

UNIVERSITY OF KWAZULU-NATAL

LONGITUDINAL ANALYSIS OF THE EFFECT OF
CLIMATIC FACTORS ON THE WOOD ANATOMY
OF TWO EUCALYPT CLONES

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CLIMATIC FACTORS ON THE WOOD ANATOMY
OF TWO EUCALYPT CLONES

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Dedication

To my mother, Ejigayehu Bereded and grand mother, Mulunesh Yeshaw

Declaration

The research work described in this thesis was carried out in the School of Statistics and Actuarial Sciences, University of KwaZulu-Natal, Pietermaritzburg, under the supervision of Prof. Temesgen Zewotir and Prof. Principal Ndlovu.

I, Dawit Getnet Ayele, declare that this thesis is my own, unaided work. It has not been submitted in any form for any degree or diploma to any other University. Where use has been made of the work of others, it is duly acknowledged.

May 2010

Mr Dawit Getnet Ayele

Date

Prof. Temesgen Zewotir

Date

Acknowledgement

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Abstract

Eucalypt trees are one of tree species used for the manufacturing of papers in South Africa. The manufacturing of paper consists of cooking the wood with chemicals until obtaining a pulp. The wood is made of different cells. The shape and structure of these cells, called wood anatomical characteristics are important for the quality of paper. In addition, the anatomical characteristics of wood are influenced by environmental factors like climatic factors, soil compositions etc.... In this study we investigated the effects of the climatic factors (temperature, rainfall, solar radiation, relative humidity, and wind speed) on wood anatomical characteristics of two *Eucalyptus* clones, a GC (*Eucalyptus grandis* × *camuldulensis*) and a GU (*Eucalyptus grandis* × *urophylla*). Nine trees per clone have been selected.

Two sets of data have been collected for this study. The first set of data was eleven anatomical characteristics of the wood formed daily over a period of five years. The second set of data was the daily measurement of temperature, rainfall, solar radiation, relative humidity and wind speed in the experimental area.

Wood is made of two kinds of cell, the fibres and the vessels. The fibres are used for the strength and support of the tree and the vessels for the nutrition. Eleven characteristics related to those cells have been measured (diameter, wall thickness, frequency). These characteristics are highly correlated. To reduce the number of response variables, the principal component analysis was used and the first four principal components accounts for about 95% of the total variation. Based on the weights associated with each component the first four principal components were labelled as vessel dimension (VD), fibre dimension (FD), fibre wall (FW) and vessel frequency (VF).

The longitudinal linear mixed model with age, season, temperature, rainfall, solar radiation, relative humidity and wind speed as the fixed effects factors and tree as random effect factor was fitted to the data. From time series modelling result, lagged order of climatic variables were identified and these lagged climatic variables were included in the model. To account for the physical characteristic of the trees we included the effect of diameter at breast height, stem radius, daily radial increment, and the suppression or dominance of the tree in the model. It was found that wood anatomical characteristics of the two clones were more affected by climatic variables when the tree was on juvenile stage as compared to mature stage.

Table of contents

Dedication	i
Declaration	ii
Acknowledgement	iii
Abstract	iv
Table of contents	v
List of tables	vii
List of figures	x
1. Introduction	1
2. Preliminary Data Analysis	6
2.1 Data Reduction Using Principal Component Analysis.....	6
2.1.1 Theory of principal component analysis	7
2.1.2 Application of principal component analysis for wood anatomy.....	9
2.2 Graphical assessment.....	13
2.2.1 Graphical assessment of the tree and age of tree effects on the wood anatomical characteristics of <i>Eucalyptus</i> clones.....	14
2.2.2 Graphical assessment of the climatic variable effects on the wood anatomical characteristics <i>Eucalyptus</i> clones	17
3. ARIMA Modelling for wood anatomical properties	19
3.1 Theory of ARIMA models.....	19
3.1.1 Definitions and notation	19
3.1.2 ARIMA models and modelling	21
3.1.3 Model estimation and diagnostics	25
3.2 Results of the ARIMA modelling approach	28
3.3.1 The effects of lagged temperature on fibre and vessel characteristics	30
3.3.2 The effects of lagged rainfall on fibre and vessel measurements.....	34
3.3.3 The effects of lagged solar radiation on fibre and vessel measurements	39
3.3.4 The effects of lagged relative humidity on fibre and vessel measurements.....	42
3.3.5 The effects of lagged wind speed on fibre and vessel measurements	47

4. Assessment of climatic factors affecting the wood anatomy.....	52
4.1 Linear Mixed model	52
4.1.1 Estimation of the fixed effects and the variance components	54
4.1.2 Covariance structures	57
4.1.3 Model reduction.....	59
4.1.4 Assessing the goodness-of-fit of the model.....	61
4.2 Application of the linear mixed model to the wood anatomy data	63
4.2.1 The effect of categorized climatic variables on the wood anatomy	64
4.2.2 The assessment of the continuous climatic variables on the wood anatomy.....	75
4.2.3 Comparison of the analysis of the categorical and continuous climatic variables	80
5. Assessment of tree height, daily increment, radius and climatic factors on wood anatomy ..	82
5.1 The effect of the dominance/suppression of the tree.....	82
5.2 The effect of daily increment, radius and diameter at breast height for wood anatomical characteristics of the Eucalyptus clones	83
5.2.1 Using categorical climatic variables.....	84
5.2.2 Using continuous climatic variables.....	101
5.3 Comparison of the analysis of the categorical and continuous climatic variables	112
6. Summary, conclusions and recommendation	115
References.....	120
Appendix A: Additional tables	125
Appendix B: Additional Figures.....	144

LIST OF TABLES

Table 1. 1: Starting and ending period for the four Phases.....	2
Table 2. 1: Correlation matrices of the fibre and vessel characteristics of the GC and GU clones for Phase I	10
Table 2. 2: Eigenvalues of the correlation matrices of the fibre and vessel characteristics of the GC and GU clones for Phase I.....	11
Table 2. 3: Eigenvectors (PC coefficients) for the correlation matrices of the fibre and vessel characteristics of the GC and GU clones for Phase I	12
Table 3. 1: The standard deviations and the optimal orders of differencing of the climatic variable series.....	29
Table 3. 2: The standard deviations and the optimal orders of differencing of the Fibre and vessel variables	30
Table 3. 3: White noise autocorrelation check for once differenced temperature series	32
Table 3. 4: Unconditional least square estimation for the temperature series	32
Table 3. 5: Cross correlation check (P – values) between lagged temperature and wood anatomical characteristics	34
Table 3. 6: White noise autocorrelation check for rainfall series	36
Table 3. 7: Unconditional least square estimation for the rainfall series.....	37
Table 3. 8: Cross correlation check (P – values) between lagged rainfall and wood anatomical characteristics	38
Table 3. 9 White noise autocorrelation check for solar radiation series	40
Table 3. 10: Unconditional least square estimation for the solar radiation series.....	41
Table 3. 11: Cross correlation check (P – values) between lagged solar radiation and wood anatomical characteristics.....	42
Table 3. 12: White noise autocorrelation check for relative humidity series.....	44
Table 3. 13: Unconditional least square estimation for the relative humidity series	45
Table 3. 14: Cross correlation check between lagged relative humidity and wood anatomical characteristics	46
Table 3. 15: white noise autocorrelation check for wind speed series.....	48
Table 3. 16: Unconditional least square estimation for the wind speed series	49
Table 3. 17: Cross correlation check between lagged wind speed and wood anatomical characteristics	50

Table 4. 1: Categories/levels of the climatic variables	64
Table 4. 2 percentage for the levels of climatic conditions by season and phase	65
Table 4. 3: Type 3 tests for FW fixed effects: Phase I	73
Table 4. 4: FW random effects variance test	75
Table 4. 5: Parameter estimates for FW Model: Phase I	78
Table 4. 6: Summary results for the wood anatomy properties for GC	81
Table 4. 7: Summary results for the wood anatomy properties for GU	81
Table 5. 1: Classification of trees by suppression and dominance	83
Table 5. 2: Type 3 tests for VD fixed effects: Phase I	89
Table 5. 3: VD random effects variance test.....	90
Table 5. 4: Type 3 tests for FD for fixed effects: Phase I	95
Table 5. 5: FD random effects variance test	97
Table 5. 6: Type 3 tests for VF for fixed effects: Phase I	99
Table 5. 7: VF random effects variance test	101
Table 5. 8: Parameter estimates for FD Model: Phase I	103
Table 5. 9: FD random effects variance test using continuous climatic variables	105
Table 5. 10: Parameter estimates for VD Model: Phase I	107
Table 5. 11: VD random effects variance test using continuous climatic variable.....	109
Table 5. 12: Parameter estimates for VF Model: Phase I	111
Table 5. 13: VF random effects variance test using continuous climatic variables.....	112
Table 5. 14: Summary results for the wood anatomy properties for GC	113
Table 5. 15: Summary results for the wood anatomy properties for GU	114
Table A. 1: Phase II correlation matrices of the wood anatomical characteristics of the GC and GU clones.....	125
Table A. 2: Phase II eigenvalues of the correlation matrices of the wood anatomical characteristics of the GC and GU clones.....	126
Table A. 3: Phase II eigenvectors (PC Coefficients) for the correlation matrices of the wood anatomical characteristics of the GC and GU clones	127
Table A. 4: Phase III correlation matrices of the wood anatomical characteristics of the GC and GU clones.....	128

Table A. 5: Phase III eigenvalues of the correlation matrices of the wood anatomical characteristics of the GC and GU clones	129
Table A. 6: Phase III eigenvectors (PC Coefficients) for the correlation matrices of the wood anatomical characteristics of the GC and GU clones	130
Table A. 7: Phase IV Phase I correlation matrices of the wood anatomical characteristics of the GC and GU clones	131
Table A. 8: Phase IV eigenvalues of the correlation matrices of the wood anatomical characteristics of the GC and GU clones	132
Table A. 9: Phase IV eigenvectors (PC Coefficients) for the correlation matrices of the wood anatomical characteristics of the GC and GU clones	133
Table A. 10: Type 3 Tests for FW for fixed effects: Phase II.....	134
Table A. 11: Type 3 Tests for FW for fixed effects: Phase III	135
Table A. 12: Type 3 Tests for FW for fixed effects: Phase IV	135
Table A. 13: Type 3 Tests for FD for fixed effects: Phase II	136
Table A. 14: Type 3 Tests for FD for fixed effects: Phase III	136
Table A. 15: Type 3 Tests for FD for fixed effects: Phase IV	137
Table A. 16: Type 3 Tests for VD for fixed effects: Phase II.....	137
Table A. 17: Type 3 Tests for VD for fixed effects: Phase III	137
Table A. 18: Type 3 Tests for VD for fixed effects: Phase IV	138
Table A. 19: Type 3 Tests for VF for fixed effects: Phase II	138
Table A. 20: Type 3 Tests for VF for fixed effects: Phase III	138
Table A. 21: Type 3 Tests for VF for fixed effects: Phase IV	139
Table A. 22: Parameter estimates for FW Model: Phase II	139
Table A. 23: Parameter estimates for FW Model: Phase III.....	140
Table A. 24: Parameter estimates for FD Model: Phase II.....	140
Table A. 25: Parameter estimates for FD Model: Phase III.....	141
Table A. 26: Parameter estimates for VD Model: Phase II	141
Table A. 27: Parameter estimates for VD Model: Phase III.....	142
Table A. 28: Parameter estimates for VF Model: Phase II	142
Table A. 29: Parameter estimates for VF Model: Phase III.....	143

LIST OF FIGURES

Figure 1. 1: Layout of the research trial.....	3
Figure 1. 2: Fibre (A) and vessel (B) of Eucalyptus tree for cross section of wood.....	4
Figure 2. 1: Fibre diameter (FD) versus age of the tree for the 4 trees for Phase I	14
Figure 2. 2: Fibre Wall (FW) versus age of the tree for the 4 trees for Phase I.....	14
Figure 2. 3: Vessel Dimension (VD) versus age of the tree for 4 trees for Phase I.....	15
Figure 2. 4: Vessel Frequency (VF) versus age of the tree for 4 trees for Phase I.....	15
Figure 2. 5: Fibre Dimension versus daily average temperature for Phase I.....	17
Figure 2. 6: Vessel Dimension versus daily average temperature for Phase I.....	18
Figure 3. 1: Autocorrelations and partial autocorrelation of the once differenced temperature series.....	31
Figure 3. 2: Autocorrelations and partial autocorrelations of the rainfall series.....	36
Figure 3. 3: Autocorrelations and partial autocorrelations of the solar radiation series	40
Figure 3. 4: Autocorrelations and partial autocorrelation of the relative humidity series	44
Figure 3. 5: Autocorrelations and partial autocorrelation of the wind speed series Phase I	48
Figure 4. 1: Plots of studentized Residuals for FW for GC and GU Phase I.....	67
Figure 4. 2: Joint effect of season and age GC Phase I.....	68
Figure 4. 3: Joint effect of season and age GU Phase I	68
Figure 4. 4: The mean FW of GC vs. Season by rainfall for Phase I.....	69
Figure 4. 5: The mean FW vs. season and solar radiation for Phase I.....	69
Figure 4. 6: The mean FW of GC vs. season and wind speed for Phase I.....	70
Figure 4. 7: The mean FW of GC vs. season and temperature at lag 13 for Phase I	70
Figure 4. 8: The mean FW of GU vs. season and solar radiation at lag 28 and rainfall for Phase I....	71
Figure 4. 9: The mean FW of GC vs. temperature and rainfall for Phase I.....	72
Figure 4. 10: The mean FW of GC vs. solar radiation and wind speed for Phase I.....	72
Figure 4. 11: Observed vs. fitted values for FW Phase I – GC.....	77
Figure 5. 1: Plots of studentized Residuals for VD, FD and VF for Phase I	85
Figure 5. 2: Joint effect of season and age GC Phase I for VD	86
Figure 5. 3: Joint effect of season and age GU Phase I for VD	86
Figure 5. 4: The mean VD of GU vs. season and relative humidity for Phase I.....	87
Figure 5. 5: The mean FV of GU vs. season and rainfall for Phase I	87

Figure 5. 6: The mean VD of GU vs. season and relative humidity for Phase I.....	88
Figure 5. 7: The mean VD of GU vs. season and temperature at lag 19 for Phase I	88
Figure 5. 8: Joint effect of season and age GC Phase I.....	91
Figure 5. 9: Joint effect of season and age GU Phase I	92
Figure 5. 10: The mean FD of GC vs. season and rainfall for Phase I	92
Figure 5. 11: The mean FD of GC vs. season and relative humidity for Phase I.....	93
Figure 5. 12: The mean FD vs. season and solar radiation for Phase I.....	93
Figure 5. 13: The mean FD of GC vs. season and solar radiation for Phase I.....	94
Figure 5. 14: The mean FD of GC vs. temperature and solar radiation for Phase I.....	94
Figure 5. 15: Joint effect of season and age GC Phase I for VF	98
Figure 5. 16: Joint effect of season and age GU Phase I for VF.....	98
Figure 5. 17: The mean VF vs. season and temperature for Phase I.....	99
Figure 5. 18: Observed vs. fitted values for FD Phase I	102
Figure 5. 19: Observed vs. fitted values for VD Phase I – GC.....	106
Figure 5. 20: Observed vs. fitted values for VF Phase I – GC.....	110
Figure B. 1: Phase II Fibre Dimension (FD) versus age of the tree for GC and GU	144
Figure B. 2: Phase II Fibre Wall (FW) versus age of the tree for GC and GU.....	144
Figure B. 3: Phase II Vessel Dimension (VD) versus age of the tree for GC and GU	144
Figure B. 4: Phase II Vessel Frequency (VF) versus age of the tree for GC and GU	144
Figure B. 5: Phase III Fibre Dimension (FD) versus age of the tree for GC and GU.....	145
Figure B. 6: Phase III Fibre Wall (FW) versus age of the tree for GC and GU.....	145
Figure B. 7: Phase III Vessel Dimension (VD) versus age of the tree for GC and GU.....	145
Figure B. 8: Phase III Vessel Frequency (VF) versus age of the tree for GC and GU	145
Figure B. 9: phase IV Fibre Dimension (FD) versus age of the tree for GC and GU.....	146
Figure B. 10: Phase IV Fibre Wall versus age of the tree for GC and GU.....	146
Figure B. 11: Phase IV Vessel Dimension versus age of the tree for GC and GU	146
Figure B. 12: Phase IV Vessel Frequency (VF) versus age of the tree for GC and GU	146
Figure B. 13: Fibre wall versus daily average temperature for GC and GU phase I	147
Figure B. 14: Fibre Dimension versus cumulative daily rainfall for GC and GU phase I.....	147
Figure B. 15: Fibre Wall versus cumulative daily rainfall for GC and GU phase I.....	147
Figure B. 16: Fibre Dimension versus daily average solar radiation for GC and GU phase I.....	147
Figure B. 17: Fibre Wall versus daily average solar radiation for GC and GU phase I	148

Figure B. 18: Fibre Dimension versus daily average relative humidity for GC and GU phase I.....	148
Figure B. 19: Fibre Wall versus daily average relative humidity for GC and GU phase I.....	148
Figure B. 20: Fibre Dimension versus daily average wind speed for GC and GU phase I.....	148
Figure B. 21: Fibre Wall versus daily average wind speed for GC and GU phase I.....	149
Figure B. 22: Vessel Dimension versus daily average temperature for GC and GU phase I.....	149
Figure B. 23: Vessel Frequency versus daily average temperature for GC and GU phase I.....	149
Figure B. 24: Vessel Dimension versus cumulative daily rainfall for GC and GU phase I.....	149
Figure B. 25: Vessel Frequency versus cumulative daily rainfall for GC and GU phase I.....	150
Figure B. 26: vessel Dimension versus daily average solar radiation for GC and GU phase I.....	150
Figure B. 27: Vessel Frequency versus daily average solar radiation for GC and GU phase I.....	150
Figure B. 28: Vessel Dimension versus daily average relative humidity for GC and GU phase I....	150
Figure B. 29: Vessel Frequency versus daily average relative humidity for GC and GU phase I....	151
Figure B. 30: Vessel Dimension versus average wind speed for GC and GU phase I.....	151
Figure B. 31: Vessel Frequency versus average wind speed for GC and GU phase I.....	151
Figure B. 32: Plots of studentized Residuals for FW.....	152
Figure B. 33: Plots of studentized Residuals for FD.....	152
Figure B. 34: Plots of studentized Residuals for VD.....	153
Figure B. 35: Plots of studentized Residuals for VF.....	153
Figure B. 36: Joint effect of season and age GC Phase II.....	154
Figure B. 37: Joint effect of season and age GU Phase II.....	154
Figure B. 38: The mean FW vs. season and relative humidity for phase II.....	154
Figure B. 39: The mean FW vs. season and solar radiation for phase II.....	154
Figure B. 40: The mean FW vs. season and temperature at lag 5 for phase II.....	155
Figure B. 41: The mean FW vs. season and solar radiation at lag 31 for phase II.....	155
Figure B. 42: Joint effect of season and age GC Phase III.....	155
Figure B. 43: Joint effect of season and age GU Phase III.....	155
Figure B. 44: The mean FW of GC vs. season and solar radiation for phase II.....	156
Figure B. 45: The mean FW vs. season and solar radiation at lag 7 for phase III.....	156
Figure B. 46: Joint effect of season and age GC Phase II.....	156
Figure B. 47: Joint effect of season and age GU Phase II.....	156
Figure B. 48: The mean FD of GU vs. season and rainfall for phase II.....	157
Figure B. 49: The mean FD vs. season and solar radiation for phase II.....	157

Figure B. 50: The mean FD of GU vs. season and wind speed for phase II.....	157
Figure B. 51: The mean FD vs. season and relative humidity at lag 23 for phase II.....	157
Figure B. 52: Joint effect of season and age GC Phase III	158
Figure B. 53: Joint effect of season and age GU Phase III.....	158
Figure B. 54: The mean FD vs. season and temperature for phase III.....	158
Figure B. 55: The mean FD of GU vs. season and solar radiation at lag 16 for phase III.....	159
Figure B. 56: Joint effect of season and age GC Phase II for VD	159
Figure B. 57: Joint effect of season and age GU Phase II for VD	159
Figure B. 58: The mean VD of GU vs. season and solar radiation for phase II	159
Figure B. 59: Joint effect of season and age GC Phase III for VD.....	160
Figure B. 60: The mean VD of GU vs. season and wind speed for phase III.....	160
Figure B. 61: The mean VD vs. season and temperature at lag 31 for phase III	160
Figure B. 62: The mean VF of GU vs. season and temperature for phase II.....	160
Figure B. 63: The mean VF vs. season and rainfall for phase II	161
Figure B. 64: The mean VF vs. season and temperature for phase III.....	161
Figure B. 65: The mean VF of GU vs. season and solar radiation for phase III.....	161
Figure B. 66: Observed vs. fitted values for FW Phase II	162
Figure B. 67: Observed vs. fitted values for FW Phase III.....	162
Figure B. 68: Observed vs. fitted values for FD Phase II	162
Figure B. 69: Observed vs. fitted values for FD Phase III.....	163
Figure B. 70: Observed vs. fitted values for VD Phase II	163
Figure B. 71: Observed vs. fitted values for VD Phase III.....	163
Figure B. 72: Observed vs. fitted values for VF Phase II	164
Figure B. 73: Observed vs. fitted values for VF Phase III.....	164

1. Introduction

Numerous *Eucalyptus* tree species have been introduced into South Africa 85 years ago, mainly for timber and firewood, pulpwood and also for ornamental purposes (Wikipedia 2009). The great advantage of the *Eucalyptus* trees are that they are fast growing, require little attention and when harvested regrow from the stumps to be harvested every ten years (Pankhurst and Richard 1968).

Eucalyptus pulp is a raw material for the manufacture of bulky and/or opaque papers. Therefore, the *Eucalyptus* wood is a composition of fibre and vessel elements. Fibre and vessel characteristics in wood are important features since they strongly affect the quality and performance of the final product. These two elements have different functions. The fibres have the function of the support and vessels have the function of conduction of water and nutrients. Therefore, the elements that are important to pulping are: the number of fibre per gram of pulp, individual fibre strength, fibre collapsibility, fibre bonding ability, fibre swelling and hydration, and fibre deformation (Cowan *et al.* 2002).

The paper sector has fundamental issues for paper production which are high productivity, the high operational efficiency, the low production costs and the uniform quality in the process and products. For achieving these targets, the raw material must be as uniform as possible, with characteristics in a narrow range of variation in order not to cause strong impacts in the papermaking process and paper quality. The quality of the wood can be affected by the environment factors like temperature, rainfall, solar radiation, wind speed and relative humidity, and soil quality among others (BFIN 2009). Therefore, it is important to have suitable climatic conditions for tree growth, then trees will be planted under such conditions.

In South Africa, Sappi is one of the leading suppliers of coated fine paper and chemical cellulose. The company has 550,000 hectares of *Eucalyptus* plantations in South Africa. From the total land owned by Sappi, 66% of the land is planted with *Eucalyptus* tree, and produces about 37 million tones of timber per annum. In addition to producing a wide range of coated and uncoated paper, Sappi produces tissues wadding and fibre board with an annual capacity of approximately 350,000 tons. To control and understand pulp

quality, Sappi started a trial to investigate the relationship between wood anatomic property and climatic factors (Sappi 2009).

A study to see the relationship between climatic conditions and tree growth was conducted in Australia by Downes, Beadle and Worledge (1999). To investigate the relationship between radial stem growth and climatic variations over a 12 – month period, they used multiple linear regression methods. Similar study was conducted by Chauke (2008) in South Africa at the University of KwaZulu - Natal. He used different statistical models to investigate the linear relationship between radial stem growth and climatic factors. But, there was no similar study conducted to investigate the relationship between wood anatomy properties of eucalypt clones and climatic factors in South Africa.

The data have been collected from an experiment put in place by Sappi. In July 2001, the eucalypt fibre research trial 092 (EFR092T referred to as the “dendrometer trial”) was established in costal Zululand in mid-2001. The experiment site of the dendrometer trial is located at Kwambonambi (Kwazulu Natal). Fundamental to the research was the aim of linking short term variations in environmental and tree physiological conditions with differences in fibre processes (Drew 2005).

For the experiment, two important Sappi hybrids (*Eucalyptus grandis* × *urophylla* (GU) and *Eucalyptus grandis* × *camuldulensis* (GC)) were established. The Sappi experiment has been designed to run over at least 8 years, in separate phases. In order to measure wood anatomical properties, the trees had to be felled after a certain period of time. Then, the measurement equipment was transferred to a new set of tree. In consequence, the data have been divided into phases. The starting and ending period for the four phases is presented in Table 1.1.

Table 1. 1: Starting and ending period for the four Phases

Phase	Starting Date	Ending Date
Phase I	April 2002	August 2003
Phase II	September 2003	August 2004
Phase III	September 2004	December 2005
Phase IV	December 2005	January 2007

The two clones were planted in alternating rows of seven trees wide each (Figure 1.1), with spacing between trees of 3 meter (east to west) × 2.5 meter (north to south). These

rows have been numbered from 1 to 6. Each row of clones consists of three plots of 12 trees, each with surrounding of trees (Figure 1.1). the plots are numbered from 1 to 12, beginning with plot 1 in the north east corner of the trial and ending with plot 18 in the south west corner. The study trees are numbered within each individual plot from 1 to 12. The total number of trees planted for the experiment are 216.

For each phase, a sample of 9 trees per clone from the research trial (Figure 1.1) was selected. Each plot consists 12 trees. Moreover, these selected trees were used to investigate the physiological and morphological variables throughout the life of the stand.

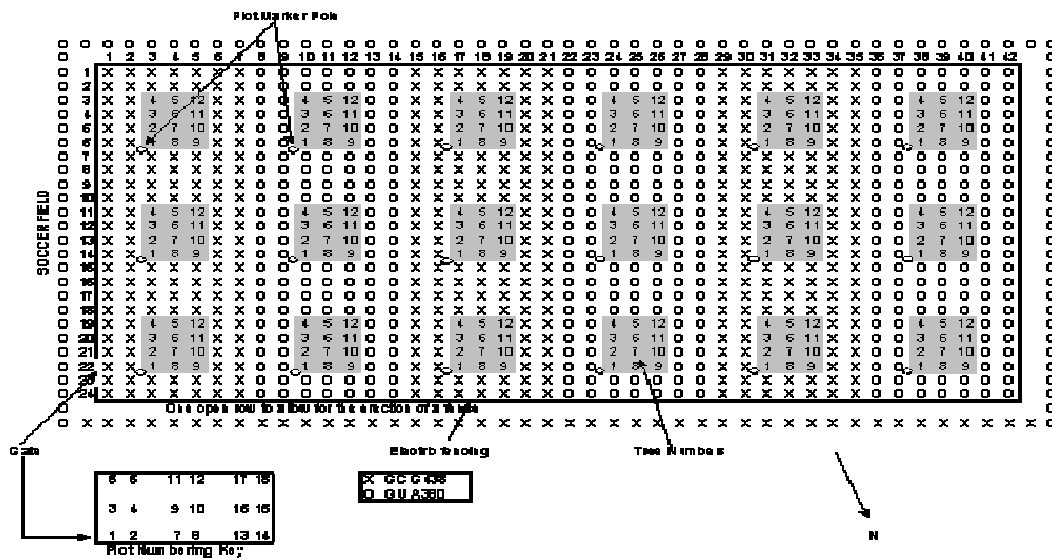


Figure 1. 1 Layout of the research trial

From the total of 18 plots, plot 9 and 10, 7 and 8, 11 and 12, and 5 and 6 were selected for monitoring during project Phase I, II, III and IV respectively (Drew 2004). For this trial, three sets of data have been collected: climatic parameters, tree growth, and wood anatomical properties. The climatic parameters were recorded using an automatic weather station installed approximately at 200m from the trial. This station recorded the following components: a temperature sensor (temperature in °C), an electronic relative humidity sensor (relative humidity in %), a radiation sensor (solar radiation in mjoules/hr), a tipping bucket rain gauge (rainfall in mm) and a wind speed sensor (wind speed in m/sec) (Drew 2004). The tree growth was recorded using an instrument called dendrometer. This instrument recorded the change in radius every 15 minutes. Wood anatomical properties were measured after cutting the tree. Disc of wood were cut and positioned under a

microscope. With the help of image analysis, the dimensions of wood cells (six fibre properties and five vessels properties) were measured. The growth data were used to identify the time of formation of the cell. These wood anatomical characteristics are:

- Fibre Characteristics:
 - Fibre Tangential Diameter (FTD), Fibre Radial Diameter (FRD), Fibre lumen Diameter (FLD), Fibre Area (FA), Fibre Wall Thickness (FWT) and Fibre Wall Area (FWA).
- Vessel Characteristics:
 - Vessel Tangential Diameter (VTD), Vessel Radial Diameter (VRD), Vessel Area (VA), Vessel Frequency (VF) and Vessel percentage (VP).

Figure 1.2 shows the cross section of wood. The one indicated with **A** represents the Fibres and **B** for vessels. The measurement for wood characteristics was done from these fibres and vessels.

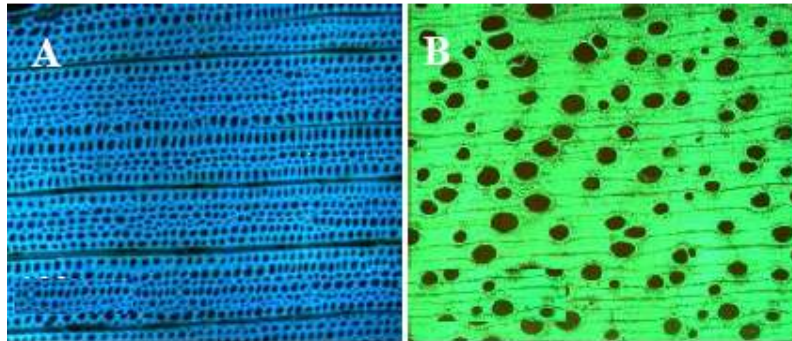


Figure 1. 2: Fibre (A) and vessel (B) of Eucalyptus tree for cross section of wood.

The unit of measurements for wood anatomical properties are for Fibre diameter, lumen diameter and wall thickness data is μm , fibre area and wall area data is μm^2 , vessel diameter is μm , vessel area is μm^2 , vessel frequency is in number of vessels (mm^{-2}), and vessel percentage is %.

The main objective of this thesis was to investigate the effect of climatic variables on wood anatomical characteristics (fibre and vessel) of *Eucalyptus* clones. To achieve this objective, the following steps were used

- In order to decrease the number of variables and make the interpretation of the data easier, principal component analysis was used
- Graphical assessment of the data was used to identify other factors than climatic variables that could explain the variability of wood anatomical characteristics (i.e age of the tree, tree effect)
- Graphical assessment was used to identify the type of relationship (linear, quadratic, etc) between anatomical characteristics and climatic variables
- To find the linear relationship between wood properties and climatic variables (to assess lag effects), ARIMA Modelling of the wood anatomical characteristics was used
- Longitudinal linear mixed model was used using categorical and continuous climatic variables to see the effects of climatic variables for wood properties

The thesis is organized as follows. This chapter gave some background about *Eucalyptus* trees, importance of *Eucalyptus* trees, about Sappi experiment and objective of the study. Chapter 2 contains the preliminary analysis of the data. The principal component analysis was applied to the fibre and vessel characteristics of the *Eucalyptus* tree and discussed. In Chapter 3, the time series analysis applied to the anatomical characteristics of the tree. The theory behind the time series analysis has been discussed and the results follows. In Chapter 4 the literature review related to linear mixed model has been discussed. Moreover, application of linear mixed model for categorical climatic variables and continuous climatic variables has been discussed in Chapter 4 and Chapter 5. The 6th chapter contains the summary and conclusion of this study.

2. Preliminary Data Analysis

As mentioned in the previous chapter, the data was collected separately in four phases for both GC and GU clones. During each phase there were nine different trees for each clones. Different trees were measured for each phase. In addition to this, because there were no continuous measurements, for this study the analysis was done for each phase separately. Therefore, before involving complex data analysis, it is of great importance to examine and get a general understanding of the data under consideration. It is this initial examination of the data that helps in determining the possible statistical techniques that could be applied to the data.

Our objectives in this chapter was 1) to perform data reduction using principal component analysis (PCA). 2) to investigate the relationship between tree and age of the trees for each phase and clone. This is because if there is any relationship between trees, this effect should be included in the analysis. And 3) to assess the type of relationship between tree and the five climatic variables for wood anatomical characteristics of *Eucalyptus* clones.

2.1 Data Reduction Using Principal Component Analysis

The appropriate procedures for investigating the effects of the climatic factors on the 11 wood anatomical properties were multivariate procedures such as multivariate analysis of variance or multivariate regression analysis rather than univariate procedures such as individual analysis of variance or regression analysis of the characteristics. This is because the 11 wood anatomical characteristics may be highly correlated as a result of being measured on the same trees. Moreover, there was correlation between wood anatomical characteristics. For example, fibre radial diameter, fibre tangential diameter and fibre lumen diameter were correlated. Alternatively, univariate procedures may be used to investigate the effects of the climatic factors on fewer than 11 linear combinations of the 11 wood anatomical characteristics. This could be achieved using principal component analysis techniques. The theory of principal component analysis is discussed in Section 2.1.1.

2.1.1 Theory of principal component analysis

Consider p continuous response X_1, X_2, \dots, X_p with covariance matrix Σ and correlation matrix \mathbf{R} . If the p variables are highly correlated, a principal component analysis of the data on the p variables can reduce the data to data on q ($< p$) variables of the form:

$$Y_i = a_{i1}X_1 + a_{i2}X_2 + \dots + a_{ip}X_p, i=1,2,\dots,p \quad (2.1)$$

where $\mathbf{a}_i = (a_{i1}, a_{i2}, \dots, a_{ip})^T$ is the i^{th} eigenvector associated with the i^{th} eigenvalue λ_i in the ordered set of the p eigenvalues of the covariance matrix Σ or correlation matrix \mathbf{R} . For $i=1,2,\dots,p$, Y_i is called the i^{th} principal component (PC) (Johnson and Wichern 2002).

Correlation matrix corresponds to finding variance – maximizing linear combination of standardized variables. Standardization means, each variable has been linearly transformed to have unit variance. The use of standardized variables is helpful to reduce variability in the dataset (Montgomery *et al.* 2006). The standardized variables can be obtained by subtracting the mean from the observed variable values and dividing the difference by the standard deviation of the observed variable values. For example, the values of a variable X are standardized as follows:

$$X_i^* = (X_i - \text{mean}(X_i))/s, i = 1, 2, \dots, n \quad (2.2)$$

where X_i^* is the i^{th} standardized value, $\bar{X} = \frac{1}{n} \sum_i^n X_i$ and $S = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (X_i - \bar{X})^2}$.

Therefore, the i^{th} PC becomes:

$$Y_i^* = a_{i1}X_1^* + a_{i2}X_2^* + \dots + a_{ip}X_p^*, i=1,2,\dots,p \quad (2.3)$$

The principal components (PCs) have the attractive property that there are uncorrelated and hence can be individually analysed using univariate statistical methods. Furthermore, PCs have easy interpretations since each PC is either a weighted average of a subset of the original p response variables or a contrast between two subsets of the original p response variables (Stevens 1986). One of the problems encountered in principal component analysis is the determination of the number $q < p$ of important or significant PCs out of the p possible number of PCs. If $\lambda_1 \geq \lambda_2 \geq \dots \geq \lambda_p \geq 0$ are ordered

set of the p eigenvalues of the covariance matrix Σ or correlation matrix \mathbf{R} , then for $i=1,2,\dots,p$, the variance of the i^{th} PC is λ_i . Furthermore, the sum of p eigenvalues or variances of the PCs is equal to Trace (Σ) or Trace(\mathbf{R}). Hence, the following are some of the criteria that have been proposed for determining important significant PCs (Johnson and Wichern 2002).

Criterion I. The i^{th} PC is important if $100\lambda_i/(\lambda_1 + \lambda_2 + \dots + \lambda_p)\%$ - the proportion of the total variance or correlation of the original p variables that is explained by the i^{th} PC – is large. As a rule of thumb, “large” may be taken to be at least 10%.

Criterion II. A scree plot (Cattell 1966) is a plot of the ordered set of eigenvalues versus the corresponding PC numbers. The plot can show a “break” between the PCs with relatively large eigenvalues and those with small eigenvalues. The PCs with relatively large eigenvalues are regarded as important or significant.

Once the important or significant PCs have been chosen or identified, the next problem is to identify the dominant of the p original variables within each important PC as well as to interpret the important PCs.

Rotation methods

Rotation serves to make the output more understandable and is usually necessary to facilitate the interpretation of factors. The sum of eigenvalues is not affected by rotation, but rotation will alter the eigenvalues of particular factors and will change the factor loadings. Since alternative rotations may have the same total eigenvalue but have different factor loadings, and since factor loadings are used to intuit the meaning of factors, this means that different meanings may be ascribed to the factors depending on the rotation. All factor loadings obtained from the initial loadings by an orthogonal transformation have the same ability to reproduce the covariance matrix. An orthogonal transformation of the factor loading is called factor rotation (Stevens 1986). Among the different rotation methods varimax rotation is one of them.

Varimax rotation is an orthogonal rotation of the factor axes to maximize the variance of the squared loadings of a factor (column) on all the variables (rows) in a factor matrix, which has the effect of differentiating the original variables by extracted factor. Each factor will tend to have either large or small loadings of any particular variable. A

varimax solution yields results which make it as easy as possible to identify each variable with a single factor. This is the most common rotation option (Stevens 1986).

2.1.2 Application of principal component analysis for wood anatomy

The principal component analysis (PCA) of the data on Fibre Tangential Diameter (FTD), Fibre Radial Diameter (FRD), Fibre Lumen Diameter (FLD), Fibre Wall Area (FWA), Fibre Wall Thickness (FWT), Fibre Area (FA), Vessel Tangential Diameter (VTD), Vessel Radial Diameter (VRD), Vessel Frequency (VF), Vessel percentage (VP) and Vessel Area (VA) was performed for each of the two eucalypt clones, and for the four phases of growth separately. This is because the trees were different for each phase and cut every year and no continuous data. All the principal component analysis were based on the correlation matrix **R** of the 11 fibre and vessel characteristics in order to ensure that the 11 variables contribute equally to the PCs. The important or significant PCs were determined using correlation matrix and varimax rotation.

We first present the analysis of Phase I wood anatomical characteristics. Table 2.1 displays the phase I correlation matrix, **R**, of the 11 fibre and vessel characteristics of eucalypt trees for both the GU and the GC clone. The results showed that some of the correlations between anatomical characteristics were as high as 0.92 in absolute value. This justified the use of principal component analysis for reducing the dimension of the data on the original 11 fibre and vessel characteristics.

Table 2.2 displays the eigenvalues of the 11 PCs, and the proportion of the variance explained by each PC. For both clones, the first four PCs account for 95 % of the total variance. The first three PCs accounts for 85% of the total variation. But, we chose the first four PCs because the VF and VP are mostly dominated in the fourth PC. Accordingly, the first four PCs are chosen as important PCs. Moreover, these four PCs eigenvalue is greater than 1.

Table 2.3 displays coefficients/weights of the 11 standardized fibre and vessel characteristics of eucalypt clones in the PCs. A study of the absolute values and the signs of the coefficients/weights in Table 2.3 show that for both clones the PCs are explained as follow:

- PC1: (VTD, VRD, VA), labelled as vessel dimension (VD).
- PC2: (FTD, FRD, FLD, FA), labelled as fibre dimension (FD)
- PC3: (FWA, FWT), labelled as fibre wall (FW)
- PC4: (VF, VP), labelled as vessel frequency (VF)

That the signs of the coefficients/weights of the dominant fibre and vessel characteristics in each of the 4 PCs are the same implies each PC can be regarded as weighted average of its dominant wood anatomical characteristic.

Table 2. 1: Correlation matrices of the fibre and vessel characteristics of the GC and GU clones for Phase I

Correlations between fibre and vessel characteristics											
GC											
	FTD	FRD	FLD	FWA	FWT	FA	VTD	VRD	VF	VP	VA
FTD	1	0.71	0.81	0.40	0.02	0.86	0.10	0.10	-0.09	-0.11	0.16
FRD	0.71	1	0.73	0.13	-0.29	0.92	0.16	0.25	-0.07	-0.07	0.26
FLD	0.81	0.73	1	-0.44	-0.80	0.75	0.18	0.21	-0.09	-0.08	0.26
FWA	0.40	0.13	-0.44	1	0.88	0.23	-0.01	0.02	-0.02	-0.02	0.00
FWT	0.02	-0.29	-0.80	0.88	1	-0.22	-0.11	-0.11	0.04	0.03	-0.15
FA	0.86	0.92	0.75	0.23	-0.22	1	0.16	0.22	-0.09	-0.10	0.25
VTD	0.10	0.16	0.18	-0.01	-0.11	0.16	1	0.92	0.07	0.41	0.94
VRD	0.10	0.25	0.21	0.02	-0.11	0.22	0.92	1	0.00	0.35	0.96
VF	-0.09	-0.07	-0.09	-0.02	0.04	-0.09	0.07	0.00	1	0.92	-0.03
VP	-0.11	-0.07	-0.08	-0.02	0.03	-0.10	0.41	0.35	0.92	1	0.32
VA	0.16	0.26	0.26	0.00	-0.15	0.25	0.94	0.96	-0.03	0.32	1
GU											
FTD	1	0.81	0.71	0.40	0.12	0.96	0.20	0.20	0.01	-0.01	0.26
FRD	0.81	1	0.73	0.13	-0.19	0.96	0.26	0.35	0.03	0.03	0.36
FLD	0.71	0.83	1	-0.44	-0.70	0.85	0.28	0.31	0.01	0.02	0.36
FWA	0.50	0.23	-0.34	1	0.98	0.33	0.09	0.12	0.08	0.08	0.10
FWT	0.12	-0.19	-0.70	0.98	1	-0.12	-0.01	-0.01	0.14	0.13	-0.05
FA	0.96	0.92	0.85	0.33	-0.12	1	0.26	0.32	0.01	0.00	0.35
VTD	0.20	0.26	0.28	0.09	-0.01	0.26	1	0.92	0.17	0.51	0.94
VRD	0.20	0.35	0.31	0.12	-0.01	0.32	0.92	1	0.10	0.45	0.96
VF	0.01	0.03	0.01	0.08	0.14	0.01	0.17	0.10	1	0.92	0.07
VP	-0.01	0.03	0.02	0.08	0.13	0.00	0.51	0.45	0.92	1	0.32
VA	0.26	0.36	0.36	0.10	-0.05	0.35	0.94	0.96	0.07	0.42	1

FTD=Fibre Tangential Diameter, FRD=Fibre Radial Diameter, FLD=Fibre Lumen Diameter, FWA=Fibre Wall Area, FWT=Fibre Wall Thickness, FA=Fibre Area, VTD=Vessel Tangential Diameter, VRD=Vessel Radial Diameter, VF=Vessel Frequency, VP=Vessel Percentage (VP), and VA=Vessel Area.

Table 2. 2: Eigenvalues of the correlation matrices of the fibre and vessel characteristics of the GC and GU clones for Phase I

Eigenvalues				
	GC			
	Eigenvalue	Difference	Proportion	Cumulative
1	4.1686	1.5551	0.379	0.379
2	2.6135	0.3812	0.2376	0.6166
3	2.2323	0.8019	0.2029	0.8195
4	1.4304	1.0913	0.13	0.9495
5	0.3391	0.261	0.0308	0.9804
6	0.0781	0.0138	0.0071	0.9874
7	0.0642	0.0318	0.0058	0.9933
8	0.0324	0.0028	0.0029	0.9962
9	0.0297	0.022	0.0027	0.9989
10	0.0077	0.0036	0.0007	0.9996
11	0.0041		0.0004	1
	GU			
1	3.9131	1.1637	0.3557	0.3557
2	2.7494	0.5201	0.2499	0.6057
3	2.2293	0.6221	0.2027	0.8084
4	1.6072	1.2688	0.1461	0.9545
5	0.3384	0.2646	0.0308	0.9852
6	0.0738	0.0409	0.0067	0.9919
7	0.0329	0.003	0.003	0.9949
8	0.0298	0.0156	0.0027	0.9976
9	0.0143	0.0067	0.0013	0.9989
10	0.0076	0.0035	0.0007	0.9996
11	0.0041		0.0004	1

From Table 2.3, the first four PCs for both the GU and GC fibre and vessel characteristics of eucalypt clones were found to be the dominant PCs. Note that for the sake of brevity, only the dominant fibre and vessel characteristics appear on the right hand side of the equation of each PC, and hence the use of “≈” in the equations.

For GC:

$$VD (PC1) \approx 0.971 VTD + 0.972 VRD + 0.977 VA$$

$$FD (PC2) \approx 0.729 FTD + 0.972 FRD + 0.717 FLD + 0.961 FA$$

$$FW (PC3) \approx 0.966 FWA + 0.969 FWT$$

$$VF (PC4) \approx 0.85 VF + 0.915 VP$$

For GU:

$$VD (PC1) \approx 0.981 VTD + 0.982 VRD + 0.987 VA$$

$$FD (PC2) \approx 0.739 FTD + 0.982 FRD + 0.727 FLD + 0.971 FA$$

$$FW (PC3) \approx 0.976 FWA + 0.979 FWT$$

$$VF (PC4) \approx 0.86 VF + 0.925 VP$$

where FTD=Fibre Tangential Diameter, FRD=Fibre Radial Diameter, FLD=Fibre Lumen Diameter, FWA=Fibre Wall Area, FWT=Fibre Wall Thickness, FA=Fibre Area, VTD=Vessel Tangential Diameter, VRD=Vessel Radial Diameter, VF=Vessel Frequency, VP=Vessel Percentage (VP), and VA=Vessel Area.

Table 2. 3: Eigenvectors (PC coefficients) for the correlation matrices of the fibre and vessel characteristics of the GC and GU clones for Phase I

	GC										
	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11
FTD	0.046	0.729	0.182	-0.090	0.652	-0.005	0.005	0.007	0.002	0.002	0.001
FRD	0.130	0.972	-0.064	-0.073	-0.147	-0.009	0.002	-0.044	0.002	-0.072	0.001
FLD	0.123	0.717	-0.646	-0.088	0.142	-0.015	-0.008	0.160	0.001	0.007	0.001
FWA	0.012	0.212	0.966	-0.017	0.108	-0.005	-0.003	0.084	-0.003	0.007	0.056
FWT	-0.069	-0.222	0.969	0.040	0.012	0.007	0.001	-0.055	0.002	-0.004	-0.055
FA	0.112	0.961	-0.001	-0.092	0.223	-0.003	-0.009	0.017	-0.001	0.074	0.007
VTD	0.971	0.046	-0.041	0.065	0.045	-0.005	0.213	-0.001	-0.040	-0.001	0.001
VRD	0.972	0.120	-0.017	-0.001	-0.041	-0.032	-0.165	0.008	-0.100	0.001	0.002
VF	-0.431	-0.178	0.053	0.850	-0.059	0.231	0.007	-0.006	0.001	0.000	-0.001
VP	0.361	-0.055	0.005	0.915	-0.002	-0.170	-0.001	0.001	-0.003	-0.001	0.000
VA	0.977	0.138	-0.051	-0.029	0.037	-0.005	-0.040	0.004	0.139	0.000	0.000
GU											
FTD	0.056	0.739	0.192	-0.080	0.662	0.005	0.015	0.017	0.012	0.012	0.011
FRD	0.140	0.982	-0.054	-0.063	-0.137	0.001	0.012	-0.034	0.012	-0.062	0.011
FLD	0.133	0.727	-0.636	-0.078	0.152	-0.005	0.002	0.170	0.011	0.017	0.011
FWA	0.022	0.222	0.976	-0.007	0.118	0.005	0.007	0.094	0.007	0.017	0.066
FWT	-0.059	-0.212	0.979	0.050	0.022	0.017	0.011	-0.045	0.012	0.006	-0.045
FA	0.122	0.971	0.009	-0.082	0.233	0.007	0.001	0.027	0.009	0.084	0.017
VTD	0.981	0.056	-0.031	0.075	0.055	0.005	0.223	0.009	-0.030	0.009	0.011
VRD	0.982	0.130	-0.007	0.009	-0.031	-0.022	-0.155	0.018	-0.090	0.011	0.012
VF	-0.421	-0.168	0.063	0.860	-0.049	0.241	0.017	0.004	0.011	0.010	0.009
VP	0.371	-0.045	0.015	0.925	0.008	-0.160	0.009	0.011	0.007	0.009	0.010
VA	0.987	0.148	-0.041	-0.019	0.047	0.005	-0.030	0.014	0.149	0.010	0.010

FTD=Fibre Tangential Diameter, FRD=Fibre Radial Diameter, FLD=Fibre Lumen Diameter, FWA=Fibre Wall Area, FWT=Fibre Wall Thickness, FA=Fibre Area, VTD=Vessel Tangential Diameter, VRD=VRD, VF=Vessel Frequency, VP=Vessel Percentage (VP), and VA=Vessel Area.

Similarly, the principal component analysis of the Phase II to Phase IV data on the 11 fibre and vessel characteristics for both clones GC and GU was performed. The correlation matrices, the eigenvalues and the eigenvectors from the principal component analysis of the data for Phases II, III and IV are presented in Figures A.1 - A.9. The results show that for both clones, the first four PCs explain over 94% the total variation of the data. These four PCs are identical of the Phase I PCs. But, unlike for Phase I, the first PC is fibre dimension and the second PC is vessel dimension. This implies that at the juvenile stage, the majority of the total variation is due to vessel dimension but after that due to fibre dimension. FW and VF remains as the third and fourth PCs, respectively, throughout the first four phases.

The 11 fibre and vessel characteristics of eucalypt clones have been reduced to a meaningful and uncorrelated four principal components which are Fibre Dimension (FD), Vessel Dimension (VD), Fibre Wall (FW) and Vessel Frequency (VF). Therefore, instead of the eleven correlated fibre and vessel characteristics of eucalypt clones we use the four independent principal components with minimal loss of information about the eleven fibre and vessel characteristics.

2.2 Graphical assessment

As presented in Chapter 1, the data was collected in separate four phases for both GC and GU clones. The wood anatomical characteristics were measured on the same tree sequentially over time. For each phase, 9 trees per clone were measured. Here, each day was considered as age of the tree. This means that while the objective of this thesis was to investigate the effects of the climatic factors on the wood anatomical characteristics of two eucalypt clones, other factors such as variability between trees (tree effects), age of the tree effects and the tree by age of the tree interaction effects could also have effects on the wood anatomical characteristics. If so, these effects would need to be account in the statistical models which explains the wood anatomical characteristics as functions of the climatic factors. The graphs of the first four PCs versus the age of the tree are used to investigate the effects of the age of the tree PCs. To avoid conjunction instead of the nine trees, only the four trees were selected to plot the graph of age of the tree against the PCs.

2.2.1 Graphical assessment of the tree and age of tree effects on the wood anatomical characteristics of *Eucalyptus* clones

Graphical assessment of Phase I wood anatomical characteristics

Figures 2.1 and 2.2 display the respective graphs of FD and FW versus age of the tree for 4 GC and 4 GU clone trees and graphs of FW versus age of the tree for 4 GC and 4 GU clone trees. The two figures show that the 4 trees of the same clone have different patterns as the age of the tree increases. For GC the variation from tree to tree seems larger than the GU tree. Therefore, for FD and FW significant tree effects are expected. Furthermore, the curves in both graphs had at least one trough and one peak (i.e, increases then decreases and started to increase) which suggests the presence of seasonal effects on FD and FW. That FD and FW appears to be neither increasing nor decreasing with the age of the trees suggests absence of the linear age effects on FD and FW.

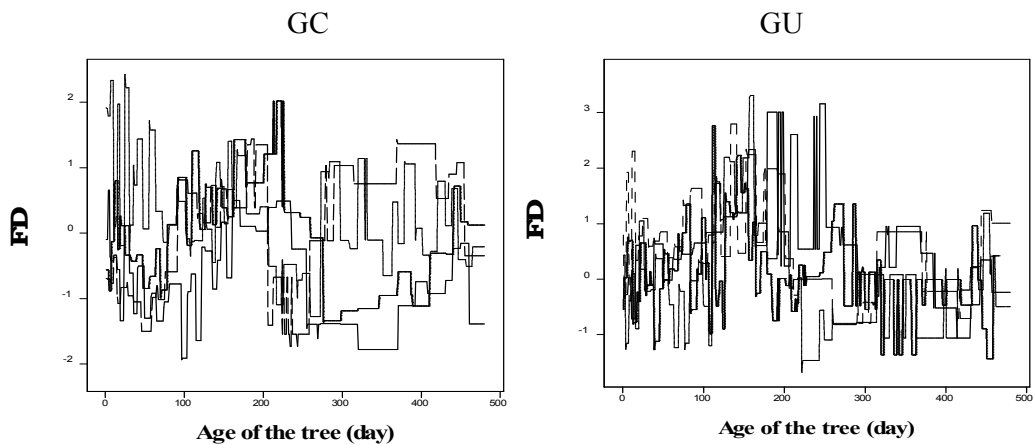


Figure 2. 1: Fibre diameter (FD) versus age of the tree for the 4 trees for Phase I

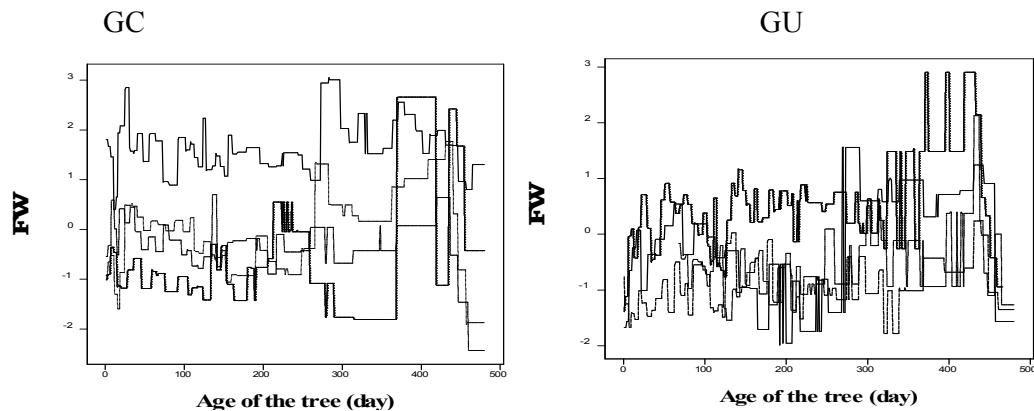


Figure 2. 2: Fibre Wall (FW) versus age of the tree for the 4 trees for Phase I

The respective graphs of VD and VF versus age of the tree for the four GC and four GU clone trees are displayed in Figures 2.3 and 2.4. Similar to FD and FW, here also four trees were used in the figure. As with FD and FW, all figures show that the 4 trees of the same clone showed different patterns as the age of the tree increases. In addition, for GC clone the variability from tree to tree seems larger than the GU clone for both VD and VF. Therefore, significant tree effects on VD and VF are expected. Similar to FD and FW, the curve for VD and VF showed pronounced troughs and peaks. This suggests seasonal effect on VD and VF. Moreover, VD and VF appears to be neither increasing nor decreasing with the age of the trees suggests no linear effects of age on VD and VF.

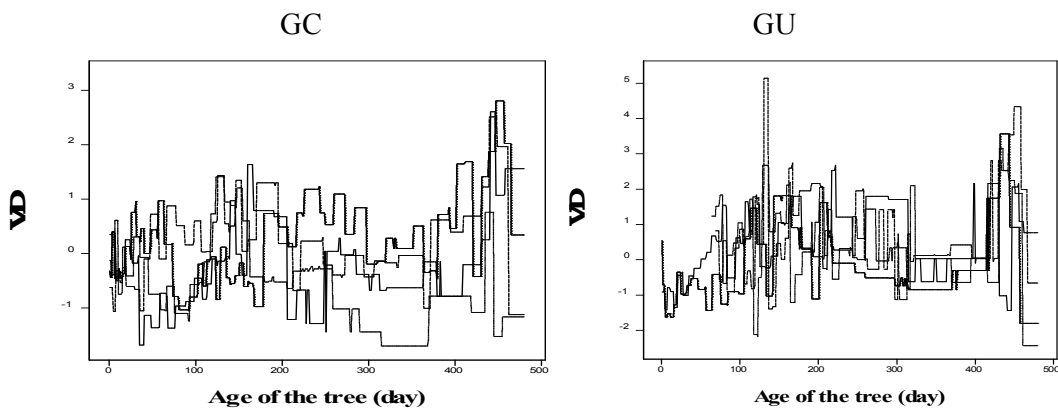


Figure 2. 3: Vessel Dimension (VD) versus age of the tree for 4 trees for Phase I

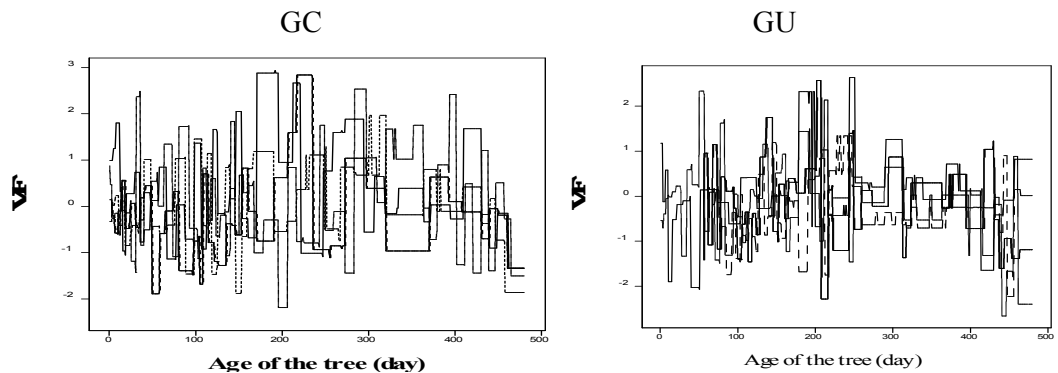


Figure 2. 4: Vessel Frequency (VF) versus age of the tree for 4 trees for Phase I

Graphical assesement of Phase II to IV wood anatomical characteristics

The graphs of FD and FW versus age of the tree for the nine GC and GU clones are displayed in Figures B.1 - B.2 for Phase II, Figure B.5 - B.6 for Phase III and Figure B.9 - B.10 for Phase IV. Similar to Phase I, FD and FW for Phase II – IV show that the 9 trees of the same clone showed different patterns for a change for age of the tree. The result

showed that there was variability between trees. Moreover, the variability from tree to tree for GC seems to be larger than GU for Phase II, III and IV. Therefore, significant tree effect on FD and FW are expected in Phase II, III and IV. Unlike for the case of Phase I, for FD, the curves do not show pronounced troughs and peaks. This suggests the absence of both seasonal effects on FD for Phase II and IV. But, FD for Phase III showed pronounced troughs and peaks and this suggested the presence of seasonal effect. Similar to Phase I, FD appears to be neither increasing nor decreasing with the age of the tree suggests absence of linear age effect on FD. On the other hand, unlike to Phase I, the curves for FW do not show pronounced troughs and peaks. This suggests the absence of seasonality for Phase II – IV for FW. And also, FW increases with age for Phase II both for GC and GU. But for Phase III and IV, FW appears to be neither increasing nor decreasing with the age of the tree suggests absence of linear age effect on FW.

The graph of VD and VF versus age of the tree for the nine GC and GU clones are displayed in Figures B.3 and B.4 for Phase II, Figure B.7 and B.8 for Phase III and Figure B.11 and B.12 for Phase IV. Similar to Phase I, for GC variation from tree to tree seems larger than that of GU. Unlike for the case of Phase I, except for Phase II, for VD, the curves do not show pronounced troughs and peak. This suggests the absence of both seasonal effects on VD for Phase III and IV. Similar to Phase I, VD appears to be neither increasing nor decreasing with the age of the tree suggests absence of linear age effect on VD. On the other hand, similar to Phase I, the curves do not show pronounced troughs and peaks. This suggests the absence of seasonality for Phase II – IV on VF. Moreover, VF appears to be neither increasing nor decreasing with the age of the tree suggests absence of linear age effect on VF.

