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## Impacts of Climate Change on Animal Behaviour: A Review

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Climate change is altering the physical and biological conditions in which animals live, and behaviour is often the first trait through which a species responds. Rising temperatures, shifting rainfall, ocean acidification and more frequent extreme weather events are changing when, where and how animals migrate, breed, forage, communicate and interact with predators and competitors. This narrative review brings together evidence from terrestrial, marine and freshwater systems, including recent primary studies on primates, ungulates, marine turtles, waterfowl, beetles and river otters, to summarise how climate change is influencing behavioural ecology across taxa. Phenological shifts in migration and reproduction are considered alongside changes in foraging and social behaviour, altered predator-prey dynamics, and the physiological pathways that underlie behavioural flexibility, before turning to conservation implications and the methodological challenges that still limit firm generalisation in this field. Behaviour appears to act both as a buffer against environmental change and as an early warning signal of ecological stress, making its study central to forecasting the fate of wild populations in a warming world. The review closes with priority directions for future work, including longer-term monitoring, multi-stressor experiments and closer collaboration between behavioural ecologists and conservation practitioners.

## Introduction

Climate change is one of the most well-documented causes of global ecological change and can impact from the level of individual physiology to ecosystem level [1]. What is striking is how consistent the evidence is across taxonomic groups and regions, forming what has been described as a coherent biological fingerprint of a warming climate [2]. Behaviour is a unique characteristic in this regard because it is often the most readily adaptable characteristic of an animal; they can adapt to it within a few hours or days, not across generations [1]. With the alterations in precipitation and the rise in global temperatures, animals are forced to adapt in order to change the timing of migration and breeding, the way they seek out food, the way they communicate with each other, and how they deal with predators and competitors [2]. The Intergovernmental Panel on Climate Change has confirmed that the pace and magnitude of these changes now exceed Holocene variability in many regions [3]. Behavioural responses can happen very quickly and are now regarded as a potential early sign of vulnerability, sometimes before survival or reproduction rates are determined [4]. This flexibility is not limitless, though: considerable variation exists among species, and even among individuals, in the capacity to adjust [5]. The present review brings together evidence examining the impact of climate change on animal behaviour in the context of migration,

reproduction, foraging, social interactions and predator prey relationships in both marine and terrestrial systems followed by a discussion of mechanisms of physiological change and conservation implications.

### Climate Change: An Overview

Climate change is the term used to describe changes in average weather conditions that happen over an extended period, mainly due to the emission of greenhouse gases by human activity since the mid- twentieth century [3]. It has a wide ecological footprint, including rising air and sea-surface temperatures, changes in rainfall, increased heatwaves and storms, sea-ice retreat, and ocean acidification due to increased dissolved carbon dioxide [3]. The physical changes have a biological pressure effect in a few ways, including through direct thermal stress, through changes in the availability of resources, and through habitat loss and fragmentation [1]. A defining feature of the ecological response is its coherence across otherwise unrelated taxa and regions, pointing to a shared climatic cause rather than local or incidental factors [2]. Behaviour sits at the interface between an animal and its surroundings, so it is often the first trait to register these pressures, well before change becomes visible in population size or genetic composition [4]. Contemporary warming is also unusually rapid in evolutionary terms: genetic adaptation alone is unlikely to keep pace in many species, leaving phenotypic plasticity, including behavioural plasticity, as the more immediately available coping mechanism, though plasticity itself has limits and maladaptive outcomes can follow where change exceeds a species' evolved capacity for flexible response [6]. Treating climate change as a multi-faceted stressor rather than a single variable is essential for interpreting the behavioural evidence in the remainder of this review [1].

