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Evidence of climate related shifts in Australian phenology

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Abstract: Relatively little is currently known about the influence of changes in climate on phenology (timing of natural events) in the southern hemisphere, even though the implications to humans and the natural environment can be large. This paper sources recent phenological Australian studies and assesses the extent to which phenological shifts have occurred and the influence of climate on any observed phenological changes. Datasets considered include avian migration timing (covering the southern edge of the Nullarbor Plain, south-western Australia, south-eastern Australia, suburban and peri-urban Melbourne), avian breeding timing (Australia wide and localised marine and terrestrial species), plant phenology (southern Australia) and insect phenology.

Results so far indicate that the impact of climatic change on species phenology is varied; depending on species, region and season. For example, over 30% of species listed in the migration timing studies appear to have altered their migration phenology in response to changes in minimum temperature; in some regions species responded by mainly altering their arrival timing while in other regions changes in departure dates dominated (e.g. Nullarbor Plain and south-western Australia). Not all studies considered changes in precipitation but, when included, rainfall changes were also associated with altered migration timing. This was particularly evident in south-western Australia, where the most notable reduction in winter rainfall occurred. In this region, changes in precipitation appeared to have a greater influence on migration phenology than temperature, particularly for waterbirds and landbirds associated with littoral zones, highlighting potential differences in responses of Australian and northern hemisphere species to climate change.

Part of the complexity of determining how changes in climate may impact on species is determining which climate variables are most relevant to that species biology. It is expected that some species will be more or less sensitive to particular meteorological conditions and that this sensitivity may vary over time (including over various aspects of their life cycle) and over the range of the species. For example, the mechanisms for causing shifts in phenology for plants are likely to differ from that for invertebrates which will, in turn, differ from vertebrates. For species which migrate, or undergo large-scale movements, precise information is required on where and when they move, and locations visited en-route, to fully model climatic influences on movement timing. In many cases, the effect of climate may be lagged.

Not all species or populations studied in Australia have changed their phenology in response to changes in climate. Is phenology in these species driven by factors other than climate or are the changes currently observed in the climate system still within that species ‘normal’ operating range? This is a question that still needs to be addressed.

Improved knowledge of the impacts of climate on species’ phenology will significantly improve natural resource management decisions, aid policy development and increases public awareness of climate change and its impacts in Australia. Currently our knowledge is limited (temporally, spatially and by taxa) but significant progress is being made to improve available data, including the development of systems to collect phenological data on multiple species for the same location. Improved observation networks are urgently required, in order to better model, understand, and manage Australia’s natural systems.

Keywords: *Climate Change, migration, breeding, phenology, Australia*

1. INTRODUCTION

Phenology is the study of periodic biological events that are influenced by environmental conditions, particularly changes in weather and climate. Examples include: migration and nesting, flowering and fruiting, insect hatching and frog spawning.

Understanding and predicting changes in phenology is important for a number of reasons. Changes in phenology can influence species interactions (including pollination), population fitness, water cycles, carbon sequestration, human health (allergenic disorders, vector borne diseases, pest insect control), tourism and recreation, transport (e.g. bird migration and aircraft collisions), timing of management activities and productivity in agriculture, etc. Given the often strong relationships between changes in climate and changes in phenology, phenological measures can also be used as proxies for climate change.

Globally most of our knowledge about changes in phenology comes from the northern hemisphere (Figure 1), with 28,115 of the total 28,671 studies coming from Europe alone. Australian phenology was poorly represented in the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC, 2007) but recent progress has been made in our understanding of the drivers of Australian phenological change and this is discussed below.