In summary, graphical assessments show that for most of the cases the relationship between wood anatomical characteristics and age of the tree were neither increasing nor decreasing with age of the tree. This suggested the absence of linear age effect. Moreover, the graphs showed that the variability from tree to tree for all the phases. Therefore, to capture from tree to tree variability, instead of using tree average measurements, we used the information at the tree level. We also observed the seasonality for some of the wood anatomical characteristics. Therefore, the seasonality will be added for ARIMA modelling in Chapter 3.

2.2.2 Graphical assessment of the climatic variable effects on the wood anatomical characteristics *Eucalyptus* clones

The graphs of the first four PCs, for each tree versus climatic variables were used to investigate the relationship between climatic variables (temperature, rainfall, solar radiation, relative humidity and wind speed) and wood anatomical characteristics (PCs). In the graphs which follow, the relationship between wood anatomical characteristics and climatic variables will be assessed. To show the figures clearly, 4 GC and 4 GU trees have been used.

Graphical analysis of Phase I wood anatomical characteristics

Figures 2.5 and B.13 – B.21 displays the graph of climatic variables versus Fibre dimension and Fibre Wall for both clones. From the plots, it can be observed that the relationships between FD and FW versus the five climatic variables were found to be neither increasing nor decreasing. This suggests that there is no linear relationship between FW and climatic variables and FD and climatic variables. Moreover, the variability between trees for both clones seems similar.

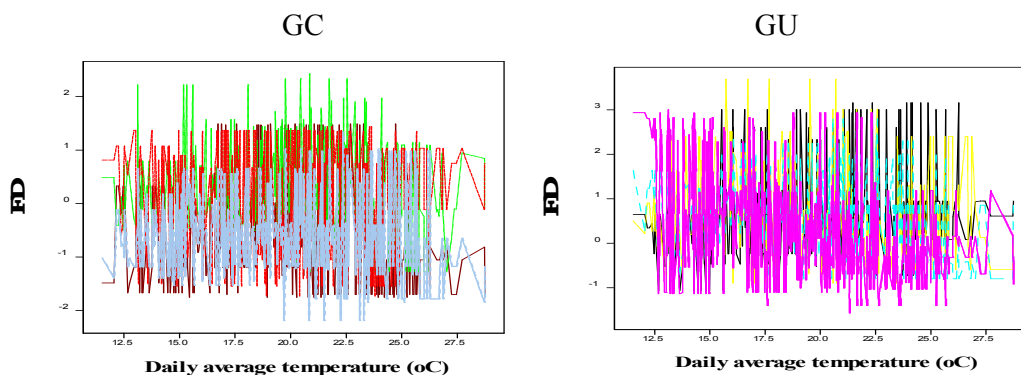


Figure 2. 5: Fibre Dimension versus daily average temperature for Phase I

The graph for the relationship between vessel characteristics (VD and VF) and climatic variables are displayed in Figure 2.6 and B.22 – B.31. From the plots, it can be observed that for most of the cases, the relationships between VD and VF versus the five climatic variables were found to be neither increasing nor decreasing. But, for the case of temperature, the relationship between VD versus daily average temperature was slightly decreasing as temperature increases. Moreover, the variability between trees for both clones seems similar.

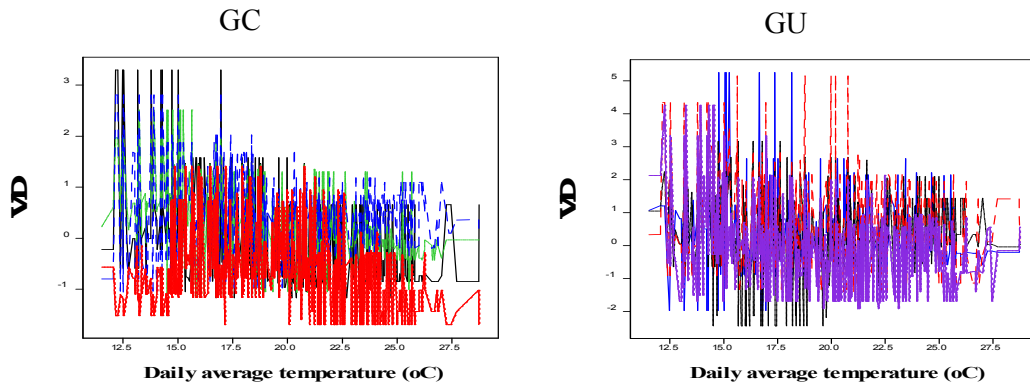


Figure 2. 6: Vessel Dimension versus daily average temperature for Phase I

The relationship between fibre and vessel characteristics and the five climatic variables (temperature, rainfall, solar radiation, relative humidity and wind speed) for Phase II, III and IV showed the same pattern as for Phase I.

In general, the graphs showed that there was noisy (up – down) relationship between anatomical properties and age of the tree. Moreover, the nine trees for each clone showed different patterns. Therefore, there was an indication of variability between trees. From the results, it can be observed that there was seasonality in the data. The seasonality will be accounted for in further analysis. On the other hand, the graph of climatic variables against anatomical characteristics of eucalyptus tree suggests that there was no definite (linear, quadratic, etc) relationship between wood anatomical characteristics and climatic variables.

3. ARIMA Modelling for wood anatomical properties

The wood anatomical characteristics were measured from the center to outside of the tree on 9 trees per clone form a new layer of wood. These measurements from the center to the outside of the tree represented measurements over time. This means measurements of each wood anatomical characteristic are classified as time series data. The same was obviously true about the climatic data. Consequently, time series data modeling approaches may help to meet the objectives of this thesis. One such modeling approach, which is the subject of this chapter, was the autoregressive integrated moving average (ARIMA) modelling approach. The relevant theory of ARIMA modeling is discussed in Section 3.1. The results of ARIMA modeling are presented in Section 3.2. We present the summary of the ARIMA modelling results in Section 3.3.

3.1 Theory of ARIMA models

3.1.1 Definitions and notation

In discussing the theory of ARIMA modelling, the following definitions and notations will be used.

1. $\{X_t\}_{t=1}^n$ or simply $\{X_t\}$ where t is time represents a time series such as average temperature recorded on day t .
2. X_{t-k} , where $k=0, \pm 1, \pm 2, \dots$ is called the lag period, is the observation/measurement of k units of time before time t if $k > 0$ or of k units of time after time t if $k < 0$. For example, temperature of k days before day t if $k > 0$ or of k days after day t if $k < 0$.
3. A backshift operator is \mathbf{B} can be defined as $\mathbf{B}X_t = X_{t-1}$. This expression can be extended to $\mathbf{B}^k X_t = X_{t-k}$ where $k=0, \pm 1, \pm 2, \dots$ is called the lag period (Shumway and Stoffer 2000).
4. The autocorrelation function (ACF), $\rho_k = \text{Correlation}(X_t, X_{t-k})$ is given by

$$\rho_k = \frac{\gamma(t+k,t)}{\sqrt{\gamma(t+k,t+k)\gamma(t,t)}}, k = 0, \pm 1, \pm 2, \dots \quad (3.1)$$

where, $\gamma(t+k,t) = \text{Covariance}(X_t, X_{t+k})$ and $\gamma(t+k,t+k) = \text{Variance}(X_{t+k})$, and

$$(\gamma(t,t) = \gamma(t+k,t+k)|_{k=0}.$$

Here, ρ_k measures the correlation between X_t and X_{t+k} and has the usual property of correlations (Gourieroux and Monfort 1990). The sample ACF can be defined as

$$\hat{\rho}_k = \frac{\hat{\gamma}(t+k,t)}{\sqrt{\hat{\gamma}(t+k,t+k)\hat{\gamma}(t,t)}}, k=0,\pm 1,\pm 2,\dots \quad (3.2)$$

where for $\bar{x} = (n-k)^{-1} \sum_{t=1}^{n-k} x_t$, $\hat{\gamma}(t+k, t+k) = (n-k)^{-1} \sum_{t=1}^{n-k} (x_{t+k} - \bar{x})^2$,
 $\hat{\gamma}(t+k, t) = (n-k)^{-1} \sum_{t=1}^{n-k} (x_{t+k} - \bar{x})(x_t - \bar{x})$, and $\hat{\gamma}(t, t) = \hat{\gamma}(t+k, t+k)|_{k=0}$.
 Note that $\gamma(t+k,t+k) \neq \gamma(t,t)$ if series is not stationary.

5. The partial autocorrelation function: The partial autocorrelation is defined as

$$\phi_{11} = \text{Correlation}(X_2, X_1) \quad (3.3)$$

and

$$\phi_{kk} = \text{Correlation}(X_k - X_k^{k-1}, X_1 - X_1^{k-1}), k \geq 2. \quad (3.4)$$

Here, $(X_k - X_k^{k-1})$ and $(X_1 - X_1^{k-1})$ are uncorrelated with X_2, \dots, X_{k-1} . Therefore, ϕ_{kk} is the correlation between X_t and X_{t-k} with the linear effects of X_2, \dots, X_{k-1} on each removed (Shumway and Stoffer 2000).

6. A series X_t is said to be second order stationarity or covariance stationary if the ACF $\rho_k = \text{Correlation}(X_t, X_{t-k})$ does not depend on t but depends only on k . Possible causes of non-stationarity of X_t are the presence of trend, seasonality and nonconstant variation of the random component of the series. Possible remedial measures to stationarize X_t are differencing X_t to remove the trend and/or seasonality, and/or transforming X_t to achieve constant variation of the random component of the series (Chatfield 2000).

7. The cross correlation function (CCF) of two time series X_t and Y_t is $\rho_{xy}(t,k) = \text{Correlation}(X_t, Y_{t-k})$ for $k=0, \pm 1, \pm 2, \dots$, and is a measure of the linear relationship (correlation) between series X_t and Y_{t-k} (Chatfield 2003). The CCF $\rho_{xy}(t,k)$ is given by

$$\rho_{xy}(k) = \frac{\gamma_{xy}}{\sqrt{\gamma_x \gamma_y}}, k = 0, \pm 1, \pm 2, \dots \quad (3.5)$$

where $\gamma_{xy} = \text{Covariance}(X_t, Y_{t-k})$, $\gamma_x = \text{Variance}(X_t)$ and $\gamma_y = \text{Variance}(Y_{t-k})$. The sample cross correlation function is given by

$$\hat{\rho}_{xy}(k) = \frac{\hat{\gamma}_{xy}}{\sqrt{\hat{\gamma}_x \hat{\gamma}_y}} \quad (3.6)$$

where $\hat{\gamma}_{xy} = (n-k)^{-1} \sum_{t=1}^{n-k} (x_t - \bar{x})(y_{t-k} - \bar{y})$, $\hat{\gamma}_x = (n-1)^{-1} \sum_{t=1}^n (x_t - \bar{x})^2$,
 and $\hat{\gamma}_y = (n-k)^{-1} \sum_{t=1}^{n-k} (y_{t-k} - \bar{y})^2$.

8. White Noise: a time series X_t is called a white noise, if $\{X_t\}$ is a sequence of independent and identically distributed random variable with the finite mean and variance (Tsay 2005).

3.1.2 ARIMA models and modelling

Here, the theories of modelling were briefly reviewed before there were applied in Section 3.3. Furthermore, in the theoretical discussions it is assumed that the series X_t is second order stationary (see definition in Section 3.2.1, item 6).

There are three basic types of ARIMA models which are: (1) the autoregressive model of order p a positive integer and is denoted by AR(p); (2) the moving average model of order q a positive integer and is denoted by MA(q); and (3) the autoregressive integrated moving average of order (p,q) denoted by ARIMA(p,q). The other relevant and related models to be discussed in this section are transfer function models.

Autoregressive models of order p (AR (p))

As the name implies, an autoregression of order p is a regression of the current value X_t of a time series on the past p - values of the series: $X_{t-1}, X_{t-2}, \dots, X_{t-p}$. Hence, the AR(p) model for a time series $\{X_t\}$ is given by

$$X_t = \alpha_1 X_{t-1} + \alpha_2 X_{t-2} + \dots + \alpha_p X_{t-p} + e_t \quad (3.7)$$

where $\alpha_1, \alpha_2, \dots, \alpha_p$ are model parameters to be estimated, and $\{e_t\}$ is a series of random errors each with zero mean and variance σ^2 . Using the backshift operator B (see Section 3.2.1, item 3), the AR (p) model may be written as

$$\alpha(B) X_t = e_t \quad (3.8)$$

where $\alpha(B) = 1 - \alpha_1 B - \alpha_2 B^2 - \dots - \alpha_p B^p$ is a polynomial in B of order p . An AR (p) processes is said to be stationary provided that the absolute roots of the polynomial in B , $1 - \alpha_1 B - \alpha_2 B^2 - \dots - \alpha_p B^p = 0$ are all greater than 1 (Chatfield 2000).

The ACF of a time series $\{X_t\}$ that is generated by an AR (p) process decays exponentially with lag k . On the other hand, the PACF cuts off after lag $k=p$, i.e. the partial correlations are equal to zero at lags $k > p$. Thus, if a time series $\{X_t\}$ is generated by an AR(p) process, then its sample ACF (see Section 3.2.1, item 4) should decrease

exponentially with lag k and the sample PACF (see Section 3.2.1, item 5) should cut off after lag k , i.e. should be zero after lags $k > p$.

Moving average models of order q (MA(q))

A time series $\{X_t\}$ generated by a moving average process of order q if

$$X_t = e_t - \beta_1 e_{t-1} - \beta_2 e_{t-2} - \dots - \beta_q e_{t-q} \quad (3.9)$$

where $\beta_1, \beta_2, \dots, \beta_q$ are model parameters to be estimated, and $\{e_t\}$ is a series of random errors each with zero mean and variance σ^2 . In model (3.9), the current value X_t of the time series is regressed on the current and past q random errors (Vandaele 1983). Alternatively, (3.9) may alternatively be written as in the form

$$X_t = \beta(B)e_t \quad (3.10)$$

where $\beta(B) = 1 + \beta_1 B + \beta_2 B^2 + \dots + \beta_q B^q$ is a polynomial in B of order q .

(Chatfield 2003) noted that the ACF of an MA (q) process is given by

$$\rho(k) = \begin{cases} 1 & \text{if } k = 0; \\ \frac{\sum_{i=1}^{q-k} (\beta_i \beta_{i+k})}{\sum_{i=0}^q (\beta_i \beta_i)} & \text{if } k \leq q; \\ \rho(-k) & \text{if } k < 0; \\ 0 & k > q; \end{cases}$$

Note that the ACF cuts off at lag $k=q$ which is a special feature of MA processes. Therefore, the sample ACF plot can be used to identify the moving average model of order q . If the sample ACF of a time series shows one or more spikes and the rest are essentially zero, this indicates a moving average model. The order of the model is identified by the lags that are significantly different from zero.

Autoregressive integrated moving average of order (p,q) (ARIMA(p,q))

In practice most time series are non-stationary. In order to fit and exploit the nice properties of a stationary model, it is necessary to remove non stationary sources of variation. If the observed time series Y_t is non-stationary only in the mean, and the mean is a polynomial in t of degree d , then the time series

$$X_t = (1 - B)^d Y_t \quad (3.11)$$

is trendless and hence stationary. If the observed time series Y_t is non-stationary only through seasonality with period s , then the time series

$$X_t = (1 - B^s)Y_t \quad (3.12)$$

has no seasonal effects and hence stationary. If the observed time series Y_t is non-stationary only through the presence of both seasonality with period s and a polynomial trend in t of degree d , then the time series

$$X_t = (1 - B^s) (1 - B)^d Y_t \quad (3.13)$$

is free of trend and seasonality, and hence is stationary. The model for the series X_t can be an AR (p) model or an MA (q) model or a combination of both the AR (p) and the MA (q) models. The latter model is called an integrated moving average of order (p, q), denoted by ARIMA(p, q), given by

$$X_t = \alpha_1 X_{t-1} + \dots + \alpha_p X_{t-p} + \varepsilon_t + \beta_1 \varepsilon_{t-1} + \dots + \beta_q \varepsilon_{t-q} \quad (3.14)$$

The model for X_t , which describes the d^{th} order differencing of Y_t is said to be an ARIMA process of order (p, d, q). The ACF of an ARMA (p, q) process decays exponentially after lag ($q-p$). On the other hand, PACF can be exponential decay, damped sinusoid or a mixture of both.

Transfer function models

The ARIMA models discussed above are for modelling univariate time series. That is, the models relate a time series with its own past. However, a series may not only be related to its own past, be influenced by the present and/or past values of other time series. Regression like models for modelling a time series as a function of other time series are referred to as transfer function models (Brocwell and Davis 2002). The following is brief overview of transfer function models.

Let the explanatory series $\{X_t\}$ is white noise and response series $\{Y_t\}$ is stationary. According to (Wei 1990), the linear model for Y_t as a function of the explanatory series $\{X_t\}$ is given by

$$Y_t = \mu + \beta_0 X_t + \beta_1 X_{t-1} + \beta_2 X_{t-2} + \dots + \beta_k X_{t-k} + e_t, \quad t \geq k \quad (3.15)$$

where ε_t is a random error with mean zero and finite variance, and which is independent of $X_t, X_{t-1}, X_{t-2}, \dots$, and $\beta_0, \beta_1, \dots, \beta_k$ are model parameters called the impulse response weights.

The cross correlation function (CCF) of X_{t-k} and Y_t (see definition in Section 3.2.1, item 7) is given by

$$\begin{aligned}\rho_{xy}(k) &= \text{Corr}(X_{t-k}, Y_t), k = 0, 1, 2, \dots \\ &= \beta_k \sigma_x / \sigma_y, k=0, 1, 2, \dots\end{aligned}$$

where $\sigma_y^2 = \text{Variance}(Y_t)$ and $\sigma_x^2 = \text{Variance}(X_t)$. Therefore, $\rho_{xy}(k) = 0$ for all k implies that $\beta_k = 0$ for all k . On the other hand, if $|\rho_{xy}(k)| > 0$ for some k , then Y_t has a linear relationship with X_{t-k} (Kendall and Ord 1990).

Suppose that X_t is stationary but not white noise. Then the cross correlation function and the transfer function are contaminated by the autocorrelation structure of the explanatory series $\{X_t\}$. Therefore, one way of overcoming this problem is to fit an ARIMA model to $\{X_t\}$. Suppose that the model is

$$\Phi(B)X_t = \theta(B)Z_t \quad (3.16)$$

where Z_t denotes a white noise process. Model (3.16) can be rewritten as

$$Z_t = \frac{\Phi(B)}{\theta(B)} X_t.$$

Let the constant term in model (3.15) be zero, and assume that the ε_t in (3.15) is negligibly small compared to the expected value of Y_t . Then (3.15) can be rewritten as

$$Y_t = \beta(B)X_t \quad (3.17)$$

where $\beta(B) = 1 + \beta_1 B + \beta_2 B^2 + \dots + \beta_k B^k$. After multiplying (3.16) by $\Phi(B)/\theta(B)$, the model becomes

$$V_t = \frac{\Phi(B)}{\theta(B)} Y_t = \frac{\Phi(B)}{\theta(B)} \beta(B) X_t = \beta(B) Z_t .$$

The CCF of V_t and Z_t provides an indication of the term of the impulse response function to retain (3.17). The sample CCF after pre-whitening is computed to obtain estimates of β_k (Chatfield 2000).

Multiple input transfer function models

So far, the discussion has been about transfer function models with a single explanatory series. But, in general the response series may be affected by multiple explanatory series. Therefore, a multiple explanatory series model for a response series can have the following form:

$$Y_t = \sum_{j=1}^k V_j(B)X_{jt} + e_t \quad (3.18)$$

where $V_j(B) = \omega_j(B) B^{b_j} / \delta_j(B)$, $\omega_j(B) = (\omega_{j1} + \omega_{j2} + \dots + \omega_{js_j})B^{b_j}$ and $\delta_j = 1 - \delta_{j1}B - \dots - \delta_{jr_j}B^{r_j}$, is the transfer function between Y_t and X_{jt} for the j^{th} input series and ϵ_t are assumed to be independent of each of the input series X_{jt} , $j = 1, 2, \dots, k$ (Wei 1990). Here, if the explanatory series X_{it} and X_{jt} ($i \neq j$) are uncorrelated, all time and frequency domains analysis of the single – input transfer function model can be extended and applied. On the other hand, if the explanatory series X_{it} and X_{jt} ($i \neq j$) are correlated, multiple input transfer function model building becomes more complicated (Liu and Hanssen 1982). In such cases, (Liu and Hanssen 1982) suggested that a common filter can be chosen from the AR polynomials of the explanatory series with roots close to one to reduce their cross correlation.

3.1.3 Model estimation and diagnostics

Estimation methods

Once a tentative ARIMA model for a series X_t or a transfer function model for the bivariate series (Y_t, X_t) , where Y_t is the response series and X_t is the explanatory series, has been identified, the model parameters are usually estimated by either the least squares method or the maximum likelihood methods. Consider the ARIMA model (3.14) which can be written as $\epsilon_t = \frac{\alpha(B)}{\beta(B)}X_t$ where $\alpha(B) = 1 + \alpha_1B + \alpha_2B^2 + \dots + \alpha_pB^p$ and $\beta(B) = 1 + \beta_1B + \beta_2B^2 + \dots + \beta_qB^q$. Let $\boldsymbol{\alpha}=(\alpha_1, \alpha_2, \dots, \alpha_p)^T$ and $\boldsymbol{\beta}=(\beta_1, \beta_2, \dots, \beta_q)^T$.

Least squares method: The least squares estimates of the parameters of the ARIMA model (3.14) are values of $(\boldsymbol{\alpha}, \boldsymbol{\beta})$ which minimize the error sum of squares:

$$SSE(\boldsymbol{\alpha}, \boldsymbol{\beta}) = \sum_{t=1}^n \epsilon_t^2. \quad \vdots$$

The estimates are found using numerical methods as there are no closed formulae for the estimators of the parameters from minimizing SSE $(\boldsymbol{\alpha}, \boldsymbol{\beta})$. Similarly, the least squares estimates of the parameters of the transfer function model (3.15) are values of $(\mu, \beta_0, \beta_1, \dots, \beta_k)$ which minimize $\sum_{t=1}^n e_t$.

Maximum likelihood method: Under the assumption that the ϵ_t in the ARIMA model (3, 14) are iid $N(0, \sigma^2)$, the maximum likelihood estimates of the model parameters are values of $(\sigma^2, \boldsymbol{\alpha}, \boldsymbol{\beta})$ which maximize the likelihood function:

$$L(\boldsymbol{\alpha}, \boldsymbol{\beta}, \sigma^2) \propto (\sigma^2)^{-n} \exp \left\{ -\frac{1}{2\sigma^2} \sum_{t=1}^n \epsilon_t^2 \right\}.$$

As with the least squares method, the maximum likelihood estimates of the model parameters are found using numerical methods as there are no closed formulae for the estimators of the parameters from minimizing $L(\boldsymbol{\alpha}, \boldsymbol{\beta}, \sigma^2)$ (Box and Jenkins 1970). Similarly, if the e_t in the transfer function model (3.15) are iid $N(0, \sigma^2)$, the maximum likelihood estimates of the model parameters are values of $(\sigma^2, \mu, \beta_0, \beta_1, \dots, \beta_k)$ which maximize the likelihood function $(\sigma^2)^{-n} \exp \left\{ -\frac{1}{2\sigma^2} \sum_{t=1}^n e_t^2 \right\}$.

Model identification

This stage involves identifying the appropriate ARIMA model by determining what the appropriate orders of the AR, MA and Integrated parts are. Model identification is also aided by examining the time plot of the series, which include the construction of the correlogram (autocorrelation function), the partial and inverse autocorrelation functions.

Model checking and inferences

Although a selected model may appear to be the best among those models considered, it is also necessary to do diagnostic checking to verify that the model is adequate. This is done using descriptive and formal testing methods. Both methods involve checking/testing: whether or not the residuals from fitting the model are white noise; and whether or not the model is the simplest best model. If the model fits the data, then the residuals are white noise. A time series plot of such residuals shows no pattern, and a plot of the ACF of the residuals shows no significant spikes (correlations) at all lags k (see Section 3.2.1).

One formal test of the null hypothesis that a time series is white noise is portmanteau test (Box and Jenkins 1970). The test works as follows: at each of specific lags k of the ACF, the ACF up to the lag k are used to calculate a chi-square test statistic which is used as in the usual chi-square test of independence. That is, the null hypothesis that the series is white noise is accepted if the chi-square statistics are equal to their corresponding degrees of freedom, or, the p-values are larger than the level of significance for all up to k lags. Provided that the series is long enough and that the residuals are white noise, the significance or insignificance of the parameters in the model are tested using the statistic

$$t = \frac{\text{estimate}}{se(\text{estimate})}$$

which is asymptotically normally distributed (Box and Jenkins 1970). Terms corresponding to insignificant parameters in the model are then removed and the reduced model fitted.

In the presence of several competing models, use of model selection criteria becomes necessary. Such criteria include the Akaike's Information Criteria (AIC), Bayesian Information Criteria (BIC) also known as Schwartz's Bayesian Criteria (SBC), Autoregressive Transfer Function Criteria (ATFC) and the Akaike's Final Prediction Error (FPE) are used to choose the most appropriate model. The formal expressions for the above criteria in terms of the log-likelihood are:

- $AIC = -2\log(\text{likelihood}) + 2r$
- $AICc = -2\log(\text{likelihood}) + 2rn/n - r - 1$
- $BIC = -2\log(\text{likelihood}) + (r + r\log(n))$
- $SBC = -2\log(\text{likelihood}) + r\log(n)$

where r denotes the number of parameters and n denotes the number of observations. The AICc is a modified form of AIC to correct for small sample data. In considering the statistics given above, there is need to strike a balance between the need for a parsimonious model, which uses as few parameters as possible but maintains its usefulness and a model that is too simple and overlooks the important effects (Chatfield 2003).

In general, Akaike Information Criterion is a tool used to compare two or more competing not necessarily nested models (with different number of parameters) using their likelihood functions (LF). For instance if model 1, with r_1 parameters with $LF = L_1$ is correct and is compared with model 2, which has an additional $(r_2 - r_1)$ parameters and its $LF = L_2$, it is well known fact that minus twice the log-likelihood ratio asymptotically follows a chi-squared distribution with $(k_2 - k_1)$ degrees of freedom.

Thus for large samples

$$E[-2\log(\text{likelihood}_1/\text{likelihood}_2)] = r_2 - r_1$$

This led to (Akaike 1994) to propose information criteria (AIC), to deal with models not necessarily nested, of the form

$$AIC = -2\log(\text{likelihood}) + r$$

where k denotes the number of parameters in the model. The model with the smallest AIC is deemed best in the sense of minimizing the forecast mean square error (FMSE). However, it was pointed out by (Schwart 1978) that AIC is not a consistent criterion in that it does not select the true model with probability approaching 1 as $N \rightarrow \infty$. To overcome this problem, Schwart proposed a Bayesian information criterion (BIC) given by:

$$BIC = -2\log(\text{likelihood}) + r\log(N)$$

where N is the length of the time series or the sample size.

3.2 Results of the ARIMA modelling approach

Our interest was to investigate the effects of the lagged climatic variables on the fibre and vessel characteristics of *Eucalyptus* clones. For most of the cases, the growth responses of trees often lag considerably behind climatic changes. For example, rainfall or temperature of yesterday may have an effect on today's formation of fibre and vessel characteristics. Therefore, the aim of this section was to assess whether or not the lag effects of climatic variables were significant for fibre and vessel characteristics of *Eucalyptus* clones. Since each climatic variable series was no white noise (see definition in Section 3.1.1), direct cross correlations of the climatic variable series and the non stationary fibre and vessel variable series may give misleading indications of the relationship between the fibre and vessel characteristics series and climatic variable series. This problem was solved by cross correlating the pre-whitened series of both fibre and vessel characteristics and the

climatic variables. Here, we have to first fit an ARIMA model to the climatic variable series which is sufficient to reduce the residuals to white noise. The stationary fibre and vessel variable series was then filtered with the same model, and the filtered stationary fibre and vessel characteristics series is cross correlated with the white noise residuals from fitting the climatic variable series.

Differencing was used as a way to remove nonstationarity from time series. Each successive differencing will decrease the variance of the series, but at some point, higher-order differencing will lead to an increase in variance. When variance increases, the series has been *over-differenced* (Anderson 1976). Therefore, order of differencing d to remove trends in each of the climatic variable series was determined using the minimum standard deviation method. The results are displayed in Table 3.1. In the table, for each phase and each climatic variable the optimal order is d corresponding to the smallest standard deviation in bold numbers. For example, in Phase I the smallest standard deviations were for once differenced temperature, wind speed and relative humidity series, and for the original rainfall and solar radiation series.

Table 3. 1: The standard deviations and the optimal orders of differencing of the climatic variable series.

Order of differencing		Temperature	Rainfall	Solar radiation	Wind speed	Relative humidity
Phase I	d=0	3.81	6.53	8.54	0.24	0.58
	d=1	2.45	7.71	9.12	0.23	0.56
	d=2	3.45	12.1	14.97	0.39	0.92
Phase II	d=0	4.01	7.56	11.18	0.32	2
	d=1	2.12	8.68	9.25	0.35	1.62
	d=2	3.11	13.78	14.11	0.59	2.61
Phase III	d=0	3.49	20.01	3.96	0.18	0.32
	d=1	2.61	9.34	6.88	0.16	0.59
	d=2	3.92	15.51	10.95	0.27	0.96
Phase IV	d=0	3.78	20.01	3.96	0.18	0.32
	d=1	1.83	25.44	5.51	0.09	0.37
	d=2	3.08	40.92	9.15	0.15	0.63

Similar to the climatic variable series, the order of differencing d to remove trends in the fibre and vessel characteristics of the two clones was also determined using the minimum standard deviation criterion. The results are displayed in Table 3.2. Here, first the fibre

and vessel series were differenced and then pre-whiten using the climatic variable series model. As can be seen from Table 3.2, the smallest standard deviations were for once differenced fibre and vessel characteristics for all phases. In the table, for each phase and fibre and vessel characteristics the optimal order is d corresponding to the smallest standard deviation in bold numbers.

Table 3. 2: The standard deviations and the optimal orders of differencing of the Fibre and vessel variables

Order of differencing		GC clone				GU clone			
		FD	VD	FW	VF	FD	VD	FW	VF
Phase I	d=0	0.88	0.71	1.12	0.9	0.72	0.48	1.24	0.62
	d=1	0.17	0.15	0.14	0.26	0.19	0.15	0.23	0.25
	d=2	0.24	0.21	0.18	0.37	0.28	0.21	0.33	0.37
Phase II	d=0	0.78	1.17	0.88	0.62	0.46	1.03	0.65	0.5
	d=1	0.28	0.24	0.17	0.18	0.15	0.16	0.14	0.13
	d=2	0.44	0.33	0.24	0.26	0.22	0.21	0.2	0.19
Phase III	d=0	1.16	0.86	0.52	0.58	1.16	0.86	1.02	0.58
	d=1	0.29	0.25	0.12	0.2	0.29	0.25	0.17	0.2
	d=2	0.44	0.37	0.17	0.3	0.44	0.37	0.27	0.3
Phase IV	d=0	0.72	28.72	0.89	17.46	1.01	37.98	1.05	11.58
	d=1	0.77	34.36	0.9	23.91	1.09	45.29	1.04	15.19
	d=2	1.27	57.06	1.43	35.97	1.81	77.67	1.61	25.01

3.3.1 The effects of lagged temperature on fibre and vessel characteristics

In this sub section, the objective was to investigate the effects of the lagged temperature on fibre and vessel characteristics for each phase. After differencing to remove trend, seasonality for temperature for Phase I was observed. The seasonality in temperature for Phase I was approximately a year (380 days). This is because the duration of Phase I was longer than the other phases. The autocorrelation and partial autocorrelation plots in Figures 3.1 suggest that the temperature series in Phase I, II, III and IV can be explained by MA (2,3), MA(3), ARMA(1,1) and MA(1,7) models, respectively (see Section 3.1.2). In particular, the estimated MA (2, 3), MA (3), ARMA (1, 1) and MA (1, 7) models for the temperature series were the following.

Phase I

$$(1 - B)(1 - B^{380})Temp_t = (1 - 0.35984B^2 - 0.27045B^3) \varepsilon_t. \quad (3.3.1.1)$$

Phase II

$$(1 - B)Temp_t = (1 - 0.26232B^1 - 0.38813B^2 - 0.10595B^3) \varepsilon_t. \quad (3.3.1.2)$$

Phase III

$$(1 - B)Temp_t = ((1 - 0.653B^1) - (1 - 0.382B^1 + 0.4172B^7))\varepsilon_t. \quad (3.3.1.3)$$

Phase IV

$$(1 - B)Temp_t = (1 - 0.3822B^1 + 0.41719B^7)\varepsilon_t. \quad (3.3.1.4)$$

where B is the Backward shift operator, $Temp_t$ is the original temperature series and ε_t is the white noise.

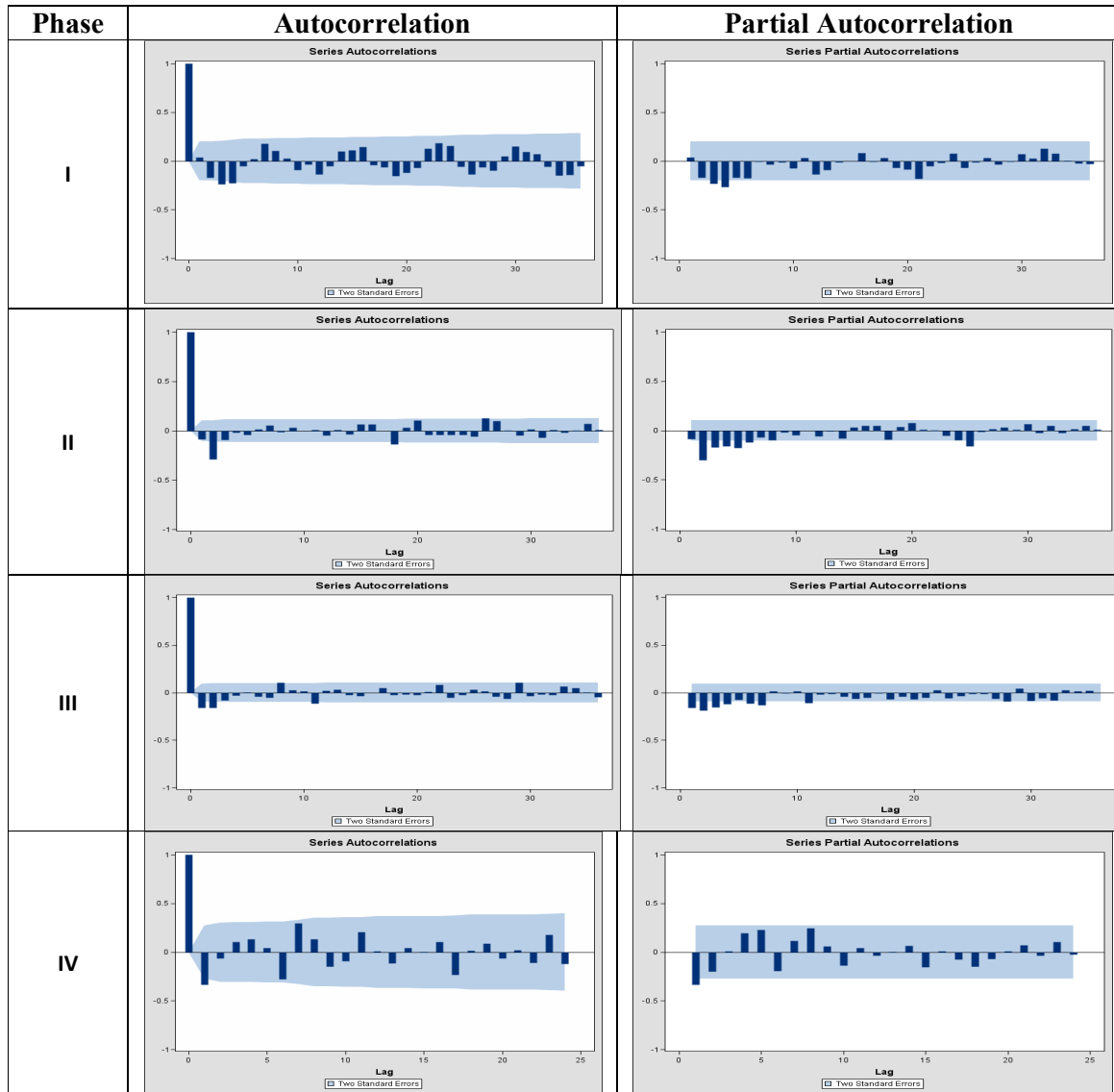


Figure 3. 1: Autocorrelations and partial autocorrelation of the once differenced temperature series

The residual check for white noise (Table 3.3) indicates that the MA (2,3), MA(3), ARMA(1,1) and MA(1,7) models for the temperature series in Phase I, II, III and IV, provides a reasonable good fit to the temperature series since p - values are large.

Furthermore, from the MA (2, 3), MA (3), ARMA (1, 1) and MA (1, 7) parameters are significant at 5% level of significance. This result is shown in Table 3.4.

Table 3. 3: White noise autocorrelation check for once differenced temperature series

Autocorrelation Check of Residuals						
	Phase I			Phase II		
To Lag	Chi-Square	DF	Pr > ChiSq	Chi-Square	DF	Pr > ChiSq
6	7.64	4	0.1058	0.66	3	0.8823
12	11.81	10	0.2979	3.85	9	0.9208
18	14.7	16	0.5466	11.28	15	0.7322
24	23.02	22	0.4006	17.11	21	0.7046
30	27.92	28	0.4689	30.41	27	0.2962
36	31.3	34	0.6005	35.12	33	0.3678
42	35.6933	40	0.6899	39.55	39	0.4455
48	39.8333	46	0.78985	45.78	45	0.4396
	Phase III			Phase IV		
6	1.9	4	0.7544	3.08	4	0.5444
12	13.66	10	0.1891	7.33	10	0.6944
18	16.38	16	0.4271	10.41	16	0.8443
24	21.07	22	0.5164	13.28	22	0.925
30	27.92	28	0.4685	16.15	35	0.996
36	32.93	34	0.5198			
42	37.5	40	0.5832			
48	47.07	46	0.4284			

Table 3. 4: Unconditional least square estimation for the temperature series

Unconditional Least Squares Estimation			
Phase I			
Parameter	Estimate	Standard Error	Approx Pr > t
MA1,1	0.35984	0.0928	0.0002
MA1,2	0.2929	0.0928	0.0021
Phase II			
MA1,1	0.26232	0.05303	<.0001
MA1,2	0.38813	0.05077	<.0001
MA1,3	0.10595	0.05305	0.0466
Phase III			
MA1,1	0.95828	0.01651	<.0001
AR1,1	0.65298	0.04374	<.0001
Phase IV			
MA1,1	0.3822	0.11389	0.0015
MA1,2	-0.4172	0.11942	0.001

After filtering the stationary series of temperature and fibre dimension, vessel dimension, fibre wall and vessel frequency, the cross correlations between the filtered series were calculated. The *p* - values, for testing the linear relationship between temperature and fibre dimension series, are presented in Table 3.5. Large *p* – value in Phase I, II and IV

result in Table 3.5 indicate that there is no linear relationship between the fibre dimension series and the lagged temperature series. Note that the cross correlation was done for 36 days. On the other hand, the p - values for Phase III GC are small at 5% level of significance. This means that there was linear relationship between the fibre dimension series and the lagged temperature series for Phase III GC. However, for GU, there was no linear relationship between the fibre dimension series and the lagged temperature series since the p - values are large. On the other hand, the correlation plot has significant spikes at lag 21 and 29 for FD of GC for Phase III. The correlation results indicate that FD of GC for Phase III was negatively correlated to the previous 29 days of temperature. On the other hand, the p - values, for testing the linear relationship between temperature and vessel dimension series, are presented in Table 3.5 are large. This result indicates that there was no linear relationship between the vessel dimension series and the lagged temperature series in Phase I, II and IV except for Phase III GU. Moreover, the p - values for Phase III GU are small for 5% level of significance. This means that there was linear relationship between the vessel dimension series and the lagged temperature series for Phase III GU. Furthermore, the correlation plot has significant spikes at lag 15 for VD of GU for Phase III. The correlation results indicate that VD of GU for Phase III was negatively correlated to the previous 15 days of temperature. The p - values, from Table 3.5 show that there was no linear relationship between the fibre wall series and the lagged temperature series in Phase I, II, III and IV except Phase I GC because the P -values are large. However, for GC, there was linear relationship between the fibre wall series and the lagged temperature series since the p - values are small. Moreover, the correlation plot has significant spikes at lag 13 for FW of GC for Phase I. The correlation results indicate that FW of GC for Phase I was positively correlated to the previous 13 days of temperature.

The p - values, for testing the linear relationship between temperature and vessel frequency series, are presented in Table 3.5. These p - values are large in Phase I GC, II, III and IV. Therefore, the result indicates that there was no linear relationship between the vessel frequency series and the lagged temperature series. On the other hand, the p - values for Phase I GU are small at 5% level of significance. This means that there was linear relationship between the vessel frequency series and the lagged temperature series for Phase I GU. Moreover, the correlation plot has significant spikes at lag 3 and 13 for

VF of GU for Phase I. The correlation results indicate that VF of GU for Phase I was positively correlated to the previous 13 days of temperature.

Table 3. 5: Cross correlation check (P – values) between lagged temperature and wood anatomical characteristics

Cross correlation Check Between Series									
To Lag	DF	FD		VD		FW		VF	
		GC	GU	GC	GU	GC	GU	GC	GU
Phase I									
5	6	0.3133	0.1411	0.7738	0.6048	0.2861	0.2861	0.3015	0.0184
11	12	0.6861	0.2585	0.9428	0.8583	0.5582	0.5582	0.7459	0.0215
17	18	0.8852	0.4526	0.9366	0.6345	0.5717	0.5717	0.6412	0.079
23	24	0.9498	0.5179	0.7054	0.6485	0.0437	0.7837	0.664	0.0469
29	30	0.8253	0.645	0.8738	0.6721	0.0312	0.8919	0.3957	0.0978
35	36	0.8116	0.6424	0.7468	0.3258	0.9674	0.9674	0.3667	0.0705
Phase II									
5	6	0.9722	0.0522	0.7804	0.2691	0.5062	0.7381	0.7562	0.0857
11	12	0.9854	0.0611	0.3908	0.3032	0.6969	0.2858	0.9515	0.3276
17	18	0.671	0.1355	0.2404	0.6057	0.8971	0.558	0.9295	0.4948
23	24	0.4708	0.0818	0.0643	0.8491	0.8783	0.4297	0.9268	0.4805
29	30	0.6793	0.2039	0.0275	0.2792	0.8883	0.0914	0.5862	0.4995
35	36	0.8571	0.4267	0.0642	0.1913	0.945	0.1895	0.6089	0.338
Phase III									
5	6	0.1944	0.2351	0.2175	<.0001	0.8948	0.0188	0.6431	0.4566
11	12	<.0001	0.4024	0.3701	0.0002	0.3919	0.0922	0.8836	0.0711
17	18	<.0001	0.5798	0.2529	0.0007	0.6612	0.1857	0.7579	0.2498
23	24	<.0001	0.6631	0.2215	0.0023	0.7876	0.2575	0.061	0.541
29	30	<.0001	0.472	0.2967	0.0112	0.4364	0.3779	0.0257	0.6163
35	36	<.0001	0.2754	0.1477	0.0456	0.5476	0.5939	0.0534	0.6123
Phase IV									
5	6	0.0066	0.0966	0.3594	0.3594	0.9766	0.9766	0.8872	0.8872
11	12	0.0925	0.0925	0.4231	0.4231	0.7287	0.7287	0.7792	0.7792
17	18	0.126	0.126	0.6528	0.6528	0.8633	0.8633	0.9343	0.9343
23	24	0.3327	0.3327	0.7675	0.7675	0.9474	0.9474	0.9645	0.9645
29	30	0.4595	0.4595	0.895	0.895	0.895	0.895	0.9938	0.9938
35	36	0.6861	0.6861	0.9509	0.9509	0.9509	0.9509	0.9981	0.9981

3.3.2 The effects of lagged rainfall on fibre and vessel measurements

In Section 3.3.1, the effects of lagged temperature on fibre and vessel measurements were investigated. In this section, our interest is to investigate the effects of lagged rainfall on fibre and vessel measurements. Therefore, the objective was to investigate the effects of the lagged rainfall on fibre and vessel characteristics. The autocorrelation and partial autocorrelation plots in Figures 3.2 suggest that the rainfall series in Phase I, II, III and IV can be explained by an MA (1,30), MA(2), MA(1) and MA(1) models, respectively (see

Section 3.1.2). In particular, the estimated MA (1, 30), MA (2), MA (1) and MA (1) models for the rainfall series were the following.

Phase I

$$(1 - B)Rain_t = (1 + 0.27436B^1 + 0.20068B^{30})\varepsilon_t \quad (3.3.2.1)$$

Phase II:

$$(1 - B)Rain_t = (1 - 0.38035B^1)\varepsilon_t \quad (3.3.2.2)$$

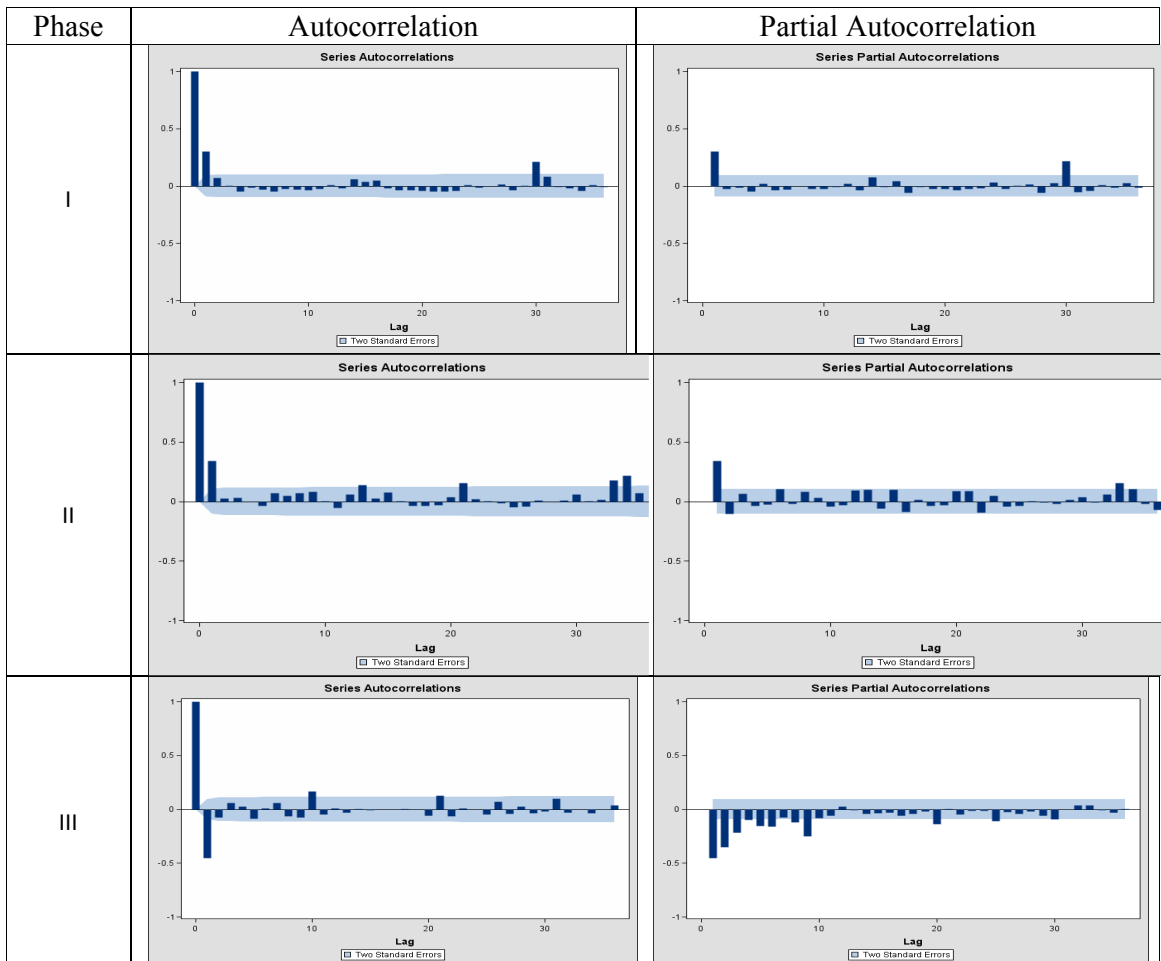
Phase III:

$$(1 - B)Rain_t = (1 - 0.96892B^1)\varepsilon_t \quad (3.3.2.3)$$

Phase IV:

$$(1 - B)Rain_t = (1 - 0.96892B^1)\varepsilon_t \quad (3.3.2.4)$$

where B is the Backward shift operator $Rain_t$ the original rainfall series and ε_t is the white noise.



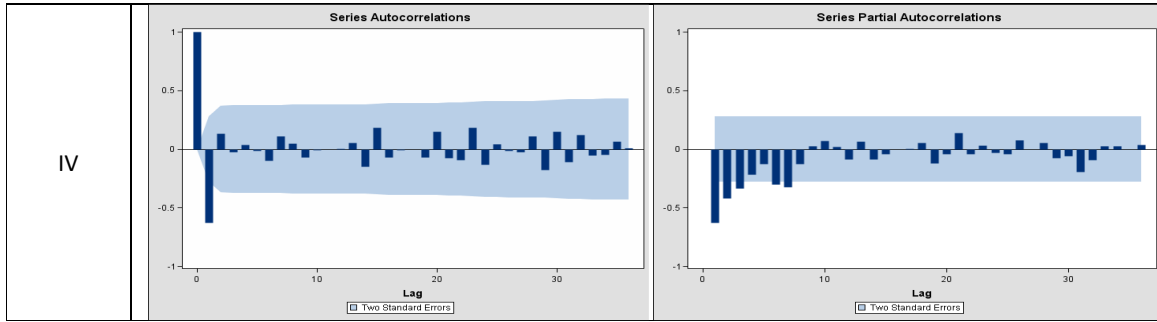


Figure 3. 2: Autocorrelations and partial autocorrelations of the rainfall series

The residual check for white noise (Table 3.6) indicates that the MA (1,30), MA(2), MA(1) and MA(1) model for the rainfall series in Phase I, II, III and IV, provides a reasonable good fit to the rainfall series since p - values are large. Furthermore, all the MA (1,30), MA(2), MA(1) and MA(1) model for Phase I, II, III and IV parameters are significant at 5% level of significance. This result is presented in Table 3.7.

Table 3. 6: White noise autocorrelation check for rainfall series

Autocorrelation Check of Residuals						
	Phase I			Phase II		
To Lag	Chi-Square	DF	Pr > ChiSq	Chi-Square	DF	Pr > ChiSq
6	5.31	4	0.2568	5.26	4	0.2612
12	6.52	10	0.7697	9.13	10	0.5198
18	12.33	16	0.7208	22.54	16	0.1265
24	15.1	22	0.858	35.77	22	0.0321
30	18.14	28	0.9226	36.79	28	0.1236
36	23.24	34	0.9181	35.57	34	0.1112
42	25.96	40	0.9579	41.56	40	0.0958
48	36.17	46	0.8501	43.97	46	0.1108
	Phase III			Phase IV		
6	2.4	5	0.7912	7.49	5	0.1867
12	11.19	11	0.4278	11.4	11	0.4103
18	16.84	17	0.4651	15.5	17	0.5597
24	22.98	23	0.4622	21.76	23	0.5345
30	30.77	29	0.3762	26.44	29	0.6021
36	33.14	35	0.5581	30.14	35	0.7018
42	34.38	41	0.758			
48	35.94	47	0.8799			

Table 3. 7: Unconditional least square estimation for the rainfall series

Unconditional Least Squares Estimation			
Phase I			
Parameter	Estimate	Standard Error	Approx Pr > t
MU	1.819	0.40827	<.0001
MA1,1	-0.2744	0.04305	<.0001
MA1,2	-0.2007	0.04394	<.0001
Phase II			
MU	2.36927	0.53983	<.0001
MA1,1	-0.3781	0.04913	<.0001
Phase III			
MA1,1	0.96892	0.01153	<.0001
Phase IV			
MA1,1	0.97375	0.03728	<.0001

After filtering the stationary series of rainfall and fibre dimension, vessel dimension, fibre wall and vessel frequency the cross correlations between the filtered series were calculated. The p - values, for testing the linear relationship between rainfall and fibre dimension series, are presented in Table 3.8. Large p -values indicate that there was no linear relationship between fibre dimension and the lagged rainfall series in Phase I, Phase II GC, Phase III GU and Phase IV. On the other hand, the p - values for Phase II GU and Phase III GC are small at 5% level of significance. This means that there was linear relationship between the fibre dimension series and the lagged rainfall series for Phase II GC and Phase III GC. Furthermore, the cross correlation plot between FD and rainfall indicate that FD of GC for Phase II and Phase III was positively correlated to the previous values of rainfall. Similarly, the p - values, for testing the linear relationship between rainfall and vessel dimension series, presented in Table 3.8 are large for Phase II GC, Phase III and Phase IV. This result indicates that there was no linear relationship between the vessel dimension series and the lagged rainfall series for Phase II GC, Phase III and Phase IV. On the other hand, the p - values presented in Table 3.8 are small for Phase I and Phase II GU. This means that there was linear relationship between vessel dimension series and lagged rainfall series. Furthermore, the cross correlation plot between VD and rainfall indicate that VD of GC for Phase I and Phase II for GC was positively correlated to the previous values of rainfall. The p - values, for testing the linear relationship between rainfall and fibre wall, presented in Table 3.8 are large. This result indicates that there was no linear relationship between the fibre wall series and the

lagged rainfall series for all phases. Moreover, the *p* - values presented in Table 3.8 for vessel frequency indicate that there was no linear relationship between the vessel frequency series and the lagged rainfall series in Phase I, Phase II GU, and Phase III GC because the *p*-values are large. On the other hand, the *p* - values for Phase II GC, Phase III GU and Phase IV are small, indicating that there was linear relationship between the vessel frequency series and the lagged rainfall for Phase II GC, Phase III GU and Phase IV. Furthermore, the cross correlation plot between VF and rainfall indicate that VF of GC for Phase II, VF of GU for III and Phase IV was negatively correlated to the previous values of rainfall.

Table 3. 8: Cross correlation check (P – values) between lagged rainfall and wood anatomical characteristics

Cross correlation Check Between Series									
To Lag	DF	FD		VD		FW		VF	
		GC	GU	GC	GU	GC	GU	GC	GU
Phase I									
5	6	0.1766	0.1975	0.0351	0.0263	0.7603	0.5314	0.0581	0.774
11	12	0.2569	0.1111	0.0368	0.0069	0.6189	0.7328	0.0426	0.86
17	18	0.5143	0.1423	0.1089	0.018	0.6417	0.904	0.1509	0.8694
23	24	0.7378	0.0327	0.1709	0.0465	0.7691	0.7164	0.2033	0.7927
29	30	0.807	0.0572	0.2276	0.043	0.9073	0.5345	0.3475	0.7336
35	36	0.9091	0.1463	0.4786	0.025	0.9707	0.6767	0.5701	0.8088
Phase II									
5	6	0.7979	0.024	0.9559	0.2906	0.2195	0.2018	<.0001	0.4001
11	12	0.5833	0.0459	0.8916	0.27	0.3999	0.1482	0.0004	0.2478
17	18	0.7604	0.079	0.9341	0.0278	0.7413	0.2733	0.0003	0.1057
23	24	0.8959	0.1903	0.832	0.0003	0.9281	0.3411	0.0002	0.1921
29	30	0.8975	0.068	0.9329	0.0009	0.9635	0.2002	<.0001	0.1045
35	36	0.1556	0.1281	0.2818	<.0001	0.5019	0.202	0.0003	0.2352
Phase III									
5	6	0.0001	0.7996	0.0678	0.48	0.9176	0.7928	0.9844	0.0733
11	12	<.0001	0.7479	0.0739	0.3636	0.4574	0.9293	0.9997	0.0451
17	18	<.0001	0.9327	0.1899	0.3831	0.643	0.8984	0.9986	0.0393
23	24	<.0001	0.92	0.425	0.4421	0.7915	0.7045	0.7964	0.01
29	30	<.0001	0.6998	0.5511	0.5325	0.358	0.6806	0.5194	0.0099
35	36	0.0006	0.4395	0.7068	0.3758	0.0003	0.6444	0.6921	0.0066
Phase IV									
5	6	0.7236	0.7236	0.1553	0.1553	0.9234	0.9234	0.0348	0.0348
11	12	0.7233	0.7233	0.1115	0.1115	0.8135	0.8135	0.0034	0.0034
17	18	0.9107	0.9107	0.3717	0.3717	0.863	0.863	0.0074	0.0074
23	24	0.9396	0.9396	0.1561	0.1561	0.9647	0.9647	0.0484	0.0484
29	30	0.9767	0.9767	0.3083	0.3083	0.9632	0.9632	0.1533	0.1533
35	36	0.9922	0.9922	0.5497	0.5497	0.9923	0.9923	0.3209	0.3209

3.3.3 The effects of lagged solar radiation on fibre and vessel measurements

Similar to Section 3.3.1 and 3.3.2, the other climatic variable which is an interest to be investigated was solar radiation. Here, the objective was to investigate the effects of the lagged solar radiation on fibre and vessel characteristics for each phase. After differencing to remove trend, seasonality for solar radiation for Phase I was observed. The seasonality in solar radiation for Phase I was approximately a year (350 days). This is because the duration of Phase I was longer than the other phases. The autocorrelation and partial autocorrelation plots in Figures 3.3 suggest that the solar radiation series in Phase I, II, III and IV can be explained by MA (1), MA(1), ARMA(1,1) and ARMA(1,1) models for Phase I, II, III and IV respectively (see Section 3.1.2). In particular, the estimated MA (1) model for Phase I and II, and ARMA (1, 1) model for Phase III and IV for the solar radiation series were the following.