### Impacts on Behavioural Ecology

Behavioural ecology provides the conceptual framework through which climate impacts on animal decision-making can be understood, given that behaviour mediates the relationship between environmental conditions and individual fitness [4]. Organisms facing altered conditions have essentially four options: move, evolve genetically, acclimate physiologically, or die, and behavioural adjustment is often the most immediately accessible of these, allowing an animal to alter its activity patterns, habitat use or thermoregulatory strategy without any change in underlying physiology [4]. This kind of flexibility has been proposed as an important mechanism by which populations persist through periods of rapid environmental change [4]. Individual variation in behavioural type, sometimes described as personality or coping style, further shapes an animal's capacity to respond; more reactive individuals generally show greater plasticity than proactive ones, and a population made up of a wider range of behavioural types may show greater collective resilience as a result [5]. This is not merely theoretical: a long-term study of a wild great tit (*Parus major*) population found that individuals with greater adaptive plasticity in laying date achieved higher fitness under changing spring temperatures, direct evidence that behavioural plasticity is itself subject to natural selection under climate change [7]. Human-induced rapid environmental change more broadly, of which climate change is one component, frequently elicits behavioural plasticity, yet this plasticity is often insufficient on its own to guarantee persistence, a tension between behaviour as a buffer and as an incomplete safeguard that recurs throughout the sections that follow [8].

### Impacts on Migration and Movement

Migration timing is among the most extensively documented behavioural traits affected by climate change, particularly in birds, where spring arrival dates have advanced in numerous populations alongside warming spring temperatures [2]. These shifts are not uniform: short-distance migrants generally track warming more closely than long-distance migrants, whose departure is governed more strongly by endogenous cues, and some short-distance populations even delay autumn departure as temperatures rise, extending time at breeding grounds [1]. Migratory birds depend on synchrony between arrival and the seasonal peak in food availability at breeding grounds, and differential rates of change between species and trophic levels can generate a phenological mismatch in which migrants breed too late relative to the resources their offspring require; populations unable to advance sufficiently have tended to decline, whereas those tracking spring warming have remained comparatively stable [9]. A tracking study of central European white storks (*Ciconia ciconia*) found that seasonal climatic niche tracking is largely a population-level, bottom-up property rather than a fixed individual trait: individual birds mainly followed short-term weather, and the broader niche only emerged once data were pooled across the population [10]. Migratory stopover habitat is itself vulnerable to climate change: modelling of the Mai Po Inner Deep Bay Ramsar site in Hong Kong, a major stopover on the East Asian-Australasian Flyway, projected that sea level rise and declining sediment accretion could inundate its tidal flats and mangroves by 2100 under most scenarios, threatening habitat used by more than 80,000 waterbirds [11]. Migration timing can carry downstream consequences beyond the migrants themselves: a modelling study of highly pathogenic avian influenza in migratory waterfowl found that a nine-day advancement in spring migration extended outbreak duration by increasing time spent at breeding grounds [12]. Climate change also alters the physical difficulty of migration: longer Arctic ice-free seasons have lengthened the fasting period faced by polar bears (*Ursus maritimus*), which must increasingly rely on energy-conserving movement rather than active foraging [13]. Movement responses are not limited

to seasonal migration, however: when Hurricane Irma made landfall in Florida, GPS-collared white-tailed deer (*Odocoileus virginianus seminolus*) shifted resource selection towards higher-elevation forest and away from marshes, most left their home ranges during the storm, and movement rates increased on the day it struck, with no attributed mortality among the monitored deer [14]. Climate change therefore affects not only when animals migrate but also the strategies used to complete the journey, whether over an annual cycle or during a single extreme event [13].

