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# Wavelet Signatures of Climate and Flowering: Identification of Species Groupings

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## 1. Introduction

Phenology: the timing of biological events (life stages such as flowering, fruiting, bird arrival underpins or influences many different ecological processes (Dunlop and Brown 2008; Forrest and Miller-Rushing 2010). These processes also have a significant role in shaping society's values (e.g. on human health, biodiversity, forestry, agriculture and tourism (Beggs 2004; Fitter and Fitter 2002; van Vliet 2010)). Since the 1990s, primarily because of climate change (Keatley & Hudson 2010, Parmesan 2006, Root et al., 2008, Schwartz 2003, Sparks 1995, 2002) phenological time series have been used to determine and report the impacts of global warming in both natural and managed systems (Menzel et al. 2006; Rosenzweig et al. 2008; Sparks et al. 2005). Determining trends in relation to long-term climate, however, is not easy as trends can be confounded by short-term interannual trends. Hence not only are long term records required, but also needed is the development of novel statistical methods which can deal with confounding factors (Badeck et al. 2004; Hudson 2010; Hudson & Keatley 2010a).

Wavelet methods (Daubechies, 1992) have been extensively applied to many arenas (eg. to the study of change in European spring temperatures (Paluš et al. 2005) and rainfall (Koch and Marković 2007), changes in vegetation cover (Lu et al. 2007), and to brain imaging (Bullmore et al. 2003; Sendur et al. 2007). It is the ability of wavelets to cope with non-stationary data: to deconstruct a time series into its subcomponents and remove noise; to accommodate multi-scale information, and to minimize correlation and time-dependency in data (Cornish et al. 2006; Gencay et al. 2001; Percival and Walden 2000; Vidakovic (1999)) that have added to their popularity. As phenological time series are usually non-stationary and noisy, and as such wavelet methods present as a useful analytic method (Hudson et al., 2005, Hudson 2010, Hudson et al., 2010a,b) for examining phenological records and for the determination of possibly changing climatic impacts on flowering, at an annual and across years basis.

The utility of wavelets in investigating the relationship of flowering to climate (three temperature variants and rainfall) is shown in this chapter by examining the flowering intensity time series records of eight Australian eucalypts – namely, *E. camaldulensis*, *E. goniocalyx*, *E. leucoxylon*, *E. macrorhyncha*, *E. melliodora*, *E. microcarpa*, *E. polyanthemos* and *E. tricarpa*. This work builds on an initial study by Kang et al. (2004) and on the early premise of Hudson et al. (2005) that wavelets *per se* could add integrity to the use of phenological records to detect climate change. This premise was recently confirmed by a study of 4 of the 8 Eucalypt species studied in this chapter by Hudson et al. (2010a, b) (see also Hudson (2010) and Keatley & Hudson, 2010).

The discrete wavelet transform (DWT), following the development of Percival and Walden (2000) and the maximal overlap DWT (MODWT) (Percival and Mofjeld 1997) is applied in this chapter. The rationale for this approach is that, given the resultant MODWT coefficients, the original (flowering) time series could be reconstructed as an additive decomposition - known as a multiresolution analysis (MRA) (Bratteli and Jorgensen 2002) and also that the individual detail (sub-component) series could be examined.

The aim of this research is to demonstrate the utility of wavelet analysis in phenology by extending the recent work of Hudson et al., (2010 a,b) from four to eight eucalypt species. This chapter contributes significantly to our understanding of the interplay between climate and the flowering of *Eucalyptus* flowering – a major southern hemisphere genus.

## 2. Methods

### 2.1 Maximal Overlap DWT (MODWT) and Multiresolution Analysis (MRA)

The discrete wavelet transform (DWT) as applied here, following Percival and Walden 2000, requires a discretization of the continuous time variable, $Y_t$. For most practical applications, the DWT, which analyzes signals over a discrete set of scales, that are usually sampled at dyadic sequences ($\lambda_j = 2^{j-1}$, $j$= 1, 2, 3, . . . ), is sufficiently accurate and can recover signals perfectly (Mallat 1989). The maximal overlap DWT (MODWT) is one discretization choice which gives $N$ wavelet coefficients for each scale (Percival and Guttorp 1994). The MODWT is a non-decimated variation of the DWT (Percival and Mofjeld 1997). It is also equivalent to the original time series, in the sense that, given the MODWT coefficients, $Y$, can be constructed as an additive decomposition, which is known as a multiresolution analysis (MRA) (Hernández and Weiss 1996, Gencay et al. 2001, Bratteli and Jorgensen 2002). The MRA decomposition is as follows:

$$Y = \sum_{j=1}^{J_0} \bar{d}_j + \bar{s}_{J_0} \tag{1}$$

where $\bar{d}_j$ are the "detail series", ( $j$= 1, 2, . . ., $J_0$ ) for a pre-specified $J_0$, and are part of the MRA of $Y$ that can be attributed to variations on a scale of $\lambda_j$ (Gencay et al. 2001, Percival and Walden 2000). Recall that scale $\lambda_2 = 2$. In equation (1) $\bar{s}_{J_0}$ is a $N$ dimensional vector, which depends on the scaling coefficients. The vector, $\bar{s}_{J_0}$, is called the "smooth series" since it is associated with averages over scales $2\lambda_{J_0}$ and longer. Note that $\bar{s}_{J_0}$ captures the slowly varying portion of $Y$, which is often considered to be the overall trend.

### 2.2 Wavelet correlation and cross-correlation

The above section considers decomposing the original time series into $J_0$+1 subcomponents. However, the scale $\lambda_j$ MODWT coefficients may also be used to examine the wavelet

correlation and wavelet cross-correlation of bivariate time series $X_t$ and $Y_t$ (Serroukh and Walden 2000, Whitcher et al. 2000, Gencay et al. 2001), as described below.
The wavelet correlation (WCORR) of ($X_t$, $Y_t$) at scale $\lambda_j=2^{j-1}$ is defined as

$$\rho_{XY,\tau=0}\left(\lambda_j\right)=\frac{\operatorname{Cov}\left\{\overline{W}_{j,t}^{X}, \overline{W}_{j,t}^{Y}\right\}}{\sigma_X\left(\lambda_j\right)\cdot\sigma_Y\left(\lambda_j\right)}=\frac{\gamma_{XY,\tau=0}\left(\lambda_j\right)}{\sigma_X\left(\lambda_j\right)\cdot\sigma_Y\left(\lambda_j\right)} \tag{2}$$

where $\sigma_X^2(\lambda_j)=\operatorname{var}\left\{\overline{W}_{j,t}^{X}\right\}$ is the wavelet variance with scale $\lambda_j$. $\overline{W}_{j,t}^{X}$ and $\overline{W}_{j,t}^{Y}$ are the scale $\lambda_j$ MODWT coefficients for $X_t$ and $Y_t$, respectively (Percival 1995). Note that Equation 2 is a theoretical quantity that is well-defined under an assumption of stationarity.
For a time lag $\tau$, between the two series, $X_t$ and $Y_t$, the wavelet cross-covariance and wavelet cross-correlation (denoted by WCCORR) (Gencay et al. 2001), for scale $\lambda_j=2^{j-1}$ and time lag $\tau$, is

$$\rho_{XY,\tau}\left(\lambda_j\right)=\frac{Cov\left\{\overline{W}_{j,t}^{X}, \overline{W}_{j,t}^{Y}\right\}}{\sigma_X\left(\lambda_j\right).\sigma_Y\left(\lambda_j\right)}=\frac{\gamma_{XY,\tau}\left(\lambda_j\right)}{\sigma_X\left(\lambda_j\right).\sigma_Y\left(\lambda_j\right)} \tag{3}$$

By setting $\tau = 0$, $\gamma_{XY,0}\left(\lambda_j\right)$ reduces to the wavelet variance for $X_t$ or $Y_t$ denoted by $\sigma_X^2\left(\lambda_j\right)$ or $\sigma_Y^2\left(\lambda_j\right)$, respectively. The wavelet cross-correlation in equation 3 is thus able to provide the lead or lag relationship on a scale-by-scale basis (Gencay et al. 2001), just as is the case for conventional cross-correlations. These can determine lead or lag relationships between two time series (Percival et al. 2000).

### 2.3 Confidence interval determination

Construction of the 95% two-sided confidence interval (CI) of WCORR and WCCORR follows the development of Gencay et al. 2001. To produce CIs for the cross-correlation coefficient, the Fisher's nonlinear z-transformation $h(\rho)$ (Percival and Walden 2000), as follows, $h(\rho)=1/2\log(1+\rho/1-\rho)=\tanh^{-1}(\rho)$ is required. For $\hat{\rho}_X$ which is an unbiased estimator of WCORR based on the MODWT, the following asymptotic normal distribution holds

$$\sqrt{N-3}\left[\,h(\hat{\rho})-h(\rho)\,\right]\sim N(0,1). \tag{4}$$

Applying the transformation tanh maps the confidence interval back to [-1, 1] to produce an approximate 95% CI for $\rho_X(\lambda_j)$ as follows (Whitcher et al. 2000, Gencay et al. 2001),

$$\tanh\left\{\mathrm{h}\left[\hat{\rho}_X\left(\lambda_j\right)\right]\pm1.96\left(\frac{1}{\overline{N}_j-3}\right)^{1/2}\right\}. \tag{5}$$

The quantity $\overline{N}_j$ in equation (5) is the number of DWT coefficients associated with scale $\lambda_j$ .

### 2.4 Data analyses

DWT, MODWT and MODWT-MRA analyses were performed using code based on the wavelet methods developed by Percival and Walden (2000) and Gencay et al. (2001).

### 2.5 Phenological data

The phenological data was collected between 1940 to 1970 and comprises the flowering intensity profiles of eight eucalypts species growing in the region of Havelock, Victoria, Australia. The eight species examined in this study were: *Eucalyptus camaldulensis, E. melliodora, E. polyanthemos; E. goniocalyx*, *E. microcarpa, E. macrorhyncha, E. leucoxylon* and *E. tricarpa* (Table 1).

Observations on the timing, quantity and distribution of flowering of these species were collected on a monthly basis (Keatley et al. 1999) (Table 1). Flowering intensity (ranging from 0 to 5) of each species was quantified by assigning a rank value (Table 1) (Keatley and Hudson, 2007), thus producing a discrete time series (see Fig. 1 where only the period from Jan 1940 to Dec 1955 is shown for visual clarity).

A score of 0 indicates that no flowering occurred, in the given month, whilst a score of 5 indicates that flowering was heavy and distributed throughout the observation area. DWT methodology (Gencay et al. 2001; Whitcher et al. 2000) was applied to the afore-mentioned eight species' flowering intensity scores (0-5). This data comprises a rare long-term 30 year record of flowering (1940-1970) of over 350 monthly time points (Keatley et al., 2002).

