

# **Evaluating parameterizations of aerodynamic resistance to heat transfer in crop canopies towards better detection of drought stress;**

**A case study using micro-meteorological measurements at plot-level (Barrax, Spain) and meteorological measurements at regional-level (Mashonaland West, Zimbabwe) using a crop growth simulation model.**

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by

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Thesis submitted to the Faculty Geo-information Science and Earth Observation in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation for Environmental Modelling and Management

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# Abstract

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Parameterizations of aerodynamic resistance to heat and water transfer have a significant impact on the accuracy of models of land atmosphere interactions and estimated surface fluxes for effective account of evapotranspiration and hence accuracy in drought monitoring. The present study aims to evaluate seven popularly used parameterizations of aerodynamic resistance to heat transfer ( $r_{ah}$ ) to see the effect, if any, of parameterization choice on detecting crop stress.

Micro-meteorological measurements at plot-level taken over a ten-day period on the heterogeneous surface of a multi – crop Agricultural test site in Barrax, Spain were used as input into the energy balance equation and used to test the performance of the different  $r_{ah}$  parameterizations. In an extension to a larger spatial and temporal extent, meteorological measurements at regional-level (Mashonaland West, Zimbabwe) were used within a crop growth simulation model to test the same  $r_{ah}$  parameterizations. In both cases, special focus was put into the definition and estimation of roughness length,  $z_0$ , and displacement height,  $d$ , which were “enhanced” from the general function of canopy height estimates to leaf area index (LAI) incorporating formulations towards a better representation of foliage density properties.

Hypothesis tests for homogeneity between  $r_{ah}$  parameterizations revealed a systematic difference in the estimation of aerodynamic resistance to heat transfer and sensible heat flux between parameterizations through a non –zero intercept and slope not equal to 1. Absolute performance tests of observed against simulated values yielded values of at least  $r^2 > 0.6$  for most  $r_{ah}$  for both the Barrax and Mashonaland West studies. When RMSE and bias statistics were used in tests for the effect of adding LAI, a systematic improvement in model performance was revealed with a stronger effect in the Barrax study.

The combined study reveals the effect of  $r_{ah}$  parameterization choice on accuracy of evapotranspiration estimates and more importantly, the improvement of roughness length, and hence  $r_{ah}$ , parameterizations through the addition of LAI.

Keywords: aerodynamic resistance, roughness length, leaf area index, micro-meteorological , crop stress

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# Table of contents

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|  |    |
|--|----|
| 1. Introduction.....   | 9  |
| 1.1. Drought monitoring.....   | 11 |
| 1.1.1. Drought and Crop stress.....  | 12 |
| 1.2. Problem statement.....  | 13 |
| 2. Objectives.....   | 17 |
| 2.1. Specific Objectives.....  | 17 |
| 2.2. Hypothesis.....   | 17 |
| 2.3. Assumptions.....  | 17 |
| 3. Research Approach.....  | 19 |
| 3.1. Research Questions.....   | 19 |
| 3.2. Phase I: Evaluating Different Parameterizations of aerodynamic<br>resistance..... | 19 |
| 3.2.1. Materials and Methods.....  | 21 |
| 3.2.2. Results and Discussion.....   | 29 |
| 3.2.1. Discussion.....   | 33 |
| 3.2.2. Preliminary conclusion.....   | 34 |
| 3.3. Phase II: Effect of Parameterization choice on Model Performance.....             | 35 |
| 3.3.1. Study Area.....   | 35 |
| 3.3.2. Methods.....  | 36 |
| 3.3.3. Data Description.....   | 42 |
| 3.3.4. Results.....  | 45 |
| 3.3.5. Discussion and preliminary conclusion.....                                      | 49 |
| 4. Discussion and Conclusions.....   | 52 |
| 5. Recommendations.....  | 53 |
| Appendices.....  | 58 |

## List of figures

---

|  |    |
|--|----|
| Figure 1: Sequence of drought occurrence and impacts (NDMC, 2007) .....  | 11 |
| Figure 2: Location of the Barrax Agricultural Experiment site .....  | 25 |
| Figure 3: Crop distribution and Instrument stations in the Barrax Site .....   | 26 |
| Figure 4: Steps for evaluating different $r_{ah}$ parameterizations .....  | 28 |
| Figure 5: Graphs for assessing homogeneity between $r_{ah}$ parameterisations  | 30 |
| Figure 6: Graphs for assessing homogeneity between Jacobs and Jackson $r_{ah}$ parameterisations .....                                   | 30 |
| Figure 7: Plots of measured $r_{ah}$ against calculated $r_{ah}$ .....   | 31 |
| Figure 8: Comparison of measured H against H calculated .....  | 31 |
| Figure 9: Methodology for comparison of $r_{ah}$ using PSn Model .....   | 37 |
| Figure 10: An overview of Algorithms from the internal processes of PSn.   | 39 |
| Figure 11: Dimensions of simulation scenarios for one year .....   | 44 |
| Figure 12: Comparisons of (1995 – 1996) PSn estimated yield by the $r_{ah}$ forms Jackson, Jacobs and Thom with the observed yield. .... | 45 |
| Figure 13: Comparisons of (1996 – 1997) PSn estimated yield by $r_{ah}$ forms Jackson, Jacobs and Thom with the observed yield. ....     | 45 |
| Figure 14: Box and whisker plot test variance per model .....  | 46 |
| Figure 15: Simulated Yield at District level .....   | 46 |
| Figure 16: Box plot showing variance in simulation results and a trend of observed yield.....  | 47 |
| Figure 17: Model performance within an error band .....  | 47 |
| Figure 18: Effect of LAI on Simulated productivity for period (1995-1999) .....  | 48 |
| Figure 19: Graphs of PSn output with cf(water).....  | 48 |
| Figure 20: Multiple Sources of Observed Yield Data.....  | 51 |

## List of tables

---

|   |    |
|---|----|
| Table 1: List of various parameterizations of $r_{ah}$ being evaluated .....                  | 22 |
| Table 2 : Data Measurements and Instrumentation.....  | 26 |
| Table 3: Surface parameters for the different land cover types .....                          | 28 |
| Table 4: Statistics of Performance of the different rah in estimating Sensible heat flux..... | 32 |

## List of Appendices

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|   |    |
|---|----|
| Appendices I: Comparison of Thom $r_{ah}$ vs Jackson $r_{ah}$ and Jacobs $r_{ah}$ ..... | 58 |
| Appendices II: Performance of various $r_{ah}$ for H estimation .....                   | 59 |
| Appendices III: Wilcoxon Sign Rank Test result .....                                    | 60 |
| Appendices IV: PSn internal processes.....  | 61 |
| Appendices VI: Meteorological Stations.....   | 62 |

# List of Acronyms

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|          |  |
|----------|--|
| AGRITEX  | Agricultural Technical and Extension services        |
| ART      | Agricultural Research Trust                          |
| AVHRR    | Advanced Very High Resolution Radiometer             |
| CANRAD   | Daily global radiation                               |
| CGSMs    | Crop Growth Simulation Model                         |
| CMI      | Crop Moisture Index                                  |
| CSO      | Central Statistical Office                           |
| DL       | Day Length   |
| DMS      | Department of Meteorological Services                |
| DOY      | Day of Year  |
| EU       | European Union                                       |
| FAO      | Food Aid Organization                                |
| FAOSTATS | FAO Statistical Database                             |
| FOODSEC  | Food Security  |
| GAA      | Gross Assimilates Availability                       |
| GAC      | Global Area Coverage                                 |
| LAI      | Leaf Area Index                                      |
| LAS      | Large Aperture Scintillometer                        |
| LST      | Land Surface Temperature                             |
| MARS     | Monitoring Agricultural Resources                    |
| NDVI     | Normalized Difference Vegetation Index               |
| PARCAN   | Photosynthetically Active Radiation at Top of Canopy |
| PDSI     | Palmer Drought Severity Index                        |
| PI       | Performance Indicator                                |
| PSn      | Production Situation analysis model                  |
| RHA      | Relative Air Humidity                                |
| RMSE     | Root Mean Square Error                               |
| SLA      | Specific Leaf Area                                   |
| SPD      | Daily windspeed                                      |
| SPI      | Standardized Precipitation Index                     |
| SVAT     | Soil Vegetation Atmosphere Transfer                  |
| TCI      | Temperature Condition Index                          |
| TLDM     | Total Living Dry Mass                                |
| VTCI     | Vegetation Temperature Condition Index               |



# 1. Introduction

Food security is a key issue in the Millennium Development Goals. One element which can be linked to a nation's food security status is the agricultural productivity of the area. Many international bodies are increasing their focus on research towards combating food insecurity through improved Agricultural methods and policies. The Joint Research Centre of the European Union, EU-JRC's Monitoring Agricultural ResourceS (MARS) is one of the championing bodies in this through its various arms such as MARS STARS and MARS FOODSEC. The Food Aid Organization (FAO) which focuses on ensuring good nutrition and improved agriculture, forestry and fisheries practices within developing countries and countries in transition also has many research programs going on (Breda, 2003; FAO, 2002).

Despite all these advances, optimum agricultural productivity is still lowered by crops' susceptibility to natural disasters such as fire, pests and disease attacks, droughts and flooding. Drought is a major threat to agricultural production. Impacts of drought range from direct impacts such water shortages and reduced crop yield to indirect ones like economic loss. For example, the 2005 drought in Portugal resulted in agricultural loss of more than 280 million Euros (Gouveia et al., 2009). Spain is also prone to periodic droughts and some major agricultural losses have been recorded in the 1990s (Roberts, 2002) and even more recently in 2005 and 2008. The major drought of the mid 1990s affected over 6 million people and four major droughts experienced between 1900 and 2009 have recorded damages of over USD10 million (EM-DAT, 2009).

The African continent is another area where drought has devastating impacts on the livelihood of many people. The country of Zimbabwe has experienced some highly costly droughts with recorded ones in the early 1980s (1981/82 to 1983/84). The worst recorded drought in Zimbabwean history was the 1991/92 drought which resulted in nearly total crop failure, resulting in the need for imports of around two million tonnes of maize for feeding the nation (Manyowa and Munyanyi, 1995).

This devastating and rather complex phenomenon has more than 150 definitions in literature (Boken et al., 2005). The American Meteorological Society defines drought in terms of three main characteristics namely intensity, duration and spatial coverage (American Meteorological Society, 1997). The intensity of drought is usually measured by the degree of deviation from the normal, of a chosen climatic index for instance daily or weekly precipitation (Liu and Juárez, 2001). However Byun and Wilhite (1999) also highlight the importance of duration of this period of water deficiency stating that the concept of consecutive occurrences of water deficiency should be considered when calculating drought indices. It may also be important to note that duration of drought is not just a long period of dryness but that the water deficiency should be intense. This intensity is generally an assessment of the temporal cumulative impact of heat and water stress on the overall vegetation condition (Gouveia et al., 2009). Very short duration, yet intense droughts can cause tremendous yield reduction (Wu and Wilhite, 2004). Another critical factor which determines the severity of drought damage is the timing or onset of drought. For instance, even if the intensity of drought is mild, if it sets in the early stages of crop development, ultimate yield may be negatively affected since the physiological development of leaves and other organs which aid in solar radiation assimilation and photosynthetic processes is hampered. On the other hand, an intense drought experienced at the end of the growing season may not have such a huge impact on the crop yield save for stimulating early flowering or ripening. It is therefore essential to have mechanisms in place for monitoring drought and more importantly, to be able to estimate or quantify crop yield before harvest time.

## 1.1. Drought monitoring

This sequence of drought occurrence and impacts in figure 1 summarizes the general problem of drought from its causes, how it manifests and its progression over time leading to environmental, economical and social impacts and the associated previously discussed losses.

