high temperatures respectively among European diving beetles.
3. Butterfly’s altitude distribution: host vs. temperature

[Implication] Reproductive success, recovered reproduction, knockdown time reflect different aspects of fitness. The correlations between thermal performance traits were challenged (Hoffmann et al. 1997; Overgaard et al. 2014; Sinclair et al. 2016). [Compare with Overgaard’s study (because it is so similar!)]. Our results show that rank of knockdown time to heat could be used as an approximate of the rank of reproduction upper limit. OTHER POSITIVE RESULTS??. These correlation may reflect a common biochemical mechanism (for example, heat-shock protein??) mediating thermal tolerance of organism’s metabolism, reproduction, development and behavior. With that said, tolerance using multiple traits are still complementary to each others to better understand fitness and thermal adaptation across environment (Kellermann et al. 2019).

[performance is dependent on the thermal history, rate of temperature change and exposure time. Ma et al 2020]

[No trade-off between heat tolerance and cold tolerance, indicated by the artificial selection exp. After 12 generations of artificial selection, lines diverged significantly for high KRHT only. Sambucetti, 2010]

[Limitation] These lab-measured thermal tolerance may not be representative among species with wide geographic range [POPULATION VARIATION CITATION], and cannot reflect the plasticity [CITATION] and evolutionary response [CITATION] to climate change. Thermal tolerance may be influenced by precipitation (Bozinovic and Pörtner 2015; Kellermann et al. 2012), diet, larval conditions (Bubli, Imasheva, and Loeschcke 1998), etc. [CITATION]. It is unsure whether the impact to different species is of similar degree. Thus, ignoring XXX may lead to overestimation of the severity of the impact of climate change [CITATION]. Nevertheless, it has been suggested that tropical species has low plasticity and evolutionary potential in adapting to warming. Geographic variation (and gene flow) and laboratory evolution can help with the first issue [CITATION]. Long-term monitoring data of population trend and climate [synchronization is also a sign!] can help to answer the second issue [CITATION] (Gade et al. 2020).

The lowland species’ safety margin is unknow from the spatial analysis. Temporal analysis with long-term monitoring data is needed. An example (Gade et al. 2020)

[Ending conclusion] Tropical lowland has high biodiversity, therefore very important (Gaston, 2000). Tropical insects have high diversity and they are important (Greenwood 1987). This study contribute to the growing literatures which show the warmer margins are also sensitive to warming (Wilson et al. 2005). We show the species turnover along altitude gradient is highly likely to result from physiological and reproductive constrains by high temperature. Upland tropical species will especially face range contraction by future warming. With numerous effort to use biophysical model to predict species range and response to climate change (Kearney and Porter 2009), it is fundamental to understand which aspects of climate elements constrain distribution.

Here, we provide evidence that tropical insect species have already undertaken altitude increases, confirming the global reach of climate change impacts on biodiversity. (Chen et al. 2009) High-altitude refuge…

[TPC implication] 1) thermal characteristics are diverse among community components. Upper thermal limits differ among and within component species in a tritrophic hostparasitoid- hyperparasitoid system (Agosta et al. 2018); 2) Thermodynamic effects on organismal performance: Is hotter better? In general, yes. (Angilletta et al. 2010)

[implication] systematic bias in climate change response study: in particular, tropical and marine systems are grossly underrepresented, as are plants and endothermic animals.

[implication] extreme tolerance is more related to range size. (Pither 2001)

[implication] We found that thermal niche estimates derived from both approaches lack general congruence (Sánchez-Fernández et al. 2012)

[implication] Even though there might be truncated thermal limit estimate (Feeley), as shown by our results, upland species will face contraction because combined effect of temperature and competition. For lowland species, it’s important to measure its real tolerance to use for predictive model (Martínez et al 2015), and to find a reliable link lab-measured tolerance with reality projection. Long-term monitoring data could be one way to understand the temperature limit for field populations.

(Martínez et al 2015) The thermal thresholds obtained in growth and survival experiments were used as proxies of the fundamental niches of two foundational marine macrophytes. The geographic projections of these species' distributions obtained using these thresholds and existing SDMs were similar in areas where the species are either absent-rare or frequent and where their potential and realized niches match, reaching consensus predictions.