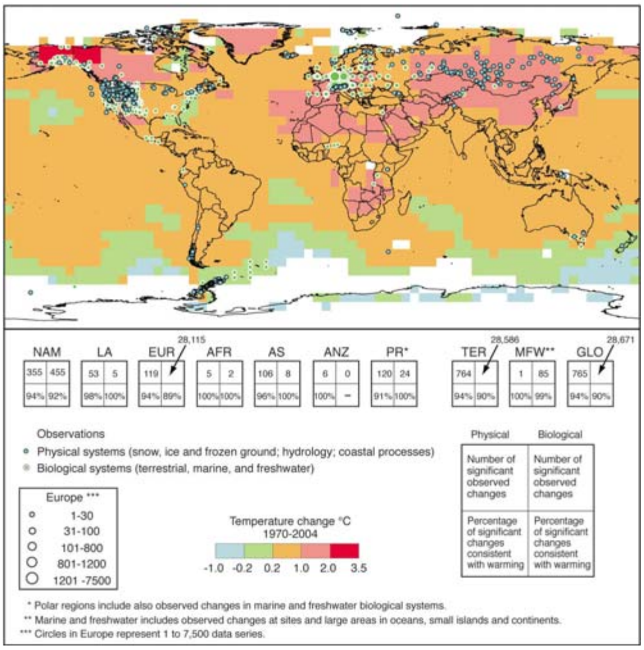

Figure 1. Locations at which systematic long-term studies meet stringent criteria documenting recent temperature-related regional climate change impacts on physical and biological systems. The 2 × 2 boxes show the total number of data series with significant changes (top row) and the percentage of those consistent with warming (bottom row) for (i) continental regions: North America (NAM), Latin America (LA), Europe (EUR), Africa (AFR), Asia (AS), Australia and New Zealand (ANZ), and Polar Regions (PR); and (ii) global scale: Terrestrial (TER), Marine and Freshwater (MFW), and Global (GLO). The numbers of studies from the seven regional boxes do not add up to the global (GLO) totals because numbers from regions except Polar do not include the numbers related to Marine and Freshwater (MFR) systems. Locations of large-area marine changes are not shown on the map. Note the small number of Australian studies and their restricted coverage (Figure TS-1 from IPCC 2007).

2. UNIQUENESS OF AUSTRALIA

Australian biota has been isolated from other parts of the globe for a long time and, in conjunction with historical climate, this has resulted in fairly unique flora and fauna (Dunlop and Brown, 2008). Australian winters are generally mild, the country is relatively dry (~50% of the country receiving less than 300 mm per year and ~90% less than 800 mm), and considerable rainfall variability results in highly variable river flows (Crowder, 2000; Dunlop and Brown, 2008). As a result, Australian species may have a greater variety of responses to environmental variation than northern hemisphere species, where photoperiod and cold winter temperatures are the primary phenological drivers (e.g. Menzel, 2003; Dingle, 2008).

3. SUMMARY OF EXISTING STUDIES

Although greater than that reported in IPCC (2007), the number of Australian studies documenting changes in phenology is still relatively small (Table 1). As in many other countries, most of our current knowledge comes from studies of terrestrial birds and plants with a general advance in phenology over time. However, Table 1 also highlights that we are largely ignorant of phenological changes that may be occurring in many other taxa, such as reptiles, mammals, amphibians, invertebrates etc. Impacts on Australian marine phenology are largely unknown. Commercial and recreational fishermen have reported changes in timing of life stages and phenology of benthic and demersal fishes (Hobday et al., 2006), but these are yet to be quantified. Few studies cover large regions, most concentrating on single sites in southern Australia, so we have little information on regional variations in phenological responses to climate and in some regions no information at all.

Table 1. Examples of reported phenological changes in Australia.