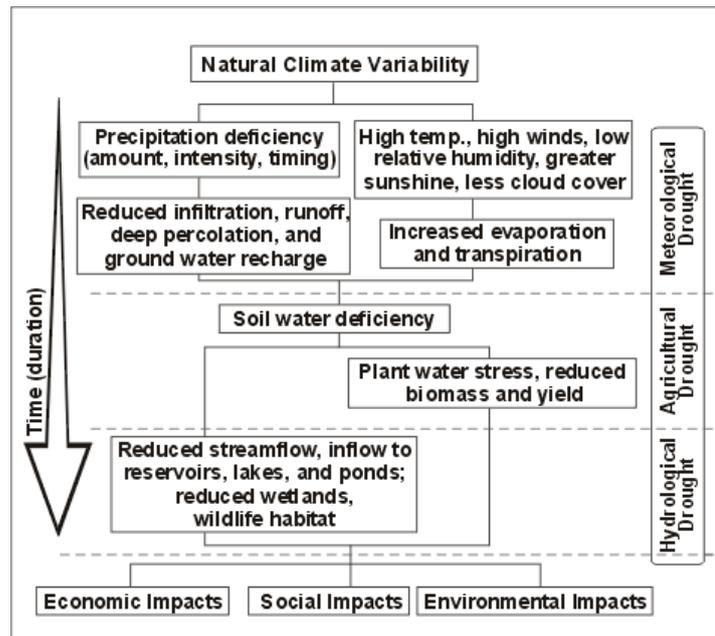


Figure 1: Sequence of drought occurrence and impacts (NDMC, 2007)

The most commonly experienced droughts are meteorological, which usually lead to agricultural drought as crops suffer stress due to insufficiency of plant-available water (Byun and Wilhite, 1999). It is thus clear that successful mitigation of drought's adverse impacts is possible through drought monitoring mechanisms. Being such an aged phenomenon, many studies aimed at drought monitoring have been undertaken over the years resulting in numerous drought monitoring approaches. Examples include the development of traditional drought indices such as the Palmer Drought Severity Index (PDSI), Crop Moisture Index (CMI) (Palmer, 1968) and Standardized Precipitation Index (SPI) (McKee, 1993). These mostly rely on variations in precipitation and soil moisture to quantify drought effect. The major drawback in such methods is the low spatial coverage since most measurements are collected from weather stations and can only be accurately extrapolated to a limited

extent. Such rain gauge based derivations are also subject to errors introduced by factors such as rain gauge distribution as determined by ease of access, or errors in measurement and recording, as well as time delays between data capture and its availability for use ( Rugege , 2002).

### **1.1.1. Drought and Crop stress**

Drought effect is usually first evident in form of vegetation/crop stress (Wan *et al.*, 2004). Crop stress reduces the productivity of the canopy below its optimal value. The effect can be either through a change on the fraction of light intercepted and absorbed by the canopy or a reduction in efficiency with which that light is used for photosynthesis, which needs adequate soil moisture. Monitoring the biomass and moisture availability can therefore provide sufficient platform for assessing crop efficiency or stress (Bikash 2006).

Based on that understanding, some semi-empirical drought monitoring methods are also in employ such as the use of vegetation indices. Indices such as Normalized Difference Vegetation Index (NDVI) have been used successfully for monitoring the growth conditions of vegetation ranging from excellent to stressed states (Kogan, 1998). Strong correlation between NDVI and monthly rainfall as well as daily rainfall was highlighted in studies by Di *et al.*,(1994). However, identification of the drought onset is not so easy due to the fact that as long as plants are green, NDVI will be high. Studies incorporating temperature effect factor have been made using the Temperature Condition Index (TCI) and applications proven successful (Dabrowska-Zielinska *et al.*, 2002; Singh *et al.*, 2003). Wan *et al.*, (2004) have found the Vegetation Temperature Condition Index (VTCI) an efficient means of assessing duration and severity of drought.

Another means for picking up water stress is the use of canopy temperatures. The general understanding is that whilst incident radiation is responsible for heating up the canopy, evapotranspiration has a cooling effect (Kalluri and Townshed, 1998). Therefore, when there is water deficit, there is less evapotranspiration resulting in increased canopy temperatures. In other words, it is possible to estimate the difference between potential evapotranspiration and actual evapotranspiration using canopy temperatures. Whilst the argument may arise that overall vegetation condition can be affected by other non-moisture issues, a regression model by Ji and Peters (2004) determined that the water balance, through processes of precipitation and evapotranspiration, “is the most important factor controlling vegetation condition at an annual timescale”. Exceptions may be in cases where other obvious factors are at play such as in extremely poor soils lacking basic nutrient

requirements. Successful mitigation against drought effects could thus be achieved through early detection of signs of crop stress and one area to capitalise on is better understanding of the evapotranspiration process.

The Penman-Monteith equation is widely viewed as the best method to estimate evapotranspiration because of its use of a combination model to explain the atmospheric and surface control on evapotranspiration. Many studies have based evapotranspiration estimation on this equation, or modifications hereof (Bailey and Davies, 1981; Driessen and Konijn, 1992.; Jacobs et al., 2002). However it requires, amongst other difficult to obtain inputs, canopy resistance, which makes the method less straightforward to implement (Li et al., 2009). This is because it cannot be measured directly, unlike the other parameters in the equation. Another parameter on which the Penman Monteith equation relies is aerodynamic resistance. In the same way that surface resistance is viewed as a bulk descriptor for the crop, aerodynamic resistance is the bulk descriptor of the role of the atmospheric turbulence in the evaporation process. In theory, aerodynamic resistance is dependent upon the wind speed, surface roughness, and atmospheric stability, all of which contribute to the level of turbulent activity (Oke, 1987).

While wind speed can be easily measured, surface roughness is difficult to quantify and often is assumed to be a function of canopy height only (Jacobs et al., 2002; McKee, 1993). This ignores effects of foliage density, possibly through leaf area index (LAI), on the surface roughness. Yet, maximum transpiration is also dependent on development on the leaf surface, which can be measured through LAI (Dorenboos and Kassam, 1979). In addition, roughness length for heat transfer can neither be taken as a constant nor be neglected because of its crucial role. The correct specification of these resistances allows for better evaluation of evaporation.

## **1.2. Problem statement**

For effective account of evapotranspiration and hence accuracy in drought monitoring, it may be necessary to ensure the integrity of models used for explaining the phenomenon. Models are a combination of several parameterizations to simulate a phenomenon. Accuracy of models may be affected by explanatory variable choice and parameterizations. Parameterizations are essentially relationships or equations designed to relate the explanatory variables towards description of physical mechanisms (Brutsaert 2005). When understanding evapotranspiration through the energy balance equation, the following formula may be used

$$LE = \frac{\Delta(R_n - G) + \rho C_p (e_s [T(z)] - e_a) / r_{ah}}{\Delta + \gamma \left( 1 + \frac{r_s}{r_{ah}} \right)} \quad (1)$$

Where

|          |  |
|----------|--|
| LE       | is the modelled latent heat of vaporization ( $\text{Jm}^{-2}\text{s}^{-1}$ ), |
| $\Delta$ | is the slope of the saturation vapour pressure and temperature,                |
| $\gamma$ | is the psychrometric constant ( $\text{kPa } ^\circ\text{C}^{-1}$ ),           |
| Rn       | is the net radiation ( $\text{Jm}^{-2}\text{s}^{-1}$ ),                        |
| G        | is the ground heat flux ( $\text{Jm}^{-2}\text{s}^{-1}$ ),                     |
| P        | is the mean air density at constant pressure ( $\text{kgm}^{-3}$ ),            |
| Cp       | is the specific heat of air ( $\text{J kg}^{-1} ^\circ\text{C}^{-1}$ ),        |
| Es       | is the vapour pressure deficit of the air (kPa),                               |
| Ea       | is the saturation vapour pressure of the air,                                  |
| T(z)     | is the air temperature at position z ,   |
| rs       | is the bulk surface resistance and   |
| $r_{ah}$ | is the aerodynamic resistance  |

Most of these parameters can be directly measured or derived from remote sensing products or are simply constants. However, one remaining and probably most difficult to explain part is thus aerodynamic resistance,  $r_{ah}$ , which if poorly represented will affect the overall result. The aerodynamic resistance itself is explained by a number of parameters which only leaves room for possible further source of error.

This concern about parameterization of aerodynamic resistance is not a new thing. Many authors have proposed different parameterizations to estimate aerodynamic resistances to heat transfer such as Monteith (1973), Verma et al., (1976), and more recently, Byun (1990), and Yang et al. (2001). Some popular examples are equations 2 and 3 from Jackson(1988) and Jacobs (2002) respectively.

$$r_a = \frac{\left\{ \ln \left( \frac{z-d}{z_o} \right) / k \right\}^2}{U} \quad (2)$$

$$\text{Or } r_a = \frac{\ln\left(\frac{z-d}{z_o}\right) \ln\left(\frac{z_{veg}-d}{z_{ov}}\right)}{k^2 U} \quad (3)$$

Where

$Z$  is the measurement height,

$z_{veg}$  is the vegetation height,

$d$  is the displacement height estimated to be  $0.7 z_{veg}$ ,

$z_0$  is the roughness length approximated as  $0.1 z_{veg}$ ,

$z_{0v}$  is roughness height for water vapour approximated as  $0.1 z_0$  and

$k = 0.42$ ; (Von Karman constant)

An interesting comparative study by Kalma (1989) compared the parameterizations proposed by Choudhury et al., (1986), Itier (1980), Monteith (1973), Hatfield et al. (1983.), and Mahrt and Ek (1984) and reported close relations between Choudhury (1986) and Itier (1980) against significant deviations from the measurements when using the parameterizations proposed by Monteith(1973), Hatfield et al. (1983.), and Mahrt and Ek (1984).

A major common source of variation in parameterization has been found to be in the definition of surface roughness which is a parameter in defining aerodynamic resistance to heat transport. Surface roughness length,  $z_0$ , is often written as a function of canopy height only (Jackson et al., 1988; Jacobs et al., 2002). Stanhill (1969), Szeicz et al.,(1969) and Tanner and Pelton (1960) all support this correlation of  $z_0$  and  $d$  with canopy height except for Bailey and Davies (1981) who argue that foliage density must also be considered. Some studies have shown relationships between  $z_0$  and canopy spread and leaf properties (van der Kwast et al., 2009). With the advent of vegetation growth simulation models, crop height can be estimated from the relative development stage, and displacement height and roughness height rewritten as a function of crop height and LAI. Considering the time and costs of ground measurements as well as their spatial restrictions, some recent studies have utilized remote sensing and determined  $z_0$  and canopy height from satellite based NDVI (van der Kwast et al., 2009).

This availability of many different options for defining surface roughness and hence an equally multiple possible parameterizations of  $r_{ah}$ , triggers the interest to evaluate the significance of the effect, if any, of employing different parameterization. A

formidable challenge definitely lies in capturing effects of canopy structure on resistance to heat transport, transpiration, and water usage within the defining parameterisations.

## 2. Objectives

The main objective of this research is therefore to assess whether, and/or how, the incorporation of foliage properties like canopy density and relative developmental stage, in parameterisations of aerodynamic resistance affect the approximation of drought stress.

### 2.1. Specific Objectives

1. To evaluate the performance of different parameterizations of  $r_{ah}$  against measured  $r_{ah}$ .
2. To “enhance” the aerodynamic resistance equation by incorporating foliage density properties according to LAI values.
3. To assess (a) homogeneity in results and (b) absolute performance in drought stress estimation in food/fiber crops by the PSn model when different parameterizations of aerodynamic resistance to heat transport in the canopy are used.
4. To evaluate the performance of different parameterizations of  $r_{ah}$  against measured  $r_{ah}$  under varying atmospheric stability levels.

### 2.2. Hypothesis

This study was guided by general hypotheses of 1) testing for homogeneity i.e whether there is a significant difference in estimations of  $r_{ah}$  by different parameterizations and, 2) determining the absolute performance rankings for a group of selected parameterisations before and after modifications are made to them. More specific details of the hypothesis are found within the introduction section of each phase of analysis.

### 2.3. Assumptions

Models are merely an abstraction of reality and the factors making the difference are numerous. For a feasible study, ‘boundaries’ have to be set. The following assumptions have been made with respect to the first and second part of the study respectively.

1. An assumption is made that vegetation is the primarily source of latent and sensible heat meaning that contribution from lower surface (i.e., soil) to H and 2 E values measured above the canopy is not significant. The understanding is that most of the incoming radiation is reflected, absorbed or emitted by the vegetation should there be a full canopy cover.
2. The measured values of H from the experiment site are accurate.
3. Due to the irregularity in shape and size of Zimbabwe's communal farms, and the common practice of inter-cropping, the actual area under maize is unknown. It is therefore assumed that the estimate used does not introduce cause inaccuracies in the yield estimates.
4. Maize yield statistics are assumed accurate. The reliability of the official maize yield statistics is an important factor. The accuracy of official yields is unknown. This makes it difficult to separate the effects of simulation results from errors in the official statistics. Therefore, historical maize yield statistics are assumed accurate.
5. Weather data is an essential part of the model used. Since the data used in this case is from selected meteorological stations it is assumed that the distribution resulting from interpolation is representative of the whole study area

## 3. Research Approach

This chapter outlines the approach taken to address the issues raised in the problem statement, the materials used and methods implemented towards achievement of the set objectives of the study.