Phase I:

$$(1 - B)(1 - B^{350})Solar_t = (1 - 0.55428 B^1) Z_t \quad (3.3.3.1)$$

Phase II:

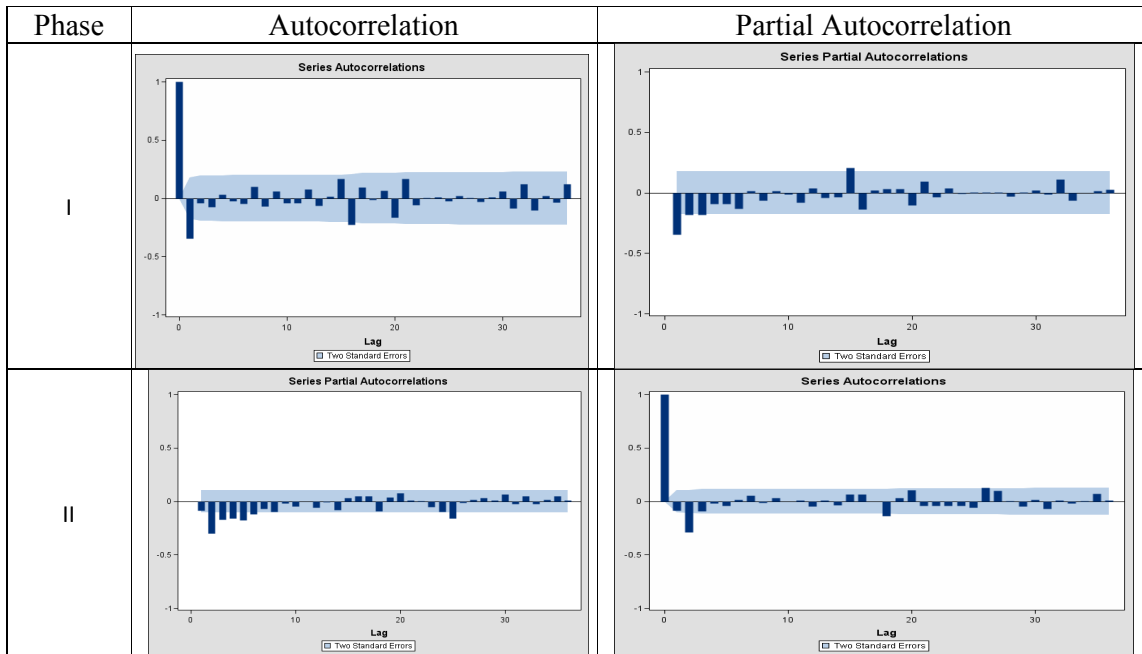
$$(1 - B)Solar_t = (1 - 0.89656 B^1) Z_t \quad (3.3.3.2)$$

Phase III:

$$(1 - B)Solar_t = ((1 - 0.19816 B^1) - (1 - 0.91872B^1) Z_t \quad (3.3.3.3)$$

Phase IV:

$$(1 - B)Solar_t = (1 - 0.9948B^1) - (1 - 0.36542B^1) Z_t \quad (3.3.3.4)$$



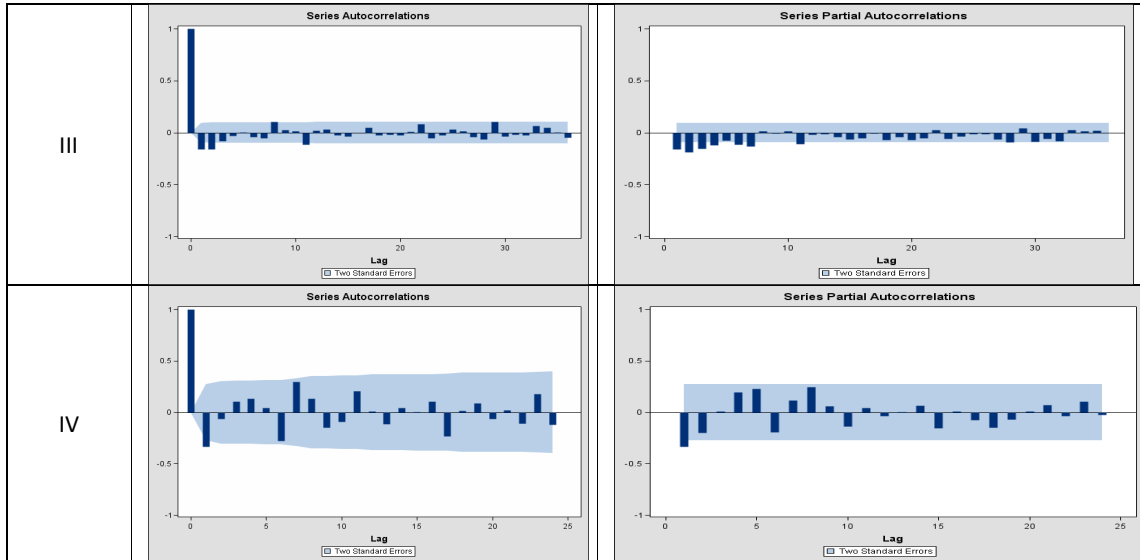


Figure 3. 3: Autocorrelations and partial autocorrelations of the solar radiation series

The residual check for white noise (Table 3.9) indicates that the MA(1), MA(1), ARMA(1,1) and ARMA(1,1) models for solar radiation series in Phase I, II, III and IV, provides a reasonable good fit to the solar radiation series since *p* - values are large. In addition to this, all the MA (1), MA (1), ARMA (1, 1) and ARMA (1, 1) parameters are significant at 5% level of significance. This result is presented in Table 3.10.

Table 3. 9 White noise autocorrelation check for solar radiation series

Autocorrelation Check of Residuals						
	Phase I			Phase II		
To Lag	Chi-Square	DF	Pr > ChiSq	Chi-Square	DF	Pr > ChiSq
6	1.64	3	0.6505	7.78	4	0.1001
12	6.7	9	0.6682	16.17	10	0.0948
18	11.66	15	0.7042	20.9	16	0.1824
24	18.45	21	0.6203	27.48	22	0.1934
30	22.68	27	0.7018	31.77	28	0.2839
36	26.71	33	0.7722	34.33	34	0.4522
42	30.74	40	0.85	38.38	40	0.5432
48	34.77	46	0.92595	42.59	46	0.6157
	Phase III			Phase IV		
6	2.41	4	0.6607	6.25	4	0.1812
12	5.97	10	0.8182	11.64	10	0.3102
18	12.24	16	0.7273	12.82	16	0.6858
24	23.08	22	0.3972	14.03	22	0.9005
30	27.56	28	0.488	18.93	28	0.9003
36	36.4	34	0.3576	28.1	34	0.7516
42	44.95	40	0.2722			
48	47.49	46	0.4116			

Table 3. 10: Unconditional least square estimation for the solar radiation series

Unconditional Least Squares Estimation			
Phase I			
Parameter	Estimate	Standard Error	Approx Pr > t
MA1,1	0.55428	0.07355	<.0001
Phase II			
MA1,1	0.89656	0.02733	<.0001
Phase III			
MA1,1	0.91872	0.02116	<.0001
AR1,1	0.19816	0.05239	0.0002
Phase IV			
MA1,1	0.36542	0.1413	0.0125
AR1,1	0.9948	0.03625	<.0001

After filtering the stationary series of solar radiation and fibre dimension, vessel dimension, fibre wall and vessel frequency the cross correlations between the filtered series were calculated. The p - values, for testing the linear relationship between solar radiation and fibre dimension, presented in Table 3.11. Large p - values indicate that there was no linear relationship between the fibre dimension series and the lagged solar radiation series in Phase I, Phase II GU, Phase III GU and Phase IV. On the other hand, the p - values for Phase II GC and Phase III GC are small at 5% level of significance. This means that there was linear relationship between the fibre dimension series and the lagged solar radiation series for Phase II GC and Phase III GC. Similarly, the p - values, for testing the linear relationship between solar radiation and vessel dimension series, presented in Table 3.11 are large, indicating that there was no linear relationship between the vessel dimension series and the lagged solar radiation series for Phase I, Phase III GU and Phase IV. But for the case of Phase II and Phase III GC, the result was different. Since the p - values presented in Table 3.11 are small at 5% level of significance, indicating that there was linear relationship between the vessel dimension series and the lagged solar radiation series. On the other hand, the p - values, for testing the linear relationship between solar radiation and fibre wall series, presented in Table 3.11 are large, indicating that there was no linear relationship between the fibre wall series and the lagged solar radiation series for Phase I, II, Phase III GU and Phase IV. On the other hand, the p - values presented in Table 3.11 are small for Phase III GC, indicating that there was linear relationship between the fibre wall series and the lagged solar radiation series. Furthermore, the p - values, for testing the linear relationship between solar

radiation and vessel frequency, presented in Table 3.11 are large. This result indicates that there was no linear relationship between the vessel frequency series and the lagged solar radiation series for Phase I, Phase II GC and Phase III. For the case of Phase II GU and Phase IV, the *p* - values presented in Table 3.11 are small. Therefore, there was linear relationship between lagged solar radiation series and vessel frequency series.

Table 3. 11: Cross correlation check (P – values) between lagged solar radiation and wood anatomical characteristics

Cross correlation Check Between Series									
To Lag	DF	FD		VD		FW		VF	
		GC	GU	GC	GU	GC	GU	GC	GU
Phase I									
5	6	0.6156	0.396	0.8691	0.7241	0.4428	0.9987	0.1447	0.0522
11	12	0.8835	0.5698	0.9672	0.9072	0.7193	0.9996	0.3212	0.1531
17	18	0.4541	0.8611	0.9648	0.9695	0.6779	0.9756	0.6054	0.3194
23	24	0.706	0.9135	0.9395	0.9755	0.8827	0.9801	0.6705	0.2756
29	30	0.8599	0.9535	0.9372	0.996	0.9665	0.9968	0.6829	0.4441
35	36	0.9535	0.9826	0.9428	0.9644	0.9617	0.9991	0.2895	0.1715
Phase II									
5	6	0.5015	0.9122	0.0041	0.0115	0.0759	0.2858	0.16	0.0063
11	12	0.5433	0.8369	0.0511	0.0779	0.239	0.575	0.4288	0.0016
17	18	0.0002	0.5008	0.0197	0.0503	0.2137	0.343	0.7469	<.0001
23	24	0.0001	0.0536	0.0703	0.0128	0.2476	0.5362	0.8152	<.0001
29	30	0.0004	0.0402	0.0636	0.0066	0.3163	0.1356	0.8934	<.0001
35	36	0.0002	0.0519	0.0129	<.0001	0.2609	0.0552	0.977	<.0001
Phase III									
5	6	0.8901	0.5979	0.9514	0.1039	0.9698	0.0052	0.3521	0.4495
11	12	<.0001	0.3229	0.981	0.0782	0.9996	0.0173	0.5798	0.0254
17	18	<.0001	0.4695	0.9905	0.2732	0.999	0.0387	0.8546	0.1386
23	24	<.0001	0.5688	0.4027	0.2818	0.9939	0.0172	0.8972	0.0795
29	30	<.0001	0.6332	0.0025	0.1099	0.9815	0.025	0.8431	0.1083
35	36	<.0001	0.6983	0.0104	0.1808	0.9934	0.0503	0.3782	0.1268
Phase IV									
5	6	0.1519	0.1519	0.9927	0.9927	0.2036	0.2036	0.0128	0.0128
11	12	0.2645	0.2645	0.9604	0.9604	0.192	0.192	0.0319	0.0319
17	18	0.3906	0.3906	0.7689	0.7689	0.2087	0.2087	0.0279	0.0279
23	24	0.5963	0.5963	0.2898	0.2898	0.537	0.537	0.1132	0.1132
29	30	0.7461	0.7461	0.4454	0.4454	0.6536	0.6536	0.3078	0.3078
35	36	0.7938	0.7938	0.572	0.572	0.7279	0.7279	0.5567	0.5567

3.3.4 The effects of lagged relative humidity on fibre and vessel measurements

The other climatic variable which is an interest to be investigated is relative humidity. The objective was to investigate the effects of the lagged relative humidity on fibre and vessel characteristics for each phase. After differencing to remove trend, seasonality for

relative humidity for Phase I was observed. The seasonality in relative humidity for Phase I was 250 days. This is because the duration of Phase I was longer than the other phases. The autocorrelation and partial autocorrelation plots in Figures 3.4 suggest that the relative humidity series in Phase I, II, III and IV can be explained by an MA(2), MA(2), AR(2) and ARMA(1,1) models. In particular, the estimate MA (2), MA (2), AR (2) and ARMA (1, 1) models for the relative humidity series were the following.

Phase I:

$$(1 - B)(1 - B^{250})relhum_t = (1 - 0.65699B^1 - 0.17074B^2) Z_t \quad (3.3.4.1)$$

Phase II:

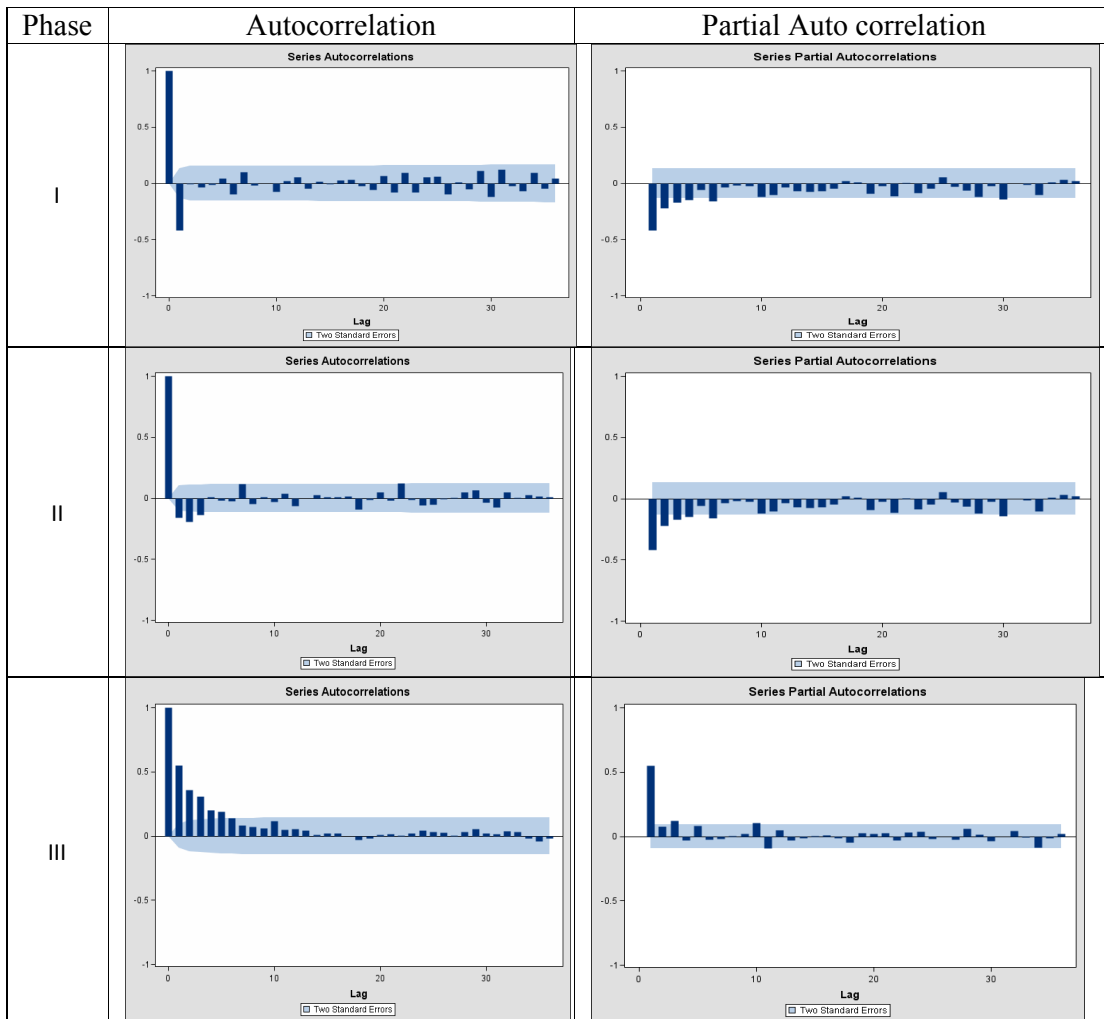
$$(1 - B)relhum_t = (1 - 0.39307B^1 - 0.34609B^2) Z_t \quad (3.3.4.2)$$

Phase III:

$$(1 - B)relhum_t = (1 - 0.50449B^1 - 0.12631B^3) Z_t \quad (3.3.4.3)$$

Phase IV:

$$(1 - B)relhum_t = ((1 - 0.33369B^1) - (1 - 0.12631B^1) Z_t \quad (3.3.4.4)$$



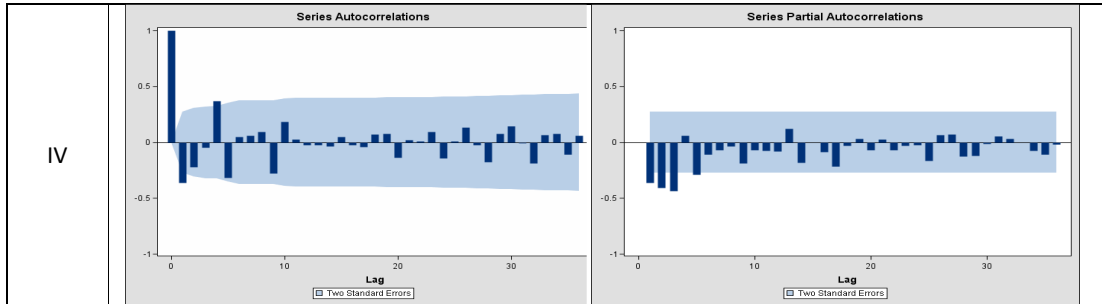


Figure 3. 4: Autocorrelations and partial autocorrelation of the relative humidity series

The residual check for white noise (Table 3.12) indicates that the MA(2), MA(2), AR(2) and ARMA(1,1) models for relative humidity series in Phase I, II, III and IV provides a reasonable good fit to the solar radiation series since *p* - values are large. Furthermore, all the MA (2), MA (2), AR (2) and ARMA (1, 1) model parameters are significant at 5% level of significance. This result is presented in Table 3.13.

Table 3. 12: White noise autocorrelation check for relative humidity series

Autocorrelation Check of Residuals						
To Lag	Phase I			Phase II		
	Chi-Square	DF	Pr > ChiSq	Chi-Square	DF	Pr > ChiSq
6	19.24	4	0.0657	7.78	4	0.1001
12	18.2	10	0.0517	16.17	10	0.0948
18	21.09	16	0.1752	20.9	16	0.1824
24	27.1	22	0.2073	27.48	22	0.1934
30	32.45	28	0.2565	31.77	28	0.2839
36	42.38	34	0.1533	34.33	34	0.4522
42	51.33	40	0.108	38.38	40	0.5432
48	60.93	46	0.081	42.59	46	0.6157
	Phase III			Phase IV		
6	3.76	4	0.4398	4.28	4	0.3691
12	13.97	10	0.1746	7.91	10	0.6381
18	15.8	16	0.4667	10.16	16	0.8579
24	17.02	22	0.7621	11.65	22	0.9642
30	19.08	28	0.8955	16.7	28	0.9542
36	22.6	34	0.9323	25.76	34	0.8439
42	30.99	40	0.8457			
48	36.11	46	0.8521			

Table 3. 13: Unconditional least square estimation for the relative humidity series

Unconditional Least Squares Estimation			
Phase I			
Parameter	Estimate	Standard Error	Approx
			Pr > t
MA1,1	0.65699	0.0654	<.0001
MA1,2	0.17074	0.06544	0.0097
Phase II			
MA1,1	0.39307	0.04989	<.0001
MA1,2	0.34609	0.0499	<.0001
Phase III			
MU	73.98635	0.79515	<.0001
AR1,1	0.50449	0.04169	<.0001
AR1,2	0.12631	0.0417	0.0026
MA1,1	0.99999	0.28009	0.0008
AR1,1	0.33369	0.14022	0.0211

After filtering the stationary series of relative humidity and fibre dimension, vessel dimension, fibre wall and vessel frequency, the cross correlations between the filtered series were calculated. The p - values, for testing the linear relationship between relative humidity and fibre dimension series, are presented in Table 3.14. Large p - values for Phase I GU, Phase II, III and IV indicate that there was no linear relationship between the fibre dimension series and the lagged relative humidity series. On the other hand, the p - values presented in Table 3.14 for Phase I GC are small, indicating that there was linear relationship between the fibre dimension and relative humidity. Similarly, the p - values, for testing the linear relationship between relative humidity and vessel dimension series, presented in Table 3.14 for Phase I and Phase II GU are small, indicating that there was linear relationship between the vessel dimension series and the lagged relative humidity series. On the other hand, the p - values presented in Table 3.14 for Phase II GC, and Phase IV are large, indicating that there was no linear relationship between the vessel dimension series and the lagged relative humidity series. This result confirms that there was no linear relationship between the vessel dimension series and the lagged relative humidity series Phase II GC, and Phase IV. Moreover, the p - values, for testing the linear relationship between relative humidity and fibre wall series, presented in Table 3.14 are large for Phase I GU, Phase II, Phase III and Phase IV, indicating that there was no linear relationship between the fibre wall series and the lagged relative humidity series. On the

other hand, the *p* - values presented in Table 3.14 for Phase I GC was small, indicating that there was linear relationship between the fibre wall and relative humidity. Finally, the *p* - values presented in Table 3.14 are large for Phase I GU, Phase II, Phase III and Phase IV, indicating that there was no linear relationship between the vessel frequency series and the lagged relative humidity series. On the other hand, the *p* - values presented in Table 3.14 for Phase I GC was small, indicating that there is linear relationship between the vessel frequency and relative humidity.

Table 3. 14: Cross correlation check between lagged relative humidity and wood anatomical characteristics

Cross correlation Check Between Series									
To Lag	DF	FD		VD		FW		VF	
		GC	GU	GC	GU	GC	GU	GC	GU
Phase I									
5	6	0.3114	0.7055	0.4354	0.0683	0.4354	0.0581	0.0004	0.1727
11	12	0.0009	0.9356	0.0172	<.0001	0.0172	0.191	0.0041	0.023
17	18	<.0001	0.977	0.0603	<.0001	0.0603	0.4134	<.0001	0.0393
23	24	<.0001	0.9912	0.052	<.0001	0.052	0.7321	<.0001	0.0901
29	30	<.0001	0.9991	0.0002	<.0001	0.0002	0.8879	<.0001	0.1499
35	36	<.0001	0.9999	0.0003	<.0001	0.0003	0.9726	<.0001	0.1762
Phase II									
5	6	0.0519	0.6986	0.936	0.0247	0.9113	0.3599	0.3603	0.6146
11	12	0.2884	0.9558	0.9707	0.0089	0.9677	0.2138	0.828	0.7069
17	18	0.0349	0.9691	0.9757	0.0184	0.9252	0.1962	0.9648	0.3063
23	24	0.0206	0.6332	0.9831	0.0075	0.0898	0.1202	0.9852	0.2524
29	30	0.0705	0.7697	0.9961	0.0057	0.1061	0.2202	0.993	0.3694
35	36	0.0972	0.6965	0.9664	0.0156	0.2045	0.3964	0.988	0.5445
Phase III									
5	6	0.2176	0.0706	0.2367	0.6332	0.66	0.1427	0.0639	0.4348
11	12	0.5672	0.2595	0.2589	0.8784	0.3862	0.4842	0.1873	0.4215
17	18	0.6444	0.5537	0.1466	0.9642	0.5468	0.4626	0.2077	0.4993
23	24	0.6444	0.8494	0.3242	0.9922	0.0223	0.7278	0.1264	0.5742
29	30	0.7153	0.8902	0.5059	0.9951	0.0604	0.3783	0.0198	0.663
35	36	0.8237	0.938	0.3568	0.9406	0.0773	0.5773	0.04	0.7617
Phase IV									
5	6	0.8757	0.8757	0.4182	0.4182	0.1796	0.1796	0.5295	0.5295
11	12	0.9109	0.9109	0.6959	0.6959	0.2765	0.2765	0.4698	0.4698
17	18	0.8965	0.8965	0.8528	0.8528	0.5824	0.5824	0.6637	0.6637
23	24	0.9404	0.9404	0.9064	0.9064	0.8276	0.8276	0.885	0.885
29	30	0.9891	0.9891	0.9508	0.9508	0.946	0.946	0.9733	0.9733
35	36	0.9944	0.9944	0.9865	0.9865	0.9903	0.9903	0.9958	0.9958

3.3.5 The effects of lagged wind speed on fibre and vessel measurements

The last climatic variable which is an interest to be investigated is wind speed. Here, the objective was to investigate the effects of the lagged wind speed on fibre and vessel characteristics for each phase. The autocorrelation and partial autocorrelation plots in Figures 3.5 suggest that the relative humidity series in Phase I, II, III and IV can be explained by an MA (1,2,6,7), ARMA(3,4), ARMA(4,5) and MA(1) models. In particular, the MA (1, 2, 6, 7), ARMA (3, 4), ARMA (4, 5) and MA (1) models for the wind speed series were the following.

Phase I:

$$(1 - B)wind_t = (1 - 0.57702B^1 - 0.28305B^2 - 0.16274B^6 + 0.1284B^7) Z_t \quad (3.1.5.1)$$

Phase II:

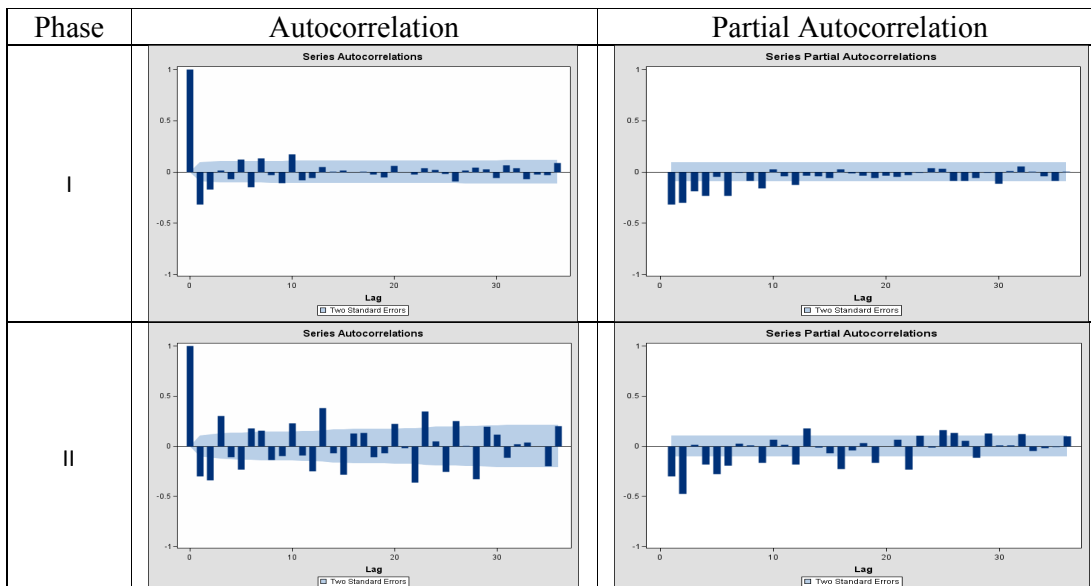
$$(1 - B)wind_t = ((1 - 0.21543B^3 - 0.16613B^6 - 0.13786B^{10} - 0.14886B^{20}) - (1 - 0.55943B^1 - 0.37615B^2 + 0.01663B^{22} - 0.0797B^{28})) Z_t \quad (3.1.5.2)$$

Phase III:

$$(1 - B)wind_t = ((1 + 0.235281B^1 + 2.53477B^2 + 1.65793B^3 + 0.59797B^4)(1 + 1.66877B^1 + 0.67713B^2 - 1.08327B^4 - 0.622809B^5)) Z_t \quad (3.1.5.3)$$

Phase IV:

$$(1 - B)relhum_t = (1 - 0.7541B^1) Z_t \quad (3.3.5.4)$$



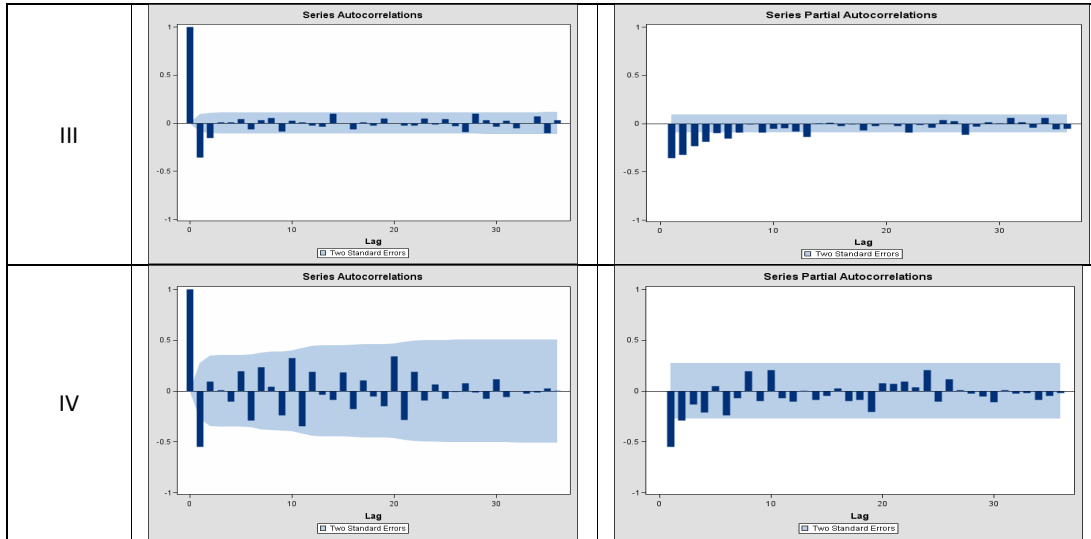


Figure 3. 5: Autocorrelations and partial autocorrelation of the wind speed series Phase I

The residual check for white noise (Table 3.15) indicates that the MA (1,2,6,7), ARMA(3,4), ARMA(4,5) and MA(1) models for wind speed series in Phase I, II, III and IV provides a reasonable good fit to the wind speed since p - values are large. Furthermore, all the MA (1,2,6,7), ARMA(3,4), ARMA(4,5) and MA(1) models parameters are significant at 5% level of significance. This result is presented in Table 3.16.

Table 3. 15: white noise autocorrelation check for wind speed series

Autocorrelation Check of Residuals						
To Lag	Phase I			Phase II		
	Chi-Square	DF	Pr > ChiSq	Chi-Square	DF	Pr > ChiSq
6	4.17	2	0.1245	7	5	0.221
12	20.04	8	0.0521	8.59	11	0.6601
18	19.85	14	0.135	14.09	17	0.6608
24	22.28	20	0.3254	15.66	23	0.8694
30	29.44	26	0.2913	22.83	29	0.7844
36	41.04	32	0.1313	24.81	35	0.8998
42	48.08	38	0.1266	34.37	41	0.7583
48	50.65	44	0.2277	44.85	47	0.5621
	Phase III			Phase IV		
6	1.69	2	0.4286	3.27	5	0.6588
12	6.43	8	0.5988	15.16	11	0.1755
18	10.82	14	0.7001	20.66	17	0.242
24	16.94	20	0.6571	30.52	23	0.1351
30	22.75	26	0.6471	33.71	29	0.2502
36	26.22	32	0.7536	34.85	35	0.4754
42	27.16	38	0.9046			
48	28.45	44	0.9666			

Table 3. 16: Unconditional least square estimation for the wind speed series

Phase I			
Parameter	Estimate	Standard Error	Approx Pr > t
MA1,1	0.57702	0.0442	<.0001
MA1,2	0.28305	0.04599	<.0001
MA1,3	0.16274	0.04631	0.0005
MA1,4	-0.1284	0.04477	0.0043
Phase II			
MA1,1	0.55943	0.05218	<.0001
MA1,2	0.37615	0.05264	<.0001
MA1,4	0.0797	0.03468	0.0222
AR1,1	0.21543	0.0579	0.0002
AR1,2	0.16613	0.05651	0.0035
AR1,3	0.13786	0.05631	0.0149
AR1,4	0.14886	0.05408	0.0062
Phase III			
MA1,1	-1.6688	0.1172	<.0001
MA1,2	-0.6771	0.15256	<.0001
MA1,3	0.65139	0.17385	0.0002
MA1,4	1.08327	0.12961	<.0001
MA1,5	0.62809	0.10166	<.0001
AR1,1	-2.3528	0.11871	<.0001
AR1,2	-2.5348	0.21782	<.0001
AR1,3	-1.6579	0.22159	<.0001
AR1,4	-0.598	0.11839	<.0001
Phase IV			
MA1,1	0.7541	0.09195	<.0001

After filtering the stationary series of wind speed and fibre dimension, vessel dimension, fibre wall and vessel frequency, the cross correlations between the filtered series were calculated. The *p* - values, for testing the linear relationship between wind speed and fibre dimension series, are presented in Table 3.17 for Phase I, II, Phase III GU and Phase IV are large, indicating that there was no linear relationship between the fibre dimension series and the lagged wind speed series. On the other hand, the *p* - values presented in Table 3.17 for Phase III GC are small indicating that there was linear relationship between fibre dimension and lagged wind speed series. On the other hand, the *p* - values presented in Table 3.17 for Phase I, II and Phase IV are large, indicating that there was no linear relationship between the vessel dimension series and the lagged wind speed series. But, the *p* - values presented in Table 3.17 for Phase III are small indicating that there was linear relationship between vessel dimension and lagged wind speed series. The *p* - values, for testing the linear relationship between wind speed and fibre wall series, presented in Table 3.17 are large, indicating that there was no linear relationship between

the fibre wall series and the lagged wind speed series. Finally, the *p* - values, for testing the linear relationship between wind speed and vessel frequency series, presented in Table 3.17 for Phase I and III are small. This result indicates that there was linear relationship between the vessel frequency series and the lagged wind speed series. On the other hand, the *p* - values presented in Table 3.32 for Phase II and IV are large, indicating that there was no linear relationship between the vessel frequency series and the lagged wind speed series.

Table 3. 17: Cross correlation check between lagged wind speed and wood anatomical characteristics

Cross correlation Check Between Series									
To Lag	DF	FD		VD		FW		VF	
		GC	GU	GC	GU	GC	GU	GC	GU
Phase I									
5	6	0.2423	0.6878	0.9818	0.7611	0.0228	0.8528	0.9381	0.3309
11	12	0.649	0.6751	0.9998	0.506	0.0712	0.9968	0.9595	0.062
17	18	0.8881	0.6363	0.9998	0.3987	0.2004	0.9998	0.2325	0.1248
23	24	0.9599	0.7654	0.9999	0.1095	0.4109	0.9999	0.0001	0.0238
29	30	0.9927	0.8502	0.9937	0.254	0.6824	0.9998	0.0006	<.0001
35	36	0.9937	0.9301	0.9538	0.3763	0.8823	1	0.0015	<.0001
Phase II									
5	6	0.8999	0.7398	0.8346	0.7292	0.0625	0.0192	0.0625	0.6484
11	12	0.9878	0.9028	0.8039	0.9786	0.3363	0.1105	0.3363	0.9201
17	18	0.9973	0.7913	0.484	0.9965	0.6754	0.1706	0.6754	0.9857
23	24	0.9992	0.8423	0.387	0.9992	0.0349	0.094	0.0349	0.991
29	30	0.9968	0.8658	0.6693	0.8979	0.0684	0.1891	0.0684	0.9981
35	36	0.9993	0.8538	0.8456	0.966	0.175	0.2953	0.175	0.9997
Phase III									
5	6	0.0109	0.9006	0.0487	0.2677	0.8063	0.9547	0.001	0.0102
11	12	<.0001	0.1722	0.0365	0.1397	0.8824	0.5763	0.0017	0.0415
17	18	<.0001	0.1865	0.0347	0.0209	0.717	0.6721	<.0001	0.0039
23	24	<.0001	0.0553	0.0008	0.0189	0.6874	0.4131	<.0001	0.0027
29	30	<.0001	0.1176	<.0001	0.0333	0.7404	0.3291	<.0001	0.0029
35	36	<.0001	0.0399	<.0001	0.0215	0.7674	0.0835	<.0001	0.0004
Phase IV									
5	6	0.6229	0.6229	0.4132	0.4132	0.7469	0.7469	0.8899	0.8899
11	12	0.6879	0.6879	0.625	0.625	0.889	0.889	0.9154	0.9154
17	18	0.8051	0.8051	0.5166	0.5166	0.9691	0.9691	0.9852	0.9852
23	24	0.8845	0.8845	0.8087	0.8087	0.9938	0.9938	0.9866	0.9866
29	30	0.9356	0.9356	0.9204	0.9204	0.9994	0.9994	0.9974	0.9974
35	36	0.9728	0.9728	0.9829	0.9829	0.9999	0.9999	0.9998	0.9998

3.3 Conclusion

In this chapter, the linear relationship between lagged climatic variables and fibre and vessel characteristics of *Eucalyptus* clones were investigated. Lagged climatic variables refer to the past values of the climatic variables. To obtain the lagged climatic variables, the climatic variables and fibre and vessel characteristics of *Eucalyptus* clones series were prewhitened to obtain the appropriate relationship between fibre and vessel characteristics of *Eucalyptus* clones and climatic variables. During the ARIMA modelling, the seasonality of fibre and vessel characteristics of *Eucalyptus* clones and climatic variables were considered. From the result, it was found that for most of fibre and vessel characteristics of the *Eucalyptus* clones there was no linear relationship between fibre and vessel characteristics of *Eucalyptus* clone and the climatic variables. Since the nine trees have been planted at the same place and measurements for climatic variables taken for all trees once, to perform the analysis for ARIMA modelling, the average of nine trees has been used. The lagged climatic variables obtained (for example, 13 days of temperature for FW Phase I, 29 days of temperature for FD GU Phase II, 15 days of temperature for VD GU Phase III, etc) in the ARIMA modelling will be used for the longitudinal linear modelling of fibre and vessel characteristics of the *Eucalyptus* clone.

4. Assessment of climatic factors affecting the wood anatomy

We investigate the effects of the climatic factors on the wood anatomical characteristics represented by principal components (PCs): Vessel Dimension (VD), Fibre Dimension (FD), Fibre Wall (FW) and Vessel Frequency (VF). As reported in Section 2.2, there is large variability in the wood anatomical characteristics of the nine trees of each clone. Hence, to account for tree to tree variability, the tree effect should be included in the models for the wood anatomical properties. Furthermore, wood anatomical characteristics were measured from the center to the outside of the tree stem on each of the 9 trees per clone repeatedly over time. Since the measurements are repeated over time, the longitudinal linear mixed model is suitable to model the data. The relevant theory of the longitudinal linear mixed model is discussed in Section 4.1. The results of fitting the longitudinal linear mixed model to the wood anatomical characteristics data are presented in Sections 4.2.

4.1 Linear Mixed model

The linear mixed model was first developed for applications in animal genetics and breeding research (Henderson *et al.* 1959). The model consists of both fixed and random effects. Fixed effects are effects which can be used only if the interest is in the effects of the levels of the factors used in the experiment. On the other hand, the effect is random if the levels in the study are randomly selected and the interest is in the effect of the population of the levels of a factor or factors. Repeated measurement data refers to data generated by measuring some specified characteristic(s) of the experimental/sampling unit(s) repeatedly over time. The experimental/sampling unit is called subject. Therefore, with repeated measurements, one can capture within subject changes. To account for the within subject changes of a certain response over time, the longitudinal models can be used. The term “longitudinal data” is also used to describe repeated measurements. The main objective of a longitudinal study is to characterize the change of the responses over time and the factors that influence the change of the response (Davis 2002).

In general, when repeated measures of responses taken from each of subject from certain population, we can have two types of variability. These are the within subject variability and the between subject variability. For subject $i=1, 2, \dots, k$, let $\mathbf{y}_i = (y_{i1}, \dots, y_{in})'$ be an $n \times 1$ vector of responses. Then the general linear mixed model for the response \mathbf{y}_i can be written as

$$\mathbf{y}_i = \mathbf{X}_i\boldsymbol{\beta} + \mathbf{Z}_i\mathbf{u}_i + \boldsymbol{\varepsilon}_i, \quad i = 1, 2, \dots, k \quad (4.1)$$

where

$\boldsymbol{\beta}$ is a $p \times 1$ vector of fixed effects;

\mathbf{y}_i is an $n \times 1$ vector of observed responses;

\mathbf{X}_i is an $n \times p$ design matrix associated with $\boldsymbol{\beta}$;

\mathbf{u}_i is a $q_i \times 1$ vector of independent random effects with a $N(\mathbf{0}, \mathbf{I}_{q_i}\sigma_i^2)$ distribution;

\mathbf{Z}_i is an $n \times q_i$ design matrix associated with \mathbf{u}_i , where \mathbf{u}_i is a $q_i \times 1$ vector of independent random variables with a $N(0, \sigma_i^2)$ distribution, $i = 1, 2, \dots, k$,

$\boldsymbol{\varepsilon}_i$ is an $n \times 1$ vector of random errors from a $N(0, \mathbf{I}_n\sigma_e^2)$, and \mathbf{u}_i and $\boldsymbol{\varepsilon}_i$ are mutually independent.

The random effects vectors \mathbf{u}_i are assumed to be independent and normally distributed with mean vector $\mathbf{0}$ and variance – covariance \mathbf{G} , i.e. $\mathbf{u} = [\mathbf{u}_1' | \mathbf{u}_2' | \dots | \mathbf{u}_k'] \sim N(\mathbf{0}, \mathbf{G})$, where \mathbf{G} is a block diagonal with the i^{th} block $\sigma_i^2\mathbf{I}_{q_i}$, and the error vectors $\boldsymbol{\varepsilon}_i$ are assumed to be independent and normally distributed with mean vector $\mathbf{0}$ and variance – covariance matrix \mathbf{R}_i , i.e. $\boldsymbol{\varepsilon}_i \sim N(\mathbf{0}, \mathbf{R}_i)$, for $i = 1, 2, \dots, k$. Here, \mathbf{G} and \mathbf{R}_i are $q \times q$ (where, $q=q_1 + q_2 + \dots + q_k$) and $n \times n$ matrices respectively. Under the assumption of normality and independence for \mathbf{u}_i and $\boldsymbol{\varepsilon}_i$, the marginal distribution of the response y_i is normal with mean $\mathbf{X}\boldsymbol{\beta}$ and variance – covariance matrix \mathbf{V}_i where $\mathbf{V}_i = \sigma_e^2\mathbf{I}_n + \mathbf{Z}\mathbf{G}\mathbf{Z}' = \sigma_e^2\mathbf{I}_n + \sum_{i=1}^r \sigma_i^2\mathbf{Z}_i\mathbf{Z}_i'$ (Zewotir and Galpin 2004). Estimation of σ_e^2 —and the σ_i^2 is done using either the analysis of variance (ANOVA) method, or the maximum likelihood and the restricted/residual maximum likelihood methods under the assumption of normality and independence for \mathbf{u}_i and $\boldsymbol{\varepsilon}_i$. The methods are described in the next section.

4.1.1 Estimation of the fixed effects and the variance components

In linear mixed models analysis, it is necessary to estimate the fixed effects and the variance components, and also to predict the random effects. For a given data vector $\mathbf{y} = [\mathbf{y}'_1 | \mathbf{y}'_2 | \dots | \mathbf{y}'_k]$ that is described by model (4.1), the vectors of the random effects \mathbf{u}_i are unobservable and have to be predicted from the data (Henderson 1953).

Before estimation of the fixed effects β , it is necessary to assume that the vector of the variance components $\alpha = (\sigma_e^2, \sigma_1^2, \sigma_2^2, \dots, \sigma_k^2)'$ is known. The vector of the fixed effects β can be estimated using the method of maximum likelihood (Davis 2002). The relevant likelihood function of β , given the variance components, is given by

$$L_m(\beta) = \prod_{i=1}^k \{2\pi\}^{-\frac{n}{2}} |V_i(\alpha)|^{-1/2} \times \exp\left(-\frac{1}{2}(\mathbf{y}_i - \beta \mathbf{X}_i)' V_i^{-1}(\alpha) (\mathbf{y}_i - \mathbf{X}_i \beta)\right).$$

The maximum likelihood estimator of β is the value of β which maximizes $L_m(\beta)$.

Differencing $\ln(L_m(\beta))$ with respect to β gives

$$\frac{\partial L}{\partial \beta} = \sum_{i=1}^k (\mathbf{X}'_i \mathbf{V}_i^{-1} \mathbf{y}_i - \mathbf{X}'_i \mathbf{V}_i^{-1} \mathbf{X}_i \beta) \quad (4.2)$$

Equating (4.2) to zero, and solving the resultant equation for β gives the maximum likelihood estimator of β as

$$\hat{\beta} = \left(\sum_{i=1}^k \mathbf{X}'_i \mathbf{W}_i \mathbf{X}_i\right)^{-1} \sum_{i=1}^k \mathbf{X}'_i \mathbf{W}_i \mathbf{y}_i, \quad \mathbf{W}_i = \mathbf{V}_i^{-1} \quad (4.3)$$

with variance –covariance matrix

$$\text{Var}(\hat{\beta}) = \left(\sum_{i=1}^k \mathbf{X}'_i \mathbf{V}_i^{-1} \mathbf{X}_i\right)^{-1}.$$

The estimates of the fixed effects depend on the variance components α (Verbeke and Molenberghs 2000).

In practice, linear mixed models often contain many fixed effects. Therefore, it is important to estimate the variance components σ_e^2 and the σ_i^2 explicitly taking into account the loss of the degrees of freedom involved in estimating the fixed effects (Verbeke and Molenberghs 2000). The variance components can be estimated using the analysis of variance (ANOVA), maximum likelihood or restricted maximum likelihood methods.

The ANOVA method can be used for balanced data where the number of observations in the subclasses of the data formed by the factor level combinations is the same. An analysis of variance of the data is performed to obtain the mean sum of squares of the effects in the model. Then the equations formed by equating the mean sum of squares to their corresponding expected values are solved simultaneously for the variance components. Estimating variance components from unbalanced data is not straight forward. Therefore, for unbalanced data, Henderson (1953) describes three ways of estimating the variance components. These are the Henderson's methods I, II and III (Henderson 1953). However, the application of the ANOVA method is limited for balanced data only. Another disadvantage of ANOVA method is that it sometimes gives negative variance estimates.

To use Maximum likelihood (ML) estimation method, it is necessary to assume the probability distribution of the data. The natural choice of the probability distribution is the normal distribution. The normality distribution is assumed because it leads to mathematically tractable methodology including for unbalanced data (Searle, Casella et al. 1992). The ML estimates of the variance components are values of the components which maximize the marginal likelihood function. The marginal likelihood function is given by

$$L_{ML}(\theta) = \prod_{i=1}^k \{2\pi\}^{-\frac{n}{2}} |V_i(\alpha)|^{-1/2} \times \exp\left(-\frac{1}{2}(\mathbf{y}_i - \beta\mathbf{X}_i)'V_i^{-1}(\alpha)(\mathbf{y}_i - \mathbf{X}_i\beta)\right) \quad (4.4)$$

where θ is s- dimensional vector of all parameters in the marginal model.

The maximum likelihood estimator of β and α is obtained by maximizing the marginal likelihood function with respect to β and α . Maximizing the likelihood function with respect to β and α requires solving the equation

$$\frac{\partial L_{ML}}{\partial \beta} = 0 \text{ and } \frac{\partial L_{ML}}{\partial \alpha} = 0$$

for β and α simultaneously. The first equation yields

$$\hat{\beta} = \left(\sum_{i=1}^k \mathbf{X}'_i \mathbf{W}_i \mathbf{X}_i\right)^{-1} \sum_{i=1}^k \mathbf{X}'_i \mathbf{W}_i \mathbf{y}_i, \quad \mathbf{W}_i = \mathbf{V}_i^{-1}$$

as shown above in equation (4.3). Thus, $\hat{\beta}$ is a function of α and can be written as $\hat{\beta}(\alpha)$. Substituting $\hat{\beta}(\alpha)$ into L_{ML} yields this log – likelihood as a function of α . The ML estimator of α can be found by solving the equation $\frac{\partial L_{ML}}{\partial \alpha} = 0$ (Verbeke and Molenberghs 2000). Therefore, in practice the equation $\frac{\partial L_{ML}}{\partial \alpha} = 0$ is solved numerically by iteration, e.g. using the Newton Raphson method. Hence, substituting α by $\hat{\alpha}$ in $\hat{\beta}(\alpha)$ gives the ML estimator of β , i.e. $\hat{\beta} = \hat{\beta}(\hat{\alpha})$.

To estimate model parameters by the restricted maximum likelihood (REML), first we have to combine all the k subjects mixed models (4.1) into one model to get

$$\mathbf{y} = \mathbf{X}\beta + \mathbf{Z}\mathbf{u} + \boldsymbol{\varepsilon} \quad (4.5)$$

where the vectors \mathbf{y} , \mathbf{u} , and $\boldsymbol{\varepsilon}$, and the matrix \mathbf{X} are obtained from stacking the \mathbf{y}_i vectors, the \mathbf{u}_i vectors, and the $\boldsymbol{\varepsilon}_i$ vectors, and \mathbf{X}_i matrices, respectively, and where \mathbf{Z}_i is the block diagonal matrix with the Z_i matrices on the main diagonal and zero elsewhere. The dimension of \mathbf{y} is n . Here, it is assumed that the distribution of \mathbf{y} is normal with mean vector $\mathbf{X}\beta$ and with covariance matrix $V(\alpha)$ equal to the block – diagonal matrix with the V_i covariance matrices on the main diagonal and zero elsewhere (Verbeke and Molenberghs 2000). The REML estimator of the variance components α is obtained from maximizing the likelihood function of a set of error contrasts $\mathbf{U} = \mathbf{A}'\mathbf{Y}$ where \mathbf{A} is any $(n \times (n - p))$ full rank matrix whose columns are orthogonal to the columns of the \mathbf{X} matrix. Here, the vector \mathbf{U} follows a normal distribution with mean vector zero and covariance matrix $\mathbf{A}'V(\alpha)\mathbf{A}$, i.e. $\mathbf{A}\mathbf{Y} \sim N(\mathbf{0}, \mathbf{A}\mathbf{V}\mathbf{A}')$ which is independent of β . Therefore, the likelihood function of the error constraints is given by

$$\begin{aligned} L(\alpha) = & (2\pi)^{-(n-p)/2} |\sum_{i=1}^k \mathbf{X}'_i \mathbf{X}_i|^{1/2} \times |\sum_{i=1}^k \mathbf{X}'_i \mathbf{V}_i^{-1} \mathbf{X}_i|^{-1/2} \prod_{i=1}^k |\mathbf{V}_i|^{1/2} \\ & \times \exp \left\{ -\frac{1}{2} \sum_{i=1}^k (Y_i - \mathbf{X}_i \hat{\beta})' \mathbf{V}_i^{-1} (Y_i - \mathbf{X}_i \hat{\beta}) \right\} \end{aligned} \quad (4.6)$$

where $\hat{\beta}$ is given by (4.3) (Harville 1974). The REML estimator $\hat{\alpha}$ can be obtained by maximizing (4.6) using an iterative procedure. Note that the likelihood function (4.6) and the REML estimator of α do not depend on the error constraints (that is the choice of \mathbf{A}).

Both ML estimation and REML estimation have the same merits of being based on the likelihood principle which leads to useful properties such as consistency, asymptotic normality and efficiency. Estimation of the fixed effects can be done using the ML method and cannot be done using the REML method. Moreover, when the data is balanced, the ANOVA and the REML estimates of the variance components are identical. One criticism of ML approach to estimate the variance components is that it takes no account of the loss of the degree of freedom that results from estimating the fixed effects. Therefore, the ML estimates of the variance components are biased downward (Verbeke and Molenberghs 2000).

4.1.2 Covariance structures

When fitting linear mixed models to the data, the choice of the covariance structures for both the random errors and the random effects is important. Selection of the covariance structure of the random errors needs to be conditional on the selected structure for the covariance of the random effects, as together these will describe all the model variance. If the random effects are chosen correctly, it can be assumed that the random effects account for most of the variability in the data and therefore simple, parsimonious models for both the error and random effects covariance structure can be chosen (Demidenko 2004). In order to select the best fitting covariance structure for a linear mixed model, for both the random errors and the random effects, the literature recommends using likelihood based tests (Verbeke and Molenberghs 2000).

In modelling the covariance structure of data, the SAS PROC MIXED procedure (SAS 9.1.3) provides a rich assortment of covariance structures from which to select. The simplest covariance structure is the variance components (VC) covariance structure. This structure assumes that there is no correlation between observations and there is constant variance, σ^2 , across all measurements. The VC covariance structure has the following form.

$$\sigma^2 \begin{bmatrix} 1 & 0 & 0 & \dots & 0 \\ 0 & 1 & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & 1 \end{bmatrix} \quad (4.7)$$

Only one parameter σ^2 needs to be estimated for this covariance structure.

The most commonly used structures in longitudinal mixed models (4.1) are the compound symmetric (CS), autoregressive order one (AR (1)) and the unstructured (UN). If measurements are taken through time, observations taken more closely in time are likely to be more highly correlated, and in this case it may be more appropriate to use AR structure (Crowder and Hand 1990). The most commonly used AR structure is an AR(1). This covariance structure assumes the variance across all occasions is the same and the correlation between two points one time/distance unit apart would be ρ , two time/distance units apart would be ρ^2 , three time/distance units apart would be ρ^3 , etc. As a result, the correlation value tends to zero as the observations gets further and further apart (Fitzmaurice *et al.* 2004). Therefore, AR (1) covariance structure has the following form.

$$\sigma^2 \begin{bmatrix} 1 & \rho & \rho^2 & \dots & \rho^{n_i-1} \\ \rho & 1 & \rho & \dots & \rho^{n_i-2} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \rho^{n_i-1} & \rho^{n_i-2} & \rho^{n_i-3} & \dots & 1 \end{bmatrix} \quad (4.8)$$

For this covariance structure, two parameters σ^2 and ρ need to be estimated.

The CS covariance structure has two unknown parameters; variance and correlation. That is, the correlation between occasions is assumed to remain constant. CS covariance structure has the following form:

$$\sigma^2 \begin{bmatrix} 1 & \rho & \rho & \dots & \rho \\ \rho & 1 & \rho & \dots & \rho \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \rho & \rho & \rho & \dots & 1 \end{bmatrix} \quad (4.9)$$

where ρ is the correlation and σ^2 is the variance (Millikan and Johnson 2000).

In unstructured (UN) covariance structure all the variances of any two occasions are different and the covariances of any two occasions are different. Therefore, for the UN structure, there are no mathematical constraints imposed on the elements of the covariance matrix. Thus, unstructured covariance have no structure (Millikan and Johnson 2000). The UN covariance structure has the following form

$$\begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} & \dots & \sigma_{1n_i} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} & \dots & \sigma_{2n_i} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \sigma_{n_i1} & \sigma_{n_i2} & \sigma_{n_i3} & \dots & \sigma_{n_in_i} \end{bmatrix} \quad (4.10)$$

When the covariance structure is UN, so that the covariance between any two observations from the same subject could be estimated to have a different value, then $n_i(n_i + 1)/2$ variance parameters will need to be estimated (Fitzmaurice *et al.* 2004). The loss of degrees of freedom due to the large number of estimated variance components would cause a decrease in the precision of the estimated parameters of interest or even a failure in fitting the model.

The problem now is how to decide which of the covariance structures to assume in the model of a given data set. This decision process can be assisted by using three model-fit criteria, the Akaike's Information Criterion (AIC), the finite-sample corrected version of AIC (AICC) and Schwarz' Bayesian Information Criterion (BIC). These are essentially log likelihood values penalized for the number of parameters estimated; hence the criteria reported here should only be used to compare models with the same mean structure but with different covariance structures. The BIC however imposes a heavier penalty than AIC. The covariance structure with the smallest values of the criteria is considered most desirable. These values can be obtained from the "Fit Statistics" table after applying the SAS PROC MIXED procedure. The interest in the covariance structure is not for its own right but for obtaining a good model for the covariance structure so that computations and inferences about the fixed effects are valid (Verbeke and Molenberghs 2000).

4.1.3 Model reduction

For model reduction of fixed effects, a full model of all possible effects is compared with reduced models (after removing/dropping insignificant fixed effects starting with the highest order interaction effects) to obtain the best simple model. For each parameter $\beta_i, i = 1, \dots, p$, an approximate Wald test can be obtained from approximating the distribution of $(\hat{\beta}_i - \beta_i)/\widehat{se}(\hat{\beta}_i)$ by the standard normal distribution, where $\widehat{se}(\hat{\beta}_i)$ is the standard error of $\hat{\beta}_i$ (Verbeke and Molenberghs 2000). Let \mathbf{L} denote a matrix of known weights and the interest is to test

$$H_0: \mathbf{L}\beta = 0 \quad Vs \quad H_A: \mathbf{L}\beta \neq 0 \quad (4.11)$$

Because the Wald test statistics are based on estimated standard errors, it under estimates the true variability in $\hat{\beta}$. This is because they do not take into account the variability introduced by estimating α of the variance components (Dempster and Tsutakawa 1981). To resolve this situation, approximate Student t and F statistics for testing hypothesis about β can be used (Verbeke and Molenberghs 2000). For each parameter $\beta_i, i = 1, \dots, p$ an approximate t – test can be obtained by approximating the distribution of $(\hat{\beta}_i - \beta_i)/\widehat{se}(\hat{\beta}_i)$ by an appropriate Student t – distribution. Moreover, the test of the linear hypothesis of the form (4.11) is based on the test statistic

$$F = \frac{(\hat{\beta} - \beta)' \mathbf{L}' \left[\mathbf{L} \left(\sum_{i=1}^k \mathbf{X}_i' \mathbf{V}_i^{-1} (\widehat{\alpha}) \mathbf{X}_i \right)^{-1} \mathbf{L}' \right]^{-1} \mathbf{L} (\hat{\beta} - \beta)}{\text{Rank}(\mathbf{L})} \quad (4.12)$$

which is distributed as F distribution with the denominator degrees of freedom can be estimated from the data and the numerator degrees of freedom are equal to rank (\mathbf{L}).

On the other hand, the likelihood ratio test (LR) is used to compare the models. The LR test is a classical statistical test for the comparison of nested models with different mean structures. The LR test statistic is defined as

$$-2 \ln \lambda_n = -2 \ln \left[\frac{L_{ML}(\hat{\beta}_{ML,0})}{L_{ML}(\hat{\beta}_{ML})} \right] \quad (4.13)$$

where $\hat{\beta}_{ML,0}$ and $\hat{\beta}_{ML}$ are the respective maximum likelihood estimates of fixed effects which maximize the likelihood functions of the full and reduced models. The LR test statistic has a chi-square distribution with the degrees of freedom equal to the difference between the numbers of parameters in the two models. The above test statistic and its distribution is not valid if the models are fitted using the REML method (Snijders and Bosker 1999). The -2 times the log likelihoods for the full and the reduced models can be obtained from the “Fit Statistics” table after running PROC MIXED for each of the two models. Then the LR test statistic is calculated using (4.13).

Similar to fixed effects, likelihood ratio test can be derived for variance component inference. The hypothesis of interest about the vector of variance components α could be $H_0: \alpha \in \Theta_{\alpha,0}$ for some subspace $\Theta_{\alpha,0}$ of the parameter space Θ_{α} of the vector of variance component α (Cox and Hinkley 1994). Then the LR test statistic become

$$-2\ln\lambda_n = -2\ln \left[\frac{L_{ML}(\hat{\alpha}_{ML,0})}{L_{ML}(\hat{\alpha}_{ML})} \right] \quad (4.14)$$

where, $\hat{\alpha}_{ML,0}$ and $\hat{\alpha}_{ML}$ are the respective maximum likelihood estimates under the reduced and full model, respectively. These estimates of the variance components obtained by maximizing likelihood function over $\theta_{\alpha,0}$ and θ_{α} . Based on the classical likelihood theory, $-2\ln\lambda_n$ follows asymptotically chi-square distribution under H_0 with degrees of freedom which are equal to the difference between dimensions of $\theta_{\alpha,0}$ and θ_{α} . For inference about the variance components, the LR test suffers from the same problems as the Wald test for fixed effect tests. However, valid LR tests can be obtained under REML estimation. The test statistic given in (4.14) can be used by replacing L_{ML} with REML likelihood function, L_{REML} which is given by

$$L_{REML}(\alpha) = \left| \sum_{i=1}^k \mathbf{X}_i' \mathbf{W}_i(\alpha) \mathbf{X}_i \right|^{-1/2} L_{ML}(\alpha) \quad (4.15)$$

Therefore, the parameter estimates of $\theta_{\alpha,0}$ and θ_{α} are replaced by the corresponding REML estimates (Verbeke and Molenberghs 2000).

In general, the REML LR test statistic which is given by

$$-2\ln\lambda_n = -2\ln \left[\frac{L_{REML}(\hat{\alpha}_{ML,0})}{L_{REML}(\hat{\alpha}_{ML})} \right] \quad (4.16)$$

performs slightly better than the ML test statistic in the sense that, on average, the rejection proportions are closer to the nominal level for the REML test statistic than for the ML test statistic (Verbeke and Molenberghs 2000). For the longitudinal mixed model, testing is done by deleting one random effect at a time from the model starting with the highest-order effect and testing for significance of whether the deleted random effect is needed in the model.