[Impact]

We show that lower elevational limits for 16 butterfly species in central Spain have risen on average by 212 m (± SE 60) in 30 years, accompanying a 1.3°C rise (equivalent to c. 225 m) in mean annual temperature. (Wilson et al., 2005)

We show that recent warming constitutes an “escalator to extinction” for birds on a remote Peruvian mountain—high-elevation species have declined in both range size and abundance, and several previously common mountaintop residents have disappeared from the local community. (Freeman et al. 2018)

Rapid upslope shifts in New Guinean birds illustrate strong distributional responses of tropical montane species to global warming (Freeman, 2014)

[research effort] publications treating latitudinal range shifts have focused primarily on changes at the distributional margins (shifts or abundance changes at the leading and trailing edges) rather than on changes within the distribution (shifts or abundance changes at the optimum position. Additionally, we found that reports studying elevational range shifts have mostly focused on changes within the core of the distribution, rather than on changes at the distributional margins. (Lenoir and Sevenning 2015)

[reflection] there are various physical constrain and biotic surrounding that could change along the altitude gradient (Jankowski et al., 2013). The correlation we found is not direct evidence of the causal effect. It’s an indication of xxx.

[tolerance and distribution study]

Negative:

1. geographic variation in thermal tolerance within species was low or negligible. Cold tolerance – northern and southern margins. no relation was observed between heat tolerance and latitudinal distribution. Heat tolerance was higher in species inhabiting openlands or the forest canopy than in those inhabiting the forest understorey. (Kimura 2004)
2. We conclude that the heat tolerance of T. hsuehshanensis (lizard) is not a crucial factor limiting its current altitudinal distribution. ShuPing & MingChun, 2008
3. Is thermal limitation the primary driver of elevational distributions? Not for montane rainforest ants in the Australian Wet Tropics (Nowrouzi et al 2018)

Positive:

1. Despite their smaller size, high altitude bumble bees tolerated colder air temperatures: they had ~1 °C lower CTmin and recovered from cold exposure at ~3-4 °C lower air temperatures. Conversely, low altitude bees tolerated ~5 °C hotter air temperatures. These altitudinal differences in thermal tolerance parallel differences in average daily minimum (1.2 °C) and maximum (7.5 °C) temperatures between these sites. (Oyen, 2016)
2. Climatic limitation is the most likely explanation for the low elevation range margin of A. crataegi, whereas the absence of host plants from high elevations sets the upper limit. (Merrill et al. 2008)
3. In general, species found at middle elevations and on mountaintops are less tolerant to high temperatures than species restricted to lowland habitats. [genotypic adaptation of local population] High-elevation beetle haplotypes are characterized by low thermal limits; this pattern supports the hypothesis that populations along elevational gradients are locally adapted genotypes. (García-Robledo et al. 2016)
4. Opposing clines for high and low temperature resistance in Drosophila melanogaster (Hoffmann, 2002)
5. species' northern and southern range limits are related to their tolerance of low and high temperatures respectively. (Calosi, 2010)

[IS THERE ANY REVIEW OF THE RELATIONSHIP BETWEEN COLD TOLERANCE AND HOT TOLERANCE WITH TEMPERATURE?]

**address the wider literature and how it relates to your results (consistent / inconsistent, & why, etc.**

1. Constrained upper thermal limits in the larger scale – but difference and environmental filter still act in the local scale like my study. (Hoffman 2013)
2. Cold tolerance vs. warm tolerance (driving factors of distribution are not the same across geographic areas)

Species from hot and relatively dry regions had higher resistance, whereas resistance was uncorrelated with temperature in wetter regions. Kellermann 2012: Current species distributions are therefore more likely to reflect environmental sorting of lineages rather than local adaptation.

1. Cold tolerance – competition trade-off

Combined effects of climate and biotic interactions on the elevational range of a phytophagous insect ----- high temperature constrain lowland distribution!

1. Abundance is sensitive to temperature gradient. Most of the literature I have seen is about range size!!!
2. Extreme vs. constant

The important influence to tropical species of daily temperature variation and extreme temperature event

1. Comparison of performance measurement

Variation in the TPC across traits and time scales suggests that TPCs using single traits may not be an accurate predictor of fitness and thermal adaptation across environments.

