

# Impacts of climate change on the amphibians and reptiles of Southeast Asia

David Bickford · Sam D. Howard · Daniel J. J. Ng · Jennifer A. Sheridan

Received: 31 August 2009 / Accepted: 9 January 2010  
© Springer Science+Business Media B.V. 2010

**Abstract** Amphibians and reptiles will be adversely affected by projected rapid changes in climate in the next decades. Here, we review the known and potential impacts of climate change on the Southeast Asian amphibians and reptiles and make mitigation recommendations for both research and policy. Current amphibian and reptile distributions and ecologies mirror climate patterns, and we expect that adaptation to changes in these parameters will be too slow relative to their rate of expected change, and that pervasive changes will occur to species assemblages, communities, and ecosystem functioning and services. Southeast Asia is a network of islands with relatively few mountains, effectively preventing most herpetofauna from migrating away from the effects of climate change. Reflecting specific known and hypothesized physiological and ecological thresholds, we estimate that in <50 years, amphibians and reptiles in Southeast Asia will have reached or exceeded most limits in their abilities to adapt to the effects of climate change and that temperature dependent sex determination, higher metabolic rates, and less bio-available water will have severe and irreversible effects on these organisms. We suggest that human decision-making and policy development have already lagged and that societal change is happening too slowly for effective mitigation. If we are to avert devastating loss of biodiversity and a complete meltdown of ecosystem services, we must quickly change our attitudes and thinking about how we interact with and use biological systems.

**Keywords** Amphibians · Climate change · Conservation · Extinction · Reptiles · Southeast Asia · Policy

## Abbreviations

CCSM Community Climate System Model  
ENSO El Niño Southern Oscillation  
IPCC International Panel on Climate Change  
NPP Net primary productivity

---

D. Bickford (✉) · S. D. Howard · D. J. J. Ng · J. A. Sheridan  
Department of Biological Sciences, National University of Singapore, 14 Science Drive 4, Block S3,  
Level 3, Singapore 117543, Republic of Singapore  
e-mail: rokrok@nus.edu.sg

TSD Temperature-dependant sex determination  
UV Ultraviolet

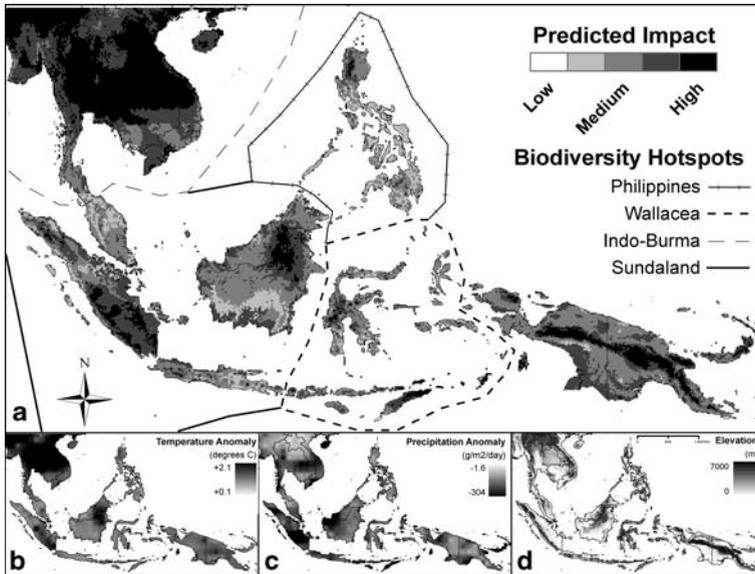
## Introduction

Although generally unseen or overlooked, ectothermic terrestrial vertebrates—amphibians and reptiles—are important components of ecosystems worldwide. They are notably abundant and species rich in wet tropical areas where they play critical roles in food webs often linking terrestrial and aquatic ecosystems. Current distributions and ecologies of both amphibians and reptiles closely reflect rainfall and temperature patterns, and climate change will have significant impacts on amphibian and reptile biodiversity.

We know that the climate is changing and that it has been largely a result of human activities (IPCC 2007). In Earth's past there have been significant periods of global warming and cooling, with average global temperatures from some past era higher than current temperatures (Zachos et al. 2001). Many species have adapted to and survived through these events (Huber 2009), but the contemporary rate of temperature increase is unprecedented and faster than previous climate change events (Houghton 1997). It will almost certainly be beyond the ability of species to adapt to or evolve with this rate of change in environmental conditions (Markham 1996; Kingsolver 2009). All major relevant parameters of climate change (e.g., air and sea surface temperature, solar radiation, UV, humidity, cloud cover, precipitation, extreme weather event frequency, and sea level rise) have implications for biodiversity. In this review we outline the specific interactions and probable directions of change for the amphibians and reptiles of Southeast Asia. Our goals are to identify the key effects of climate change on amphibians and reptiles, possible biological scenarios, research gaps, and management strategies and policies best suited for real world mitigation. We offer this review as a synergy of what we know with a good deal of certainty and what we hypothesize to be possible biological scenarios and critical areas for intervention with important strategies for embracing a future where biological diversity is more highly valued. In addition, we point out relatively unexplored aspects of ectotherm ecology that might have far-reaching and devastating implications as ecosystems change in response to changing climate.

## The amphibians and reptiles of Southeast Asia

In Southeast Asia, there are more than 700 known species of amphibians (IUCN Red List 2009) and over 1,400 species of reptiles (TIGR Reptile Database 2009), in four major biodiversity hotspots (Myers et al. 2000): Wallacea, Sundaland, Indo-Burma, and the Philippines (Fig. 1a). Each of these regions has high levels of endemism with many endemic genera (Table 1). These regions are also likely to host many cryptic species (Stuart et al. 2006; Bickford et al. 2007) and undescribed taxa (Giam et al. this issue) because of a relative lack of research and knowledge about the ecological, behavioral, and taxonomic aspects of many amphibians and reptiles in Southeast Asia. These animals are at high risk of extinction before we even know of their existence. This highly specialised and unique fauna owes much to the island biogeography and geologic history of the region. Volcanoes, tectonic activity and historical processes have given rise to many areas of



**Fig. 1** Predictions for climate change across Southeast Asia (see footnote 1); Map **a** simplified model of predicted areas of impact on Southeast Asian amphibians and reptiles species; Map **b** predicted maximum monthly surface air temperature anomalies by 2050; Map **c** predicted maximum monthly precipitation flux anomalies by 2050; Map **d** elevation above sea level

**Table 1** Hotspot species richness and endemism

	Amphibians		Reptiles	
	# of species	Endemic species/genera	# of species	Endemic species/genera
Sundaland	240	200/7	450	250/24
Wallacea	50	30/0	220	100/3
Philippines	90	75/0	240	160/6
Indo-Burma	280	150/3	520	200/12

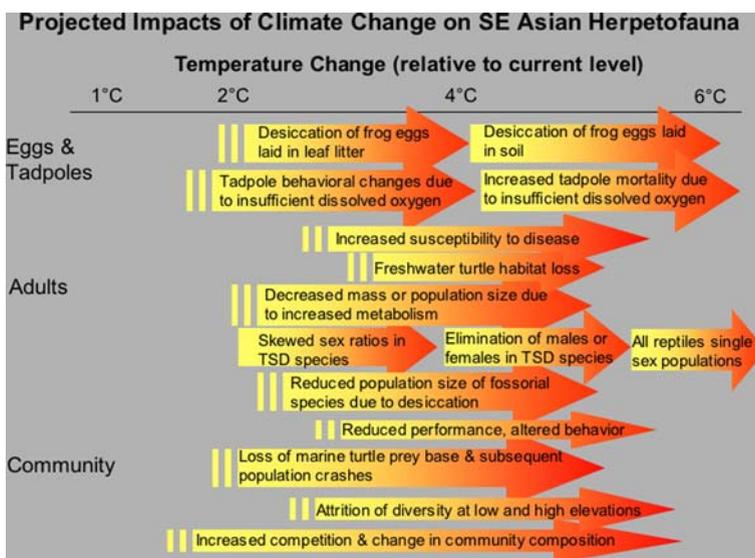
From Conservation International revisited hotspot data ([www.biodiversityhotspots.org](http://www.biodiversityhotspots.org))

rapidly changing elevations and habitats (Whitten et al. 2002; Hall 2009). The amphibians and reptiles are comprised of multiple evolutionary lineages converging in a relatively small area: the Austronesian fauna in the southeast, the Indo-Malay fauna in the northwest, and the convergence zone of Wallacea in the middle. Unique radiations of taxa occur throughout the region with many islands hosting their own endemic species as well as some of the most recognised mega-herpetofauna species (the Komodo Dragon *Varanus komodoensis*, false gharial *Tomistoma schlegelii*, and Reticulated Python *Broghammer [Python] reticulatus*) and some of the most enigmatic amphibian and reptile species (the horned dragons *Harpesaurus* and *Thaumatorhynchus*, lungless frog *Barbourula kalimantanensis*, and earless monitor *Lanthanotus borneensis*).