4.1.4 Assessing the goodness-of-fit of the model

After fitting the model, the next step is to check the assumptions of the model, i.e. to check if the normality assumption for the random effects and the behaviour of residuals is appropriate. Here, we can use the probability plots, and tests using the Shapiro-Wilk test and the Kolmogorov-Smirnov test to assess the normality assumptions. Specifically the W-statistic (in the Shapiro-Wilk test), suggested by (Shapiro and Wilk 1965) has been shown to be a good omnibus test of normality.

Sometimes the assumption of the random effects can be violated by longitudinal data. In most cases, histograms and scatter plots of the random components and the residuals are often used for the diagnostic purposes. In particular, the scatter plots are used to pinpoint outlying observations which arise from subjects that seem to evolve differently from the other subjects in the sample. But, the histograms of the residuals can be used to check for the normality of the random effects and the error terms.

Assessment of model misfit or appropriateness can also be done using information criteria. Residual analysis can also be used to assess model misfit or appropriateness. In general, the information criteria can be used to assess the fit of longitudinal models. The choice of the best model will be dependent on the criteria chosen for assessing model adequacy.

To select the best model, the Akaike's information criterion (AIC) and Schwarz's Bayesian information criterion (BIC) can be used (Verbeke and Molenberghs 2000). The AIC is defined as:

$$\begin{aligned} \text{AIC} &= -2(\text{maximised log-likelihood}) + 2(\text{number of parameters}) \\ &= -2\hat{L} + 2p \end{aligned}$$

where, L is maximized log-likelihood and p is number of parameters in the covariance parameters, and the BIC is defined as:

$$\begin{aligned} \text{BIC} &= -2(\text{maximised log-likelihood}) + \log N (\text{number of parameters}) \\ &= -2\hat{L} + kp \log \end{aligned}$$

where k is the number of subjects and p is the number of parameters (Fitzmaurice *et al.*, 2004). According to the two criteria, the best model among the competing models is one that has the smallest AIC or BIC. (Duong 1984) states that models that are within two units of the lowest AIC can be considered as competitive for the best model. Models can then be selected according to those that have the fewest number of parameters, and this will be achieved by comparing the BIC of these models, as it penalises the number of parameters more strictly (Fitzmaurice *et al.* 2004).

Outlier and influence diagnostic is essential for a valid inference. (Zewotir and Galpin 2005) extended influence diagnostics for linear mixed models, from the ordinary linear regression influence diagnostics. The statistics which have been extended included Cook's distance (Cook 1977), the likelihood distance (Cook and Weisberg 1982), the variance (information) ratio (Belsley, Kuh et al. 1980) and the Cook-Weisberg statistic (Cook and Weisberg 1980). As shown in Zewotir and Galpin (2005) a one step form of the diagnostics adequately provide information on the influence of the data on various aspects of model fit. These statistics were tested using clustered, but not longitudinal, data. The sensitivity of these statistics have been studied by (Zewotir and Galpin 2006) and they found that these statistics are capable of detecting influential points, but masking effects could occur under certain circumstances, for example when there are multiple outliers in the same observation. (Demidenko and Stukel 2005) have also proposed extensions to the leverage, infinitesimal influence, case deletion diagnostics, Cook's distance, and local influence used for regression models to accommodate linear mixed effects models, which are in the form of explicitly defined functions.

4.2 Application of the linear mixed model to the wood anatomy data

The effect of climatic conditions on the wood fibre and vessel characteristics of *Eucalyptus* tree is assessed by accounting for the effect of the age of the tree. Accordingly, we fit a mixed model with the age and climatic variables as fixed effects and trees as random effects. The climatic variable effects include the lagged climatic variables (as discussed in Chapter 3) and the interaction between climatic variables. Moreover, the season effect is included in the model in order to assess the interaction between the season and climatic variables.

It is important to note that the relationship between age and anatomical variables is not linear (refer Chapter 2). Of all possible transformations, the square root of age is linearly related with the anatomical variables. Accordingly, throughout the analysis the square root of age is used instead of the age itself. Moreover, we assessed the effect of climatic variables on the wood anatomy (i) using the daily average climatic measurements, obtained from dendrometer trial experiment (ii) by categorizing the daily climatic measurements obtained from dendrometer experiment as high, low and normal. In case

(i), the daily climatic variable takes any values between 0 and 58. Accordingly, case (i) is referred as continuous climatic variable effect. On the other hand, case (ii) is referred as categorical climatic variable effect.

In the case of continuous climatic variable effect, our interest is to assess the rate of change of the wood anatomy for a unit change in the climatic variable. In the case of categorical climatic variables, our interest is to assess if the wood anatomy is identical at high, low and normal climatic conditions. The effect of categorized climatic variables on the wood anatomy is presented in Section 4.2.1. The assessment of the continuous climatic variables is discussed in Section 4.2.2. The comparison of the analysis of the categorical and continuous climatic variables is presented in Section 4.2.3.

4.2.1 The effect of categorized climatic variables on the wood anatomy

The response of the tree may be different at different levels of the climatic variables i.e., for high, low or normal levels of climatic variables. So, it is useful to classify and assess the effects of the climatic variables on fibre and vessel characteristics of a tree. The categories or levels of each climatic variable are given in Table 4.1. Except for temperature, the boundary values of the climatic variables were the first and third quantiles obtained from the fifty years Zululand area data where the Sappi Dendrometer experiment is conducted. In the case of temperature, the classification was done according to the fact that the normal mean annual temperature (MAT) for Zululand is between 21 and 22 degrees centigrade. Furthermore, the classification for rainfall was done on the seven day moving sum (seven day cumulative sum) of the fifty years daily rainfall data obtained from the Zululand area.

Table 4. 1: Categories/levels of the climatic variables

Variable	Low	Normal	High
Temperature	< 21	[21,22]	> 22
Rainfall (seven day cumulative)	< 2	[2,4]	> 4
Solar radiation	<=0.4	(0.4,0.6]	> 0.6
Relative humidity	<=79	(79,86.54]	> 86.54
Wind speed	<=1.17	(1.17,2.05]	> 2.05

The table of categorical climatic variables by season for each phase are displayed in Table 4.2. Season was classified as Summer from Dec 22 – Mar 21, Autumn from Mar 22 – June 21, Winter from June 22 – Sept 21 and Spring from Sept 22 – Dec 21. Table 4.2

shows that the phases had similar temperature distributions. However, within each phase, the seasons had different temperature distributions. For example, for temperature in Summer, 91.11% were high. However, for Autumn, Winter and Spring high temperature is 18.4%, 2.21% and 36.26% respectively. Similar to temperature, the seasons had different distributions of rainfall, solar radiation, relative humidity and wind speed. Moreover, the phases had different distributions of rainfall, solar radiation, relative humidity and wind speed. As we can see in the table, for example for rainfall, low rainfall were found to be 22.84 %, 17.9 %, 56.03 % and 13.33 % for Phase I, II, III and IV. This shows that phases have different percentage distributions.

Table 4. 2 Percentage for the levels of climatic conditions by season and phase

Temperature												
season	Phase I			Phase II			Phase III			Phase IV		
	Low	Normal	High	Low	Normal	High	Low	Normal	High	Low	Normal	High
Summer	5.56	3.33	91.11	6.74	8.82	84.44	33.33	3.33	63.33	0	0	100
Autumn	68.1	13.5	18.4	63.04	13.04	23.91	60.87	9.78	29.35	69.23	7.69	23.08
Winter	93.38	4.41	2.21	97.8	1.17	1.04	83.81	6.67	9.52	100	0	0
Spring	46.15	17.58	36.26	47.62	9.52	42.86	47.22	11.03	41.75	25	25	50
Rainfall												
Summer	22.84	12.96	64.2	17.9	11.54	70.56	56.03	4.76	39.21	13.33	13.33	73.33
Autumn	38.31	10.29	51.4	35.51	10.02	54.47	63.98	10.25	25.78	0	30.77	69.23
Winter	29.58	11.36	59.07	37.82	10.75	51.42	66.67	13.61	19.73	38.46	7.69	53.85
Spring	26.13	9.77	64.1	19.05	13.1	67.86	62.67	5.21	32.13	25	18.75	56.25
Solar radiation												
Summer	10	8.89	81.11	73.93	6.36	19.71	60	34.44	5.56	66.67	33.33	0
Autumn	18.4	57.06	24.54	27.17	33.7	39.13	85.87	14.13	0	100	0	0
Winter	30.15	55.15	14.71	64.64	15.8	19.56	86.67	13.33	0	100	0	0
Spring	12.09	21.98	65.93	14.29	20.24	65.48	53.22	41.22	5.56	31.25	62.5	6.25
Wind speed												
Summer	5.56	74.44	20	20.75	15.56	63.68	52.22	42.22	5.56	0	66.67	33.33
Autumn	47.85	45.4	6.75	51.09	27.17	21.74	42.39	54.35	3.26	15.38	76.92	7.69
Winter	33.09	55.15	11.76	39.64	49.48	10.88	32.38	61.9	5.71	0	100	0
Spring	9.89	42.86	47.25	5.95	57.14	36.9	17.3	44.13	38.57	0	62.5	37.5
Relative humidity												
Summer	27.78	37.78	34.44	34.76	41.37	23.87	87.78	12.22	0	73.33	26.67	0
Autumn	22.7	28.83	48.47	10.87	31.52	57.61	81.52	18.48	0	76.92	23.08	0
Winter	24.26	32.35	43.38	5.31	19.17	75.52	79.05	17.14	3.81	61.54	38.46	0
Spring	39.56	29.67	30.77	38.1	30.95	30.95	91.7	7.15	1.15	62.5	37.5	0

To fit the analysis of covariance model for the fibre and vessel characteristics of *Eucalyptus* tree, the fixed effects were climatic variables effects, season, age of tree effects and interaction effects between fixed effects, and the random effects were tree effects and tree by age of tree interaction effects. The lagged climatic variables were used as factors in the model because in Chapter 3 it was found that wood anatomical characteristics are linearly related to some of the climatic variables. The model selection process for fixed effects interaction was started by removing the insignificant highest order interaction effects from the full model then refitting the reduced model. This process continued until the final reduced model was obtained.

To choose the appropriate covariance structure, the model was fitted with ANTE (1), AR (1), ARH (1), ARMA (1, 1), CS, CSH, HF, TOEP, TOEPH, UN and VC covariance structures. From these covariance structures, the Compound symmetry (CS) and AR (1) were found to be the best covariance structures for between and within subject effects respectively. The compound symmetry and first order autoregressive AR (1) covariance structures forms are presented in Section 4.1.2. To choose the best covariance structure, we have used Akaike's information criterion. The Akaike's information criterion (AIC) is equal to $-2 \text{ Res Log Likelihood} + 2 \times \text{number of parameters}$ in the covariance parameter structure model (Littell, Milliken et al. 2006). Here, AICC is the AIC corrected. It is the version of AIC which is adjusted for the effects of estimating parameters on the AIC itself (Burnham and Anderson 1998). BIC (Bayesian information criterion) is also based on $-2 \text{ Res Log Likelihood}$. This value charges penalty when we have large number of parameters. The models were fitted using SAS PROC MIXED (ver. 9.1.3).

For this chapter from the four PCs of the fibre and vessel characteristics, the results for FW will be discussed. The results for other three PCs will be presented briefly in this chapter. The detailed interpretation of FD, VD and VF will be discussed in Chapter 5. The result for tests for fixed effects for Fibre Wall (FW), which includes climatic variables (including lagged variables) effects, season, age of tree effects, and interaction effects between fixed effects is presented in Table 4.3. The p -values for testing the significance of the effects in the final reduced model for Phase II, III and IV are displayed

in Table A.10 - A.12. After fitting the full model, the significant effects, at the 0.05 level of significance, are explained. To test the fixed effects we used the type 3 test. The type 3 test represents the effect of each term to the model by including all other possible terms (Dear and Everitt 2006). The usual Analysis of Covariance (ANCOVA) model error assumptions for these models (for FW) were checked using the residual plots in Figure 4.1 for Phase I and Figure B.32 for Phase II, III and IV. From the plots, the first plot is of the predicted values against studentized residuals. This plot show that the studentized residuals vary between 2 and -2 for both clones. The next two plots are a histogram and q-q plot of studentized residuals, and intended to show the normality of the studentized residuals. These plots show that the usual assumptions of the linear mixed model were not seriously violated by the data for Phase I. Similarly, from the plots Figure B.32, it can be observed that the usual model assumptions for Phase II, III and IV were not seriously violated by the data.

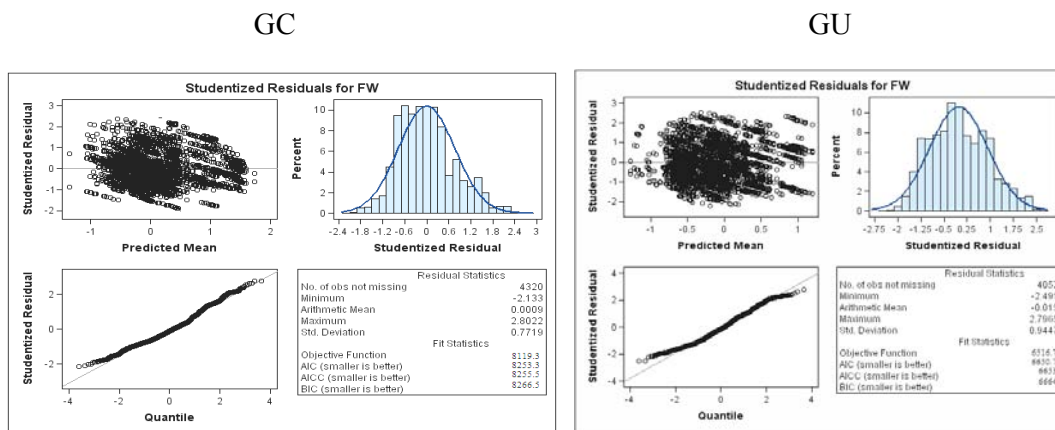


Figure 4. 1: Plots of studentized Residuals for FW for GC and GU Phase I

Table 4.3 shows the significant effects of the fixed effects for FW for Phase I. As we can see from the table the significant effects with p – values were Season ($<.0001$), Tempn ($<.0001$), Humc (0.0073), Solarc (0.0194), temp_lag13c (0.0078), sqtage*season ($<.0001$), season*rainn ($<.0001$), season*solarc (0.003), season*speedc (0.0279), season*temp_lag13c (0.0054), tempn*rainn (0.0457) and solarc*speedc (0.0007 for GC. Similarly, the significant effects for GU were season ($<.0001$), temp_lag13c ($<.0001$), tempc (0.0001), humc (0.0008), sqtage*season ($<.0001$), humc*speedc ($<.0001$), temp_lag13c*season (0.0222) and rainc*season (0.0321) for GU. From Table 4.3, it was observed that the significant effects for GC and GU found to be different for Phase I FW. This implies that we cannot have common

model for the two clones. The interpretation of the significant results presented as follows.

Square root of age by season interaction: The square root of age by season interaction effect on FW was significant (p -value = $0 < .0001$) for GC and GU. This means the mean difference between the FW's for GC and GU depends on the combination of the levels of square root of age by season holding the other effects constant. In particular, Figure 4.2 and 4.3 show that within each season FW increases with age for both clones. The highest rate of increase was in autumn (0.08) for GC and (0.21) for GU. On the other hand, the lowest rate of increase was in summer (0.01) for GC and in spring (0.016) for GU for Phase I. The intercepts for summer, autumn, winter and spring were not statistically different. Furthermore, the slopes, except between autumn and winter, were not statistically different for FW GC. On the other hand, except between autumn and winter, the intercepts and slopes were not statistically different for GU.

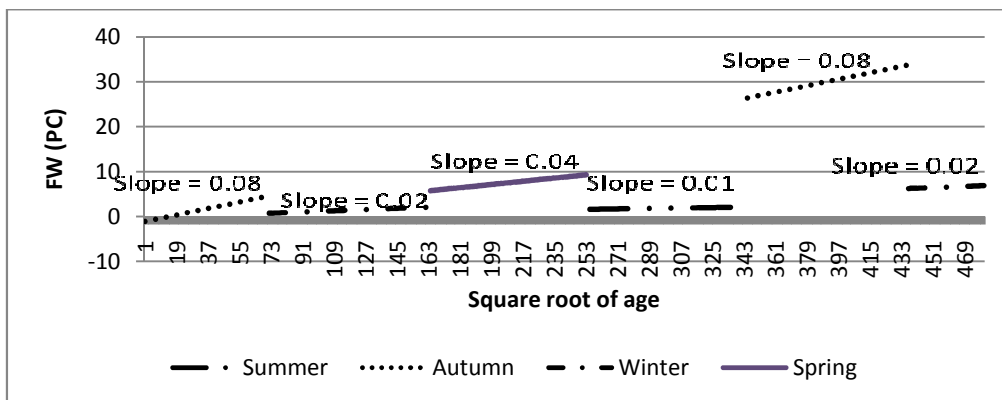


Figure 4. 2: Joint effect of season and age GC Phase I

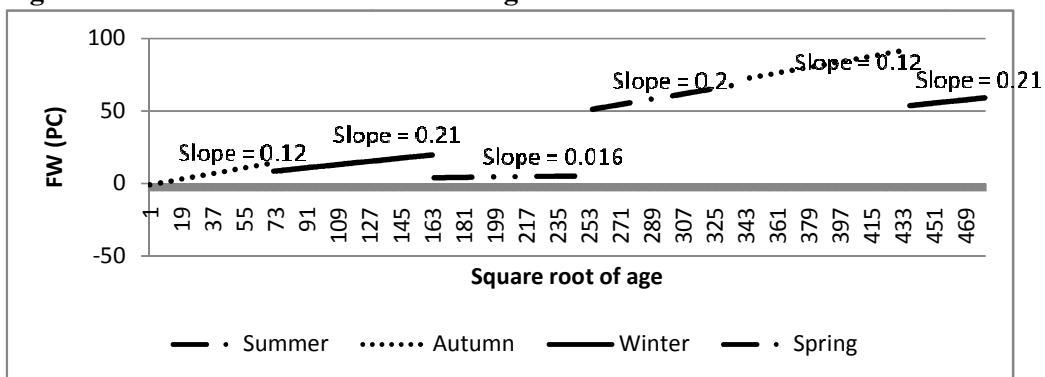


Figure 4. 3: Joint effect of season and age GU Phase I

Season by rainfall interaction: The season by rainfall interaction effect on FW was significant (p -value < 0.0001) for GC. However, this interaction effect was not significant (p – value = 0.1748) for GU. This means the mean difference between the FW’s for GC depends on the combination of the levels of season by rainfall holding the other effects constant. Figure 4.4 shows that the respective maximum means FW and minimum mean FW results from low/normal rainfall when the season was autumn and when the season was winter respectively for GC Phase I.

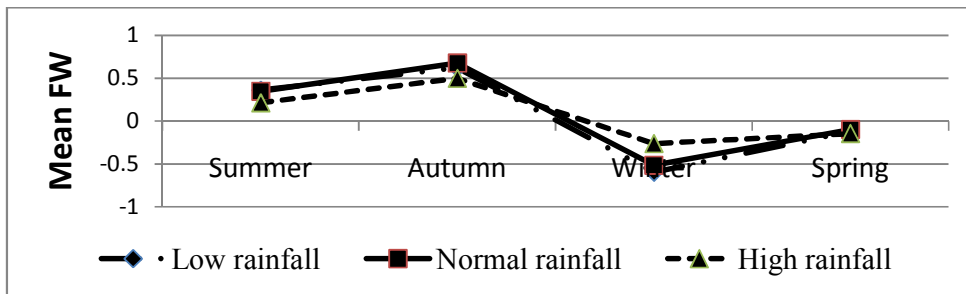


Figure 4. 4: The mean FW of GC vs. Season by rainfall for Phase I

Season by solar radiation interaction: The season by solar radiation interaction effect on FW was significant (p -value = 0.003) for GC and (p -value < 0.0001) for GU. Therefore, the mean difference between the FW’s for GC and GU depends on the combination of the levels of season by solar radiation holding the other effects constant. As can be seen in Figure 4.5, the respective maximum means for FW resulted from low solar radiation and minimum mean FW resulted from normal/high solar radiation when the season was autumn and winter respectively for GC Phase I. On the other hand, Figure 4.5 shows that the maximum mean FW for GU was in autumn for low solar radiation and the minimum value was in spring when solar radiation was high for Phase I.

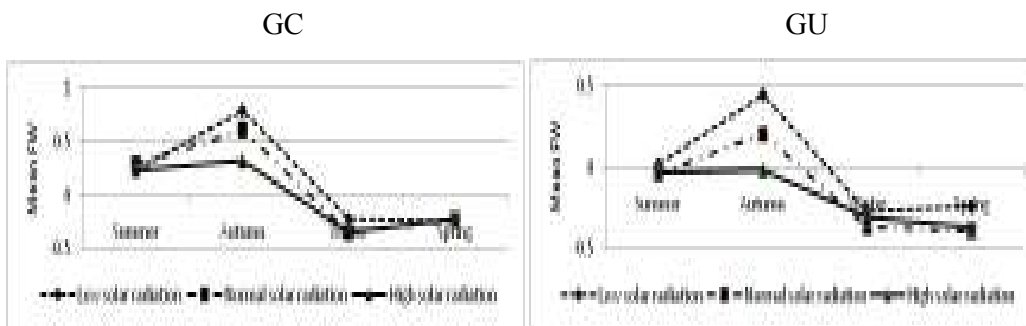


Figure 4. 5: The mean FW vs. season and solar radiation for Phase I

Season by wind speed interaction: The season by wind speed interaction effect on FW was significant (p -value = 0.0279) for GC. Nevertheless, this effect was not significant (p -value = 0.0608) for GU. This means the mean difference between the FW's for GC depends on the combination of the levels of season by wind speed holding the other effects constant. Figure 4.6 shows that the respective maximum means FW resulted from high wind speed where the season was autumn and minimum mean FW results from normal wind speed when the season was winter for GC Phase I.

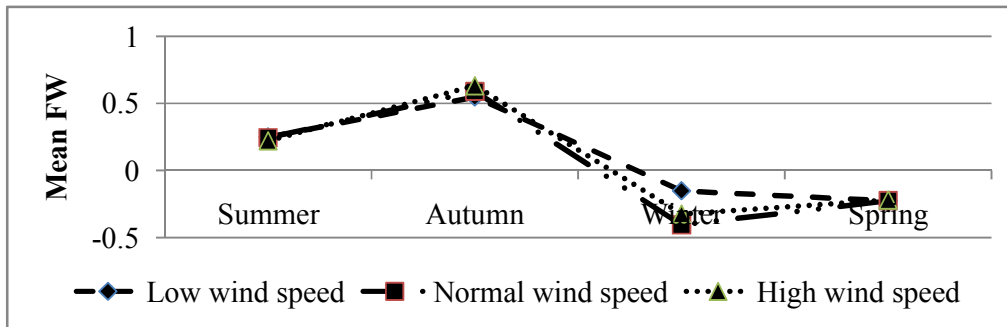


Figure 4. 6: The mean FW of GC vs. season and wind speed for Phase I

Season by temperature at lag 13 interaction: The season by temperature at lag 13 (13th day of temperature) interaction effect on FW was significant (p -value = 0.0054) for GC. Temperature at lag 31 means temperature of 13 days before the measurement, but this effect was not significant (p -value = 0.1183) for GU. Therefore, the mean difference between the FW's for GC depends on the combination of the levels of season by temperature at lag 13 holding the other effects constant. In particular, Figure 4.7 shows that the respective maximum means FW resulted from normal/low temperature at lag 13 and minimum mean FW results from low/normal/high temperature at lag 13 when the season was autumn and winter respectively for GC Phase I.

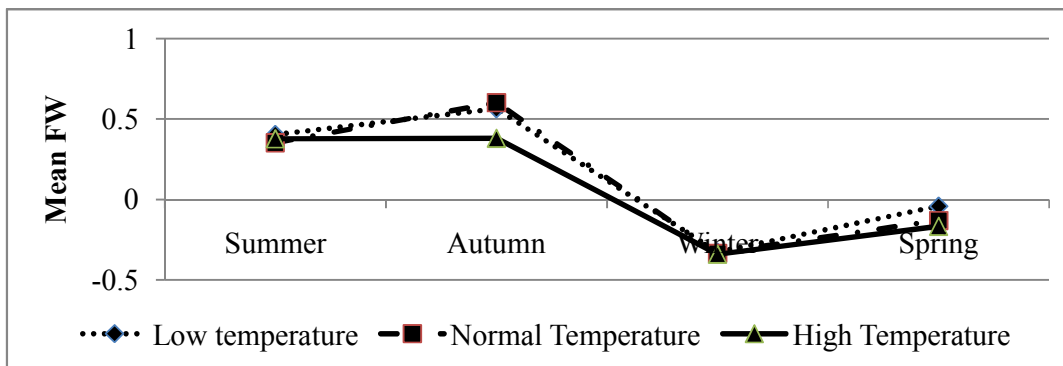


Figure 4. 7: The mean FW of GC vs. season and temperature at lag 13 for Phase I

Season by solar radiation at lag 28 interaction: Season by solar radiation at lag 28 interaction effects on FW were significant (p -value = 0.0284) for GU. However, this interaction effect was not significant for GC. This means the mean difference between the FW for GU depends on the combination of the levels of season by solar radiation at lag 28 holding the other effects constant. In particular, Figure 4.8 shows that the respective maximum and minimum means of FW for solar radiation at lag 28 and season interactions for GU. As we can see from Figure 4.8, the maximum mean FW is obtained when solar radiation at lag 28 was low/normal and season was autumn. In addition to this, minimum mean FW is obtained when there was low/normal/high solar radiation at lag 28 and season was winter.

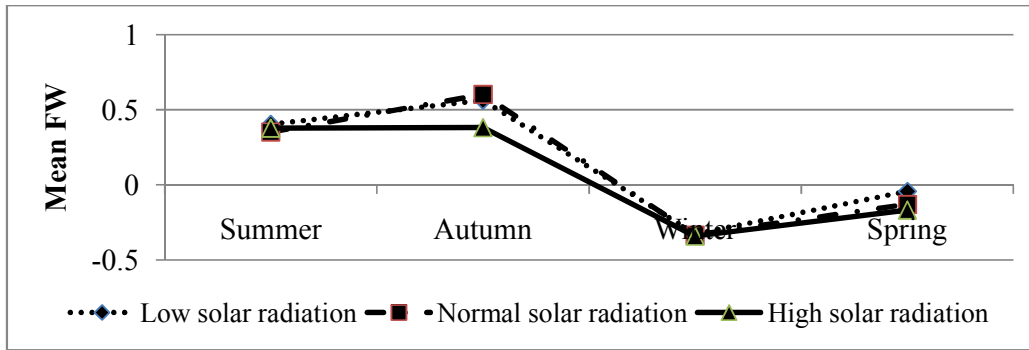


Figure 4. 8: The mean FW of GU vs. season and solar radiation at lag 28 and rainfall for Phase I

Temperature by rainfall interaction: Temperature by rainfall interaction effects on FW were significant (p -value = 0.0457) for GC. However, this interaction effect was not significant for GU. This means the mean difference between the FW for GC depends on the combination of the levels of temperature and rainfall holding the other effects constant. In particular, Figure 4.9 shows that the respective maximum and minimum means of FW for temperature and rainfall interactions for GC. As we can see from Figure 5.9, the maximum mean FW is obtained when rainfall and temperature was normal. In addition to this, minimum mean FW is obtained when there was low rainfall and high temperature.

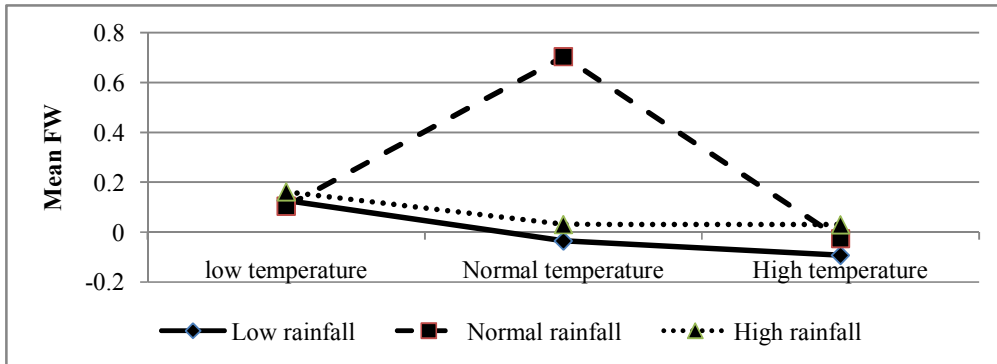


Figure 4. 9: The mean FW of GC vs. temperature and rainfall for Phase I

Solar radiation by wind speed interaction: solar radiation by wind speed interaction effects on FW were significant (p -value = 0.0007) for GC. But this effect was not significant (p – value = 0.1267) for GU. This means the mean difference between the FW for GC depends on the combination of the levels of solar radiation and wind speed holding the other effects constant. This result is presented in Figure 4.10. As we can see from the figures, the maximum mean FW was obtained when solar radiation was low and wind speed was normal for GC. On the other hand, the minimum Mean FW was obtained when there was high wind speed and solar radiation for GC Phase I.

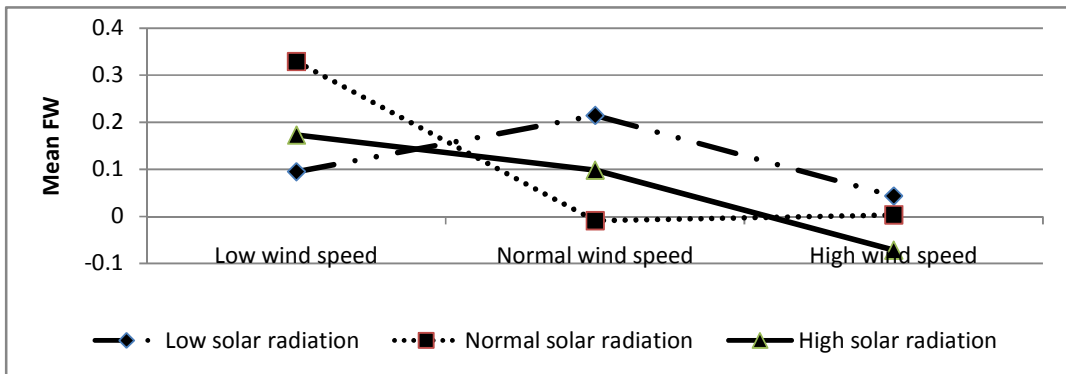


Figure 4. 10: The mean FW of GC vs. solar radiation and wind speed for Phase I

Table 4. 3: Type 3 tests for FW fixed effects: Phase I

Effect	Type 3 Tests of Fixed Effects							
	GC				GU			
	Num DF	Den DF	F Value	Pr > F	Num DF	Den DF	F Value	Pr > F
Sqtage	1	4232	3.84	0.0856	1	3962	3.73	0.0894
Season	3	4232	14.69	<.0001	3	3962	25.53	<.0001
Tempn	2	4232	13.01	<.0001	2	3962	0.82	0.4384
Rain	2	4232	0.2	0.8156	2	3962	2.08	0.1246
Humc	2	4232	4.92	0.0073	2	3962	0.79	0.4538
Solarc	2	4232	3.95	0.0194	2	3962	1.55	0.212
Speedc	2	4232	0.4	0.6725	2	3962	0.19	0.828
temp_lag13c	2	4232	4.86	0.0078	2	3962	3.27	0.038
solar_lag28c	2	4232	2.04	0.1308	2	3962	2.43	0.0884
sqtage*season	3	4232	144.18	<.0001	3	3962	87.54	<.0001
season*rainn	6	4232	5.76	<.0001	6	3962	1.5	0.1748
season*humc	6	4232	1.22	0.2932	6	3962	1.73	0.1105
season*solarc	6	4232	3.3	0.003	6	3962	7.5	<.0001
season*speedc	6	4232	2.36	0.0279	6	3962	2.01	0.0608
season*temp_lag13c	4	4232	3.67	0.0054	6	3962	1.69	0.1183
season*solar_lag28c	6	4232	1.6	0.1041	6	3962	2.36	0.0284
tempn*rainn	4	4232	2.43	0.0457	4	3962	1.69	0.1495
solarc*speedc	4	4232	4.83	0.0007	4	3962	1.8	0.1267
rainn*humc	4	4232	2.31	0.0554	4	3962	0.76	0.5483
rainn*speedc	4	4232	0.89	0.4695	4	3962	0.5	0.7382

Sqtage – square root of age, Tempn - Classified Temperature, Rainn - Classified Rainfall, Solarc - Classified Solar radiation, Speedc - Classified wind speed, Humc - classified Relative humidity, temp_lag13c – classified temperature at lag 13, solar_lag28c – classified solar radiation at lag 28.

Tests for fixed effects for FW for Phase II – IV are presented in Table A.10 - A.12. From the table it was observed that the significant effects of FW for GC and GU found to be different. Moreover, the significant effects between phases were different. This implies that we cannot have common model for the two clones and for the four phases. To interpret the significant results, we have used graphs. These graphs are presented in Figure B.36 - B.45. The summarized results are presented as follows.

From the Figure B.36 - B.45, it was observed that Fibre Wall was maximum in summer for GC and summer and autumn for GU. On the other hand, FW was maximum in summer and autumn for both clones for Phase III. Moreover, the other significant result in the model was the interaction between solar relation and season. This effect was significant for Phase II only. As the result indicates, FW was maximum in autumn for

low solar radiation for GC and in summer for normal solar radiation for GU Phase II. Moreover, the other significant effect in the model was the interaction between season and wind speed. This interaction effect was found to be significant only for Phase III GC only. As the result implies, FW was maximum in winter for high and low/normal wind speed for Phase III GC respectively. Furthermore, the combined effect of relative humidity and season was found to be significant only for Phase II. As the result indicates, maximum FW was obtained in autumn when relative humidity was low and low/high for GC and GU respectively. Similarly, the combined effect of the 5th day of temperature and season was significant for Phase II. As the result indicates, FW was maximum in spring for low temperature at lag 5. On the other hand, the combined effect of season and the 31st day of solar radiation was found to be significant for Phase II. As the result indicates, maximum FW was obtained in winter when solar radiation at lag 31 was low for GC. This result for GU shows that maximum FW was obtained in summer for high/normal solar radiation at lag 31st. From the result, it was observed that there were no significant effects for Phase IV.

As we discussed above, the model for FW was linear mixed model. Since the model was linear mixed model, we have random effects in addition to the fixed effect. The results for the random effects for Phase I - IV is presented in Table 4.4. The table shows that the effect of tree variability was significant (p -value = 0.04) for GC. However, the effect of tree for GU (p -value = 0.16) was not significant for Phase I. This implies that there was variation between trees for GC. This result shows that there was variability from tree to tree for GC for the change in mean FW. This result conforms our finding of Chapter 2 Section 2.2. On the other hand, tree by age interaction effects were not significant (p -value = 0.08 for GC and p -value = 0.39 for GU). Therefore, the slope of each tree for the two clones is the same. Moreover, the estimated value 0.85 for GC and 0.21 for GU were found to be significant. These results indicate that the measurements between trees were different. On the other hand, the results for the random effects for Phase II to IV are presented in Table 4.4. As the result for the random effects indicates, there was tree to tree variability for Phase II GU and Phase III GU. However, there was no tree to tree variability for the rest phases. Similarly, there was variability within tree for all phases. On the other hand, there was variability for the combined effect of age and tree.

Table 4. 4: FW random effects variance test

Covariance Parameter Estimates							
Cov Parm	Subject	GC			GU		
		Estimate	Z Value	Pr Z	Estimate	Z Value	Pr Z
Phase I							
Variance	treeno	0.03	1.79	0.04	0.01	1.01	0.16
CS	treeno	0.03	1.76	0.08	0.01	0.86	0.39
AR(1)	treeno	0.85	2.1	0.04	0.21	2.01	0.04
Residual		0.43	46.38	<.0001	0.3	44.91	<.0001
Phase II							
Variance	treeno	0.02	2.18	0.01	0.03	1.86	0.03
CS	treeno	0.02	2.17	0.03	0.02	1.84	0.07
AR(1)	treeno	0.94	123.4	<.0001	0.92	119.35	<.0001
Residual		0.39	8.21	<.0001	1.24	10.7	<.0001
Phase III							
Variance	treeno	0.2094	1.24	0.0283	0.4458	1.97	0.0439
CS	treeno	0.0133	1.1	0.2701	0.5329	1.94	0.0492
AR(1)	treeno	0.5472	10.18	<.0001	0.512	0.05251	<.0001
Residual		0.7501	9.34	<.0001	1.0228	0.1034	<.0001
Phase IV							
Variance	treeno	0.02094	1.24	0.1083	0	.	.
CS	treeno	0.0133	1.1	0.2701	0.00329	1.2	0.2292
AR(1)	treeno	0.5472	10.18	<.0001	0.512	9.75	<.0001
Residual		0.7501	9.34	<.0001	1.0228	9.9	<.0001

4.2.2 The assessment of the continuous climatic variables on the wood anatomy

In Section 4.2.1, we have considered categorical climatic variables. Our interest was to assess the effects of the level of climatic variables (high, low and normal) for the change of the fibre and vessel characteristics of the two *Eucalyptus* clones. Here, our interest was to assess the rate of change of fibre and vessel characteristics of the two *Eucalyptus* clones for a unit change in the climatic variables.

A point, which arises repeatedly when interactions involving continuous variables are being considered, is the value of 'centring' the variables. Since the units of the regression coefficient are units of the response variable per units of the explanatory variable, it is helpful to work with standardized variables. The use of standardized variables is helpful to reduce variability in the dataset (Montgomery, Peck et al. 2006). In general, the

advantages of standardizing variables helps to avoid possible problems caused by multicollinearity (Aiken and West 1991). To standardize, we have subtracted the mean from the observed variable values and dividing the difference by the standard deviation of the observed variable values. For example, the values of a variable X are standardized as follows:

$$X_i^* = \frac{X_i - \bar{X}}{s}, \quad i = 1, 2, \dots, n$$

Where X_i^* is the i^{th} standardized value, $\bar{X} = \frac{1}{n} \sum_{i=1}^n X_i$ and $s = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (X_i - \bar{X})^2}$

To fit initial full longitudinal linear mixed model for the Fibre and vessel characteristics of *Eucalyptus* tree, similar to the previous Section (4.2.1), in addition to the five standardize climatic variables, we have included the lagged standardized climatic variables, which were obtained in Chapter 3. Similar to the previous section, the full longitudinal linear mixed model contained season, age, daily climatic variables and the lagged climatic variables. For the random effects, tree and interaction between tree and age was considered. Here also the covariance structures CS for between subjects (tree) effect and AR (1) within subject effects were used. The model selection process was started by removing the insignificant highest order interaction effects from the full model then refitting the reduced model. This process continued until the final reduced model was obtained. Furthermore, similar to Section 4.2.1, the usual model error assumptions were checked using the residual plots. From the result, it was observed that the usual assumptions of the linear mixed model were not seriously violated by the data. The result for Fibre Wall (FW) will be discussed in this section. The results for the other PCs will be discussed in Chapter 5.

Preliminary fitting of the model for FW included season, age, standardized climatic variables and the standardized lagged climatic variables effect under various covariance structures. The p -values for testing the significance of the effects in the final reduced model for Phase I are displayed in Tables 4.5, A.22 - A.23. The significant effects, at the 0.05 level of significance, are explained as follows. After fitting the model, the observed and fitted values of FW for both clones are presented in Figures 4.11. As can be seen in

Figures 4.11, the model for FW with the significant predictor variables fits well for both clones. The interpretation for significant effects is presented as follows.

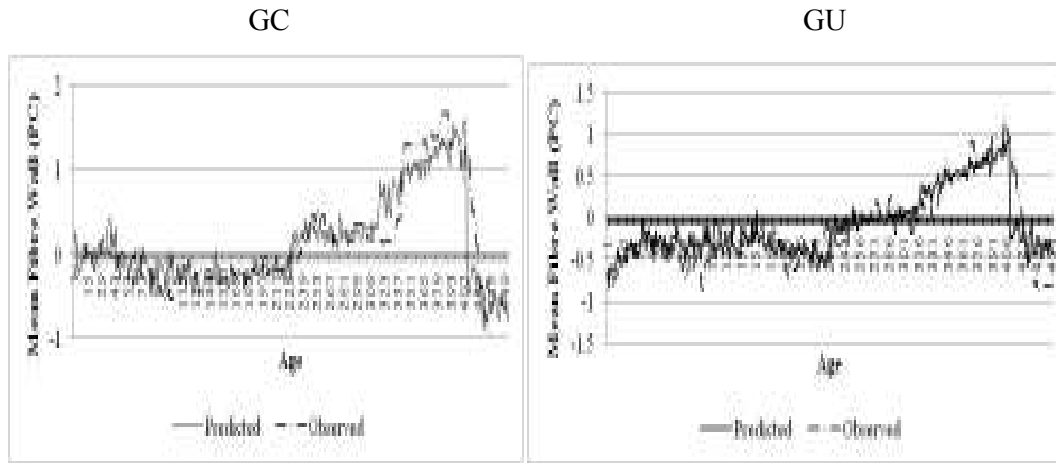


Figure 4. 11: Observed vs. fitted values for FW Phase I – GC

As we can see in Table 4.5, the effect of season for FW Phase I was found to be significant. This result indicates that the rate of increase for FW was higher in winter (1.65) as compared to spring (the reference season) for GC. The rate of increase for the other seasons found to be summer (1.42) and autumn (0.85) as compared to spring (the reference season) for GC. On the other hand, the effect of winter was not significant for GU Phase I. But, the effect of other seasons found to be significant. As the result indicates, the rate of increase for FW was higher in summer (1.58) and lower in autumn (-0.96) as compared to spring for GU Phase I.

One of the significant results in our model was the interaction between season and age. As we can see from the result, FW increases with age for summer (0.02), and autumn (0.08) as compared to spring. But, unlike for summer and autumn, FW decreases with age in winter (-0.04) for GC. On the other hand, FW increases with age for summer (0.12) and (0.10) as compared to spring for GU.

From Table 4.5, we found that the interaction between temperature at lag 13 and season was found to be significant for autumn and summer for GC and GU respectively. As we can see from Table 4.5, FW decreases with temperature at lag 13 in autumn (-0.14) and increases in summer (0.09) for GC and GU respectively.

The other significant effects on FW for Phase I in our model were rainfall and relative humidity, temperature and solar radiation, and relative humidity and wind speed interactions for GC. But, for GU the only interaction effect between climatic variables was interaction between relative humidity and wind speed. From our result, we observed that the interaction between rainfall and relative humidity has positive (0.04) effect on FW for GC. On the other hand, the interaction between temperature and solar radiation (-0.04) and relative humidity and wind speed (-0.05) has a negative effect on FW for GC Phase I. Similarly, the combined effect of relative humidity and wind speed (-0.06) has negative effect for GU Phase I.

In our model, the effect of rainfall and season interaction was significant for summer and winter. Our result showed that FW decreases (-0.18) in summer and increases (0.11) in winter for GC with rainfall. On the other hand, FW decreases in summer (-0.12) and winter (-0.08) with rainfall as compared to spring for GU Phase I.

Table 4. 5: Parameter estimates for FW Model: Phase I

Effect	GC			GU		
	Estimate	SE	Pr > t	Estimate	SE	Pr > t
Sqtage	0.09	0.03	0.0243	-0.03	0.03	0.3814
Summer	1.42	0.69	0.0393	-1.58	0.59	0.0079
Autumn	0.85	0.40	0.0342	-0.96	0.36	0.0068
Winter	1.65	0.40	<.0001	-0.37	0.35	0.2945
DBH	0.348	0.032	<.0001	0.584	0.026	<.0001
radius	1.6E-05	7.60E-06	0.0346	-4E-05	3.87E-06	<.0001
increment	1.7E-6	2.62E-06	0.03	1.79E-06	1.78E-06	0.3137
temp_lag13c	-0.03	0.03	0.3501	-0.11	0.03	<.0001
Tempc	-0.05	0.02	0.0056	-0.06	0.02	0.0001
sqtage*summer	-0.07	0.04	0.0092	0.12	0.04	0.0012
sqtage*autumn	-0.01	0.03	0.0019	0.10	0.02	<.0001
sqtage*winter	-0.13	0.03	<.0001	0.02	0.02	0.3949
rainc*humc	0.04	0.02	0.0393	0.01	0.01	0.3988
tempc*solarc	-0.04	0.01	0.0066	0.01	0.01	0.5210
humc*speedc	-0.05	0.01	<.0001	-0.06	0.01	<.0001
temp_lag13c*summer	0.09	0.06	0.1462	0.09	0.04	0.0201
temp_lag13c*autumn	-0.11	0.04	0.0106	0.02	0.04	0.5569
temp_lag13c*winter	0.02	0.05	0.6038	0.06	0.04	0.1196
rainc*summer	-0.18	0.06	0.0040	-0.12	0.05	0.0117
rainc*autumn	0.03	0.05	0.5245	-0.06	0.04	0.0858
rainc*winter	0.11	0.05	0.0181	-0.08	0.04	0.0464

Table A.22 - A.23 shows the significant effects for Fibre Wall (FW) for Phase II - III for both clones. After fitting the model, the observed and fitted values of FW for both clones are presented in Figure B.66 – B.67 for Phase II - III. As we have seen from Figure B.66 – B.67, the model for FW with the significant predictor variables fits well for both clones for Phase II - IV. The summarized results are presented as follows.

In the model, the combined effect of square root of age and season was found to be significant for Phase II and III. As the result indicates, FW was found to be maximum in august for GC and summer for GU for Phase II. Moreover, FW was maximum in summer for GC and august for GU for Phase III. The other significant result in the model was the combined effect of relative humidity and wind speed. This effect was significant only for Phase II GC only. As the result indicates, the combined effect of relative humidity and wind speed for Phase II GC has a positive effect. Therefore, FW increases for a change in the combined effect of relative humidity and wind speed. The other significant effect only for Phase II GU was the combined effect of the 5th day temperature and season. As can be seen from the result, FW was decreasing in summer for a change of the 5th day of temperature for GU Phase II. Similarly, the combined effect of wind speed and season was found to be significant for only Phase II. Here, FW decreases in summer for both clones for a change of wind speed. Moreover, the combined effect of the 7th day temperature and season was found to be significant only for Phase III. As the result indicates, FW decreases with the 7th day temperature for both clones. From the result, it was observed that there were no significant effects for Phase IV.

The results for the other fibre and vessel characteristics of Eucalyptus clone i.e., for FD, VD and VF shows that for FD Square root of age, Season, temperature, rainfall, joint effects of square root of age and season, season and rainfall, season and relative humidity, season and solar radiation, rainfall and relative humidity, and temperature and solar radiation found to be significant for GC Phase I. Similarly, for FD GU clone the significant effects were square root of age, season, temperature, rainfall, relative humidity, solar radiation, wind speed and joint effects of square root of age and season, season and solar radiation, and temperature and solar radiation. On the other hand the square root of age, season, relative humidity, solar radiation, 13th and 19th lagged

temperatures, the joint effects of square root of age and season, season and rainfall, and season and relative humidity found to be significant for Phase I VD for GC clone. Likewise, square root of age, season, temperature, rainfall, 13th lagged temperature and the joint effects of square root of age and season, season and 19th lagged temperature were found to be significant for Phase I VD for GU clone. Further more, the joint effects of square root of age and season, season and temperature for GC clone; season, the joint effects of square root of age and season, season and temperature for GU clone found to be significant results for Phase I VF. The detailed interpretation of the significant result will be presented in Chapter 5.

4.2.3 Comparison of the analysis of the categorical and continuous climatic variables

The summary values of the significant results for the fibre and vessel characteristics of *Eucalyptus* clones are presented in Table 4.9 - 4.10 for GC and GU respectively. As can be seen from the tables, the two clones have different models for all fibre and vessel characteristics. Based on the results, it was observed that the GC clone affected by more effects than GU. Moreover, each fibre and vessel characteristics have different models. The only common significant result for all fibre and vessel characteristics is the interaction between square root of age and season. From the four fibre and vessel characteristics of *Eucalyptus* clones VD and FD were affected by more effects than FW and VF. Similarly, for each fibre and vessel characteristics of *Eucalyptus* clones, the models are different.

Table 4. 6: Summary results for the wood anatomy properties for GC

Effect	Categorical Result				Continuous Result			
	FW	FD	VD	VF	FW	FD	VD	VF
Sqtage	NS	Sig.	Sig.	NS	NS	Sig.	NS	NS
Season	Sig.	Sig.	Sig.	NS	Sig.	Sig.	Sig.	NS
Tempn	Sig.	Sig.	NS	NS	Sig.	NS	NS	NS
Rain	NS	Sig.	NS	NS	NS	Sig.	NS	NS
Humc	Sig.	NS	Sig.	NS	NS	NS	NS	NS
Solarc	Sig.	Sig.	Sig.	NS	NS	NS	NS	NS
temp_lag13c	Sig.	NS	Sig.	NS	Sig.	NS	Sig.	NS
temp_lag19c	NS	NS	Sig.	NS	NS	NS	Sig.	NS
sqtage*season	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.
season*rainn	Sig.	Sig.	Sig.	NS	NS	Sig.	Sig.	NS
season*tempn	NS	NS	NS	Sig.	Sig.	NS	NS	Sig.
season*humc	NS	Sig.	Sig.	NS	Sig.	NS	Sig.	NS
season*solarc	Sig.	Sig.	NS	NS	NS	Sig.	Sig.	NS
season*speedc	Sig.	NS	NS	NS	NS	NS	NS	NS
season*temp_lag13c	Sig.	NS	NS	NS	Sig.	NS	NS	NS
tempn*rainn	Sig.	NS	NS	NS	NS	NS	Sig.	NS
solarc*speedc	Sig.	NS	NS	NS	Sig.	NS	NS	NS
rainn*humc	NS	Sig.	NS	NS	NS	Sig.	Sig.	NS
tempn*solarc	NS	Sig.	NS	NS	Sig.	NS	NS	NS

Sig. - significant, NS - not significant

Table 4. 7: Summary results for the wood anatomy properties for GU

Effect	Categorical Result				Continuous Result			
	FW	FD	VD	VF	FW	FD	VD	VF
Sqtage	NS	Sig.	Sig.	NS	NS	Sig.	Sig.	NS
Season	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.
Tempn	NS	Sig.	Sig.	NS	NS	Sig.	Sig.	NS
Rain	NS	Sig.	Sig.	NS	NS	Sig.	Sig.	NS
Humc	NS	Sig.	NS	NS	NS	Sig.	Sig.	NS
Solarc	NS	Sig.	NS	NS	NS	Sig.	NS	NS
Speedc	NS	Sig.	NS	NS	NS	Sig.	NS	NS
temp_lag13c	Sig.	NS	Sig.	NS	Sig.	NS	NS	NS
sqtage*season	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.
season*tempn	NS	NS	NS	Sig.	NS	Sig.	Sig.	Sig.
season*solarc	Sig.	Sig.	NS	NS	Sig.	Sig.	NS	NS
season*temp_lag19c	NS	NS	Sig.	NS	NS	NS	NS	NS
tempn*solarc	NS	Sig.	NS	NS	NS	Sig.	NS	NS

Sig. - significant, NS - not significant

5. Assessment of tree height, daily increment, radius and climatic factors on wood anatomy

In Chapter 4 we investigated the effect of age, climatic variables and season on the wood anatomy. In this chapter, other factors of the tree, which are diameter at breast height (DBH), radius and increment, are used. These additional factors are added in to the model, which was found in Chapter 4. These factors are added in order to improve the model. The classification of trees according to dominance and suppression is discussed in Section 5.1. The results using the categorical and continuous climatic variables are presented in Sections 5.2. The comparison of the analysis of the categorical and continuous climatic variables is presented in Section 5.3.

5.1 The effect of the dominance/suppression of the tree

The information about dominant and suppressed trees could have importance. Some trees might be dominant in their neighbourhood. We classified the trees according to their dominance in their neighbourhood. For this purpose, diameter at breast height (DBH) of the tree was used. The idea behind the classification of trees according to DBH was to relatively quantify how much “crown space” each tree had in relation to other trees around it when dendrometer measurements were taken, i.e. the difference between dominant and suppressed is that some trees are growing faster compared to other and this could affect the characteristics of the wood formed. To determine the dominance of the trees, average and the standard deviation of DBH of all trees in the plot (selected plots for the experiment) was calculated. Based on the results, the trees were classified as follows:

- If tree DBH was greater than mean plus one standard deviation as dominant.
- If it was less than mean minus one standard deviation as suppressed.
- If the DBH is within one standard deviation of the average the tree classified as neither suppressed nor dominant

The classification of trees is given in the Table 5.1. From Table 5.1, it can be seen that for Phase I, six trees were dominant and two trees were suppressed for GC. On the other hand, the dominant trees for GU were four and the suppressed were six. Similarly, for Phase II, three and four trees were dominant for GC and GU respectively. GC and GU

have equal number of suppressed trees in Phase II. In Phase III, five trees were found to be suppressed in each clone. On the other hand, each clone has four dominant trees in Phase III. Finally, for Phase IV, four trees were dominant for each clone and three trees for GC and four trees for GU were suppressed. Therefore, the information of dominance and suppressed trees will be added for longitudinal linear mixed model obtained from Chapter 4.

Table 5. 1: Classification of trees by suppression and dominance

Phase I				Phase II			
GC		GU		GC		GU	
Dominant	suppressed	Dominant	suppressed	Dominant	suppressed	Dominant	suppressed
98			108		74		86
	99		110		75		87
100		111			76		88
101			112	77			89
102			113				90
	103	114			79	91	
106			115	82		94	
107		118			83	95	
			119	84		96	
		120					
Phase III				Phase IV			
121			134	49		61	
	122	135		51			63
124		136			52	64	
	125	137			54		66
	127	138		55		67	
	128		139		56	68	
	129		142		57	69	
130			143		58		71
131			144		60		72

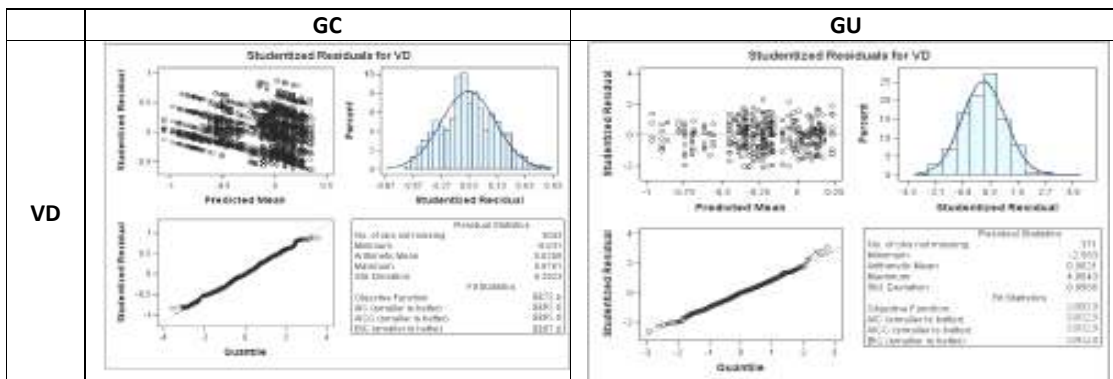
5.2 The effect of daily increment, radius and diameter at breast height for wood anatomical characteristics of the *Eucalyptus* clones

In Chapter 4, a model with season, age, climatic variables (including lags) as fixed effect and tree as random effect was identified. To improve the model the results of DBH, radius and increment have been added to the model. Therefore, the results using categorical and continuous climatic variables are presented in Sections 5.2.1 and 5.2.2 respectively.

5.2.1 Using categorical climatic variables

Preliminary fitting of the model included the season, age, DBH, radius, increment and the climatic variables (including lags) effect under various covariance structures. Similar to Chapter 4, the Compound symmetry (CS) for between subject effects and AR (1) for within subject effects were found to be the best covariance structures. In Chapter 4, the result for Fibre Wall (FW) was discussed. For this chapter the results for the remaining wood anatomical characteristics of the *Eucalyptus* clones, i.e., for VD, FD and VF, are discussed in detail.

The *p*-values for testing the significance of the effects of VD, FD and VF in the final reduced model for Phase I up to IV are displayed in Tables 5.2, 5.4, 5.6, A.13 - A.21. The significant effects, at the 0.05 level of significance, are explained in the sub sections that follows. The usual Analysis of Covariance (ANCOVA) model error assumptions for these models were checked using the residual plots in Figures 5.1 for Phase I and Figures B.33 - B.35 for Phase II – IV. From the figures, the first plot is of the predicted values against studentized residuals. These plots show that the studentized residuals vary between -1 and 1 for GC and between -2 and 2 GU. The next two plots are a histogram and q-q plot of studentized residuals, and intended to show the normality of the studentized residuals. These plots show that the usual assumptions of the linear mixed model were not seriously violated by the data for Phase I. Similarly, from the plots Figure B.33 – B.35, it can be observed that the usual model assumptions for Phase II, III and IV were not seriously violated by the data.



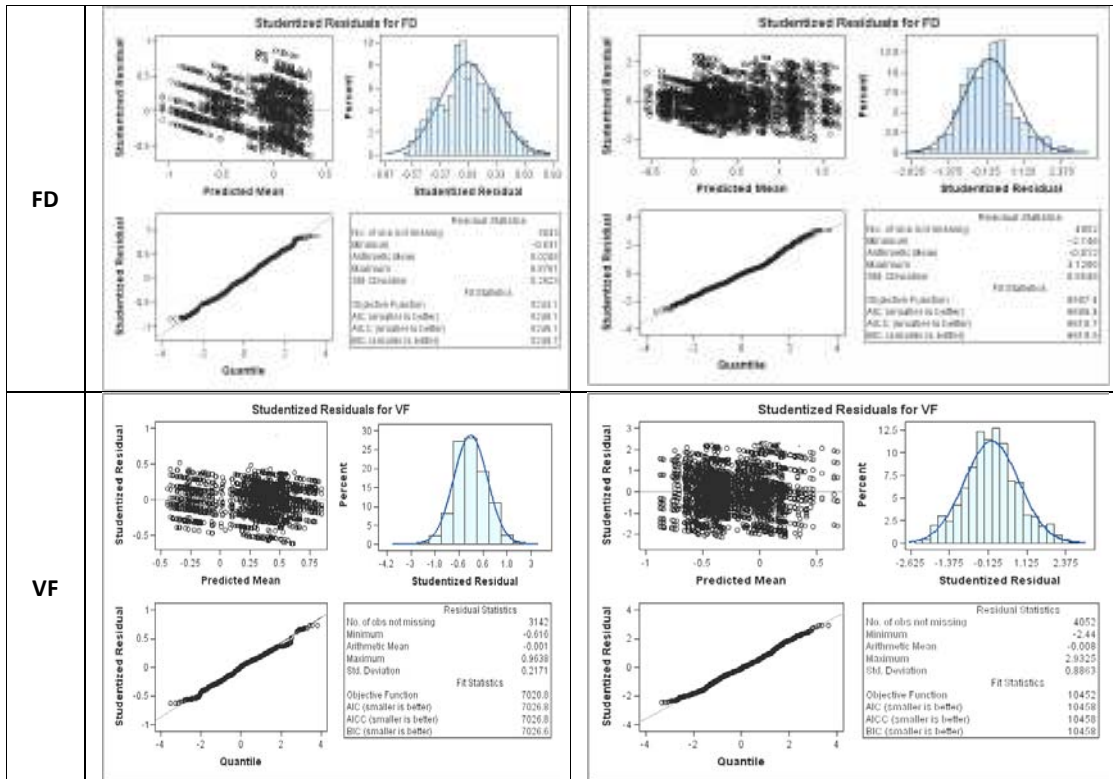


Figure 5. 1: Plots of studentized Residuals for VD, FD and VF for Phase I

The first fibre and vessel characteristic to be interpreted is the vessel dimension (VD). Table 5.2 shows the significant effects for VD for Phase I. From the table, the significant effects with p – values for GC were found to be Sqtage (0.0055), Season (<.0001), DBH (0.009), Humc (0.0001), Solarc (0.0415), temp_lag19c (0.0265), sqtage*season (<.0001), season*rainn (0.0111), season*humc (<.0001) and season*solarc (<.0001). On the other hand, the significant effects for GU were Sqtage (0.0454), Season (<.0001), Tempn (0.0055), Rain (0.0198), temp_lag19c (0.0174), sqtage*season (0.0001) and season*temp_lag19c (<.0001). From the table it was observed that the significant effects for GC and GU found to be different. This implies that we cannot have one model for the two clones. The interpretations for the significant effects are presented as follows.