1. Interpretation of the results
2. Cold vs warm limit of distribution: The relationship between this finding and the commonly-accepted understanding of latitudinal distribution pattern.
3. Relationship with biotic interaction: 1) environmental filtering and biotic interaction have different relative importance in different areas; [It might not be good to compare the relative role of environmental filtering and biotic interaction. First, definition problem of environmental filtering; second, if they work together to generate the end result – extirpation, then how to rigorously compare their ‘importance’?]
4. Limitation: Thermal performance curves are not fixed (acclimation, trans-generational effect, diet…). Behavior tolerance, plasticity, inter-population variability, and evolution were not addressed in this study. What do we already know about them in terms of tropical species?
5. Implication: 1) driving factors of distribution are not the same across geographic areas; 2) The important influence to tropical species of daily temperature variation and extreme temperature event; 3) Tropical species are already living close to their upper thermal limits; 4) Thermal performance curve could be used to estimated individual species effect to warming (but competition is not considered. 5) Rank of knockdown time to heat could be used as an approximate of the rank of reproduction upper limit. They may all involve in the fitness of insects in adapting to high temperatures.

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**Figure 1. a) Proportion of samples found in the low-, middle- and high-altitude site for the nine Drosophila species. b) Regression coefficients and hIndex unanimously describe altitudinal distribution patterns. *D. bunnanda* is not included in the graph because its regression coefficient and standard error are peculiarly large in absolute value due to its small sample size. Error bars show 90% confidence intervals.**

A close up of a logo

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**Figure 2. The thermal performance curve of reproduction. Color is ordered by their distribution pattern, with highland-biased species labeled by cold color and lowland-biased species labeled by warm color.**

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**Figure 3. Reproduction in stressful temperature treatment and after the temperature treatment. The species on the horizontal axis are ordered descendingly by the mean relative altitude of their distribution (hIndex). hIndex of *D. simulans* and *D. melanogaster* is unavailable.**

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**Figure 4. Physiological responses to lethal heat stress and cold stress. The species on the horizontal axis are ordered descendingly by the mean relative altitude of their distribution (hIndex). hIndex of *D. simulans* and *D. melanogaster* is unavailable. Measurements of females were labeled by red, males were labeled by blue.**

**A screenshot of a cell phone

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**Table 1 Estimated parameters of thermal performance functions and their 90% credible intervals (CI) of the nine species.**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **species** | **a** | **CI\_a** | **b** | **CI\_b** | **RTmin** | **CI\_RTmin** | **RTmax** | **CI\_RTmax** |
| *D. bipectinata* | 0.0046 | 0.0030 - 0.0059 | 1.26 | 1.01 - 1.55 | 15.28 | 14.56 - 15.88 | 30.45 | 30.08 - 31.05 |
| *D. birchii* | 0.0034 | 0.0022 - 0.0056 | 1.17 | 0.95 - 1.57 | 13.45 | 13.08 - 13.79 | 29.25 | 28.11 - 29.80 |
| *D. bunnanda* | 0.0017 | 0.0012 - 0.0026 | 0.88 | 0.81 - 1.07 | 14.58 | 14.09 - 15.20 | 31.19 | 30.61 - 31.77 |
| *D. melanogaster* | 0.0037 | 0.0032 - 0.0042 | 1.72 | 1.48 - 2.02 | 8.32 | 6.93 - 9.38 | 32.13 | 32.03 - 32.28 |
| *D. palidifrons* | 0.0073 | 0.0055 - 0.0099 | 1.74 | 1.36 - 2.39 | 16.23 | 15.51 - 16.77 | 29.07 | 28.14 - 29.39 |
| *D. pandora* | 0.0052 | 0.0037 - 0.0065 | 1.25 | 1.03 - 1.51 | 15.26 | 14.56 - 15.79 | 30.13 | 29.88 - 30.57 |
| *D. pseudoananassae* | 0.0053 | 0.0035 - 0.0071 | 1.67 | 1.22 - 2.33 | 15.07 | 14.15 - 15.91 | 29.22 | 28.42 - 29.80 |
| *D. simulans* | 0.0035 | 0.0027 - 0.0047 | 1.68 | 1.36 - 2.22 | 8.51 | 6.94 - 9.66 | 31.08 | 30.38 - 31.78 |
| *D. sulfurigaster* | 0.0040 | 0.0027 - 0.0051 | 1.26 | 1.03 - 1.53 | 14.37 | 13.92 - 14.94 | 30.12 | 29.84 - 30.63 |

