Shift In Flowering Dates Of Australian Plants Related To Climate: 1983-2006

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EXTENDED ABSTRACT

The majority of phenological studies have been carried out in the northern hemisphere (IPCC 2007; Parmesan and Yohe 2003; Root *et al.* 2003). This paucity of published work on natural systems in Australia, and other parts of the southern hemisphere is attributable to a rarity of natural datasets of 20 years or longer; the duration required to detect such trends (IPCC 2007; Keatley et al. 2002; Sparks and Menzel 2002).

This study, therefore, uses a rare dataset from Victoria to examine the date of first flowering (DOFF) of 65 species via linear regression to determine whether there had been a change in commencement between 1983 and 2006.

Linear and forward stepwise regressions were also used to determine whether there was any significant relationship between DOFF and annual rainfall and annual mean minimum, maximum and mean daily temperatures, monthly rainfall and monthly mean minimum, maximum and daily temperatures, as well as seasonal (spring, summer, autumn and winter) rainfall and seasonal mean minimum, maximum and daily temperatures.

Each of the climate variables were examined by linear regression to determine whether there was a change in local temperature or rainfall over the 24 years that flowering was observed.

All 65 species examined had shifts in their flowering commencement date. The overall shift in all species examined was to earlier flowering (8.81 days over the study period or 0.37 days per year (d/y)), although the shift was not statistically significant (P = 0.125). When only the 38 species which flowered earlier were examined the mean advancement was 0.9 days per year (d/y) (21.7 days over the 24 years). Whilst this shift was significant (P = 0.001), the mean delay in flowering of 0.8 d/y (19 days) for the remaining species was not (P = 0.452).

The reported range in significant and non-significant changes in phenological phases of plants is between 0.08 and 0.51 days earlier per year (IPCC 2007; Parmesan and Yohe 2003; Root *et al.* 2003). The average shift to earlier flowering of 0.37 days per year (d/y) for the species examined in this study sits within this range.

Thirteen species had a significant ($P \leq 0.05$) shift in their date of first flowering. Eight species flowered earlier ($\bar{x}$ = 1.7 d/y (40.3 days over the 24 years), range 0.7 to 3.3 d/y (16.4 to 78.2 days)) and 5 species flowered later ($\bar{x}$ = 1.8 d/y (43.2 days)), range 1.0 to 2.9 d/y (23.4 to 69.1 days) (Figure 1).

The shift within these species is larger than those reported in the literature. A contributing factor could be the period over which the observations were undertaken. Many of the other datasets include periods prior to when the effects of climate change were evident (Menzel 2003). This is illustrated by Fitter and Fitter (2002) who found that the DOFF between 1991 and 2000 had advanced more ($\bar{x}$ = 4.5 days) than in the previous 37 years.

The findings suggest that climate change is likely to affect the reproductive behaviour and distribution of plants in south-eastern Australia.

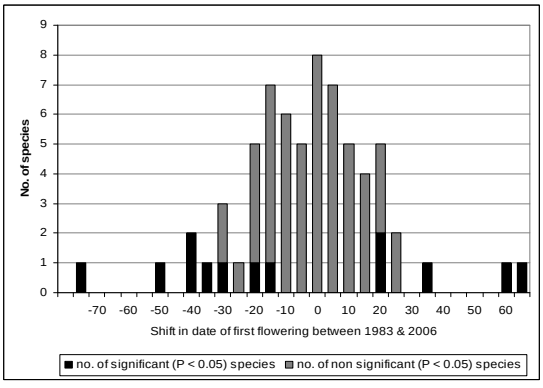

Figure 1. Shift, in number of days, for date of first flowering between 1983 & 2006. Darker shading indicates change was significant ($P \leq 0.05$).

