Phenological Research

Irene L. Hudson · Marie R. Keatley
Editors

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Methods for Environmental and Climate Change Analysis

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To our partners, parents and children who have given much support and shown great practice

Foreword

Nearly 6 years have passed since the publication of my edited book, Phenology: an integrative environmental science, in late 2003. During this time phenological research has continued to increase both in visibility and importance within the broader scientific community. For example, the latest Intergovernmental Panel on Climate Change report stated that phenology "... is perhaps the simplest process in which to track changes in the ecology of species in response to climate change." (IPCC 2007). Further, an initiative that has been a passion of mine for several decades has finally come to fruition over the past four years, namely the creation of a National Phenology Network in the United States (USA-NPN, which you can read more about in Chapter 2, Section 3.7).

However, not surprisingly, despite these and many other notably advances, phenological science still faces a number of long-term challenges. Thus, I was extremely pleased to learn of the plans to develop this book, focusing on phenological research methods, and to accept Marie Keatley and Irene Hudson's invitation to write this foreword, as it affords me an opportunity to briefly review these challenges in the context of this volume's contributions.

I see a three-fold set of major challenges facing phenology as we move forward in the coming decades:

1. broadening the methodological "tool kit" used in phenological studies;
2. expanding the scope of research questions addressed by phenology; and
3. expanding the depth, diversity, and geographic extent of in situ and remotely sensed phenological data collection, as well as integration of existing (and creation of new) national phenology networks into a global monitoring system.

The first and the second challenges are really two aspects of the same issue. Phenological research is still very often conducted through regression-based studies that look for temporal trends. While there is power and elegance in these findings to-date, which underscore the impacts of a warming world on phenological timing, the scientific community needs the perspective of phenology to address other critical issues in species interactions, population dynamics, and ultimately adaptation strategies within managed and natural ecosystems. The majority of the chapters in this book are designed to broaden the "phenological thinking" of both students and established scholars alike, not only through exposure to new methodologies, but also by expanding the range of research questions that they see possibilities to consider.

The third challenge is in many ways unending (i.e. you rarely have too much data), but Chapter 2 reports on the current status of phenological data collection around the world, and offers several worthwhile perspectives and approaches to advance the objectives of coordinated global phenological monitoring. In the near future, I want to use the structure of the International Society of Biometeorology (ISB) Phenology Commission (of which I am currently Chair) to help us continue moving forward with the long-term work of coordinating and expanding phenology observations and networks around the world. We (Elisabeth Koch, Jake Weltzin, and I) aim to lead this effort through a Group on Earth Observations (GEO) sub-Task, and possibly a World Meteorological Organization Expert Team.

So in conclusion, I call phenology an integrative (rather than integrated) environmental science, because I see it as a field of study that brings together researchers from many different disciplines, rather than being a unique discipline unto itself. Clearly, phenology's multi-disciplinary perspective is a powerful approach for addressing real-world problems. However, we can only achieve this objective fully if there is enough "cross-training" so everyone can "speak the same language." With this text, Marie, Irene, and their contributing colleagues have both broadened and deepened our world-wide phenological research "conversation."

Mark D.

Mark D. Schwartz
Milwaukee, May 2009

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Chapter 1
Introduction and Overview

Marie R. Keatley and Irene L. Hudson

1.1 History

The term phenology was first introduced by Charles Morren in 1849 in a public lecture on the 16th of December entitled "Le globe, le temps et la vie" (Morren 1849, 1851). Phenology which he took from the Greek $\varphi\alpha\iota\nu o\mu\alpha\iota$, (Morren 1849), was defined as "apparaître, se manifester: phénologie, la science des phénomènes qui apparaissent successivement sur le globe." This translates as: to show, to appear: the science of phenomena that appear successively on the globe.

The term, phenology, grew out of Morren's work on the "periodic phenomena of vegetation" with articles being published in the Les Annales de la Société Royale d'agriculture et de botanique de Gand (Annals of the Royal Society of Agriculture and Botany of Ghent). These articles were apparently compiled under one title "Traité historique de Phénologie" (de Selys-Longchamps 1853). It is, however, Morren's paper "Souvenirs phénologiques de l'hiver 1852–1853" published in 1853 which is credited with the term's introduction (Demarée and Curnel 2008) and the reason that 1853 is the date usually cited for this (Abbe 1905, Hopp 1974, Grove 1988, Puppi 2007).

Phenology, in its adjectival form, was introduced into the English language in 1875 (Lynn 1910, Egerton 1977) when instructions were issued by the Council of the Meteorological Society for recording phenological events (Anon 1875). The first definition of phenology published in English "is the observation of the first flowering and fruiting of plants, the foliation and defoliation of trees, the arrival, nesting, and departure of birds, and such like" was in 1884 (Anon 1884, Oxford English Dictionary 2008).