Much of the fauna of the region is threatened with habitat loss associated with deforestation, and climate change could have devastating synergistic effects on Southeast Asian amphibians and reptiles. Most of Southeast Asia is an archipelago with isolated island-specific amphibian and reptile populations, assemblages, and communities. Already reduced to small population sizes by isolation and habitat loss, increased temperatures and

decreased precipitation could drive populations and species extinct. Even in mainland areas, habitats have been reduced to virtual islands in seas of degraded matrix habitats. Isolation makes the amphibians and reptiles of Southeast Asia particularly vulnerable to climate change because island animals do not have the ability to migrate to cooler latitudes. The higher level of endemism and specific interactions within species assemblages that are unique to each island will make the amphibians and reptiles more vulnerable to even small climate shifts. The fate of Southeast Asia's natural habitats—and how we as a society deal with predicted changes—will hinge on monitoring, understanding, and ultimately mitigating the impacts of climate change on ecosystem services.

With predicted temperature rise of up to 6°C by the end of the next century (IPCC 2007), any migration involving latitude or elevation will need to be major. Elevation is coupled to temperature such that a one degree change in temperature occurs over an elevation of 100 m (dry conditions) or 200 m (wet conditions) since moisture acts as a temperature buffer (Danielson et al. 2002). The relationship between latitude and temperature is far more complex and variable but averages a change of 0.5° latitude per degree temperature change (Peterson and Vose 1997), a polar movement of 55 km per degree of warming. Within the next century we could see 100–1400 m of elevation shifts and/or 60–400 km of poleward movements. The lower bounds may not be insurmountable, but the upper bounds are enormous distances for species to shift, especially small amphibian and reptile species. Most islands in Southeast Asia, however, lack the area to allow for latitudinal or altitudinal range shifts, resulting in probable extinctions due to climate change. In addition, species may suffer from dispersal inhibition (Massot et al. 2008) making them susceptible to localised climate effects even if migration space is available. Over the next century, Southeast Asia is generally predicted to get warmer and drier with greater variability in rainfall in both time and space (Allen and Ingram 2002; Neelin et al. 2006; Allan and Soden 2008; Fig. 1). Increased temperature and decreased and/or more variable precipitation will strongly influence amphibians and reptiles (see Fig. 2 for brief summary).



**Fig. 2** Projected impacts of changing temperature on amphibians and reptiles of Southeast Asia. Based on IPCC 2007 figures

## Temperature

Increased temperature can result in changes in water regulation, oxygen uptake, emergence, mating, development, metamorphosis, growth, and sex reversal in amphibians (Feder and Burggren 1992). Many studies have shown that increased temperature can hasten the development rate of embryos and larvae by directly increasing development rate or by increasing desiccation of larval environments, leading to accelerated development (Alvarez and Nicieza 2002; Loman 2002; Sanuy et al. 2008). This can lead to early emergence from aquatic environments, which may reduce aquatic predation, but also can result in reduced size and mass (Crump 1989), which increases post-metamorphic predation and reduces lifetime fitness (Sibly and Atkinson 1994; Beck and Congdon 2000).

Global increases in temperature will also affect amphibians and reptiles in subtle or poorly understood ways because of their inter- and intra-specific variation in thermal tolerances. Lethal thermal temperatures for most lowland tropical herpetofauna are approximately 38–42°C, while thermal tolerances of highland species are lower (Brattstrom 1968; Snyder and Weathers 1975). However, most ectotherms do not perform optimally at the high end of their thermal tolerance, but function better at a lower temperature known as the thermal optimum (Feder and Burggren 1992). Although it is unlikely that the critical thermal maxima will be reached with projected temperature increases, thermal optima will probably be exceeded for most species given the small thermal safety margin and any increase beyond that will have deleterious effects and reduce overall fitness. Mating success in amphibians may also be affected by temperature changes as the frequency of mating calls is directly influenced by temperature (Gerhardt and Mudry 1980).

Increased environmental temperatures will also reduce the amount of dissolved oxygen in freshwater while increasing metabolic demand for oxygen in aquatic animals. Until tadpoles reach Gosner (1960) developmental stage 25, they must absorb all of their oxygen from water (McDiarmid and Altig 1999). With less dissolved oxygen available, swimming and evasion performance will decrease and mortality of young tadpoles is expected to increase (Wassersug and Feder 1983). Once tadpoles start breathing air, they will still have to increase their oxygen intake from the water surface or reduce their oxygen requirements by reducing activity or restricting growth.

Increased temperatures can affect population sex ratios of reptiles, and to a lesser degree, amphibians. The sex of many reptiles is determined by egg incubation temperature (TSD denotes temperature dependant sex determination), with temperature increases of 2–4°C leading to all female offspring (Crews et al. 1994; Ewert et al. 1994; Janzen 1994), or all male offspring (Bull 1980; Ciofi and Swingland 1997; Pieau et al. 1999) in crocodylians, turtles, and some lizards. Even in snakes and amphibians, which are typically non-TSD taxa, sex ratios can be skewed by extreme temperatures during incubation (Shine et al. 2002; Eggert 2004; Bull 2008; Nakamura 2009). Although few data on TSD in Southeast Asian amphibians and reptiles exist, it is likely that rising temperatures in the region will cause highly female-skewed populations in many reptiles and some amphibians. The effects of ambient temperature increases may be partly mitigated by females choosing cooler nest sites to modify offspring sex ratios (Ewert et al. 2005; Allsop et al. 2006; Doody et al. 2006; Telemeco et al. 2009), but it is unlikely that behavioural modifications can fully offset the effects of climate change (Telemeco et al. 2009). Thus, all reptiles and some amphibians are potentially vulnerable to becoming single sex populations within the next 100 years (Fig. 2).

Temperature increases are also likely to lead to altered distributions of amphibians and reptiles. Species may seek out cooler microhabitats in their current range (Bickford 2005) or cooler temperatures at higher elevations, leading to lowland biotic attrition. Some amphibian species have already been displaced elevationally upwards in the past 30 years (Raxworthy et al. 2008). In Southeast Asia, at least nine lowland amphibian species have moved 500 m or more upward in their elevational distribution in the past 70 years, while many high elevation species have shifted down slope (Bickford et al., unpublished data). This seemingly paradoxical trend may be the result of increased ultraviolet B (UV-B) radiation and fewer clouds at higher altitudes, forcing amphibians from high elevations lacking canopy and cloud cover down slope to seek shelter and moisture. This sandwiching of amphibians at mid-level elevations may lead to increased competition, decreased population sizes, and alteration of assemblages and community structure, ultimately decreasing biodiversity. Although initially there is likely to be increased species richness at these elevations due to range shifts, limited resources will likely lead to changes in community composition with weaker competitors being extirpated.

### Precipitation

Precipitation will affect both reptiles and amphibians in different ways, reptiles being generally more adapted to drier conditions than amphibians. Although rainfall and cloud cover will vary greatly geographically, there are many areas that will get drier and very few areas that will get wetter (Fig. 1c). Overall, however, there will be a higher degree of variation in precipitation, with rainfall events being spaced further apart at one extreme, and becoming more intense at the other (IPCC 2007).