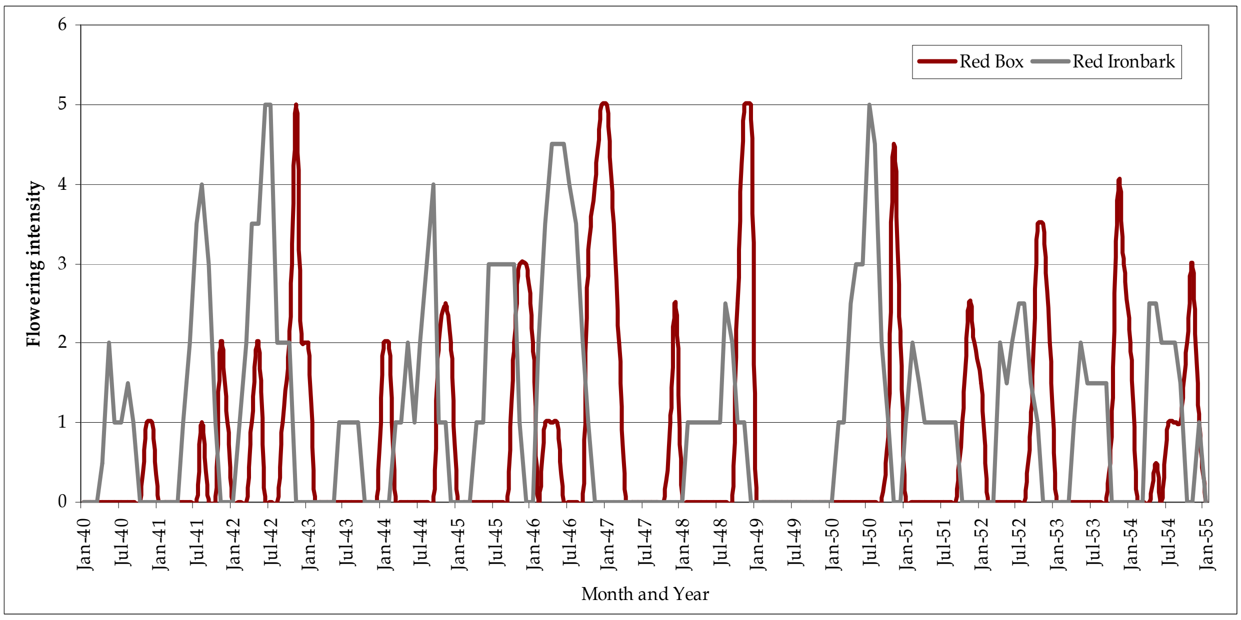


Fig. 1. Time series of E. *polyanthemos* (red box) and *E. tricarpa* (red ironbark) for the period between January 1945-January1955(wherein only the period January 1945 to January 1955 is shown for visual clarity).

| Species | Common name & taxonomic authority | Median duration | Most probable month | Peak Flowering# | Flowering start month | Flowering cessation months | Flowering intensity score | Description | Assigned Value |
|---|---|---|---|---|---|---|---|---|---|
| *E. camaldulensis* | River red gum Dehnh | 4.0 | January | January | November /December | January | Quantity | No flowering | 0 |
| *E. goniocalyx* | Long-leaf box F. Muell | 3.0 | March/April | March | February | May | | Very scattered or isolated | 0.5 |
| *E. leucoxylon* | Yellow gum F. Muell | 9 | October | September | May | December | | Light Flowering | 1 |
| *E. macrorhyncha* | Red stringy bark F. Muell | 4.0 | March/April | January | January | May | | Medium Flowering | 2 |
| *E. melliodora* | Yellow box Cunn | 5.0 | January | January | November | March | | Heavy Flowering | 3 |
| *E. microcarpa* | Grey box Maiden | 4.0 | March | March | February | May | Distribution | Isolated | 0.5 |
| *E. polyanthemos* | Red box L. A. S. Johnson & K. D Hill | 3.5 | November | November | October | December | | Scattered | 1 |
| *E. tricarpa* | Red ironbark L. A. S. Johnson & K.D Hill | 6.0 | July | July | April | September | | Fairly General | 1.5 |
| | | | | | | | | General | 2 |

ϕ Based on actual likelihood/probabilities for Havelock (Keatley and Hudson, 2007) for all species, except for *E. camaldulensis, E. goniocalyx* and *E. macrorhyncha*.

# The month with the highest mean intensity within a flowering year.

Table 1. Eight eucalypt species' median flowering duration and months in which the main phenophases occur. Terms describing flowering intensity and their assigned value (Keatley 1999) (Table sourced from Hudson et al., 2011a).

Daily minimum and maximum temperature along with daily rainfall were obtained from the Bureau of Meteorology, for the closest weather station (approximately 3.5 km away), in Maryborough, Victoria (37°03'22"S 143°43'55"E, 249.3 m elevation). The temperature dataset had some missing data. When only one day was missing, the average of the temperature either side of the missing date was used. If two or more days were not recorded, then the mean minimum or maximum temperature for that month was substituted. Daily mean temperature was calculated as the average of daily minimum and maximum temperature. Monthly means for minimum, maximum, diurnal temperature and rainfall were used in the analyses.

## 3. Results

### 3.1 MODWT-MRA

Maximal overlap discrete wavelet transform – multi-resolution analysis (MODWT-MRA) with $J_0 = 4$ provided the subcomponents of the flowering signal within each species (see Figure 2). The raw series is given by X, d1 to d4 are the different subcomponents (detail) of the original series X. Traditionally, d1 to d4 are associated with changes in averages over 1, 2, 4 and 8 months, respectively (Figure 2). Also s4, which is the smoothed series associated with averages over 8 months, is also provided by MODWT-MRA (see Figure 2 for *E. tricarpa*).

The first two sub-components reflect duration and the overall pattern of the original flowering data. d1 and d2 appear similar in their profiles (see Figure 3 for *E. macrorhyncha*), however, d1 contains subcycles per year (in a flowering year) but it is unclear as to what these cycles are related.

The annual cycle is delineated by d3, and d4 relates to the annual or biennial cycling of intensity of flowering years. S4 is the smoothed series and indicative of the overall trend.

d3 not only delineates the annual cycle of flowering, but reveals (by its peaks), in the majority of cases, the month of peak flowering in a flowering year (or within the month on either side) (Figure 4). Note that for *E. Goniocalyx,* all but one peak is selected (97%), however, this does include two years (1965 and 1966) when three months exhibited equal flowering intensity and for these years the middle month was nominated as the peak month. The selection of the middle month also occurred in *E. marcrorhyncha* (overall 68% peak selection) in five years (1945/46; 1952/52, 1957/58, 1960/61 and 1967/68). *Eucalyptus marcrorhyncha* flowering period usually includes December and January therefore two years are given. For the remaining species, *E. melliodora* 97%, *E. camaldulenis* 90%, *E. leucoxylon* 73%, *E. microcarpa* 72%, for *E. polyanthemos* 69% and for *E. tricarpa* 65%.

Additionally, d3 highlights years when flowering does not occur – this is seen in Figure 4 for *E. goniocalyx* when d3 is near zero for the years 1944, 1945, 1948, 1950, 1953, 1955 and 1956. This occurred in all species except *E. leucoxylon* which always flowered (Figure 4). For the other species, years of non-flowering are given in Table 2. As with *E. Macrorhyncha,* three other species, *E. camaldulensis*, *E. melliodora* and *E. polyanthemos* flowering periods also include December and January so two years are also given. The year 1958 or 1958/59 as a non-flowering year was common to five species: *E. camaldulensis, E. melliodora, E. microcarpa, E. polyanthemos* and *E. tricarpa.*

d4 outlines the flowering intensity for each species. For all species, except *E. leucoxylon* the cycle is associated with years of low flowering intensity (< 2) and also includes years of no flowering (i.e. flowering intensity = 0). The longest average period between peaks was

*E .goniocalyx* with 29.0 months with a range of 12 to 48 months. This is particularly influenced by the large number of non-flowering years (Table 2). The species with the smallest average number of months between peaks was *E. melliodora* (18.5 months with a range of 11 to 25 months). For the remaining species the average between peaks was *E. leucoxylon* 19.1 months, *E. marcrorhyncha* 19.5 months, *E. polyanthemos* 20.3 months, *E. camaldulensis* 20.5 months, *E. tricarpa* 21.3 months and for *E. microcarpa* 22.5 months (Figure 5). All species had at least one year between the period 1952 and 1958 when the number of months between peaks was between 11 to 14 months. For *E. camaldulensis* this occurred for five years between December 1953 and March 1958 (Figure 5).

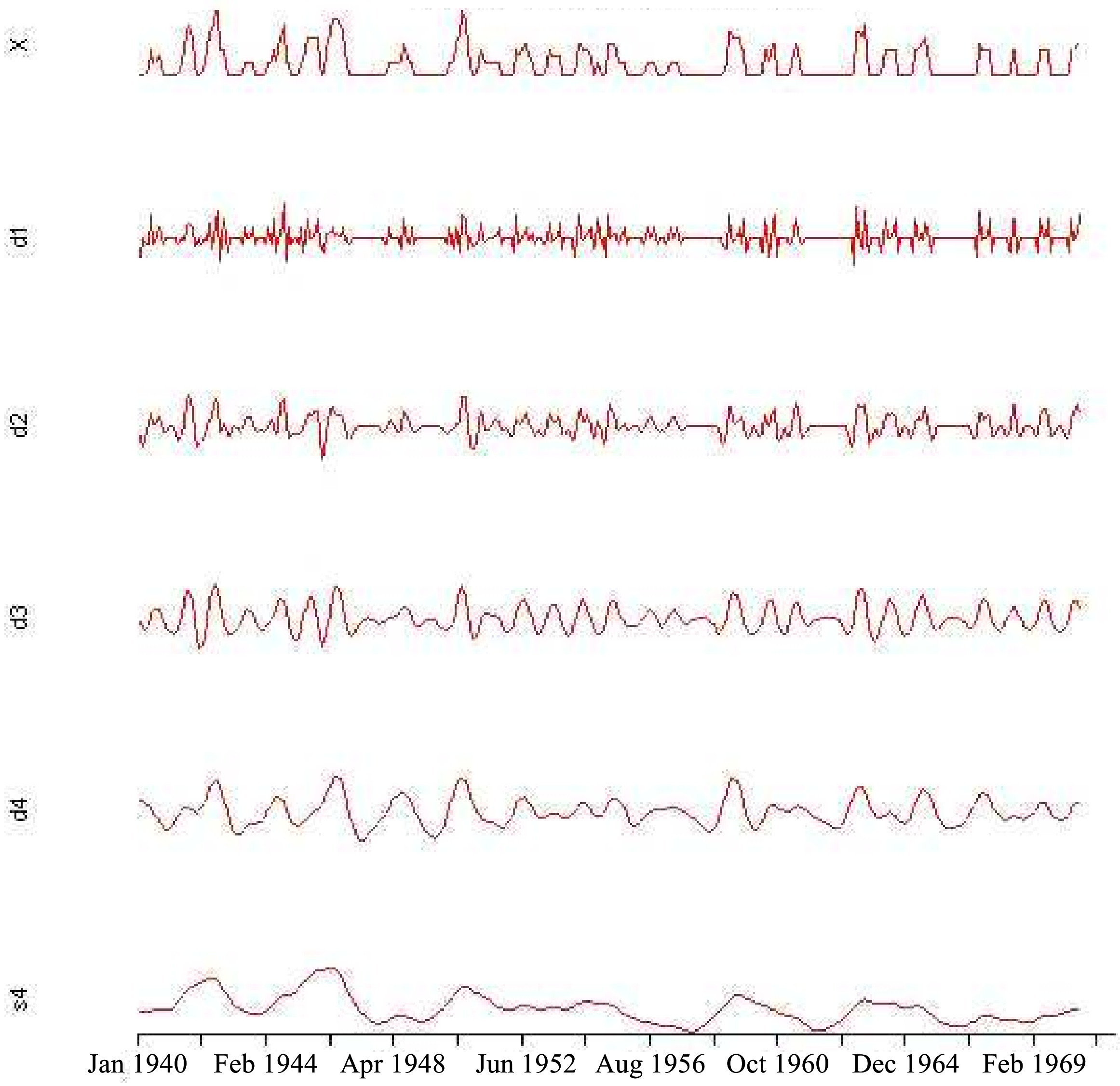


Fig. 2. Example of MODWT-MRA output for *E. tricarpa*. X = the raw data, d1 to d4 different subcomponents (details) of the original series X, and s4 = the smooth series

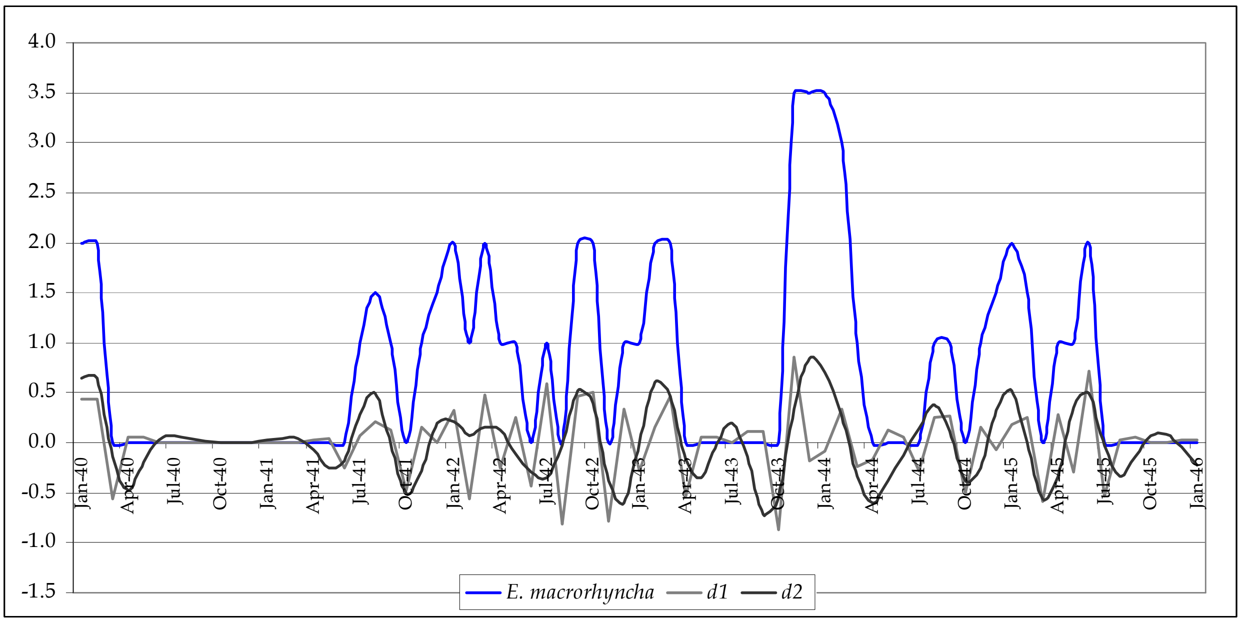


Fig. 3. Raw data, $d_1$ and $d_2$ of *E. macrorhyncha* between January 1940 and January 1946.