In 1972 as part of their contribution to the International Biological Program (IBP) the United States of America established a committee on phenology (Leith 1974). This Committee defined phenology as:

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> *the study of the timing of recurring biological events, the causes of their timing with regard to biotic and abiotic forces and the interactions among phases of the same or different species* (Leith 1974 p4).

The committee suggested further refinements of the definition, to add a spatial and temporal framework:

> *the unit of study may vary from a single species (or variety, clone etc.) to a complete ecosystem. The area involved may be small (for intensive studies on all phenostages of entire ecosystems) or very large (for interregional comparison of significant phenostages). The unit of time is usually the solar year with which the events to be studied are in phase. The events themselves may cover variable time spans, often shorter than the solar year* (Leith 1974 p5).

Regardless of its definition, and whether phenology includes seasonal events such as snow thaw (see Chapter 3 by Jeanneret and Rutishauser), phenology has a long history with agricultural phenological calendars dating from 1700 BC (Kramer 1963 in Aitken 1974), the longest phenological recording of flowering dating from 705 AD in Japan (Menzel 2003a) and Carl Linnaeus, outlining methods for collecting “calendrier florae” phenological data in 1751 (Linne 1751). Indeed, prior to the invention of thermometers the observation of agricultural phenological phases was used to judge whether a particular year’s climate was different to a so-called normal year (Pfister 1980).

In what follows we review and give the phenological, mathematical and statistical context of each chapter of this book (with broad references for the reader to glean the areas of research and publication and application; and choice what best interests him or her). This introduction and overview aims to inform the reader also of the scope of the topics discussed, as well as to provide a conceptual framework for past, new and ongoing and future developments in the field of phenological research.

With the exception of agricultural phenology, phenology has been regarded by the wider scientific community as the domain of natural historians (Sparks and Menzel 2002), and therefore lacking scientific rigour. This is despite many significant scientific contributions over the years to phenological methods and modelling (e.g. Bassett et al. 1961, Caprio 1966, Dierschke 1972, Caprio et al. 1974, Leith 1974, Idso et al. 1978, Pfister 1980, Alm et al. 1991, Kramer 1995, Degrandi-Hoffman et al. 1996, Linkosalo et al. 1996, Cenci et al. 1997, Chen et al. 1999). This view started to change in the 1990s (Fig. 1.1 and Schwartz 2003b) when the inherent value of phenology, primarily driven by the insights into the impacts of climate change which phenological observations and analyses can provide, was recognised (Sparks and Carey 1995, IPCC 2001, Root et al. 2003, Parmesan and Yohe 2003, Parmesan 2007). Changes in phenological processes have significant consequences for human health, biodiversity, forestry, agriculture, the economy etc (de Vries 1980, McMichael 1993, IPCC 2001, Walther et al. 2002, van Vliet et al. 2003, World Health Organisation 2003, Mackey 2007, Thuiller et al. 2008). Chapter 4 by van Vliet details these impacts on human health and primary production and presents

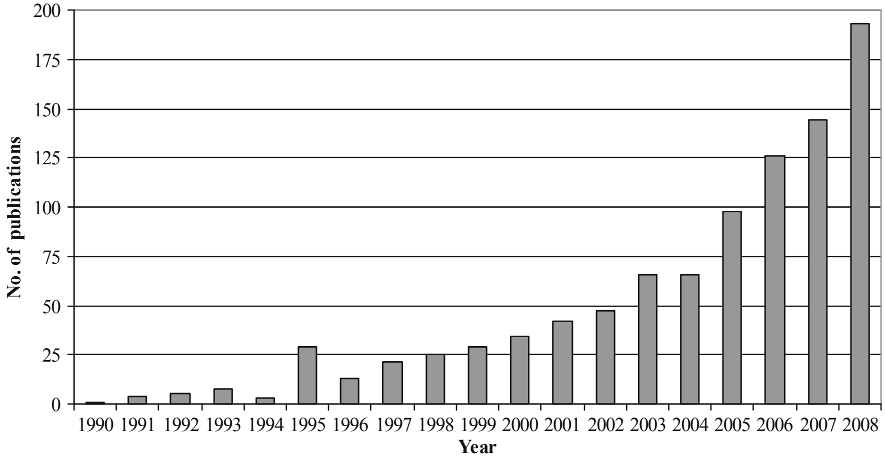

Fig. 1.1 No. of papers published between 1990 and 2008 (indexed in the ISI web of science) in which both phenology and climate change are topics (ISI accessed on 26/02/09)

ways for these sectors to adapt to climate change. As noted by him in Chapter 4 the IPCC (Schneider et al. 2007) conclude that market and social systems have a considerable adaptation potential but that the economic costs are potentially large, for the most part unknown and unequally distributed, as is the adaptation potential itself. van Vliet also highlights the contribution that phenological monitoring continues to make, the need to improve the analysis of phenological time series and quantify both the societal and environmental impact, as well as the communication of the results.