One of the most obvious and direct effects of reduced precipitation in SE Asia on herpetofauna is a reduction in breeding cues and available breeding sites for amphibians. Many species require not just adequate water for tadpoles to survive, but rainfall to trigger mating (Sheridan, unpublished data). Increased variation in rainfall will alter the availability of breeding sites for frogs in the genus *Meristogenys*, for example, which only breed in fast-flowing streams. The drier climates expected throughout SE Asia may lead to decreased stream flow and a population reduction of taxa which require rapidly flowing water. Additionally, species with direct development (e.g., *Philautus* species) may experience increased mortality because of drier, warmer conditions. With less precipitation or with extended droughts, eggs and tadpoles will be vulnerable to mortality from drying (Donnelly and Crump 1998). Prolonged droughts could also lead to reproductive failure in consecutive years, causing population crashes of many species. Paradoxically, common prolonged breeders like *Polypedates leucomystax* and *Microhyla heymonsii* could be the hardest hit, since they are accustomed to breeding over long periods of time and may require longer hydroperiods for tadpoles to reach metamorphosis. In the Philippines, which is expected to get wetter (Fig. 1c), amphibians and reptiles will still face other challenges. Heavier precipitation may lead to increased mortality of amphibians that breed in slow-flowing water, as eggs and tadpoles are more likely to get washed away or damaged by stronger torrents. Similarly, mortality of reptiles and amphibians that lay their eggs on land may increase due to nest flooding and increased fungal growth on eggs (Kraemer and Bell 1980; Houghton et al. 2007).

Changes in precipitation will also affect reptiles through indirect effects on food supply and habitat (Araújo et al. 2006) and potentially cause reduction in body size, growth rate, and lifetime fitness (Brown and Shine 2007; Loehr et al. 2007). Higher temperatures and lower humidity can influence color polymorphism (Harkey and Semlitsch 1988), which

may affect abilities to avoid predators and capture prey. Furthermore, visual sensitivity may be lowered (Aho et al. 1988), impairing ability to identify predators and locate food resources and mates.

As the environment dries out, individuals may stay closer to water sources (Bickford 2005). This higher density of individuals near moist microhabitats will increase competition and facilitate disease vectors, again, potentially making population sizes smaller. Increased temperatures due to climate change will also increase water requirements in amphibians and reptiles. Additionally, as water is necessary for many metabolic processes, increased metabolic rates associated with increased temperatures will raise water requirements. Increased temperatures will increase evaporation, which will require amphibians, and to a lesser extent reptiles, to increase their water uptake. However, in all parts of Southeast Asia except the Philippines, climates are expected to get drier, and everywhere, droughts are expected to increase in frequency, becoming longer and more severe. Hence, amphibians and reptiles will have a harder time meeting their water requirements, as water bodies will be fewer, smaller, and farther apart. This may also lead to significant habitat loss for most non-marine turtles, and probable decreases in population sizes. Moreover, shorter hydroperiods could mean that the percentage of males in a given population of frogs that breed in ponds or puddles will go down, resulting in reduced genetic variability of the population (Donnelly and Crump 1998).

### Synergistic vulnerabilities

Increased number and length of drought periods coupled with rising temperatures and increased fragmentation are likely to cause forests to become drier and more fire prone (Nepstad et al. 1999). The effects (micro-climate changes, nutrient availability spikes, and greater susceptibility to more fires) of this have been documented in the Americas (Nepstad et al. 1999; Laurance 2002; Malhi et al. 2008) but not yet thoroughly reported from Southeast Asia (Walsh 1996). The majority of Southeast Asian amphibians and reptiles have not co-evolved with a fire regime ecology and mortality in an increased fire scenario will be high. If the El Niño Southern Oscillation (ENSO) event of 1997–1998 is any indication, the region is highly susceptible to synergies revolving around and leading to fires. Except for heavier rains in the Philippines (Fig. 1), most of the region will have climate change effects exacerbating the propensity for fires. The loss of forest cover due to fire can also result in soil erosion which will result in increased sedimentation of streams. In addition, eutrophication may occur and negatively affect water quality, further affecting amphibians that breed in those waters (Green et al. 2004; Peltzer et al. 2006). These various effects may interact synergistically and greatly elevate the damaging impacts on amphibian and reptile populations.

Drier soils caused by warmer temperatures and decreased precipitation will force fossorial taxa such as *Glyphoglossus*, *Calamaria*, *Gastrophrynoidea*, *Ichthyophis*, and *Caluella* to burrow deeper into the soil to find sufficient moisture. Frogs that lay their eggs on land (many Megophryids and Microhylids) may experience increased mortality due to decreased soil moisture and increased evaporation in the drier, warmer environments. Similarly, canopy dwellers (e.g., direct-developing microhylid frogs in the genera *Cophixalus* and *Albericus* from New Guinea) will come out of the tree-tops as they become desiccated and inhospitable (Bickford 2005). As these arboreal taxa come into contact with species at the ground level, they will potentially compete for food and conflict with species occupying similar niches at ground level for their breeding habitats if those canopy habitats remain unsuitable for egg-laying.

Since environmental temperature is known to significantly affect disease resistance, we also expect that there might be synergistic effects of climate changes on both reptile and amphibian pathogen resistance (Carey et al. 1999; Rojas et al. 2005). A particular case in point concerns amphibians. In Southeast Asia, the environmental conditions in the lowlands are generally either too dry or too hot for the survival of the chytrid fungus (*Batrachochytrium dendrobatidis*), which has been implicated for massive declines and some extinctions of amphibian species in other parts of the world (Daszak et al. 1999; Pounds et al. 2006; Skerratt et al. 2007). However, in places where moisture level is higher and temperature is cooler (e.g. mountainous areas above 1000 m elevation), the chytrid fungus can survive. Within Southeast Asia, this fungus was recently detected among native amphibians in Mount Gede Pangrango National Park, Indonesia (Kusrini et al. 2008) and with global warming, the fungus has the potential to spread upward in elevation.

Because of the high probability of food limitation (see endothermic metabolic rate rules below), we also hypothesize that populations of many reptiles and amphibians will decrease. Even if net primary productivity (NPP) does not change (and it almost certainly will decrease, Clark et al. 2003), there will be lower assimilation efficiencies as organisms deal with water limitations and smaller amounts of biomass at each trophic level, ultimately creating smaller population sizes. Because NPP will probably decline in the humid tropics (Clark et al. 2003), biomass at each trophic level will be even less and population crashes will be more likely for many species, especially top predators such as Komodo dragons and pythons. As populations of predators are affected, trophic cascades and loss of ecosystem functions (Petchey et al. 1999) become tangible problems. In addition, as body sizes shrink, there is greater chance for population sizes to get smaller since many amphibians and reptiles have a direct ratio of body size to number eggs per clutch (Tejedo 1992; Marquez 1995; Arntzen 1999). Smaller females have fewer eggs and fewer eggs can lead to smaller populations.

Predatory reptiles will undoubtedly be affected by prey species' densities or changes in their populations. Snakes respond very strongly to prey densities (Madsen and Shine 1996; Shine and Madsen 1997; Madsen and Shine 2000) and their responses to climate change will be due to temperature effects on physiological processes as well as indirect synergistic effects with habitat losses causing local extinction and migration of their prey base. Like many of the synergistic effects for both reptiles and amphibians, this will have population-level and species-level outcomes.

The hyper-fragmented nature of Southeast Asia's remaining pristine habitats—literally islands on islands—and the relatively small sizes of many populations exacerbate obvious synergies of temperature, rainfall, UV, cloud cover, fires, and habitat degradation. Some, but not many of these will be problems and vulnerabilities specific to amphibians and reptiles. Foremost amongst these are the effects of having an ectothermic metabolism tied directly to ambient temperatures.