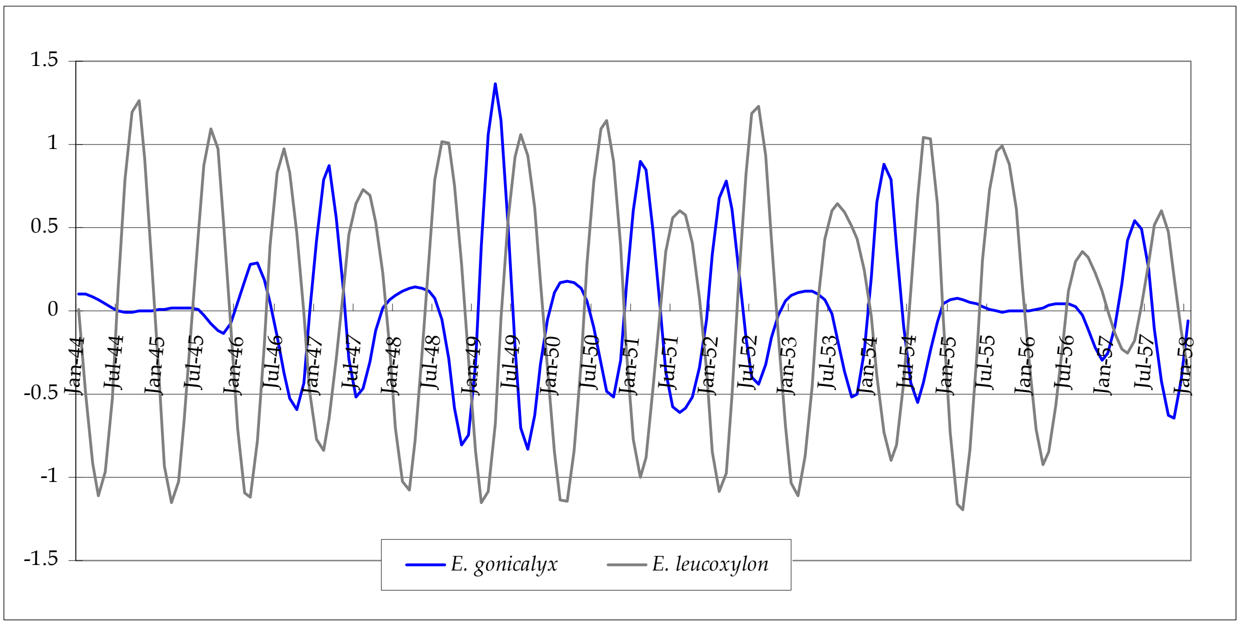


Fig. 4. $d_3$ subcomponent for *E. goniocalyx* and *E. Leucoxylon* between Jan. 1940 and Jan. 1946.

Although s4 is the smoothed series it is also reflective of the trend and variation in flowering intensity. s4 indicates that flowering has become less intense from 1940 to 1970 for all species except *E. camaldulensis* and *E. goniocalyx* (Figure 6A &B). These two species do not change their flowering intensity. *Eucalyptus leucoxylon* on average (mean intensity 1.63) flowers more intensely than the other 7 species except for two brief periods, between June 1945 and July 1946, when *E. tricarpa* flowered the most (Figure 6B) and January and August 1962 during which *E. melliodora* did. *Eucalyptus melliodora* is the next most intense flowering species (mean intensity = 0.97) (Figure 6A) and *E. goniocalyx* is the species which has flowered with the least intensity (0.37) (Figure 6B).

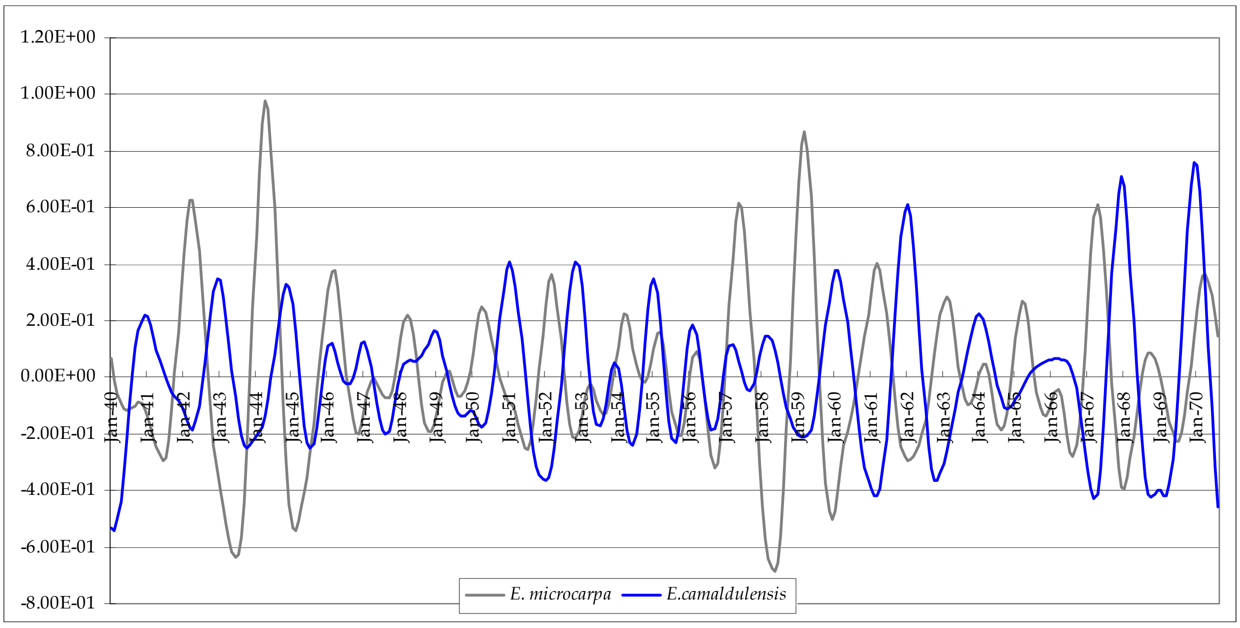


Fig. 5. $d_4$ subcomponent of E. microcarpa and E. Camaldulensis.

A trough indicating the non flowering year in all species except *E. leucoxylon* and *E. macrorhyncha,* where it is indicative of lower flowering intensity, is noticeable between March 1958 (*E. microcarpa*) to July 1959 (*E. macroryhncha*) (Figure 6A & B)). The most intense flowering period for all species (except *E. camaldulensis* and *E. Goniocalyx)* occurred prior to 1958. Hudson et al. 2005 noted wetter years than average in the mid 1940's to the end of the 1950's; and maximum temperature at Maryborough was increasing until late 1967/early 1968 (also reflected by the Southern Oscillation Index (Trenberth et al., 1996, Ghil et al., 2002).

| Species | Non-flowering years |
|---|---|
| *E. camaldulensis* | 1951/52, 1958/59, 1960/61, 1962/63 and 1966/67 |
| *E. goniocalyx* | 1942, 1944, 1945, 1948, 1950, 1953, 1955, 1956, 1959, 1961, 1963, 1964 and 1967 |
| *E. leucoxylon* | Always flowered |
| *E. macrorhyncha* | 1940/41, 1953/52, 1954/55, 1963/64 and 1969/70 |
| *E. melliodora* | 1958/59 |
| *E. microcarpa* | 1943, 1958, 1962, 1968 and 1969 |
| *E. polyanthemos* | 1949/50, 1956/57, 1958/59 and 1961/62 |
| *E. tricarpa* | 1947, 1949, 1958, 1962 and 1966 |

Table 2. Species and their years of non-flowering

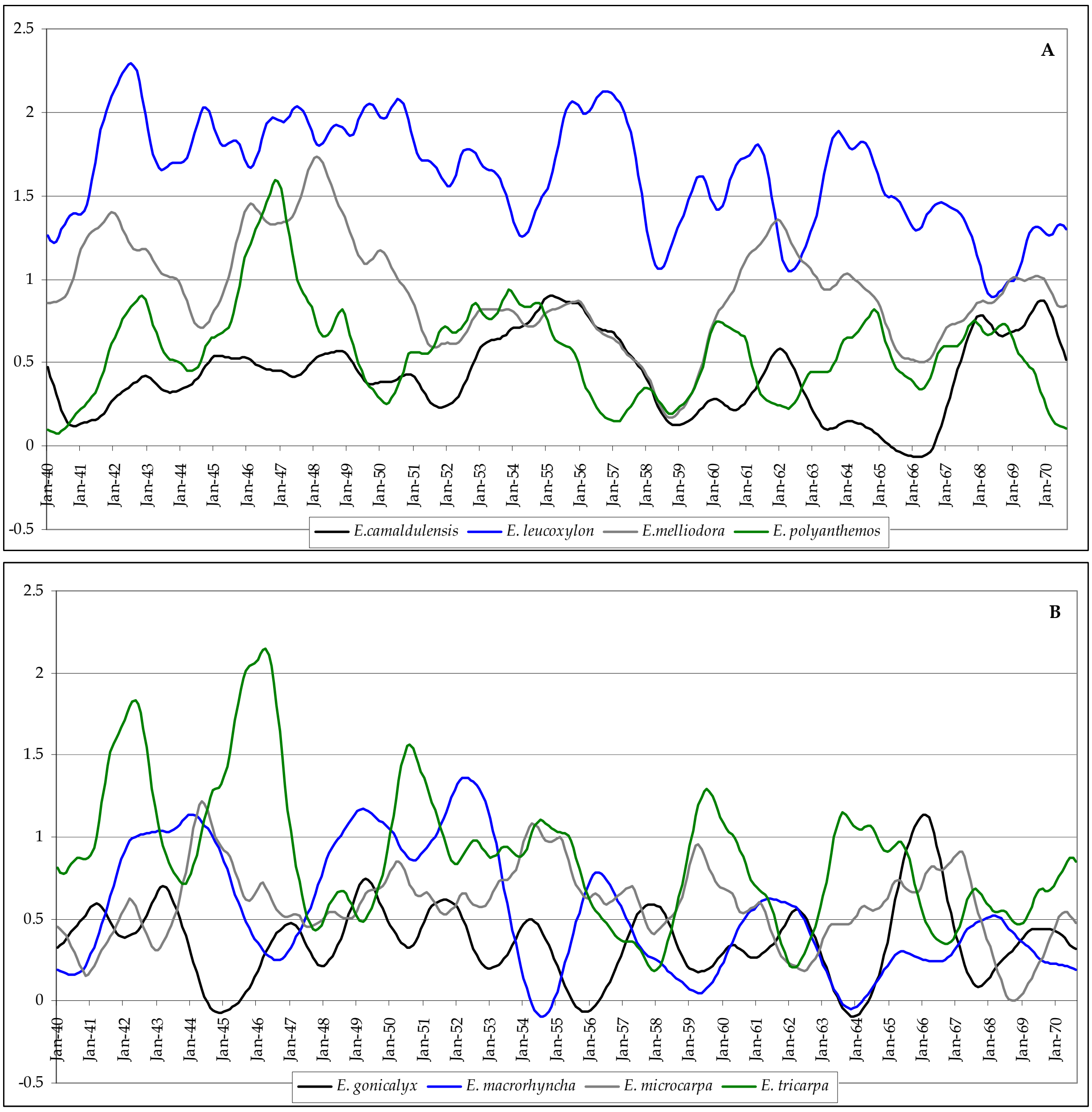


Fig. 6.A & B. $s_4$ subcomponents for each group of four species.

### 3.1.1 Wavelet correlation of flowering with temperature and rainfall

The wavelet correlation between minimum temperature and rainfall with peak flowering intensity at different wavelet levels or scales (1, 2, 4, 8, 16 and 32 months) were examined for all species. See Figure 7 and Figure 8, where significant ($P < 0.05$) wavelet correlations are those, where the upper (U) and lower (L) confidence limits are on the same side of the zero horizontal line. Correlations at 1, 8, 16 and 32 months with respect to minimum temperature (Figure 7) and rainfall (Figure 8) were not significant for any species. It can be seen that correlations with minimum temperature at either scale 2 ($2^{2-1} = 2$ months) or 3 ($2^{3-1} = 4$ months) are significant for all species, except for *E. goniocalyx* (Table 3, Figure 7).