Chapter 2 on phenological networks compiled by Elizabeth Koch, with contributions from authors from both hemispheres, confirms that there is now a worldwide recognition that phenology can be used as an integrative indicator not only for regional impacts of climate change but also at the global level (Donnelly et al. 2004, Parmesan 2006, Cleland et al. 2007, Rosenzweig et al. 2008). Chapter 2 supplements and updates the information on networks and databases provided in Schwartz (2003a) and Nekovář et al. (2008) as well as adding information for countries where phenological information was previously lacking (e.g. Africa and Russia).

The publication of “Phenology: An Integrative Environmental Science” (Schwartz 2003a) also heralded a new age of acceptance of phenological practice, application and research. This book builds on the book of Leith (1974) and following a similar format contains detailed information on: (1) phenological data, networks and research (2) the phenology of various bioclimatic zones, (3) phenological modelling, (4) remote sensing phenology; as well as (5) applications. It also highlights the multidisciplinary nature of phenology.

1.2 Current Issues in Phenology

The accelerated interest in phenology is highlighted by the fact that since the publication of "Phenology: An Integrative Environmental Science" (Schwartz 2003a), there has been a growing awareness, as expressed in the recent phenological literature, that popular analytical methods used in phenological research, whilst useful, have their limitations (Dose and Menzel 2004, Hudson et al. 2005, Sparks and Tryjanowski 2005, Cleland et al. 2007). Phenological studies almost certainly are observational and therefore often rely on correlation analysis for inference (Parmesan and Yohe 2003, Sparks and Tryjanowski 2005).

One example is the popular practice of analysing phenological records by simple linear regression (which has a correlational basis) - often used to determine whether there has been a change in the commencement time of a phenostage; indicated by a significant estimate of the slope. It has been highlighted (Sparks and Menzel 2002, Menzel 2003b, Hudson et al. 2005, Sparks and Tryjanowski 2005) that the slopes of the resultant regression lines are influenced by when the series commences and finishes and, also by the length of the series. Menzel et al. (2008) also noted that when utilising simple linear regression, the length of a time series and its start and end dates are crucial in correct detection of changes, and in estimating their magnitude. This is particularly so when highly variable, multi-decadal, phenological time series are analysed (Dose and Menzel 2004). As temperature in the last 12 years (1997–2008) encompasses the warmest period recorded (Goddard Institute for Space Studies 2009), this also impacts on the slope of the regression lines and on the ability of regression methods to accurately estimate the true rate of change over time of a phenological stage (Sparks and Tryjanowski 2005). However, this analysis is robust and has a role to play in phenology. In Chapter 6, Sparks and Tryjanowski present ways to ensure that the method is applied appropriately and provide examples of alternate methods: polynomial and multiple regression. Multiple linear regression (MLR) or stepwise regression (Draper and Smith 1981) are regularly used to investigate the influence of temperature on the first day of flowering or to relate a phenological response to weather measurements (Fitter et al. 1995, Sparks and Carey 1995, Keatley and Hudson 2000, Roy and Sparks 2000, Lu et al. 2006). To date, MLR or stepwise methods have delineated similar results across different regions (Fitter and Fitter 2002, Roberts et al. 2004). Stepwise regression is a procedure that selects the subset of the regressors that best explains the variation in the phenological response. Stepwise regression, however, has limitations in studies relating a phenological response to weather data. Firstly, it does not accommodate for large numbers of highly correlated regressors. This is an issue if daily or weekly measurements are used as regressors (see also Chapter 12 Roberts). In practice monthly aggregates of weather data are then used and clearly information is lost. Stepwise regression, like simple linear regression, does not take into account the marked auto-correlated structure in the regressors. Indeed what has not often been highlighted in the phenological literature is that phenological series (or fine time scale weather series) are correlated by nature, an aspect not accounted for by linear, MLR, nor stepwise regression methods (Chapter 13 Kelly, Hudson et al. 2005).

Roberts in Chapter 12 describes a recently introduced approach, penalized signal regression (PSR), to examine the relationship between phenology and weather (following Roberts 2008). PSR is based on linear regression, and thus retains the benefit of flexibility, but can be used with weekly or daily weather data and gives intuitively appealing and interpretable results.The penalised regression method avoids difficulties due to multicollinearity (correlated regressors) and illustrates the concept of penalising differences between regression coefficients so as to obtain a smooth profile. Roberts discusses how the PSR approach can also be expanded to investigate the effect of one or more covariates, for example latitude, on the regression coefficients (Eilers and Marx 2003) or to study how two or more banks of predictors, such as daily temperature and rainfall measurements, affect the phenological response.