### *Repercussions of ectotherm metabolic rate rules*

The basal metabolic rate of ectotherms is directly dependent on the temperature of the external environment (Gillooly et al. 2001). At the projected average global temperature increases of 1.1–6.4°C by year 2100 (IPCC 2007), metabolic rates of Southeast Asian amphibians and reptiles will increase 10–75% (Table 2). To maintain mean body size at higher metabolic rates, caloric intake (food consumption) will have to increase. However, food resources are not unlimited and will thus likely support either a reduced number of individuals in a population, or a similar population size of individuals that are 12–53%

**Table 2** Representative small and large amphibians and reptiles and their respective predicted changes in body mass due to expected metabolic rate change

Organism	Body size (g)	Reduction in body mass (g)	Extra kcal required per year to maintain size	Extra prey items needed per year to maintain size
<b>Amphibians</b>				
<i>Microhyla ornata</i>	0.36	0.04–0.19	0.27–2.04	57–426 termites <sup>a</sup>
<i>Limnonectes blythii</i>	1,500	184–791	128.46–963.45	6,424–48,179 carabid beetles <sup>b</sup>
<b>Reptiles</b>				
<i>Hemiphyllodactylus typus</i>	2.5	0.30–1.32	1.88–14.13	394–2,957 termites <sup>a</sup>
<i>Varanus komodoensis</i>	91,000	11,193–48,000	68,589–514,418	30–224 chickens <sup>c</sup>

<sup>a</sup> Brian MV (ed) (1978) Production ecology of ants and termites. 426 pp. London: Cambridge University Press

<sup>b</sup> Maryanski M, Kramarz P, Laskowski R et al (2002) Accumulation of metals in carabid beetles (*Poecilus cupreus* L.) exposed to zinc- or cadmium-contaminated food. *Ecotoxicol* 11:127–139

<sup>c</sup> Bird DM, Ho SK (1976) Nutritive values of whole-animal diets for captive birds of prey. *Raptor Res* 10:45–49

smaller. To maintain current body size, animals may need to eat substantially more prey items (Table 2), which may be difficult if not impossible. Reduced body size associated with global warming has already been demonstrated in birds (Gardner et al. 2009), sheep (Ozgul et al. 2009), and aquatic ectotherms (Daufresne et al. 2009). If NPP declines in the humid tropics as predicted (Clark et al. 2003), biomass at each trophic level will decline even further, potentially causing population crashes of most species of amphibians and reptiles as well as other top predators, and will likely lead to a trophic cascade and loss of ecosystem function (Petchey et al. 1999). We do not discount the effects of behavior to modify or offset some daily or even seasonal temperature fluctuations, but long-term and overall climate warming will not be effectively dealt with by individual organism behavior unless it involves long distance migration to higher latitudes or elevations, which might not be feasible in Southeast Asia (discussed above). We assume that as the climate gets warmer, so do the amphibians and reptiles.

In addition to shrinking populations or individuals, increased metabolic rates due to increased ambient temperatures can also have negative effects on fitness. Smaller females resulting from higher ambient temperatures will have lower fecundity, further contributing to declines in population size. Additionally, increased metabolic rates often draw on energy normally allocated for maintenance (Fitzpatrick 1976; Scott and Fore 1995), resulting in increased susceptibility to disease (Pounds et al. 2006). Survival of amphibians and many small fossorial reptiles will be further affected by increased metabolic rates due to the resulting increased surface area to volume ratio. At the projected rise in ambient temperature, this ratio will increase by 14%, escalating drying risk at a similar scale. Given that the rise in temperature will also hasten evaporative water loss in amphibians (Spotila 1972) and small fossorial reptiles, the risk of desiccation will be greater than that expected from decreased body size or increased temperature alone. As a result, these taxa will be forced to stay closer to water sources, restricting their dispersal capabilities. This can result in clumping of populations and potentially facilitate spread of diseases, resulting in mass mortality (Pounds and Crump 1994; Donnelly and Crump 1998).

## Ultraviolet radiation

Tadpoles exposed to elevated levels of UV-B experience increased mortality (Tietge et al. 2001), developmental and physiological abnormalities (Romansic et al. 2009), reduced growth rate (Belden and Blaustein 2002), epithelial damage (Nagl and Hofer 1997), impaired vision (Fite et al. 1998) and altered behaviour (Kats et al. 2000). Numerous agents (pathogens, heavy metals, chemical contaminants) are known to interact synergistically with UV-B, resulting in significantly greater effects than expected from an additive effect of individual factors (Hatch and Blaustein 2003). In Southeast Asia, montane species are likely to be extremely vulnerable to such effects as reduced cloud cover will result in greater UV-B transmission through the atmosphere (Cess et al. 1990; Estupinan et al. 1996; Calbó et al. 2005).

### Special case study: marine turtles (superfamily Cheloniodea)

Marine turtles deserve special mention because they differ from most terrestrial reptiles in life history, ecology, body size, and conservation. Six of the eight marine turtle species occur in Southeast Asia and they face many climate related problems: increased nest temperature and subsequently skewed sex ratios, declining food supplies, habitat loss and degradation, and migration alteration. Sea-level rise coupled with human encroachment will minimise available nesting locations. Increased UV radiation and rising temperatures will promote female biased populations (+2–4°C) and eventually eliminate males (>+4°C; (Hays et al. 2003). Increased precipitation in the Philippines can cause nest inundation and mortality and potentially increase fungal pathogen loads. Juveniles rely heavily on oceanic plankton that is often scarce but becomes abundant around patchily distributed oceanic upwellings. There is a general pole-ward movement of planktonic biomass with temperature (Beaugrand et al. 2002) and a reduction of biomass within upwellings (Roemmich and McGowan 1995; Wiafe et al. 2008) that will make food resources more scarce and difficult to locate (Limpus 2006). Global warming has already been responsible for mass mortality events in corals (Hughes et al. 2003), and increased tidal activity will likely damage sea grasses while greater local precipitation will increase surface run-off and sedimentation (Duarte 2002). Predicted increases in the number and severity of tropical storms will likely cause more structural damage to reef and sea grass systems. These processes will negatively impact food supplies and refugia for turtles. Juvenile and adult turtles often use established ocean currents for dispersal and migration (Polovina et al. 2000, 2004). The potential for the Gulf Stream current in the Atlantic to be shut-off or deflected as global warming proceeds is well documented (Manabe and Stouffer 1993; Rahmstorf 1997; Stocker and Schmittner 1997). There are no model predictions for Asian current systems but the impacts on turtles could be profound; no longer able to locate feeding or breeding grounds, the populations could drastically diminish while still being subject to the additional threats posed by global warming.

Although there have been some successes in management of sea turtle populations in Southeast Asia (Palma 1997), trans-boundary management remains problematic as they move freely through the oceans and territories of different national control. Global warming has the potential to increase ocean temperatures such that turtles are able to survive in ocean regions previously too cold given sufficient food supplies (McMahon and Hays 2006). This will require new trans-boundary management plans including countries not previously associated with turtle conservation, and may therefore be difficult to

implement. Despite potentials for range extensions, detrimental effects caused by global warming will probably outweigh the benefits of new open habitats.

## Methods<sup>1</sup> and mitigation

Undeniably, there is still a large amount of basic biological surveying that needs to become a priority for research in the region. Major portions of New Guinea, Borneo, Sumatra, and smaller parts of the Philippines still need to be explored herpetologically and the species there must be described before we can do any reasonable conservation mitigation or planning. Building complete species inventories and establishing monitoring programs is the first step to virtually any other research activities, although experiments can be done on well-known human commensals (e.g., *Hemidactylus frenatus*, *Gekko gekko*, *Bufo melanostictus*, *Kaloula pulchra*, *Polypedates leucomystax*) as proxies for the most plastic and adaptable taxa in the region. Unfortunately, although logistically easiest, working with these species tells us little about the habitat preferences, prey bases, thermal tolerances, and moisture requirements of most species. Research priorities for the future should focus not only on increasing basic biodiversity research (inventories, monitoring, species descriptions, etc.) but also on experimental approaches to determine the effects of increased temperatures and variability in rainfall on amphibian and reptile growth, reproduction, behavior, and feeding ecologies. Although these kinds of experiments may only hint at the ramifications of synergies that will undoubtedly be fulfilled in nature, we should first attempt to understand the mechanisms behind at least some of the simpler responses.