For *E. tricarpa* minimum, maximum and mean temperatures have a significant negative relationship at these scales (Figure 7 and Table 3). *Eucalyptus tricarpa* was the only species for which rainfall had a significant, positive relationship with flowering at the 4 month scale (Figure 8). This indicates that cooler, wetter periods lead to greater flowering intensity for *E. tricarpa*. The relationship for *E. leucoxylon* and rainfall was positive but was not significant, as in *E. tricarpa.* In contrast two species, *E. camaldulensis* and *E. melliodora* had a significant negative relationship with rainfall also at the 4 month scale (Table 3). Both of the latter species also had a significant positive relationship with all the temperature variables.

| Species/<br>Period (months) | Tmean | | Tmin | | Tmax | | Rainfall | |
|---|---|---|---|---|---|---|---|---|
| | 2 | 4 | 2 | 4 | 2 | 4 | 2 | 4 |
| *E. leucoxylon* | -0.49* | -0.59* | -0.52* | -0.62* | -0.46* | -0.56* | 0.03 | 0.28 |
| *E. tricarpa* | -0.51* | -0.75* | -0.49* | -0.72* | -0.51* | -0.76* | 0.20 | 0.40* |
| *E. polyanthemos* | 0.15 | 0.48* | 0.14 | 0.43* | 0.16 | 0.50* | -0.06 | -0.17 |
| *E. camaldulensis* | 0.34* | 0.75* | 0.34* | 0.74* | 0.33* | 0.75* | -0.01 | -0.30* |
| *E. melliodora* | 0.54* | 0.86* | 0.52* | 0.84* | 0.54* | 0.87* | -0.09 | -0.41* |
| *E. gonicalyx* | 0.13* | 0.23* | 0.14 | 0.27 | 0.12 | 0.21 | -0.06 | -0.22 |
| *E. microcarpa* | 0.18 | 0.27 | 0.23* | 0.31* | 0.15 | 0.25 | -0.01 | -0.25 |
| *E. macrorhyncha* | 0.24 | 0.43 | 0.25* | 0.44* | 0.24* | 0.42* | -0.05 | -0.28 |

Table 3. Wavelet correlation of peak flowering intensity and climate variables (* P< 0.05)

For *E. camaldulensis* both mean temperature and maximum temperature at the 4 month scale had equal influence (Table 3), whereas for *E. melliodora* it was maximum temperature (and then mean temperature) at this scale that had the greatest impact. Therefore for these species warmer and dryer periods result in greater flowering intensity. For the remaining species a negative correlation (although not significant) with rainfall was indicated.

All temperature variables (mean, minimum and maximum) at 2 and 4 months were also significant for *E. leucoxylon*. At peak flowering intensity both *E. leucoxylon* and *E. tricarpa* have a negative relationship with each of the temperature variables, indicating increased intensity of flowering with decreasing temperature. However, there is a slight difference in the strength of the relationship of flowering across the temperature variants (Table 3). It is noteworthy that for *E. leucoxylon* the main relationship with flowering intensity is with minimum temperature and for *E. tricarpa* it is with maximum temperature (Table 3), both significant at the 4 month scale.

For each of the remaining six species an inverse relationship between flowering and the temperature variants was shown (Table 3 and Figure 7): that is an increase in flowering intensity with increasing temperature. However, for the species pair (*E. goniocalyx* and *E. microcarpa*) there was only one temperature variant which impacts significantly on flowering. For *E. goniocalyx* it is mean temperature and for *E. microcarpa* minimum temperature, indicating that for the individual species these climate predictors may be the primary climatic driver of flowering. In contrast, for *E. polyanthemos,* there was a significant positive relationship with all three temperature variables (at 4 months) with maximum temperature being identified as having a slightly greater influence on flowering (Table 3). This is in agreement with a recent Generalised Additive Model for Location, Scale and Shape (GAMLSS) analysis of the data studied here (Hudson et al. 2009; 2011b). Flowering intensity in *Eucalyptus macrorhyncha* is influenced positively by both minimum and maximum temperatures with minimum temperatures at the 4 month scale being the most significant.

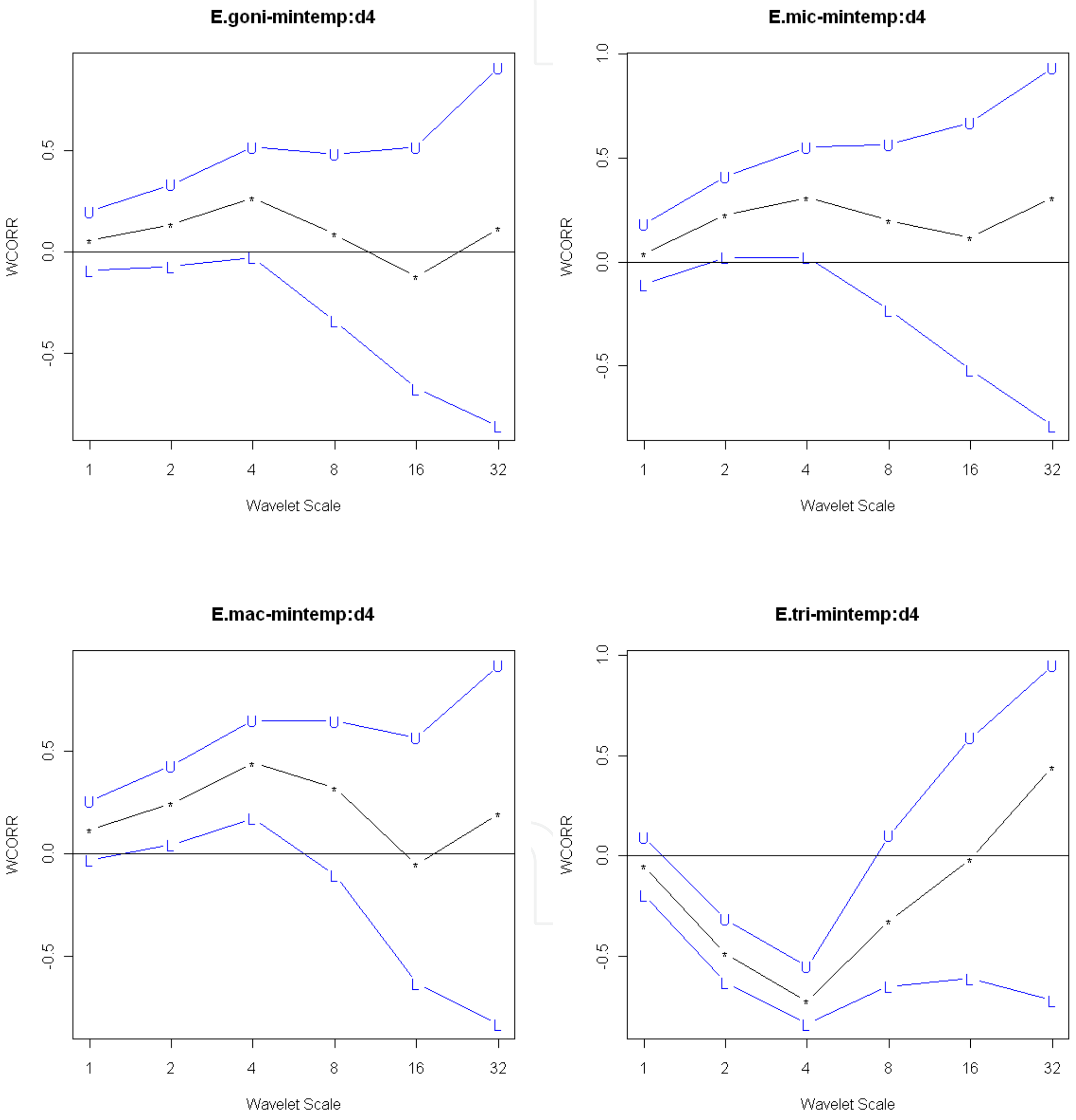


Fig. 7. Wavelet correlations (WCORR) of the flowering of *E. goniocalyx*, *E. microcarpa, E. macrorhyncha* and *E. tricarpa* with minimum temperature (95% confidence interval limits indicated by L and U).

Broadly speaking, *E. leucoxylon* and *E. tricarpa* can be grouped together with respect to their relationship with temperature and rainfall. The relationship of the remaining six species with climate is similar, however, when the significance of the relationship is taken into account two other species clearly grouped together: *E. camaldulensis* and *E. melliodora*. As already discussed they are the only two species which have a significant negative relationship with rainfall (similar WCORR signatures between their flowering and rainfall (Figure 8)) and a significant positive relationship with all three climate parameters at both

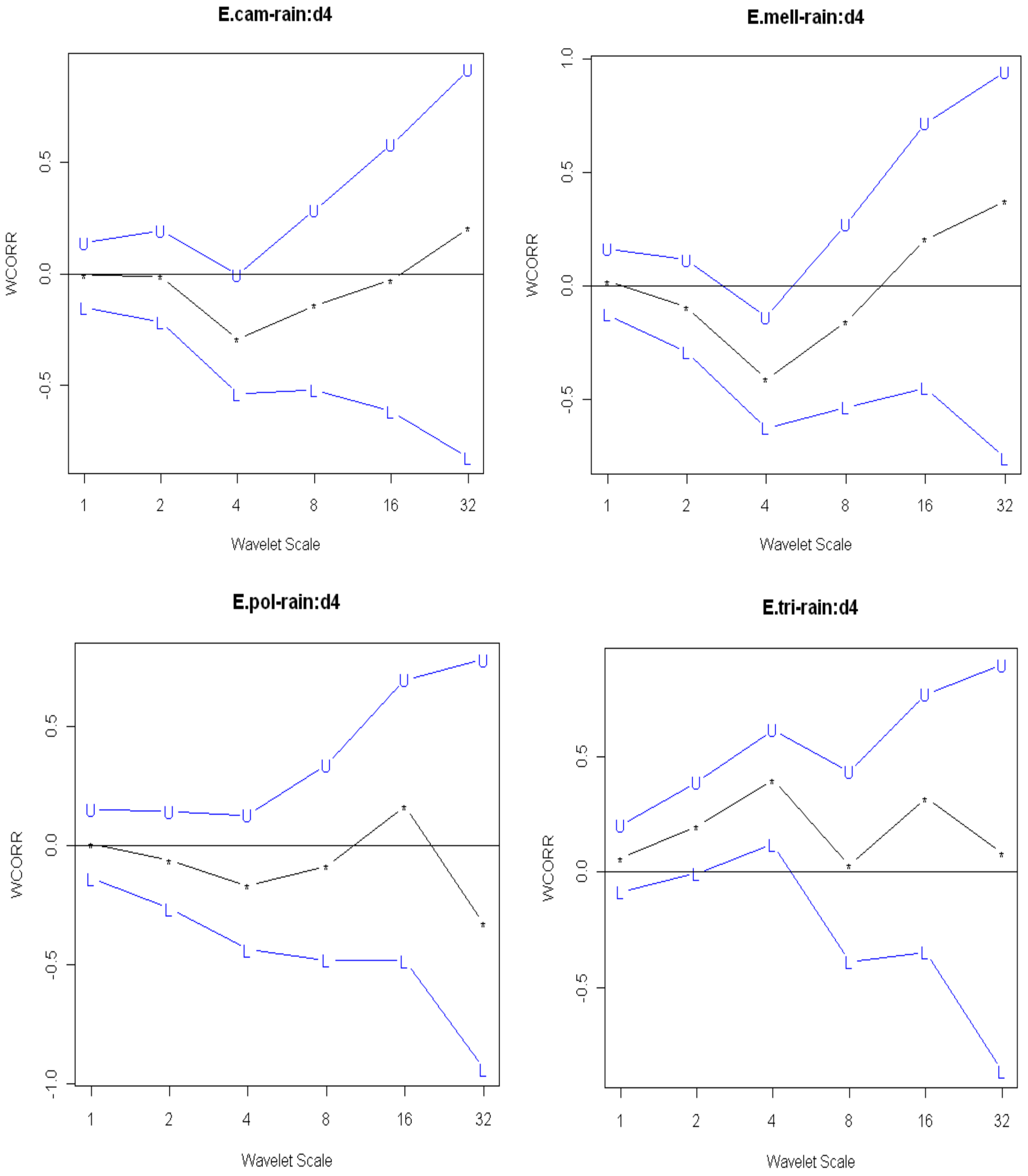


Fig. 8. Wavelet correlations (WCORR) of the flowering of *E. camaldulensis*, *E. melliodora*, *E. polyanthemos* and *E. tricarpa* with rainfall (95% confidence limits indicated by L and U).

scales. *Eucalyptus polyanthemos* aligns with this group as it also has a significant positive relationship with all three climate parameters, but only at the 4 month scale. Additionally, its main influence is maximum temperature as is the case with the other two species (albeit that *E. camaldulensis* is equally influenced by mean temperature).