Square root of age by season interaction: The square root of age by season interaction effect on VD was significant (p -value = 0<.0001) for GC and GU. This means the mean difference between the VD's for GC and GU depends on the combination of the levels of square root of age by season holding the other effects constant. In particular, Figure 5.2 shows that within season (summer and autumn) VD increases with age for GC. The

highest rate of increase was in summer (0.29) for GC. On the other hand, the lowest rate was in autumn (0.23) for GC. Similarly, Figure 5.3 shows that within each season VD increases with age for GU. But, this effect was not significant for spring. The highest rate of increase was in autumn (0.37) for GU. On the other hand, the lowest rate of increase was in winter (0.062) for GU for Phase I.

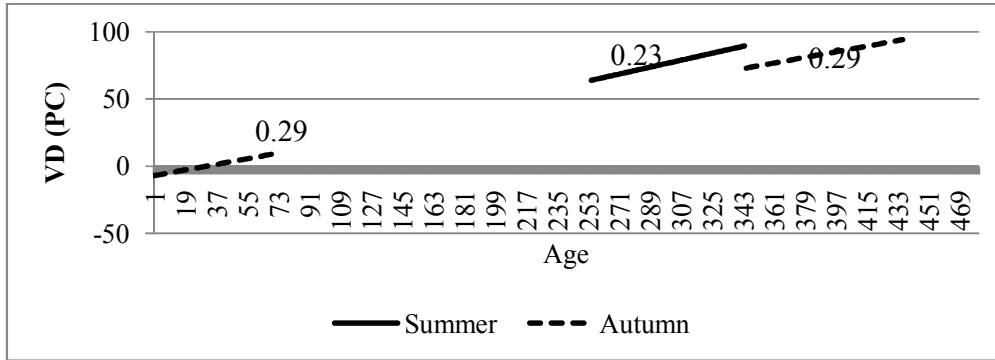


Figure 5. 2: Joint effect of season and age GC Phase I for VD

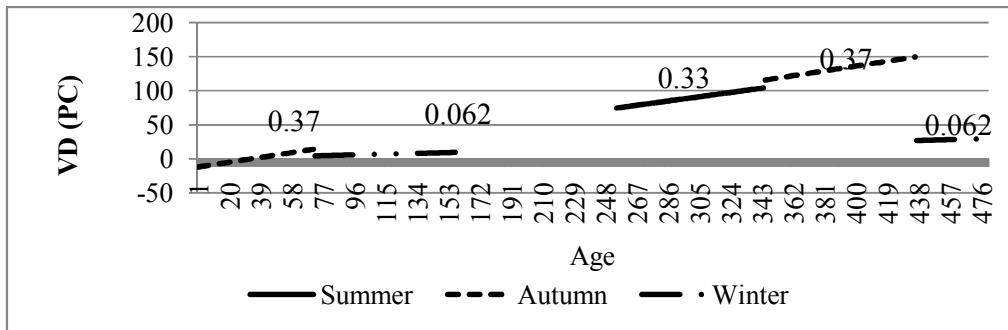


Figure 5. 3: Joint effect of season and age GU Phase I for VD

Season by relative humidity interaction: The season by relative humidity interaction effect on VD was significant (p -value < 0.0001) for GC. However, this interaction effect was not significant (p -value = 0.0506) for GU. This means the mean difference between the VD's for GC depends on the combination of the levels of season by relative humidity holding the other effects constant. Figure 5.4 shows the respective maximum and minimum means for VD for GC. As we can see from the figure, the maximum VD for GC was obtained in winter when relative humidity was high. On the other hand, the minimum mean VD resulted from normal and high relative humidity when season was summer for Phase I.

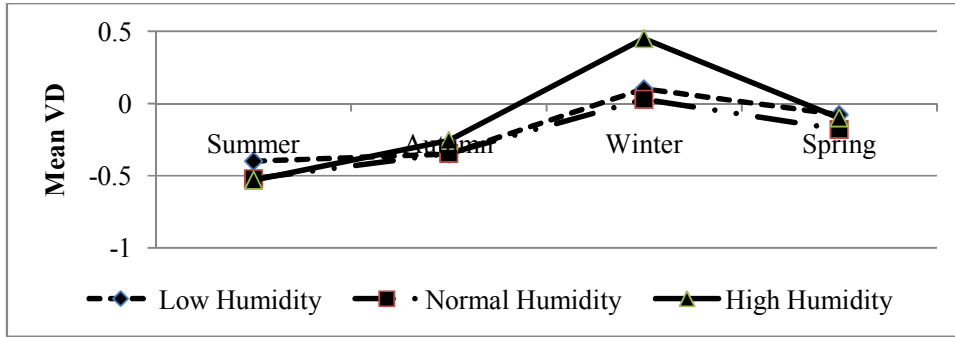


Figure 5. 4: The mean VD of GU vs. season and relative humidity for Phase I

Season by rainfall interaction: The season by rainfall interaction effect on VD was significant (p -value <0.0111) for GC. Nevertheless, this interaction effect was not significant (p -value = 0.3793) for GU. This means the mean difference between the VD's for GC depends on the combination of the levels of season by rainfall holding the other effects constant. Figure 5.5 shows the respective maximum and minimum means for VD for GC. As we can see from the figure, the maximum VD for GC was obtained in winter when rainfall was normal-. On the other hand, the minimum mean VD resulted from normal rainfall when season was spring for Phase I.

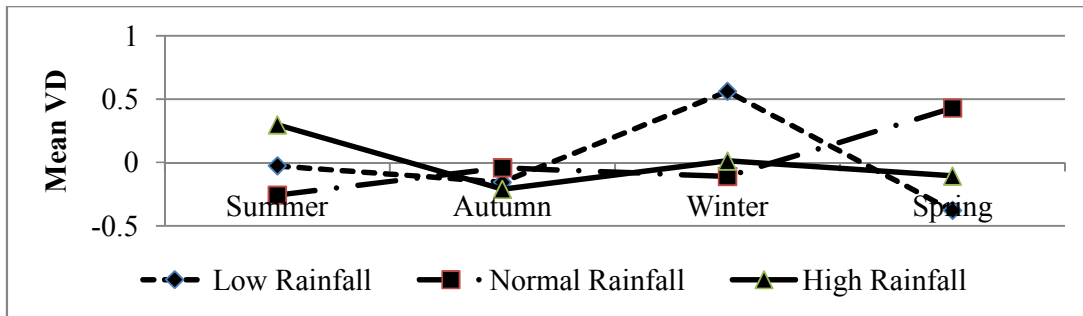


Figure 5. 5: The mean FV of GU vs. season and rainfall for Phase I

Season by solar radiation interaction: The season by solar radiation interaction effect on VD was significant (p -value = 0.004) for GC. However, this interaction effect was not significant (p -value = 0.0502) for GU. This means the mean difference between the VD's for GC depends on the combination of the levels of season by solar radiation holding the other effects constant. Figure 5.6 shows the respective maximum and minimum means for VD for GC. As we can see from the figure, the maximum VD for GC was obtained in winter when solar radiation was high. On the other hand, the minimum mean VD resulted from normal and low solar radiation when season was summer for Phase I.

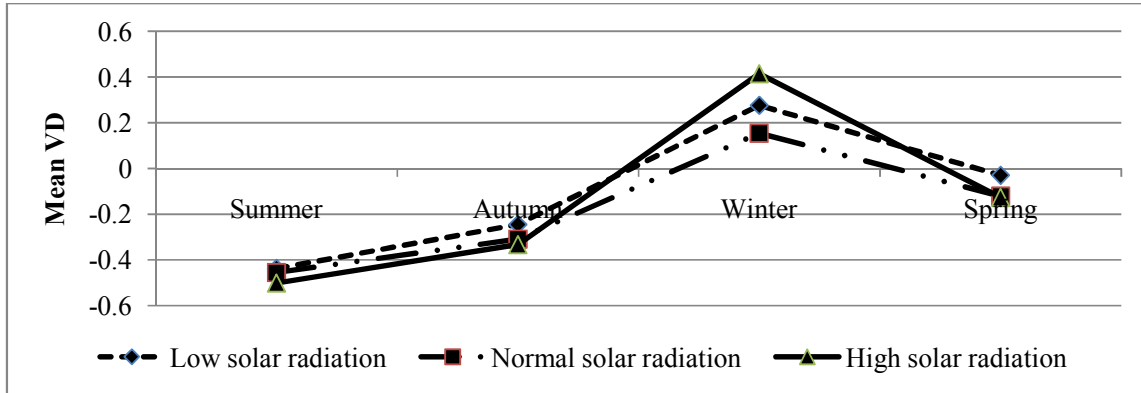


Figure 5. 6: The mean VD of GU vs. season and relative humidity for Phase I

Season by temperature at lag 19 interaction: The season by temperature at lag 19 interaction effect on VD was significant (p -value < 0.0001) for GU. But, this interaction effect was not significant (p -value = 0.0782) for GC. This means the mean difference between the VD's for GU depends on the combination of the levels of season by temperature at lag 19 holding the other effects constant. Figure 5.7 shows the respective maximum and minimum means for VD for GU. As we can see from the figure, the maximum VD for GU was obtained in winter when temperature at lag 19 was high. On the other hand, the minimum mean VD resulted from high temperature at lag 19 when season was autumn for Phase I.

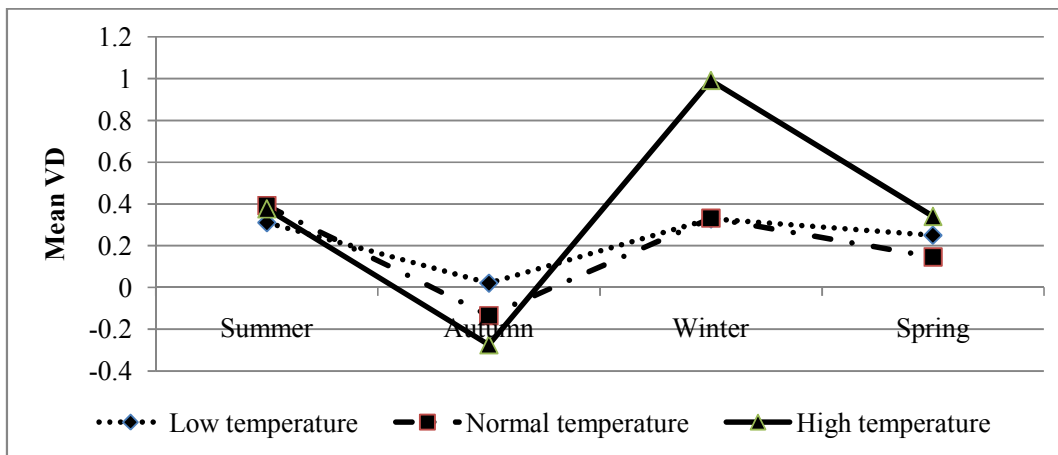


Figure 5. 7: The mean VD of GU vs. season and temperature at lag 19 for Phase I

Table 5. 2: Type 3 tests for VD fixed effects: Phase I

Effect	GC				GU			
	Num DF	Den DF	F Value	Pr > F	Num DF	Den DF	F Value	Pr > F
Sqtage	1	4258	14.14	0.0055	1	3988	5.61	0.0454
Season	3	4258	21.35	<.0001	3	3988	11.36	<.0001
DBH	1	4258	6.83	0.009	1	3988	9.34	0.0023
radius	1	4258	35.26	<.0001	1	3988	108.88	<.0001
increment	1	4258	0.49	0.4823	1	3988	2.51	0.1132
Tempn	2	4258	2.18	0.113	2	3988	5.21	0.0055
Rain	2	4258	2.75	0.0638	2	3988	3.92	0.0198
Humc	2	4258	9.08	0.0001	2	3988	2.33	0.0972
Solarc	2	4258	3.19	0.0415	2	3988	0.39	0.6762
Speedc	2	4258	0.31	0.7311	2	3988	1.41	0.2453
temp_lag19c	2	4258	3.63	0.0265	2	3988	4.06	0.0174
sqtage*season	3	4258	46.34	<.0001	3	3988	6.85	0.0001
season*rainn	6	4258	2.76	0.0111	6	3988	1.07	0.3793
season*humc	6	4258	6.34	<.0001	6	3988	2.96	0.0506
season*solarc	6	4258	9.05	<.0001	6	3988	2.32	0.0502
season*temp_lag19c	4	4258	2.1	0.0782	6	3988	5.62	<.0001
rainn*solarc	4	4258	0.15	0.9646	4	3988	1.79	0.055

Tests for fixed effects for VD for Phase II – IV are presented in Table A.16 - A.18. From the table it was observed that the significant effects for GC and GU found to be different. Moreover, the significant effects between phases were different. This implies that we cannot have one model for the two clones and for the four phases. To interpret the significant results, we have used graphs. These graphs are presented in Figure B.56 - B.61. The summarized results are presented as follows.

As the result indicates, VD was maximum in autumn and summer for GC and GU respectively for Phase II. For Phase II, the combined effect of season and square root of age was not significant for GU. Moreover, VD increases with age for summer and autumn and VD was maximum in summer. The other significant effect in the model for VD was the combined effect of season and solar radiation. This effect was found to be significant for only Phase II GC. In the study autumn for low/high solar radiation for Phase II GC was preferred to obtain maximum VD. Furthermore, the combined effect of season and wind speed was found to be significant only for Phase III GC. As can be seen from the result, VD was maximum in autumn when winter speed was low. Similarly, the combined effect of season and 31st day of temperature found to be significant only for

Phase III. As the result indicates VD, was maximum in autumn when temperature at lag 31 was low for GC and in autumn when temperature at lay 31 was high for GU. Similar to Fibre wall and Fibre Dimension, there were no significant effects for Phase IV.

The results for the random effects for Phase I are presented in Table 5.3. The table shows that the effect of tree was not significant for both clones. This result shows that there was no variability from tree to tree for GC and GU for the change in mean VD. On the other hand, tree by age interaction were significant (p-value = 0.03) for GC. But, this effect was not significant for GU (p - value = 0.06). These results indicate that the slopes of each tree were statistically different for GC clone. On the other hand, the estimated value 0.06 for GC and 0.10 for GU were found to be significant. These results indicate that the measurements between trees were different for Phase I VD.

Table 5. 3: VD random effects variance test

Covariance Parameter Estimates							
Cov Parm	Subject	GC			GU		
		Estimate	Z Value	Pr Z	Estimate	Z Value	Pr Z
Variance	treeno	0.08	0.97	0.17	0.15	0.96	0.17
CS	treeno	0.02	1.97	0.02	0.01	1.72	0.04
AR(1)	treeno	0.06	46.14	<.0001	0.1	44.63	<.0001
Residual		0.42	46.14	<.0001	1.09	44.63	<.0001
Phase II							
Variance	treeno	0.4670	2.83	0.043	0.02	2.14	0.044
CS	treeno	0	0.88	0.38	0	0.13	0.9
AR(1)	treeno	0.95	136.26	<.0001	0.94	140.48	<.0001
Residual		0.2	7.56	<.0001	0.45	8.53	<.0001
Phase III							
Variance	treeno	0.1	1.62	0.05	0.66	1.93	0.03
CS	treeno	0.1	1.62	0.11	0.64	1.93	0.05
AR(1)	treeno	0.67	1.81	0.11	0.69	1.95	0.05
Residual		0.34	39.23	<.0001	1.12	43.27	<.0001
Phase IV							
Variance	treeno	0.01	1.02	0.06	0	.	.
CS	treeno	0.01	1.85	0.08	0	1.36	0.17
AR(1)	treeno	0.27	4.51	<.0001	0.2	3.23	0.01
Residual		0.63	12.12	<.0001	1.12	12.48	<.0001

Furthermore, the results for the random effects for Phase II to IV are presented in Table 5.3. As the result for the random effects indicates, there was variability from tree to tree only for Phase II both clones and Phase III GU. For the rest phases there was no variability between trees. Similarly, there was no variability for the combined effect of

age and tree for all phases. On the other hand, except for Phase III there was variability within trees for Phase II and IV.

The other fibre and vessel characteristics to be considered is the fibre dimension (FD). Table 5.4 shows the significant effects for FD for Phase I. The significant effects with p – values for GC were Sqtage (<.0001), Season (<.0001), Tempn (0.0013), Rain (<.0001), Solarc (0.0174), sqtage*season (<.0001), season*rainn (0.0422), season*humc (0.0006), season*solarc (<.0001), rainn*humc (0.0198) and tempn*solarc (<.0001). On the other hand, the significant effects with p – values for GC were Sqtage (<.0001), Season (<.0001), Tempn (<.0001), Rain (0.0422), Humc (0.0196), Solarc (0.0436), Speedc (0.0437), sqtage*season (<.0001), season*solarc (0.0072) and tempn*solarc (0.0161). From Table 5.4, it was observed that the significant effects for GC and GU found to be different. This implies that we cannot have one model for the two clones. The interpretations for the significant effects are presented as follows.

Square root of age by season interaction: The square root of age by season interaction effect on FD was significant (p -value = $0 < .0001$) for GC and GU. This means the mean difference between the FD’s for GC and GU depends on the combination of the levels of square root of age by season holding the other effects constant. In particular, Figure 5.8 and 5.9 show that within each season FD decreases with age for both clones. The highest rate was in winter (-0.01) and (-0.04) for both clones. On the other hand, the lowest rate was in spring (-0.45) for GC and in summer and spring (-0.21) GU for Phase I. Furthermore, except for autumn and winter, the intercepts were not statistically different for both clones. On the other hand, the slops for seasons were not statistically different.

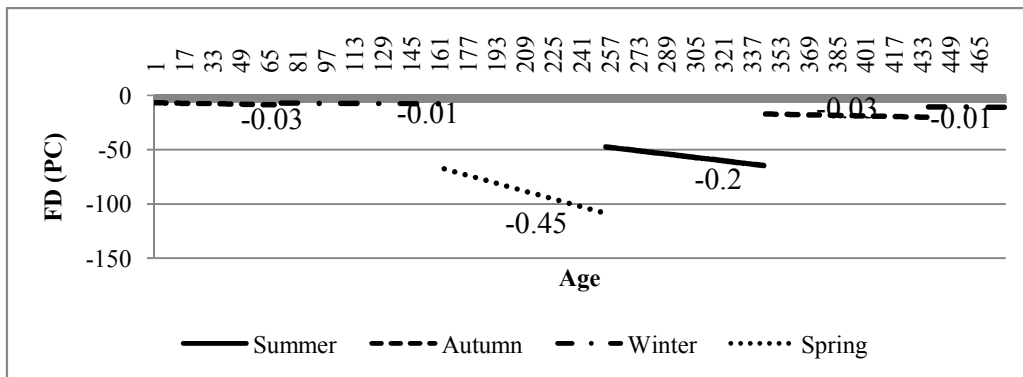


Figure 5. 8: Joint effect of season and age GC Phase I

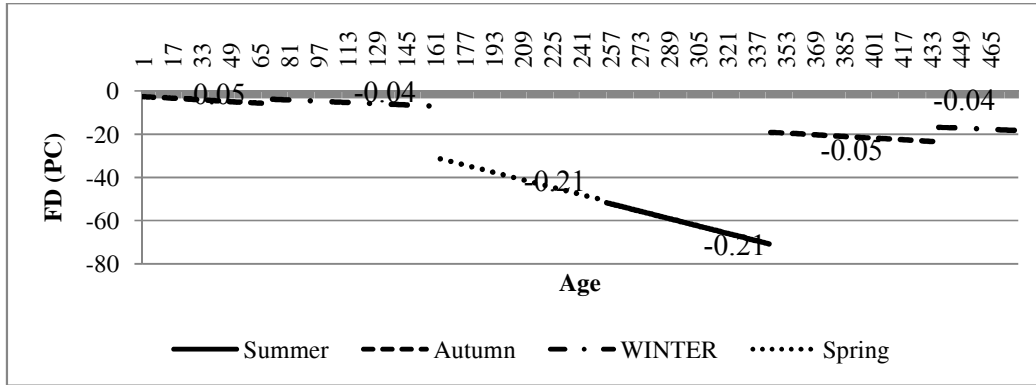


Figure 5. 9: Joint effect of season and age GU Phase I

Season by rainfall interaction: The season by rainfall interaction effect on FD was significant (p -value < 0.0422) for GC. However, this effect was not significant for GU (p -value = 0.8135). This means the mean difference between the FD's for GC depends on the combination of the levels of season by rainfall holding the other effects constant. Figure 5.10 shows the respective maximum and minimum means for FD for GC. As we can see from the figure, the maximum FD for GC was obtained in winter when rainfall was low/high. On the other hand, the minimum mean FD resulted from low/normal rainfall when season was autumn for Phase I.

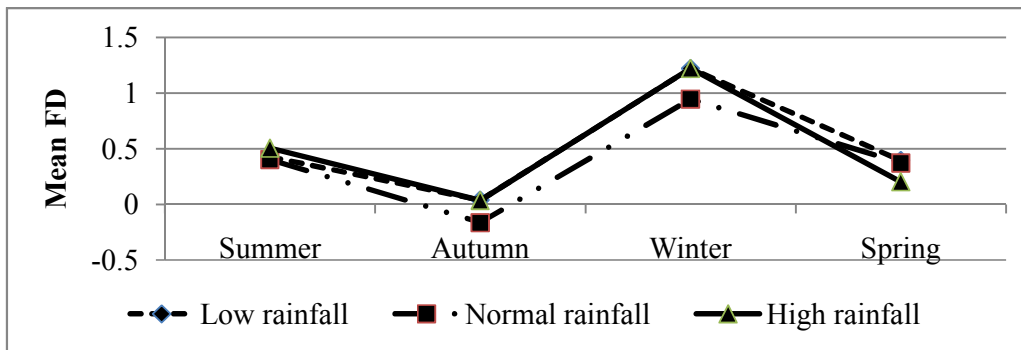


Figure 5. 10: The mean FD of GC vs. season and rainfall for Phase I

Season by relative humidity interaction: The season by relative humidity interaction effect on FD was significant (p -value = 0.006) for GC. But, this effect was not significant for GU (p -value = 0.7106). This means the mean difference between the FD's for GC depends on the combination of the levels of season by relative humidity holding the other effects constant. Figure 5.11 shows the respective maximum and minimum means for FD for GC. As we can see from the figure, the maximum FD for GC was obtained in spring

when relative humidity was normal. On the other hand, the minimum mean FD resulted from normal relative humidity when season was autumn for Phase I.

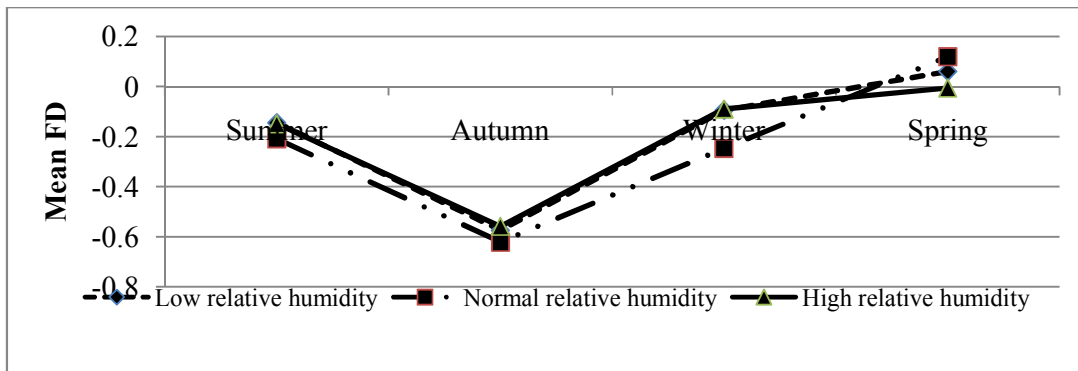


Figure 5. 11: The mean FD of GC vs. season and relative humidity for Phase I

Season by solar radiation interaction: The season by solar radiation interaction effect on FD was significant (p -value < 0.0001) for GC and (p -value = 0.0072) for GU. This means the mean difference between the FD's for GC and GU depends on the combination of the levels of season by solar radiation holding the other effects constant. In particular, Figure 5.12 shows that the respective maximum means FD resulted from low solar radiation and minimum mean FD results from normal/high solar radiation when the season was spring and autumn respectively for GC Phase I. On the other hand, Figure 5.12 shows that the maximum mean FD for GU was in winter for high solar radiation and the minimum value was in autumn when solar radiation was low/normal or high for Phase I.

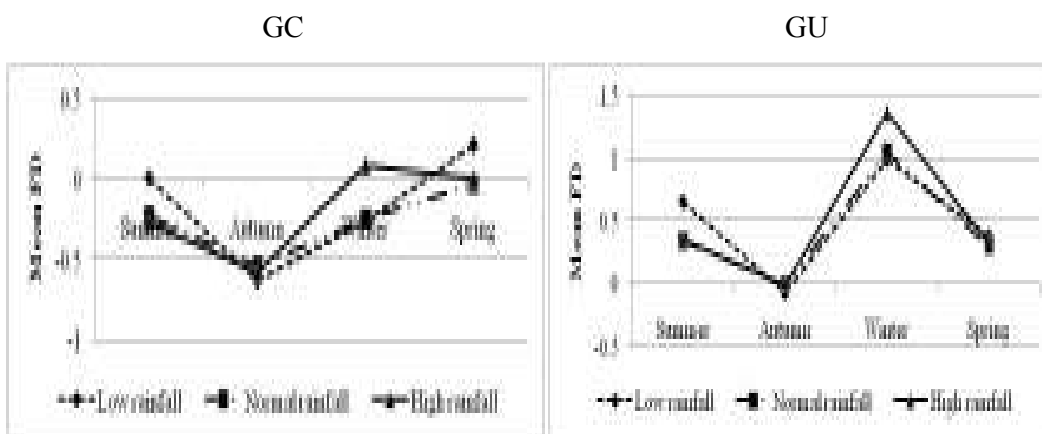


Figure 5. 12: The mean FD vs. season and solar radiation for Phase I

Rainfall by relative humidity interaction: The rainfall by relative humidity interaction effect on FD was significant (p -value = 0.0198) for GC. But, this effect was not

significant for GU (p -value = 0.1559). This means the mean difference between the FD's for GC depends on the combination of the levels of season by solar radiation holding the other effects constant. In particular, Figure 5.13 shows that the respective maximum means FD resulted from low rainfall and minimum mean FD results from normal rainfall when the relative humidity was high and low respectively for GC Phase I.

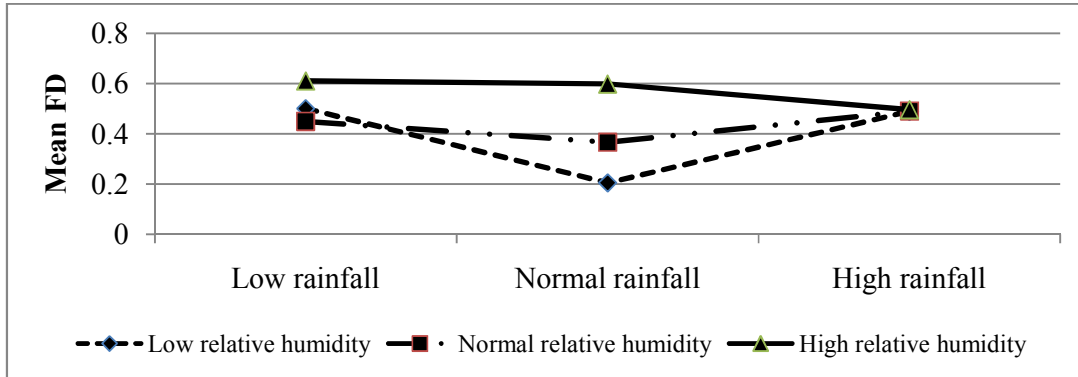


Figure 5. 13: The mean FD of GC vs. season and solar radiation for Phase I

Temperature by solar radiation interaction: The temperature by solar radiation interaction effect on FD was significant (p -value < 0.0001) for GC and (p -value = 0.0161) for GU. This means the mean difference between the FD's for GC and GU depends on the combination of the levels of temperature by solar radiation holding the other effects constant. In particular, Figure 5.14 shows that the respective maximum means FD resulted from normal temperature and minimum mean FD results from high temperature when solar radiation was low and normal respectively for GC Phase I. On the other hand, Figure 5.14 shows that the maximum mean FD for GU was for normal temperature for high solar radiation and the minimum value was for high temperature when solar radiation was low for Phase I.

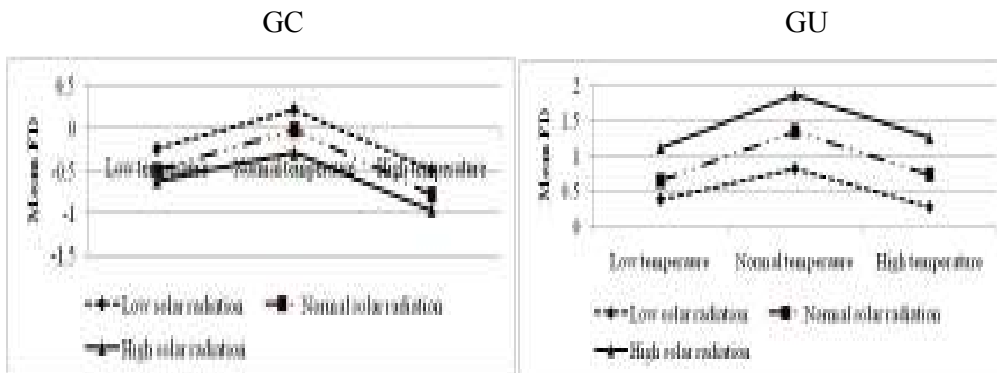


Figure 5. 14: The mean FD of GC vs. temperature and solar radiation for Phase I

Table 5. 4: Type 3 tests for FD for fixed effects: Phase I

Effect	GC				GU			
	Num DF	Den DF	F Value	Pr > F	Num DF	Den DF	F Value	Pr > F
Sqtage	1	4256	81.28	<.0001	1	3988	51.59	<.0001
Season	3	4256	116.73	<.0001	3	3988	38.14	<.0001
DBH	1	4256	0.92	0.3382	1	3998	15.67	<.0001
radius	1	4259	66.31	<.0001	1	3998	0.14	0.713
increment	1	4259	0.23	0.635	1	3998	4.4	0.036
Tempn	2	4256	6.63	0.0013	2	3988	12.02	<.0001
Rain	2	4256	9.29	<.0001	2	3988	3.17	0.0422
Humc	2	4256	0.74	0.4783	2	3988	3.94	0.0196
Solarc	2	4256	4.05	0.0174	2	3988	3.14	0.0436
Speedc	2	4256	0.91	0.4016	2	3988	3.13	0.0437
sqtage*season	3	4256	104.18	<.0001	3	3988	16.35	<.0001
season*rainn	6	4256	2.18	0.0422	6	3988	0.49	0.8135
season*humc	6	4256	3.94	0.0006	6	3988	0.62	0.7106
season*solarc	6	4256	5.53	<.0001	6	3988	2.95	0.0072
rainn*humc	4	4256	2.93	0.0198	4	3988	1.66	0.1559
rainn*speedc	4	4256	2.11	0.0525	4	3988	1.54	0.0581
tempn*solarc	4	4256	7.78	<.0001	4	3988	3.05	0.0161

Tests for fixed effects for FD for Phase II – IV are presented in Table A.13 - A.15. From the table it was observed that the significant effects for GC and GU found to be different. Moreover, the significant effects between Phases were different. This implies that we cannot have one model for the two clones and for the four phases. To interpret the significant results, we have used graphs. These graphs are presented in Figure B.46 - B.56. The summarized results are presented as follows.

The result from it was observed that FD decrease for autumn, winter and spring and increases for summer with age for GC Phase II. However, for GU Phase II, FD increases in autumn but decreases for the rest reasons. Similarly, FD increases within each season except for autumn for GC Phase III. Nevertheless, within each season FD increases with age for GU Phase III. The other significant result in the model was the combined effect of rainfall and season. This effect found to be significant only for Phase II GU. As the result indicates, FD was maximum in summer when rainfall was high for Phase II GU. Similarly, the combined effect of season and solar radiation found to be significant for only Phase II. As the result indicates, FD was maximum in summer when solar radiation was high and low for GC and GU respectively.

The other significant effect only for Phase II GU was the combined effect season and wind speed. As the result indicates, summer and high wind speed was preferred to obtain maximum FD for Phase II GC. On the other hand, the combined effect of the 23rd relative humidity and season was found to be significant for Phase II both clones. As the result indicates, autumn was preferred to obtain maximum FD for both clones. Furthermore, the combined effect of season and temperature was found to be significant for Phase III GC only. As the result indicates, spring and high temperature was preferred to obtain maximum FD for Phase III GC. On the other hand, the combined effect of season and wind speed was found to be significant for Phase III GC. From the result, it was observed that summer and spring, and normal wind speed was preferred to obtain maximum FD. Similarly, the combined effect of season and solar radiation at lag 16 was found to be significant for Phase III GC only. As the result indicates, FD was maximum in autumn when solar radiation at lag 16 was high. From the result, it was observed that there were no significant effects for Phase IV.

Table 5.5 presents the results for the random effects for Phase I - IV. The table shows that the effect of tree was not significant (p -value = 0.16 for GC) and (p – value = 0.15 for GU) for both clones. This result shows that there was no variability from tree to tree for GC and GU for the change in mean FD. On the other hand, tree by square root of age interaction were significant (p -value = 0.02) for GC and (p -value = 0.03) for GU. These results indicates that the slope of each tree were statistically different. On the other hand, the estimated value 0.19 for GC and 0.10 for GU were found to be significant. These results indicate that the measurements between trees were different for Phase I FD. On the other hand, the results for the random effects for Phase II to IV are presented in Table 5.5. As the result implies, there was tree to tree variability for Phase II and III. However, there was no tree to tree variability for IV. Similarly, there was variability within trees for Phase II and IV. Nevertheless, for Phase III there was no within subject (tree) effect. On the other hand, for Phase II GC, there was variability for the combined effect of tree and age.

Table 5. 5: FD random effects variance test

Covariance Parameter Estimates							
Cov Parm	Subject	GC			GU		
		Estimate	Z Value	Pr Z	Estimate	Z Value	Pr Z
Phase I							
Variance	treeno	0.23	1.01	0.16	0.16	1.03	0.15
CS	treeno	0.02	1.97	0.02	0.01	1.83	0.03
AR(1)	treeno	0.19	46.13	<.0001	0.1	44.64	<.0001
Residual		0.4	46.13	<.0001	0.61	44.64	<.0001
Phase II							
Variance	treeno	0.02	2.18	0.01	0.03	1.86	0.03
CS	treeno	0.02	2.17	0.03	0.02	1.84	0.07
AR(1)	treeno	0.94	123.4	<.0001	0.92	119.35	<.0001
Residual		0.39	8.21	<.0001	1.24	10.7	<.0001
Phase III							
Variance	treeno	0.22	1.71	0.04	0.36	1.93	0.03
CS	treeno	0.21	1.71	0.09	0.35	1.93	0.05
AR(1)	treeno	0.58	1.71	0.09	0.49	1.94	0.05
Residual		0.15	39.29	<.0001	0.4	43.33	<.0001
Phase IV							
Variance	treeno	0.04	0.51	0.31	0		
CS	treeno	0.02	0.34	0.74	0	1.33	0.19
AR(1)	treeno	0.56	11.47	<.0001	0.35	6.02	<.0001
Residual		0.21	9.43	<.0001	0.4	11.5	<.0001

The last fibre and vessel characteristic to be considered is the vessel frequency (VF). Table 5.6 shows the significant effects for VF for Phase I. From the table, it can be observed that the significant effects with p – values for GC were $reciage*season$ (0.0142) and $season*tempn$ (0.0445). Similarly, the significant effects for GU were $reciage*season$ (0.0085) and $season*tempn$ (0.0112). From the table it was observed that the significant effects for GC and GU found to be different. This implies that we can not have one model for the two clones. The interpretations for significant effects are presented as follows.

Square root of age by season interaction: The square root of age by season interaction effect on VF was significant (p -value =0.0142) for GC and (p -value =0.0085) for GU. This means the mean difference between the VF's for GC and GU depends on the combination of the levels of square root of age by season holding the other effects constant. In particular, Figure 5.15 shows that for autumn VF increases with age for GC. But, this effect is not significant for summer and winter. The rate of increase was in autumn (0.57) for GC. On the other hand, Figure 5.16 shows that for summer VF

increases with age for GU. But, this effect was not significant for autumn and winter. The highest rate of increase was in summer (481.4) for GU for Phase I.



Figure 5. 15: Joint effect of season and age GC Phase I for VF

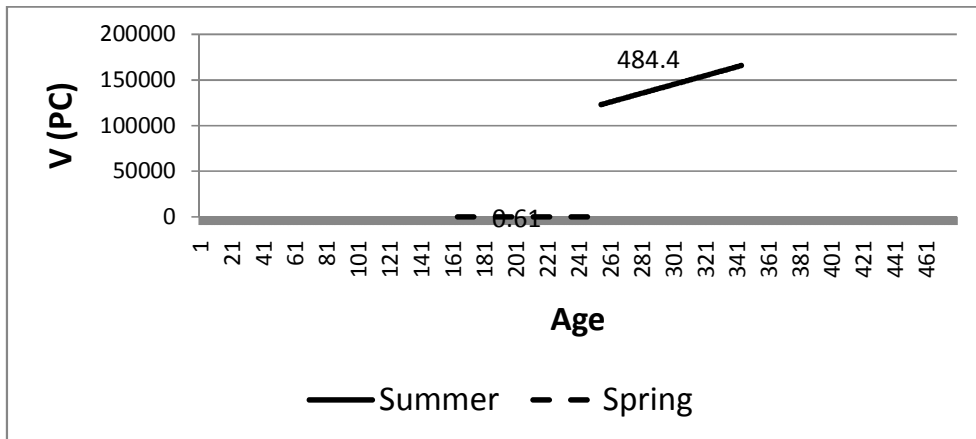


Figure 5. 16: Joint effect of season and age GU Phase I for VF

Season by temperature interaction: The season by temperature interaction effect on VF was significant (p -value = 0.0445) for GC and (p -value = 0.0112) for GU. This means the mean difference between the VF's for GC and GU depends on the combination of the levels of season by temperature holding the other effects constant. Figure 5.17 shows the respective maximum and minimum means for VF for GC. As we can see from the figure, the maximum VF for GC was obtained in spring. On the other hand, the minimum mean VF resulted from low/normal/high temperature when season was autumn for Phase I. Moreover, the maximum VF for GU was obtained in summer and the minimum VF value for GU was obtained in spring.

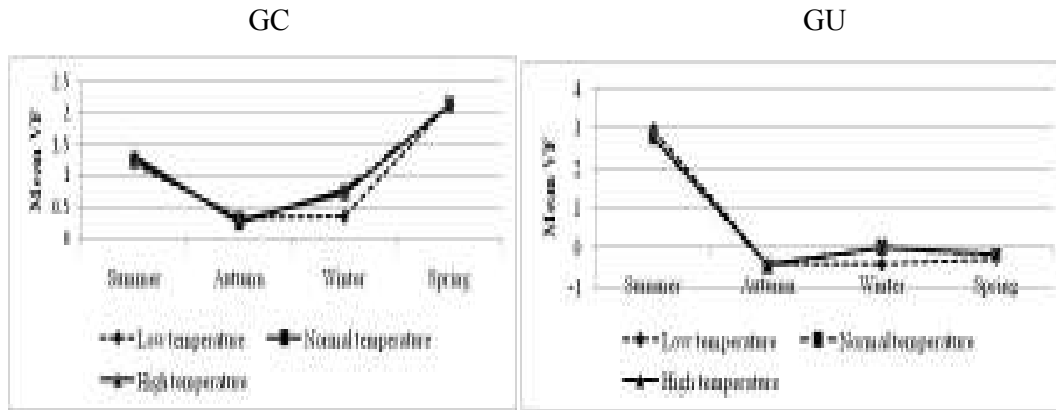


Figure 5. 17: The mean VF vs. season and temperature for Phase I

Table 5. 6: Type 3 tests for VF for fixed effects: Phase I

Effect	GC				GU			
	Num DF	Den DF	F Value	Pr > F	Num DF	Den DF	F Value	Pr > F
Reciage	1	4273	0.93	0.3358	1	4012	0.85	0.3565
Season	3	4273	2.24	0.0817	3	4012	2.92	0.0326
DBH	1	4273	2.24	<.0001	1	4012	35.55	<.0001
radius	1	4273	7.5	0.0062	1	4012	4.26	0.039
increment	1	4273	2.5	0.1142	1	4012	4.31	0.0379
Tempn	2	4273	2.11	0.1217	2	4012	4.8	0.0083
Rain	2	4273	0.29	0.7485	2	4012	0.37	0.6939
Humc	2	4273	0.7	0.4978	2	4012	0.79	0.4548
Solarc	2	4273	1.77	0.1707	2	4012	2.02	0.133
Speedc	2	4273	0.95	0.387	2	4012	0.01	0.9866
temp_lag13c	2	4273	0.49	0.6147	2	4012	1.5	0.2233
reciage*season	3	4273	3.53	0.0142	3	4012	3.9	0.0085
season*tempn	6	4273	2.47	0.0445	6	4012	2.76	0.0112
season*rainn	6	4273	0.42	0.866	6	4012	1.01	0.4166
season*temp_lag13c	4	4273	1.02	0.3944	6	4012	0.58	0.7493

Tests for fixed effects for VF for Phase II – IV are presented in Table A.19 - A.21. From the table it was observed that the significant effects for GC and GU found to be different. Moreover, the significant effects between phases were different. This implies that we cannot have one model for the two clones and for the four phases. To interpret the significant results, we have used graphs. These graphs are presented in Figure B.62 – B.65. The summarized results are presented as follows.

As the result indicates one of the significant effects Phase II GU was the combined effect of season and temperature. As can be seen from the result winter and high temperature

was preferred to obtain maximum VF for Phase II GU. On the other hand, the combined effect of season and rainfall was found to be significant for Phase II and Phase III. As the result indicates winter and normal rainfall for GC and spring and low rainfall for GU was preferred to obtain maximum FV for Phase II. Similarly, winter and normal rainfall for GC and summer and low rainfall for GU was preferred to obtain maximum VF for Phase III. On the other hand, the combined effect of season and solar radiation was found to be significant only for Phase III GU. As the result indicates, winter and low solar radiation was preferred to obtain maximum VF. Similar to the other wood anatomical properties (FW, FD and VD), there were no significant effects for Phase IV.

Similar to FW, FD and VD, tests for the random effects were performed. Table 5.7 presents the random effect results for Phase I - IV7. The table shows that the effect of tree was not significant (p - value = 0.22) for GC and GU. This result shows that there was no variability from tree to tree for both clones for the change in mean VF. On the other hand, tree by reciprocal root of age interaction was not significant (p -value = 0.47) for GC and (p - value = 0.36) for GU. These results indicate that the slopes of each tree were not statistically different for both clones. On the other hand, the estimated value 0.89 for GC and 0.862 for GU were found to be significant. As the result for the random effect indicates (Table 5.7), there was tree to tree variation only for Phase II GC. For the other phases, there was no variability between trees. Similarly, there was combined effect of reciprocal of age and tree for Phase II GC only. There was variability between trees with age. On the other hand, there was variability within trees for all phases except for Phase IV.

Table 5. 7: VF random effects variance test

Covariance Parameter Estimates							
Cov Parm	Subject	GC			GU		
		Estimate	Z Value	Pr Z	Estimate	Z Value	Pr Z
Phase I							
Variance	treeno	0.1	0.78	0.22	0	.	.
CS	treeno	0.07	0.72	0.47	0.02	0.92	0.36
AR(1)	treeno	0.89	117.91	<.0001	0.86	104.59	<.0001
Residual		0.87	14.58	<.0001	0.81	16.57	<.0001
Phase II							
Variance	treeno	0.58	2.26	0.01	0	.	.
CS	treeno	0.57	2.26	0.02	0.49	1.35	0.18
AR(1)	treeno	0.93	111.35	<.0001	0.88	95.5	<.0001
Residual		13.15	8.98	<.0001	19.78	12.8	<.0001
Phase III							
Variance	treeno	0	.	.	0.115	0.83	0.2
CS	treeno	0.01	0.36	0.72	0.114	0.83	0.4
AR(1)	treeno	0.94	137.97	<.0001	0.89	111.32	<.0001
Residual		0.66	8.73	<.0001	1.05	14.49	<.0001
Phase IV							
Variance	treeno	0.1	0.84	0.2	0.44	1.13	0.13
CS	treeno	0.09	0.97	0.33	0.23	0.89	0.37
AR(1)	treeno	0.09	1.26	0.21	0.06	0.87	0.38
Residual		1.93	13.08	<.0001	1.81	12.98	<.0001

5.2.2 Using continuous climatic variables.

Similar to the previous sub section, preliminary fitting of the model included the season, age, DBH, radius, increment and the climatic variables (including lags) effect under various covariance structures. However, the climatic variables considered in this section were the continuous climatic variables. The appropriate covariance structures were the Compound symmetry (CS) for between subject effects and AR (1) for within subject effects. Similar to the previous section, the results for the remaining wood anatomical characteristics of the *Eucalyptus* clones, i.e., for VD, FD and VF, are discussed in detail. Similar to the previous section, the usual model assumptions were checked and the usual model assumptions were not violated by the data.

The first fibre and vessel characteristics to be considered is the fibre dimension (FD). The p-values for testing the significance of the effects in the final reduced model for Phase I - IV are displayed in Tables 5.8 and A.24 - A.25. The significant effects, at the 0.05 level of significance, are explained in the sub sections that follow. As we can see from the table, the significant effects for GC and GU found to be different. This implies that we cannot have one model for the two clones. Table 5.8 shows the significant effects for FD for Phase I. From the table, similar to the categorical climatic variables result, it was observed that the significant effects for GC and GU found to be different. This implies that we cannot have one model for the two clones. After fitting the model, the observed and fitted values of FD for both clones are presented in Figure 5.18.

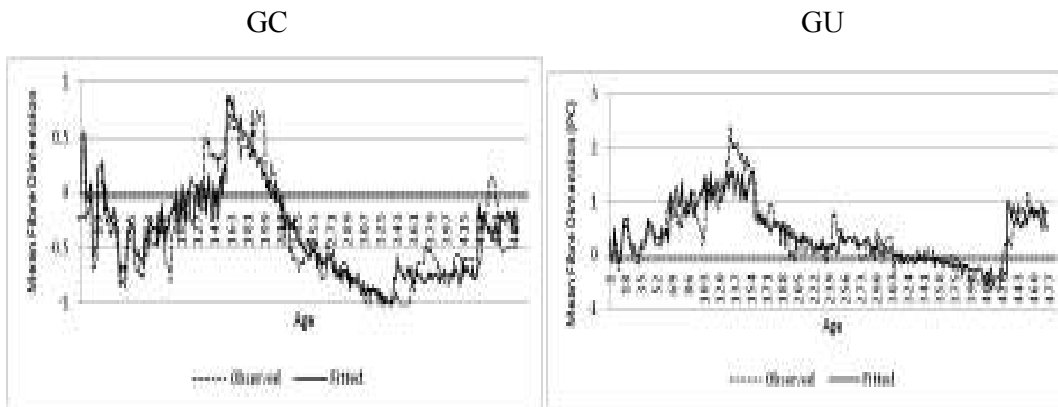


Figure 5. 18: Observed vs. fitted values for FD Phase I

As we have seen in Figure 5.18, the model for FD with the significant predictor variables fits well for both clones. The estimated values for the significant effects are presented in Table 5.8.

As we can see in Table 5.8, the effect of season for FD Phase I was found to be significant. This result indicates that the rate of increase for FD was found to be in summer (-4.35), autumn (-7.08) and winter (-6.80) as compared to spring (the reference season) for GC. This result implies that season has negative effect on FD. On the other hand, the effect of seasons found to be significant for GU. As the result indicates, FD was lower in autumn (-2.8) and winter (-1.79) as compared to spring for GU Phase I. But, for summer there was no significant effect.

One of the significant results in our model was the interaction between season and age. As we can see from the result, FD decreases with age in summer (-0.15), autumn (-0.02) and winter (-0.004) as compared to spring. On the other hand, FD decreases with age for autumn (-0.07) and winter (-0.03) as compared to spring for GU. But, similar to the season effect, when age interacts with summer, there was no significant effect.

From Table 5.8, we found that the interaction between temperature and season was found to be significant for autumn and winter for GC and GU respectively. As we can see from Table 5.8, FD decreases with temperature in autumn (-0.14) and increases in winter (0.307) for GC and GU respectively.

Table 5. 8: Parameter estimates for FD Model: Phase I

Solution for Fixed Effects						
Effect	GC			GU		
	Estimate	SE	Pr > t	Estimate	SE	Pr > t
Intercept	6.8748	0.4489	<.0001	3.6071	0.5133	0.0001
Sqtage	-0.4716	0.0318	<.0001	-0.2271	0.03552	0.0002
Summer	-4.3547	0.6584	<.0001	-0.5311	0.8104	0.5123
Autumn	-7.0766	0.393	<.0001	-2.9864	0.4899	<.0001
Winter	-6.7982	0.3952	<.0001	-1.7878	0.4892	0.0003
Spring	0	.	.	0	.	.
DBH	0.2505	0.02486	<.0001	0.09543	0.02653	0.0003
Increment	7.12E-06	1.83E-06	<.0001	2.76E-06	1.76E-06	0.1172
Tempc	0.05892	0.0381	0.1221	0.1214	0.04691	0.0097
sqtage*summer	0.2805	0.04112	<.0001	0.05532	0.05065	0.2748
sqtage*Autumn	0.4459	0.02737	<.0001	0.1848	0.034	<.0001
sqtage*winter	0.4679	0.02746	<.0001	0.1962	0.03397	<.0001
sqtage*spring	0	.	.	0	.	.
tempc*summer	-0.0889	0.065	0.1713	-0.09	0.07984	0.2599
tempc*autumn	-0.1371	0.04708	0.0036	-0.0754	0.05908	0.202
tempc*winter	0.09148	0.05228	0.0802	0.1859	0.06437	0.0039
tempc*spring	0	.	.	0	.	.
solarc*autumn	0.07228	0.04698	0.124	0.1269	0.0599	0.0341
solarc*winter	0.1576	0.04843	0.0011	0.146	0.05978	0.0146
solarc*spring	0	.	.	0	.	.
humc*solarc	-0.032	0.01359	0.0186	-0.0178	0.01689	0.2933

The other significant result in the model was the between solar radiation and season. The result was found to be significant for winter for GC and for autumn and winter for GU. As we can see from Table 5.8, FD increases with solar radiation in autumn (0.16) for GC. Similarly, FD for GU increases with solar radiation in autumn (0.13) and winter (0.15).

The other significant effects on FD for Phase I in the model were relative humidity and solar radiation interactions. This interaction effect found to be significant only for GC. From our result, we observed that the interaction between relative humidity and solar radiation has negative (-0.032) effect on FD for GC.

Table A.24 - A.25 show the significant effects for Fibre Dimension (FD) for Phase II - IV for both clones. After fitting the model, the observed and fitted values of FD for both clones are presented from Figure B.68 – B.69 for Phase II - IV. As we have seen in Figure B.68 - B.69, the model for FD with the significant predictor variables fits well for both clones for Phase II - IV. The summarized results are presented as follows.

The combined effect of square root of age and season was found to be significant for Phase II and III. As the result indicates FD increases with age in summer for both clones for Phase II. Moreover, FD increases in winter with age for GC and in autumn for GU Phase III. The other significant effect for Phase II only was the combined effect of temperature and season. As can be seen from the result, FD was decreasing in winter for both clones for a change in temperature for Phase II. Furthermore, the combined effect of rainfall and season was found to be significant only for Phase II. As the result indicates, FD was increasing in winter for both clones for a change in rainfall. Similarly, the combined effect of the 16th day of solar radiation and season was found to be significant only for Phase III. As the result indicates FD increases in summer for a change in the 16th day of solar radiation. From the result, it was observed that there were no significant effects for Phase IV.

The results for the random effects for Phase I-IV are presented in Table 5.9. The table shows that the effect of tree was significant (p – value = 0.0453 for GU) but not significant for GC (p -value = 0.073) for Phase I. This result shows that there was variability from tree to tree for GC and GU for the change in mean FD. On the other hand, tree by square root of age interaction was significant (p -value = 0.0346) for GC but not for GU (p -value = 0.0942). Moreover, the result indicates that the slope of each tree was statistically different for GC clone. On the other hand, the estimated value 0.44 for GC and 0.60 for GU were found to be significant. These results indicate that the measurements between trees were different for FD Phase I.

Table 5. 9: FD random effects variance test using continuous climatic variables

Covariance Parameter Estimates							
Cov Parm	Subject	GC			GU		
		Estimate	Z Value	Pr Z	Estimate	Z Value	Pr Z
Phase I							
Variance	treeno	0.0302	1.79	0.073	0.01607	1.69	0.0453
CS	treeno	0.0278	1.82	0.0346	0.0149	1.67	0.0942
AR(1)	treeno	0.4415	1.96	0.05	0.2659	1.83	0.0471
Residual		0.4028	45.89	<.0001	0.6042	44.44	<.0001
Phase II							
Variance	treeno	0.1798	1.83	0.0429	0.2078	2.98	0.0498
CS	treeno	0.1803	1.94	0.0452	0.1931	1.98	0.1382
AR(1)	treeno	0.9807	156.47	<.0001	0.9378	107.66	<.0001
Residual		1.1978	3.09	0.001	0.7869	7.18	<.0001
Phase III							
Variance	treeno	0.1798	1.83	0.0429	0.2078	1.98	0.0498
CS	treeno	0.1803	1.94	0.0452	0.1931	1.98	0.0482
AR(1)	treeno	0.9807	156.47	<.0001	0.9378	107.66	<.0001
Residual		1.1978	3.09	0.001	0.7869	7.18	<.0001
Phase IV							
Variance	treeno	0.0052	0.69	0.2443	0	.	.
CS	treeno	0.0031	0.56	0.5762	0.00095	1.38	0.1682
AR(1)	treeno	0.5475	9.52	<.0001	0.4045	6.39	<.0001
Residual		0.2101	8.57	<.0001	0.3482	9.96	<.0001

On the other hand, the results for the random effects for Phase II to IV are presented in Table 5.9. As the result implies, there was tree to tree variability for Phase II and III. Nevertheless, there was no tree to tree variability for IV. Similarly, there was variability within trees for Phase II and IV. But, for Phase III there was no within subject (tree) effect. On the other hand, for Phase II GC, there was variability for the combined effect of tree and age.

The second fibre and vessel characteristic is the vessel dimension (VD). Table 5.10 shows the significant effects for VD for Phase I. From the table, similar to the categorical climatic variables result, it was observed that the significant effects for GC and GU found to be different. This implies that we cannot have one model for the two clones. After fitting the model, the observed and fitted values of VD for both clones are presented in Figure 5.19.

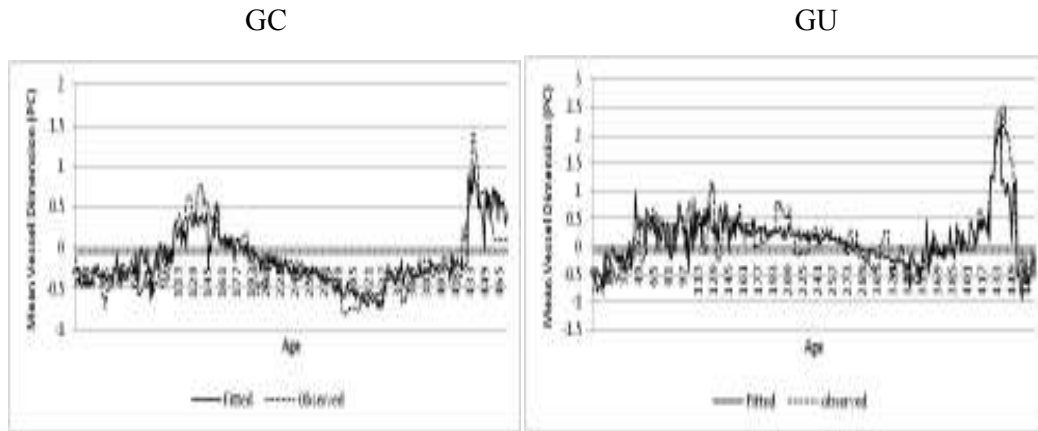


Figure 5. 19: Observed vs. fitted values for VD Phase I – GC

As we have seen in Figure 5.19, the model for VD with the significant predictor variables fits well for both clones. The estimated values for the significant effects are presented in Table 5.10.

As we can see in Table 5.10, the effect of season for VD Phase I was found to be significant for GC. But, this effect was not significant for GU. This result indicates that VD was lower in autumn (-2.32) and winter (-2.15) as compared to spring (the reference season) for GC. This result implies that season has negative effect on VD for Phase I.

One of the significant results in our model was the interaction between season and age. As we can see from the result, VD increases with age in autumn (0.16) and winter (0.20) as compared to spring for GC. On the other hand, VD increases with age in winter (0.11) as compared to spring for GU.

From Table 5.10, we found that the interaction between temperature and season was found to be significant for both clones. As we can see from Table 5.10, VD decreases with the temperature in autumn (-0.11) for GC. On the other hand, VD decreases in autumn (-0.28) and winter (-0.18) as compared to spring for GU.

Similarly, from Table 5.10, we found that the interaction between relative humidity and season was found to be significant for both clones. As we can see from Table 5.10, VD increases in winter (0.24 and 0.20) for GC and GU respectively as compared to spring.

As we can see from Table 5.14, the interaction between solar radiation and season was found to be significant for both clones. As we can see from Table 5.10, VD increases in winter (0.21 and 0.16) for GC and GU respectively as compared to spring.

The other significant effects in the model were the interaction between temperature and wind speed, and the interaction between relative humidity and solar radiation for GC. But, these interaction effects were not significant for GU. As we can see from Table 5.10, the interaction effect between temperature and wind speed has negative (-0.036) effect on VD for GC. Similarly, the interaction between relative humidity and solar radiation has negative effect on VD for GC.