Specific research plans could focus on indicator taxa (e.g., leaf litter specialists, stream obligates, the lungless frog, apex predators, etc.; Table 3), large-scale and long-term monitoring programs at designated high-impact sites (Fig. 1), applied programs to establish biodiversity corridors between protected areas, and comparisons of historical and

<sup>1</sup> In order to better visualize the areas that might be at higher possible threat due to climate change, we gathered the best available data on factors most responsible for changes to biotic systems. Temperature and precipitation data were downloaded from [www.gisclimatechange.org](http://www.gisclimatechange.org) (accessed on 25 August 2009) from the global CCSM projection dataset bounded at 22° to -12° latitude and 94° to 154° longitude. To develop the 50-year anomaly values of precipitation and temperature, ensemble average Climate Change Commitment scenario data for Surface Air Temperature (tas) and Precipitation flux (pr) were downloaded for years 2000 and 2050. Data were imported into Microsoft Excel (Microsoft Ltd) and the 50 year monthly anomalies were calculated.

For each latitude and longitude point (approximately 1.4° grid) the maximum monthly tas and maximum negative pr were identified and exported into Arcmap 9.3 (ESRI Ltd). Elevation data were downloaded from [www.worldclim.org](http://www.worldclim.org) (accessed 25 August 2009) at 2.5 arcmin resolution (Hijmans et al. 2005) and imported to Arcmap bounded the same as tas and pr data. World borders (wb) were downloaded from [http://mappinghacks.com/data/world\\_borders.zip](http://mappinghacks.com/data/world_borders.zip) (accessed 25 August 2009). The tas and pr data were interpolated to raster format using inverse distance weighting, 2nd power and six local points (Arcmap, spatial analyst extension) and cropped, along with elevation data, to land area using the wb mask. The tas, pr, and elevation were then mapped as shown.

Calculation of impact was as follows: pr was squared to make the direction of reduced precipitation positive to match tas and elevation layers and tas, pr reclassified (slice, spatial analyst) to 255 equal interval units. Elevations below 20 m were reclassified to 1000 m (corresponding to median value of sliced layer) to reflect the probable inundation of low lying areas and reclassified to 255 equal interval units. Impact was then predicted as  $[0.45 \times \text{tas} + 0.35 \times \text{pr} + 0.2 \times \text{elevation}]$  based on our a priori perception that impacts on amphibian and reptile species will be based mostly on temperature changes, closely followed by precipitation and exacerbated by elevation. Boundaries corresponding to approximate limits of biodiversity hotspots (Hotspots Revisited, Conservation International 2004) were overlaid to the map in Fig. 1a layer in freehand. All maps are displayed overlaid with wb edges for clarity.

**Table 3** Amphibian and reptile families and selected species of high conservation concern for probable climate change scenarios in Southeast Asia

Organism	Endemic	Risk with drier conditions	Risk with hotter conditions	Comments
<b>Amphibians</b>				
<b>Anura</b>				
Bombinatoridae		Y	Y	
<i>Barbourula</i>	Y	Y	Y	Stream obligate, 1 lungless species
Bufonidae				Many endemic species
<i>Ansonia</i>	Y	Y		
<i>Pedostibes</i>	Y	Y		Arboreal
Ceratobatrachidae		Y	Y	
Dicroglossidae		Y	Y	Many endemic species
Hylidae				
Limnodynastidae				
Megophryidae		Y		Many endemic species
<i>Leptobranchella</i>	Y	Y		Leaf litter specialist
Microhylidae		Y		Many endemic species; Many direct developers
<i>Oreophryne</i>		Y	Y	Many endemic species; habitat specialists; direct developers
<i>Gastrophrynoidea borneensis</i>		Y	Y	Fossorial
Myobatrachidae				Many endemic species
Ranidae				Many endemic species
<i>Staurois</i>	Y	Y	Y	Stream obligate
<i>Meristogenys</i>	Y	Y	Y	Stream obligate
Rhacophoridae		Y	Y	Many endemic species
<i>Philautus mjobergi</i>	Y	Y	Y	Direct developers
<b>Caudata</b>				
Salamandridae		Y	Y	
<i>Paramesotriton</i>		Y	Y	Stream obligate
<i>Tylostotriton</i>		Y	Y	Stream obligate
<b>Gymnophiona</b>				
Ichthyophiidae		Y		Many endemic species; fossorial
<i>Caudacaecilia</i>	Y	Y		Fossorial
<i>Ichthyophis</i>	Y	Y		Fossorial
<b>Reptiles</b>				
Temperature dependent sex determination				
<b>Crocodylia</b>				
Crocodylidae				Restricted range; nesting sites and habitats highly vulnerable
<i>Crocodylus mindorensis</i>	Y	Y	Y	Most endangered crocodylian
<i>Tomistoma schleglii</i>	Y	Y	Y	IUCN/CITES listed

**Table 3** continued

Organism	Endemic	Risk with drier conditions	Risk with hotter conditions	Comments
Squamata-Sauria				
Agamidae		Y	Y	Many endemic species
<i>Draco</i>	Y			Eggs laid in soil
<i>Thaumatorhynchus</i>	Y			Arboreal
Dibamidae		Y	Y	Fossorial
Gekkonidae		Y	Y	Many endemic species Smaller species vulnerable
Lanthanotidae	Y	Y	Y	Stream obligate; monotypic
<i>Lanthanotus borneensis</i>	Y			Endemic to Borneo
Scincidae		Y	Y	Many endemic species; Some fossorial; diverse group
<i>Brachymeles</i>	Y	Y	Y	15 Philippine endemics, 1 Bornean species; fossorial
Varanidae		Y	Y	Many endemic species; large body size increases vulnerability to reduced prey densities
<i>Varanus komodoensis</i>	Y			Indonesia endemic; large size; restricted island range; apex predator
<i>Varanus olivaceus</i>	Y	Y	Y	Phillipine endemic; frugivore
<i>Varanus mabitang</i>	Y	Y	Y	Phillipine endemic; frugivore
Squamata-Serpentes				
Acrochordidae		Y	Y	Vulnerable to ocean warming
Cylindrophiiidae		Y	Y	Fossorial
Xenopeltidae		Y	Y	
<i>Xenopeltis unicolor</i>	Y			Fossorial
Boidae		Y	Y	Many endemic species
Colubridae		Y	Y	Many endemic species; small fossorial species most at risk
<i>Calamorphidium</i>	Y			Suawesi endemic genus; fossorial
<i>Myersophis alpestris</i>	Y			Philippine endemic genus
Elapidae		Y	Y	Many endemic species
Viperidae		Y	Y	Many endemic species; low motility
Homalopsidae			Y	Sea snakes; vulnerable to ocean warming
Typhlopidae		Y	Y	Fossorial
<i>Cyclotyphlops deharvengi</i>	Y	Y	Y	Sulawesi endemic
Pythonidae		Y	Y	Large body size increases vulnerability to reduced prey densities
<i>Brogammerus reticulatus</i>	Y	Y	Y	

**Table 3** continued

Organism	Endemic	Risk with drier conditions	Risk with hotter conditions	Comments
Testudines				Sex ratios threatened by rising temperatures; most over-harvested
Bataguridae		Y	Y	Many endemic species; breeding sites and habitats at risk
<i>Heosemys leytensis</i>				Philippine endemic genus
Cheloniidae		Y	Y	IUCN/CITES I
<i>Natator depressus</i>		Y	Y	Marine species
Chelidae		Y	Y	
<i>Chelodina mccordi</i>				
Testudinidae				
<i>Manouria emys</i>		Y	Y	
Trionychidae		Y	Y	
<i>Chitra chitra</i>	Y	Y	Y	

contemporary species distribution, abundance, and richness data. These research foci will provide the necessary data for making reasonable conservation decisions, plans, and mitigation strategies. A regional effort including multi-national collaboration is critical for the success of such research and conservation planning.

Nearly the entire region of Southeast Asia falls under either the Wallacea, Sundaland, Philippines, or Indo-Burma biodiversity hotspots (Myers et al 2000; Fig. 1). Despite the relatively high importance of most of the region for direct conservation actions, targeting specific areas first will enable a more realistic application of funds and expertise. Based on predicted changes in rainfall and temperature, certain areas in Southeast Asia are expected to be heavily impacted by climate change. Much of central Thailand and Laos are expected to get drier and warmer (Fig. 1)<sup>2</sup>. Of the 57 species of freshwater turtles currently known from this area, 43 species are already threatened. The drier climate will lead to habitat loss as freshwater bodies dry up, and a decrease in food supply will exacerbate population declines. Endemic Indo-Burma hotspot amphibians like *Rhacophorus orlovi* and *Ansonia inthanon* are also likely to be threatened with extinction due to the higher temperatures and drier climate.