### 3.1. Research Questions

For an objective and focused study, some research questions were formulated to guide the research. These relate to the main aim of the study and correspond with the previously discussed objectives. The resultant approach opted for was a “two –phase” one where each phase involved independent data acquisition, processing and results, yet both led to a better understanding of the questions raised. There were also differences between the two phases in terms of spatial extent as well as temporally.

The research questions to be answered by this study were

1. Do certain tested different parameterizations of aerodynamic resistance give significantly different results when compared to either a ‘standard’ parameterization or to measured values?
2. Can incorporation of LAI in the aerodynamic resistance parameterization significantly improve the performance of a crop growth model in estimating crop development and hence crop water stress?
3. To what extent is the absence or presence of atmospheric stability correction factors in  $r_{ah}$  parameterizations a major effect on overall sensible heat flux estimation?

### 3.2. Phase 1: Evaluating Different Parameterizations of aerodynamic resistance

As already asserted, many parameterizations of aerodynamic resistance to heat transfer do exist. These can be categorised into empirical, semi- empirical and non –

empirical (Brutsaert 1996). Though describing the same phenomenon, the variations in the formulations tend to cause the attainment of different results. In order to assess and quantify the magnitude of variation between estimates of  $r_{ah}$  by some of these formulae, a study for the following proposed hypothesis was carried out.

1) Tests for Homogeneity

**Null hypothesis (Ho):** There is no systematic difference in estimation of sensible heat flux, and hence evapotranspiration, between different parameterizations of aerodynamic resistance to heat transport in the canopy and the measured values. This can be expressed as:

Ho: intercept  $\alpha_i = 0$  and Ho: slope  $\beta_i = 1$ , where  $i = i, j$  or  $k$  for all three indicators

**Alternative hypothesis (Ha):** There is a systematic difference in estimation of sensible heat flux, and hence evapotranspiration, between different parameterizations of aerodynamic resistance to heat transport in the canopy.

Ha: intercept  $\alpha_i \neq 0$  and Ha: slope  $\beta_i \neq 1$

2) Tests for absolute performance

**Null hypothesis (Ho):** There is no significant difference in estimation of sensible heat flux, and hence evapotranspiration, between different parameterizations of aerodynamic resistance to heat transport in the canopy and the measured values when foliage density properties are factored in.

This can be expressed as:

$$\text{Ho: } \text{PI}_i = \text{PI}_j = \text{PI}_n$$

where  $\text{PI}$  = Performance Indicator such as RMSE or bias and  $i, j$  or  $n$  are parameterizations of  $r_{ah}$

**Alternative hypothesis (Ha):** There is a significant difference in estimation of sensible heat flux, and hence evapotranspiration, between different parameterizations of aerodynamic resistance to heat transport in the canopy.

$$\text{Ha: } \text{PI}_i \neq \text{PI}_j \neq \text{PI}_n$$

where  $\text{PI}$  = is as in Null hypothesis.

### 3.2.1. Materials and Methods

A group of parameterizations of  $r_{ah}$  was selected for the study. Selection was guided by the attempt covering wide schools of thoughts behind these parameterizations, scientific progress over the years, issues of area specificity, available literature variation in data requirements. Table 1 summarises the parameterizations considered in this study.

#### 3.2.1.1. The concept

From the Energy balance equation, aerodynamic resistance to heat transfer can be determined by:

$$r_{ah} = \frac{\rho C_p (T_s - T_a)}{H} \quad (4)$$

where

- H is the sensible heat flux ( $\text{Wm}^{-2}$ ),
- P is the mean air density at constant pressure ( $\text{kgm}^{-3}$ ),
- C<sub>p</sub> is the specific heat of air ( $\text{J kg}^{-1} \text{°K}^{-1}$ ),
- T is the air temperature ( $\text{°K}$ ) and
- T<sub>s</sub> is the surface temperature ( $\text{°K}$ )

The values of aerodynamic resistance to heat transfer  $r_{ah}$  obtained from equation 3 are referred to as “measured aerodynamic resistance”. This is because they were calculated from “measured” sensible heat flux, air temperature, and surface temperature. The “measured aerodynamic resistance” were used to evaluate the other various proposed parameterizations of  $r_{ah}$ . The parameterizations were divided into two sets, one where influence of atmospheric stability on the flux-gradient relationship in the surface layer was accounted for by inclusion of the Bulk Richardson number  $Ri_B$  (Monteith, 1973), and the first set without  $Ri_B$ .

Estimates of H obtained with the some of the different parameterizations of  $r_{ah}$  described in Tables 1 were also evaluated against the H values measured by an eddy covariance system as a test for absolute performance. The final test is on the effect of LAI in the performance of the different parameterization of  $r_{ah}$ .

Table 1: List of various parameterizations of  $r_{ah}$  being evaluated

| <b>SET I</b>  |  |
|---|--|
| $r_{ah} = 4.72\{\ln[(z-d)/z0]\}^2 / (1 + 0.$  | <b>(Thom and Oliver 1977)</b><br><br>where $z0 = 0.13 * \text{canopy height}$<br>$d = 0.63 * \text{canopy height}$   |
| $r_{ah} = \{\ln[(z-d)/z0]/k\}^2/U$  | <b>(Jackson 1988)</b><br>where $z = \text{measurement height}$   |
| $r_{ah} = \ln[(z-d)/z0]\ln[(z-d)/z0v] / k^2 * U$  | <b>(Jacobs 2002)</b><br>where $z0 = 0.1 * \text{canopy height}$<br>$d = 0.7 * \text{canopy height}$  |
| <b>SET II</b>   |  |
| $r_{ah} = (1/(k^2 * u)) * \{\ln[(z-d)/zom]\} * \{\ln[(z-d)/zoh]\} * (1 - \beta * Ri_b)^{-0.75}$                     | <b>(Choudhury et al. 1986)</b><br><br>where $Ri_b = (g/Ta) * \{(Ta - Ts) * (Z-d)/u^2\}$<br>$\beta = 5$   |
| $r_{ah} = (1/(k^2 * u)) * \{\ln[(z-d)/zom]\}^2 * (1 - 16 Ri_b)^{-0.25}$   | <b>(Verma et al. 1976)</b>   |
| $r_{ah} = (1/(k^2 * u)) * \{\ln[(z-d)/zom]\}^2 * \{(1 + c * (- Ri_b)^{0.5}) / (1 + c * (- Ri_b)^{0.5}) - 15 Ri_b\}$ | <b>(Mahrt and Ek 1984)</b><br><br>where $c = [ 75 * k^2 * \{(z+zom)/zom\}^{0.5} / \{\ln[(z+zom)/zom]\}^2$  |
| $r_{ah} = (1/(k^2 * u)) * \{\ln[(z-d)/zom]\} * \{\ln[(z-d)/zoh]\} * [ a + b(- Ri_b)^c ]^{-1}$                       | <b>(Viney 1991)</b><br><br>where $a = 1.0591 - 0.0552 \ln\{ 1.72 + [4.03 - \ln \{(z-d)/zom\}]^2\}$<br>$b = 1.9117 - 0.2237 \ln\{ 1.86 + [2.12 - \ln \{(z-d)/zom\}]^2\}$<br>$c = 0.8473 - 0.1243 \ln\{ 3.49 + [2.79 - \ln \{(z-d)/zom\}]^2\}$ |

## Variations in Aerodynamic resistance to heat transfer parameterizations

The parameterization of  $r_{ah}$  by Thom in 1975 is one of the earliest documented formulae. As with all other scientific disciplines, continuous research has seen the modification and in some cases improvement of the formulae as new understanding is acquired. Evolution of the parameterizations has been due to numerous factors both mathematical and improved understanding of biophysical processes in vegetation. More refined platforms for measuring and explaining interactions between soil, vegetation and the atmosphere such as the increasingly popular SVAT

models have contributed to better parameterization of  $r_{ah}$ . Another cause of variation is the issue of datasets and methods in which the formula are developed. An experimental study will produce an empirical, semi empirical formulae while other forms may be non empirical.

Environmental and atmospheric conditions also affect the form of parameterization. Much of the variations are due to differences in derivation and validity of the stability correction functions, or to the degrees of simplification in formulation. The stability correction function for stable conditions, i.e. when there is negligible difference between surface and air temperature, is linear, thus, relatively easy to solve. However, for non stable conditions, it is non linear and hence requires more complex solutions (Yang et al., 2001). Iterations have been the common solution for this but advancements have been made over the years to try and avoid the iterative process.

### **‘Enhancing’ the Existing Formulae**

As previously highlighted in the problem statement, most of the parameterizations stated for evaluation in this study have focussed on crop or canopy height. However, there are other crop properties which may have an effect on the approximation  $r_{ah}$  and hence evapotranspiration and ultimately crop water stress. For example, foliage density could be an influencing factor when defining surface roughness since it actually decreases with vegetation density. Raupach 1992, 1994 attempted to incorporate foliage density properties in roughness length estimation by use of the frontal area of the crop. However, subsequent studies denoted inaccuracies from this approach (Schaudt 1998). On the other hand, Bailey and Davies 1988 did an experimental study within confined spatial extent and noted what could be dependence of  $z0$  on LAI. Consequently, the use of leaf area index (LAI) was considered in this study and equations 5 and 6 show the proposed ‘enhancement’ to the parameterizations of  $z0$  and  $d$  using the available data.

$$z0 = 0.025 + 0.281 * canopyheight - 0.028 * LAI \quad (5)$$

$$d = 0.245 * canopyheight + 0.091 * LAI \quad (6)$$

These new forms for  $z0$  and  $d$  were applied to the original parameterizations of  $r_{ah}$  previously discussed.

## **LAI**

LAI is defined as the total one-sided area of photosynthetic tissue per unit ground surface area. It represents the amount of leaf material in an ecosystem hence can serve as a means for detecting variation in density of the canopy. Ultimately, the goal is to get a model that gives the most accurate output. Since for this study, the main aim is to understand the effect of these parameterizations of  $r_{ah}$  on sensitivity to crop water stress. It is therefore important to include all available crop properties information in the assessment hence the option to test the LAI effect.

## **Validity, Parsimony and Robustness**

According to Brutsaert 2005, a parameterization is only useful if it is valid, and satisfies the dual requirements of robustness and parsimony. Validity refers to the parameterization's ability to adequately and accurately describe the phenomenon under study. In this study, the measured  $r_{ah}$  offers a good test of validity. A more parsimonious parameterization is one which can describe a phenomena better than the next, using fewer variables and parameters. The proposed addition of LAI to the existing formulae may seem to be breaching parsimony requirements but the results of absolute performance comparison can be used to decide. Further, to avoid colinearity between explanatory variables, correlation matrices are used and variance inflation factors checked. Insensitivity to input errors and uncertainties is a good measure of the robustness of a parameterization. A sensitivity analysis procedure tests the robustness of the various parameterizations

### **3.2.1.2. Barrax Study Area (micro-meteorological study)**

The test area chosen for this part of the study is the Barrax test site located in the south of Spain in La Mancha. Figure 2 shows the location of Barrax near Albacete in Spain. The area around Barrax has been used for agricultural research for many years. It has relatively flat terrain at an altitude of 700 m above sea level and the regional water table is about 20-30 m below the land surface. The type of climate is Mediterranean with annual rainfall average of about 400 mm most of which fall in autumn and spring. Lowest rainfall is in summer. Being one of the driest regions of Europe, La Mancha is made up of about 65% dry land and a portion of 35% under irrigation with agricultural fruit production.



Figure 2: Location of the Barrax Agricultural Experiment site

For this study, the test site used was a rectangular area with an extent of 5 km x 30 km = 150 km<sup>2</sup>. The actual measurements were done in a 25 km<sup>2</sup> area within which numerous crops are grown - on both irrigated and dry land - alongside fields of bare soil.