Table 5. 10: Parameter estimates for VD Model: Phase I

Solution for Fixed Effects						
Effect	GC			GU		
	Estimate	S E	Pr > t	Estimate	S E	Pr > t
Intercept	1.4566	0.4956	0.0187	-0.6386	0.6977	0.3868
Summer	0.1215	0.6736	0.8569	1.4227	1.0883	0.1912
Autumn	-2.3228	0.398	<.0001	-1.1908	0.6539	0.0687
Winter	-2.1486	0.4044	<.0001	-1.1916	0.6559	0.0693
Spring	0	.	.	0	.	.
DBH	-0.407	0.02425	<.0001	0.1208	0.0347	0.0005
Radius	1.8E-05	7.34E-06	0.0134	4.5E-05	5.98E-06	<.0001
tempc	0.0914	0.0386	0.018	0.0015	0.0626	0.0083
Rainc	0.03339	0.0302	0.269	0.1125	0.04566	0.0138
sqtage*summer	0.00201	0.04207	0.9619	-0.0839	0.06803	0.2176
sqtage*autumn	0.1559	0.02776	<.0001	0.07475	0.0454	0.0998
sqtage*winter	0.1982	0.02829	<.0001	0.1113	0.04567	0.0148
sqtage*spring	0	.	.	0	.	.
tempc*summer	-0.1006	0.06583	0.1266	-0.0531	0.1066	0.6184
tempc*autumn	-0.199	0.0477	<.0001	-0.276	0.07892	0.0005
tempc*winter	0.08825	0.05325	0.0975	-0.1792	0.08618	0.0376
tempc*spring	0	.	.	0	.	.
humc*summer	-0.0455	0.05363	0.3963	-0.0423	0.08725	0.6278
humc*autumn	0.02097	0.04124	0.6111	-0.0458	0.06853	0.5042
humc*winter	0.2422	0.04041	<.0001	0.2003	0.06525	0.0022
humc*spring	0	.	.	0	.	.
solarc*summer	-0.0043	0.04609	0.9265	0.01314	0.07434	0.8598
solarc*autumn	0.06994	0.0477	0.1427	-0.1517	0.07993	0.0578
solarc*winter	0.2077	0.04932	<.0001	0.1554	0.07987	0.0517
solarc*spring	0	.	.	0	.	.
tempc*speedc	-0.0358	0.01555	0.0214	-0.0181	0.02592	0.4853
humc*solarc	-0.0298	0.01378	0.0307	-0.0123	0.02256	0.586

Table A.26 - A.27 show the significant effects for Vessel Dimension (VD) for Phase II - IV for both clones. After fitting the model, the observed and fitted values of VD for both clones are presented in Figure B.70 –B.71 for Phase II - IV. As we have seen in Figure B.70 –B.71, the model for FD with the significant predictor variables fits well for both clones for Phase II - IV. The summarized results are presented as follows.

Similar to VD Phase I, the combined effect of square root of age and season was found to be significant for Phase II and III. As the result indicates, VD increases with age in autumn for both clones for Phase II. On the other hand, this combined effect for Phase III showed that VD decreases with age in summer and winter for GC and GU respectively. The other significant result in the model was the combined effect of temperature and season. This effect was significant only for Phase II. The result for Phase II shows that VD was decreasing in summer for GC and increasing in winter for GU for a change in temperature for Phase II. The combined effect of season and relative humidity was found to be significant only for Phase III GU. As the result indicates, VD was increasing for all seasons for a change in relative humidity for Phase III GU. Moreover, the combined effect of solar radiation and season was found to be significant for Phase II GC only. As the result indicates VD increases in winter for a change in solar radiation for GC Phase II. The other significant effect in the model for Phase II was the combined effect of temperature and relative humidity for both clones and the combined effect of rainfall and solar radiation for GC only. As the result indicates, the combined effect of temperature and relative humidity has negative effect for both clones. Similarly, the combined effect of temperature and wind speed has negative effect on VD for GU Phase III. From the result, it was observed that there were no significant effects for Phase IV.

The random effect tests for VD for Phase I – IV are presented in Table 5.11. The table shows that the effect of tree was significant for GC. However, the tree effect was not significant for GU. This result shows that there was variability from tree to tree for GC for the change in mean VD. On the other hand, tree by square root of age interaction was not significant (p -value = 0.0668) for GC and (p - value = 0.1071) for GU. These results indicate that the slopes of each tree are not statistically different for both clones. On the other hand, the estimated value 0.95 for GC and 0.904 for GU were found to be

significant. These results indicate that the measurements between trees were different for VD Phase I.

Table 5. 11: VD random effects variance test using continuous climatic variable

Covariance Parameter Estimates							
Cov Parm	Subject	GC			GU		
		Estimate	Z Value	Pr Z	Estimate	Z Value	Pr Z
Phase I							
Variance	Treeno	0.02967	1.85	0.0321	0.01598	1.63	0.0518
CS	Treeno	0.0273	1.83	0.0668	0.0148	1.61	0.1071
AR(1)	Treeno	0.9494	172.18	<.0001	0.9037	124.68	<.0001
Residual		0.5804	9.2	<.0001	1.2421	13.3	<.0001
Phase II							
Variance	treeno	0.3681	1.81	0.0353	0.2172	1.89	0.0295
CS	treeno	0.3556	1.81	0.0705	0.2084	1.89	0.0593
AR(1)	treeno	0.9347	1.91	0.0698	0.561	1.98	0.0594
Residual		0.126	33.27	<.0001	0.2066	32.53	<.0001
Phase III							
Variance	treeno	0.3681	1.81	0.0553	0.2172	1.89	0.0295
CS	treeno	0.3556	1.81	0.0705	0.2084	1.89	0.0593
AR(1)	treeno	0.1347	1.81	0.0698	0.0641	1.88	0.0594
Residual		0.126	33.27	<.0001	0.2066	32.53	<.0001
Phase IV							
Variance	treeno	0.1004	1.52	0.0638	0.03612	0.77	0.2196
CS	treeno	0.0823	1.51	0.1306	0.0272	0.7	0.4834
AR(1)	treeno	0.3626	1.45	0.1484	0.173	0.85	0.3975
Residual		0.5751	12.58	<.0001	1.0934	12.59	<.0001

Furthermore, the results for the random effects for Phase II to IV are presented in Table 5.11. As the result for the random effects indicates, there was variability from tree to tree only for Phase II GU and Phase IV GC. For the rest phases, there was no variability between trees. Similarly, there was variability for the combined effect of age and tree for Phase IV GC. On the other hand, except for Phase III there was variability within trees for Phase II and IV.

The last fibre and vessel characteristic to be considered is the vessel frequency. Table 5.12 shows the significant effects for VF for Phase I. From the table, similar to the categorical climatic variables result, it was observed that the significant effects for GC and GU found to be different. This implies that we cannot have common model for the

two clones. After fitting the model, the observed and fitted values of VF for both clones are presented in Figure 5.20.

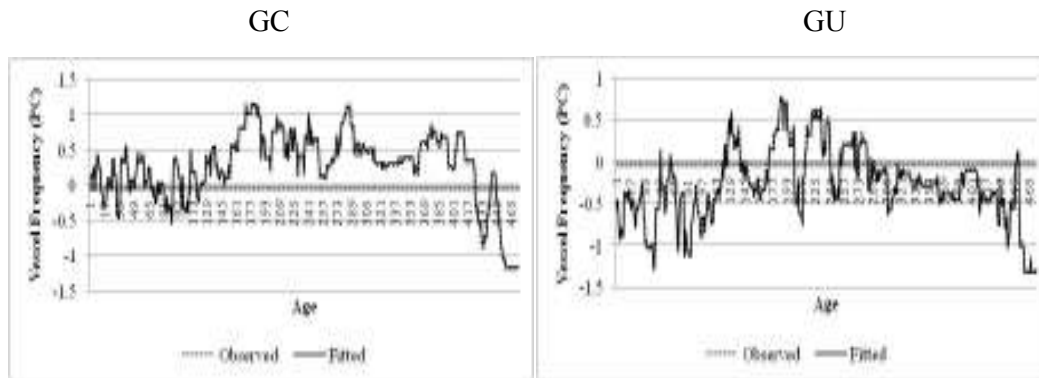


Figure 5. 20: Observed vs. fitted values for VF Phase I – GC

As we have seen in Figure 5.20, the model for VF with the significant predictor variables fits well for both clones. The estimated values for the significant effects are presented in Table 5.12.

As we can see in Table 5.12, the effect of season for VF Phase I was found to be significant for both clones. This result indicates that VF decreases in autumn (-1.49) and winter (-1.85) for GC and in summer (-3.5), autumn (-1.77) and winter (-1.996) for GU as compared to spring (the reference season). This result implies that season has negative effect on VF for both clones.

One of the significant results in our model was the interaction between season and age. As we can see from the result, VF increases with age in autumn (248.09) and winter (278.79) for GC. Similarly, VF increases with age in summer (886.01), autumn (286.82) and winter (308.45) for GU as compared to spring for Phase I.

From Table 5.12, we found that the interaction between temperature and season was found to be significant for both clones. As we can see from Table 5.16, VF increases with temperature in summer (0.019), autumn (0.077) and winter (0.053) for GC as compared to spring. On the other hand, VF increases with temperature in summer (0.031), autumn (0.035) and winter (0.023) for GU as compared to spring for Phase I.

Table 5. 12: Parameter estimates for VF Model: Phase I

Solution for Fixed Effects						
Effect	GC			GU		
	Estimate	S E	Pr > t	Estimate	S E	Pr > t
Summer	-2.6484	1.349	0.0613	-3.5025	1.2123	0.0081
Autumn	-1.4894	0.6724	0.0365	-1.7704	0.6081	0.0077
Winter	-1.8511	0.6952	0.0136	-1.9962	0.6305	0.0042
Spring	0	.	.	0	.	.
Humc	0.01109	0.01066	0.298	0.0263	0.01185	0.0265
DBH	0.3008	0.03025	<.0001	0.1617	0.02873	<.0001
radius	2.06E-07	4.04E-06	0.9593	0.00001	3.18E-06	0.0011
recipage*summer	656.65	347.78	0.0591	886.01	314.2	0.0048
recipage*autumn	248.09	123.41	0.0445	286.82	114.55	0.0123
recipage*winter	278.79	125.06	0.0259	308.45	116.21	0.008
recipage*spring	0	.	.	0	.	.
tempc*summer	0.0191	0.04989	0.0118	0.0314	0.05401	0.0211
tempc*autumn	0.0769	0.03531	0.0277	0.0351	0.04042	0.0354
tempc*winter	0.05337	0.03464	0.0234	0.0298	0.03745	0.0464
tempc*spring	0	.	.	0	.	.

Table A.28 - A.29 show the significant effects for Vessel Frequency (VF) for Phase II - IV for both clones. After fitting the model, the observed and fitted values of VD for both clones are presented from Figure B.72 - B.73 for Phase II - IV. As we have seen in from Figure B.72 - B.73, the model for FD with the significant predictor variables fits well for both clones for Phase II - IV. The summarized results are presented as follows.

Similar to VD, the results for the random effects for Phase I - IV are presented in Table 5.13. The table shows that the effect of tree was not significant (p - value = 0.217) for GC and (p -value = 0.413) for GU. This result shows that there was no variability from tree to tree for both clones for a change in mean VF. On the other hand, tree by square root of age interaction was not significant (p -value = 0.719) for GC and (p - value = 0.141) for GU. These results indicates that the slope of each tree were not statistically different for both clones. On the other hand, the estimated value 0.92 for GC and 0.83 for GU were found to be significant. These results indicate that the measurements between trees were different for Phase VF I. As the result for the random effect indicates, there was tree to tree variation only for Phase II GC. For the other phases there was no variability between trees. Similarly, there was combined effect of reciprocal of age and tree for Phase II GC only. There was variability between trees with age. On the other hand, there was variability within trees for all phases except for Phase IV.

Table 5. 13: VF random effects variance test using continuous climatic variables

Covariance Parameter Estimates							
Cov Parm	Subject	GC			GU		
		Estimate	Z Value	Pr Z	Estimate	Z Value	Pr Z
Phase I							
Variance	treeno	0.6046	0.78	0.2165	0.03728	0.22	0.4132
CS	treeno	0.0079	0.36	0.7192	0.01203	1.47	0.1412
AR(1)	treeno	0.8964	127.67	<.0001	0.8667	108	<.0001
Residual		0.9219	14.79	<.0001	0.831	16.61	<.0001
Phase II							
Variance	treeno	0.7241	1.8	0.0359	0	.	.
CS	treeno	0.00345	1.88	0.0303	0.00099	1.26	0.209
AR(1)	treeno	0.3897	1.98	0.0482	0.9778	239.15	<.0001
Residual		9.7851	33.37	<.0001	0.9587	5.44	<.0001
Phase III							
Variance	treeno	0	.	0.2632	0	.	.
CS	treeno	0.04002	1.12	<.0001	0.01997	0.93	0.3548
AR(1)	treeno	0.9486	151.18	<.0001	0.9042	116.23	<.0001
Residual		0.6751	8.21		1.1632	12.37	<.0001
Phase IV							
Variance	treeno	0.2918	1.47	0.071	0.1004	1.52	0.0638
CS	treeno	0.0325	1.46	0.0726	-0.0823	-1.51	0.1306
AR(1)	treeno	0.06885	0.96	0.3385	0.07155	1.02	0.3088

5.3 Comparison of the analysis of the categorical and continuous climatic variables

The summary values of the significant results for the fibre and vessel characteristics of *Eucalyptus* clones are presented in Table 5.14 - 5.15 for GC and GU respectively. As can be seen from the tables, the two clones have different models for all fibre and vessel characteristics. Based on the results, it was observed that the GC clone affected by more effects than GU. Moreover, each fibre and vessel characteristics have different models. In this chapter, we have included DBH, radius and increment to improve the model. As can be seen from Table 5.14 and 5.15, most of the fibre and vessel characteristics of *Eucalyptus* clones affected by the additional factors. For example, FW was affected by DBH and increment, VD was affected by radius for GC. From the four fibre and vessel characteristics of *Eucalyptus* clones VD and FD were affected by more effects than FW and VF. Similarly, for each fibre and vessel characteristics of *Eucalyptus* clones, the models are different. The only similar effect for GC was found to be the interaction between square root of age and season. For GU the only similar significant effects for the

four PCs found to be the square root of age by season interaction and DBH. This result found to be similar for the other three phases.

Table 5. 14: Summary results for the wood anatomy properties for GC

Effect	Categorical Result				Continuous Result			
	FW	FD	VD	VF	FW	FD	VD	VF
Sqtage	NS	Sig.	Sig.	NS	NS	Sig.	Sig.	NS
Season	Sig.	Sig.	Sig.	NS	Sig.	Sig.	Sig.	Sig.
DBH	Sig.	Sig.	NS	Sig.	Sig.	Sig.	Sig.	Sig.
Radius	NS	Sig.	Sig.	Sig.	Sig.	NS	Sig.	Sig.
Increment	Sig.	NS	NS	NS	Sig.	NS	NS	NS
Tempn	Sig.	NS	Sig.	NS	Sig.	Sig.	Sig.	NS
Rain	NS	NS	Sig.	NS	NS	NS	NS	NS
Humc	Sig.	Sig.	NS	NS	NS	NS	NS	NS
Solarc	Sig.	Sig.	Sig.	NS	NS	NS	NS	NS
temp_lag13c	Sig.	NS	NS	NS	Sig.	NS	NS	NS
temp_lag19c	NS	Sig.	Sig.	Sig.	NS	Sig.	Sig.	NS
sqtage*season	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.
season*tempn	NS	NS	Sig.	NS	Sig.	Sig.	Sig.	Sig.
season*rain	Sig.	Sig.	Sig.	NS	NS	NS	NS	NS
season*humc	NS	Sig.	Sig.	NS	Sig.	Sig.	Sig.	NS
season*solarc	Sig.	Sig.	NS	NS	NS	Sig.	Sig.	NS
season*speedc	Sig.	NS	NS	NS	NS	NS	NS	NS
season*temp_lag13c	Sig.	NS	NS	NS	Sig.	NS	NS	NS
season*temp_lag19c	Sig.	NS	NS	NS	NS	NS	NS	NS
rainn*solarc	NS	NS	Sig.	NS	NS	Sig.	NS	NS
rainn*speedc	NS	NS	Sig.	NS	NS	Sig.	NS	NS
tempn*solarc	NS	NS	NS	NS	Sig.	NS	NS	NS
solarc*speedc	Sig.	NS	NS	NS	Sig.	NS	NS	NS

Sig. – significant, NS – Not significant

Table 5. 15: Summary results for the wood anatomy properties for GU

Effect	Categorical Result				Continuous Result			
	FW	FD	VD	VF	FW	FD	VD	VF
Sqtage	NS	Sig.	Sig.	NS	NS	Sig.	Sig.	NS
Season	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.
DBH	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.
Radius	Sig.	Sig.	NS	Sig.	Sig.	Sig.	Sig.	Sig.
Increment	NS	NS	Sig.	Sig.	NS	NS	NS	NS
Tempn	NS	Sig.	Sig.	NS	NS	Sig.	Sig.	NS
Rain	NS	Sig.	Sig.	NS	NS	NS	Sig.	NS
Humc	NS	NS	Sig.	NS	NS	NS	NS	NS
Solarc	NS	NS	Sig.	NS	NS	NS	NS	NS
Speedc	NS	NS	Sig.	NS	NS	NS	NS	NS
temp_lag13c	Sig.	NS	NS	NS	Sig.	NS	NS	NS
temp_lag19c	NS	Sig.	NS	NS	NS	NS	NS	NS
sqtage*season	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.
season*tempn	NS	NS	NS	Sig.	NS	NS	Sig.	Sig.
season*solarc	Sig.	NS	Sig.	NS	Sig.	Sig.	Sig.	NS
season*temp_lag19c	NS	Sig.	NS	NS	NS	Sig.	NS	NS
tempn*solarc	NS	NS	Sig.	NS	NS	NS	Sig.	NS

Sig. – significant, NS – Not significant

In summary, as we have seen in the previous sections, it was found that for fibre and vessel characteristics of *Eucalyptus* tree (FW, FD, VD, and VF) the number of significant two-way climatic interaction effects decreases as phase increases. To improve the model, DBH, radius and increment were included. Inclusions of these additional factors have effect on FW, VD, FD and VF. Therefore, as we have seen in this chapter, it was found that for fibre and vessel characteristics of *eucalyptus* tree (FW, FD, VD, and VF) the number of significant two-way climatic interaction effects decreases as phase increases. This result indicates that each phase and each clone has different models for each variable (FW, FD, VD, and VF). Therefore, there was no universal model to explain variation of wood properties. Moreover, there were no any significant effects for Phase IV.

6. Summary, conclusions and recommendation

The main objective of this study was to investigate the effect of climatic variables on the wood anatomical characteristics of two *Eucalyptus* clones: GU and GC. The understanding of the impact of climatic parameters on wood properties will help to understand which wood quality could be expected under a certain set of climatic conditions. Two sets of data were recorded daily, the climatic parameters (temperature, rainfall, solar radiation, relative humidity and wind speed) and the tree growth. After cutting the trees, the anatomical properties of the wood (six fibre and five vessel characteristics variables) was measured using microscope and image analysis. The wood anatomical data were linked to growth data in order to identify the data when cells were formed.

The first step of the study was the reduction of the number of variable (six fibre and five vessel characteristics) in order to facilitate the interpretation of results. These eleven wood anatomical characteristics were found to be highly correlated. Accordingly the principal component analysis was used to reduce the number of response variables and group them according to their correlations. The principal component analysis was done for each phase and clone separately. From which the eleven fibre and vessel characteristic variables were reduced to four principal components. The first principal component was heavily weighted by vessel tangential diameter, vessel radial diameter and vessel area. Accordingly the first principal component was labelled as vessel dimension (VD). The second principal component was dominated by fibre tangential diameter, fibre radial diameter, fibre lumen diameter and fibre area; and classified as fibre dimension (FD). The third principal component was dominated by fibre wall area and fibre wall thickness; and it was labelled as fibre wall (FW). And the fourth principal component was mainly vessel frequency and vessel percentage and was labelled as vessel frequency (VF). These four principal components were found to be identical for all the phases and all the clones. These four principal components account for about 95 % of the total variation of the 11 variables.

The first two principal components, VD and FD, account for about 61% of the total variations. Note that, the order of FD and VD changes for Phases II - IV. This might

show that at the juvenile stage, vessel dimension relatively accounts for more variability than the fibre dimension does. FW and VF remain as the third and fourth principal components, respectively, throughout the four phases and both clones.

The graphical assessments of the wood anatomical characteristics show that neither steady increasing nor decreasing with the age of the tree. Moreover, the graphs showed that there was no systematic pattern of the variation of wood anatomical properties with age for all the phases. From this result, it was clear that further analysis should be done at tree level. The between tree variability was captured by including tree effect in the modelling. In addition, the wood anatomical characteristics plots with age showed seasonality patterns. In consequence, the seasonality effect was also included in the analysis.

The cross correlation between the fibre and vessel characteristics of *Eucalyptus* clones and the five climatic variables were investigated using the ARIMA model. Before starting the modelling, the lag of climatic variables was investigated. It was expected, that not only the climatic parameters of today, but also the climatic parameters of the previous days could have an impact on the wood anatomical properties. From the analysis the order of the climatic variables lag which has significant relationship with FW, FD, VD and VF was identified. The result showed that there was no common lag order for the four wood anatomy measures. In fact, for each phase and each clone different lag orders were found to be significant. For instance, for Phase I and GC clone the 13th and 15th day lags temperature were significant for FW and VD respectively; but no significant lagged temperature for FD and VF. On the other hand, for Phase I and GU clone the 13th and 15th, and 16th day lags temperature were significant for FW and VD respectively. Similar to Phase I GC, there was no significant lagged temperature for FD and VF. Likewise, for Phase I GC clone there was no significant lag rainfall correlated with FW, FD, VD and VF. But for Phase I GU clone, the 18th day lag for FD and the 8th, 11th, and 17th day lags for VD were found to be significant.

The longitudinal linear mixed model with age, season, temperature, rainfall, solar radiation, relative humidity, wind speed and lagged climate variables as fixed effect

factors and tree as random effect factor was fitted to the data. The lagged climatic variables discussed above were used as factors in the model. The effect of the climatic variables was assessed by classifying the daily climatic measures as high, normal and low. The classification was based on the fifty year daily climatic data obtained from the experimental area. Moreover, to check if the result obtained from such analysis is due to classification we assessed the climatic variables effect by considering the daily climatic variables as they were. Nevertheless the result is found to identical for categorical and continuous climatic variable measures.

The model selection process for fixed effects interaction was started by removing the insignificant highest order interaction effects from the full model then refitting the reduced model. This process continued until the final reduced model was obtained. Accordingly the highest order interactions in the model were three factor interactions. The interaction between tree and age was regarded as random effect.

Choosing the appropriate covariance structure is very important. To choose the best covariance structure, we have used likelihood based information criteria: the AIC, AICC and BIC. From the available different covariance structures, the compound symmetry and Autoregressive order 1 (AR (1)) were found to be the best covariance structures for between and within subject effects respectively.

Besides the age, season and climatic variables (including lags) to improve the model, we included the dominance or suppression of the tree, the tree radius and daily radial increment in the model. To classify the trees as dominant and suppressed, the diameter at breast height (DBH) of the tree was used. The difference between the dominant and suppressed is that some trees are growing faster compared to other and this could affect the characteristics of the wood formed. To determine the dominance of the trees, the mean and the standard deviation of DBH of all trees in the plot was calculated. The trees were classified as dominant if the tree DBH was greater than mean plus one standard deviation, suppressed if it was less than mean minus one standard deviation and neither suppressed nor dominant if the DBH is within one standard deviation of the average.

From the fitted model analysis, the only common effect for FW, FD, VD and VF was found to be the joint effect of the square root of age and season. This means that the rate of increase/decrease of FW, FD, VD and VF against the square of age differed from season to season. For instance, for Phase I the GC clone FW increases in autumn but the GU clone FW increases in summer and autumn. On the other hand, FD decreases with age for both clones and VD increases in winter with age for both clones for Phase I. On the contrary VF increases with age in summer and autumn for both clones for Phase I.

The joint effect of two climatic variables on FW, FD, VD and VF were different for each phase and each clone. For example for phase I, the joint effect of season and rainfall, season and solar radiation, season and wind speed, season and temperature at lag13, and solar radiation and wind speed were significant for GC clone FW. On the other hand, the significant joint effects for GU clone FW were relative humidity and wind speed, temperature at lag13 and season, and rainfall and season. Similarly, for Phase I GC clone FD, the significant joint effects were season and rainfall, season and relative humidity, season and solar radiation, rainfall and relative humidity and temperature and solar radiation. On the other hand, the significant joint effects for GU clone FD were season and solar radiation, and temperature and solar radiation.

The results of the random effects in the mixed model show that there was significant tree to tree FW variability for Phase I, Phase II GU and Phase III GU. But there was no significant tree to tree VD variability for Phase I, Phase II GC clone and Phase IV GC clone. Similarly, there was significant tree to tree FD and VF variability for Phases II and III. Moreover, there was a significant tree by age interaction effects for FW, FD and VD for all the phases, which shows that the slopes (the rate of daily increase/decrease) of FW, FD and VD of each tree were statistically different. But, for VF the slopes were identical for each tree.

In general, the two clones have different models for all fibre and vessel characteristics. The GC clone has more significant explanatory variables than the GU clone. Moreover, the fibre and vessel characteristics have different significant factors. For example, FW was affected by DBH and daily radial increment, VD was affected by the radius size for

GC. From the four fibre and vessel characteristics VD and FD were affected by more variables than FW and VF. The only common significant factor for GC clone fibre and vessel characteristics was found to be the interaction between square root of age and season. But for the GU clone wood anatomy the only common significant factors were found to be the square root of age by season interaction and DBH. Generally summer and autumn are found to be the best seasons to produce larger fibre and vessel characteristics of the two *Eucalyptus* clones.

In conclusion, the number of significant two-way interaction between climatic variables decreases as the phase increases. This might show that at the juvenile stage a combination of appropriate climatic conditions is more useful than the effect of a single climatic condition. But as the tree matures the joint effect of climatic variables combinations is minimal. The wood anatomy characteristics for the two clones were affected by climatic variables when the tree was on juvenile stage. But as the tree matures it might withstand with any climatic condition of the Zululand. This was supported by none existence of any significant climatic effects for Phase IV analyses.

There are limitations associated with this study. Firstly throughout this thesis we investigated the linear relationship between the wood anatomy of *Eucalyptus* clones and the climatic variables. The insignificance of the climatic effects might show that the climatic variables and the fibre/vessel characteristics of two *Eucalyptus* clones have complex non-linear relationships. Therefore, a future direction of this research can be to investigate the non-linear relationship using non-linear mixed model or spline analysis.

The second drawback is the ARIMA model used in this thesis is the univariate approach. The multivariate ARIMA model is complex and not well – developed. The other future avenue of research will be to investigate the climatic variables lagged effect using multivariate ARIMA model.

References

- Aiken, L. S. & West, S. G. (1991) *Multiple regression: Testing and Interpreting Interactions*, California, SAGE publications.
- Akaike, H. (1994) A new look at the statistical model identification. *IEEE transactions on automatic control*, 19, 716 - 723.
- Anderson, O. (1976) *Time series analysis and forecasting: the Box-Jenkins approach*, London, Butterworths.
- Belsley, D. A., Kuh, E. & Welsch, R. E. (1980) *Regression Diagnostics: Identifying Influential Data and Sources of Collinearity*, New York, Wiley.
- Bioenergy Feedstock Information Network (BFIN) (2009) Short - Rotation Eucalypt Plantation in Brazil: Environmental issue. <http://bioenergy.ornl.gov/reports/euc-braz/eucaly2.html>, accessed 24 September 2009.
- Box, G. E. P. & Jenkins, G. M. (1970) *Time series Analysis: Forecasting and control*, San Francisco, Holden Day.
- Brockwell, P. J. & Davis, R. (2002) *Introduction to time series and forecasting*, New Jersey, Springer.
- Burnham, K. P. & Anderson, D. R. (1998) *Model Selection and Inference: A practical Information- Theoretic Approach*, New York: Springer Verlag.
- Cattell, R. B. (1966) The scree test for the number of factors. *Multivariate Behavioural Research*, 1, 245 - 276.
- Chatfield, C. (2000) *Time Series Forecasting*, London, Chapman and Hall/CRC.
- Chatfield, C. (2003) *The Analysis of Time Series: An Introduction*, London, Chapman and Hall/CRC.
- Chauke, M. (2008) Modelling Environmental factors for two eucalypt clones. *Statistics*. Pietermaritzburg, University of Kwazulu - Natal.

- Cook, R. D. (1977) Detection of influential observation in linear regression. *Technometrics*, 19, 15 - 18.
- Cook, R. D. & WEISBERG, S. (1980) Characterizations of an empirical influence function for detecting influential cases in regression. *Technometrics*, 22, 495-508.
- Cook, R. D. & WEISBERG, S. (1982) *Residuals and Influence in Regression*, New York, Chapman and Hall.
- Cowan, W. F., Cowan, J. & Foelkel, C. (2002) Z-Span testing of eucalyptus bleached pulps obtained from different bleaching sequences. *Proceedings 35th ABTCP Annual Congress*, 11p.
- Cox, D. R. & Hinkley, D. V. (1994) *Theoretical Statistics*, London, Chapman and Hall.
- Crowder, M. J. & Hand, D. J. (1990) *Analysis of Repeated Measures*, London, Chapman and Hall/CRC.
- Davis, C. S. (2002) *Statistical Methods for the Analysis of Repeated Measurements*, New York, Springer.
- Dear, G. & Everitt, B. S. (2006) *Statistical Analysis of Medical Data using SAS*, Boca Raton, Chapman and Hall.
- Demidenko, E. (2004) *Mixed Models: Theory and Applications*, New Jersey, Wiley-Interscience.
- Demidenko, E. & Stukel, T. A. (2005) Influence analysis for linear mixed-effects models. *Statistics in Medicine*, 24, 893-909.
- Dempster, A. P. & Tsutakawa, R. B., Rubin R. K. (1981) Estimation in covariance component models. *Journal of American Statistical Association*, 341 - 353.

- Drew, D. M. (2004) EFR092T "Dendrometer Trial" Phase one technical report. Division of Water, Environment and Forestry Technology, CSIR.
- Drew, D. M. (2005) EFR092T "Dendrometer Trial" Phase two technical report. Division of Water, Environment and Forestry Technology, CSIR.
- Drew, D. M., Naido, W. & Grzeskowiak, V. (2006) EFR092T Dendrometer trial Phase 3 Final report. Division of Water, Environment and Forestry Technology, CSIR.
- Downes, G., Beadle, C. & Worledge, D. (1999) Daily stem growth patterns in irrigated *Eucalyptus globules* and *E. nitens* in relation to climate. *Journal of Trees - Structure and Function: Springer Berlin*, 14, 102-111.
- Duong, Q. P. (1984) On the choice of the order of autoregressive models: a ranking and selection approach *Journal of Time Series Analysis*, 5 145-157.
- Fitzmaurice, M., Laird, N. & Ware, J. (2004) *Applied Longitudinal Analysis*, New Jersey, John Wiley.
- Gourieroux, C. & Monfort, A. (1990) *Time Series and Dynamic Models*, New York, Cambridge University Press.
- Harville, D. A. (1974) Bayesian inference for variance components using only error contrasts. *Biometrika*, 61, 383 - 385.
- Henderson, C. R. (1953) Estimation of variance and covariance components. *Biometrics*, 9, 226 - 252.
- Henderson, C. R., Kempthorne, O., Searle, S. R. & Krosig, C. N. V. (1959) Estimation of environmental and genetic trends from records subject to culling. *Biometrika*, 15, 192 - 218.

- Johnson, R. A. & Wichern, D. W. (2002) *Applied multivariate statistical analysis*, New Jersey, Prentice Hall.
- Kendall, M. & Ord, J. K. (1990) *Time series*, London, Arnold press.
- Littell, R. C., Milliken, G. A., Stroup, W. W., Wolfinger, R. D. & Schabenberger, O. (2006) *SAS for Mixed Models 2nd Edition*, California, SAS Institute Inc.
- Liu, L. M. & Hanssen, D. M. (1982) Identification of multiple input transfer function models. *Communication in Statistics*, 11, 297 - 303.
- Millikan, G. A. & Johnson, D. E. (2000) *Analysis of Messy Data*, New York, Chapman and Hall/CRC.
- Montgomery, D. C., Peck, E. A. & Vining, G. G. (2006) *Introduction to Linear Regression Analysis*, New Jersey, Wiley Series.
- Pankhurst & Richard (1968) *Economic History of Ethiopia*, Addis Ababa, Addis Ababa: Haile Selassie I University.
- Sappi (2009) Our company. <http://www.sappi.com/SappiWeb/About+Sappi/Sappi+Fine+Paper+South+Africa/Our+company.htm>, accessed 24 September 2009.
- SAS9.1.3 (2003) SAS system for mixed models. *SAS Institute Inc. Cary: NC, USA*.
- Schwart, G. E. (1978) Estimating the dimension of a model. *Annals of statistics*, volume 6 (2), 461-464.
- Searle, S. R., Casella, G. & McCulloch, C. E. (1992) *Variance components*, New York: Wiley.
- Shapiro, S. S. & Wilk, M. B. (1965) An analysis of variance test for normality (complete samples). *Biometrika*, 52, 591-611.

- Shumway, R. H. & Stoffer, D. S. (2000) *Time Series Analysis and Its Applications*, New York, Springer.
- Snijders, A. B. T. & Bosker, J. R. (1999) *Multilevel Analysis: An introduction to the basic and advanced multilevel modelling.*, London, Sage
- Stevens, J. (1986) *Applied Multivariate Statistics for the social science*, New Jersey, Lawrence Erlbaum Associates.
- Tsay, R. S. (2005) *Analysis of Financial Time Series*, New York, John Wiley & sons.
- Vandaele, W. (1983) *Applied Time series and Box-Jenkins Models*, California, Academic Press, Inc.
- Verbeke, G. & Molenberghs, G. (2000) *Linear Mixed Models for Longitudinal Data*, New York, Springer.
- Wei, W. S. (1990) *Time series analysis: Univariate and Multivariate Methods*, California, Addison - Wesley Publishing Company, Inc.
- Wikipedia (2009) Eucalyptus. <http://en.wikipedia.org/wiki/Eucalyptus>, accessed 24 September 2009.
- Zewotir, T. & Galpin, J. S. (2004) The Behaviour of Normal Plots under Non-normality for Mixed Models. *South African Statistical Association Journal*, 38 (2), 115 - 138.
- Zewotir, T. & Galpin, J. S. (2005) Influence diagnostics for linear mixed models. *Journal of Data Science*, 3, 153-177.
- Zewotir, T. & Galpin, J. S. (2006) Evaluation of linear mixed model case deletion diagnostic tools by Monte Carlo simulation. *Communication in Statistics – Simulation and Computation*, 35, 645 - 682.

Appendix A: Additional tables

Table A. 1: Phase II correlation matrices of the wood anatomical characteristics of the GC and GU clones

GC											
	FTD	FRD	FLD	FWA	FWT	FA	VTD	VRD	VF	VP	VA
FTD	1	0.76	0.72	0.16	-0.35	0.91	0.18	0.17	-0.44	-0.20	0.24
FRD	0.76	1	0.84	0.00	-0.52	0.96	0.29	0.35	-0.41	0.00	0.37
FLD	0.72	0.84	1	-0.41	-0.86	0.84	0.21	0.27	-0.44	-0.08	0.32
FWA	0.16	0.00	-0.41	1	0.81	0.07	-0.01	-0.07	0.05	-0.07	-0.09
FWT	-0.35	-0.52	-0.86	0.81	1	-0.48	-0.15	-0.22	0.30	0.01	-0.26
FA	0.91	0.96	0.84	0.07	-0.48	1	0.25	0.29	-0.47	-0.10	0.33
VTD	0.18	0.29	0.21	-0.01	-0.15	0.25	1	0.94	-0.37	0.44	0.95
VRD	0.17	0.35	0.27	-0.07	-0.22	0.29	0.94	1	-0.36	0.47	0.96
VF	-0.44	-0.41	-0.44	0.05	0.30	-0.47	-0.37	-0.36	1	0.53	-0.43
VP	-0.20	0.00	-0.08	-0.07	0.01	-0.10	0.44	0.47	0.53	1	0.42
VA	0.24	0.37	0.32	-0.09	-0.26	0.33	0.95	0.96	-0.43	0.42	1
GU											
FTD	1	0.86	0.82	0.26	-0.25	0.98	0.28	0.27	-0.34	-0.10	0.34
FRD	0.86	1	0.94	0.10	-0.42	0.96	0.39	0.45	-0.31	0.10	0.47
FLD	0.82	0.94	1	-0.31	-0.76	0.94	0.31	0.37	-0.34	0.02	0.42
FWA	0.26	0.10	-0.31	1	0.91	0.17	0.09	0.03	0.15	0.03	0.01
FWT	-0.25	-0.42	-0.76	0.91	1	-0.38	-0.05	-0.12	0.40	0.11	-0.16
FA	0.98	0.96	0.94	0.17	-0.38	1	0.35	0.39	-0.37	0.00	0.43
VTD	0.28	0.39	0.31	0.09	-0.05	0.35	1	0.94	-0.27	0.54	1.05
VRD	0.27	0.45	0.37	0.03	-0.12	0.39	0.94	1	-0.26	0.57	1.06
VF	-0.34	-0.31	-0.34	0.15	0.40	-0.37	-0.27	-0.36	1	0.63	-0.33
VP	-0.10	0.10	0.02	0.03	0.11	0.00	0.54	0.47	0.53	1	0.52
VA	0.34	0.47	0.42	0.01	-0.16	0.43	0.95	0.96	-0.43	0.42	1

Table A. 2: Phase II eigenvalues of the correlation matrices of the wood anatomical characteristics of the GC and GU clones

Eigenvalues of the Correlation Matrix: Total(= 11 Average = 1)				
GC				
	Eigenvalue	Difference	Proportion	Cumulative
1	4.936	2.285	0.449	0.449
2	2.651	0.872	0.241	0.69
3	1.779	0.599	0.162	0.852
4	1.18	0.967	0.107	0.959
5	0.213	0.121	0.019	0.978
6	0.092	0.036	0.008	0.987
7	0.056	0.006	0.005	0.992
8	0.05	0.021	0.005	0.996
9	0.03	0.023	0.003	0.999
10	0.007	0.003	6E-04	1
11	0.004		4E-04	1
GU				
1	4.852	2.476	0.441	0.441
2	2.376	0.285	0.216	0.657
3	2.09	0.826	0.19	0.847
4	1.265	1.038	0.115	0.962
5	0.227	0.16	0.021	0.983
6	0.067	0.012	0.006	0.989
7	0.055	0.016	0.005	0.994
8	0.039	0.025	0.004	0.998
9	0.014	0.003	0.001	0.999
10	0.012	0.01	0.001	1
11	0.002		2E-04	1

Table A. 3: Phase II eigenvectors (PC Coefficients) for the correlation matrices of the wood anatomical characteristics of the GC and GU clones

GC											
	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11
FTD	0.893	0.076	0.057	-0.182	0.399	0.005	-0.009	-0.011	-0.001	-0.002	0.009
FRD	0.940	0.200	-0.096	-0.048	-0.243	-0.021	-0.029	-0.006	-0.008	-0.016	0.059
FLD	0.808	0.130	-0.525	-0.115	-0.014	0.001	0.203	0.007	0.008	0.001	-0.001
FWA	0.112	-0.022	0.989	-0.023	0.007	0.008	0.078	-0.007	-0.006	-0.050	0.005
FWT	-0.434	-0.100	0.884	0.065	0.012	0.004	-0.106	0.006	0.006	0.075	-0.008
FA	0.977	0.152	-0.041	-0.130	0.006	-0.017	-0.028	0.013	0.008	0.004	-0.055
VTD	0.111	0.976	-0.001	0.018	0.031	-0.003	-0.007	-0.163	-0.081	-0.004	0.003
VRD	0.145	0.968	-0.066	0.044	-0.049	-0.020	0.004	0.174	-0.056	-0.001	0.000
VF	-0.305	-0.358	0.091	0.842	0.006	0.249	-0.003	-0.004	-0.006	0.001	0.000
VP	-0.065	0.444	-0.035	0.865	-0.035	-0.219	-0.005	0.005	0.004	0.001	0.000
VA	0.180	0.968	-0.091	-0.010	0.011	-0.032	0.015	-0.004	0.144	0.001	-0.002
GU											
FTD	0.993	0.176	0.157	-0.082	0.499	0.105	0.092	0.089	0.099	0.098	0.109
FRD	0.940	0.300	0.004	0.052	-0.143	0.079	0.071	0.094	0.092	0.084	0.159
FLD	0.908	0.230	-0.425	-0.015	0.086	0.101	0.303	0.107	0.108	0.101	0.099
FWA	0.212	0.078	0.989	0.077	0.107	0.108	0.178	0.093	0.094	0.050	0.105
FWT	-0.334	0.011	0.984	0.165	0.112	0.104	-0.006	0.106	0.106	0.175	0.092
FA	0.977	0.252	0.059	-0.030	0.106	0.083	0.072	0.113	0.108	0.104	0.045
VTD	0.211	0.976	0.099	0.118	0.131	0.097	0.093	-0.063	0.019	0.096	0.103
VRD	0.245	0.968	0.034	0.144	0.051	0.080	0.104	0.274	0.044	0.099	0.100
VF	-0.205	-0.258	0.191	0.942	0.106	0.349	0.097	0.096	0.094	0.101	0.100
VP	0.035	0.544	0.065	0.965	0.065	-0.119	0.095	0.105	0.104	0.101	0.100
VA	0.280	0.968	0.009	0.090	0.111	0.068	0.115	0.096	0.244	0.101	0.098

Table A. 4: Phase III correlation matrices of the wood anatomical characteristics of the GC and GU clones

Correlations between fibre and vessel characteristics											
GC											
	FTD	FRD	FLD	FWA	FWT	FA	VTD	VRD	VF	VP	VA
FTD	1	0.64	0.57	0.50	0.01	0.90	0.07	0.05	-0.39	-0.27	0.11
FRD	0.64	1	0.73	0.28	-0.22	0.90	0.22	0.33	-0.40	-0.05	0.33
FLD	0.57	0.73	1	-0.30	-0.76	0.76	0.19	0.28	-0.46	-0.11	0.30
FWA	0.50	0.28	-0.30	1	0.84	0.38	-0.02	-0.07	-0.02	-0.12	-0.04
FWT	0.01	-0.22	-0.76	0.84	1	-0.17	-0.13	-0.20	0.26	-0.01	-0.19
FA	0.90	0.90	0.76	0.38	-0.17	1	0.16	0.22	-0.46	-0.19	0.25
VTD	0.07	0.22	0.19	-0.02	-0.13	0.16	1	0.94	-0.37	0.39	0.93
VRD	0.05	0.33	0.28	-0.07	-0.20	0.22	0.94	1	-0.40	0.38	0.97
VF	-0.39	-0.40	-0.46	-0.02	0.26	-0.46	-0.37	-0.40	1	0.57	-0.44
VP	-0.27	-0.05	-0.11	-0.12	-0.01	-0.19	0.39	0.38	0.57	1	0.30
VA	0.11	0.33	0.30	-0.04	-0.19	0.25	0.93	0.97	-0.44	0.30	1
GU											
FTD	1	0.74	0.67	0.60	0.11	0.98	0.17	0.15	-0.29	-0.17	0.21
FRD	0.74	1	0.83	0.38	-0.12	0.90	0.32	0.43	-0.30	0.05	0.43
FLD	0.67	0.83	1	-0.20	-0.66	0.86	0.29	0.38	-0.36	-0.01	0.40
FWA	0.60	0.38	-0.20	1	0.94	0.48	0.08	0.03	0.08	-0.02	0.06
FWT	0.11	-0.12	-0.66	0.94	1	-0.07	-0.03	-0.10	0.36	0.09	-0.09
FA	0.98	0.90	0.86	0.48	-0.07	1	0.26	0.32	-0.36	-0.09	0.35
VTD	0.17	0.32	0.29	0.08	-0.03	0.26	1	0.94	-0.27	0.49	0.93
VRD	0.15	0.43	0.38	0.03	-0.10	0.32	0.94	1	-0.30	0.48	0.97
VF	-0.29	-0.30	-0.36	0.08	0.36	-0.36	-0.27	-0.30	1	0.67	-0.34
VP	-0.17	0.05	-0.01	-0.02	0.09	-0.09	0.49	0.48	0.67	1	0.40
VA	0.21	0.43	0.40	0.06	-0.09	0.35	0.93	0.97	-0.34	0.40	1

Table A. 5: Phase III eigenvalues of the correlation matrices of the wood anatomical characteristics of the GC and GU clones

Eigenvalues of the Correlation Matrix: (Total = 11 Average = 1)				
GC				
	Eigenvalue	Difference	Proportion	Cumulative
1	4.36561	1.57769	0.3969	0.3969
2	2.78792	0.67721	0.2534	0.6503
3	2.11071	0.90064	0.1919	0.8422
4	1.21007	0.90254	0.11	0.9522
5	0.30752	0.1939	0.028	0.9802
6	0.11362	0.0574	0.0103	0.9905
7	0.05622	0.02872	0.0051	0.9956
8	0.0275	0.0155	0.0025	0.9981
9	0.01201	0.00643	0.0011	0.9992
10	0.00558	0.00235	0.0005	0.9997
11	0.00323		0.0003	1
GU				
1	3.78162	0.61347	0.3438	0.3438
2	3.16816	1.124	0.288	0.6318
3	2.04416	0.53031	0.1858	0.8176
4	1.51385	1.12881	0.1376	0.9553
5	0.38504	0.33164	0.035	0.9903
6	0.0534	0.02826	0.0049	0.9951
7	0.02514	0.01189	0.0023	0.9974
8	0.01325	0.00268	0.0012	0.9986
9	0.01057	0.00724	0.001	0.9996
10	0.00332	0.00181	0.0003	0.9999
11	0.00151		0.0001	1

Table A. 6: Phase III eigenvectors (PC Coefficients) for the correlation matrices of the wood anatomical characteristics of the GC and GU clones

GC											
	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11
FTD	0.847	0.006	0.196	-0.189	0.056	-0.010	0.011	-0.001	-0.006	0.017	0.002
FRD	0.921	0.192	-0.010	-0.049	-0.328	-0.020	-0.001	0.010	-0.025	0.061	0.003
FLD	0.767	0.145	-0.605	-0.118	0.027	-0.027	-0.007	-0.004	0.100	-0.005	0.007
FWA	0.333	-0.022	0.938	-0.045	0.052	-0.001	0.008	-0.006	0.039	-0.001	0.054
FWT	-0.200	-0.098	0.972	0.049	0.003	0.016	-0.006	0.004	-0.022	0.000	-0.046
FA	0.977	0.117	0.048	-0.144	0.070	-0.019	-0.007	-0.007	-0.003	-0.055	0.004
VTD	0.056	0.973	-0.025	0.062	0.060	-0.038	0.203	-0.011	0.000	0.000	0.001
VRD	0.128	0.972	-0.087	0.053	-0.073	-0.037	-0.081	0.125	0.000	0.002	0.000
VF	-0.306	-0.389	0.116	0.789	-0.009	0.044	-0.008	-0.003	-0.002	0.000	-0.001
VP	-0.095	0.337	-0.037	0.922	-0.028	-0.158	0.008	0.004	-0.002	0.001	-0.001
VA	0.145	0.974	-0.069	-0.013	-0.014	0.005	-0.112	-0.111	0.005	-0.001	0.002
GU											
FTD	0.947	0.106	0.296	-0.089	0.156	0.090	0.111	0.099	0.094	0.117	0.102
FRD	0.921	0.292	0.090	0.051	-0.228	0.080	0.099	0.110	0.075	0.161	0.103
FLD	0.867	0.245	-0.505	-0.018	0.127	0.073	0.093	0.096	0.200	0.095	0.107
FWA	0.433	0.078	0.938	0.055	0.152	0.099	0.108	0.094	0.139	0.099	0.154
FWT	-0.100	0.002	0.972	0.149	0.103	0.116	0.094	0.104	0.078	0.100	0.054
FA	0.977	0.217	0.148	-0.044	0.170	0.081	0.093	0.093	0.097	0.045	0.104
VTD	0.156	0.973	0.075	0.162	0.160	0.062	0.303	0.089	0.100	0.100	0.101
VRD	0.228	0.972	0.013	0.153	0.027	0.063	0.019	0.225	0.100	0.102	0.100
VF	-0.206	-0.289	0.216	0.889	0.091	0.144	0.092	0.097	0.098	0.100	0.099
VP	0.005	0.437	0.064	0.922	0.072	-0.058	0.108	0.104	0.098	0.101	0.099
VA	0.245	0.974	0.031	0.087	0.086	0.105	-0.012	-0.011	0.105	0.099	0.102

Table A. 7: Phase IV Phase I correlation matrices of the wood anatomical characteristics of the GC and GU clones

Correlations between fibre and vessel characteristics											
GC											
	FTD	FRD	FLD	FWA	FWT	FA	VTD	VRD	VF	VP	VA
FTD	1	0.63	0.77	0.32	-0.38	0.90	-0.08	-0.05	-0.09	-0.08	0.02
FRD	0.63	1	0.77	0.28	-0.39	0.89	0.05	0.11	-0.07	0.01	0.15
FLD	0.77	0.77	1	-0.18	-0.83	0.88	0.02	0.09	-0.14	-0.05	0.15
FWA	0.32	0.28	-0.18	1	0.68	0.29	-0.06	-0.09	0.08	0.03	-0.10
FWT	-0.38	-0.39	-0.83	0.68	1	-0.48	-0.05	-0.11	0.14	0.05	-0.16
FA	0.90	0.89	0.88	0.29	-0.48	1	-0.01	0.04	-0.10	-0.04	0.10
VTD	-0.08	0.05	0.02	-0.06	-0.05	-0.01	1	0.95	-0.10	0.44	0.94
VRD	-0.05	0.11	0.09	-0.09	-0.11	0.04	0.95	1	-0.13	0.42	0.96
VF	-0.09	-0.07	-0.14	0.08	0.14	-0.10	-0.10	-0.13	1	0.74	-0.14
VP	-0.08	0.01	-0.05	0.03	0.05	-0.04	0.44	0.42	0.74	1	0.42
VA	0.02	0.15	0.15	-0.10	-0.16	0.10	0.94	0.96	-0.14	0.42	1
GU											
FTD	1	0.73	0.87	0.42	-0.28	0.90	0.02	0.05	0.01	0.02	0.12
FRD	0.73	1	0.87	0.38	-0.29	0.99	0.15	0.21	0.03	0.11	0.25
FLD	0.87	0.87	1	-0.08	-0.73	0.98	0.12	0.19	-0.04	0.05	0.25
FWA	0.42	0.38	-0.08	1	0.78	0.39	0.04	0.01	0.18	0.13	0.00
FWT	-0.28	-0.29	-0.73	0.78	1	-0.38	0.05	-0.01	0.24	0.15	-0.06
FA	0.90	0.99	0.98	0.39	-0.38	1	0.09	0.14	0.00	0.06	0.20
VTD	0.02	0.15	0.12	0.04	0.05	0.09	1	0.95	0.00	0.54	0.94
VRD	0.05	0.21	0.19	0.01	-0.01	0.14	0.95	1	-0.03	0.52	0.96
VF	0.01	0.03	-0.04	0.18	0.24	0.00	0.00	-0.03	1	0.84	-0.04
VP	0.02	0.11	0.05	0.13	0.15	0.06	0.54	0.52	0.84	1	0.52
VA	0.12	0.25	0.25	0.00	-0.06	0.20	0.94	0.96	-0.04	0.52	1

Table A. 8: Phase IV eigenvalues of the correlation matrices of the wood anatomical characteristics of the GC and GU clones

Eigenvalues of the Correlation Matrix: (Total = 11 Average = 1)				
GC				
	Eigenvalue	Difference	Proportion	Cumulative
1	3.909	0.764	0.355	0.355
2	3.145	1.292	0.286	0.641
3	1.853	0.341	0.169	0.81
4	1.512	1.157	0.138	0.947
5	0.355	0.26	0.032	0.98
6	0.096	0.036	0.009	0.988
7	0.06	0.027	0.005	0.994
8	0.033	0.008	0.003	0.997
9	0.026	0.016	0.002	0.999
10	0.01	0.008	9E-04	1
11	0.001		1E-04	1
GU				
1	3.509	0.522	0.319	0.319
2	2.988	0.759	0.272	0.591
3	2.229	0.713	0.203	0.793
4	1.515	0.924	0.138	0.931
5	0.592	0.534	0.054	0.985
6	0.057	0.013	0.005	0.99
7	0.045	0.013	0.004	0.994
8	0.031	0.006	0.003	0.997
9	0.026	0.02	0.002	0.999
10	0.005	0.002	5E-04	1
11	0.003		3E-04	1

Table A. 9: Phase IV eigenvectors (PC Coefficients) for the correlation matrices of the wood anatomical characteristics of the GC and GU clones

GC											
	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11
FTD	0.929	-0.050	0.113	-0.043	-0.028	-0.007	-0.002	0.001	0.036	0.105	-0.006
FRD	0.854	0.083	0.076	-0.005	0.507	-0.001	-0.001	-0.001	0.006	0.018	-0.001
FLD	0.904	0.052	-0.412	-0.049	0.047	0.002	0.005	0.002	-0.066	-0.026	0.034
FWA	0.240	-0.052	0.966	0.035	0.014	0.000	0.010	-0.002	-0.072	-0.010	-0.001
FWT	-0.524	-0.066	0.838	0.053	-0.007	-0.002	-0.013	0.002	0.123	0.019	0.001
FA	0.992	0.021	0.058	-0.037	0.067	0.008	-0.008	0.002	-0.002	-0.073	-0.018
VTD	-0.031	0.977	-0.008	0.055	0.001	0.008	0.203	-0.004	-0.005	0.000	0.000
VRD	0.021	0.985	-0.048	0.031	0.028	0.007	-0.095	-0.126	-0.001	-0.002	0.000
VF	-0.067	-0.160	0.054	0.967	0.000	-0.178	0.000	-0.002	0.001	0.001	0.000
VP	-0.022	0.398	0.023	0.875	0.003	0.274	0.002	0.003	0.000	-0.001	0.000
VA	0.082	0.980	-0.069	0.029	0.009	0.026	-0.094	0.133	0.001	-0.001	0.000
GU											
FTD	0.939	-0.040	0.123	-0.033	-0.018	0.003	0.008	0.011	0.046	0.115	0.004
FRD	0.864	0.093	0.086	0.005	0.517	0.009	0.009	0.009	0.016	0.028	0.009
FLD	0.914	0.062	-0.402	-0.039	0.057	0.012	0.015	0.012	-0.056	-0.016	0.044
FWA	0.250	-0.042	0.976	0.045	0.024	0.010	0.020	0.008	-0.062	0.000	0.009
FWT	-0.514	-0.056	0.848	0.063	0.003	0.008	-0.003	0.012	0.133	0.029	0.011
FA	0.992	0.031	0.068	-0.027	0.077	0.018	0.002	0.012	0.008	-0.063	-0.008
VTD	-0.021	0.987	0.002	0.065	0.011	0.018	0.213	0.006	0.005	0.010	0.010
VRD	0.031	0.995	-0.038	0.041	0.038	0.017	-0.085	-0.116	0.009	0.008	0.010
VF	-0.057	-0.150	0.064	0.977	0.010	-0.168	0.010	0.008	0.011	0.011	0.010
VP	-0.012	0.408	0.033	0.885	0.013	0.284	0.012	0.013	0.010	0.009	0.010
VA	0.092	0.990	-0.059	0.039	0.019	0.036	-0.084	0.143	0.011	0.009	0.010

Table A. 10: Type 3 Tests for FW for fixed effects: Phase II

Effect	Type 3 Tests of Fixed Effects							
	GC				GU			
	Num DF	Den DF	F Value	Pr > F	Num DF	Den DF	F Value	Pr > F
Sqtage	1	2921	11.12	0.0009	1	2836	56.54	<.0001
DBH	1	2921	2.17	0.141	1	2836	8.61	0.0034
radius	1	2921	2.73	0.0986	1	2836	3.36	0.0667
increment	1	2921	2.23	0.1357	1	2836	1.26	0.2623
Season	3	2921	60.15	<.0001	3	2836	10.39	<.0001
Tempn	2	2921	0.71	0.5081	2	2836	0.21	0.8103
Humc	2	2921	4.65	0.0255	2	2836	3.8	0.0448
Solarc	2	2921	11.76	0.0007	2	2836	1.19	0.3296
Speedc	2	2921	0.07	0.9351	2	2836	0.27	0.7688
templag21c	2	2921	0.88	0.4163	2	2836	0.08	0.9232
templag5c	2	2921	5.87	0.0028	2	2836	3.34	0.0354
solarlag31c	2	2921	2.93	0.0538	2	2836	13.9	<.0001
sqtage*season	3	2921	62.32	<.0001	3	2836	10.43	<.0001
season*tempn	6	2921	1.06	0.384	6	2836	0.18	0.9821
season*humc	6	2921	16.11	<.0001	6	2836	10.27	<.0001
season*solarc	6	2921	48.57	<.0001	6	2836	8.36	<.0001
season*speedc	6	2921	1.56	0.1548	6	2836	0.82	0.558
season*templag21c	6	2921	0.35	0.9119	5	2836	0.11	0.8555
season*templag5c	6	2921	2.55	0.0181	5	2836	3.83	0.0018
season*solarlag31c	6	2921	13.36	<.0001	6	2836	5.56	<.0001
tempn*humc	4	2921	1.42	0.2256	4	2836	1.05	0.3821
tempn*solarc	4	2921	1.17	0.3216	4	2836	0.48	0.7509

Sqtage – square root of age, DBH – Diameter at breast height, Tempn - Classified Temperature, Rainn - Classified Rainfall, Solarc - Classified Solar radiation, Speedc - Classified wind speed, Humc - classified Relative humidity, templag21c – classified temperature at lag 21, , templag5c – classified temperature at lag 5, solarlag31c – classified solar radiation at lag 31.

Table A. 11: Type 3 Tests for FW for fixed effects: Phase III

Effect	Type 3 Tests of Fixed Effects							
	GC				GU			
	Num DF	Den DF	F Value	Pr > F	Num DF	Den DF	F Value	Pr > F
Sqtage	1	3030	104.96	<.0001	1	3742	27.73	0.0008
DBH	1	3030	268.03	<.0001	1	3742	0.05	0.8148
radius	1	3030	15.53	<.0001	1	3742	0	0.9509
increment	1	3030	6.05	0.0139	1	3742	2.31	0.1287
Season	3	3030	15.02	<.0001	3	3742	40.47	<.0001
Tempn	2	3030	0.09	0.9186	2	3742	1.7	0.2146
Rain	2	3030	0.77	0.4856	2	3742	0.3	0.7452
Humc	2	3030	0.48	0.6296	2	3742	0.43	0.6552
Solarc	2	3030	1.92	0.1885	2	3742	1.53	0.2473
Speedc	2	3030	0.03	0.97	2	3742	0.49	0.6199
sqtage*season	3	3030	19.75	<.0001	3	3678	36.46	<.0001
season*tempn	6	3030	1.85	0.0865	6	3678	1.05	0.3887
season*humc	4	3030	1.17	0.3213	4	3678	1.5	0.1999
season*solarc	4	3030	1.09	0.362	4	3678	0.62	0.6498
season*speedc	6	3030	1.94	0.0702	6	3678	6.33	<.0001
season*templag7c	6	3076	13.09	<.0001	6	3742	3.45	0.0021
tempn*humc	2	3030	0.3	0.7425	2	3678	0.68	0.506
rainn*humc	2	3030	1.9	0.1499	3	3678	0.23	0.8772
tempn*solarc	4	3030	0.43	0.7891	4	3678	1.31	0.2647

Sqtage – square root of age, DBH – Diameter at breast height, Tempn - Classified Temperature, Rainn - Classified Rainfall, Solarc - Classified Solar radiation, Speedc - Classified wind speed, Humc - classified Relative humidity, templag7c – classified temperature at lag 7.

Table A. 12: Type 3 Tests for FW for fixed effects: Phase IV

Effect	Type 3 Tests of Fixed Effects							
	GC				GU			
	Num DF	Den DF	F Value	Pr > F	Num DF	Den DF	F Value	Pr > F
Sqtage	1	338	3.3	0.107	1	338	4.63	0.329
DBH	1	338	0.37	0.5411	1	338	0.48	0.487
Season	3	338	1.96	0.1203	3	338	1.66	0.1027
Tempn	2	338	0.71	0.491	2	338	1.45	0.2354
Rain	2	338	1.2	0.3017	2	338	0.08	0.9251
Humc	1	338	0.41	0.5218	1	338	3.51	0.0619
Solarc	2	338	0.78	0.4595	2	338	2.63	0.0738
Speedc	2	338	0.33	0.7222	2	338	0.84	0.4328
sqtage*Season	3	338	1.67	0.1729	3	338	1.65	0.1218

Sqtage – square root of age, DBH – Diameter at breast height, Tempn - Classified Temperature, Rainn - Classified Rainfall, Solarc - Classified Solar radiation, Speedc - Classified wind speed, Humc - classified Relative humidity.