Kelly in Chapter 13 points out that whilst multiple-location phenological data is reasonably uncommon, the impetus of expanding phenological networks will ensure data of this type will be available in the future (Cleland et al. 2007). Results from studies of trends in phenophases at a regional (rather than local) level provide more power to detect climate change. The representativeness of locations of phenophase observations is, however, an important issue (Rötzer et al. 2000, Thompson and Clark 2006, Siljamo et al. 2008), in that data from an individual location may unduly influence or bias models of phenological change, through factors that cannot be controlled for nor quantified. As Kelly cautions, data containing phenophase time series from multiple locations has an inherent correlated error structure which standard statistical methods cannot accommodate. She advocates and demonstrates alternative modelling approaches to account for both multiple localities and for the longitudinal nature of phenological data - data resolution and random effects modelling, both extensions of simple linear regression (see Verbeke and Molenberghs 2000 and Diggle et al. 2002).

Non-linear modelling has not been addressed much to date in phenology. Indeed it will be difficult to find a linear regression model that fits the data well for essentially non-linear processes. This is true particularly as the range of the data increases (Schleip et al. 2008). The pertinent question is how can we accommodate for non-linear responses of phenology to time and/or to climatic factors? This has been addressed by Hudson and her colleagues in Chapter 10, by the application of Generalised Additive Models for Location, Scale and Shape (GAMLSS) (see Rigby and Stasinopoulos 2005, and Hudson et al. 2009). Hudson et al. illustrate the advantages of GAMLSS to phenology is that GAMLSS: [1] can identify the main drivers of the event of interest from a multiplicity of predictors such as temperature and rainfall; [2] allow for non-linear impacts of time and/or the explanatory variables; [3] can statistically detect thresholds; for example, the lowest temperature for the commencement of flowering; and [4] can model the auto-correlated nature inherent in the phenological series (see also Chapter 13 of Kelly). In Chapter 19 MacGillivray's et al. present the GAMLSS approach to show its greater accuracy and relevance to the assessment of non-linear trends over time (year) for herbarium records.

Modelling nonlinear phenological responses with time have been addressed in the context of meta-analytic studies in phenology by Hudson (Chapter 20) and from a Bayesian viewpoint by Schleip and his colleagues (Chapter 11). Bayesian analysis offers the possibility to overcome the pitfalls of linear regression models. Indeed Bayesian statistical methods have been applied to date in climate change detection, analysis and attribution (e.g. Hobbs 1997, Hasselmann 1998, Leroy 1998, Berliner et al. 2000), and also in climate reconstructions (Robertson et al. 1999, Schoelzel 2006). Recently various studies show that Bayesian analysis offers huge benefits in the analysis of varying changes, model probabilities and change-point probabilities of time series, when nonlinear changes in phenological and climate time series exist. Along with these rates of change, rigorously calculated uncertainties of model-averaged rates of change and linear trends can be described by Bayesian statistics (Dose and Menzel 2004, Menzel et al. 2008, Schleip et al. 2008).

A handful of papers have used other methods to account for the possible non-linearity and for the complex interdependencies and changing structure in phenological time series: namely dynamic factor analysis (by Gordo and Sanz 2005) and chronological clustering (Doi 2007, Doi and Katano 2008). These methods prove valuable in separating out underlying components of a univariate (single) time series that show significantly different patterns; aspects achievable by the techniques of wavelets and singular spectrum analysis discussed by Hudson and her colleagues in Chapters 17 and 18, respectively.

Much focus has gone into developing a better definition of phenophases and provision of greater precision and accuracy for data collected across phenological networks and stations (see Chapter 2; Meier 2003, COST 725 2008). However, the influence of sampling method, sample size and the frequency of observations on the analysis and interpretation of plant phenology has been rarely addressed in the phenological literature (Fournier and Carpantier 1975, Chapman et al. 1992, 1994, Hemingway and Overdorff 1999, D'Eça Neves and Morellato 2004). Such issues of sampling method, sample size and the frequency of observations are discussed by Morellato and her colleagues in Chapter 5 via a case study of tropical forest trees, where direct observations on transects are compared with those from litter traps. The lack of a coherent set of sampling rules and methods, if not analytic methods and procedures, is even more evident in tropical phenology, where there is a high diversity of species and complex ecosystems (Frankie et al. 1974, Newstrom et al. 1994, Sakai 2001, Morellato 2003). In Chapter 5 Morellato et al. advocate the combination of presence/absence data and a quantification method to estimate plant phenology, and recommend careful estimation of indices (Fournier intensity index (Fournier 1974) and activity index (Bencke and Morellato 2002)) and a cautious generalisation of pattern(s).

Reaching some concensus on design, method of collection and comparable analytic methods is much needed to advance the generalisability of phenological results. What has also been recently discussed is the need for the phenological community to reach a consensus on inclusion criterion for studies selected for phenological meta-analytic studies (Parmesan 2007). As noted by Hudson in Chapter 20 in a discussion of meta-analysis in phenology – these criteria likewise relate to sampling and observation frequency, that is length of observations (length of the time series) and pertain to selection criteria of studies for inclusion into the synthetic analysis; this based in part on whether a reported neutral, negative or positive result was exhibited in regard to climate change impact on phenology (see Chapter 20 of this book and Parmesan 2007).