### 3.2.1.3. Data Capture

Secondary data was used for this study. The data collection was done during an intensive field campaign carried out in the period 10-21 July 2004 as part of an EU 6FP EAGLE Project. The campaign involved use of multiple field, satellite and airborne instruments for characterizing the state of the atmosphere, the vegetation and the soil from visible to microwave range of the spectrum. However of interest to the current study is emphasis of this mission on the in-situ measurements of land-atmosphere exchanges of water, energy and CO<sub>2</sub>. The period of measurement was from July 11 to July 21 2004, (DOY 193 – 203).

Using several mobile instrument towers, including four eddy covariance devices, two scintillometers, sonic anemometer and fast response thermocouples, measurements relevant to land-atmosphere exchanges (fluxes and state variables) were made. Measurements of incoming and outgoing shortwave and longwave radiation were also made. Table 2 outlines the measurements and the respective instruments used. Their on site locations are shown in Figure 3 which shows the

crop distribution at the time of the campaign and the locations of the data capture instruments. The vineyard portion shows two different measurements namely the LAS measurement (V-LAS) and H the eddy correlation system measurement (V-EC).

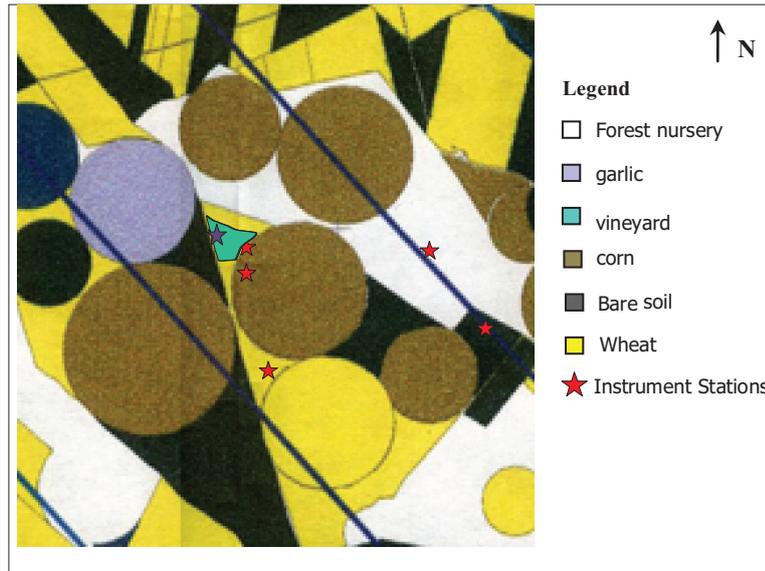


Figure 3: Crop distribution and Instrument stations in the Barrax Site

Table 2 : Data Measurements and Instrumentation

| DATASET   | INSTRUMENT  | COMMENTS   |
|---|---|--|
| -Turbulent Sensible heat Flux<br>-Water Vapour Flux<br>-CO <sub>2</sub> Flux<br>-CO <sub>2</sub> concentration                      | Eddy Correlation System (Gill 3D sonic + closed path Licor gas analyser: CO <sub>2</sub> and H <sub>2</sub> O + nitrogen reference gas + pneumatic mast + data loggers) | - 2 Levels were set up in order to allow for gradient calculations<br>- Frequency was at 1minute intervals |
| -Incoming and outgoing longwave and shortwave radiation<br>-Air temperature<br>-Relative humidity<br>-Wind speed<br>-Wind direction | Scintillometer System<br>LAS<br>Thermometers at different levels  | LAS measurements were taken simultaneously with meteorological recordings of the same variables            |
| Radiometric surface temperature measurements  |   |  |

### Surface temperature

While the previously described measurements yielded most data, the calculation of  $r_{ah}$  also requires surface temperature ( $T_s$ ) and for this study, this was computed according to the Stefan-Boltzmann law using the longwave radiation flux measurements according to equation 5.

$$T_s = \left( \frac{RL\uparrow - (1-\varepsilon)RL\downarrow}{\varepsilon\sigma} \right)^{0.25} \quad (5)$$

Where

- $\sigma$  is Stefan- Boltzmann constant ( $\sigma = 5.8678 \times 10^{-8}$ );
- $RL\uparrow$  is the upwards longwave radiation flux from the surface ( $Wm^{-2}$ );
- $RL\downarrow$  is the incident longwave radiation flux ( $Wm^{-2}$ ); and
- $\varepsilon$  is the emissivity of the surface

### Data Filters

Data quality is a critical factor in many models. For this study this was insured by using only data that met the criteria listed below from Liu et al., (2007). These filters ensure data integrity by the elimination of values that may result in negative values of  $r_{ah}$  or high  $Ri_B$  values (greater than 0);

- a) wind speed  $u$  greater than  $1.0 \text{ ms}^{-1}$
- b) friction velocity  $u^*$  greater than  $0.1 \text{ ms}^{-1}$
- c) absolute difference between surface temperature and air temperature larger than  $0.1K$
- d) sensible heat flux  $H$  greater than  $10Wm^{-2}$
- e) the sensible heat flux has the same sign as  $(T_s - T_a)$
- f) no rainfall experienced
- g) measurements done between 07:00am and 18:00pm

The 540 and 130 measurements used in this study with  $r_{ah}$  parameterization sets 1 and 2 respectively met the above criteria.

Some in situ measurements essential to the overall calculation of sensible heat flux and  $r_{ah}$  were determined at the site. Table 3 shows the surface parameters for the different land cover types determined at the time of the campaign.

Table 3: Surface parameters for the different land cover types

| <b>LAND COVER</b> | <b>hc [m]</b> | <b>zOM [m]</b> | <b>*d0 [m]</b> |
|-------------------|---------------|----------------|----------------|
| Corn              | 2             | 0.25           | 1.3            |
| Vineyard          | 1.25          | 0.15           | 0.813          |
| Sunflower         | 1             | 0.125          | 0.65           |
| Wheat stubble     | 0.15          | 0.015          | 0.1            |
| Crops             | 0.25          | 0.03           | 0.163          |
| Forest nursery    | 0.35          | 0.06           | 0.228          |

\*d0 was eventually used for “non LAI” parameterizations only.

The discussed methodology and flow of analysis followed is outlined in the flowchart in figure 4 which shows steps for evaluating different parameterizations.

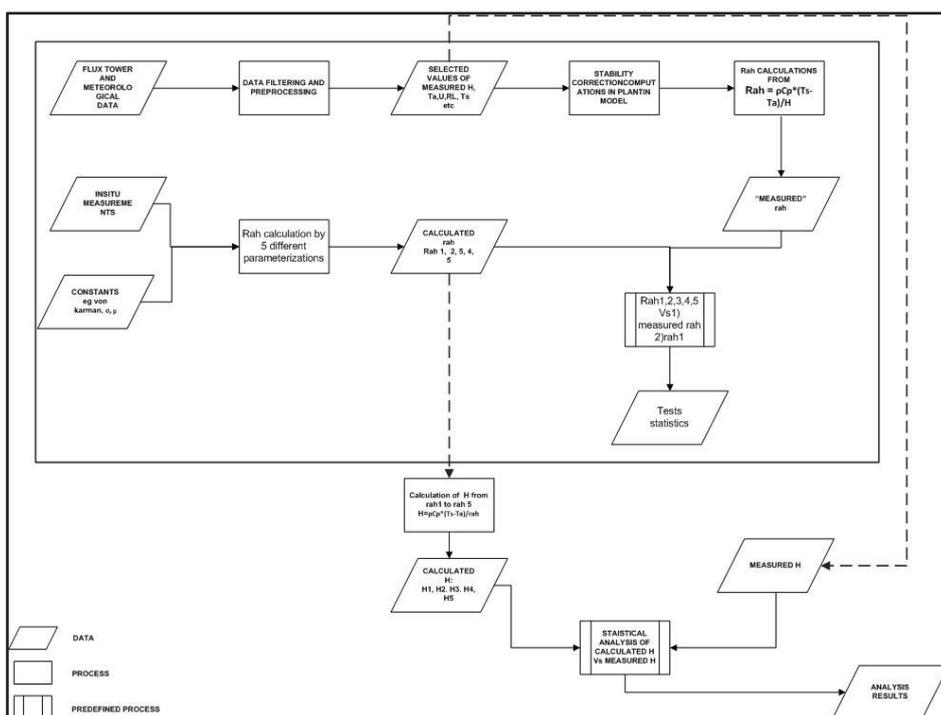


Figure 4: Steps for evaluating different  $\tau_{ah}$  parameterizations

### 3.2.2. Results and Discussion

In this section, results obtained from the previously discussed approaches are presented. A discussion of the further analysis carried out on the output is also included. The order assumed is concurrent with the order of the respective objectives and hypothesis.

#### Homogeneity

The first objective and hypothesis aimed at detecting the variation, if any, between and amongst different parameterizations of  $r_{ah}$ . The parameterization by Thom and Oliver (1975), henceforth referred to as 'Thom  $r_{ah}$ ', gives a precise solution by iteration (Liu et al. 2007) so it was taken as the standard solution against which other parameterizations were evaluated. Output from a so called homogeneity test that was carried out is presented in figure 5 which shows the results of comparisons of  $r_{ah}$ .

The trend appeared to be that whilst there were clear correlation between values of  $r_{ah}$  according to Jackson or Jacobs with Thom  $r_{ah}$  values, there was no homogeneity between either set. Both parameterizations overestimate  $r_{ah}$  values according to the 'standard', Thom, parameterization. The degree of over estimation is generally similar in either case for corresponding crop types. To evaluate possible reasons for the similarity, a comparison of  $r_{ah}$  values from Jackson against the corresponding ones from Jacobs was carried out. Figure 6 shows the scatter plots of Jackson  $r_{ah}$  against Jacobs  $r_{ah}$ . The relationships in all crop types showed a strong positive correlation hence the common pattern of behaviour in the tests against Thom  $r_{ah}$ .

For all comparisons, the scatter of points fell away from the displayed 1:1 line. Trend line equations added for each plot as well as regression table outputs revealed 'none – zero' intercepts and slopes greater or smaller than 1 (Appendix I). Therefore, for objective 1 and hypothesis 1 previously discussed, **we rejected  $H_0$**  and concluded with 95% confidence that estimation of sensible heat flux, and hence evapotranspiration, between different parameterizations of aerodynamic resistance to heat transport in the canopy varies. This further emphasises the importance of knowing which parameterization outperforms others since numerous estimates can be obtained from the same dataset.

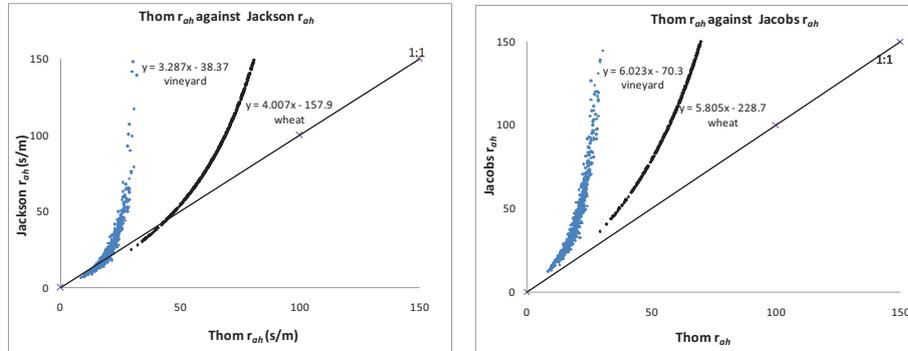


Figure 5: Graphs for assessing homogeneity between  $r_{ah}$  parameterisations

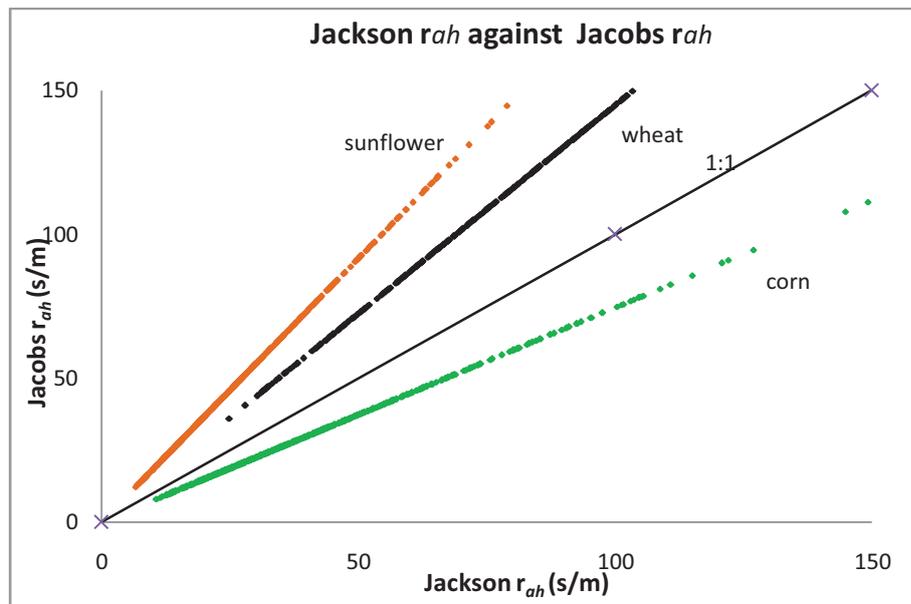


Figure 6: Graphs for assessing homogeneity between Jacobs and Jackson  $r_{ah}$  parameterisations

### Tests for absolute performance

The next stage of analysis, for hypothesis 2, was to evaluate the absolute performance of the selected parameterizations in estimating  $r_{ah}$  using measured values of  $r_{ah}$  and sensible heat flux. Figure 7 shows the comparison on Jackson  $r_{ah}$ , Thom  $r_{ah}$  and Jacobs  $r_{ah}$  against measured  $r_{ah}$ .