**Table 1. Selected documented behavioural responses to climate change across taxa.**

| Behavioural category               | Representative taxon                                          | Documented response                                                                                         | Reference |
|------------------------------------|---------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------|-----------|
| Migration timing                   | Migratory passerine birds                                     | Spring arrival advanced; long-distance migrants track warming less closely than short-distance migrants     | [1,2]     |
| Seasonal niche tracking            | White stork ( <i>Ciconia ciconia</i> )                        | Climatic niche tracking is a population-level property; individuals mainly track short-term weather         | [10]      |
| Migration timing and disease       | Migratory waterfowl (HPAI hosts)                              | A 9-day advance in spring migration extended avian influenza outbreak duration in simulations               | [12]      |
| Movement during extreme events     | White-tailed deer ( <i>Odocoileus virginianus seminolus</i> ) | Deer left home ranges, shifted to higher-elevation forest and increased movement rate during Hurricane Irma | [14]      |
| Reproductive output                | Multiple bird species (global meta-analysis)                  | Average decline in offspring production, most marked in migratory and larger-bodied species                 | [15]      |
| Breeding phenology                 | Loggerhead turtle ( <i>Caretta caretta</i> )                  | Nesting activity linked to rising sea surface and air temperatures at Mediterranean rookeries, 1982-2012    | [17]      |
| Reproduction vs body condition     | African buffalo ( <i>Syncerus caffer</i> )                    | Reproductive success fell in a high-floodwater year even as body condition improved                         | [18]      |
| Foraging behaviour                 | Japanese macaque ( <i>Macaca fuscata</i> )                    | Reduced foraging on aquatic insects in streams during a winter warming and flooding event                   | [19]      |
| Food-caching behaviour             | Dung beetle ( <i>Phanaeus vindex</i> )                        | Food caches buried deeper under experimental warming; brood ball burial depth unaffected                    | [20]      |
| Cooperative behaviour              | Burying beetle ( <i>Nicrophorus nepalensis</i> )              | Cooperative groups act as thermal generalists across a wider elevational and temperature range              | [23]      |
| Social structure and communication | Coastal river otter ( <i>Lontra canadensis</i> )              | Group-living otters use latrine sites for group signalling; solitary otters use scent marking to            | [24]      |

| Behavioural category                    | Representative taxon                                     | Documented response                                                                                                                  | Reference |
|-----------------------------------------|----------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------|-----------|
| Social group dynamics                   | White-faced capuchin monkey<br>( <i>Cebus imitator</i> ) | avoid conspecifics<br>El Nino droughts and La Nina floods eroded the foraging advantages of larger groups over long-term observation | [25]      |
| Acoustic communication                  | Birds and echolocating bats                              | Atmospheric absorption alters transmission distance and quality of acoustic signals                                                  | [26]      |
| Predator avoidance                      | Coral reef fishes                                        | Ocean acidification effects on avoidance behaviour not reproducible in large-scale replication                                       | [27]      |
| Behavioural and physiological deviation | Marine fish and invertebrates<br>(meta-analysis)         | Warming and acidification caused significant deviations in behaviour at moderate as well as severe stress levels                     | [28]      |
| Hibernation timing<br>(amphibians)      | Pond frog ( <i>Pelophylax nigromaculatus</i> )           | Shortened hibernation period; earlier spring emergence, later autumn entry                                                           | [30]      |
| Hibernation timing (mammals)            | Various hibernating mammals                              | Warmer soil and hibernaculum temperatures reduce metabolic efficiency and increase costly arousals                                   | [29]      |
| Movement and energetics                 | Polar bear ( <i>Ursus maritimus</i> )                    | Extended fasting period associated with a longer ice-free season                                                                     | [13]      |

### Impacts on Reproductive Behaviour

Reproductive timing in many species is closely tied to environmental cues that historically predicted favourable conditions for offspring survival, and climate change is undermining the reliability of these cues [1]. A global meta-analysis covering more than 700,000 clutches found that annual offspring production has, on average, declined in recent decades, although the direction of change varied considerably, with migratory and larger-bodied species faring worse than smaller-bodied, sedentary ones [15]. Climate change is also extending breeding-season duration in many populations as temperatures warm [16]. Where migratory birds fail to adjust breeding timing in step with the earlier availability of insect prey, a phenological mismatch can arise between hatching dates and peak resource abundance, proposed as a contributing factor in some migrant declines [9]. Marine reptiles show comparable sensitivity: a long-term dataset from major loggerhead turtle (*Caretta caretta*) nesting beaches in Greece found sea surface and air temperatures at the main nesting and foraging sites rose steadily between 1982 and 2012, with sea surface temperature closely tied to nesting activity at these Mediterranean rookeries [17]. Water availability can reshape reproductive outcomes independently of temperature, as shown by a multi-year African buffalo (*Syncerus caffer*) study in the Okavango Delta, discussed further below, in which a near doubling of floodwater volume reduced reproductive success even as body condition improved [18]. Extreme weather events present a further challenge, as parents must balance provisioning offspring against their own thermoregulatory needs during thermal stress [1]. Climate change is therefore reshaping reproductive behaviour through a diverse set of species-specific interactions rather than a single uniform mechanism [15].