Phenological time series are often incomplete and of limited temporal range. As Schaber and his colleagues point out in Chapter 7 with ongoing efforts to expand the databases of phenological observations by data mining it is likely that more data sets with sparse data and data gaps will become available in the near future (see Aono and Kazui 2007). The problem of the uncertainty of individual time series and gaps is often accommodated for by averaging a set of phenological time series over a geographical area of interest or a time period of interest (Estrella and Menzel 2006, Menzel et al. 2006, 2008). To date, there are applications of methods for combining phenological time. One application is to obtain a reliable series from several time series (Häkkinen et al. 1995, Linkosalo et al. 1996, 2009, Linkosalo 1999, Schaber and Badeck 2002). Another is to construct a long time series for trend analysis, where data gap filling is of primary interest (Schaber and Badeck 2005). In addition combined time series can also be used to find outliers in individual time series (Linkosalo et al. 2000, Schaber and Badeck 2002, Doktor et al. 2005). Schaber and his colleagues in Chapter 7 present a method for combining phenological time series which imputes missing data within records as well as detecting outliers. Schaber et al. also quantify the effect of the extension of the outlier detection algorithm using Gaussian Mixture Models. Their outlier detection method is based on Gaussian Mixture Models (Doktor et al. 2005) and accounts for year-location interactions. The approach of Gaussian mixtures, discussed in Chapter 7 which allows for station x year effects, can be further developed by assigning stations to tentative mixture components before checking for outliers. Schaber et al. (Chapter 7) point to the future application of Bayes statistics as an alternative way of analysing messy phenological datasets (see Dose and Menzel 2004), and suggest that further work would entail comparison of Bayes methods to the methods discussed in Chapter 7.

Recent technological advances in studying the earth from space have resulted in a new field of phenological research which concerns itself with observing the phenology of whole ecosystems and stands of vegetation on a global scale using proxy approaches (Reed et al. 2003, Stöckli and Vidale 2004). These remote sensing methods complement the traditional phenological methods which record the first occurrences of individual species and phenophases, and, in part, overcome one other limitation of phenological time series is that they have limited geographical range. But as de Beurs and Henebry in Chapter 9 point out, further research is required on the relationship between satellite derived metrics for the start and end of season with ground-based phenological observations. Jeanneret and Rutishauser in Chapter 8 on phenological mapping show also that technical and analytical challenges still remain, (e.g. the comparability of different data sources and/or frequent temporal gaps). These satellite derived phenological parameters are an approximation of the true biological growth stages; mainly due to the limitation of current space based remote sensing and the nature of vegetation index. As pointed out by Jeanneret and Rutishauser in Chapter 8 motivations to map phenology are often driven by practical issues such as: regional planning (Jeanneret 1974, Messerli et al. 1978), aerobiology (pollen emission, Branzi and Zanotti 1989, García-Mozo et al. 2006), and agronomy (Mariani et al. 2007). They contend that "large-scale phenological maps are unequalled and irreplaceable in providing a maximum amount of topoclimatic information" and recommend that in a transition from cartographic intuition to future mapping algorithms we need to utilize and link all available sources of data, terrain information, knowledge and experience.

In Chapter 9 de Beur and Henebry present twelve methods commonly used in land surface phenology along with their limitations, in determining start and end of season, reiterating the point that, relating satellite observation with ground-based phenology, remains a significant challenge. The different spatio-temporal statistical methods are grouped into the following categories: [1] thresholds (Lloyd 1990, Fischer 1994, Myneni et al. 1997, White et al. 1997, Shabanov et al. 2002, Zhou et al. 2003, Karlsen et al. (2006, 2007), Delbart et al. 2005); [2] derivatives (White et al. 1997, Tateishi and Ebata 2004, Baltzer et al. 2007); [3] smoothing algorithms (e.g. moving average models (Reed et al. 1994)), discrete Fourier analysis (Moody and Johnson 2001), Principal component analysis (Eastman and Fulk 1993, Hall-Beyer 2003); and [4] fitted models (logistic models (Zhang et al. 2004)), Gaussian models or lower order Fourier estimates (Jönsson and Eklundh 2002), quadratic models with accumulated growing degree days (de Beurs and Henebry 2008). In Chapter 9 de Beur and Henebry also point to the as yet unresolved problems with a lack of statistical error structure from most of these methods and in oversmoothing.