Region	**Phenological Change**	**Reference**
Southeastern Australia	Flowering dates in four perennial species; range 0-46 days later over 20 year period	Keatley et al. (2004)
	Flowering dates of 65 native species, over 24 years; 8 species flowered significantly earlier (average 1.7 days/year), 5 later (1.8 days/year)	Keatley and Hudson (2007)
	Increased temperature and summer rainfall related to earlier flowering in two eucalpt species and later flowering to two others	Keatley et al. (2002)
	Later breeding in Little Penguins *Eudyptula minor* on Phillip Island, Victoria, linked to sea surface temperatures (1968-1998) – cooler oceans leads to later laying	Chambers (2004)
	Earlier avian arrival (~3.5 days/decade) and later departure (~5.1 days/decade) with differences between short and long distance migrants. Earlier arrival with increasing minimum temperature (>9 days / ºC)	Beaumont et al. (2006)
	Earlier breeding in Helmeted Honeyeater *Lichenostomus melanops cassidix* over 1989-2006 related to reduction in rainfall and mild warming (maximum & minimum temperature)	Chambers et al. (2008a)
Southeastern Australia, Snowy Mountains	Earlier arrival of migratory birds; many several weeks earlier in 1980s-90s than in 1970s	Green and Pickering (2002)
	Arrival and breeding timing in Richard's Pipit *Anthus novaeseelandiae* earlier when snowmelt earlier	Norment and Green (2004)
South Australia	Pairing dates in Sleepy Lizards *Tiliqua rugosa* earlier when winters warmer and drier	Bull and Burzacott (2002)
Western Australia	Changes in arrival and departure dates of birds in semi-arid region; overall trend for earlier arrival and departure; generally earlier arrivals with increasing maximum and minimum temperatures	Chambers (2005)
	Avian migration timing shifts in south-western Australia stronger relationship to rainfall than temperature changes	Chambers (2008)
Continental	Changes in timing of breeding in Australian Magpie *Gymnorhina tibicen* – climate variables: latitude, altitude, South Oscillation Index	Gibbs (2007)
	Shifts in timing of laying in Masked Lapwings *Vanellus miles* varied by region (late in south-east; earlier in north-east) – some evidence of rainfall effect in some regions	Chambers et al. (2008b)

The relative impact of changes in climate on species phenology varied with species, region and season. For example, over 30% of species listed in the migration timing studies appear to have altered their migration phenology in response to changes in minimum temperature; in some regions species responded by mainly altering their arrival timing while in other regions changes in departure dates dominated. Not all studies considered changes in precipitation but, when included, rainfall changes were also associated with altered migration timing. This was particularly evident in south-western Australia, where the most notable reduction in winter rainfall occurred. In this region, changes in precipitation appeared to have a greater influence on migration phenology than temperature, particularly for waterbirds and landbirds associated with littoral zones, highlighting potential differences in responses of Australian and northern hemisphere species to climate change.

4. IMPLICATIONS OF DATA LIMITATIONS

Given Australia's high level of endemic species, already adapted to a highly variable climate system, the phenological changes, and drivers for this change, seen in the Northern Hemipshere may not be directly transferable to Australian species. In order to adequately model changes in phenology over time and to determine which environmental factors play key roles, good quality biological and environmental data is required. This can come from a variety of sources, including government departments, non-government organizations, universities, published literature or private journals. The Australian experiences highlight that these data are often difficult to locate or access and can have irregular coverage, both temporally and spatially. Very little is known about interactions between species or with other threatening processes, particularly under a changing climate. With insufficient information it is difficult to set priorities for the management of climate change impacts, though Chambers et al. (2005) offer some suggestions.

4.1. Species Implications

For most Australian species, their responses to changes in climate is largely unknown. For highly mobile species obtaining an understanding of climate drivers to movement is further complicated by limited knowledge of movement patterns and by variation in the amount of movement undertaken by sub-populations of some species (e.g. Grey Fantail *Rhipidura albiscapa* which can be either resident, migratory or a partial migrant; Chan, 2001). With little information on where some species move to and from it is difficult to model species-climate relationships over the species range and seasonal or life cycle.

Climate can affect not only a single species but also species on which it depends. For example, shifts in the timing of flowering and fruiting or the emergence of insects are likely to affect the food supply of many bird species. Not all species may be affected in the same way and mismatches between species and their food sources may reduce survival and reproductive success of some species (Chambers et al., 2005). We currently have no information on phenological changes in dependent species in Australia. This lack of data severely limits our ability to accurately model species outcomes under a changing climate.

4.2. Spatial Implications

Most published Australian studies cover limited spatial areas, with few covering the northern tropical regions, the arid interior, or the marine environment. There is a real need for datasets and studies covering a greater proportion of species' ranges including, where appropriate, a variety of climate zones and habitats. This will assist in modeling the relative impact of climate change on the species and help to remove other potentially confounding factors such as land-use change and observer effects. As most of the current phenological studies cover the temperate climate zones, further information is required for the tropical, arid and marine regions.