1. INTRODUCTION

Phenology is the study of the timing of recurring natural phenomena (e.g. flowering, bird migration), as well as the causes of this timing with regard to climate and the interrelation among phases of the same or different species (Leith 1974). Hence phenological datasets have been used to document effects of climate change on natural systems (e.g. Chambers 2006; Cotton 2003; Menzel *et al.* 2006; Root *et al.* 2003). The results of these, and many other studies, show that there have been changes in phenology (e.g. an advancement in the commencement of leafing and flowering, earlier arrival of migratory birds) as well as changes in plant and animal distribution (e.g. extension of the range of butterflies) associated with changes in climate.

Whilst the majority of published studies have been carried out in the northern hemisphere (IPCC 2007; Parmesan and Yohe 2003; Root *et al.* 2003) very few studies have documented changes in Australia (Chambers 2006; IPCC 2007). This paucity of published work on natural systems in Australia and other parts of the southern hemisphere is attributable to a rarity of natural datasets of 20 years or longer; the duration required to detect such trends (IPCC 2007; Keatley *et al.* 2002; Sparks and Menzel 2002).

A review (Hughes 2003) of the potential effects of climate change on biodiversity highlighted the need for such studies and suggested that a change in the timing of reproductive activity may lead to major changes in community composition, and thus biodiversity of Australian ecosystems.

The study reported here examines whether there has been a change in the date of first flowering over a 24 year flowering record (1983-2006) of 65 species. It also examines the relationship between flowering commencement and 68 climate variables, as well as whether there has been a change in local temperature and rainfall over the observation period.

2. METHOD

2.1. Weather data

Weather data (temperature and rainfall) were obtained from the Bureau of Meteorology from the nearest weather station (approx. 22kms from the site), Scoresby (station number 086104, Latitude: 37.87 °S Longitude: 145.26 °E). Data from 1983 until December 2006 were used although both datasets were incomplete. When only 1 day was missing, the average of the temperature either side of the missing date was used. If 2 to 5 days were not recorded, then the mean minimum or maximum temperature for that particular month was substituted. Gaps of greater than 5 days were not interpolated, and thus were excluded from the analysis. Blocks of data were missing between December 1989 and March 1990, as well as October 1994 and August 1996. Rainfall data for the February to December 2003 were missing.

From these data 68 climatic variables were derived: annual rainfall and annual mean minimum, maximum and daily temperatures, monthly rainfall and monthly mean minimum, maximum and daily temperatures, as well as seasonal (spring, summer, autumn and winter) rainfall and seasonal mean minimum, maximum and daily temperatures.

2.2. Phenological data

The dates of flowering commencement records examined come from one site (Upper Beaconsfield) in south-east Australia and were collected by a naturalist between 1983 and the present. Observations by naturalists have been recognised as a resource for studies of climate change effects on natural systems (Fitter and Fitter 2002; Sparks and Carey 1995).

Observations were initially undertaken 3 times a week but since the late 1990s have been recorded weekly. There are approximately 126 species in the dataset of which records for 65 species are currently available for examination. Species chosen had to have a first record between 1983 and 1986 and a final record 20 years later or greater to satisfy the requirement of at least 20 years of data, from which to determine trends (IPCC 2007; Sparks and Menzel 2002). They also had to have a minimum of 10 records. The average number of years was 20.2 ± 3.3.

2.3. Data analyses

Each of the climate variables were examined by linear regression to determine whether there was a change in temperature or rainfall over the 24 years that flowering was observed.

The date of first flowering (DOFF) of 65 species was also examined via linear regression to determine whether there had been a change in flowering commencement over that time. Linear and forward stepwise regression were also used to determine whether there was any significant relationship between DOFF and rainfall, mean minimum, maximum and mean daily temperatures,

calculated on an annual, monthly as well as seasonal (spring, summer, autumn, winter) basis.

These climate variables were also examined via correlation methods to determine whether collinearity was present. If collinearity was found (r values > 0.80) between predictors one of them was considered redundant, as much of one variable is explained by the other. The variable which explained more of the variance in the DOFF was used in the analyses. Only the species which had a significant shift in flowering commencement were examined by stepwise regression analyses.