One of the only endemic amphibian and reptile families in the region, Lanthanotidae, contains a single species, *Lanthanotus borneensis*, known only from Borneo in the Sundaland hotspot (Table 3). This enigmatic family will be threatened with extinction before much is known about its biology or life history. Endemic fauna of the Lesser Sundas like *Chelodina mccordi* and *Oreophryne jeffersoniana* will likely disappear before the end of this century due to sea level rises on these low-lying islands, which will also be subject to extended droughts and warmer temperatures. Most of the montane areas in Southeast Asia also have heightened risks of adverse climate change (Fig. 1) and face many of the same problems in biodiversity conservation and the management and protection of ecosystem services. As most of these areas are already extremely degraded and have very few remaining forests or protected areas, the

<sup>2</sup> See footnote 1.

remaining intact forest needs to be protected, and should be the focus of increased research and conservation efforts. In addition, linking the remaining habitats suitable for reptiles and amphibians needs to be prioritized throughout SE Asia. Unfortunately, high human densities in many areas make it necessary to compromise between human and wildlife needs. Areas predicted to suffer the highest level of impact of climate change (Fig. 1) should be targeted for both research and conservation immediately.

In addition, programs like the Amphibian Ark ([www.amphibianark.org](http://www.amphibianark.org)) should be utilized or thought about in more realistic terms. The mission of Amphibian Ark is to rescue threatened species (from habitats thought to be disappearing and/or becoming rapidly degraded) and to build capacity of regional zoos and parks to house and care for those species until the habitats can be restored. Capacity building and animal rescue must occur sequentially (i.e., there must be expert capacity and competence before any rescue attempts can be made) so that species are not removed prematurely and left to become extinct in the wild. Success of last-ditch programs like this will be achieved only if a species is released back to suitable native habitats with no need for active management of that species. There is undoubtedly a shortage of expertise and funding to see any program like this become regionally effective in time to help curb the massive potential problems. Partnerships among governments, universities, and non-governmental conservation organizations will help enable these programs in the region and might be the only way to see effective outcomes from such drastic measures. Although not one of our priority suggestions (which are to prevent such habitat degradation in the first place or mitigate in situ), this strategy may be the only way to save some species.

Across the region, policy changes need to be implemented as soon as possible and should range from protected area connectivity programs and park management plans to urban planning and environmental education. Although there is nothing we can do to immediately halt the progression of temperature and rainfall fluctuations due to human activities, we can severely limit more negative impacts by curbing our carbon emissions and consumption of natural resources. Policy should target focal areas, from individual reduction in consumption of goods and services (especially in highly developed countries like Singapore), to whole-society economic responses to meet the challenges of averting a full-blown ecological catastrophe. Some of the society-level responses can be encouraged by governments that proactively engage in sustainable energy use, provide incentives to industries that reduce their carbon footprints, and promote higher efficiency and lower energy use of citizens. As a society, we need to value durable, reusable, and non-toxic goods more than disposable, replaceable products made from toxic ingredients. Programs like Bangladesh's country-wide ban on plastic bags are an important first step, and there are limitless intervention points that can be actuated at larger scales. Ultimately, what will matter most in the short-term will be large-scale actions from governments like Singapore, who could realistically and rapidly legislate and implement a country-wide reduction in carbon emissions.

Land use changes, history, and the inertia of changing attitudes are all standing in the way of curbing the effects of climate change on biodiversity. While effective execution of meaningful programs will be difficult, acquiring the expertise, money, and political will to start the changes that lead to these programs is the immediate hurdle. Education and word-of-mouth delivery of information have been undervalued. Changing attitudes and re-educating people to become concerned enough to act will be one of the most effective and positive strategies for many environmental problems.

## Conclusions

Even if the most optimistic projections of the IPCC come to fruition, the next 50 years will see severe alterations of ecosystem function that humankind depends on for our basic needs. Although amphibians and reptiles are only parts of the larger picture, we can learn much from their current endangered status and quick response to environmental degradation. Southeast Asia will bear the brunt of sweeping climatic changes with potential results ranging from shrinking individuals, declining population sizes, and altered community structures to widespread trophic cascades, extinctions, and loss of ecosystem services. Amphibians and reptiles may be some of the first taxa to be affected by climate changes in abrupt and severe ways. We should not wait until populations have crashed or species gone extinct before acting to prevent further effects from accruing. We must focus attention on the biogeographic areas and biodiversity hotspots where groups of organisms are at highest risk. Southeast Asia and its amphibians and reptiles deserve focus at multiple levels, from basic and applied research and experimentation on the probable effects of climate change, to the actuation of public policy and governmental programs aimed at reducing consumption, human population growth, energy, waste, and pollution. Only by changing human attitudes and behavior toward the environment as well as increasing our understanding of biodiversity will we realistically meet the needs of the future.

**Acknowledgements** We thank Lian Pin Koh and Navjot Sodhi for the invitation to contribute this article. Funding support was provided by the Ministry of Education and the National University of Singapore (NUS) Grants # R-154-000-383-133 and R-154-000-434-112. We thank the members of the Environmental Biology group at NUS for fruitful discussions. This research uses data provided by the Community Climate System Model project (<http://www.cesm.ucar.edu>), supported by the Directorate for Geosciences of the National Science Foundation and the Office of Biological and Environmental Research of the U.S. Department of Energy. NCAR GIS Initiative provided CCSM data in a GIS format through GIS Climate Change Scenarios portal (<http://www.gisclimatechange.org>). We thank Maureen Donnelly and her lab and an anonymous reviewer for constructive and insightful comments that improved the manuscript considerably.

## References

- Aho AC, Donner K, Hyden C et al (1988) Low retinal noise in animals with low body-temperature allows high visual sensitivity. *Nature* 334:348–350
- Allan RP, Soden BJ (2008) Atmospheric warming and the amplification of precipitation extremes. *Science* 321:481–484
- Allen MR, Ingram WJ (2002) Constraints on future changes in climate and the hydrologic cycle. *Nature* 419:224–232
- Allsop DJ, Warner DA, Langkilde T et al (2006) Do operational sex ratios influence sex allocation in viviparous lizards with temperature-dependent sex determination? *J Evol Biol* 19:1175–1182
- Alvarez D, Nicieza AG (2002) Effects of temperature and food quality on anuran larval growth and metamorphosis. *Funct Ecol* 16:640–648
- Araújo MB, Thuiller W, Pearson RG (2006) Climate warming and the decline of amphibians and reptiles in Europe. *J Biogeogr* 33:1712–1728
- Arntzen JW (1999) Sexual selection and male mate choice in the common toad, *Bufo bufo*. *Ethol Ecol Evol* 11:407–414
- Beaugrand G, Reid PC, Ibanez F et al (2002) Reorganization of North Atlantic marine copepod biodiversity and climate. *Science* 296:1692–1694
- Beck CW, Congdon JD (2000) Effects of age and size at metamorphosis on performance and metabolic rates of Southern Toad, *Bufo terrestris*, metamorphs. *Funct Ecol* 14:32–38
- Belden LK, Blaustein AR (2002) Exposure of red-legged frog embryos to ambient UV-B radiation in the field negatively affects larval growth and development. *Oecologia (Heidelberg)* 130:551–554