### Impacts on Feeding and Foraging Behaviour

Foraging behaviour is highly sensitive to climate-driven changes in prey distribution, abundance and quality, and many species must adjust search effort, diet breadth or foraging range as one of the more immediately available forms of behavioural flexibility [4]. A direct illustration comes from the Kamikochi population of Japanese macaque (*Macaca fuscata*), the northernmost-distributed non-human primate, which forages for aquatic insects in mountain streams during winters

when terrestrial food is scarce; when a mid-February 2024 warming event brought rain and snowmelt that flooded the streams, direct observation and DNA metabarcoding showed the macaques reduced this foraging compared with typical winter conditions [19]. Warming can also alter caching behaviour: a field experiment with a tunnelling dung beetle (*Phanaeus vindex*) found beetles buried food caches deeper under warmer conditions, although burial depth of brood balls used for reproduction was unaffected, suggesting warming can selectively alter one class of caching behaviour and thereby influence the fate of the seeds these caches contain [20]. Large herbivores can show contrasting responses to the same driver depending on which measure is examined: in the Okavango Delta, a near doubling of floodwater volume reduced dry-season forage availability for African buffalo (*Syncerus caffer*) and shifted habitat selection towards drier ground, yet produced no significant change in resting or movement time, even as reproductive success fell and body condition improved [18]. In aquatic systems, prey capture depends heavily on rapid locomotor performance, and elevated temperature, hypoxia and acidification each independently affect the muscular and sensory systems underlying pursuit and escape, a mechanism discussed further below [21]. On land, warmer winters are reshaping foraging in hibernating and food-caching species more generally by increasing costly arousal from torpor [4]. Foraging behaviour, while flexible, is therefore subject to real physiological and energetic limits that climate change is increasingly testing across marine and terrestrial systems alike [21].

### Impacts on Social Behaviour and Communications

Social behaviour, including group formation, cooperative breeding and communication, is also responding to climate-driven environmental variability [22]. Cooperative breeding and group living occur disproportionately in regions with high climatic variability, suggesting sociality itself can buffer against unpredictable environments [22]. In burying beetles (*Nicrophorus nepalensis*), cooperative groups perform consistently well across a wide range of temperatures and elevations, behaving as thermal generalists, whereas smaller non-cooperative groups perform well only within a narrower range [23]. A modelling study of coastal river otters (*Lontra canadensis*) in Alaska showed social structure itself can depend on prey conditions expected to shift under climate change: otters cooperatively foraging on schooling fish use shared latrine sites to signal group membership, whereas otters feeding alone on demersal fish instead use scent marking for mutual avoidance, and simulations indicated declining schooling-fish availability would reduce group size and time spent with conspecifics [24]. Extreme climatic events can also destabilise social structures: a long-term capuchin monkey (*Cebus imitator*) study found El Nino droughts and La Nina floods disrupted the balance between within- and between-group competition, eroding the foraging advantage larger groups normally hold [25]. Communication is affected through a different pathway, since acoustic signal transmission depends on temperature and humidity, so the same call may carry differently under altered conditions, with implications for species relying on long-range signalling, including birds and bats [26]. Both cooperative structure and communication underpin reproduction and group defence, so their climatic sensitivity carries consequences beyond the immediate behaviours themselves [22].