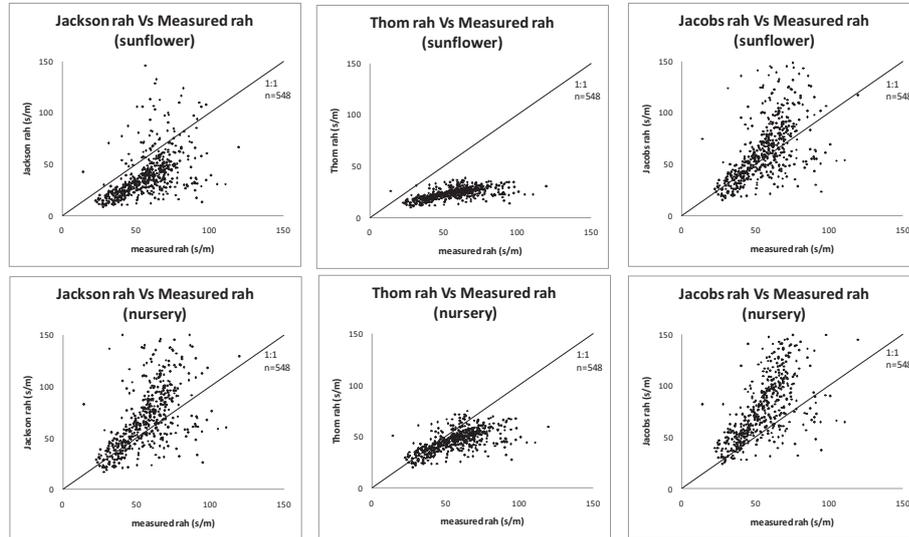


Figure 7: Plots of measured  $r_{ah}$  against calculated  $r_{ah}$

The spread of clouds around the 1:1 line was generally unfavourable for most scatter plots of measured  $r_{ah}$  against calculated  $r_{ah}$ . Thom  $r_{ah}$  generally underestimated the measured  $r_{ah}$  whilst the opposite is true of Jacobs  $r_{ah}$ . Further to comparison of measured  $r_{ah}$  against calculated  $r_{ah}$ , absolute performance of the parameterizations was also tested by using a comparison of measured sensible heat flux,  $H$  from eddy covariance with calculated  $H$  from the original forms of  $r_{ah}$  parameterizations as stated in the methods. Figure 8 shows the comparison of measured  $H$  and  $H$  calculated using original forms of Jackson  $r_{ah}$ , Thom  $r_{ah}$  and Jacobs  $r_{ah}$ . Only three graphs are shown. See appendix II for graphs of the other crops.

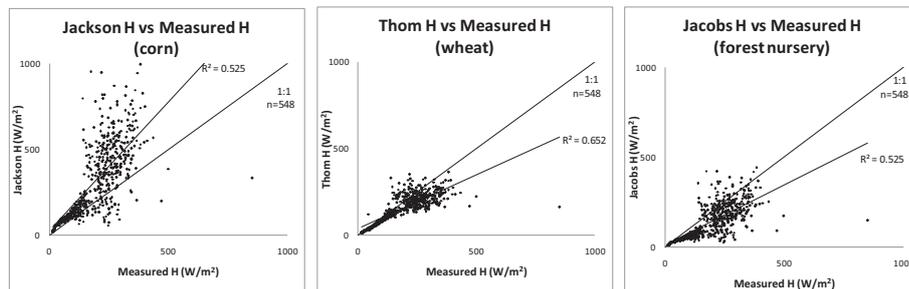


Figure 8: Comparison of measured  $H$  against  $H$  calculated

The spread of points around the 1:1 line was found to be better than that observed in the  $r_{ah}$  to  $r_{ah}$  comparison. A linear trend can be discerned from the plots. The

coefficient of determination,  $r^2$ , was chosen as one of the Performance indicator (PI) for this test, and, in agreement with the visual trends in the graph, Thom rah shows the highest value of the three figures displayed.,  $r^2 = 0.652$ . Now this may not be a statistically high value but it offers an argument for ranking the parameterizations. Of interest however, was the fact that the graphs tended to exhibit a nearly perfect trend up to a point before a sudden dispersion of points. This could be indicative of the effect of limiting factors. The next steps of analysis aimed to address this possibility by looking into use of LAI for consideration of foliage density properties and, atmospheric stability effects.

The list of equations previously defined under set II in table 1 were added for this analysis and the proposed roughness length definitions enhanced with LAI replaced the old ones. Table 4 shows the list of results for the full set of parameterizations.

Table 4: Statistics of Performance of the different rah in estimating Sensible heat flux

| $r_{ah}$      | <i>RMSE</i> | <i>Bias</i> | <i>Positive LAI effect</i> |
|---------------|-------------|-------------|----------------------------|
| Jackson       | 26.88858    | -18.3577    |                            |
| Jackson_LAI   | 25.4415     | -9.67582    | √                          |
| Thom          | 26.26199    | -22.4507    |                            |
| Thom_LAI      | 31.54005    | -29.1437    |                            |
| Jacobs        | 39.19452    | 19.24496    |                            |
| Jacobs_LAI    | 30.25747    | 8.237736    | √                          |
| Choudhury     | 45.58948    | -43.9998    |                            |
| Choudhury_LAI | 36.7813     | -34.6471    | √                          |
| Mahrt         | 29.7973     | -24.4163    |                            |
| Mahrt_LAI     | 42.83196    | 29.83555    |                            |
| Verma         | 38.87837    | -37.1229    |                            |
| Verna_LAI     | 15.82844    | 2.603973    | √                          |
| Viney         | 47.14156    | 38.06598    |                            |
| Viney_LAI     | 23.83232    | -3.75476    | √                          |

Two Performance indicators were used, namely, Bias and Root Mean Square Error (RMSE). The enhanced parameterization by Viney is shown to have the best score when compared with the measured H. The results show an improvement in five out of seven cases when LAI is introduced. With respect to atmospheric stability, the table shoes that four out of the five noted improvements are from the set II of equation with Stability correction.

### 3.2.1. Discussion

- Parameterization effect

The overall  $r_{ah}$  is a function of roughness length and displacement height. One source of variation between the  $r_{ah}$  values is definitely in the definition of  $z_0$  and  $d_0$  which varies for instance  $z_0$  in Jacobs is 0.1 of canopy height whereas in Thom it is 1.3 of canopy height. The same is true of definition of  $d_0$ .

- Input effect

The estimation of the inputs (  $h_c$ ,  $z_0$ ,  $z_{0m}$ ,  $d_0$ ), is another cause for deviations in modelling sensible heat flux. The idea of a constant surface roughness also fails to account the fact that surface roughness is high for sparse vegetation and low for dense canopies.

- Data

The actual input values generally introduce error into any model. For the data used in this study, the energy disclosure ( ie sum of sensible heat flux + sum of Latent heat) over estimate of 10% which can be attributed to neighbouring field through local circulation ( Su et al., 2008)

- Atmospheric Stability

Atmospheric stability has an influence on the flux – gradient in the surface layer. For stable conditions, ( ie  $T_s - T_a$  is low) profile functions are of the stability parameters and making easier the calculation of for aerodynamic resistance ( Liu et al, 2007). For unstable conditions, the relation sip becomes non linear prompting the need for iterative calculations or stability correction factors. The results presented a general improvement where stability correction is in place. When the total data points were segmented according to stability levels, again some improvement was noted especially for Jacobs and Jackson  $r_{ah}$ . Main stability criteria were;

$T_s - T_a > 5K$ , strongly unstable

$T_s - T_a < 5K$ , less unstable towards near neutral.

$T_s - T_a = 0$ , neutral

### 3.2.2. Preliminary conclusion

#### Hypothesis testing

##### Hypothesis1:

The first hypothesis raised issue of homogeneity between different  $r_{ah}$  forms and from the equations presented in figure 5 and the graphs in appendix I,

We reject  $H_0$  since intercept is not zero and slope not 1,  
( $\alpha_i \neq 0$  and  $\beta_i \neq 1$ ) for all comparisons  $i$ ,

And conclude that there is a systematic difference in the estimation of  $r_{ah}$  and H by the listed parameterizations of  $r_{ah}$

##### Hypothesis 2:

In order to validate the presumably positive effect of LAI inclusion in the  $r_{ah}$  parameterizations, the PI's from table 4 were subjected to a Wilcoxon Signed Rank Test. A test on the RMSE and bias values for the seven parameterizations of  $r_{ah}$  in terms of before and after LAI enhancement yielded a lower T score calculated of 20 against the tabulated T critical of 21 See appendix III. Therefore since

$$T\text{-score obtained (20)} < T \text{ critical (21)}$$

We reject  $H_0$  at  $\alpha= 0.05$ , and conclude that for the study carried out, there is a systematic improvement in estimation of sensible heat flux by the tested  $r_{ah}$  forms when LAI is included.

### **3.3. Phase II: Effect of Parameterization choice on Model Performance**

The aim of this analysis was to test the effect of choice of  $r_{ah}$  parameterization on the performance of a Crop Growth Simulation Model (CGSMs) in crop water stress detection and yield estimation. Global use of CGSMs has increased over the years and of interest, is this progression in Zimbabwe where in the early 1990s only a few organisations were using CGMS for example AGRITEX's Irrigation section, the Department of Meteorological Services' (DMS) National Early Warning Unit, and the Agricultural Research Trust (ART), (Manyowa and Munyanyi , 1995). Today, more organisations and research institutions are using these forecasting models. The crop growth model chosen is Production Situation analysis model (PSn) which can allow for the simulation of crop produce as well as signal crop water stress during the growing season.

#### **3.3.1. Study Area**

The overall aim of this study is to generally determine ways of improving means of drought stress detection through the reduction of errors in model parameterizations and inputs. As a result, it was seen fit to incorporate in the study, an area with high Agricultural activity yet also prone to drought. Zimbabwe is a Southern African country which is heavily reliant on agriculture for both income and food. While numerous irrigation schemes have been established in some places, majority of the farming community still practice rain fed agriculture and hence experience much loss due to crop water stress. Data availability was another key factor in the selection with much interest in weather and agricultural produce information. For the historical period chosen for this study, Zimbabwe had a "relatively dense and well-maintained network of meteorological stations", (Venus 1999). The country's then department of Agricultural Technical and Extension services (AGRITEX) collected yield statistics in a relative objective manner.

##### **3.3.1.1. Location and extent**

The area chosen for the study is a province in the northern part of Zimbabwe. Mashonaland West province falls within the geographical extent of 15° 30' - 18° 50' S, 28° 00' -31° 00' E. The province is divided into six administrative districts as shown in figure 9.