3. RESULTS

Climate: Over the observation period, 1983 to 2006, there were significant changes in 13 of the climatic variables examined. There was a range of responses, based on the regression equations. Maximum temperatures either monthly mean or annual as well as September mean daily temperature increased between 0.8 and 2.2ºC (Table 1, Figure 2a). Monthly mean minimum temperatures and May mean daily temperatures decreased between 1.0 and 1.8 ºC (Table 1, Figure 2c). Each of the rainfall variables decreased; monthly rainfall between 34.1 and 60.1 mm, and annual rainfall by 257.5 mm (Table 1, Figure 2b).

Table 1. Significant (P < 0.05) climate variables. Temp (ºC), Rainfall (mm), ↑ = increase or ↓ = decrease over the observation period.

Climate variable	N	P value	Shift	R^2
Annual mean maximum temperature	19	0.020	↑0.79	0.28
Annual total rainfall	24	0.012	↓257.5	0.25
Monthly/ seasonal mean maximum temperature				
July	22	0.008	↑1.3	0.30
September	23	0.004	↑2.2	0.33
Spring	21	0.001	↑1.6	0.43
Winter	22	0.003	↑1.0	0.36
Monthly/seasonal mean minimum temperature				
May	22	0.003	↓1.8	0.36
Autumn	22	0.008	↓1.7	0.30
Monthly mean daily temperature				
May	22	0.024	↓1.0	0.23
September	23	0.023	↑1.3	0.22
Monthly total rainfall				
July	23	0.020	↓60.1	0.23
Seasonal total rainfall				
Spring	23	0.013	↓34.1	0.26
Winter	23	0.048	↓40.7	0.17

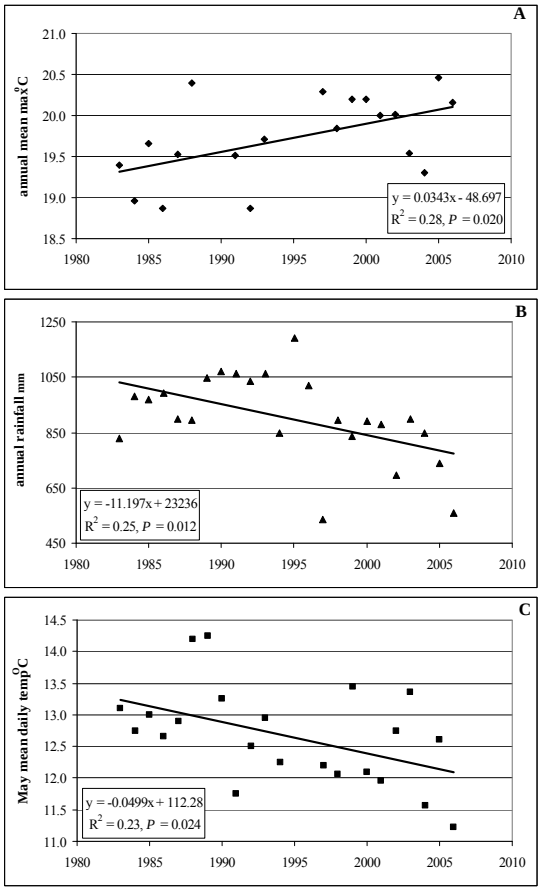

Figure 2. Changes in annual maximum daily temperature (A), annual rainfall (B) and May mean daily temperature (C).

Phenological: The overall shift in all species examined was to earlier flowering (8.81 days or 0.37 days per year (d/y)), but this shift was not significant (P = 0.125). An examination of the 38 species which flowered earlier found that the mean advancement of 0.9 days per year (d/y) (21.7 days over the 24 years) was significant (P = 0.001), however, the mean delay in flowering of 0.8 d/y (19 days) for the remaining species was not (P = 0.452).

Thirteen species (20% of the dataset) had a significant (P ≤ 0.05) shift in their date of first flowering (Table 2). Each of these is a perennial species. Eight of these species flowered earlier ($\bar{x}$ = 1.7 d/y (40.3 days), range 0.7 to 3.3 d/y (16.4 to 78.2 days)) and 5 species flowered later ($\bar{x}$ = 1.8 d/y (43.2 days), range 1.0 to 2.9 d/y (23.4 to 69.1 days) (Table 2). An example of early and late flowering is Figure 3.