Table A. 13: Type 3 Tests for FD for fixed effects: Phase II

Effect	Num DF	Den DF	F Value	Pr > F	Num DF	Den DF	F Value	Pr > F
Sqtage	1	2987	1.59	0.2425	1	2900	4.63	0.0636
DBH	1	2987	0.5	0.4782	1	2900	0.86	0.3532
radius	1	2687	51.04	<.0001	1	2900	0.3	0.5853
increment	1	2687	4.98	0.0258	1	2900	0.04	0.85
Season	3	2987	12.5	<.0001	3	2900	10.96	<.0001
Tempn	2	2987	2.29	0.101	2	2900	0.33	0.7193
Rain	2	2987	0.81	0.4451	2	2900	7.09	0.0008
Humc	2	2987	4.34	0.0132	2	2900	1.65	0.1924
Solarc	2	2987	2.62	0.0731	2	2900	12.5	<.0001
Speedc	2	2987	0.59	0.5534	2	2900	0.52	0.5968
humlag23c	2	2987	0.61	0.5433	2	2892	4.93	0.0073
sqtage*season	3	2987	13.8	<.0001	3	2900	11.16	<.0001
season*rainn	6	2987	0.75	0.6122	6	2900	5.49	<.0001
season*solarc	6	2987	6.28	<.0001	6	2900	5.77	<.0001
season*speedc	6	2987	1.38	0.2201	6	2900	2.58	0.017
season*humlag23c	6	2987	2.38	0.0271	6	2892	3.1	0.005
tempn*humc	4	2987	0.35	0.8425	4	2900	0.31	0.8724

Table A. 14: Type 3 Tests for FD for fixed effects: Phase III

Effect	Num DF	Den DF	F Value	Pr > F	Num DF	Den DF	F Value	Pr > F
Sqtage	1	3096	6.49	0.0437	1	3763	38.82	0.0003
DBH	1	3096	2.22	0.1365	1	3763	0.27	0.6009
radius	1	3096	14.32	0.0002	1	3763	2.52	0.1127
increment	1	3096	21.24	<.0001	1	3763	18.4	<.0001
Season	3	3096	43.37	<.0001	3	3763	28.8	<.0001
Tempn	2	3096	3.1	0.0452	2	3763	2.37	0.0933
Solarc	2	3096	0.68	0.5052	2	3763	0.59	0.5566
Rain	2	3096	0.27	0.7643	2	3763	2.44	0.0874
Humc	2	3096	1.54	0.2146	2	3763	0.26	0.7728
Speedc	2	3096	0.57	0.566	2	3763	4.87	0.0077
solarlag16c	2	3096	3.86	0.0211	2	3755	2.77	0.0628
sqtage*season	3	3096	43.04	<.0001	3	3763	29.78	<.0001
season*tempn	6	3096	4.68	<.0001	6	3763	1.7	0.1174
season*solarc	4	3096	0.28	0.8879	4	3763	0.51	0.7273
season*speedc	6	3096	2.16	0.0439	6	3763	0.91	0.4829
season*solarlag16c	6	3096	14.81	<.0001	6	3755	1.72	0.1111

Table A. 15: Type 3 Tests for FD for fixed effects: Phase IV

Effect	Num DF	Den DF	F Value	Pr > F	Num DF	Den DF	F Value	Pr > F
sqtage	1	326	0.57	0.4714	1	326	0.03	0.8738
season	3	326	1.92	0.1263	3	326	2.78	0.0411
tempn	2	326	0.59	0.5531	2	326	1.02	0.3626
rainn	2	326	0.28	0.7549	2	326	0.65	0.5244
humc	1	326	0.43	0.5139	1	326	0.05	0.8312
speedc	2	326	0.11	0.8981	2	326	0.02	0.979
solarc	2	326	1.78	0.1698	2	326	1.18	0.3085
sqtage*season	3	326	2.23	0.0528	3	326	2.79	0.0607

Table A. 16: Type 3 Tests for VD for fixed effects: Phase II

Effect	Num DF	Den DF	F Value	Pr > F	Num DF	Den DF	F Value	Pr > F
Sqtage	1	2987	8.65	0.0187	1	2900	54.25	<.0001
DBH	1	2987	0.05	0.8181	1	2900	280.82	<.001
radius	1	2987	94.33	<.0001	1	2900	46.33	<.0001
increment	1	2987	2.34	0.126	1	2900	0.72	0.3965
Season	3	2987	99.16	<.0001	3	2900	103.29	<.0001
Tempn	2	2987	1.57	0.2088	2	2900	0.25	0.777
Rain	2	2987	4.58	0.0103	2	2900	3.11	0.0449
Humc	2	2987	0.64	0.5258	2	2900	4.21	0.015
Solarc	2	2987	1.28	0.2777	2	2900	3.55	0.0289
Speedc	2	2987	2.34	0.0963	2	2900	15.72	<.0001
sqtage*season	3	2987	97.6	<.0001	3	2900	101.76	<.0001

Table A. 17: Type 3 Tests for VD for fixed effects: Phase III

Effect	Num DF	Den DF	F Value	Pr > F	Num DF	Den DF	F Value	Pr > F
sqtage	1	3086	11.25	0.0153	1	3752	3.96	0.0816
dbh	1	3086	161.8	<.0001	1	3752	763.4	<.0001
radius	1	3086	15.95	<.0001	1	3752	1.34	0.247
increment	1	3086	20.8	<.0001	1	3752	18.75	<.0001
season	3	3086	7.22	<.0001	3	3752	2.44	0.0629
humc	2	3086	1.51	0.2218	2	3752	1.75	0.1738
rainn	2	3086	0.01	0.9863	2	3752	2.91	0.0544
speedc	2	3086	1.92	0.1464	2	3752	0.5	0.605
tempn	2	3086	2	0.1353	2	3752	1.75	0.1733
solarc	2	3086	1.15	0.3159	2	3752	0.16	0.8538
templag31c	2	3086	1.13	0.3226	2	3744	4.87	0.0078
sqtage*season	3	3086	8.01	<.0001	3	3752	3.32	0.0519
season*speedc	6	3086	3.75	0.001	6	3752	0.8	0.5672
season*templag31c	6	3086	12.05	<.0001	6	3744	4.41	0.0002

Table A. 18: Type 3 Tests for VD for fixed effects: Phase IV

Effect	Num DF	Den DF	F Value	Pr > F	Num DF	Den DF	F Value	Pr > F
Sqtage	1	2957	2.53	0.0515	1	3582	2.88	0.558
Season	3	2957	3.06	0.0501	3	3582	2.48	0.509
Tempn	2	2957	2.53	0.0509	2	3582	0.62	0.5372
Rain	2	2957	0.21	0.8125	2	3582	2.39	0.0546
Humc	2	2957	1.92	0.1467	2	3582	1.52	0.2191
Solarc	2	2957	1.89	0.152	2	3582	0.6	0.5493
Speedc	2	2957	1.12	0.0606	2	3582	0.77	0.4635
sqtage*season	3	2957	2.13	0.0557	3	3582	1.48	0.559

Table A. 19: Type 3 Tests for VF for fixed effects: Phase II

Effect	Num DF	Den DF	F Value	Pr > F	Num DF	Den DF	F Value	Pr > F
Reciage	1	4247	13.45	0.0063	1	4006	3.41	0.1019
DBH	1	4274	0.07	0.7901	1	4006	0.85	0.3565
radius	1	2653	93.83	<.0001	1	4006	45.73	<.0001
Season	3	4274	16.43	<.0001	3	4006	15.74	<.0001
Tempn	2	4274	1.38	0.2509	2	4006	1.38	0.2512
Rain	2	4274	0.01	0.9886	2	4006	0.26	0.7746
Humc	2	4274	2.43	0.0881	2	4006	4.31	0.0135
Solarc	2	4274	5.6	0.0037	2	4006	1.6	0.2017
Speedc	2	4274	0.4	0.6709	2	4006	0.13	0.8778
reciage*season	3	4274	2.15	0.1161	3	4006	2.86	0.0981
season*tempn	6	4274	1.41	0.2072	6	4006	2.98	0.0067
season*rainn	6	4274	2.41	0.0252	6	4006	3.53	0.0018

Table A. 20: Type 3 Tests for VF for fixed effects: Phase III

Effect	Num DF	Den DF	F Value	Pr > F	Num DF	Den DF	F Value	Pr > F
Reciage	1	3033	1.14	0.2848	1	3682	0.49	0.4858
dbh	1	3033	30.82	<.0001	1	3682	67.89	<.0001
radius	1	3033	18.54	<.0001	1	3682	24.92	<.0001
increment	1	3033	0.23	0.6299	1	3682	7.52	0.0061
Season	3	3033	16.18	<.0001	3	3682	0.3	0.8219
Tempn	2	3033	0.06	0.9408	2	3682	0.69	0.5173
Rainn	2	3033	0.54	0.5962	2	3682	0.25	0.7799
Humc	2	3033	1.57	0.2486	2	3682	1.21	0.3253
Solarc	2	3033	1.26	0.3175	2	3682	2.96	0.0808
Speedc	2	3033	0.43	0.6578	2	3682	0.19	0.8271
reciage*season	3	3033	1.34	0.0957	3	3682	0.34	0.7957
season*rainn	6	3033	2.52	0.0195	6	3682	4.34	0.0002
season*solarc	4	3033	1.12	0.3466	4	3682	4.18	0.0022
season*speedc	6	3033	0.55	0.7706	6	3682	1.43	0.1985
humc*speedc	3	3033	0.83	0.4764	3	3682	0.69	0.5588

Table A. 21: Type 3 Tests for VF for fixed effects: Phase IV

Effect	Num DF	Den DF	F Value	Pr > F	Num DF	Den DF	F Value	Pr > F
sqtage	1	338	0.9	0.3711	1	338	0.11	0.7442
season	3	338	0.24	0.8689	3	338	2.15	0.0932
tempn	2	338	1.62	0.1985	2	338	1.18	0.308
rainn	2	338	3.77	0.0241	2	338	2.06	0.1296
humc	1	338	4.36	0.0376	1	338	2.05	0.1535
solarc	2	338	2.69	0.0693	2	338	1.11	0.3295
speedc	2	338	0.97	0.382	2	338	1.09	0.3384
sqtage*season	3	338	0.35	0.7864	3	338	2.14	0.0567

Table A. 22: Parameter estimates for FW Model: Phase II

Effect	GC			GU		
	Estimate	SE	Pr > t	Estimate	SE	Pr > t
Intercept	4.5031	5.0498	0.3986	-0.7501	4.5193	0.8723
sqtage	-0.1577	0.2161	0.4864	0.00734	0.1945	0.9708
Summer	17.2557	7.77	0.0265	-85.133	31.688	0.0073
Autumn	5.7172	11.0446	0.6048	1.1776	8.8673	0.8944
Winter	1.5988	4.2867	0.7092	-0.8386	3.9701	0.8327
Spring	0	.	.	0	.	.
dbh	-0.4733	0.0388	<.0001	-0.3599	0.05547	<.0001
radius	-2E-05	5.83E-06	0.0006	3.2E-05	9.13E-06	0.0005
increment	-1E-05	1.5E-05	0.4229	-2E-05	8.75E-06	0.0221
humc	0.03439	0.01504	0.0223	-0.0004	0.0217	0.9844
speedc	0.07795	0.03352	0.0202	0.01237	0.0506	0.8068
sqtage*summer	0.71	0.3191	0.0262	3.5058	1.302	0.0071
sqtage*autumn	0.8225	0.4298	0.0048	0.0232	0.344	0.0462
sqtage*winter	-0.0715	0.1907	0.7076	0.03908	0.1757	0.824
sqtage*spring	0	.	.	0	.	.
templag5c*summer	-0.0386	0.03703	0.2974	-0.4366	0.1381	0.0016
templag5c*autumn	-0.0272	0.02674	0.3098	0.06001	0.0402	0.1354
templag5c*winter	0.00206	0.02531	0.9352	-0.0563	0.0366	0.1239
templag5c*spring	0	.	.	0	.	.
humc*summer	-0.0836	0.03053	0.0063	-0.2362	0.0739	0.0014
humc*autumn	-0.0095	0.0164	0.5633	-0.0429	0.0253	0.0876
humc*winter	-0.0411	0.01672	0.0141	-0.0061	0.0247	0.8039
humc*spring	0	.	.	0	.	.
speedc*summer	-0.1495	0.06273	0.0173	-0.502	0.1722	0.0036
speedc*autumn	-0.0857	0.0575	0.1362	-0.1056	0.0844	0.2108
speedc*winter	-0.0982	0.05082	0.0533	-0.0414	0.0769	0.5906
speedc*spring	0	.	.	0	.	.
humc*speedc	0.0442	0.01854	0.0172	-0.0135	0.0285	0.6346

Table A. 23: Parameter estimates for FW Model: Phase III

Effect	GC			GU		
	Estimate	SE	Pr > t	Estimate	SE	Pr > t
Intercept	-8.9392	1.0634	0.0002	-6.4434	1.7416	0.006
Sqtage	0.2837	0.03456	0.0002	0.1911	0.0506	0.0054
Summer	-17.757	4.1227	<.0001	-33	3.4819	<.0001
Autumn	-8.8897	2.9425	0.0025	19.515	2.6313	<.0001
Winter	-0.0734	0.5034	0.8842	0.9084	0.4988	0.0687
Dbh	-0.537	0.03336	<.0001	0.02347	0.02573	0.3617
Radius	-3E-05	8.4E-06	<.0001	-5E-07	5.9E-06	0.9369
Humc	-0.0047	0.01906	0.8048	-0.0064	0.0169	0.7061
speedc	-0.0137	0.01671	0.4114	0.00768	0.01486	0.6053
templag7c	-0.0413	0.02153	0.0555	0.07092	0.01944	0.0003
sqtage*summer	0.27	0.1281	<.0001	1.0292	0.1082	<.0001
sqtage*autumn	0.5582	0.08912	0.0025	-0.5898	0.07973	<.0001
sqtage*winter	0.0051	0.01491	0.7326	-0.023	0.01464	0.1156
tempc*summer	-0.2018	0.07731	0.0091	0.09059	0.06801	0.183
tempc*autumn	-0.0493	0.04853	0.3094	0.06264	0.04427	0.1572
tempc*winter	0.04128	0.04041	0.3071	0.06607	0.03629	0.0688
templag7c*summer	0.0349	0.03184	0.2731	-0.0689	0.03271	0.0353
templag7c*autumn	-0.0897	0.0329	0.0065	-0.076	0.02844	0.0076
templag7c*winter	0.1555	0.03244	<.0001	-0.0634	0.02666	0.0174

Table A. 24: Parameter estimates for FD Model: Phase II

Effect	GC			GU		
	Estimate	SE	Pr > t	Estimate	SE	Pr > t
Intercept	5.5939	1.0862	0.0009	5.2253	3.0982	0.1302
Summer	-21.061	2.9414	<.0001	-12.7281	5.3761	0.018
Autumn	1.4052	2.6346	0.5938	15.4318	4.8291	0.0014
Dbh	-0.1925	3.44E-02	<.0001	0.198	8.47E-02	0.0195
Radius	-3E-05	5.36E-06	<.0001	3.1E-05	1.40E-05	0.0282
Winter	-5.3277	0.9973	<.0001	-4.1885	1.7878	0.0192
Tempc	0.03327	0.03442	0.0339	-0.1108	0.06105	0.0398
Humc	0.00749	0.01652	0.6501	-0.07349	0.03052	0.0161
sqtage*summer	0.8574	0.1207	<.0001	0.5231	0.2204	0.0177
sqtage*Autumn	0.00662	0.1	0.9472	-0.534	0.1831	0.0036
sqtage*winter	0.2447	0.04272	<.0001	0.1698	0.07648	0.0265
humlag23c*summer	0.00732	0.05738	0.8984	-0.08564	0.1174	0.4657
humlag23c*autumn	0.00594	0.0371	0.8729	-0.09551	0.06049	0.1145
humlag23c*winter	-0.083	0.03386	0.0143	-0.01548	0.06021	0.7971
tempc*summer	-0.0342	0.07601	0.6531	0.09166	0.1343	0.4949
tempc*autumn	-0.0153	0.0571	0.7885	0.01847	0.1037	0.8587
tempc*winter	-0.3065	0.04486	<.0001	-0.466	0.08575	<.0001
rainc*summer	-0.0182	0.06395	0.7762	-0.03023	0.0881	0.7315
rainc*autumn	-0.026	0.0394	0.5095	0.02288	0.07297	0.7539
rainc*winter	0.09272	0.03701	0.0123	0.1919	0.08073	0.0176

Table A. 25: Parameter estimates for FD Model: Phase III

Effect	GC			GU		
	Estimate	SE	Pr > t	Estimate	SE	Pr > t
Intercept	-2.271	1.1229	0.0778	-3.7665	0.1797	<.0001
Sqtage	0.07919	0.03288	0.0426	0.08848	0.00546	<.0001
Summer	-21.2	4.0248	<.0001	-19.265	3.1686	<.0001
Autumn	-0.5613	2.9382	0.8485	15.0911	2.3003	<.0001
Winter	1.3941	0.5684	0.0142	0.9158	0.4058	0.0241
Dbh	-0.1818	0.01727	<.0001	0.6393	0.02704	<.0001
Radius	-1E-05	4.3E-06	0.0201	3.2E-06	6.2E-06	0.6063
increment	1.4E-05	3.3E-06	<.0001	-2E-05	5.5E-06	0.0038
solarlag16c	0.03852	0.0191	0.0438	-0.0295	0.0134	0.0278
sqtage*summer	0.6876	0.1252	<.0001	0.6123	0.09858	<.0001
sqtage*autumn	0.03641	0.08895	0.6823	-0.4446	0.06965	<.0001
sqtage*winter	-0.0368	0.01667	0.0273	-0.025	0.01196	0.0368
solarlag16c*summer	-0.0644	0.0304	0.0344	-0.0273	0.02119	0.1985
solarlag16c*autumn	-0.0149	0.02612	0.5687	0.08041	0.02041	<.0001
solarlag16c*winter	0.01074	0.02744	0.6955	0.1204	0.02107	<.0001

Table A. 26: Parameter estimates for VD Model: Phase II

Effect	GC			GU		
	Estimate	SE	Pr > t	Estimate	SE	Pr > t
Intercept	-8.1396	1.2605	0.0002	-7.4779	1.1468	0.0002
Sqtage	0.3157	0.04724	0.0002	0.3059	0.0486	0.0002
Summer	-1.8248	2.1111	0.3875	-14.861	2.7163	<.0001
Autumn	21.0259	1.8525	<.0001	19.6616	2.3774	<.0001
Winter	9.0396	0.6884	<.0001	5.7548	0.8894	<.0001
Dbh	0.1575	2.22E-02	<.0001	-0.571	4.05E-02	<.0001
Radius	-4E-05	3.46E-06	<.0001	4.9E-05	6.68E-06	<.0001
increment	2.5E-05	9.25E-06	0.0072	1.5E-05	6.52E-06	0.0208
Radius	-1E-05	8.92E-06	0.2571	3.7E-05	9.07E-06	<.0001
Tempc	0.01465	0.02656	0.5813	0.00855	0.03382	0.0404
sqtage*summer	0.07426	0.08643	0.3903	0.5975	0.1112	<.0001
sqtage*autumn	-0.8035	0.07012	<.0001	-0.7236	0.09001	<.0001
sqtage*winter	-0.3783	0.02935	<.0001	-0.2236	0.03795	<.0001
solarc*summer	-0.0222	0.04546	0.6251	-0.0982	0.05797	0.0904
solarc*autumn	-0.0094	0.02926	0.747	-0.0477	0.03733	0.2011
solarc*winter	0.07658	0.03607	0.0338	0.03017	0.04606	0.5126
tempc*summer	-0.1177	0.05668	0.0379	-0.0159	0.07013	0.8209
tempc*autumn	-0.0124	0.0449	0.7832	0.04689	0.05743	0.4143
tempc*winter	0.08264	0.04102	0.0441	0.1615	0.05426	0.003

Table A. 27: Parameter estimates for VD Model: Phase III

Effect	GC			GU		
	Estimate	S E	Pr > t	Estimate	S E	Pr > t
Intercept	0.7321	0.6822	0.3245	1.3662	2.4072	0.5859
Summer	-0.2443	4.1299	0.9528	-3.2983	6.4283	0.6079
Autumn	-7.1383	2.5605	0.0053	-20.719	4.269	<.0001
Winter	-0.2247	0.5798	0.6984	0.03847	0.9467	0.9676
Radius	4.71E-06	6.17E-06	0.4449	8.8E-05	0.00001	<.0001
Tempc	-0.0737	0.0204	0.0003	-0.0628	0.03573	0.0789
Rainc	-0.0575	0.02389	0.0163	-0.0267	0.03521	0.449
templag3lc	0.01717	0.02355	0.4659	0.05403	0.04063	0.1837
sqtage*summer	0.01541	0.1296	0.9054	0.1068	0.2017	0.5964
sqtage*autumn	0.2268	0.07756	0.0035	0.6236	0.1292	<.0001
sqtage*winter	0.01299	0.01742	0.4557	0.01063	0.02798	0.7042
templag3lc*summer	0.06203	0.0407	0.1276	0.1148	0.06168	0.0629
templag3lc*autumn	-0.0696	0.0358	0.0521	-0.0484	0.05823	0.4057
templag3lc*winter	0.05636	0.05422	0.0497	0.187	0.05601	0.0009
humc*summer	0.01981	0.06044	0.7432	0.1904	0.09168	0.0379
humc*autumn	0.1066	0.05042	0.0545	0.211	0.08279	0.0109
humc*winter	0.02348	0.04464	0.599	0.156	0.07294	0.0326
tempc*rainc	0.02136	0.01551	0.1687	0.0464	0.02407	0.054
tempc*humc	-0.0407	0.01619	0.0121	-0.0606	0.02729	0.0264
humc*solarc	0.04443	0.01491	0.0029	0.03424	0.02444	0.1614
tempc*speedc	-0.0239	0.02112	0.2589	-0.0833	0.03426	0.0151
rainc*speedc	-0.0798	0.027	0.0032	-0.0338	0.03886	0.3851

Table A. 28: Parameter estimates for VF Model: Phase II

Effect	GC			GU		
	Estimate	S E		Estimate	S E	
Reciage	-19718	1576.08	<.0001	-832.92	2066.92	0.687
Summer	-101.97	10.1085	<.0001	-11.829	13.1221	0.3767
Autumn	-10.634	8.1967	0.2074	-21.295	10.6913	0.0584
Winter	-43.244	3.0126	<.0001	-16.003	3.9557	0.0005
Tempc	0.1809	0.228	0.4277	0.6113	0.292	0.0365
reciage*summer	61090	6034.5	<.0001	6618.11	7840.25	0.3987
reciage*autumn	-2298.9	5791.13	0.6914	10011	7552.26	0.1851
reciage*winter	22885	1633.39	<.0001	7853.27	2141.75	0.0003
tempc*summer	-0.2897	0.4954	0.5588	-0.8851	0.6214	0.0445
tempc*autumn	-0.0217	0.3838	0.955	-0.7281	0.5013	0.0165
tempc*winter	0.8995	0.3009	0.0028	0.7584	0.4084	0.0335
rainc*summer	0.1849	0.3661	0.6137	0.4183	0.353	0.0361
rainc*autumn	0.1592	0.233	0.4945	-0.2649	0.3106	0.0839
rainc*winter	-0.4219	0.2201	0.0554	-0.4719	0.3491	0.0766

Table A. 29: Parameter estimates for VF Model: Phase III

Effect	GC			GU		
	Estimate	SE	Pr > t	Estimate	SE	Pr > t
Summer	5.8821	5.1996	0.2728	14.6398	5.5737	0.0148
Autumn	-1.1102	3.5925	0.7608	0.1638	3.9071	0.9669
Winter	-0.5843	0.412	0.1733	0.3061	0.6392	0.6363
Spring	0	.	.	0	.	.
Humc	0.01038	0.0115	0.3669	-0.0021	0.01926	0.9121
Solarc	0.001666	0.009125	0.8552	-0.0083	0.01542	0.5905
rainc*summer	-0.01533	0.04122	0.0199	-0.1351	0.066	0.0408
rainc*autumn	0.02244	0.02779	0.0195	-0.031	0.0445	0.0458
rainc*winter	-0.00606	0.02519	0.0399	-0.007	0.04136	0.0466
rainc*spring	0	.	.	0	.	.
solarc*summer	0.04549	0.01962	0.0505	0.00854	0.03164	0.7873
solarc*autumn	0.02099	0.02036	0.3028	0.09643	0.03291	0.0034
solarc*winter	-0.00309	0.01859	0.8678	0.02051	0.03104	0.5087
solarc*spring	0	.	.	0	.	.

Appendix B: Additional Figures

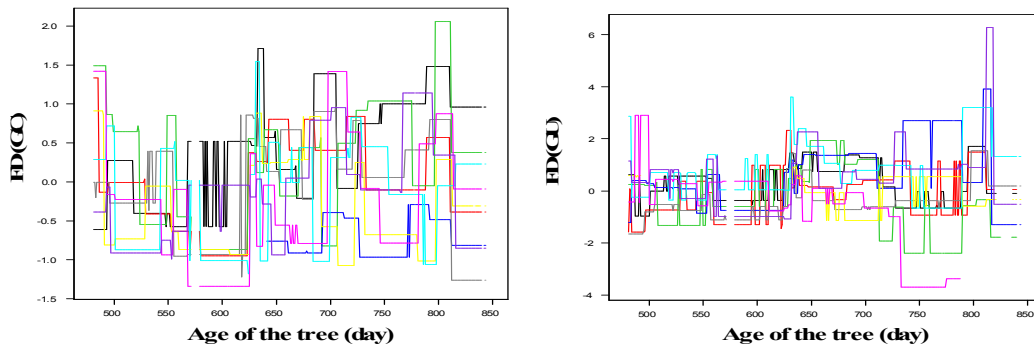


Figure B. 1: Phase II Fibre Dimension (FD) versus age of the tree for GC and GU

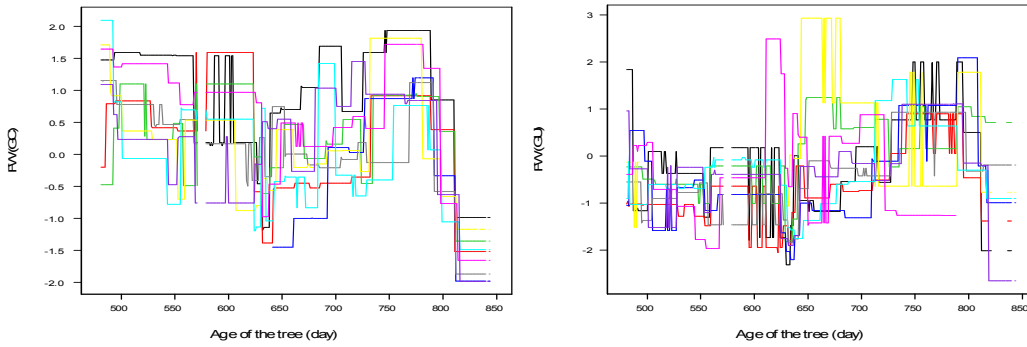


Figure B. 2: Phase II Fibre Wall (FW) versus age of the tree for GC and GU

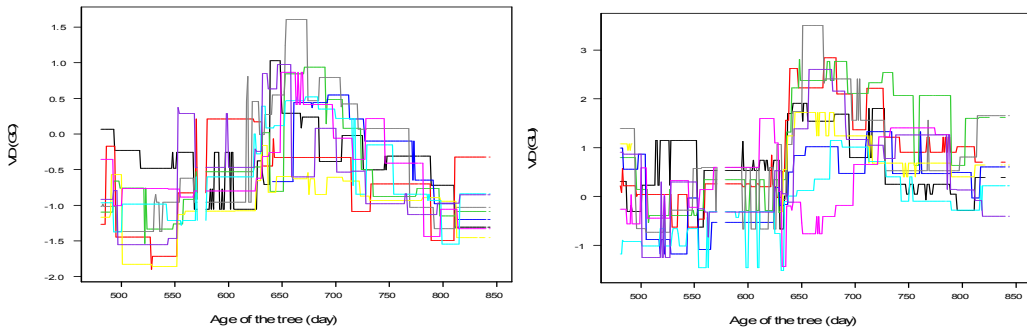


Figure B. 3: Phase II Vessel Dimension (VD) versus age of the tree for GC and GU

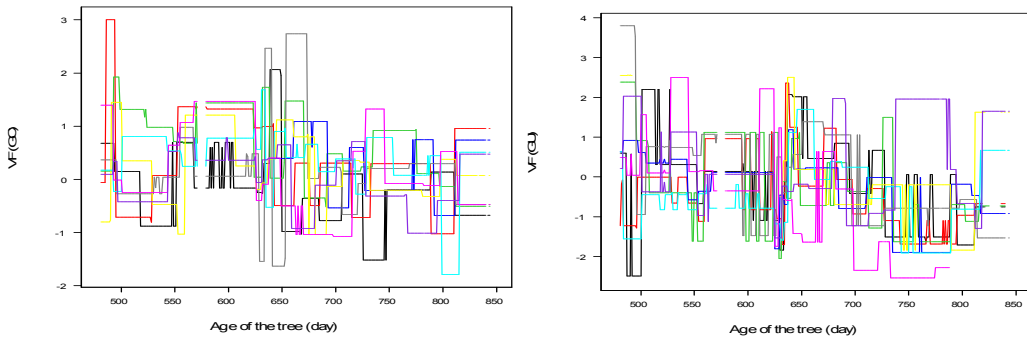


Figure B. 4: Phase II Vessel Frequency (VF) versus age of the tree for GC and GU

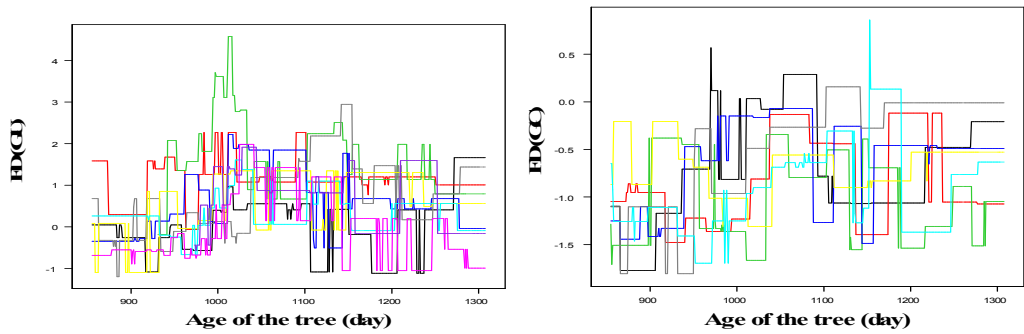


Figure B. 5: Phase III Fibre Dimension (FD) versus age of the tree for GC and GU

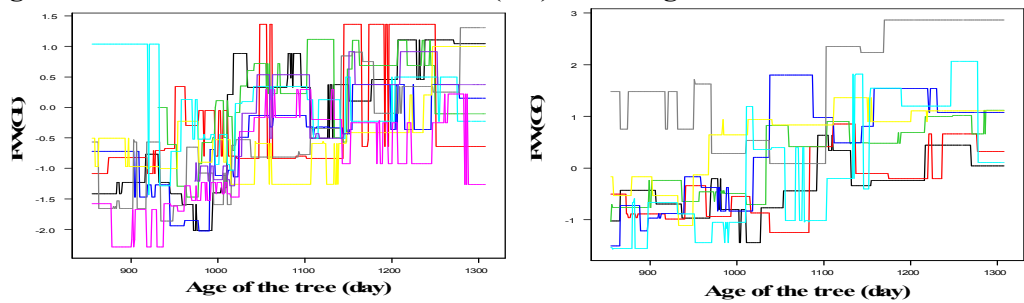


Figure B. 6: Phase III Fibre Wall (FW) versus age of the tree for GC and GU

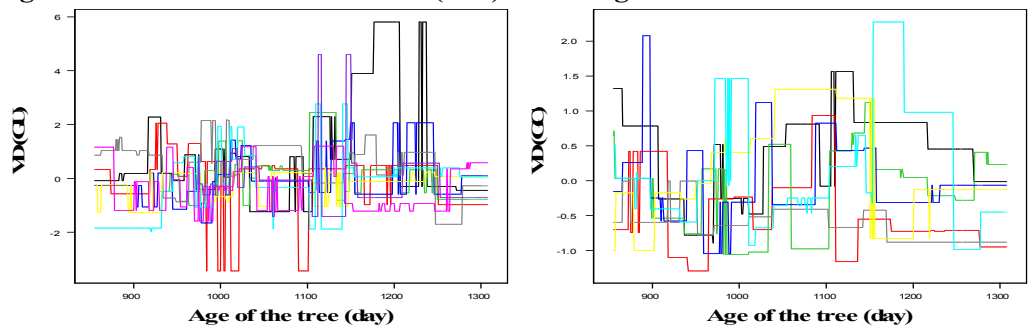


Figure B. 7: Phase III Vessel Dimension (VD) versus age of the tree for GC and GU

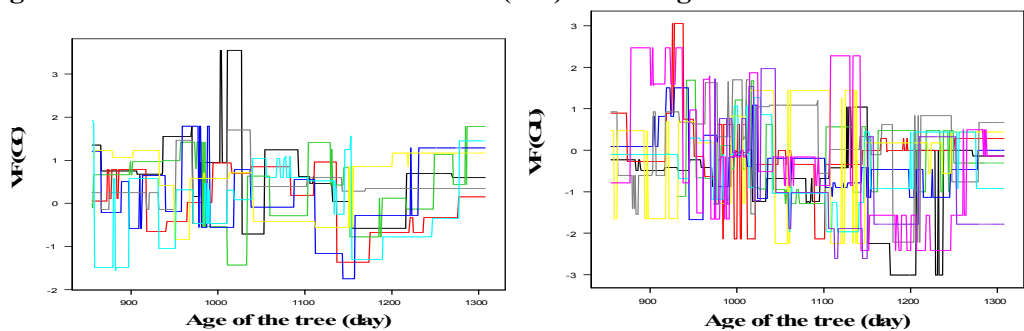


Figure B. 8: Phase III Vessel Frequency (VF) versus age of the tree for GC and GU

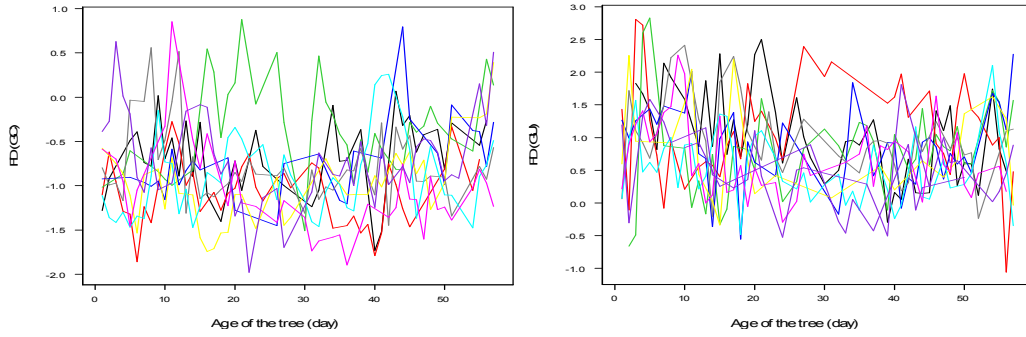


Figure B. 9: phase IV Fibre Dimension (FD) versus age of the tree for GC and GU

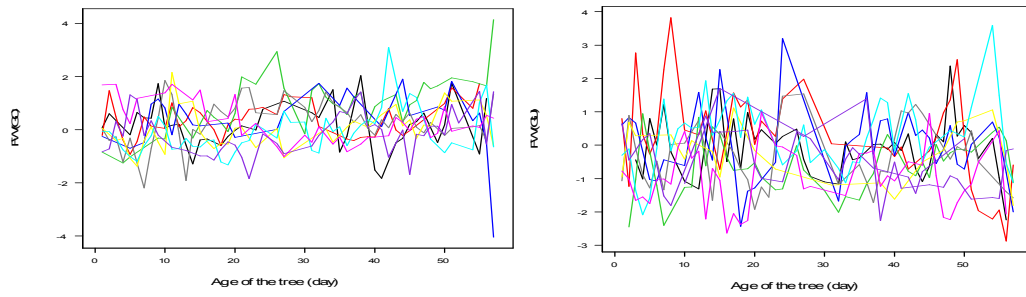


Figure B. 10: Phase IV Fibre Wall versus age of the tree for GC and GU

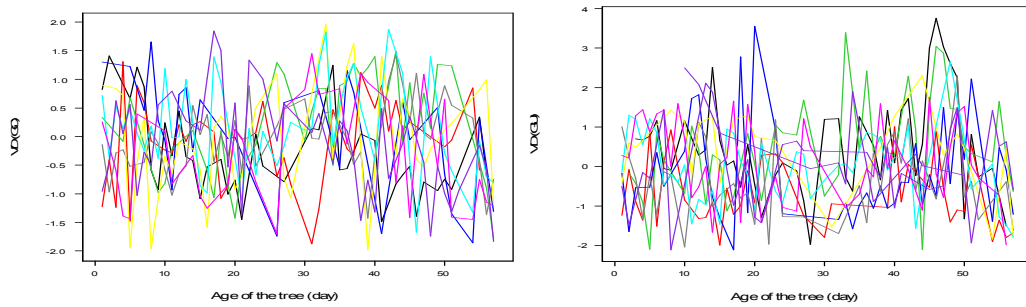


Figure B. 11: Phase IV Vessel Dimension versus age of the tree for GC and GU

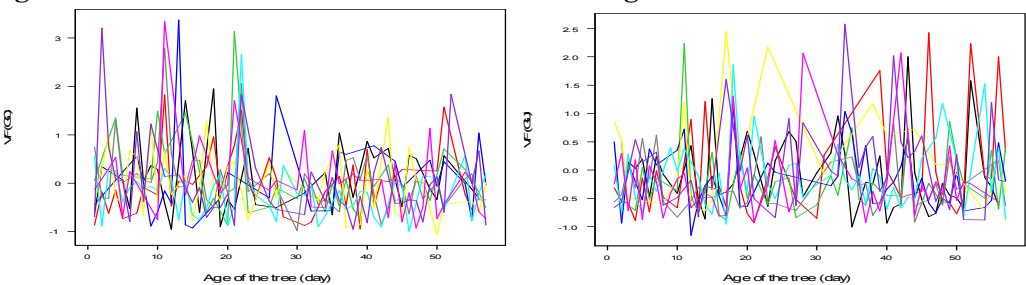


Figure B. 12: Phase IV Vessel Frequency (VF) versus age of the tree for GC and GU

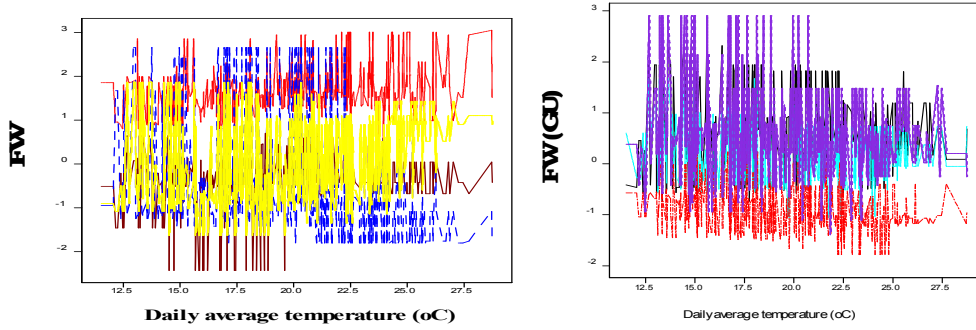


Figure B. 13: Fibre wall versus daily average temperature for GC and GU phase I

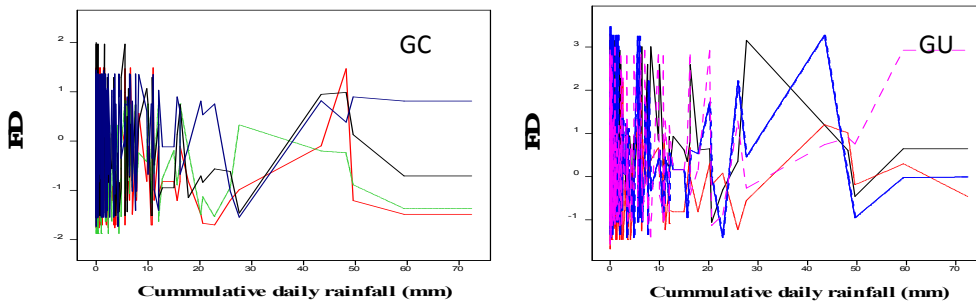


Figure B. 14: Fibre Dimension versus cummulative daily rainfall for GC and GU phase I

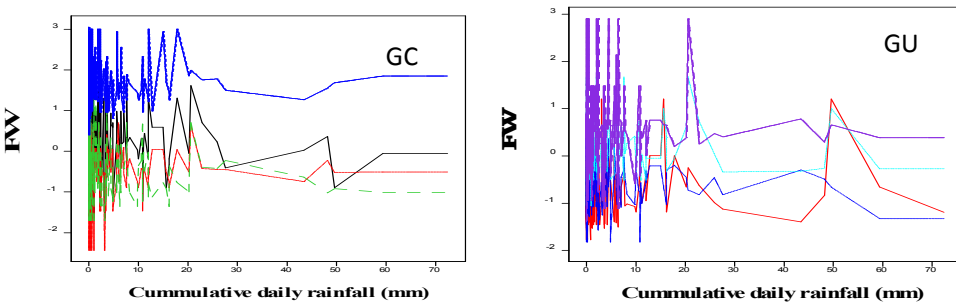


Figure B. 15: Fibre Wall versus cummulative daily rainfall for GC and GU phase I

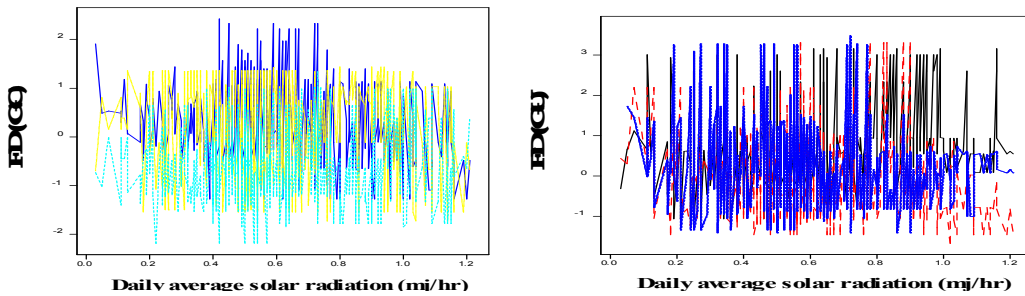


Figure B. 16: Fibre Dimension versus daily average solar radiation for GC and GU phase I

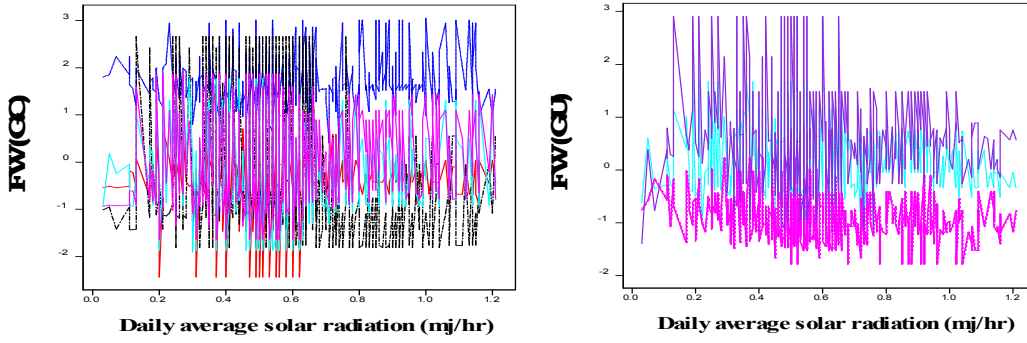


Figure B. 17: Fibre Wall versus daily average solar radiation for GC and GU phase I

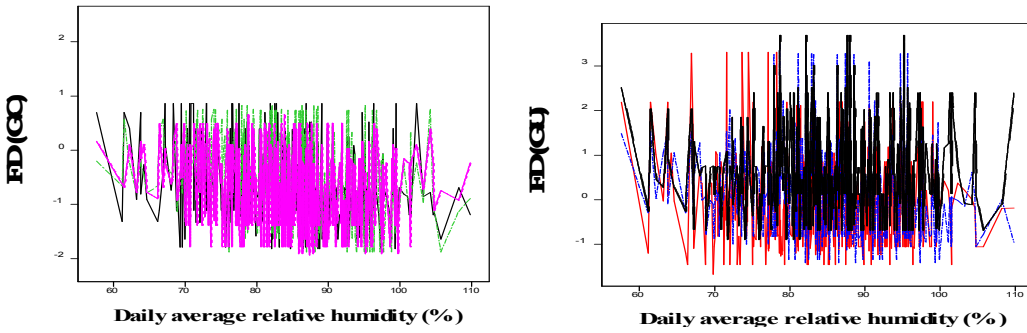


Figure B. 18: Fibre Dimension versus daily average relative humidity for GC and GU phase I

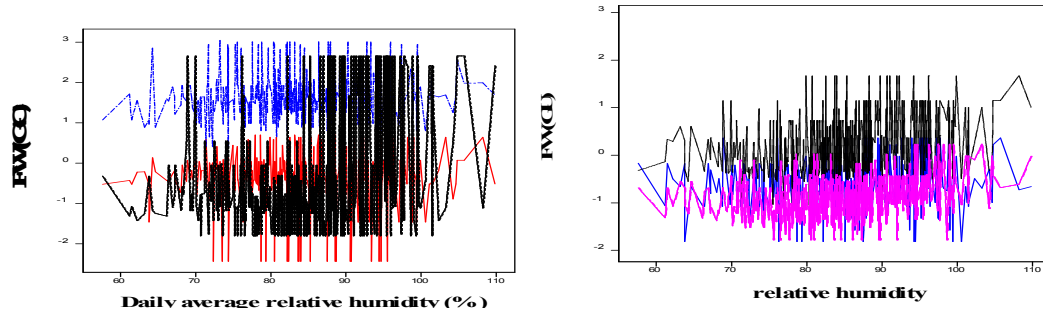


Figure B. 19: Fibre Wall versus daily average relative humidity for GC and GU phase I

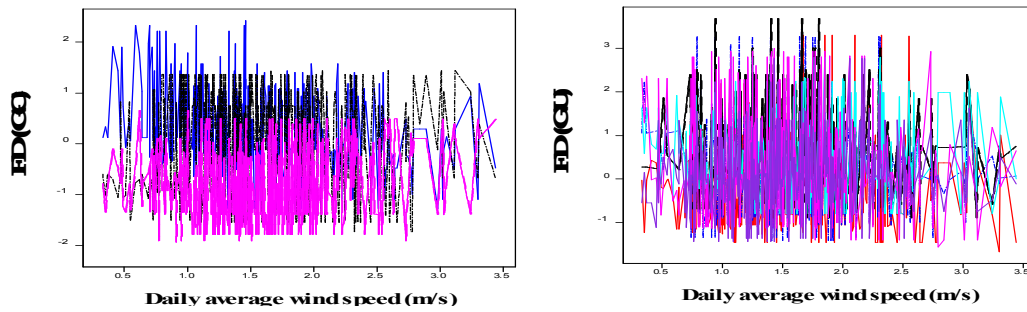


Figure B. 20: Fibre Dimension versus daily average wind speed for GC and GU phase I

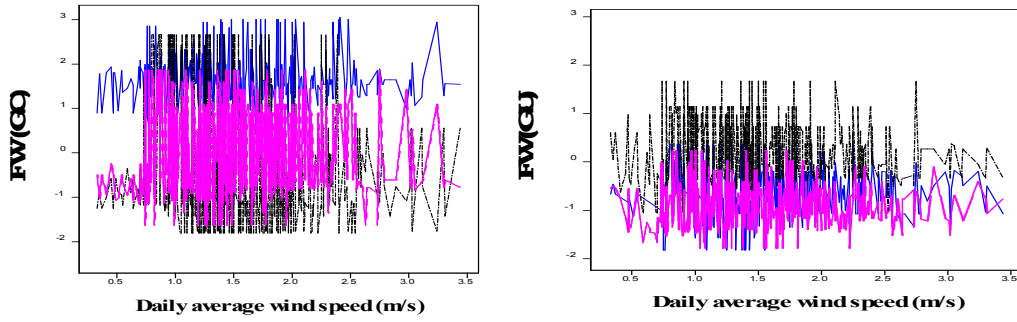


Figure B. 21: Fibre Wall versus daily average wind speed for GC and GU phase I

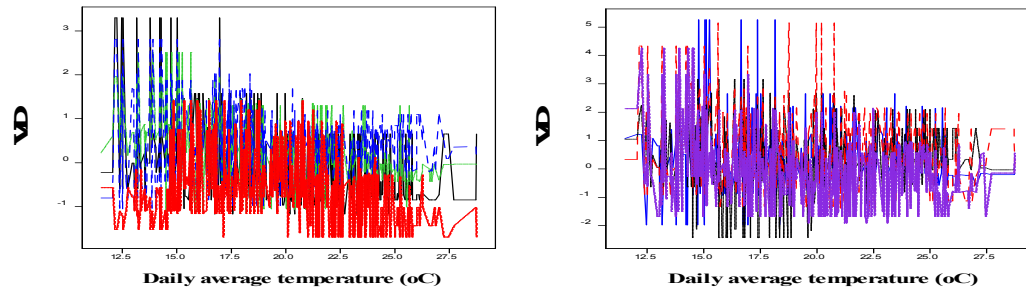


Figure B. 22: Vessel Dimension versus daily average temperature for GC and GU phase I

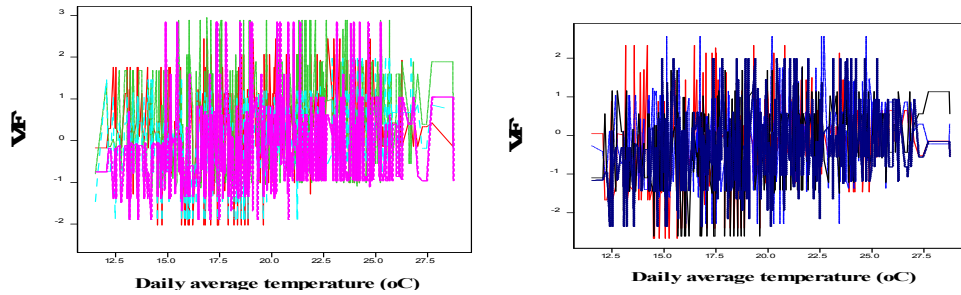


Figure B. 23: Vessel Frequency versus daily average temperature for GC and GU phase I

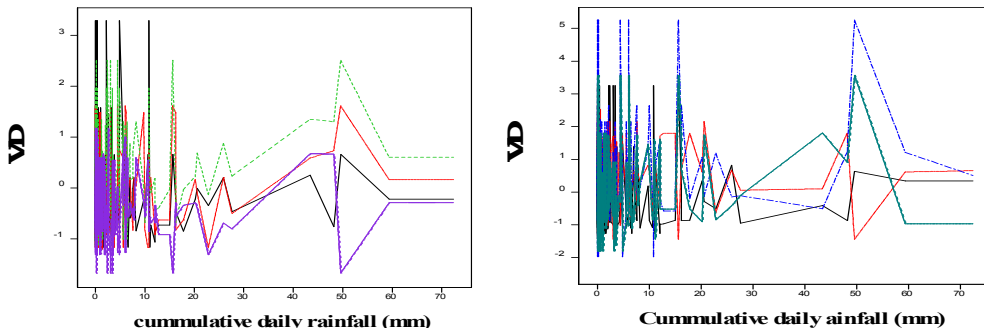


Figure B. 24: Vessel Dimension versus cumulative daily rainfall for GC and GU phase I

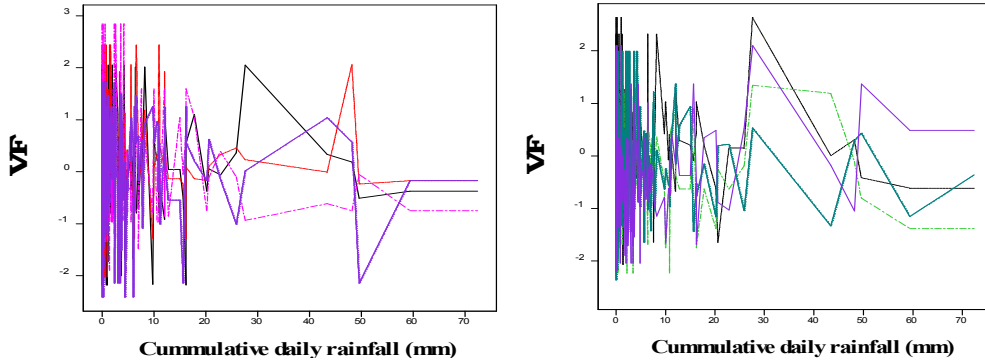


Figure B. 25: Vessel Frequency versus cumulative daily rainfall for GC and GU phase I

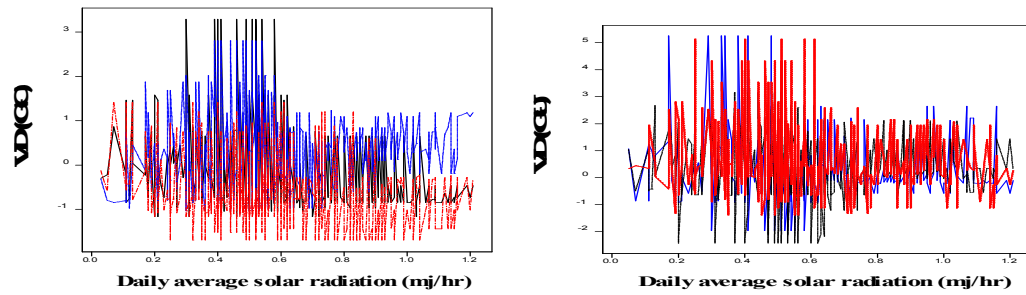


Figure B. 26: vessel Dimension versus daily average solar radiation for GC and GU phase I

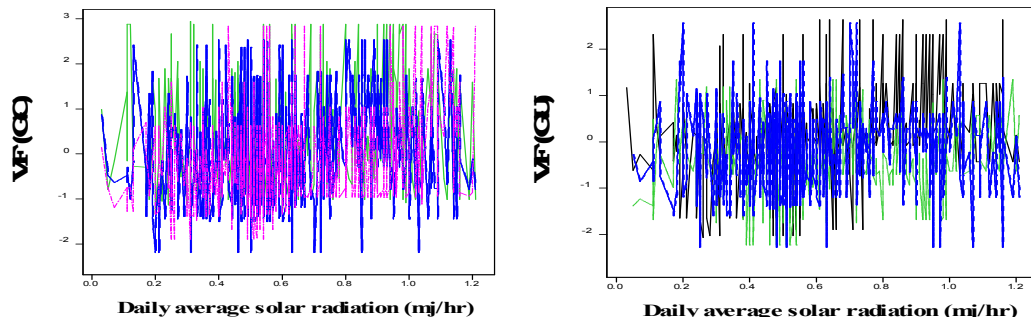


Figure B. 27: Vessel Frequency versus daily average solar radiation for GC and GU phase I

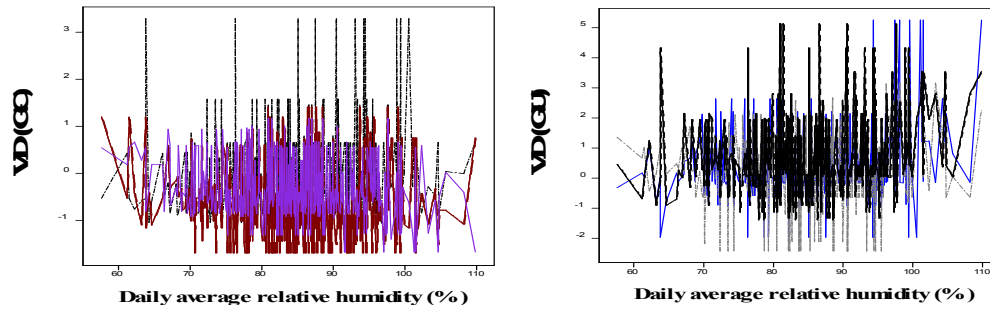


Figure B. 28: Vessel Dimension versus daily average relative humidity for GC and GU phase I

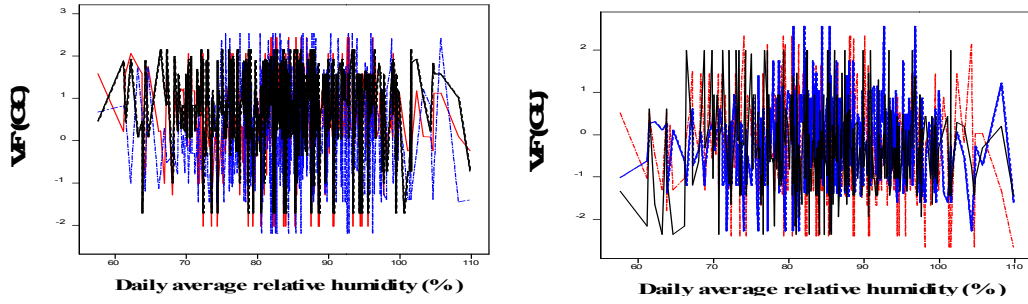


Figure B. 29: Vessel Frequency versus daily average relative humidity for GC and GU phase I

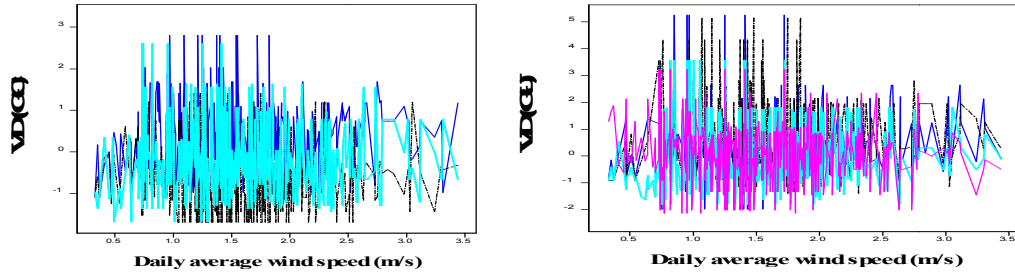


Figure B. 30: Vessel Dimension versus average wind speed for GC and GU phase I

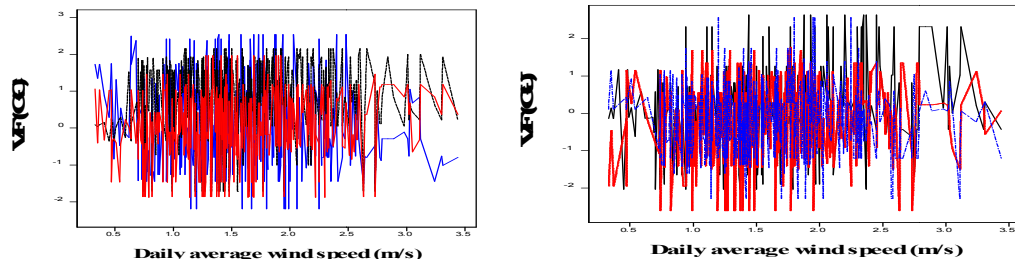


Figure B. 31: Vessel Frequency versus average wind speed for GC and GU phase I

Phase	GC	GU
IL		
	<p>Residual Statistics</p> <ul style="list-style-type: none"> No. of obs not missing: 3043 Minimum: -3.743 Arithmetic Mean: 0.0157 Maximum: 0.7538 Std. Deviation: 0.2193 <p>Fit Statistics</p> <ul style="list-style-type: none"> Objective Function: 6792.9 AIC (smaller is better): 5798.9 AICC (smaller is better): 5798.9 BIC (smaller is better): 5799.5 	<p>Residual Statistics</p> <ul style="list-style-type: none"> No. of obs not missing: 2956 Minimum: -5.144 Arithmetic Mean: -2.009 Maximum: 0.7683 Std. Deviation: 0.1969 <p>Fit Statistics</p> <ul style="list-style-type: none"> Objective Function: 7420.3 AIC (smaller is better): 7426.3 AICC (smaller is better): 7426.3 BIC (smaller is better): 7435.6