In Chapter 3 Jeanneret and Rutishauser advocate that phenological observations are crucial as the basis for a description of a seasonal classification and seasonality. They show that a well designed phenological diagram can offer a comprehensive picture of the rhythm and amplitude of seasons and they detail the basic requirements of drawing up a phenological diagram. They suggest the inclusion of abiotic observations such as the timing of frost, thawing, icing, snow and fog provides seasonality descriptions beyond the vegetation period – offering thus a year-round, combined topoclimatic typology. In terms of utility Jeanneret and Rutishauser claim that phenological season diagrams are a compelling and cheap tool for extracting typologies of seasonal patterns based on an analysis of single years or of different stations; and have the potential for global application; despite phenology having, not as yet achieved international or global standardization (Bruns and van Vliet 2003).

Additionally given the increased worldwide momentum on reporting results from climate impact studies and now from phenological series, as the value of long-term data is being recognised, it seems that every attempt is being made to extract climate signals contained within these records (Stenseth et al. 2002, Walther et al. 2002, Parmesan and Yohe 2003, Root et al. 2003, Rosenzweig et al. 2008). However, it is still not fully appreciated, that the identification of points of significant change (change-points), in long-term phenological time series, is a prerequisite for the analysis and the interpretation of phenological observations as bio-indicators of climate change (Hudson et al 2005). Rapid shifts in climate can lead to, or be contemporaneous with, abrupt phenological changes. These cannot be well detected by regression nor correlation, methods traditionally used to detect temporal changes in phenology (Cleland et al. 2007). The non-uniform periods of change that typify the climate of the twentieth century (Dose and Menzel 2004, Rutishauser et al. 2007) pose a particular challenge when linear regression analysis is used for the reconstruction of trends.

Indeed there are few studies to date determining change points in phenological series using precise statistical models (Dose and Menzel 2004, 2006, Hudson et al. 2004, 2005, Schleip et al. 2006, Keatley and Hudson 2008, Menzel et al. 2008). The Chapter (11) by Schliep and his colleagues presents a single change point method and the associated rates of change in flowering using nonparametric Bayesian functionals to time series. Bayesian analysis of the change-point probabilities as described by Schleip and his colleagues provides both visualisation and quantification of major changes in long-term time series (see also Dose and Menzel 2004, Menzel and Dose 2005, Menzel et al. 2008, Schleip et al. 2008, 2009). In Chapter 19 MacGillivray and her colleagues present the results from a multiple change point analytic approach, on herbarium records, following Moskvina and Zhigljavsky (2003), which is model free change point method, based on the sequential application of singular-spectrum analysis (SSA) (see Chapter 18) to subseries of the original series. They also determined, not only the significant points of change, but also the rates of change using both change point analysis and nonlinear modelling via Generalized Additive Models for Location, Scale and Shape (GAMLSS) (Chapter 10). MacGillivray's et al. (Chapter 19) advocate the combined use of both non-linear methods (GAMLSS) and change points methods in phenological analysis, particularly of herbarium records. The detection of change points has also been applied to the area of circular statistics (Jammalamadaka and SenGupta 2001), whose potential to phenology research is discussed in Chapter 16 by Morellato and her colleagues. Change point methods for linear scaled data are discussed in other chapters of this book (Chapter 11). Indeed the reconstructed subcomponents of phenological time series discussed by Hudson et al. (Chapter 18) point to significant points of change in cyclicity and amplitude of flowering in four species of eucalypt. Hudson also discusses the need for change point identification in phenological meta-analytic studies (Chapter 20); this is a problem not appreciated, nor accounted, for, to date, in phenology. The presence of significant and abrupt change points affects both the accuracy of the estimates of local climate impact and of the pooled estimates of climate effect from meta-analytic studies, which are traditionally conducted across wide geographical locations (Chapter 20).

It has been advocated for some time that statistical techniques used in phenology need to accommodate for the inherent complexity of phenological records (Dose and Menzel 2004, Hudson et al. 2005) which is often ignored. Complexity, such as their time series (correlated) nature, their often discrete and non-stationary properties, and the presence of excess zeros (non occurrence of a phenostage of interest). More sophisticated statistical methods for examining phenological time series are still needed. In Chapters 17 and 18 Hudson and her colleagues apply two such methods for time series decomposition and cross-correlation, namely wavelets analytic methods (Percival and Walden 2000, Kang et al. 2004) and singular value decomposition (SVD) using singular spectrum analysis (SSA) (Golyandina et al. 2001, Hudson et al. 2004, Fukuda and Hudson 2005, Golyandina and Osipov 2007). It is noteworthy that whilst wavelet analysis has been used in a study of European spring temperatures (Paluš et al. 2005) and rainfall (Koch and Marković 2007) and changes in vegetation cover (Lu et al. 2007), it is as yet under utilised in traditional land based phenology. SSA is also not as yet very widely applied to phenological data (D'Odorico et al. 2002, Hudson et al. 2004, 2005, Studer et al. 2005, 2007). These chapters illustrate the worth of both wavelets and SSA, and associated cross correlational analysis to phenology, demonstrating that these methods offer us ways to: [1] identify spatial and climate niche across species; [2] decompose time series into its sub components (e.g. trends, oscillatory modes or seasonalities, change-points and noise); [3] establish whether a given species is uniquely influenced by climate through the year (i.e. has its own climatic signature); [4] determine the relationship between multiple climate indicators; [5] succinctly display how the association between the two processes, say climate and flowering, change with scale and time; and [6] identify the primary climatic drivers of flowering or of any phenophase.