Table 2. Shift in no. of days of first flowering for significant species (P < 0.05).

Earlier flowering species	R^2	*P* value	Total no. of days	Days per year
Acacia myrtifolia	0.14	0.045	32.6	-1.4
Comesperma volubile	0.21	0.036	16.2	-0.7
Dipodium roseum	0.30	0.004	21.3	-0.7
Geranium solanderi	0.32	0.004	39.1	-1.6
Indigofera australis	0.32	0.012	40.4	-1.7
Pterostylis alpina	0.25	0.003	41.1	-1.7
Ranunculus lappaceus	0.39	0.002	78.2	-3.3
Thysanotus tubersosus	0.27	0.010	53.3	-2.2
Later flowering species				
Acaena novae-zelandiae	0.23	0.039	23.4	1.0
Corybas aconitiflorus	0.22	0.025	38.6	1.6
Helichrysum scorpioides	0.65	0.001	69.1	2.9
Hypoxis glabella	0.25	0.012	61.0	2.5
Microtis unifolia	0.15	0.042	24.1	1.0

Additionally, there were 4 species whose date of first flowering shifted, at the P < 0.10 level of significance. Three species, *Acacia paradoxa, Gahnia radula* and *Wahlenbergia stricta*, flowered earlier with a mean shift of 0.86 d/y or 19.3 days over the observation period. *Leptospermum continentale* flowered later: 0.99 d/y (23.6 days over the observation period).

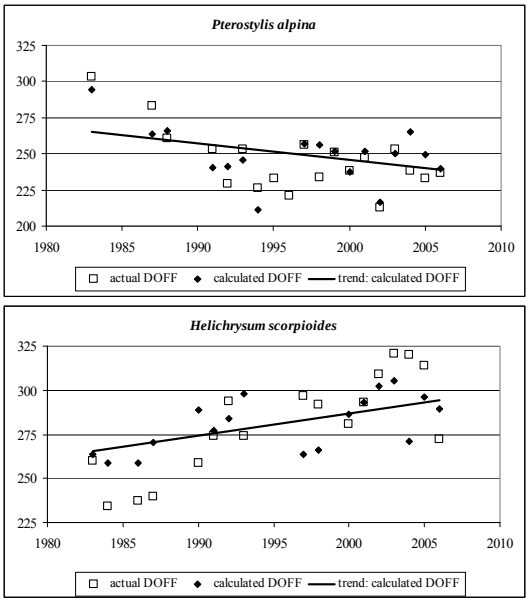

Figure 3. Actual DOFF (□), calculated DOFF using regression equations (◆) and trend in calculated DOFF.

Phenological and climate variables: Linear regression delineated 61 of the 68 climate variables as significant (P < 0.05) in describing the variation in date of first flowering in 60 species. The seven climate variables which were not significant were: February, April, and May mean monthly maximum temperatures, autumn maximum temperature, March and April mean daily temperature and January rainfall. Flowering in ten species was significantly related to an individual climate variable, whilst flowering in the remaining 3 species had a significant relationship with 2 or more climate variables.

The species which did not have any significant (P > 0.05) relationship with any individual climate variable were: *Acacia melanoxylon, Corbys aconitiflorus, Dianella longifolia, Microtis unifolia* and *Platylobium obtusangulum.*

Multiple regression analyses were only used to examine the species which had a significant shift in flowering commencement date.

For six species, forward stepwise regression of multiple variables provided no significant increase in the variance explained over that achieved by simple linear regression (Table 3). For the remaining seven species a multiple variable predictive approach was supported.

Table 3. Species with significant changes in date of first flowering and their climate predictors. ↑ = increase, ↓ = decrease.