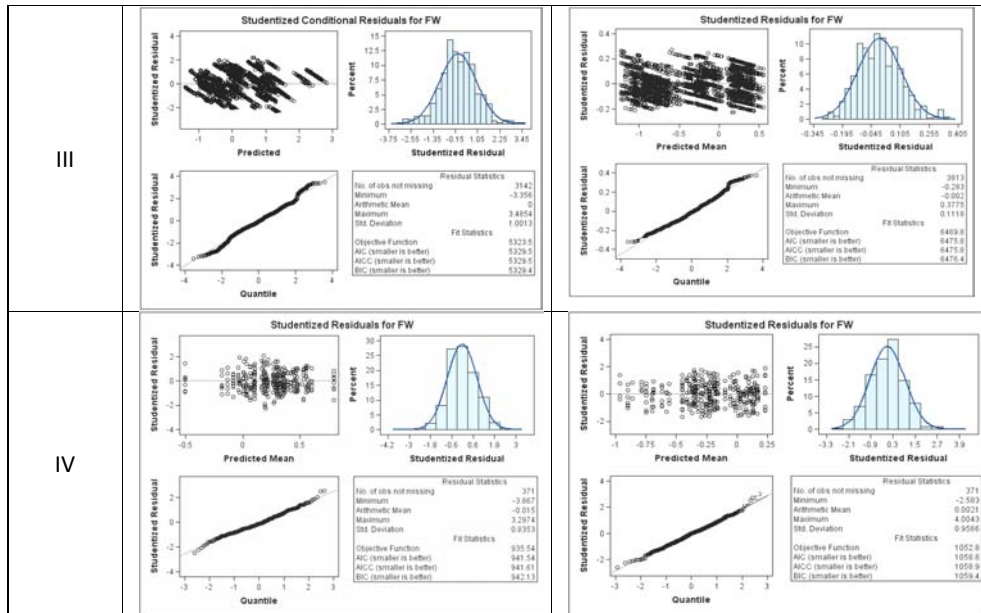


Figure B. 32: Plots of studentized Residuals for FW

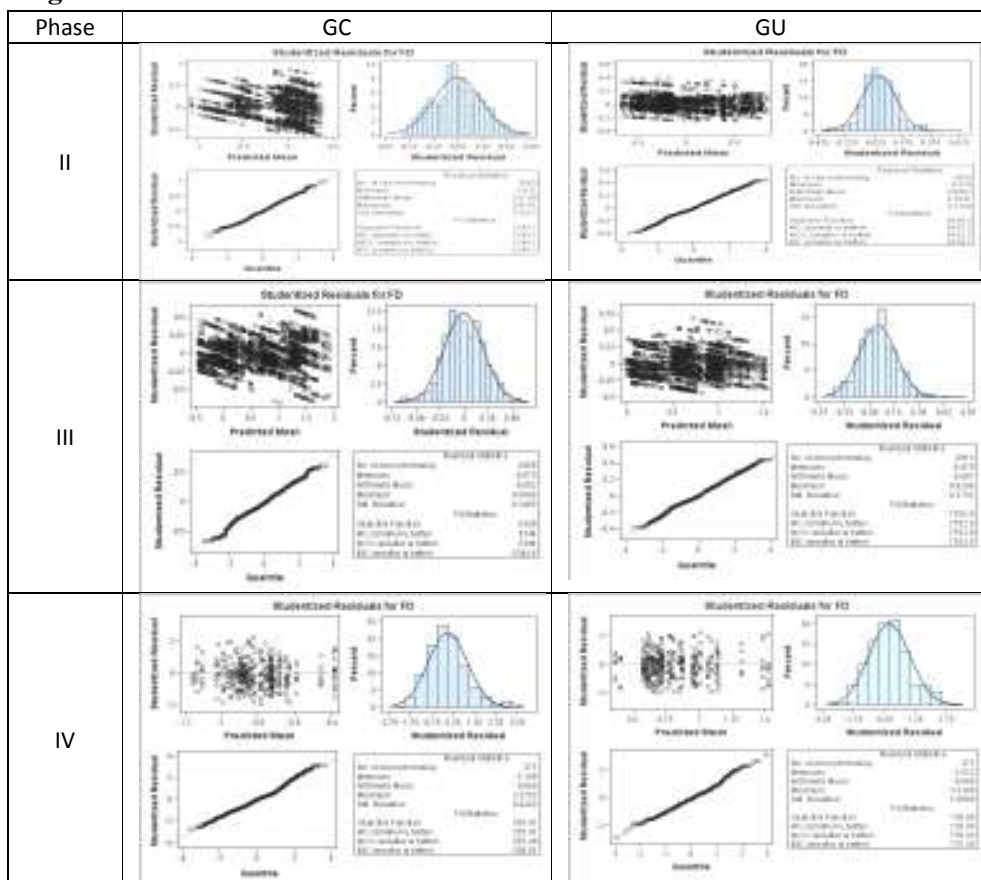


Figure B. 33: Plots of studentized Residuals for FD

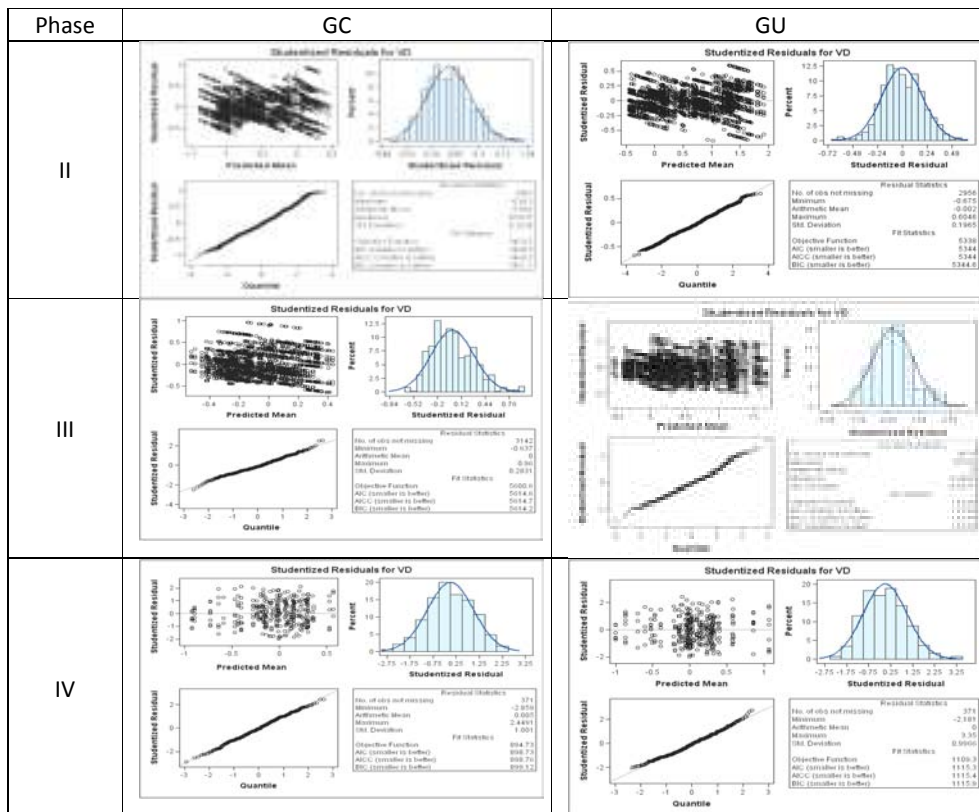


Figure B. 34: Plots of studentized Residuals for VD

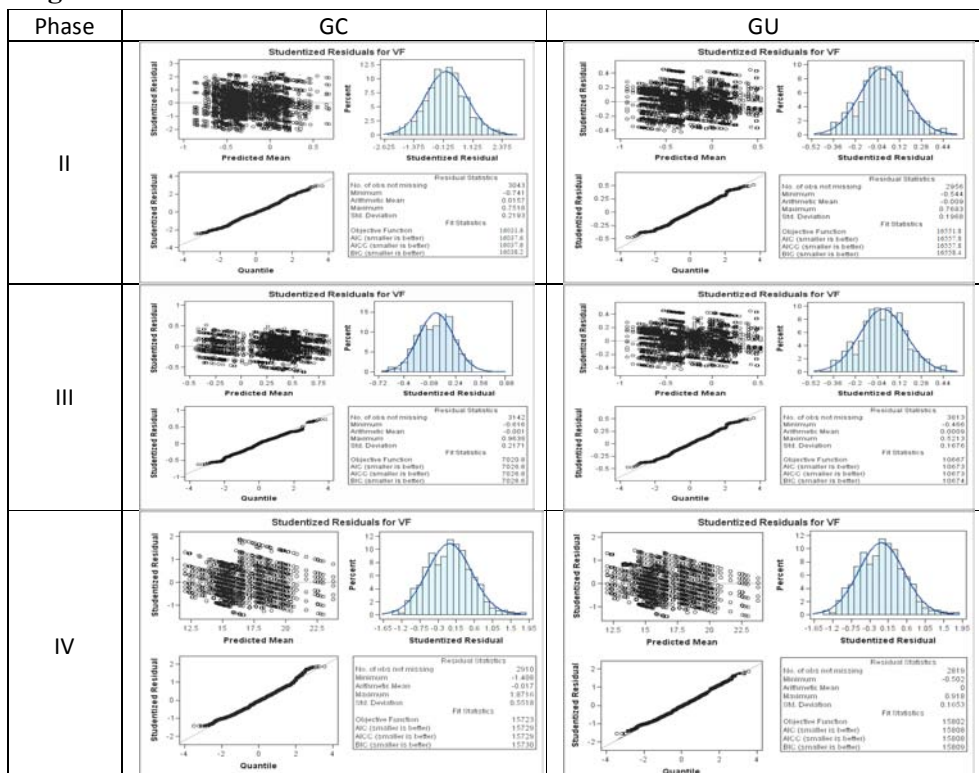


Figure B. 35: Plots of studentized Residuals for VF

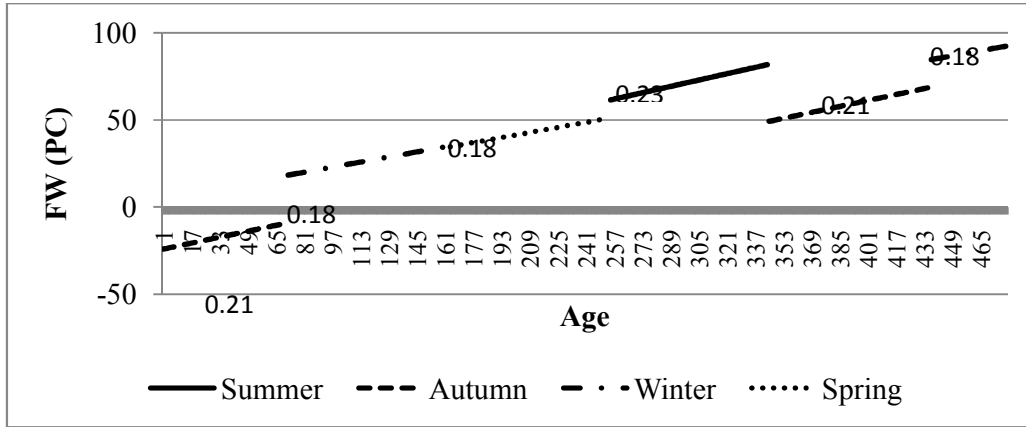


Figure B. 36: Joint effect of season and age GC Phase II

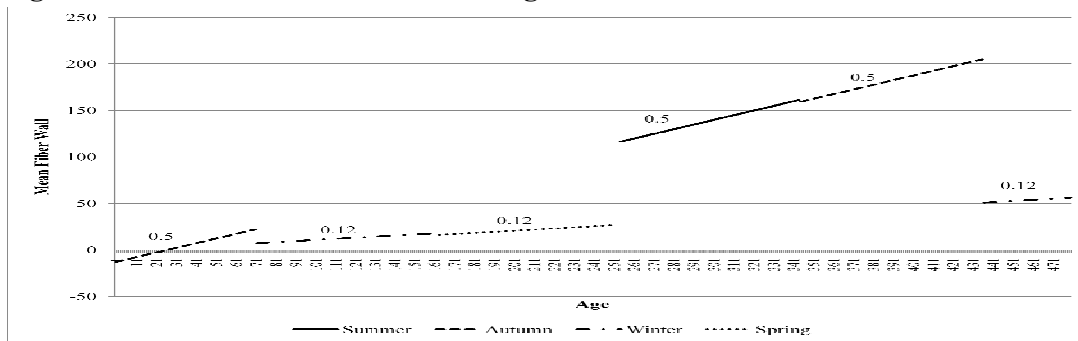


Figure B. 37: Joint effect of season and age GU Phase II

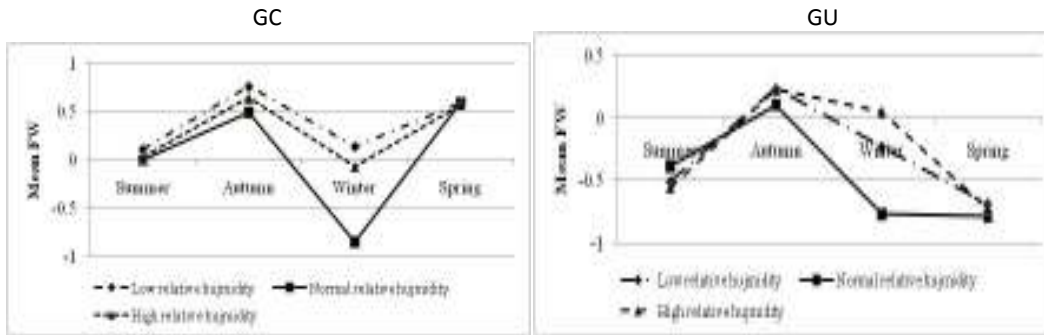


Figure B. 38: The mean FW vs. season and relative humidity for phase II

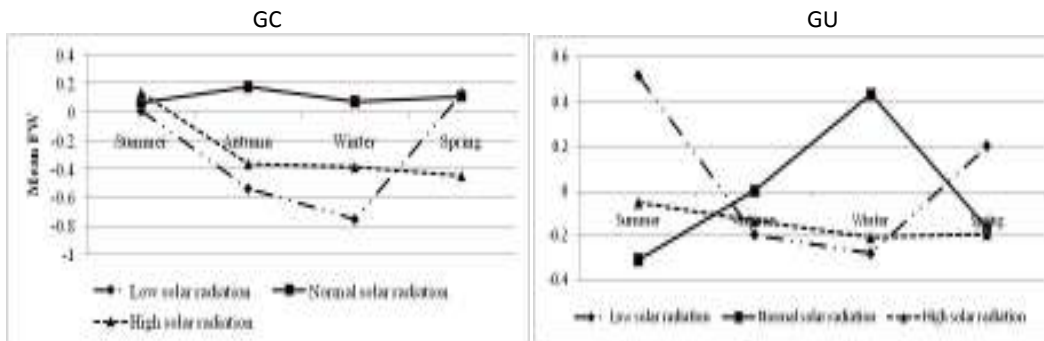


Figure B. 39: The mean FW vs. season and solar radiation for phase II

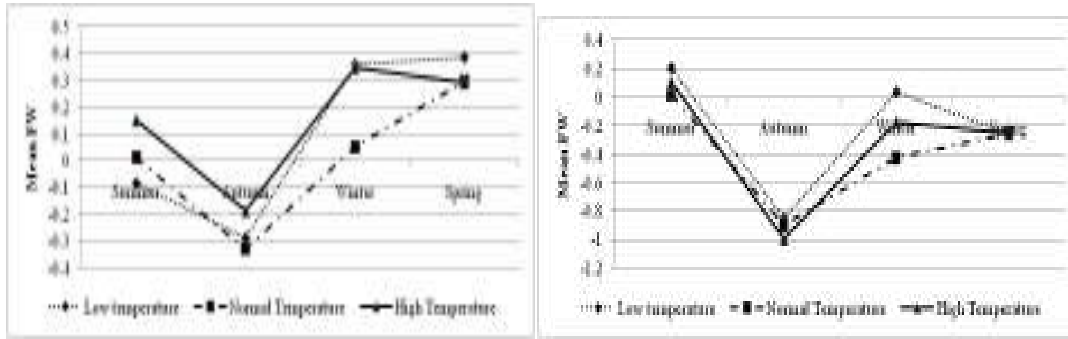


Figure B. 40: The mean FW vs. season and temperature at lag 5 for phase II

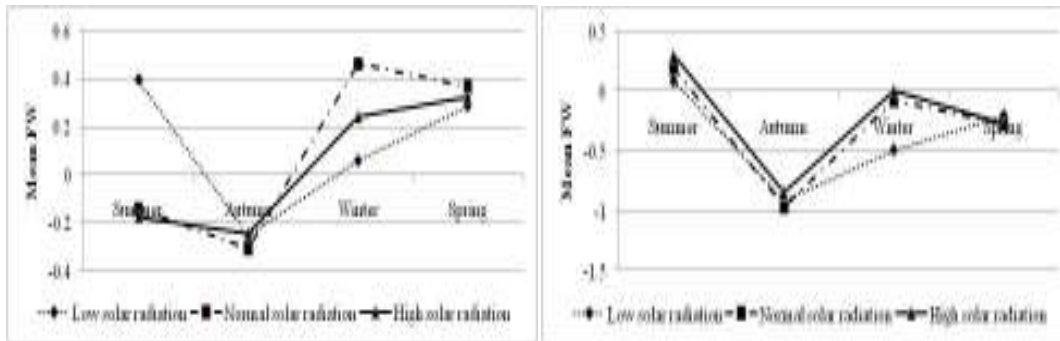


Figure B. 41: The mean FW vs. season and solar radiation at lag 31 for phase II

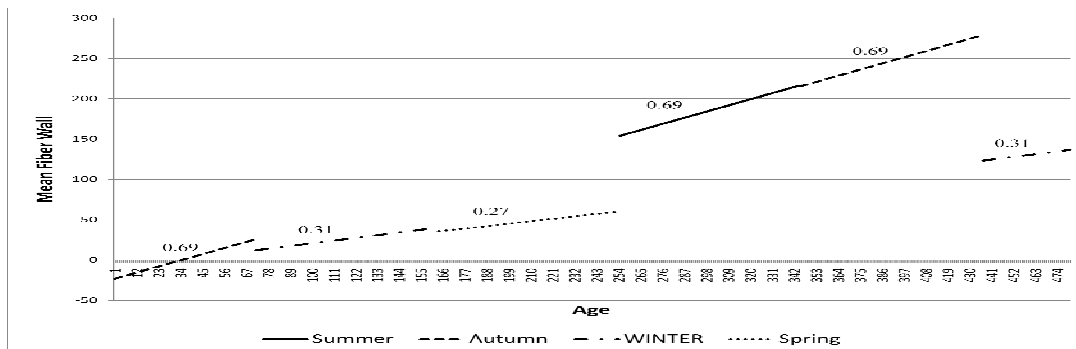


Figure B. 42: Joint effect of season and age GC Phase III

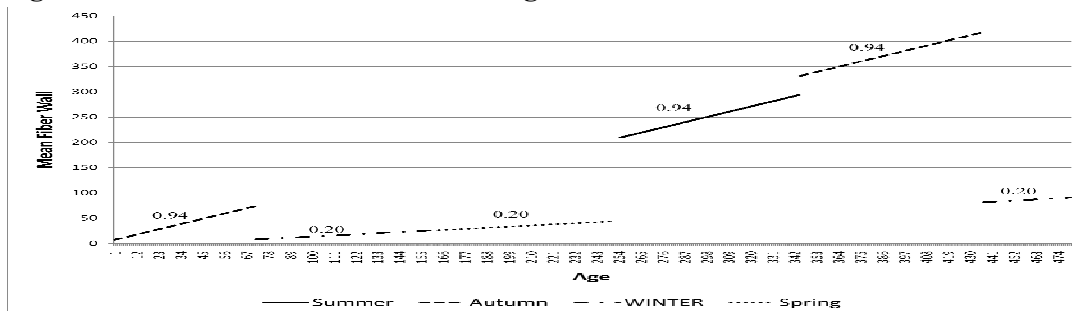


Figure B. 43: Joint effect of season and age GU Phase III

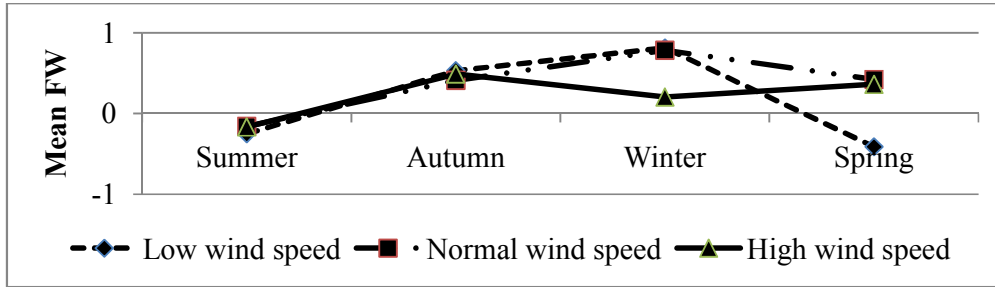


Figure B. 44: The mean FW of GC vs. season and solar radiation for phase II

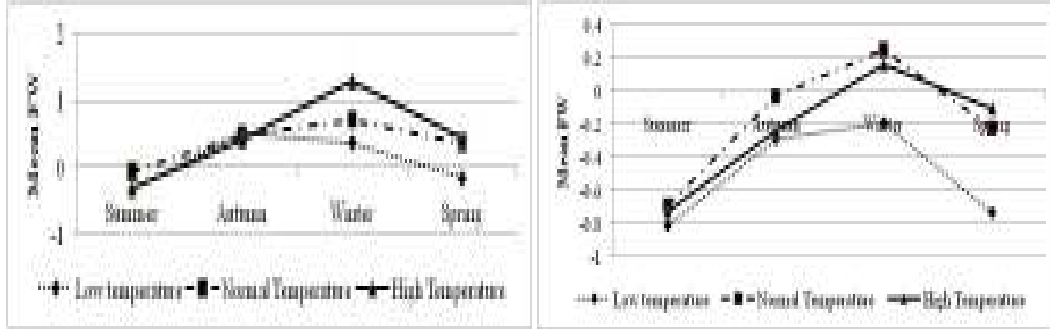


Figure B. 45: The mean FW vs. season and solar radiation at lag 7 for phase III

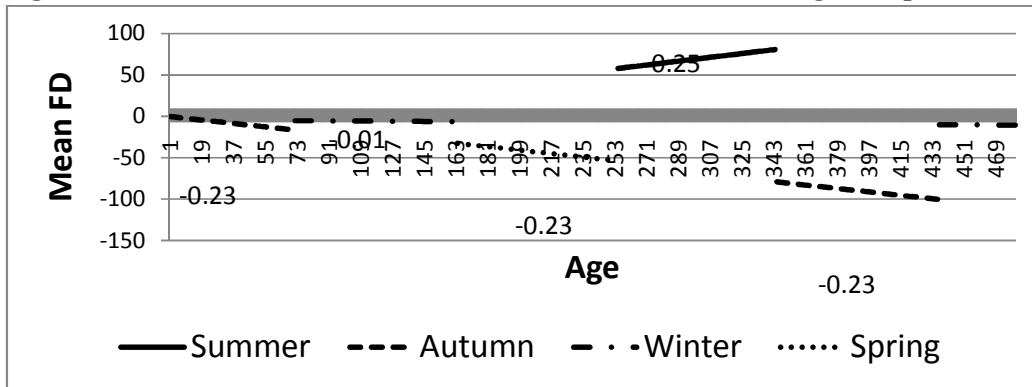


Figure B. 46: Joint effect of season and age GC Phase II

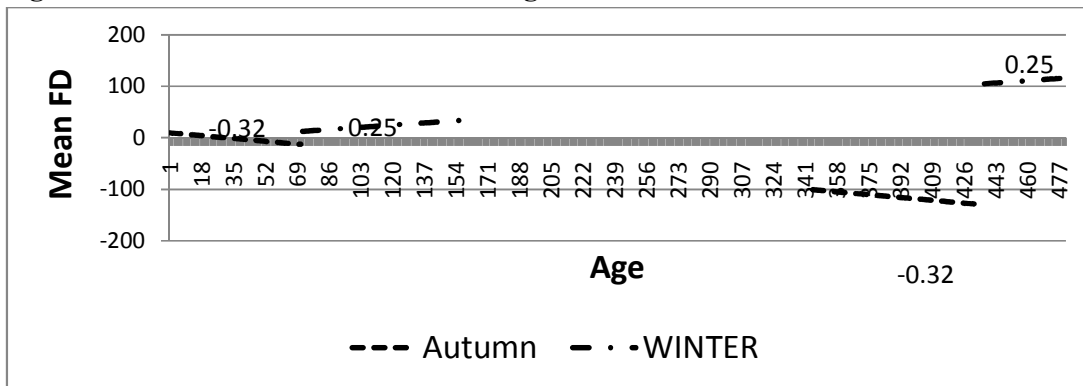


Figure B. 47: Joint effect of season and age GU Phase II

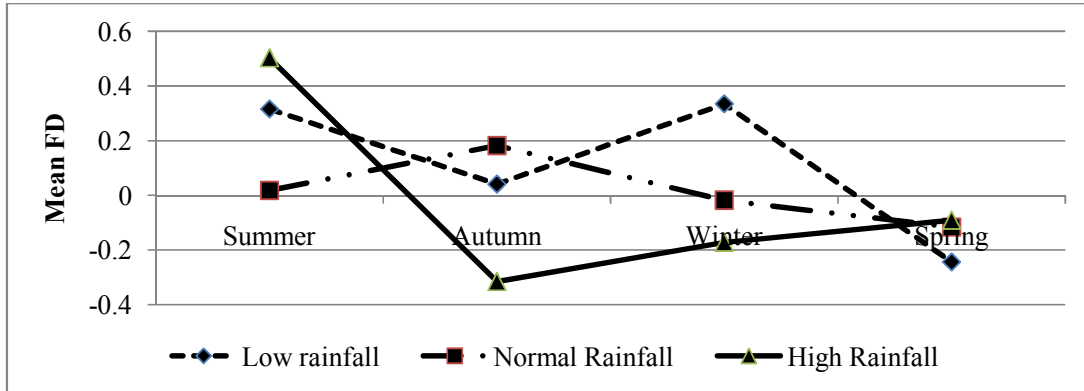


Figure B. 48: The mean FD of GU vs. season and rainfall for phase II

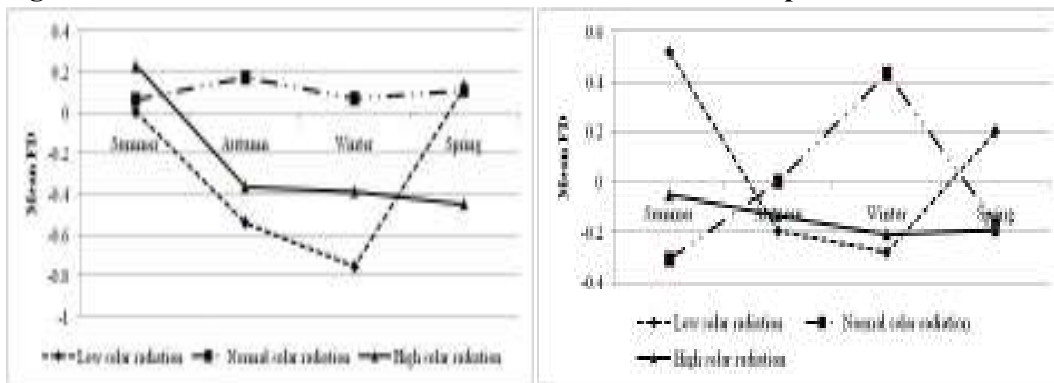


Figure B. 49: The mean FD vs. season and solar radiation for phase II

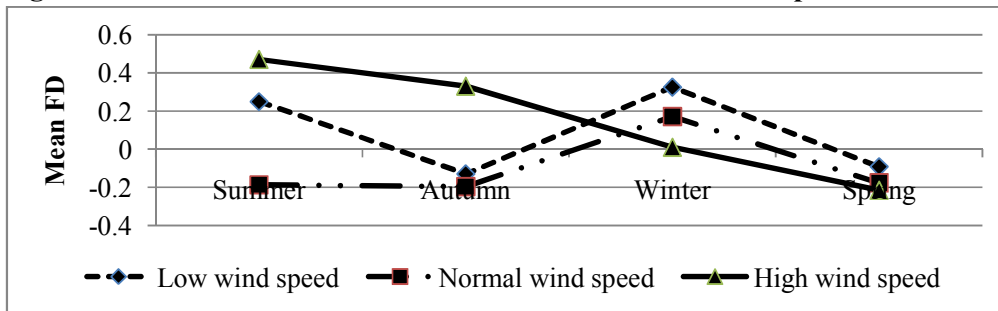


Figure B. 50: The mean FD of GU vs. season and wind speed for phase II

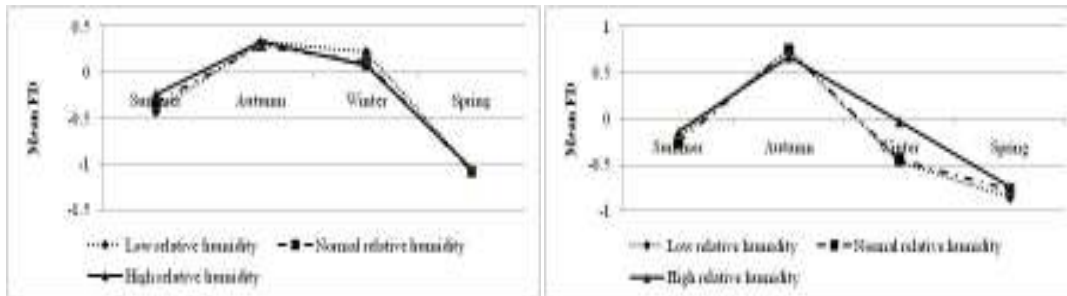


Figure B. 51: The mean FD vs. season and relative humidity at lag 23 for phase II

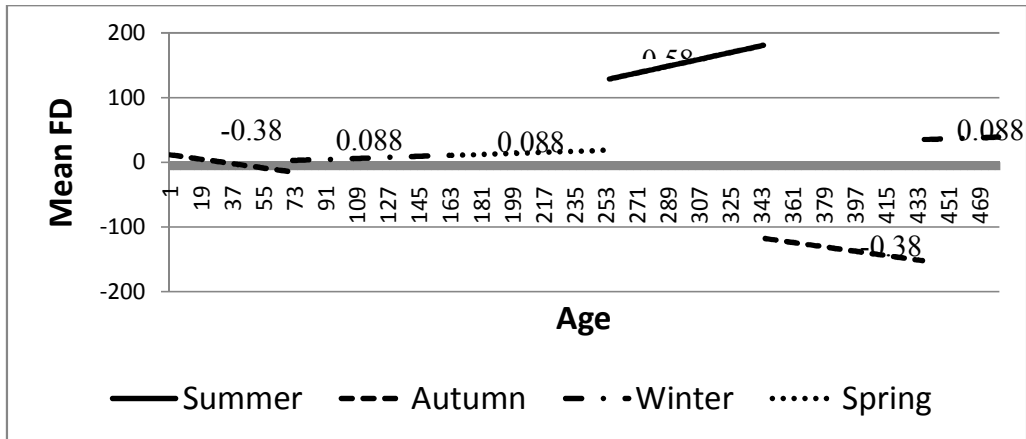


Figure B. 52: Joint effect of season and age GC Phase III

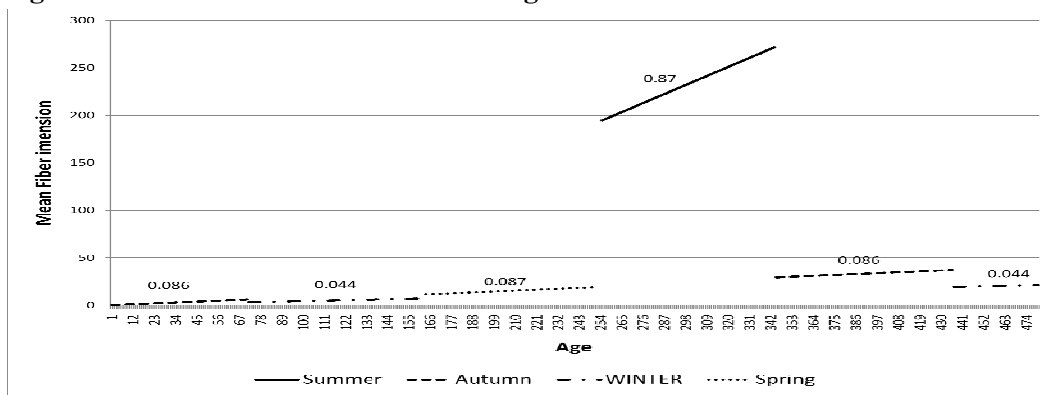


Figure B. 53: Joint effect of season and age GU Phase III

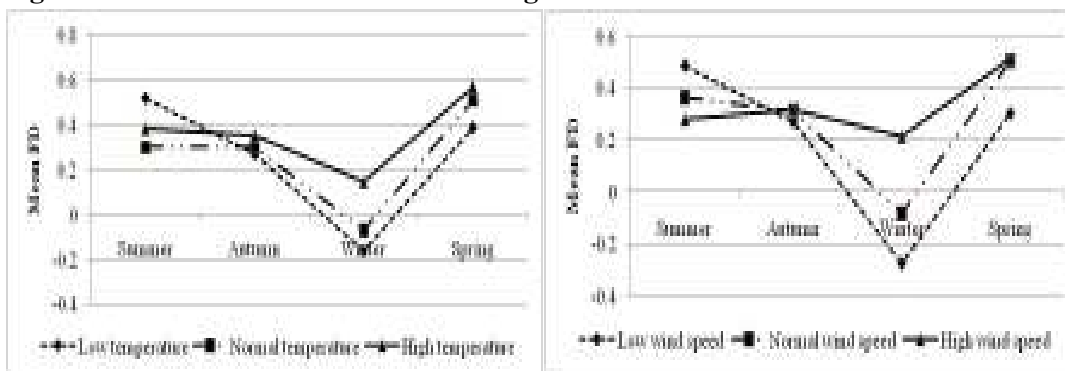


Figure B. 54: The mean FD vs. season and temperature for phase III

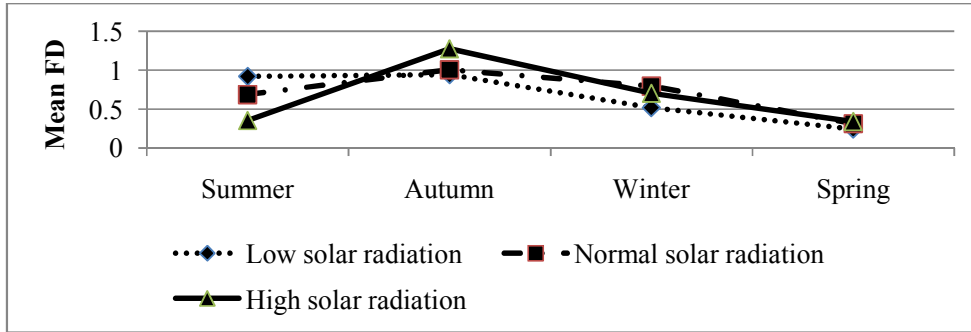


Figure B. 55: The mean FD of GU vs. season and solar radiation at lag 16 for phase III

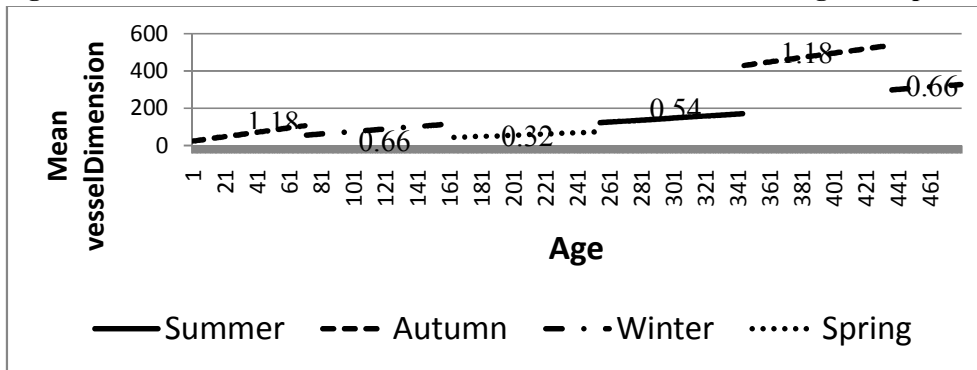


Figure B. 56: Joint effect of season and age GC Phase II for VD

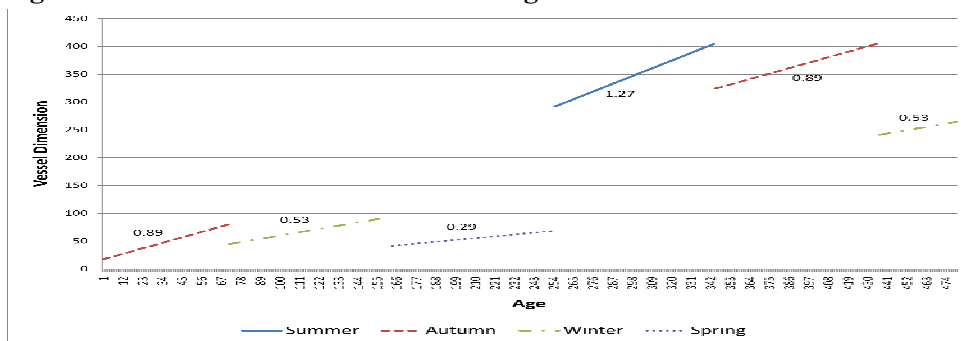


Figure B. 57: Joint effect of season and age GU Phase II for VD

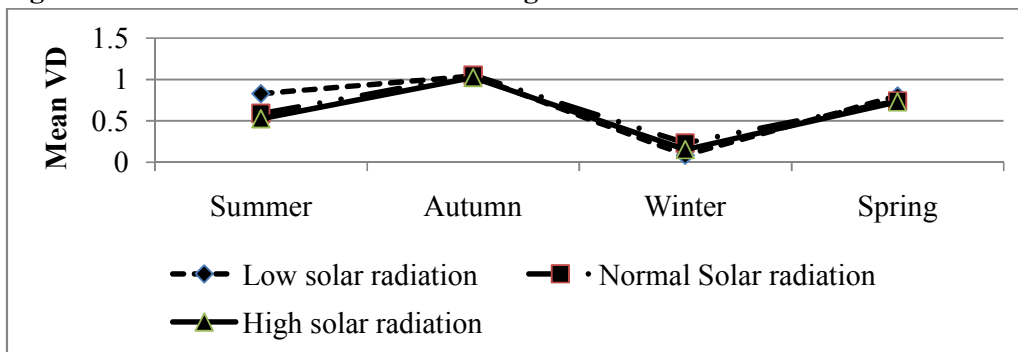


Figure B. 58: The mean VD of GU vs. season and solar radiation for phase II

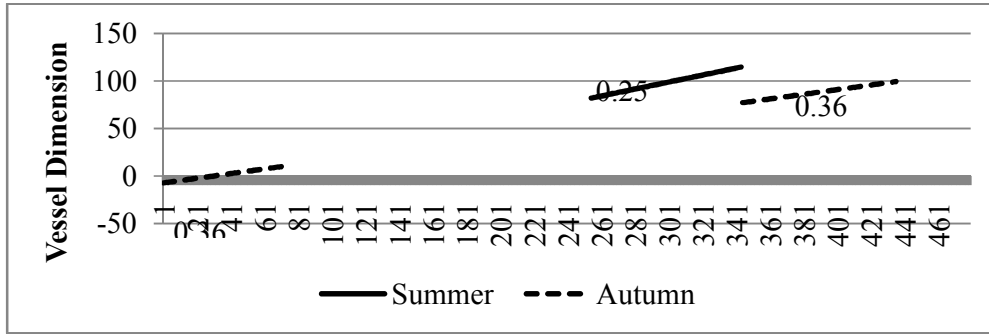


Figure B. 59: Joint effect of season and age GC Phase III for VD

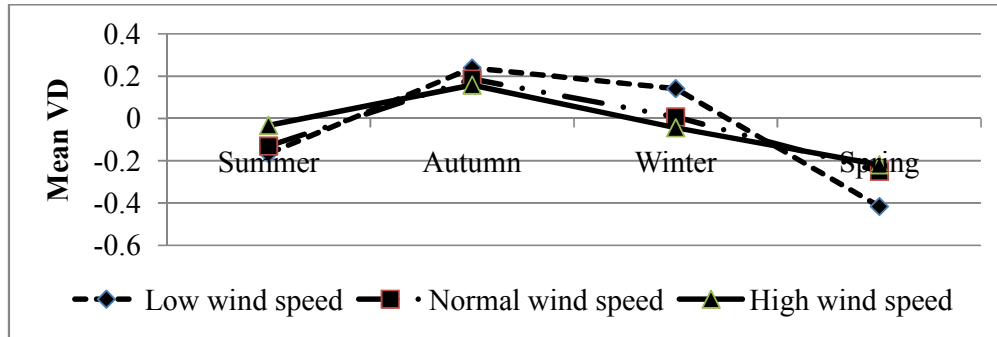


Figure B. 60: The mean VD of GU vs. season and wind speed for phase III

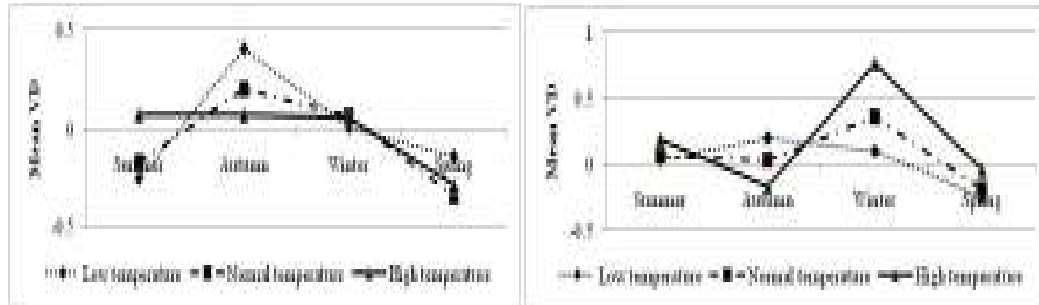


Figure B. 61: The mean VD vs. season and temperature at lag 31 for phase III

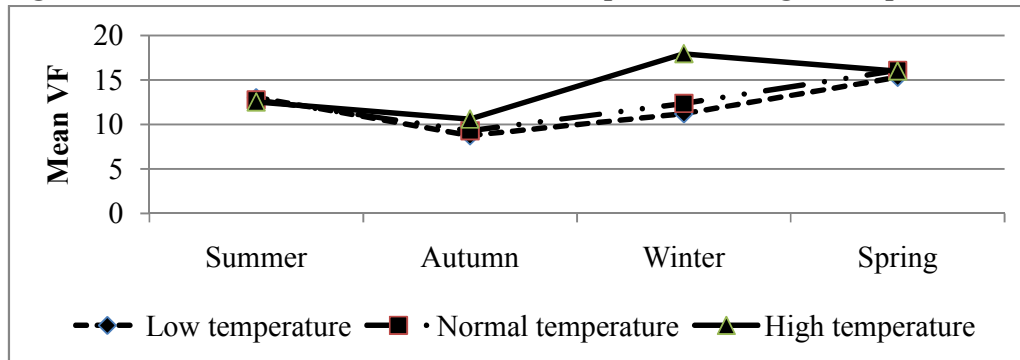


Figure B. 62: The mean VF of GU vs. season and temperature for phase II

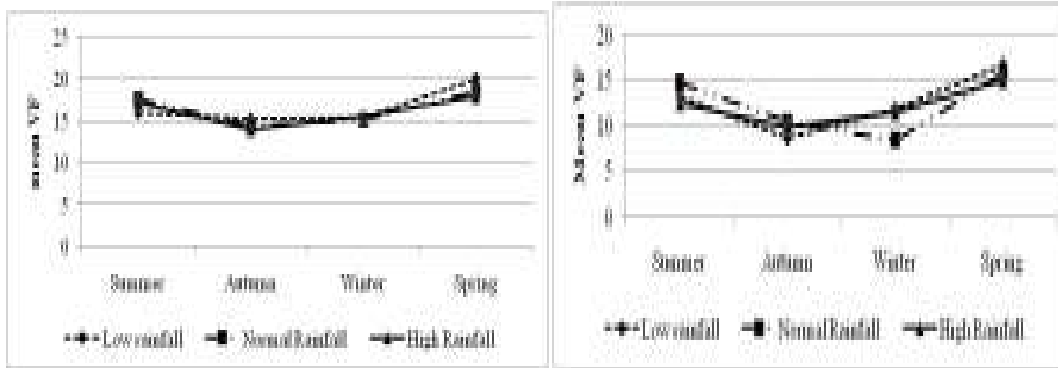


Figure B. 63: The mean VF vs. season and rainfall for phase II

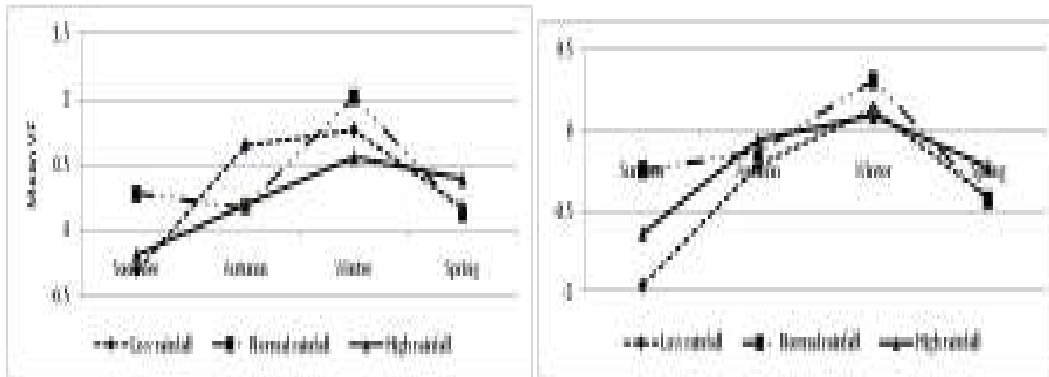


Figure B. 64: The mean VF vs. season and temperature for phase III

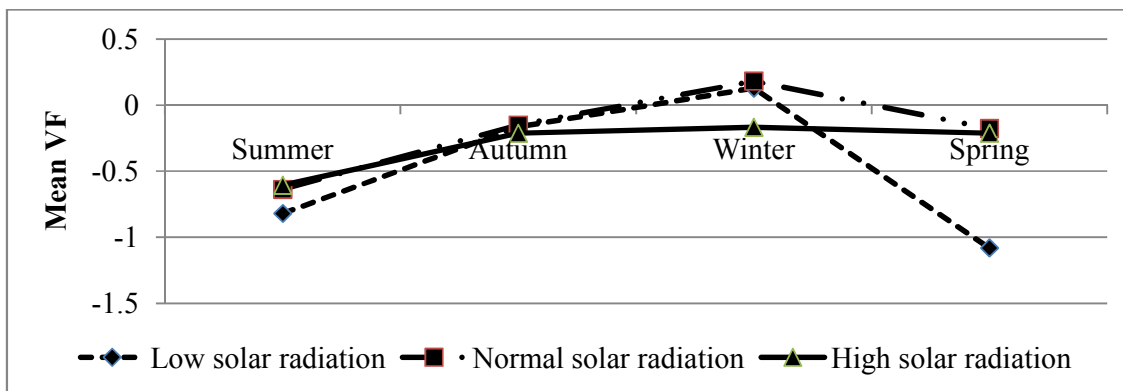


Figure B. 65: The mean VF of GU vs. season and solar radiation for phase III

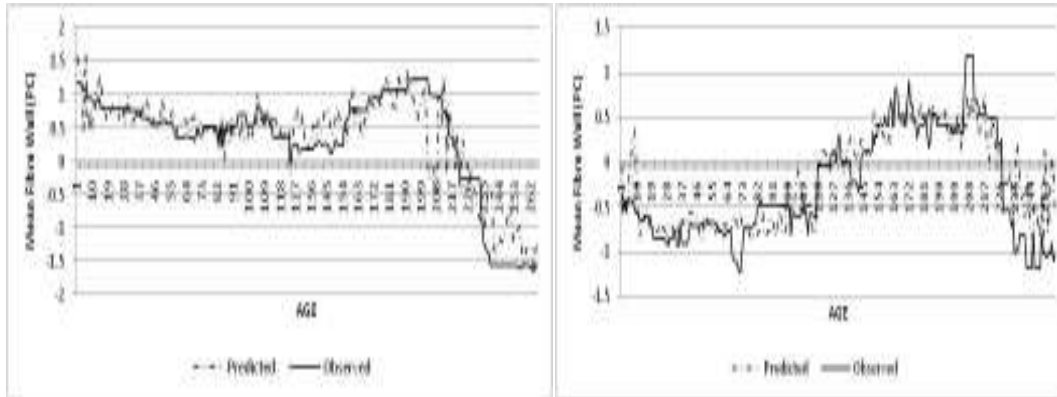


Figure B. 66: Observed vs. fitted values for FW Phase II

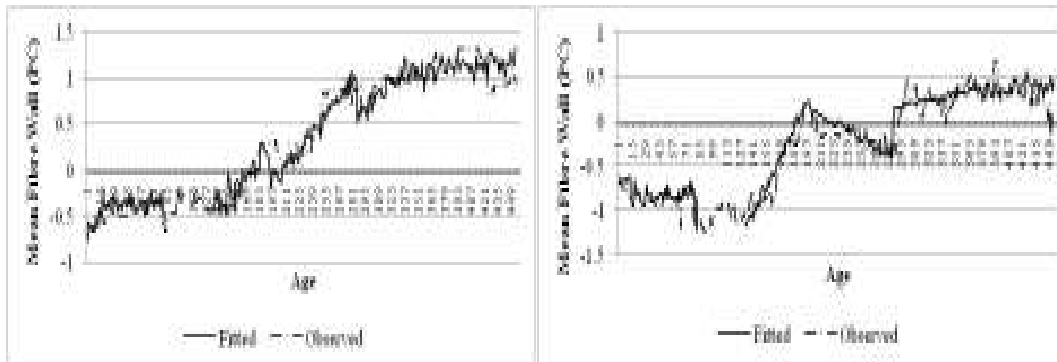


Figure B. 67: Observed vs. fitted values for FW Phase III

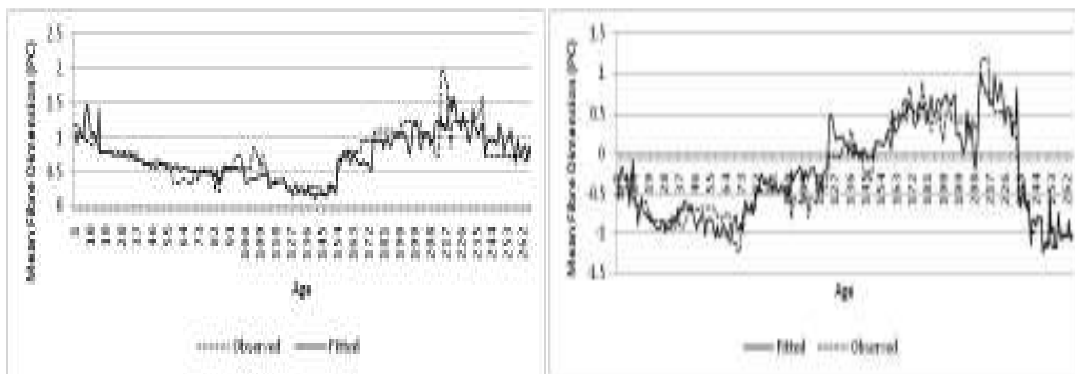


Figure B. 68: Observed vs. fitted values for FD Phase II

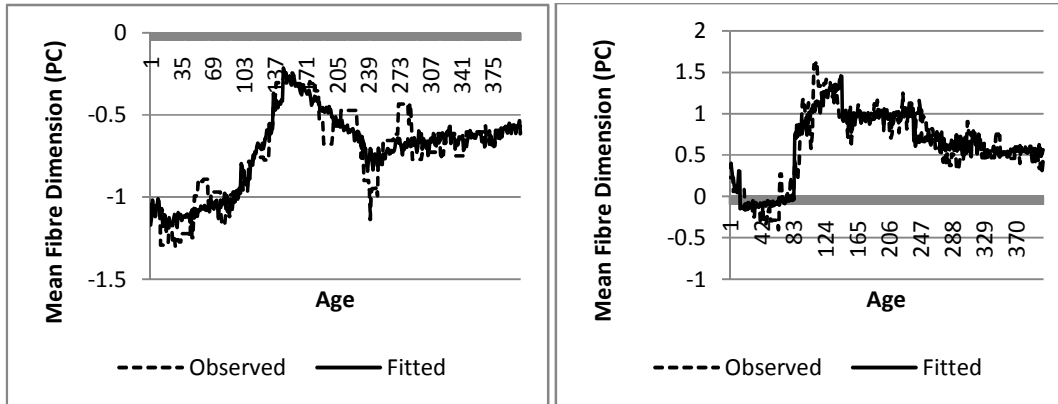


Figure B. 69: Observed vs. fitted values for FD Phase III

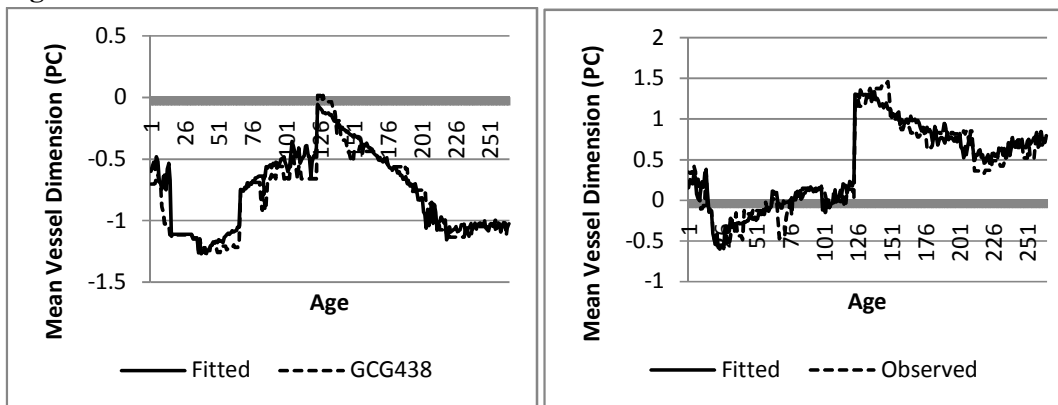


Figure B. 70: Observed vs. fitted values for VD Phase II

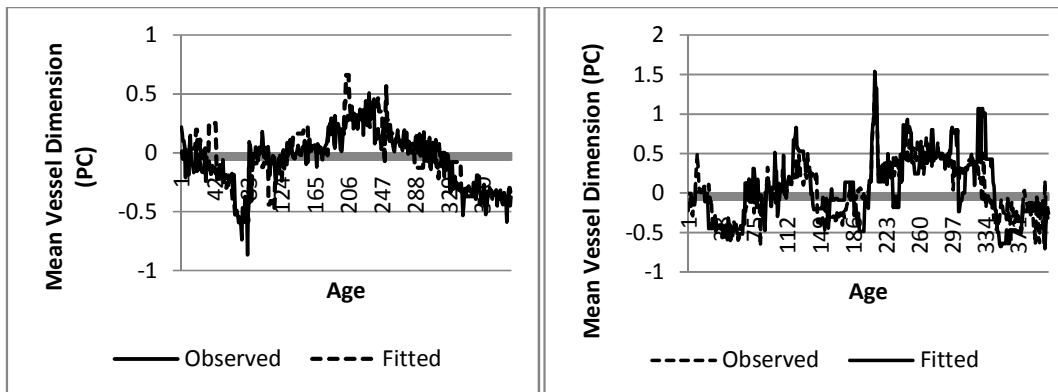


Figure B. 71: Observed vs. fitted values for VD Phase III

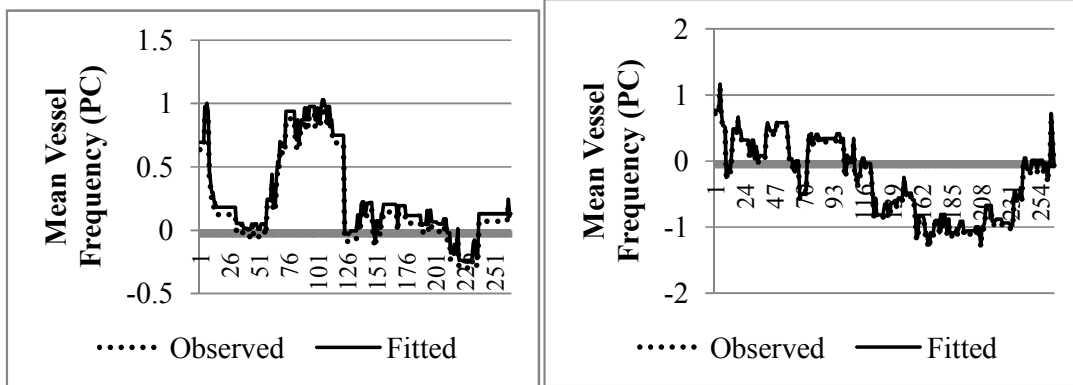


Figure B. 72: Observed vs. fitted values for VF Phase II

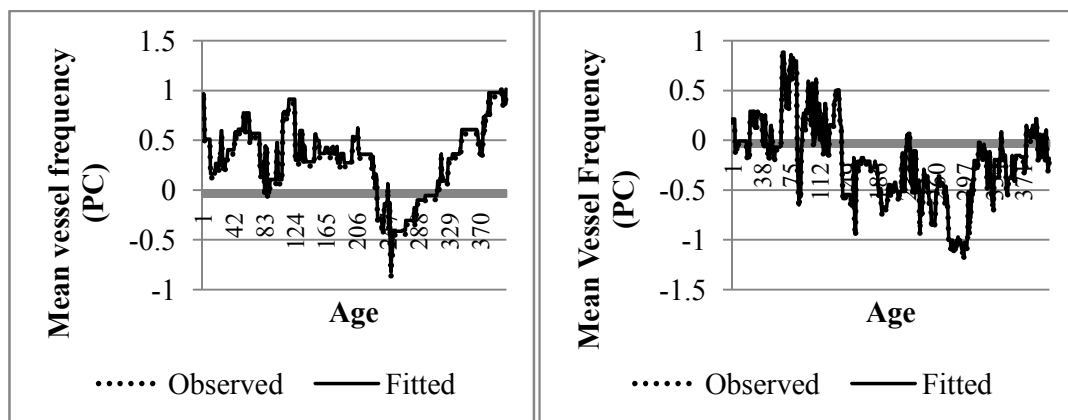


Figure B. 73: Observed vs. fitted values for VF Phase III