- Bickford D (2005) Long-term frog monitoring with local people in Papua New Guinea and the 1997–98 el Niño Southern Oscillation Event. In: Donnelly M, White M, Crother B, Wake C (eds) Ecology and evolution in the tropics—a herpetological perspective. University of Chicago Press, Chicago
- Bickford D, Lohman DJ, Sodhi NS et al (2007) Cryptic species as a window on diversity and conservation. *Trends Ecol Evol* 22:148–155
- Brattstrom BH (1968) Thermal acclimation in anuran amphibians as a function of latitude and altitude. *Comp Biochem Physiol* 24:93–111
- Brown GP, Shine R (2007) Rain, prey and predators: climatically driven shifts in frog abundance modify reproductive allometry in a tropical snake. *Oecologia* 154:361–368
- Bull JJ (1980) Sex determination in reptiles. *Q Rev Biol* 55:3–21
- Bull JJ (2008) Sex determination: are two mechanisms better than one? *J Biosci* 33:5–8
- Calbó J, Pages D, Gonzalez JA (2005) Empirical studies of cloud effects on UV radiation: a review. *Rev Geophys* 43:RG2002 10.1029/2004RG000155
- Carey C, Cohen N, Rollins-Smith L (1999) Amphibian declines: an immunological perspective. *Dev Comp Immunol* 23:459–472
- Cess RD, Potter GL, Blanchet P et al (1990) Intercomparison and interpretation of climate feedback processes in 19 atmospheric general circulation models. *J Geophys Res* 95(10):16601–16615
- Ciofi C, Swingland IR (1997) Environmental sex determination in reptiles. *Appl Anim Behav Sci* 51:251–265
- Clark DA, Piper SC, Keeling CD et al (2003) Tropical rain forest tree growth and atmospheric carbon dynamics linked to interannual temperature variation during 1984–2000. *Proc Natl Acad Sci USA* 100:5852–5857
- Crews D, Bergeron JM, Bull JJ et al (1994) Temperature-dependent sex determination in reptiles: proximate mechanisms, ultimate outcomes, and practical applications. *Dev Genet* 15:297–312
- Crump ML (1989) Effect of habitat drying on developmental time and size at metamorphosis in *Hyla pseudopuma*. *Copeia* 1989:794–797
- Danielson E, Levin EW, Abrams J (2002) *Meteorology*, 2nd edn. McGraw Hill, New York
- Daszak P, Berger L, Cunningham AA et al (1999) Emerging infectious diseases and amphibian population declines. *Emerg Infect Dis* 5:735–748
- TIGR Reptile Database (2009) [www.reptile-database.org](http://www.reptile-database.org). Cited 24 December 2009
- Daufresne M, Lengfellner K, Sommer U (2009) Global warming benefits the small in aquatic ecosystems. *Proc Natl Acad Sci* 106:12788–12793
- Donnelly MA, Crump ML (1998) Potential effects of climate change on two Neotropical amphibian assemblages. *Climatic Change* 39:541–561
- Doody JS, Guarino E, Georges A et al (2006) Nest site choice compensates for climate effects on sex ratios in a lizard with environmental sex determination. *Evol Ecol* 20:307–330
- Duarte CM (2002) The future of seagrass meadows. *Environ Conserv* 29:192–206
- Eggert C (2004) Sex determination: the amphibian models. *Reprod Nutr Dev* 44:539–549
- Estupinan JG, Raman S, Crescenti GH et al (1996) Effects of clouds and haze on UV-B radiation. *J Geophys Res* 101(D11):16807–16816
- Ewert MA, Jackson DR, Nelson CE (1994) Patterns of temperature-dependent sex determination in turtles. *J Exp Zool* 270:3–15
- Ewert MA, Lang JW, Nelson CE (2005) Geographic variation in the pattern of temperature-dependent sex determination in the American snapping turtle (*Chelydra serpentina*). *J Zool* 265:81–95
- Feder ME, Burggren WW (eds) (1992) *Environmental physiology of the amphibians*. University of Chicago Press, Chicago
- Fite KV, Blaustein AR, Bengston L et al (1998) Evidence of retinal light damage in *Rana cascadae*: a declining amphibian species. *Copeia* 1998:906–914
- Fitzpatrick LC (1976) Life history patterns of storage and utilization of lipids for energy in amphibians. *Am Zool* 16:725–732
- Gardner JL, Heinsohn R, Joseph L (2009) Shifting latitudinal clines in avian body size correlate with global warming in Australian passerines. *Proc R Soc B* 276:3845–3852
- Gerhardt HC, Mudry KM (1980) Temperature effects on frequency preferences and mating call frequencies in the green treefrog *Hyla cinerea* (Anura: Hylidae). *J Comp Physiol A Sens Neural Behav Physiol A* 137:1–6
- Gillooly JF, Brown JH, West GB et al (2001) Effects of size and temperature on metabolic rate. *Science* 293:2248–2251
- Gosner KL (1960) A simplified table for staging anuran embryos and larvae with notes on identification. *Herpetologica* 16:183–190

- Green M, Thompson MB, Lemckert FL (2004) The effects of suspended sediments on the tadpoles of two stream-breeding and forest dwelling frogs, *Mixophyes balbus* and *Heleioporus australiacus*. In: Lunney D (ed) Conservation of Australia's Forest Fauna, 2nd edn. University of Minnesota Press, Royal Zoological Society of New South Wales
- Hall R (2009) Southeast Asia's changing palaeogeography. *Blumea* 54:148–161
- Harkey GA, Semlitsch RD (1988) Effects of temperature on growth, development and color polymorphism in the ornate chorus frog *Pseudacris ornata*. *Copeia* 1001–1007
- Hatch AC, Blaustein AR (2003) Combined effects of the UV-B radiation and nitrate fertilizer on larval amphibians. *Ecol Appl* 13:1083–1093
- Hays GC, Broderick AC, Glen F et al (2003) Climate change and sea turtles: a 150-year reconstruction of incubation temperatures at a major marine turtle rookery. *Glob Change Biol* 9:642–646
- Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A (2005) Very high resolution interpolated climate surfaces for global land areas. *Int J Climatol* 25:1965–1978
- Houghton J (1997) Global warming. Cambridge University Press, Cambridge, 267 pp
- Houghton JDR, Myers AE, Lloyd C et al (2007) Protracted rainfall decreases temperature within leatherback turtle (*Dermochelys coriacea*) clutches in Grenada, West Indies: ecological implications for a species displaying temperature dependent sex determination. *J Exp Mar Biol Ecol* 345:71–77
- Huber M (2009) Climate change: snakes tell a torrid tale. *Nature* 457:669–671
- Hughes TP, Baird AH, Bellwood DR, Card M, Connolly SR, Folke C, Grosberg R, Hoegh-Guldberg O, Jackson JBC, Kleypas J, Lough JM, Marshall P, Nystrom M, Palumbi SR, Pandolfi JM, Rosen B, Roughgarden J (2003) Climate change, human impacts, and the resilience of coral reefs. *Science* 301:929–933
- IPCC (2007) Summary for policymakers. In: Solomon SD, Qin M, Manning Z et al (eds) Climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, New York
- Janzen FJ (1994) Climate-change and temperature-dependent sex determination in reptiles. *Proc Natl Acad Sci USA* 91:7484–7490
- Kats LB, Kiesecker JM, Chivers DP et al (2000) Effects of UV-B radiation on anti-predator behavior in three species of amphibians. *Ethology* 106:921–931
- Kingsolver JG (2009) The well-temperated biologist. *Am Nat* 174:755–768
- Kraemer JE, Bell R (1980) Rain-induced mortality of eggs and hatchlings of loggerhead sea turtles (*Caretta caretta*) on the Georgia coast. *Herpetologica* 36:72–77
- Kusrini MD, Skerratt LF, Garland S et al (2008) Chytridiomycosis in frogs of Mount Gede Pangrango, Indonesia. *Dis Aquat Org* 82:187–194
- Laurance WF (2002) Forest-climate interactions in fragmented tropical landscapes. *Phil Trans Roy Soc B* 359:345–352
- Limpus CA (2006) Impacts of climate change on marine turtles: a case study. In: Migratory species and climate change: impacts of a changing environment on wild animals. UNEP/CMS Secretariat, Bonn, 68 pp
- IUCN Red List (2009) <http://www.iucnredlist.org/amphibians>. Cited 10 August 2009
- Loehr VJT, Hofmeyr MD, Henen BT (2007) Growing and shrinking in the smallest tortoise, *Homopus signatus signatus*: the importance of rain. *Oecologia* 153:479–488
- Loman J (2002) Temperature, genetic and hydroperiod effects on metamorphosis of brown frogs *Rana arvalis* and *R. temporaria* in the field. *J Zool (Lond)* 258:115–129
- Madsen T, Shine R (1996) Seasonal migration of predators and prey—a study of pythons and rats in tropical Australia. *Ecology* 77:149–156
- Madsen T, Shine R (2000) Rain, fish and snakes: climatically driven population dynamics of Arafura filesnakes in tropical Australia. *Oecologia* 124:208–215
- Malhi Y, Roberts JT, Betts RA et al (2008) Climate change, deforestation, and the fate of the Amazon. *Science* 319:169–172
- Manabe S, Stouffer RJ (1993) Century-scale effects of increased atmospheric CO<sub>2</sub> on the ocean-atmosphere system. *Nature* 364:215–218
- Markham A (1996) Potential impacts of climate change on ecosystems: a review of implications for policymakers and conservation biologists. *Climate Res* 6(2):179–191
- Marquez R (1995) Female choice in the midwife toads (*Alytes obstetricians* and *A. cisternasii*). *Behaviour* 132:151–161
- Massot M, Clobert J, Ferriere R (2008) Climate warming, dispersal inhibition and extinction risk. *Glob Change Biol* 14:461–469
- McDiarmid RW, Altig R (eds) (1999) Tadpoles, the biology of anuran larvae. University of Chicago Press, Chicago