Earlier flowering species	R^2	*P* value	Climate predictors & relationship with flowering	Change in climate predictors
Acacia myrtifolia	0.21	0.045	- Nov Max Temp	↑
Comesperma volubile	0.66	<0.001	- Sept Mean Temp +Nov Min Temp	↑ ↓
Dipodium roseum	0.20	0.023	- Feb Rain, + Apr Mean Temp	↑ ↓
Geranium solanderi	0.51	0.001	+Annual Rain	↓
Indigofera australis	0.21	0.024	- Spring Max Temp	↑
Pterostylis alpina	0.75	0.001	- Jul Max Temp + Aug Min Temp	↑ ↓
Ranunculus lappaceus	0.75	<0.001	+Sept Rain +Dec Min Temp +Oct Min Temp	↓ ↓ ↓
Thysanotus tubersosus	0.60	<0.001	+May Min Temp -Aug Max Temp	↓ ↑
Later flowering species				
Acaena novae-zelandiae	0.31	0.039	+Jul Max Temp	↑
Corybas aconitiflorus	0.14	0.071	+Dec Max Temp	↑
Helichrysum scorpioides	0.31	0.024	+Jul Max Temp	↑
Hypoxis glabella	0.34	0.014	-Annual Mean Min Temp	↓
Microtis unifolia	0.53	0.007	-Autumn Rainfall + Oct Min Temp	↓ ↓

The direction of shift in the date of first flowering was, as expected; that is, the shift is explained by their relationship with the climate variable/s.

When a single climate variable was found to be the significant predictor, this relationship was intuitive (Table 3). For example, *Helichrysum scorpioides* has shifted to later flowering over the 24 years (Table 2, Figure 3). It is positively influenced ($P = 0.008$, $R^2 = 0.30$) by the mean July maximum temperature. That is, warmer temperatures in July would result in later flowering. Over the observation period mean July maximum temperature has become warmer (Table 1).

In *Pterostylis alpina*, two climate predictors influenced the date of first flowering: mean July maximum temperature (negatively) and mean August minimum temperature (positively). As previously mentioned July has become significantly warmer, but the negative relationship indicates flowering in *Pterostylis alpina* would occur earlier. August minimum temperature has become cooler, although not significantly ($P = 0.421$, $R^2 = 0.03$). This positive influence would favour a shift to earlier flowering (Figure 3).

4. DISCUSSION

Climate: The annual mean maximum temperature increased significantly (0.79 ºC) over the twenty-four year observation period (1983 – 2006). This increase in maximum temperature aligns with the state of Victoria's maximum temperature increase of 0.8ºC since 1950 (CSIRO (Atmospheric Research) 2007). The significant minimum temperatures in this study have become cooler over the observation period; this is not the case for Victoria overall, where the daily minimum temperature has increased by 0.4 ºC since 1950. However, changes in temperature and rainfall are known not to be uniform across the state (CSIRO (Atmospheric Research) 2007).

Phenology: The range in significant and non-significant changes in phenological phases of plants reported is between 0.08 and 0.51 days earlier per year (IPCC 2007; Parmesan and Yohe 2003; Root *et al.* 2003). The average shift to earlier flowering of 0.37 days per year (d/y) for the species examined in this study sits within this range.

Each of the species which had a significant shift is outside this range (earlier flowering 0.7 to 3.3 d/y; later flowering 1.0 to 2.9 d/y). A contributing factor to this observation could be the period over which the observations were undertaken. Many of the other reported datasets include periods prior to when the effects of climate change were evident (Menzel 2003). This is illustrated by Fitter and Fitter (2002) who found that the date of first flowering between 1991 and 2000 had advanced more (mean = 4.5 days) than that observed in the previous 37 years (1954-1990).