Transitional state modelling, which assumes the existence of underlying heterogeneity (mixtures) in multivariate time series, is a novel technique developed by Hudson and her colleagues and applied to eucalypt flowering, as detailed in Chapter 14. Hudson et al's. approach allows for modelling possible *interactive effects* of two or more climate variables on phenological response (where the phenological response and climatic predictors are discrete state processes). Interactive effects have as yet not been tested for in phenology; even though there is an appreciation that climate drivers, other than temperature, such as rainfall, and drought etc need to be modelled in addition to temperature forcing (Schleip et al. 2008).

Exploring the impacts of single and multiple climate variables, and even which temperatures impact from different months, or combinations and interactions of such variables, constitutes a significant modelling exercise (Sparks and Carey 1995, Keatley et al. 2002). Transitional state modelling (see e.g. Berchtold and Raftery 2002) has also, as yet, not been embraced in phenology. Hudson et al. (Chapter 14) develop the work of Kim et al. (2005, 2008, 2009), which uses mixed transition distribution (MTD) models (Berchtold 2006) to study the relationship between the probability of (on/off) eucalypt flowering with respect to two discrete states (high/low) of rainfall and of temperature. Allowing for interactive effects between climate predictors in modelling phenological response opens up new dimensions of interpretation of results. For example, the four eucalypt species examined in Chapter 14 are shown to be influenced by temperature (see also Keatley et al. 2002) and in some instances are influenced by rainfall and its interaction with temperature. Hudson et al. then conclude that as a consequence their flowering phenology will change in response to climate change, and propose that there may be a rainfall threshold required before flowering can occur (Hodgkinson and Freudenberger 1997).

Increased synchrony can mean less potential for genetic or demographic rescue effects (Brown and Kodric-Brown 1977, Tallmon et al. 2004). In the study of population dynamics the degree of synchrony (the temporal match of events in space and time) is frequently estimated by the cross-correlation of population sizes in two spatially distinct localities; with synchrony tending to decrease with distance (Ranta et al. 1997, 1999). In Chapter 15 Ranta and his colleagues demonstrate that phenological events can indeed be synchronized in a similar manner as population fluctuations. Ranta et al. show that the Moran effect (i.e. a common external perturbation) is capable of synchronizing two distinct life history events, that of leafing in European aspen (*Populus tremula*) and that of mast seeding in both Scotch pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) in Finland. Using a threshold-triggered phenology model Ranta et al. demonstrate that the conceptual framework of Moran effect may be extended to cover the timing of life history events, events not directly regulated by density-dependent feedback. Tests for synchrony based on circular statistics are also discussed by Morellato et al. (Chapter 16).

As mentioned cross-correlational methods underpin synchrony tests, but as yet, like testing for interaction effects of multiple climatic indicators, are underutilized in phenology. Schleip and his colleagues (Chapter 11) discuss correlational methods of phenological data with temperature (see also Dose and Menzel 2006 and Schleip et al. 2008). Wavelet cross correlation methods for bivariate time series are also discussed in Chapter 17 of this book when relating either bivariate phenological-series or say one phenological-series with climate time series indicators. See also the cross correlation methods based on the SSA reconstructions of both phenological and climate time series in this book (Chapter 18). Finally in the realm of circular statistics (Chapter 16) cross correlational methods are now available (Zimmerman et al. 2007).

In Chapter 16 Morellato et al. discuss circular statistics (Batschelet 1981, Fisher 1993, Zar 1999, Mardia and Jupp 2000), an area of statistics also not much used in phenology to date. This is possibly due to its difficult and less traditional mathematical and statistical formulation, and the lack of easily available software, till recently (see listing in Chapter 16). Most of the earlier animal and plant applications of circular statistics involved the analysis of directional data (e.g. the orientation and direction of movements of animals, such as flight direction of birds and butterflies and the orientation on salamanders and dragonflies (Batschelet 1981, Fisher 1993)). Morellato et al. show that the connection between the evaluation of temporal, recurring events and the analysis of directional data have converged in several papers (Herrera 1988, Milton 1991, Wolda 1988, 1989, Morellato et al. 1989, 2000, Alonso 1997, Davies and Ashton 1999, Hamer et al. 2005, Zimmerman et al. 2007) and show circular statistics to be a tool by which to better describe and to compare both plant and animal phenology. Morellato et al. advocate that circular statistics has particular value and application when flowering onset (or fruiting) occurs almost continuously in an annual cycle or where flowering time may not have a logical starting point, such as mid-winter dormancy. They conclude that circular statistics applies well to phenological research where one wants to test for relationships between flowering time and other phenological traits (e.g. shoot growth), or with functional traits such as plant height. Circular statistical methods also allows grouping of species into annual, supra-annual, irregular and continuous reproducers; and for rigorous study of seasonality in reproduction and growth; and the assessment of synchronization of species (see also Chapter 15 for more discussion on synchrony methods).