Theother three species (*E. goniocalyx, E. microcarpa, E. macrorhyncha*) also broadly group, as evidenced by their similar climate signatures as shown in their WCORR profiles (Figure 7). Note that all members of this species triple, have a positive relationship between flowering and at least one temperature variant; and a negative (though not significant) relationship between flowering and rainfall.

### 3.1.2 Wavelet cross-correlation of flowering with temperature and rainfall variables

Wavelet cross-correlations were examined for all wavelet scales (1 to 32 months). Significant relationships ($P \leq 0.005$) were found only at 4 months (level 3) for rainfall; but at 2, 4 and 8 months (levels 2, 3 and 4) for the temperature variants (Figure 9 illustrates this for *E.leucoxylon*). The strongest (highest absolute value of the correlation profile) and most significant relationship for all species with temperature was at 4 months (level 3) (Figure 9). This mirrors the correlation results (Table 3), where level 3 correlations were significant. Recall that correlations are the equivalent of cross-correlations at lag zero.

| Mean temperature | Positive to negative | | Negative to positive | |
|---|---|---|---|---|
| Species | Month | Season | Month | Season |
| *E. leucoxylon* | August | Winter | February | Summer |
| *E. tricarpa* | April | Autumn | October | Spring |
| *E. polyanthemos* | December | Summer | July | Winter |
| *E. camaldulensis* | April | Autumn | October | Spring |
| *E. melliodora* | April | Autumn | October | Spring |
| *E. microcarpa* | September | Spring | March | Autumn |
| *E. goniocalyx* | October | Spring | April | Autumn |
| *E. macrorhyncha* | June | Autumn | December | Summer |
| Rainfall | Positive to negative | | Negative to positive | |
| Species | Month | Season | Month | Season |
| *E. leucoxylon* | February | Summer | August | Winter |
| *E. tricarpa* | October | Spring | April | Autumn |
| *E. polyanthemos* | June | Winter | November | Summer |
| *E. camaldulensis* | October | Spring | April | Autumn |
| *E. melliodora* | October | Spring | April | Autumn |
| *E. microcarpa* | February | Summer | August | Winter |
| *E. goniocalyx* | August | Winter | February | Summer |
| *E. macrorhyncha* | December | Summer | May | Autumn |

Table 4. Species specific change points (month, season) for mean temperature and rainfall.

### 3.1.3 Level 3 wavelet cross-correlations

Cross-correlations between peak flowering intensity and the temperature variants and rainfall were lagged from 1 and 12 months prior to the species specific peak flowering month. An illustration of these cross-correlation profiles between mean temperature and flowering, and between rainfall and flowering is given in Figure 10 and 11, respectively, for each species. These sinusoidal profiles show that there are positive and negative relationships of 6 months duration and as a consequence there are clear seasonal change points from positive to negative cross-correlation and vice-versa (see Table 4, where the season specific to each change point month is given per species).

The cross-correlation profiles also show there is a maximum positive and negative cross-correlation, and these occur systematically 6 months apart for each species (Figures 10 -11 and delta values (Δ) in Table 5). These cross-correlations can be viewed as the highest absolute value of the wavelet cross-correlations, for lags either in the short term (≤ 6 months to peak flowering intensity), or the long term (> 6 months). The number of months at which either lag, occurs prior to peak flowering intensity, differs for each species (Figures 10-11 and Table 5). Note that *E. polyanthemos's* maximum short term temperature lag is positive (0.73) and occurs in September, which is 2 months before peak flowering intensity, whereas *E. macrorhyncha's* short term lag is negative (-0.52) and occurs in August, this being 5 months prior to peak flowering intensity. The long term lag for *E. polyanthemos* is in March, which is 8 months before peak flowering intensity and negative (-0.71), compared to the February positive (0.52), long term lag for *E. macrorhyncha,* which occurs 11 months before its peak flowering intensity in July (Figure 10 and Table 5).

According to these wavelet cross-correlations the eight species form two groups based on their, similar cross-correlational relationships (or signatures) between flowering with temperature and between flowering and rainfall *E. leucoxylon, E. polyanthemos, E. camaldulensis and E. melliodora* are in one group and the remaining species in the other. This first group has cross -correlations with temperature which are positive in the short-term (≤ 6 months) and negative in the long-term (> 6 months) (Figure 10 and Table 5). With rainfall, the short-term cross-correlations are negative and positive in the long-term. The second group (comprising *E. goniocalyx*, *E. microcarpa, E. macrorhyncha* and *E. tricarpa*) has cross-correlations with temperature which are negative in the short-term (≤ 6 months) and positive in the long-term (> 6 months) – and with rainfall, the short-term cross-correlations are positive in the short-term and negative in the long-term (Figure 11 and Table 5).

It is noteworthy that, if one examines the whole 12 month pattern of the wavelet cross-correlation, so-called WCCORR *signatures* (sinusoids in Figures 10-11), in relation to flowering duration, flowering cessation and 12 months back (note the vertical line in Figures 10-11 delineate 12 months prior to peak flowering and the horizontal line depicts flowering duration) - rather than on focusing on primarily the signs of the WCCORR at months of maximum positive or negative cross-correlation (Table 5), there are three (3) clear species groupings, according to their similar WCCORR wavelet signatures, namely, *E. camaldulensis*, *E. melliodora*, *E. polyanthemos; E. goniocalyx*, *E. microcarpa*, *E. macrorhyncha;* and *E. leucoxylon* and *E. tricarpa*. Indeed the species within each of these groupings were recently shown to flower synchronously according to advanced methods for time series clustering of the patterns underlying the phenological series (Hudson et al., 2011a).

The cross-correlations in Figure 10 and Figure 11 also show, as did correlations, that for all species the temperature and rainfall variables do not act in concert. That is, within a given species, if the cross-correlation with temperature is positive, at a particular time of year, then

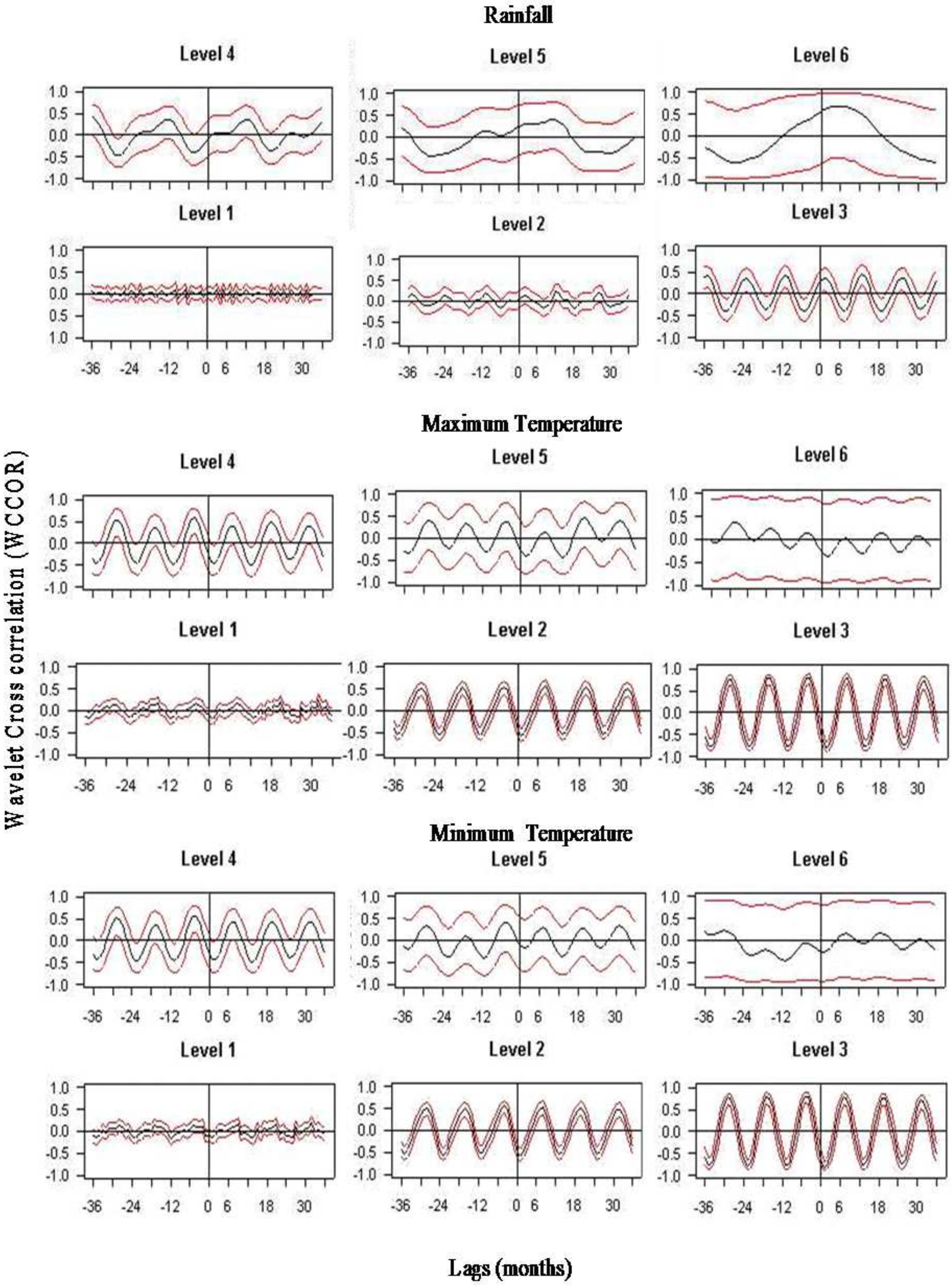
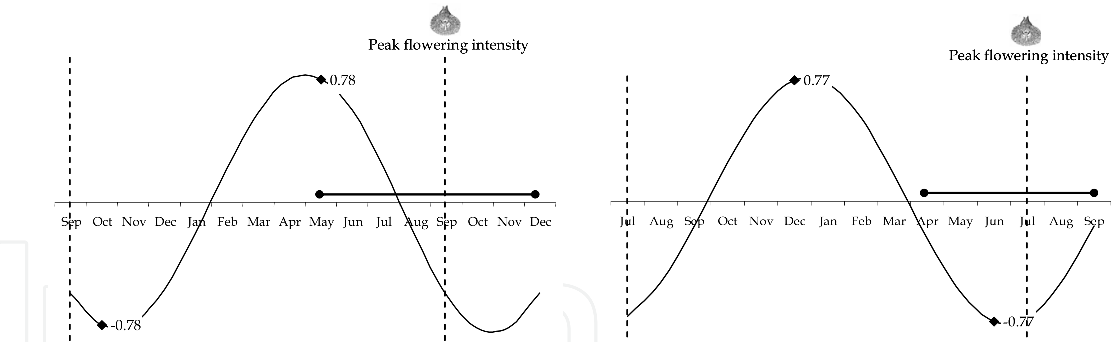
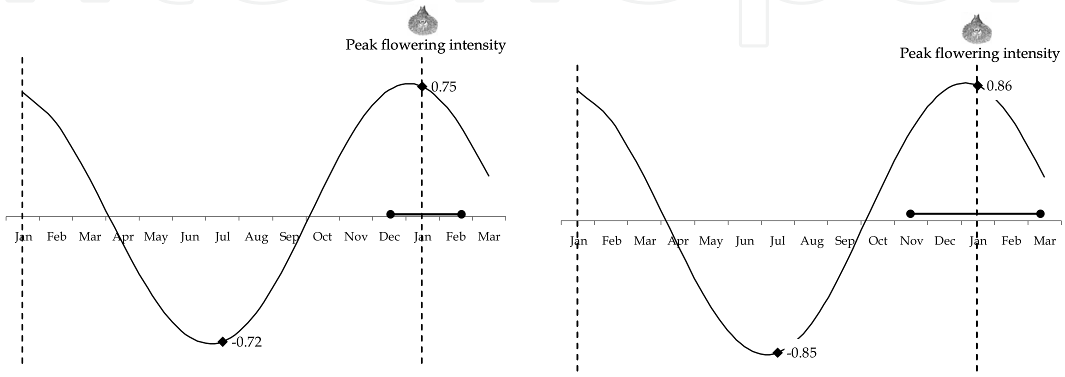