### Impacts on Predator–Prey Interactions

Predator-prey dynamics are particularly sensitive to climate change, since warming, hypoxia and acidification can each independently alter the sensory and locomotor performance underlying attack and escape behaviour, with escape latency, kinematics and swimming speed in fish measurably affected by temperature and hypoxia primarily disrupting the directionality of escape manoeuvres [21]. Ocean acidification research offers a particularly instructive example of how scientific consensus here has evolved: early studies reported that elevated carbon dioxide caused coral reef fish to lose their normal avoidance of predator cues, in some cases even attracting them towards danger, whereas more recent, large-scale replication involving several species instead found negligible effects on predator avoidance, activity and behavioural lateralisation, suggesting some earlier effect sizes may not be fully reproducible [27]. This divergence underlines how important replication and transparency are in this field [27]. Temperature-driven changes in muscle performance and neural function remain a more consistent pathway by which warming alters predator-prey outcomes, independent of the carbon dioxide effects debated above [21]. Sea ice loss has produced a further, indirect effect in the Arctic, since polar bears losing access to ice-based seal hunting for longer each year must rely instead on stored energy reserves, with consequences for long-term persistence [13]. Climate change rarely affects a single species in isolation; it tends instead to propagate through predator-prey networks in ways difficult to anticipate [21].

### Impacts on Marine and Quatic Animal Behaviour

Marine and aquatic ecosystems are affected by warming, acidification, deoxygenation and altered currents, which influence animal behaviour individually or together [21]. In fish, temperature alters metabolism, muscle performance and neural function, affecting swimming, foraging and predator avoidance [21]. A meta-analysis showed that warming and acidification caused significant behavioural deviations more often than conventional analyses detected, although acidification had no consistent effect on fish behaviour, while most invertebrates responded negatively [28]. Aquatic systems also expose animals to climate driven changes in dissolved gas chemistry, producing complex behavioural responses [21].

## Impacts on Terrestrial Animal Behaviour

Terrestrial animals face climate pressures that differ in character from those of aquatic species, with behavioural thermoregulation, hibernation and activity timing forming particularly important response mechanisms [4]. Hibernating mammals are especially useful indicators of climate impact, since survival depends on a precise energetic balance between torpor and periodic arousal sensitive to ambient winter temperature [29]. Warmer winter soil and cave temperatures are expected to reduce hibernation's metabolic efficiency in some species, increasing costly arousals and potentially lowering spring body condition, although shorter, milder winters can also extend the active season for foraging and reproduction, so the net effect depends on the balance between these opposing pressures [29]. A comparable pattern has been documented in an amphibian, in which experimental warming altered hibernation duration and timing in a pond frog species (*Pelophylax nigromaculatus*), showing these dynamics are not confined to endotherms [30]. Microhabitat selection and shifts in daily activity timing allow many terrestrial species to buffer rising temperature through behavioural thermoregulation, though such compensation may carry hidden costs, and some species with insufficient plasticity are instead expected to shift range towards higher latitudes or elevations [4]. A theme recurs here that runs throughout this review: behavioural adjustment can delay, but does not necessarily prevent, the pressures imposed by a changing climate [6].

## Physiological and Neurological Mechanisms

Physiological and neurological processes link climate change to animal behaviour by affecting sensory, hormonal and cognitive functions [31]. Heat stress can impair cognition, reducing predator detection, foraging and social interactions, with effects that may persist after exposure [31]. Stress induced glucocorticoids also influence activity, vigilance and risk taking, with stronger responses in reactive than proactive individuals [5]. Although chemosensory disruption has been proposed to explain acidification effects on fish behaviour, evidence remains inconsistent [27]. In contrast, reduced muscle performance and impaired sensory and brain function consistently explain altered escape behaviour under warming, hypoxia and acidification [21]. Overall, behavioural responses to climate change are closely constrained by underlying physiology [31].

**Table 2. Physiological and neurological pathways linking climatic stressors to behavioural outcomes.**

| Climatic stressor                         | Physiological pathway                              | Behavioural outcome                                                                             | Reference |
|-------------------------------------------|----------------------------------------------------|-------------------------------------------------------------------------------------------------|-----------|
| Heat stress                               | Impaired cognitive processing                      | Reduced accuracy in learning, memory and decision-making tasks                                  | [31]      |
| Acute stressors and extreme events        | Hypothalamic-pituitary-adrenal axis activation     | Altered vigilance, activity level and risk-taking; marked individual variation                  | [5]       |
| Warming, hypoxia and acidification        | Muscle contractile performance and neural function | Altered escape kinematics and predator-prey interaction outcomes                                | [21]      |
| Ocean acidification (contested)           | Chemosensory cue processing                        | Minimal effect on predator avoidance in large, replicated studies                               | [27]      |
| Warming and acidification (meta-analysis) | Multiple physiological systems                     | Behavioural deviation detected roughly twice as often as directional change alone would suggest | [28]      |