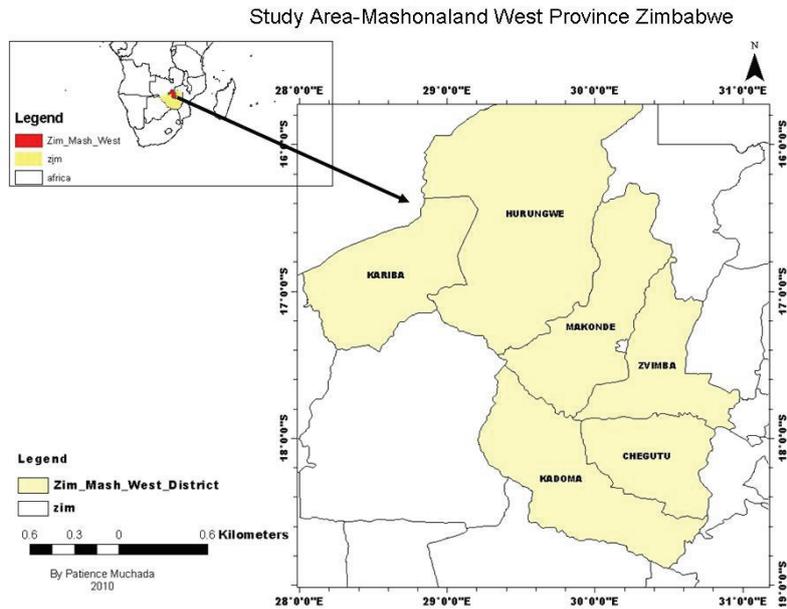


Figure 9: Location of Mashonaland West Province in Zimbabwe

### 3.3.1.2. Climate and Agriculture

Zimbabwe is generally divided into five natural regions of Zimbabwe and Mashonaland West province falls mostly in regions II and III where rainfall is 500 - 1 050 mm rainfall per year mm. (FAOSTATS 2000). Periodic seasonal droughts are common, as well as prolonged mid-season dry spells or delayed starts of the rainy season. Irrigation is in some cases employed for sustaining crop production and the dominant commercial crop is maize (Manyowa and Munyanyi , 1995).

### 3.3.2. Methods

The aerodynamic resistance module of the PSn model was modified to incorporate the ability to choose the parameterization of  $r_{ah}$  utilised at each run. As only three parameterizations were selected for this part of the study, they were labelled Model A ( $r_{ah}$  according to Thom), Model B ( $r_{ah}$  according to Jackson), and Model C ( $r_{ah}$  according to Jacobs). Daily weather data from meteorological stations within the study area was combined with crop information and farm management data to form inputs of the model. The model was run for a full growing season of the maize crop and the output included the crop productivity values and water sufficiency index at a daily time step as well as at ends of season, per pixel in the study area. The following sections describe further details about PSn model, the actual scenarios run and data inputs. Figure 8 is a flow chart of the steps followed in this section of the study. The following hypothesis guided the analysis.

**Null hypothesis (Ho):** there is no significant difference or improvement in performance in estimating crop yield and drought stress by model A, model B or model C when LAI is incorporated

$$H_0: PI_A = PI_B = PI_C$$

Where PI is a performance indicator such as RMSE or R2

**Alternative hypothesis (Ha):** there is a significant difference or improvement in performance in estimating crop yield drought stress by model A, model B or model C when LAI is incorporated

$$H_0: PI_A \neq PI_B \neq PI_C$$

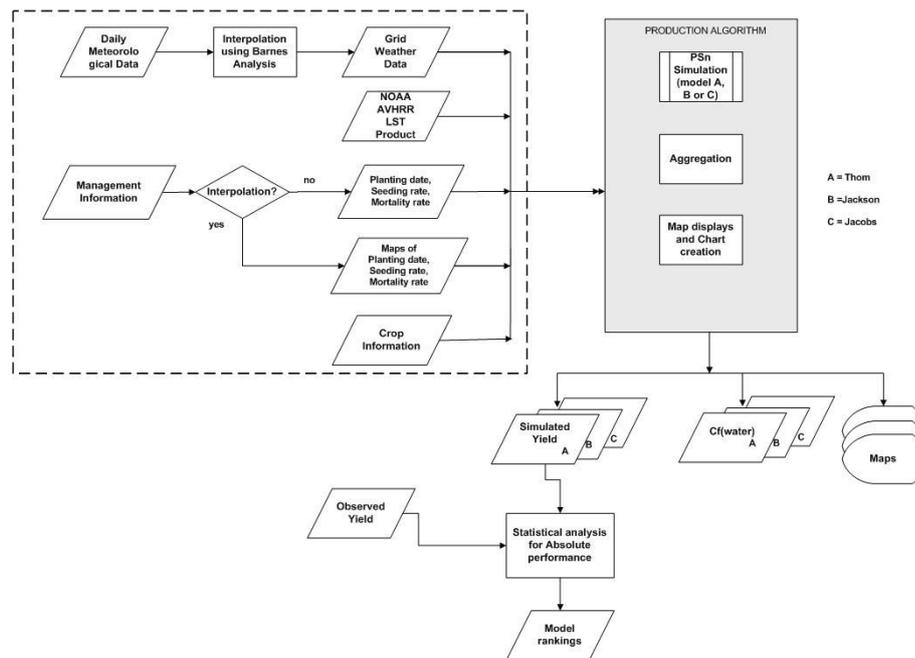


Figure 9: Methodology for comparison of  $r_{ah}$  using PSn Model

### 3.3.2.1. Production Situation model

(PSn) is a crop growth simulation model which monitors the dynamics of crop growth by dividing the crop cycle in successive (short) time intervals during which processes are assumed to take place at steady rates. The state of the system during a particular interval is indicated by state variables such as leaf, root, stem and storage organ masses. These values are updated after each cycle of interval calculations. The relative simplicity and low data needs of these production situation analyses allow to accurately quantifying reference yield (i.e. the harvested produce) and production (i.e. total dry plant mass) levels (Rugege, 2000). PSn follows a similar line of reasoning as some analytical models of biophysical production potential of annual food and fiber crops that have been built and tested since the 1960's (De-Wit and Penning-de-Vries, 1985) but tries to improve upon its regional applicability by incorporating satellite derived parameter values. The PSn is an adaptation from algorithms documented by Driessen and Konijn (1992).

The first configuration of the model, Production Situation 1 (PS1) simulates production/ yield as a function of light, the temperature and the photosynthetic mechanism of the crop. At this state, all other factors affecting crop growth and productivity are assumed to be in perfect or most favourable quantities. For example, zero weeds, or pests and ideal supply of nutrients and water to meet exact crop requirements.

The next level then incorporates the effect of water availability since this may be a major constraint to crop growth as is the case in dry regions or in periods of drought. This is achieved by the inclusion of a water budget routine that matches actual consumptive water use with the crop's water requirement, i.e. with the theoretical transpiration rate of a constraint-free crop. The so-defined 'Production Situation 2', (PS-2), calculates the water-limited production potential of the crop as a function of available light, temperature, photosynthetic mechanism and available water. A 'coefficient of water sufficiency' (cf(water)), with daily equivalent values of 0-1 is obtained by separating the transpiration term from the energy budget then dividing it by the theoretical transpiration rate of a constraint-free reference crop (Venus and Rugege, 2004). Cf(water) is further explained in the Model Outputs section.

Beyond the cf(water) computation is a higher level of simulation, PSn, allows for the simulation of actual farmer's production level of the crop as a function of available light, temperature, photosynthetic mechanism and compounded constraints (or crop stress) as reflected by the heating of the canopy. PS-n:  $P, Y = f(\text{light},$

temperature, C3/C4, canopy heating). Figure 10 shows an overview of algorithms of the internal processes of PSn. See appendix for further diagrams of PSn internal processes.

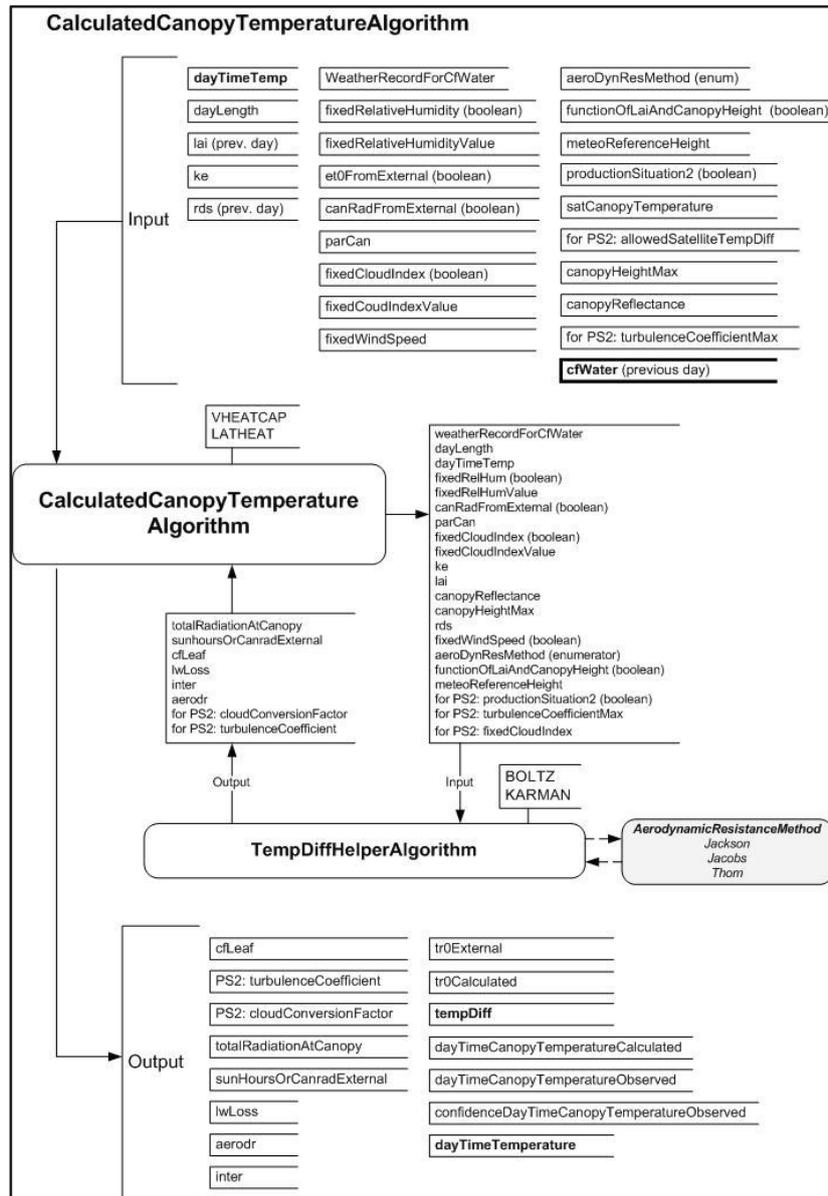


Figure 10: An overview of Algorithms from the internal processes of PSn

A general cycle from initial stage to output may be broken down into three basic modules.

**Module 1: Initialisation**

System constants are input: management data, crop data and location and interval data, and Initial state variable values at crop emergence or planting are recorded (stem, leaf and root masses).

**Module 2: Recurrent interval analyses**

- i. Interval-specific (i.e. daily) weather data are input into the model:  
minimum and maximum temperatures ( $T_{max}$ ,  $T_{min}$ ), relative air humidity RHA) and for PS 2, the mean Daily windspeed (SPD), Penman potential evaporation from a free water surface ( $E_0$ ), Penman potential transpiration from a crop canopy ( $ET_0$ ), Daily global radiation (CANRAD) and daily Land Surface temperature (LST).
- ii. Calculation of gross rate of assimilate production ( $F_{gass}$ ) as a function of photosynthetically active radiation' at top of canopy (PARCAN), day length (DL), momentary leaf area index (LAI), maximum assimilation rate at actual temperature (adjusted AMAX) and canopy properties, notably the extinction coefficient for visible light ( $k_e$ ) and the light use efficiency at low light intensity (EFF),
- iii. Apportioning of gross assimilates production to the various plant organs and calculation of Gross Assimilates Availability to each plant organ ( $GAA(org)$ )
- iv. Loss of assimilates in respiration to maintain living plant matter, by plant organ ( $MRR(org)$ ),
- v. Conversion of the remaining ('net') assimilates production into dry organ mass increments ( $DWI(org)$ ).
- vi. Adding up all organ masses ( $S(org)$ ) to total dry mass (TDM) and/or total living dry mass (TLDM)  
(Rugege 2000).

**Module 3: Model Output**

At the end of the physiological development, the biophysical production potential (TDM) and the yield potential, in form of the storage organ mass ( $S(so)$ ), as well as the Coefficient of water sufficiency ( $cf(water)$ ), are output.