Fig. 9. Wavelet cross-correlation (WCCORR) plots of flowering with respect to rainfall, and maximum and minimum temperature for *E. leucoxylon.*



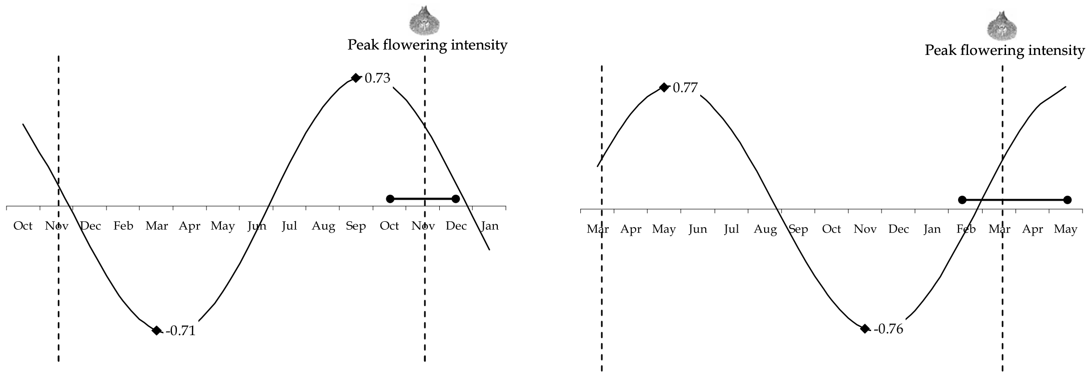
*Eucalyptus leucoxylon*

*Eucalyptus tricarpa*



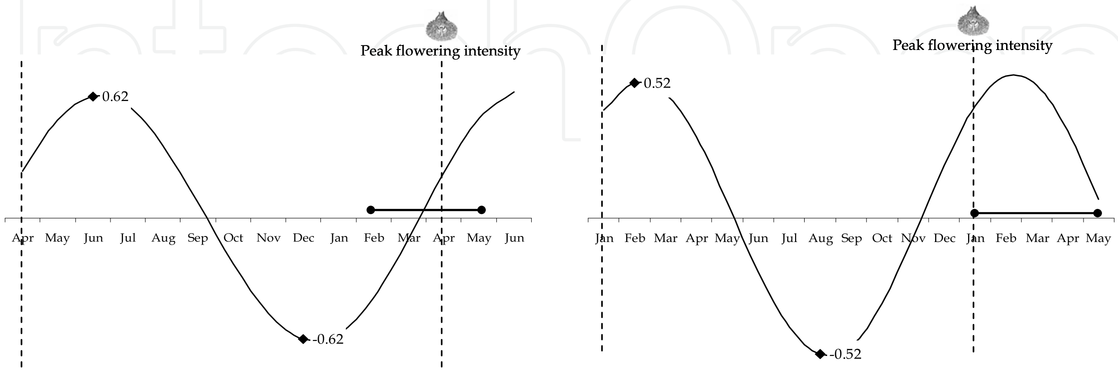
*Eucalyptus camaldulensis*

*Eucalyptus melliodora*



*Eucalyptus polyanthemos*

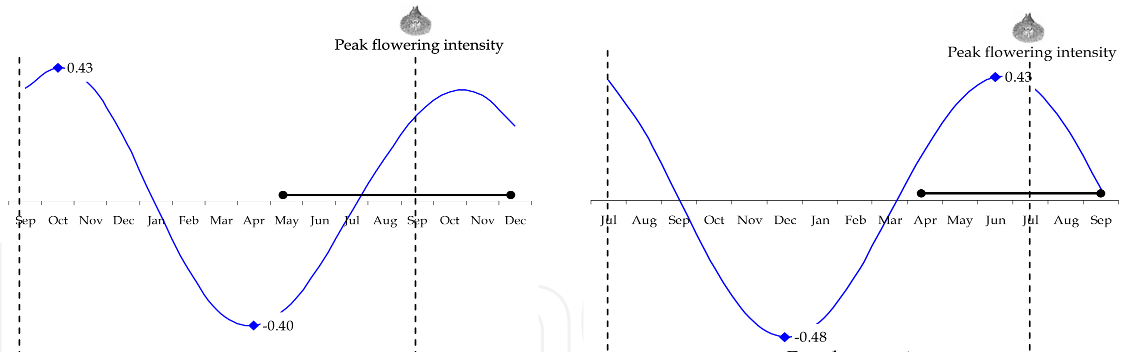
*Eucalyptus microcarpa*



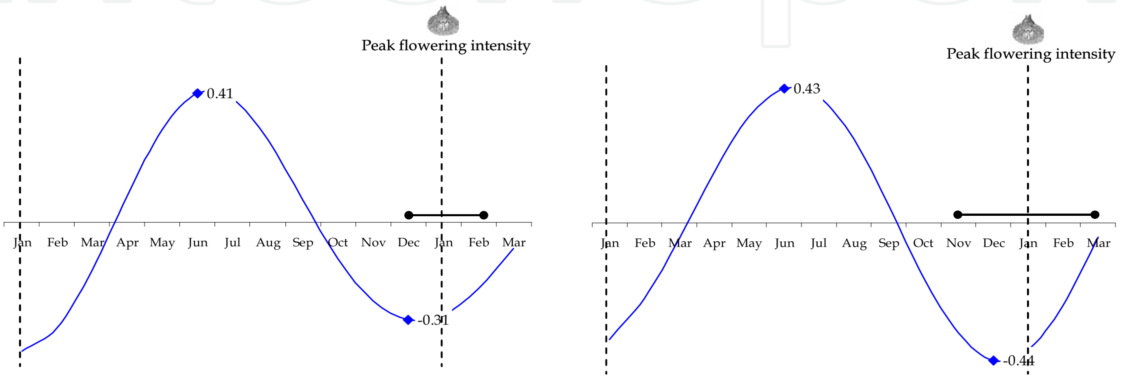
*Eucalyptus goniocalyx*

*Eucalyptus macrorhyncha*

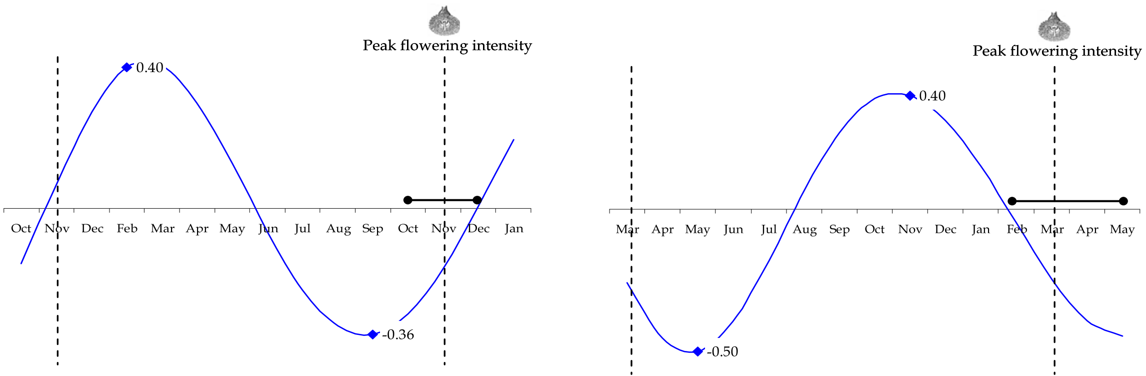
Fig. 10. Individual wavelet cross-correlation plots for daily mean temperature with flowering intensity for all species. Vertical lines encapsulate the 12 months prior to peak flowering. The small horizontal interval indicates the annual flowering period (duration).



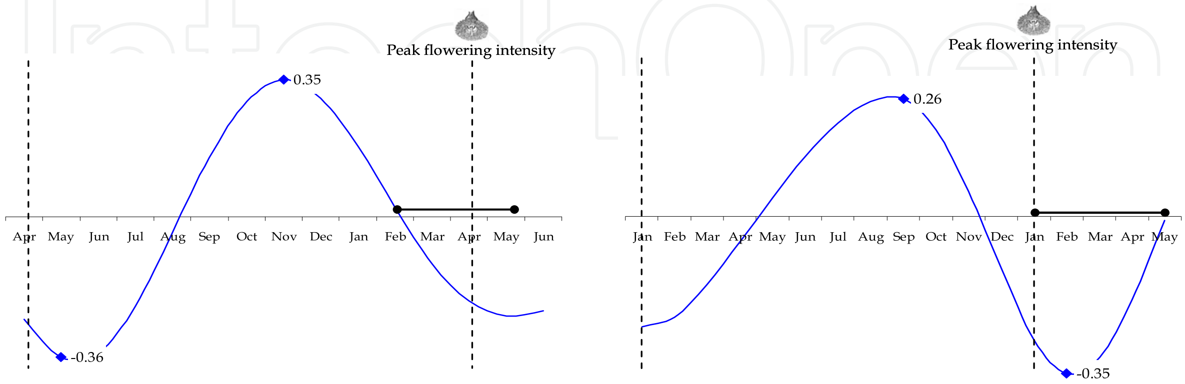
*Eucalyptus leucoxylon* *Eucalyptus tricarpa*



*Eucalyptus camaldulensis* *Eucalyptus melliodora*



*Eucalyptus polyanthemos* *Eucalyptus microcarpa*



*Eucalyptus goniocalyx* *Eucalyptus macrorhyncha*

Fig. 11. Individual wavelet cross-correlation plots for daily rainfall with flowering intensity for all species. Vertical lines encapsulate the 12 months prior to peak flowering. The small horizontal interval indicates the annual flowering period (duration).

the relationship with rainfall is negative (Table 5) and vice versa (see opposite directionality between the wavelet WCCORR signatures in Figure 10 versus Figure 11). For example, each of *E. goniocalyx's* short term lags for temperature is negative and occurs in December. Its short term rainfall lag occurs in November, but is positive. Cross-correlations thus provide further insight into the dynamic, changing relationship between climate and peak flowering intensity for each eucalypt species.

| **Species** | **Tmean** | **Tmax** | **Tmin** | **Rainfall** |
|---|---|---|---|---|
| *E. leucoxylon*<br>Peak: September<br>Start: May<br>End: December | 0.78 [-4]<br>May | 0.79 [-4]<br>May | 0.78 [-5]<br>April | -0.41 [-5]<br>April |
| | -0.80 [-11]<br>October Δ = 7 | -0.80 [-10]<br>Nov Δ = 6 | -0.81 [-11]<br>October Δ = 6 | 0.35 [-11]<br>October Δ = 6 |
| *E. tricarpa*<br>Peak: July<br>Start: April<br>End: September | -0.73 [-1]<br>June | -0.73 [-1]<br>June | -0.73 [-1]<br>June | 0.46 [-1]<br>June |
| | 0.75 [-7]<br>December Δ = 6 | 0.74 [-7]<br>December Δ = 6 | 0.75 [-7]<br>December Δ = 6 | -0.45 [-7]<br>December Δ = 6 |
| *E. polyanthemos*<br>Peak: November<br>Start: October<br>End: December | 0.73 [-2]<br>September | 0.72 [-2]<br>September | 0.72 [-2]<br>September | - 0.32 [-2]<br>September |
| | -0.71[-8]<br>March Δ = 6 | - 0.72 [-8]<br>March Δ = 6 | - 0.73[-8]<br>March Δ = 6 | 0.39 [-8]<br>March Δ = 6 |
| *E. camaldulensis*<br>Peak: January<br>Start: Nov/Dec<br>End: January | 0.73 [0]<br>January | 0.71 [-1]<br>December | 0.75 [-1]<br>December | -0.31 [-1]<br>December |
| | -0.69 [-6]<br>July Δ = 6 | 0.69 [-7]<br>June Δ = 6 | 0.70 [-7]<br>June Δ = 6 | 0.41 [-7]<br>June Δ = 6 |
| *E. melliodora* Peak:<br>January<br>Start: November<br>End: March | 0.86 [0]<br>January | 0.82 [-1]<br>January | 0.84 [-1]<br>December | -0.44 [-1]<br>December |
| | -0.80 [-6]<br>July Δ = 6 | 0.80 [-6]<br>July Δ = 6 | -0.81 [-7]<br>June Δ = 6 | 0.43 [-7]<br>June Δ = 6 |
| *E. microcarpa*<br>Peak: March<br>Start: February<br>End: May | -0.77 [-4]<br>November | -0.77 [-4]<br>November | -0.76 [-4]<br>November | 0.48 [-4]<br>November |
| | 0.78 [-10]<br>May Δ = 6 | 0.78 [-10]<br>May Δ = 6 | 0.78 [-10]<br>May Δ = 6 | -0.44 [-10]<br>May Δ = 6 |
| *E. gonicalyx*<br>Peak: March<br>Start: February<br>End: May | -0.62 [-4]<br>December | -0.61 [-4]<br>December | -0.63 [-4]<br>December | 0.35 [-5]<br>November |
| | 0.64 [-10]<br>June Δ = 6 | 0.62 [-10]<br>June Δ = 6 | 0.63 [-10]<br>June Δ = 6 | -0.36 [-11]<br>May Δ = 6 |
| *E. macrorhyncha*<br>Peak: January<br>Start: January<br>End: May | -0.52 [-5]<br>August | -0.52<br>[-5] August | -0.52<br>[-5] August | 0.26 [-5]<br>August |
| | 0.52 [-11]<br>February Δ = 6 | 0.51 [-11]<br>February Δ = 6 | 0.52 [-11]<br>February Δ = 6 | -0.22 [-11]<br>February Δ = 6 |

Table 5. Significant ($P < 0.0001$) wavelet cross correlations (4 months, $\lambda_3$ scale) between peak flowering and climate: shorter [≤ 6 months] and longer lags [> 6 months] prior to peak flowering intensity. (Δ signifies the difference in months between shorter and longer lags).