## Conservation Implications

Behaviour is often the earliest detectable response to environmental change, making it a valuable tool in conservation planning [32]. Conservation behaviour applies behavioural ecology to assess human impacts, guide management and monitor conservation outcomes [32]. Behavioural data can improve decisions on reserve design, population monitoring and climate adaptation [33]. Phenological changes, such as shifts in migration or breeding, provide early warning signals of climate stress before population declines occur [15]. Climate based projections, including polar bear fasting under sea ice loss, also help identify thresholds for population persistence [13]. Because behavioural flexibility varies among species, identifying adaptive capacity is essential for effective conservation planning [4,32].

## **Challenges and Limitations**

Several methodological and conceptual challenges continue to limit the field's ability to generalise about climate impacts on animal behaviour, despite substantial progress [8]. Much experimental evidence on topics such as ocean acidification has come from laboratory conditions using elevated carbon dioxide over short timescales, and recent large-scale replication has shown some widely cited effects are not consistently reproducible, raising questions about effect size inflation in this literature [27]. Long-term behavioural datasets sufficient to detect gradual trends remain rare outside well-studied bird populations in Europe and North America, limiting the breadth of firm conclusions [1]. Disentangling climate effects from other simultaneous pressures, including habitat loss, pollution and human disturbance, is a persistent difficulty, since these stressors frequently co-occur and interact in non-additive ways [8]. Much research has also examined single stressors in isolation, even though wild animals typically experience multiple interacting stressors whose joint effects may differ from single-stressor predictions [21]. Behavioural flexibility is, finally, difficult to measure and compare across species, making it hard to rank taxa reliably by likely resilience, and addressing these limitations will require sustained investment in long-term, multi-stressor, cross-taxa research [8].

## **Future Directions**

Future research would benefit from expanding long-term behavioural monitoring beyond the narrow set of well-studied bird and marine taxa that currently dominate the literature [1]. Multi-stressor experimental designs, manipulating temperature alongside other realistic co-occurring pressures such as altered oxygen or pH, deserve greater emphasis, since this would help resolve inconsistencies apparent in single-stressor studies [21]. Incorporating individual variation in personality and stress responses into predictive models is also important, since population-level resilience likely depends on behavioural diversity within a population rather than its average characteristics alone [5]. Closer collaboration between behavioural ecologists and wildlife managers would help translate findings into practical conservation tools, building on the framework provided by conservation behaviour [32]. More work is needed connecting physiological and neurological mechanisms to demographic outcomes in wild populations, since this link remains underexplored relative to descriptive behavioural studies [31]. Expanding replication across additional taxa, following the model recently applied to ocean acidification research on reef fish, would help establish which reported effects are reliable rather than context specific [27]. Finally, integrating socio-economic and policy considerations into behavioural research would help ensure findings are incorporated into international conservation frameworks and national wildlife policy [3].

## **Conclusion**

Climate change is altering animal behaviour across virtually every taxonomic group and ecosystem examined to date, from the timing of bird migration and breeding to primate and ungulate foraging, marine turtle nesting, and the social structure of mammals dependent on shifting prey. Behaviour functions both as a buffer that allows some populations to persist under changing conditions and as an early warning signal that can reveal vulnerability before it becomes apparent in survival or reproductive statistics. Behavioural responses are highly variable, shaped by species-specific life histories, individual differences in personality and stress physiology, and the particular combination of climatic stressors experienced in a given environment. The debate over ocean acidification and coral reef fish behaviour is a useful reminder of why careful replication matters, since some early and widely cited findings have not held up under more rigorous later testing. Progress from here will depend on sustained long-term monitoring, experiments reflecting the multiple stressors animals actually experience, and closer collaboration between behavioural scientists and conservation practitioners. Understanding how and why animal behaviour changes in a warming world remains essential, not only for predicting the fate of individual species but also for protecting the wider ecological processes that depend on them.

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## **Conflicts of interest**

The authors declare no conflicts of interest.

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