**Table 2. Correlation matrix among thermal traits (RTmin, RTmax, RTopt, female knockdown time to heat, male knockdown time to heat, female knockdown time to cold, male knockdown time to cold, female recovery time from cold, male recovery time from cold). Spearman’s rank correlation rho is shown in the table. Significant correlation (p < 0.05) is labeled as bold.**

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | RTmin | RTmax | RTopt | FKDHEAT | MKDHEAT | FKDCOLD | MKDCOLD | FRCCOLD | MRCCOLD |
| RTmin | 1.00 | -0.55 | 0.02 | **-0.89** | -0.53 | -0.31 | -0.56 | 0.53 | 0.65 |
| RTmax |  | 1.00 | 0.17 | **0.71** | **0.93** | 0.64 | 0.61 | **-0.88** | **-0.85** |
| RTopt |  |  | 1.00 | -0.01 | 0.33 | 0.63 | 0.54 | -0.41 | -0.30 |
| FKDHEAT |  |  |  | 1.00 | **0.72** | 0.53 | **0.71** | -0.57 | **-0.68** |
| MKDHEAT |  |  |  |  | 1.00 | **0.79** | **0.71** | **-0.89** | **-0.83** |
| FKDCOLD |  |  |  |  |  | 1.00 | **0.85** | **-0.74** | **-0.75** |
| MKDCOLD |  |  |  |  |  |  | 1.00 | **-0.72** | **-0.70** |
| FRCCOLD |  |  |  |  |  |  |  | 1.00 | **0.93** |
| MRCCOLD |  |  |  |  |  |  |  |  | 1.00 |

Supplementary figure 1. The change of fecundity during 1st – 2nd day to 7th – 8th day in different temperature.

A close up of a whiteboard

Description automatically generated

Supplementary figure 2. Time table of fecundity measurement.

A screenshot of a cell phone

Description automatically generated

Supplementary figures 3. Diagnostics of model fitting of thermal performance curve.

A screenshot of a cell phone

Description automatically generatedA close up of a white wall

Description automatically generatedA close up of a map

Description automatically generated

Supplementary figure 4. Examples of logistic regression on occurrence data. *D. bipectinata* is lowland-biased species. *D. rubida* shows no bias. *D. palidifrons* is highland-biased species.

A screenshot of a video game

Description automatically generated

Supplementary figure 5. Daily fecundity and fitted thermal performance curve of each of the nine species.

A bunch of different colors

Description automatically generated

Supplementary figure 6. Scatter plot of posterior samples of RTmin and RTmax parameters.

A screenshot of a cell phone

Description automatically generated

Supplementary figure 6. Daily temperature of Feb. against the lowest CTmax and highest CTmin.

Chart, application

Description automatically generated

**Supplementary table 1. Isofemale line used to construct MBLs.**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Species | Origin of cultured lines (yes/no) | | | | Lines for MBLs |
| Kirrama low1 | Kirrama high1 | Paluma low1 | Paluma high1 |
| *D. bunnanda* | yes | no | yes | no | KL87, KL134, KL127, PL114 |
| *D. pandora* | no | no | yes | no | PL17, PL21, PL012 |
| *D. bipectinata* | yes | no | yes | no | KL84, KL43, PL85, PL20 |
| *D. pseudoananassae* | yes | yes | yes | no | KL19, KH25, PL30, KH42 |
| *D. sulfurigaster* | yes | yes | yes | yes | KL08, KH10, PL51, PH18 |
| *D. rubida* | yes | yes | yes | yes | Construction unfinished3. |
| *D. birchii* | yes | yes | yes | yes | KL22, KH26, PL122, PH169 |
| *D. palidifrons* | no | yes | no | yes | KH20, KH69, PH183, PH184 |
| *D. simulans* | no | no | yes | no | PL45, PL34, PL42, PL43 |
| *D. pseudotakahashii* | no | yes | no | yes | Did not construct MBLs4 |

Note:

1. “Low” means sites from low altitude. “High” means sites from high altitude.
2. The three isofemale lines were the only lines cultured at the lab.
3. Construction is not finished by the start of the experiment in May. *D. rubida* grew poorly on the purchased fly medium before changing food recipe and made at the lab. Therefore, its crossing starts later than other species (April 5th). Additionally, *D. rubida* has significantly longer generation time than other species.
4. Only two isofemale lines were cultured at the lab.