Even for species within a similar grouping, say *E. tricarpa* and *E. leucoxylon,* we observe that, although at zero lag *E. tricarpa* and *E. leucoxylon* have a similar correlational (WCORR) relationship with climate (somewhat intuitive as their flowering overlaps, see Table 1 and Table 5), their cross-correlational relationship over the 12 months annual cycle differs, having opposite sinusoidal WCCORR profiles for peaks and troughs; with a positive and a negative short term lag for *E. leucoxylon* and *E. tricarpa,* respectively (Table 5) (see Figure 10 and Figure 11).

## 4. Discussion

### 4.1 Subcomponents

Wavelets Multiresolution analysis (MRA) has identified four subcomponents in each flowering series: these are a non-flowering phase, duration, annual cycle, flowering intensity, as well as the overall trend for each species. More specifically:

d1 is the non-flowering phase per species. These so-called "off phases" coincide with other reproductive phases (e.g. budding, seeding) in Eucalypts (Ashton 1975, Bassett 1995, Murray and Lutze 2004). This phenomenon has also been reported specifically in *E. tricarpa* (Keatley and Murray 2006).

The second sub-component, d2, reflects both the duration and the pattern of the original flowering record, for a given species; as shown also earlier for 4 of the 8 species studied in this chapter by Hudson et al. (2010a,b).

The annual cycle has been clearly delineated by subcomponent d3, with the mean month of peak intensity, so identified by peaks in d3 (e.g. *E. leucoxylon*: September, *E. tricarpa*: July, *E. melliodora*: January, *E. goniocalyx*: March). For five of the species (*E. leucoxylon, E. melliodora, E. microcarpa, E. tricarpa* and *E.polyanthemos*) this is in agreement with the trends identified by other analytic methods (e.g. the mean flowering intensity in a flowering year (Keatley & Hudson 2007) and/or by singular spectrum analysis (SSA) (Hudson et al. 2005; Hudson & Keatley, 2010b).

d4 relates to the annual or biennial cycling of the intensity of flowering years. In all eight species, except *E. leucoxylon,* the biennial cycle is related to years of low flowering intensity (< 2). Note that in these three species low flowering intensity also includes years of no flowering (i.e. flowering intensity = 0). In *E. leucoxylon* flowering generally alternates between a quasi-biennial (1950 to 1952, 1955 until 1963) and an annual cycle. It is the only species in this study, where the biennial cycle is associated solely with low (< 2) intensity, and/or late commencement with short duration (commencing in September or October compared to the most probable month of commencement in April (Keatley & Hudson, 2007).

Since Chambers (1893) and others, the variability in flowering intensity, in general, as well as its cyclic behavior has been long reported in eucalypts. Flowering intensity exhibiting two year cycles in these species has also been previously discussed, as based on the judgment and expertise of apiarists (Goodman 1973, Somerville and Campbell 1997, Paton et al. 2004); the collection of reproductive components (see Keatley and Murray 2006) and more recently confirmed by statistical autocorrelogram analysis (Wells 2000), and by singular spectrum analysis (SSA) (Hudson & Keatley, 2010b). A 4 year cycle, previously detected by SSA for *E. tricarpa* (Hudson & Keatley, 2010b), was however, not demonstrated by the wavelet analysis reported in this chapter. A four year cycle for this species has, on the other hand, been delineated earlier via autocorrelograms (Wells 2000). Wells's study and also the work of Somerville and Campbell (1997) have also identified a four year flowering cycle in *E. microcarpa.* Note that SSA is a global analysis (see Hudson et al. 2005; Hudson & Keatley, 2010b) in contrast to wavelets which afford a localized analysis. The reader is referred to Yiou et al. (2000) who discussed methods by which SSA can be made more wavelet-like specifically via the use of a windowing technique. This nonstandard version of SSA, however, was not applied in the analysis of the data of interest here, as reported in the SSA research applications of Hudson et al. (2005), and of Hudson & Keatley, 2010b).

$s_4$ is the smoothed series that illustrates the slowly varying portion of the flowering signal, and is taken to be an estimate of the trend. Again the results of wavelet analysis, namely a decreasing trend in flowering intensity over the period of study, agree with the SSA results (Hudson & Keatley, 2010b). Note that the so-called trend is usually the first primary reconstructed component in SSA (Elsner and Tsonis 1996) and mirrors the smoothed overall trend $s_4$ discussed in this chapter.

#### 4.1.1 Temperature and rainfall wavelet correlations

Wavelet correlation analysis of the flowering and climate series found the same contemporaneous effects of temperature on the flowering of *E. tricarpa* and of *E. leucoxylon;* significantly increased flowering with decreased temperature; with the main drivers for each species being different, maximum temperature for *E. tricarpa* and minimum temperature for *E. leucoxylon* as the main species specific temperature influences on flowering. Maximum temperatures are often associated with day temperatures and minimum with night temperatures. Additionally, although both these species had a positive relationship with rainfall it was only significant in *E.tricarpa*, in opposition to *E. camaldulensis* and *E. melliodora* (which exhibited significantly increased flowering with increased minimum temperature and decreased rainfall). Hence for *E. leucoxylon,* it is cooler minimum temperatures, and in *E. tricarpa* cooler maximum temperatures which have a greater influence on peak flowering intensity. For *E. tricarpa* also wetter conditions tend to increase flowering intensity.

*E. microcarpa, E. macrorhyncha* and *E. polyanthemos* had a significant positive wavelet correlation with minimum temperature (at wavelet scale 4), with a trend (though not significant) for increased flowering with decreasing rain. *E. leucoxylon* and *E. tricarpa* were the only species of the eight species to exhibit a negative wavelet correlation with minimum temperature (at 2 and 4 months). *Eucalyptus tricarpa* was the only species for which rainfall had a significant, *positive* relationship with flowering (at the 4 month scale). This indicates that warmer, wetter periods lead to greater flowering intensity for *E. tricarpa*. The relationship for *E. leucoxylon* and rainfall was positive, but was not significant, as in *E. tricarpa. E. camaldulensis* and *E. melliodora,* which were the only species for which rainfall had a significant, *negative* relationship with flowering (at the 4 month scale); indicating that dryer periods lead to greater flowering intensity for these species. For *E. gonicalyx, E. microcarpa, E. macrorhyncha* and *E. polyanthemos* a negative correlation (but not significant) with rainfall was also indicated. Similar climatic drivers and relationships were found for 4 of the 8 Eucalypt species studied in this chapter by singular spectrum analysis (Hudson & Keatley (2010b)); by mixed transition distribution models (Kim et al. (2009); Hudson et al. (2010d)) and via Generalised Additive Models for Local, Scale and Shape (GAMLSS) modelling (Hudson et al., 2009, Hudson et al., 2010c;, Hudson et al., 2011b).

*Eucalyptus microcarpa* and *E. polyanthemos* were shown in this chapter to share a similar wavelet correlation relationship with temperature (positive) and rainfall (negative). Their flowering durations do not generally overlap (Keatley et al. 2004, Kim et al. 2008) and their months of peak flowering intensity are separated by four months. However, mean diurnal temperature and mean monthly rainfall over their respective flowering duration is similar, 16.2ºC and 38.7 mm for *E. microcarpa* and 16.3ºC and 42.0 mm for *E. polyanthemos*. Rainfall did not have a significant influence in either of the latter species. In *E. microcarpa* flowering intensity is significantly correlated only with one of the three temperature variants, namely minimum temperature (at the 2 and 4 month scale), indicating that warmer minimum temperatures are associated with more intense flowering. Note that minimum temperature has also been previously nominated as the primary driver for *E. microcarpa* (Hudson et al. 2011b). Similar relationships between temperature and / or rainfall with flowering commencement (or flowering intensity), have also been shown by other studies of these species (Porter 1978, Keatley & Hudson 2000, Hudson et al. (2009, 2010a,b,c,d), and Kim et al., (2008, 2009)).

### 4.1.2 Temperature and rainfall wavelet cross- correlations

Four species (*E. leucoxylon, E. camaldulensis, E. melliodora and E. polyanthemos)* group together based on the 'sinusoidal' influence of the climate variables (evidenced by their wavelet WCCORR signatures), but separate themselves out by when that influence occurs - *E. leucoxylon* differentiates as such from the remaining 3 species (namely, *E. camaldulensis, E. melliodora and E. polyanthemos*).

Many of these species occur together. For example, *E. tricarpa* may be found with *E. leucoxylon*, *E. microcarpa*, *E. polyanthemos*, *E. goniocalyx* and *E. macrorhyncha*. Separation of flowering times is one mechanism to avoid competition for pollinators and reduce hybridization, being in a different sub-genus is another. For example, *E. tricarpa's* mean overlap with *E. polyanthemos* and *E. microcarpa* is low (0.13 and 0.36, respectively), however, in some years their flowering period can largely overlap (0.53 and 0.78, respectively) (Keatley and Hudson 2007). This higher overlap is probably due the similar temperature (influence) signatures (i.e. both species are negatively influenced by temperature at shorter lags and positively influenced in the longer term (prior to peak flowering), whereas *E. polyanthemos* has the opposite signature.

According to the wavelet cross-correlations, a similar relationship between flowering and temperature and between flowering and rainfall occurs in *E. leucoxylon* and *E. polyanthemos.* The reverse relationship between flowering and temperature and with rainfall was observed in *E. tricarpa* and *E. microcarpa.* In *E.camaldulensis,* and *E.melliodora* the rainfall 6 or 7 months prior to peak flowering intensity most strongly and positively influences subsequent flowering intensity, whilst the shorter term lags of *E. leucoxylon, E. polyanthemos, E. goniocalyx, E. microcarpa* and*E. macrorhyncha* were associated with negative cross-correlations with rainfall. Longer term lags of *E. leucoxylon, E. polyanthemos, E. goniocalyx, E. microcarpa* and *E. macrorhyncha* were associated with positive cross-correlations with rainfall.

Wavelet cross-correlation analysis identified the cyclical influence of temperature and rainfall on peak flowering intensity. For each species there are 6 months of the annual cycle in which any given climate variable positively influences flowering intensity and 6 months of negative influence. For all species, rainfall exerts a negative influence when temperature is positive. Wavelet cross-correlations between peak flowering intensity and the temperature variants and rainfall were lagged from 0 and 12 months prior to the species specific peak flowering month. These sinusoidal wavelet WCCORR signatures or profiles clearly demonstrated that there are positive and negative relationships of 6 months duration and as a consequence there are seasonal change points from positive to negative cross-correlation and vice-versa.

Wavelets clearly demonstrate the cyclical influence of climate (temperature and rainfall) on peak flowering intensity for the eight species examined in this chapter. There are 6 months of an annual cycle in which any given climate variable positively influences flowering intensity and 6 months of negative influence, within a given species. This phenomenon results in distinctive seasonal change points. In very broad terms, for example, more intense peak flowering is likely to occur in *E. leucoxylon* when cool, wet conditions coincide with its peak flowering. However, peak flowering would be furthered enhanced if the preceding autumn and winter were warm and dry, and the previous spring and summer cool and wet. This supports the upper threshold mean temperature of 18.5ºC found for this species by Hudson et al. (2003) (see also Hudson et al., 2011b). *Eucalyptus tricarpa* requires the identical conditions at peak flowering intensity (i.e. cool and wet) but more or less the reverse conditions to *E. leucoxylon* in the months leading up to flowering: namely a cool, wet autumn and winter, with a warm, dry spring and summer. This supports the upper threshold temperature of 21.3ºC recently demonstrated for maximum temperature for this species by Hudson et al. (2011b). A warm, dry autumn and winter with a cooler, wet spring, and summer with warm, dry conditions at peak flowering, favours more intense flowering in *E. microcarpa*. Flowering is enhanced in *E. polyanthemos* with warm, dry conditions coinciding with peak flowering, preceded by a warm, dry winter and spring and cool, wet summer and autumn, in contrast to *E. microcarpa*. Correspondingly an upper threshold temperature of 16.1ºC was demonstrated for mean temperature for this species by Hudson et al. (2011b) via GAMLSS modelling.