4.3. Temporal Implications

Most Australian studies have relatively short phenological records, with a lack of long-term climate-phenology studies with data prior to the 1950s, when global temperatures began to rapidly rise. Current recommendations are that at least 20 years of data is needed to detect climate signals in phenological time series (Chambers et al., 2005). However, in a country such as Australia, with regions of high rainfall variability, will this requirement be enough to detect rainfall related phenological shifts?

5. IMPROVING THE MODELS

5.1. Data Needs

A variety of approaches are currently being adopted to improve data availability and, therefore, knowledge of climate-related changes in Australian phenology. A three step approach is suggested to improve spatial, temporal and species coverage.

- Search: This step involves searching and documenting all existing long-term datasets. These can be difficult to locate and there is a need to consider non-mainstream data sources (such as the general public).
- Compile: This involves the creation of new datasets through systematic searches of the literature and other sources (e.g. photographic records or egg collections and Figure 2).
- Generation: The creation of new datasets, for example through new monitoring programs.

Figure 2. An example of a previous untapped source of phenological data. The diaries and art work of Rica Erickson (1908-) provide information on the location, date and phenological phase of many native Australian plants.

An example of a system designed to document existing long-term datasets is the National Ecological Meta Database (http://www.bom.gov.au/nemd/). Held by the Bureau of Meteorology, this database encourages users to list long-term ecological data, such as flowering, budding, fruiting, migration and breeding dates. The site can also be used to search for existing datasets. This project relies of people's willingness to share information about their datasets.

Recently the University of Melbourne and the Bureau of Meteorology (funded by ARCNESS) initiated a project to enhance the phenological record by systematically searching Australian literature. So far the project has been very successful, with over 21,000 records from over 960 references listed in PhenoARC's database.

In the northern hemisphere there are a number of highly successful networks which use members of the public to record phenological events on multiple species and over large areas (e.g. UK Phenology Network). These have proved incredibly popular and, together with the sourcing of long-term historical records, have provided valuable insights into species' responses to climate. Such a system is in development for Australia. Climate Watch will test the use of a dispersed observer network to gather information on biological responses to climate change. The progress of the project can be followed at http://www.climate-watch.org.au.

5.2. Complex Systems

Part of the complexity of determining how changes in climate may impact on species is determining which climate variables are most relevant to that species' biology. Many studies look at mean temperature, or minimum and maximum temperature, and only sometimes include rainfall or climate extremes. It is expected that some species will be more or less sensitive to particular meteorological conditions and that this sensitivity may vary over time (including over various aspects of their life cycle) and over the range of the species. For example, the mechanisms for causing shifts in phenology for plants are likely to differ to those for invertebrates which will, in turn, differ from vertebrates (Visser and Both, 2005). For species which migrate, or undergo large-scale movements, precise information is required on where and when they move, and locations visited along route, to fully model climatic influences on movement timing. In many cases, the effect of climate may be lagged.

If the main selection pressure on species' phenology is food, as suggested by Visser and Both (2005), then understanding the role that changes in climate play on individual species and populations may be complex and may need to involve looking at the role of climate on the phenology of individual elements of the food web. A mismatch between the phenology of a species and that of species on which it depends can have severe consequences for the species and for the food web (Visser and Both, 2005). At present it is not possible to look at phenological changes for any dependent species in Australia, due to a lack of data.

Not all species or populations studied in Australia have changed their phenology in response to changes in climate. Is phenology in these species driven by factors other than climate or are the changes currently observed in the climate system still within that species 'normal' operating range? We currently do not have the information to answer this question.

6. CONCLUSIONS

Improved knowledge of the impacts of climate on species' phenology will significantly improve natural resource management decisions, aid policy development and increases public awareness of climate change and its impacts in Australia. Currently our knowledge is limited (temporally, spatially and by taxa) but significant progress is being made to improve available data, including the development of systems to collect phenological data on multiple species for the same location. In order to better model, understand, and manage Australia's natural systems, improved observation networks are urgently required.

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