### Yield

Yield estimations produced from the concepts similar to PSn have been shown to agree closely with actual yield observed by the farmers (Rugege and Driessen, 2002.). A yield gap between a simulated crop yield and the actual recorded yield is then used as a basis for quantifying the effect of drought on crop yield (Driessen and Konijn, 1992.).

### Coefficient of water sufficiency

Water availability to the crop is one of the main constraints to crop growth. Transpiration levels of maize may reach 100 000 l ha<sup>-1</sup>d<sup>-1</sup> in dry regions on a clear sunny day (Rugege 2002). For evaporation and/ or transpiration to occur, energy is required for the conversion of liquid water to gas through an increase of the separation between liquid water molecules. This energy is known as Latent heat of vaporization. Sources of this energy are radiation, heat stored below the surface or heat transfer from the atmosphere. When the transpiration term from the energy budget is divided by the theoretical transpiration rate of a constraint-free reference crop, an index ranging from 0 to 1 is obtained. This index is the ‘coefficient of water sufficiency’ which indicates the degree stomata closure and thus a measure of the degree to which photosynthetic activity is reduced by the compounded constraints to the actual crop. “Recurrent reading at short intervals accounts for the dynamics of crop growth and produces successive, near real-time estimates of actual crop performance”, (Venus and Rugege, 2004).

$$cf(water) = \left[ \frac{TR_{act}}{TR_{max}} \right] \quad (7)$$

Where  $TR_{act}$  is actual transpiration rate ( $\text{kg m}^{-2}\text{s}^{-1}$ )

$TR_{max}$  is potential transpiration rate from Penman type canopy ( $\text{kgm}^{-2}\text{s}^{-1}$ )

Or

$$cf(water) = \left[ \frac{INTER - \left( \frac{\Delta T * VHEATCAP}{r_{ah}} \right)}{LATHEAT * TRO * CFLEAF * TC} \right] \quad (8)$$

|          |  |
|----------|--|
| Where    |  |
| INTER    | is net radiation intercepted by the canopy                             |
| VT       | is temperature difference between canopy and air temperature (K)       |
| VHEATCAP | is volumetric heat capacity ( $\text{Jm}^{-3}\text{K}^{-1}$ )          |
| LATHEAT  | is Latent heat of vaporisation ( $2.46 \cdot 10^6 \text{ J kg}^{-1}$ ) |
| TC       | is Actual turbulence coefficient                                       |
| CFLEAF   | is ground cover fraction of the actual canopy (0 – 1)                  |

If water uptake by the roots is less than required to meet the maximum transpiration needs, actual transpiration is limited to the actual water uptake rate. In this case the water sufficiency coefficient assumes a value  $<1.0$  and assimilation and growth are less than in Production Situation 1. A  $C_f(\text{water})$  below 1 indicates crop water stress and may signal the onset of drought.

### 3.3.3. Data Description

The data collection for this study was guided by the data requirements of the PSn model as well as the need for validation data. The period chosen for the study was the 1994/95 to 1998/99 growing seasons. Data collected for each year included weather data, crop information, management information and the actual observed yield.

#### Crop Information

This is information about the crop under study. The model uses this information to simulate actual crop development.

|            |   |
|------------|---|
| Crop type. | i.e. whether the crop is a C3 or a C4 plant.                        |
| SLA        | minimum specific leaf area ( $\text{m}^2 \text{ kg}^{-1}$ )         |
| SLA max    | maximum specific leaf area ( $\text{m}^2 \text{ kg}^{-1}$ )         |
| Ke         | extinction coefficient for visible light                            |
| Tleaf      | heat requirement for full leaf development ( $^{\circ}\text{C d}$ ) |
| Tsum       | heat requirement for full crop development ( $^{\circ}\text{C d}$ ) |
| TO         | threshold temperature for development ( $^{\circ}\text{C}$ )        |
| Fr(org)    | mass fraction of $F_{\text{gass}}$ allocated to organ 'org'         |
| r(org)     | relative maintenance respiration rates                              |
| Ec(org)    | efficiency of conversion  |
| RDSroot    | (tabulated) RDS at which root growth ceases                         |
| RDm        | maximum depth of rooting system (cm)                                |

PSIleaf           critical leaf water head (cm)  
TCM               (tabulated) maximum turbulence coefficient

This information is available in form of a crop file which is unique for each crop type and variety.

### **Crop Yield statistics**

Observed Crop yield statistics for the period 1994 to 1999 were been collected for all six in districts from local, provincial and national headquarters offices of various departments monitoring agriculture in Zimbabwe. Statistics used in this study was from Chinhoyi Provincial Office for Agricultural Extension Services (AGRITEX), their head Office in Harare and statistics from the Central Statistical Office (CSO).

### **Management Information**

At three values are required to start the simulation namely, Planting date or Date of germination, the amount of planting material used in kilograms of seed used per hectare, and the mortality rate of the seed or planting material.

### **Weather Data**

- Meteorological:

Meteorological data was collected from 20 stations which were relatively spread across the entire Mashonaland West province. The parameter includes rainfall, maximum temperature, minimum temperature, solar radiation, and evapotranspiration for the period of 1994 to 1999. Appendix V shows the spread of metrological stations used. Interpolation of the point data into raster grids was done using the Barnes Objective Analysis in Unidata IDV (Barnes, 1994).

- Land Surface Temperature

As a key indicator of land surface states, Land Surface Temperature (LST) can be a source of information on surface-atmosphere heat and mass fluxes, soil moisture and vegetation water stress. The daily LST values used for this study were obtained from LST maps derived from Advanced Very High Resolution Radiometer (AVHRR) Global Area Coverage (GAC; 4 km resolution) data. A split window technique (Ulivieri et al ., 1994) was used to estimate the LST values based on differential absorption of thermal infrared signal in bands 4 and 5(Pinheiro et al. 2006).

### Simulation

A total of 90 simulations were run for the six districts in Mashonaland West Province. These scenarios were created from the combination of 3 parameterizations of  $r_{ah}$  X 3 maize seed varieties X 2 with/without LAI factor X 5 years. Figure show axes of the dimensions of the simulations. Some output is presented in the preliminary results section as part of a statistical analysis of the model output against the observed yields.

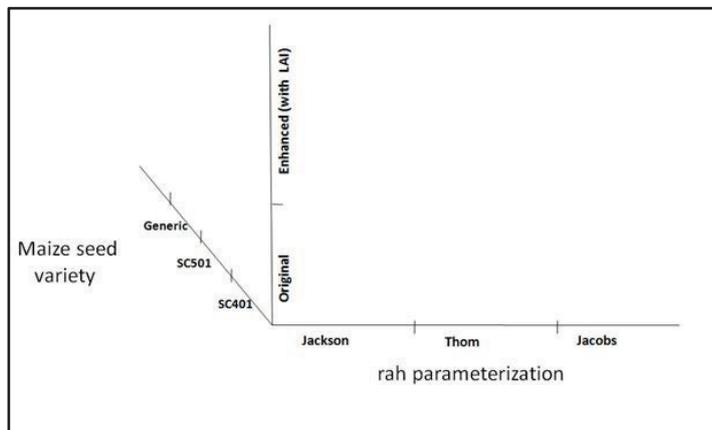


Figure 11: Dimensions of simulation scenarios for one year

### 3.3.4. Results

Model output e.g. simulated yield values from each pixel were aggregated to district and provincial levels using Jython scripts. This allowed for analysis at different spatial levels. The main question to be answered in this section was whether the absolute performance of the PSn model in crop yield estimation and crop water stress detection could be improved by incorporating LAI in the three selected  $r_{ah}$  parameterizations used in the model. The initial comparison of simulated yield by different  $r_{ah}$  models against observed yield gave results like the ones shown in figures 12 and 13. The R2 values revealed that the three models gave strikingly similar output for each run.

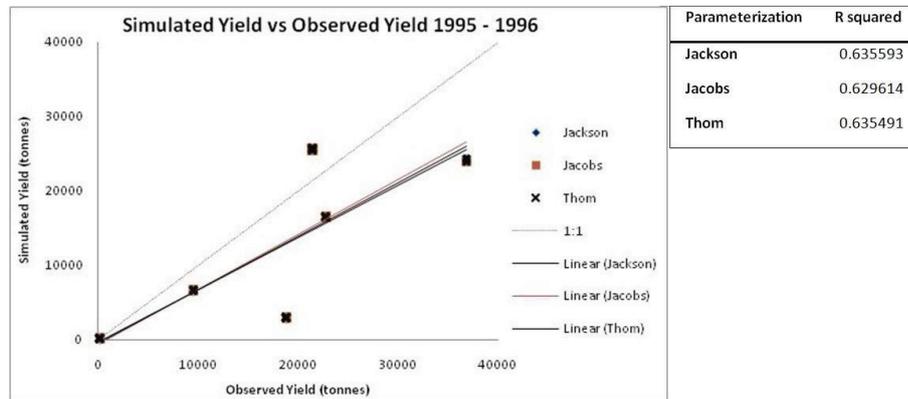


Figure 12: Comparisons of (1995 – 1996) PSn estimated yield by the  $r_{ah}$  forms Jackson, Jacobs and Thom with the observed yield.

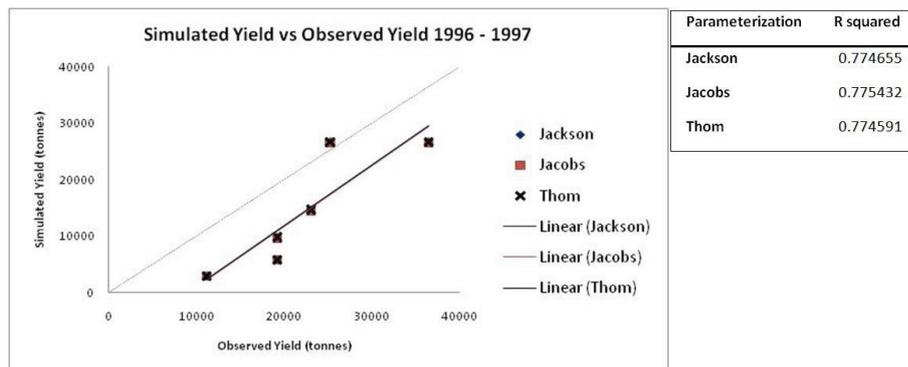


Figure 13: Comparisons of (1996 – 1997) PSn estimated yield by  $r_{ah}$  forms Jackson, Jacobs and Thom with the observed yield.

A box and whisker plot was created to test variance explained by either  $r_{ah}$  model. The close similarity in the shape and extent of the box plots confirmed the sticking similarity noted in figures 12 and 13.

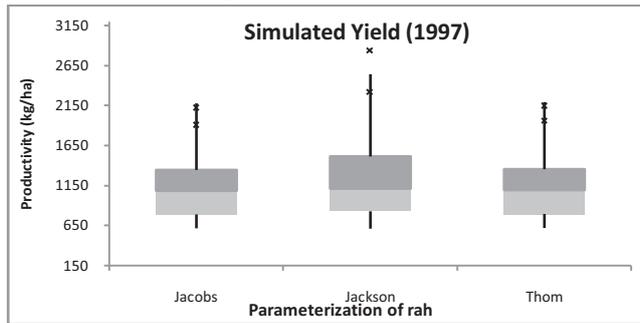


Figure 14: Box and whisker plot test variance per model

The spatial distribution of the recorded simulated yield at District level is shown in figure 15. For all districts, similar trends were observed where the model output showed very subtle differences.

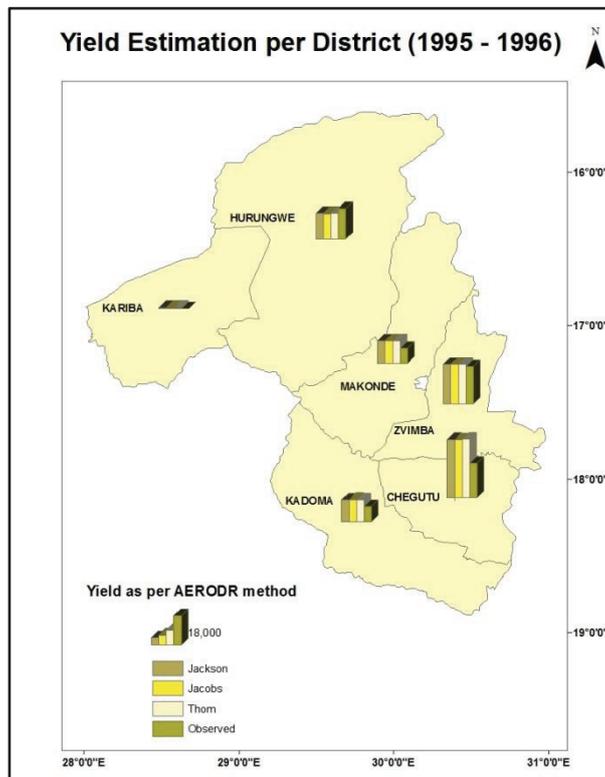


Figure 15: Simulated Yield at District level

Analysis at provincial level was also carried out in order to test the absolute performance of the model. Figure 16 shows the simulated productivity for the whole study period as box plots, relative to the line graph of the observed productivity.