There is evidence of this cycling in correlation between flowering and climate in previous research - specifically this 6 month cycling phenomenon can be observed in the reported tables and/or figures of the following studies; [1] in an examination of flowering commencement between 1954 - 1989 (by multiple linear regression) and the effect of mean monthly temperature by Fitter et al. (1995, Figure 4); [2] in an examination of flowering commencement, from 1978 to 2001, with respect to mean daily maximum temperature using P-splines by Roberts (2008, Figure 3) – there being an approximately 6 month period in which the sign of the smoothed regression coefficients of Roberts changed from negative to positive (see also Roberts 2010, 2011); [3] in Sparks and Carey (1995, see Table 2 of that study) there is evidence of this cycling in correlation between the flowering in wood anemone and turnip and monthly temperature in central England, for the months preceding mean observed date, over a 212 year period (1736 - 1947). Until now this phenomenon of 6 monthly cycling has not been commented on, apart from the recent studies of Hudson et al. (2010a,b) , nor formalised quantitatively as is achieved in this present chapter (via wavelets).

According to Hudson et al. (2010b) the relationships between phenophases and climatic variables, may be considered to be physiologically and/or statistically based (Yang et al. 1995, Spano et al. 1999). In this chapter the relationships between peak flowering intensity and the temperature and rainfall variables could partly be reflecting the time of year these species flower for each of the species examined. For example, *E. tricarpa's* peak flowering intensity occurs in winter, and this species has a negative relationship with temperature, indicating increased flowering with decreasing temperature. Previously, this scenario has been suggested for explaining, at least partially, the relationship between flowering commencement and climate in three (*E. leucoxylon, E. tricarpa* and *E. polyanthemos*) species

(Keatley and Hudson 2000). Additionally, it has been shown that when rainfall and temperature have been accounted for, there is no significant remaining trend in the flowering intensity of *E. leucoxylon* (Hudson et al. 2003), indicating that there is a physiological basis to this relationship. Previous work (Porter 1978, Keatley and Hudson 2000, Keatley et al., 2002, Hudson et al., 2003) examining the influence of temperature and rainfall on flowering intensity of these species have found similar results, but have used different analytical methods (singular spectrum analysis, generalized additive models (GAMs) and Bayesian hierarchical models (BHMs) and regression). As stated earlier comparable climatic drivers and relationships were found for 4 of the 8 Eucalypt species studied in this chapter by singular spectrum analysis (Hudson and Keatley, 2010b)); by mixed transition distribution models (Kim et al., 2009; Hudson et al., 2010d) and via Generalised Additive Models for Local, Scale and Shape (GAMLSS) modelling (Hudson et al., 2010c, Hudson et al., 2009, Hudson et al., 2011b).

In an earlier study House (1997) suggested that even though flowering time seems to be under the control of climatic conditions, it is during bud formation and development that there may be genetic control of the actual flowering dates in local (sub-) populations. Also noted was that the patchy distribution of time of flowering commencment and duration between groups of *E. tricarpa* and *E. regnans* was suggestive of local genetic control of these flowering traits (House, 1997). It was advocated that heavy and light flowering seasons appear to occur in cycles in many species (also evidenced in some species in this chapter) and are related to resource availability. House (1997) stated that there are few data available to demonstrate any systematic differences in reproductive traits that may help elucidate the co-existence of closely related species. Because hybridisation rarely occurs between different subgenera, flowering seasons should be more similar between subgenera than within them House (1997). In the research presented in this chapter all species are in the same subgenera except for *E. macrorhyncha.*

Wavelet cross-correlations add additional insight into and more detail on the changing relationship between climate and peak flowering intensity (over an annual cycle) for the eight eucalypt species (see also the study of Hudson et al., 2011c). They show that whilst the pairing of *E. leucoxylon* and *E. tricarpa,* and the pairing of *E. microcarpa* and *E. polyanthemos,* respectively, have similar relationships with the climate variables at zero lag; the relationship between peak flowering intensity and climate during the 12 months prior to each species' peak flowering is individual or species specific; and therefore is not just a mirroring of the time of year in which the species flower. Note that, four months prior to peak flowering intensity, *E. leucoxylon* is most strongly and positively influenced by temperature, whereas the influence on *E. tricarpa* is not significant. The influence of temperature on each of these species likewise switches from negative to positive and back again in different seasons pointing to a possible physiological basis for this interplay.

## 5. Conclusion

Broadly speaking, *E. leucoxylon* and *E. tricarpa* can be grouped together with respect to their relationship with temperature and rainfall. The relationship between flowering and climate of the remaining six species is similar, however, when the significance of the relationship is taken into account two other species clearly grouped together: *E. camaldulensis* and *E. melliodora*. As already discussed they are the only two species which have significant negative relationship with rainfall (similar WCORR signature between their flowering and rainfall and a significant positive relationship with all three climate parameters at both scales. *Eucalyptus polyanthemos* aligns with this group as it has a significant positive relationship with all three climate parameters but only at the 4 month scale. Additionally, its main influence is maximum temperature as is the case with the other two species (albeit that *E. camaldulensis* is equally influenced by mean temperature). The other three species (namely, *E. goniocalyx*, *E. microcarpa* and *E. macrorhyncha*) also broadly group, as evidenced by the similar climate signature shown in their WCORR profiles. Note that that all members of this species triple, have a positive relationship between flowering and at least one temperature variant; and a negative (though not significant) relationship between flowering and rainfall.

According to wavelet cross-correlations the eight species form two groups based on their, similar cross-correlation relationship between flowering with temperature and between flowering and rainfall - *E. leucoxylon, E. polyanthemos, E. camaldulensis and E. melliodora* are in one group and the remaining species in the other. This first group has cross correlations with temperature which are positive in the short-term (≤ 6 months) and negative in the long-term (> 6 months). With rainfall, the short-term cross-correlations are negative in the short-term and positive in the long-term. The second group (comprising *E. goniocalyx*, *E. microcarpa, E. macrorhyncha* and *E. tricarpa*) has correlations with temperature which are negative in the short-term (≤ 6 months) and positive in the long-term (> 6 months) – and with rainfall the short-term cross-correlations are positive and negative in the long-term.

It is noteworthy that if one examines the whole 12 month pattern of the wavelet cross-correlation WCCORR signatures (sinusoids), in relation to flowering duration, cessation and 12 months back, rather than focusing on the signs of the WCCORR at months of maximum positive or negative cross-correlation, there are 3 groupings, namely, *E. camaldulensis*, *E. melliodora, E. polyanthemos; E. goniocalyx*, *E. microcarpa, E. macrorhyncha;* and *E. leucoxylon* and *E. tricarpa*. Indeed the members within each of these groupings were recently shown to flowering synchronously in a study using self organising map (SOM) methods for time series clustering (Hudson et al., 2011a). The resultant SOM correlations, which were based on clustering the *patterns* underlying the time series records in Hudson et al. (2011a), also showed similar trends to the correlations gleaned from Moran based correlations obtained from the raw flowering records (see Kim et al., 2008).

In agreement with the SOM clustering results, the wavelet based findings of this chapter (of the same eight species) showed via similarities in the wavelet correlation, wavelet cross-correlation signatures and in the identification of the main species specific climatic drivers of flowering: *Eucalyptus microcarpa* to be asynchronising with *E. leucoxylon* and *E. polyanthemos*. *Eucalyptus tricarpa* to be flowering asynchronously to the species triple (*E. camaldulensis*, *E. melliodora* and *E. polyanthemos). Eucalyptus leucoxylon* was demonstrated to be synchronous with both *E. polyanthemos* and *E. tricarpa,* and asynchronous to all remaining species. Hudson et al. (2011a) demonstrated that the main influence for grouping or clustering (synchronisation of flowering) was the season in which flowering commences, however, other flowering characteristics such as the timing of peak flowering and start and cessation of flowering were also contributing factors to synchronisation. In the wavelets based WCORR and WCCORR analyses in this chapter timing of peak intensity was also shown to be an important factor, as reflected by the common seasonal change points for synchronous species groupings (Table 4).

This study shows that the DWT and the MODWT, with multiresolution analysis (MRA) are ideally suitable for investigating the inter-relatedness between climate and phenological time series which may exhibit non-stationarity. As such this chapter adds further knowledge about the interplay between climate and the flowering of eight Eucalypt species - recognised as a major southern hemisphere genus. MODWT-MRA successfully identified the sub-components (annual cycle duration, non-flowering and trend) within each flowering series. Wavelets cross-correlation analysis: (i) determined the strength, directionality and lagged nature of the relationship between climate and flowering; (ii) identified the primary climatic drivers at peak flowering intensity, and (iii) confirmed the dynamic nature of the relationship between peak flowering and climate for each of the 8 species. Our results allude to a physiological basis for this interplay. Species specific wavelet correlation and cross-correlation signatures were established relating flowering intensity with climate; indicating climatic impacts and possibly signatures for synchronisation between specific species groups, in agreement to those recently identified by Hudson et al., 2010e; Hudson et al., 2011a). Wavelet methods are demonstrated to be valuable tools for the analysis of phenological time series, and in studies which aim to detect and understand local climatic impacts on phenological phases and possibly global climate change.

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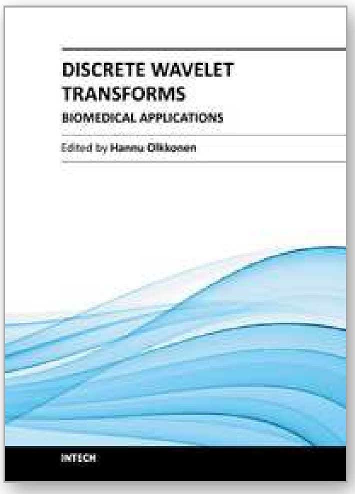

**Discrete Wavelet Transforms - Biomedical Applications**
Edited by Prof. Hannu Olkkonen

ISBN 978-953-307-654-6
Hard cover, 366 pages
**Publisher** InTech
**Published online** 12, September, 2011
**Published in print edition** September, 2011

The discrete wavelet transform (DWT) algorithms have a firm position in processing of signals in several areas of research and industry. As DWT provides both octave-scale frequency and spatial timing of the analyzed signal, it is constantly used to solve and treat more and more advanced problems. The present book: Discrete Wavelet Transforms - Biomedical Applications reviews the recent progress in discrete wavelet transform algorithms and applications. The book reviews the recent progress in DWT algorithms for biomedical applications. The book covers a wide range of architectures (e.g. lifting, shift invariance, multi-scale analysis) for constructing DWTs. The book chapters are organized into four major parts. Part I describes the progress in implementations of the DWT algorithms in biomedical signal analysis. Applications include compression and filtering of biomedical signals, DWT based selection of salient EEG frequency band, shift invariant DWTs for multiscale analysis and DWT assisted heart sound analysis. Part II addresses speech analysis, modeling and understanding of speech and speaker recognition. Part III focuses biosensor applications such as calibration of enzymatic sensors, multiscale analysis of wireless capsule endoscopy recordings, DWT assisted electronic nose analysis and optical fibre sensor analyses. Finally, Part IV describes DWT algorithms for tools in identification and diagnostics: identification based on hand geometry, identification of species groupings, object detection and tracking, DWT signatures and diagnostics for assessment of ICU agitation-sedation controllers and DWT based diagnostics of power transformers.The chapters of the present book consist of both tutorial and highly advanced material. Therefore, the book is intended to be a reference text for graduate students and researchers to obtain state-of-the-art knowledge on specific applications.

Irene Lena Hudson, Marie R Keatley and In Kang (2011). Wavelet Signatures of Climate and Flowering: Identification of Species Groupings, Discrete Wavelet Transforms - Biomedical Applications, Prof. Hannu Olkkonen (Ed.), ISBN: 978-953-307-654-6, InTech, Available from: http://www.intechopen.com/books/discrete-wavelet-transforms-biomedical-applications/wavelet-signatures-of-climate-and-flowering-identification-of-species-groupings

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