Recently it has been appreciated that extending phenological records over time and particularly over geographical location is much needed (Chambers 2006, Sparks et al. 2006, Parmesan 2007, Sparks 2007, Bertin 2008). In Chapter 19 MacGillivray et al. present what Sparks (2007) calls "lateral thinking" – the use of herbaria specimens and photographs to examine the effects of climate change on phenology (see also Miller-Rushing et al. 2006, Lavoie and Lachance 2006, Miller-Rushing and Primack 2008, Loiselle et al. 2008, Gallagher et al. 2009). The relevance of such collections to a range of ecological conservation and biological studies has been, to date, largely underappreciated in Australia (Rumpff et al. 2008). MacGillivray et al. outline the constraints which need to be considered when linking phenological changes with climatic fluctuations and long-term trends. They offer some cautionary principles for analysis and interpretation - these include issues regarding sparcity of data and irregularity of records over time, as well as the need for more complex underlying distributions. How best, if possible, to infer first flowering dates and actual stage of flowering from snap records remains an issue for inference, modelling and interpretation. MacGillivray's et al. (Chapter 19) also contend that to properly address the question of change, periods of no change must also be considered as important; vital also is the determination of events throughout periods of reasonably stable conditions.

In the final chapter, Hudson presents a review of the general methodology of meta-analysis, assesses its advantages and disadvantages, synthesizes its use in global climate change phenology and suggests new statistical directions and an underlying paradigm for a unified meat analytic approach. Specifically Hudson proposes new statistical methods, as yet not applied to phenological research, and only recently applied, in part, in the health-climate-pollution epidemiological literature. Hudson discusses three approaches and applications to the modelling of *nonlinear* phenological response over time namely, Generalised additive models for location scale and shape (GAMLSS) (Stasinopoulos and Rigby 2007) (see Chapter 10 and Chapter 19 for GAMLSS analyses on eucalypt flowering and orchid peak flowering, respectively), penalised signal regression (Chapter 12 of Roberts) and Bayesian nonparametric function estimation (see Chapter 11 Schleip et al. and Chapter 19 by MacGillivray et al.). These are shown by Hudson to be inter-related to three recent epidemiological approaches of exposure (pollution/climate) to response (health/hospitalizations) modelling which Hudson contends hold much promise for future meta-analytic studies in phenology. These are nonlinear "dose/exposure to response" functionals in epidemiology (Gamborg et al. 2007, Baccini et al. 2008, Peng et al. 2009), Bayesian hierarchical meta-analysis (Baccini et al. 2008 and Michelozzi et al. 2009) and Bayesian hierarchical distributed lag models (BHDLMs) (Peng et al. 2009). Proof of concept of this application to phenology is an important area of future research, which we hope will be a challenge taken up by mathematicians, phenologists, statisticians and others. Hudson shows that the overarching paradigm for all the meta-analytic methods suggested for phenological synthetic studies is the area of semiparametric regression (Ruppert et al. 2009); which she proposes as a possible way towards a unified meta-analytic approach in phenology.

1.3 Aims of This Book

There is both art and science in the analyzing and assessing of phenological impacts of climate change. Forecasting and anticipating such impacts remains an even greater challenge. A similar viewpoint with respect to climatological research and environmental change is espoused by von Storch et al. (2007). Von Storch and Zwiers have helped to inject statistical thinking and method into climatology research (von Storch and Zwiers 2001, Zwiers and von Storch 2004). Our book in a similar vein hopes firstly to build on Leith (1974) and of Schwartz (2003a), and thereby bring to readers the art and science, complexity and beauty of phenological research. It presents statistical, graphical, image analytic and sampling methods (via case studies and some theoretical exposition), both for those commencing in phenological research and for those more experienced in the area. In addition it embraces the call that "phenologists need to link with other disciplines" (Dunlop and Howden 2003, van Vliet et al. 2003), with contributions from botanists, ecologists, geographers, foresters, climatologists, meteorologists, GIS experts, phenologists, mathematical statisticians and health epidemiologists. We hope this book will also be valuable as a reference source for these disciplines and add rigour to and possibly change the focus of some directions of global climate change research towards a more mathematically and statistically rigorous exploration. We believe the book will add to the momentum and contribute to the robustness of the science, which is phenology; and bring together the disciplines needed to further advance this science. We shall then be better placed to propose future scenarios, so as to, in the words of von Storch et al. (2007), "confront stakeholders and policy makers with possible future conditions so that they can analyse the availability and usefulness of options to confront an unknown future".

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