However, there have been other species with similarly sized changes in their date of first flowering reported: *Lamium album*: 5.5 d/y earlier, *Cymbalaria muralis*: 3.5 d/y earlier, *Buddleja davidii*: 3.6 d/y later over 10 years (Fitter and Fitter 2002), *Duchesnea indica*: 1.5 d/y earlier, *Cardamine hirsuta*: 1.4 d/y earlier, *Lamium purpureum*: 1.3 d/y earlier over a 30 year time frame (Abu-Asab *et al.* 2001), *Alnus glutinosa*: 1.1 d/y earlier, *Rubus ulmifolius*: 0.8 d/y earlier, *Spartium junceum*: 0.7 d/y later over 38 years (Peñuelas *et al.* 2002); *Cornus mas*: 0.7 d/y later over a 38 collection period, *Prunus apetela*: 1.4 d/y later over 17 years (Primack *et al.* 2004). With the exception of *Cornus mas* and *Prunus apetela*, these species are included in studies which have contributed to the analyses which defined the range previously outlined (IPCC 2007; Parmesan and Yohe 2003; Root *et al.* 2003).

As temperature is a major influence on spring phenological phases (Abu-Asab *et al.* 2001; Schwartz 2003; Sparks and Carey 1995), increases in temperatures would be expected to result in earlier occurrence of phenological events. Intuitively therefore, an advance in phenology is expected (Menzel *et al.* 2006; Parmesan and Yohe 2003), as the mean temperature has risen globally and increases have also occurred in Victoria (CSIRO (Atmospheric Research) 2007) and at this study site. Many previous studies support this hypothesis, with between 78 to 89% of species examined exhibiting an advance in one or more of their phenological phases (IPCC 2007; Menzel *et al.* 2006). Delays do also occur, but this is often referred to as “not as expected” (Menzel *et al.* 2006; Parmesan and Yohe 2003). However, other parameters such as daylength and rainfall are also significant drivers (Freidel *et al.* 1993; Keatley and Hudson 2000; Opler *et al.* 1976; White 1995). In this study, temperature, rainfall or a combination of rainfall and temperature have had an influence on flowering.

The influence of temperature is not uniform across the dataset. In the instances where temperature is the only significant influence on flowering commencement, increases in temperature result in *earlier flowering* in some species, and *later flowering* in other species. For example, July has become significantly warmer but has a negative influence on DOFF in *Pterostylis alpina*. On the

other hand, it has a positive influence on DOFF in *Acaena novae-zelandiae*. It cannot be assumed therefore, that warmer temperatures will always result in earlier flowering. Furthermore, whilst overall temperatures have increased, some temperature statistics (e.g. May minimum temperature) have decreased.

Each of the shifts in DOFF, whether to earlier or later, was therefore as expected when the relationship with the climate predictor/s which significantly influenced the individual's flowering was examined.

These changes in phenology are viewed as a short-term response to climate change (Rehfeldt *et al.* 2004) with many studies outlining the consequences, short and longer-term, of such changes (e.g. decoupling of previous synchronous events, changes in reproductive success and in distribution, through migration and/or extinction, as well as changes in genotypes; Davis *et al.* 2005; Fitter and Fitter 2002; Rehfeldt *et al.* 2004; Visser and Holleman 2001; Walther *et al.* 2002).

As differences in phenological traits occur (Caprio 1966; Davis *et al.* 2005) and changes in temperatures and rainfall are not consistent across Victoria or Australia (CSIRO (Atmospheric Research) 2007; Pittock 2003), it is probable that these same species would exhibit a different rate of change in dates of first flowering to those which have occurred in some species in Europe and North America (Sparks and Menzel 2002; Tryjanowski *et al.* 2006). This of course requires further examination.

Additionally, the implications of this study go beyond the species for which there was a significant change in date of first flowering; species whose flowering commencement might not have changed significantly may be indirectly affected by those species whose flowering has changed, due to changes in factors such as pollinator competition, facilitation, production of hybrids (Walther *et al.* 2002).

5. CONCLUSION

This study indicates that there has been a significant change in the date of first flowering in 13 species over a 24 year period, and that flowering within these species is influenced by local climate. Additionally, there has been a significant change in local climate over the same timeframe.

Whilst the 65 species examined here are a small sample, they demonstrate a diversity of responses occurring in Australian plants, similar to those recorded in studies in other parts of the world: no change, earlier and later flowering.

The findings suggest that climate change is likely to affect the reproductive behaviour and distribution of plants in south-eastern Australia.

6. ACKNOWLEDGMENTS

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