- McMahon CR, Hays GC (2006) Thermal niche, large-scale movements and implications of climate change for a critically endangered marine vertebrate. *Glob Change Biol* 12:1330–1338
- Myers N, Mittermeier RA, Mittermeier CG et al (2000) Biodiversity hotspots for conservation priorities. *Nature* 403:853–858
- Nagl AM, Hofer R (1997) Effects of ultraviolet radiation on early larval stages of the Alpine newt, *Triturus alpestris*, under natural and laboratory conditions. *Oecologia (Heidelb)* 110:514–519
- Nakamura M (2009) Sex determination in amphibians. *Semin Cell Dev Biol* 20:271–282
- Neelin JD, Munnich M, Su H et al (2006) Tropical drying trends in global warming models and observations. *Proc Natl Acad Sci USA* 103(16):6110–6115
- Nepstad DC, Verissimo A, Alencar A et al (1999) Large-scale impoverishment of Amazonian forests by logging and fire. *Nature* 398:505–508
- Ozgul A, Tuljapurkar S, Benton TG et al (2009) The dynamics of phenotypic change and the shrinking sheep of St. Kilda. *Science* 325:464–467
- Palma JAM (1997) Marine turtle conservation in the Philippines and initiatives towards a regional management and conservation programme. In: Proceedings of the workshop on marine turtle research and management in Indonesia. Wetlands international-Indonesia programme, Indonesia, pp 121–138
- Peltzer PM, Lajmanovich RC, Sánchez-Hernández JC et al (2006) Effects of agricultural pond eutrophication on survival and health status of *Scinax nasicus* tadpoles. *Ecotoxicol Environ Saf* 70:185–197
- Petchey OL, McPhearson PT, Casey TM et al (1999) Environmental warming alters food-web structure and ecosystem function. *Nature* 402:69–72
- Peterson TC, Vose RS (1997) An overview of the Global Historical Climatology Network temperature database. *Bull Am Meteorol Soc* 78:2837–2849
- Pieau C, Dorizzi M, Richard-Mercier N (1999) Temperature-dependent sex determination and gonadal differentiation in reptiles. *Cell Mol Life Sci* 55:887–900
- Polovina JJ, Kobayahi DR, Parker DM et al (2000) Turtles on the edge: movement of loggerhead turtles (*Caretta caretta*) along oceanic fronts, spanning longline fishing grounds in the central North Pacific, 1997–1998. *Fish Oceanogr* 9:71–82
- Polovina JJ, Balazs GH, Howell EA et al (2004) Forage and migration habitat of loggerhead (*Caretta caretta*) and olive ridley (*Lepidochelys olivacea*) sea turtles in the central North Pacific Ocean. *Fish Oceanogr* 13:36–51
- Pounds JA, Crump ML (1994) Amphibian declines and climate disturbance: the case of the golden toad and the harlequin frog. *Conserv Biol* 8:72–85
- Pounds JA, Bustamante MR, Coloma LA et al (2006) Widespread amphibian extinctions from epidemic disease driven by global warming. *Nature* 439:161–167
- Rahmstorf S (1997) Risk of sea-change in the Atlantic. *Nature* 388:825–826
- Raxworthy CJ, Pearson RG, Rabibisoa N et al (2008) Extinction vulnerability of tropical montane endemism from warming and upslope displacement: a preliminary appraisal for the highest massif in Madagascar. *Glob Change Biol* 14:1703–1720
- Roemmich D, McGowan J (1995) Climatic warming and the decline of zooplankton in the California current. *Science* 267:1324–1326
- Rojas S, Richards K, Jancovich JK et al (2005) Influence of temperature on Ranavirus infection in larval salamanders *Ambystoma tigrinum*. *Dis Aquat Org* 63:95–100
- Romansic JM, Waggener AA, Bancroft BA et al (2009) Influence of ultraviolet-B radiation on growth, prevalence of deformities, and susceptibility to predation in Cascades frog (*Rana cascadae*) larvae. *Hydrobiologia* 624:219–233
- Sanuy D, Oromí N, Galofré A (2008) Effects of temperature on embryonic and larval development and growth in the natterjack toad (*Bufo calamita*) in a semi-arid zone. *Anim Biodiversity Conserv* 31(1):41–46
- Scott DE, Fore MR (1995) The effect of food limitation on lipid levels, growth, and reproduction in the marbled salamander, *Ambystoma opacum*. *Herpetologica* 51:462–471
- Shine R, Madsen T (1997) Prey abundance and predator reproduction: rats and pythons on a tropical Australian floodplain. *Ecology* 78:1078–1086
- Shine R, Elphick MJ, Donnellan S (2002) Co-occurrence of multiple, supposedly incompatible modes of sex determination in a lizard population. *Ecol Lett* 5:486–489
- Sibly RM, Atkinson D (1994) How rearing temperature affects optimal adult size in ectotherms. *Funct Ecol* 8:486–493
- Skerratt LF, Berger L, Speare R et al (2007) Spread of chytridiomycosis has caused the rapid global decline and extinction of frogs. *EcoHealth* 4:125–134
- Snyder GK, Weathers WW (1975) Temperature adaptations in amphibians. *Am Nat* 109:93–101

- Spotila JR (1972) Role of temperature and water in the ecology of lungless salamanders. *Ecol Monogr* 42:95–124
- Stocker TF, Schmittner A (1997) Influence of CO<sub>2</sub> emission rates on the stability of the thermohaline circulation. *Nature* 388:862–865
- Stuart BL, Inger RF, Voris HK (2006) High level of cryptic species diversity revealed by sympatric lineages of Southeast Asian forest frogs. *Biol Lett* 2:470–474
- Tejedo M (1992) Effects of body size and timing of reproduction on reproductive success in female natterjack toads *Bufo calamita*. *J Zool (Lond)* 228:545–555
- Telemeco RS, Elphick MJ, Shine R (2009) Nesting lizards (*Bassiana duperreyi*) compensate partly, but not completely, for climate change. *Ecology* 90:17–22
- Tietge JE, Diamond SA, Ankley GT et al (2001) Ambient solar UV radiation causes mortality in larvae of three species of *Rana* under controlled exposure conditions. *Photochem Photobiol* 74:261–268
- Walsh RPD (1996) Drought frequency changes in Sabah and adjacent parts of northern Borneo since the late nineteenth century and possible implications for tropical rain forest dynamics. *J Trop Ecol* 12:385–407
- Wassersug R, Feder M (1983) The effects of aquatic oxygen concentration, body size and respiratory behaviour on the stamina of obligate (*Bufo americanus*) and facultative air-breathing (*Xenopus laevis* and *Rana berlandieri*) anuran larvae. *J Exp Biol* 105:173–190
- Whitten T, Mustafa M, Henderson GS (2002) The ecology of Sulawesi. Periplus Editions, Singapore
- Wiafe G, Yaqub HB, Mensah MA et al (2008) Impact of climate change on long-term zooplankton biomass in the upwelling region of the Gulf of Guinea. *ICES J Mar Sci* 65:318–324
- Zachos J, Pagani M, Sloan L et al (2001) Trends, rhythms, and aberrations in global climate 65 Ma to present. *Science* 292:686–693