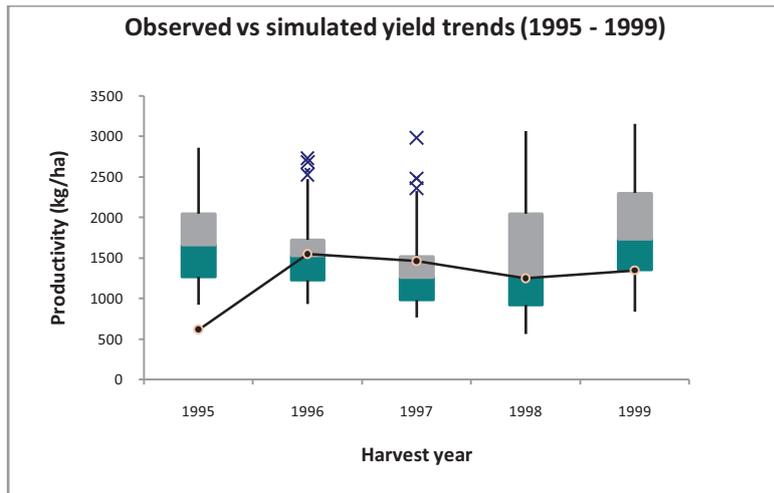


Figure 16: Box plot showing variance in simulation results and a trend of observed yield

Generally the model captured the trend well except for the first harvest year, 1995. The year has been described as a difficult year. The provincial level values c

Uncertainty is inevitable in any modelling exercise due to different sources of error as well as the use of assumptions. The performance of the PSn model was also assessed within an uncertainty band created from the variances of the multiple sources of observed yield. Figure 17 shows that analysis.

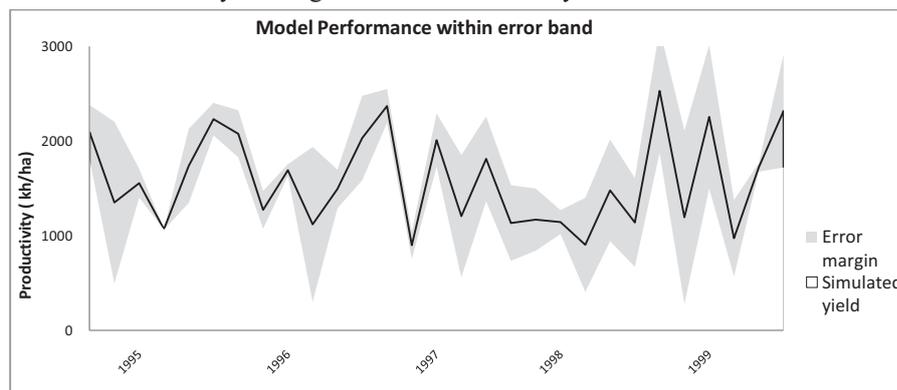


Figure 17: Model performance within an error band

As previously determined in Phase 1 of this study, the incorporation of LAI in  $r_{ch}$  parameterizations has an effect on the output. For the PSn simulations conducted in this study, this effect was rather subtle but nevertheless present.

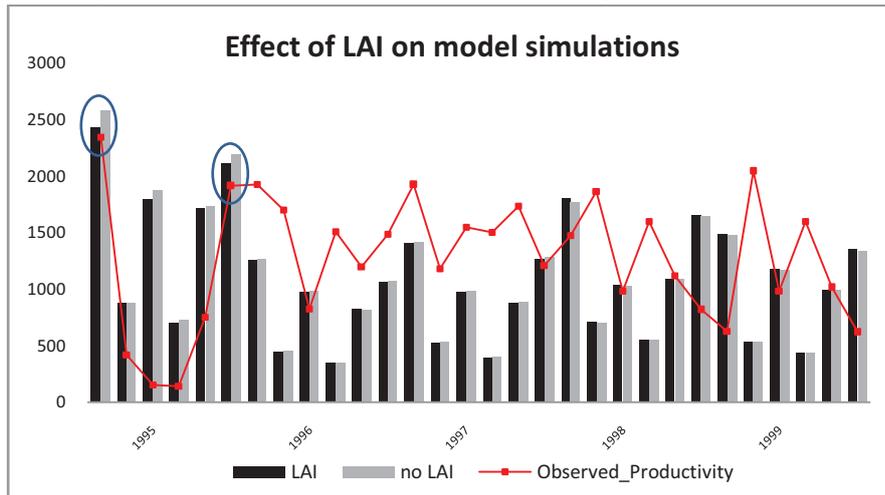


Figure 18: Effect of LAI on Simulated productivity for period (1995-1999)

Figure 18 shows the Effect of LAI on Simulated productivity for period (1995-1999) relative to the observed yield. For most of the other simulations, the LAI-enhanced model gave as highlighted in the chart.

### Drought stress

For the detection of crop water stress, PSn offers a within season monitoring index  $cf(water)$  previously discussed. Figure 19 shows a plot of  $cf(water)$  index during the 1998/99 growing season for a pixel in the Chegutu district of Mashonaland West.

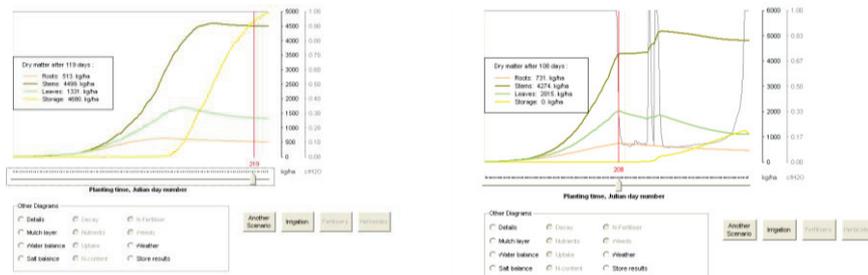


Figure 19: Graphs of PSn output with  $cf(water)$

From the graph, one can observe a steady and undisturbed increase in biomass organs of the crop from the beginning of the season until Julian Day Number 2009

where the biomass drops. This decline corresponds with a drop in the  $cf$  (water) value from 1 to lower values. With such observations, it is possible to detect the exact dates when crop stress sets. The numerical nature of  $cf$  (water) also serves as a measure of the degree of crop water stress such that one can determine the intensity and severity of the water shortage or drought.

### 3.3.5. Discussion and preliminary conclusion

The overall performance the model is subject to other factors mostly related to the inputs. The use of daily averages is convenient and provides a first but rough impression of the weather conditions under which a given crop develops. A single daily average value can in fact be adequate for some plant processes the development rate of a crop can be estimated quite well by making use of the average air temperature. After all, it is not possible to measure accurately the stages of development from day to day, which means that the effect of temperature must be integrated over at least a week. For this study the concept of 'temperature sum' (TSUM) was used and calculated as the integral of the value with which the (average) temperature exceeds a certain lower threshold value ( $7^{\circ}\text{C}$ ). This procedure implicitly assumes a linear response above the lower threshold. However, anomalies may arise if the actual situation has a non linear response for example the photosynthesis-light response that becomes saturated at high light intensities. At this point, a daily value becomes inadequate.

Combined factor effects are also distorted when averages are used. An example is the rate of evaporation of open water, which increases with wind speed, but also with radiation, and with the dryness of the atmosphere. Because of this interaction, it is not permitted to simply enter the average values in the equation. Yet, in the calculation of the Penman evaporation average daily values are used (Penman, 1948). Its success can be attributed to the fact that diurnal courses are repetitive and that the values of empirical coefficients were found by calibration. The response has a time delay within the daily rhythm. An example is the plant's water content, which exhibits a minimum in the late afternoon. If the minimum should be very pronounced, the photosynthesis-light response will be higher in the morning than in the afternoon. (Venus, 2004)

Because of these kinds of effects, it is often necessary to take account of the daily progress of the weather conditions when modelling crop growth. For most crops,

processes like carbon dioxide (CO<sub>2</sub>) assimilation are overestimated when the time step simplification and integration technique is used to derive daily integrated radiation and temperature to estimate daily integrated CO<sub>2</sub> assimilation compared with daily instantaneous CO<sub>2</sub> assimilation. This overestimation is related to the diurnal dynamics of radiation and temperature which are not well captured when the time step simplification and integration technique are used to derive daily total or average radiation and temperature. (Venus, 2004) Consequently, the overall simulation result, be it yield or cf(water) , is affected.

#### **Weather data**

The issue of station based meteorological data previously discussed may also have affected the output of the model. Point weather data extrapolation to grid data introduces uncertainty. For the LST data, the resolution was at 4km which was not equal to the resolution of the rest of the gridded data. This resulted in there being about four different LST values per each modelled pixel. An algorithm to select only the largest LST value was created and used but again, this generalisation may affect the model output.

#### **Multiple sources of Observed/ Actual yield.**

The data used as observed yield in this study is meant to represent the actual yield realised. However, there were many sources supplying the so called actual yield data. Main players were the Central Statistical Office (CSO), and the Agricultural Research and Extension Services (AGRITEX, now AREX) which supplied different values from its Head quarters in Harare and its regional office in Chinhoyi. Figure 20 depicts the different data sources and how the definition of “actual yield” becomes unclear.

The choice of independent value to use in absolute performance test would definitely have an impact on the test results. For purposes of this study, all three sources were used but based on the recommendation of tests on the same datasets in previous studies (Venus, 1999 and Rugege, 2002) the CSO dataset was regarded the standard.

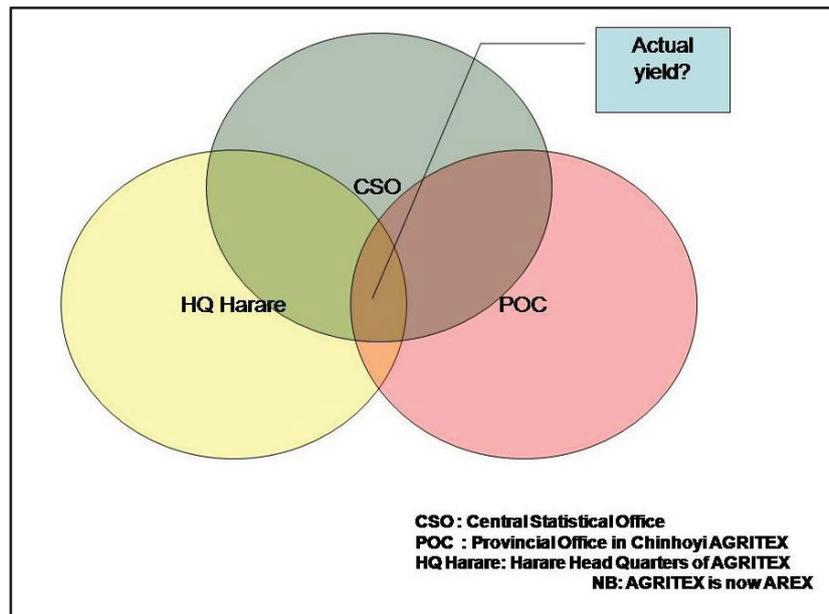


Figure 20: Multiple Sources of Observed Yield Data

### Effect of Assumptions

The assumptions declared in section 2.3 of this study may have aided in making the study feasible but when the modelled output was tested against reality, it may be that some of the anomalies can be attributed to the generalisation introduced by the assumptions.

### Preliminary conclusion

The model output in terms of yield estimation by the various parameterizations of  $r_{ah}$  allowed us to reject  $H_0$  of the hypothesis and conclude that there is a significant difference between models A, B and C based on the inequality of the  $r^2$  for the different models against the observed yield.

The applicability of  $cf(\text{water})$  as a signal for crop stress was shown in the comparison in figure 19 where the drop in  $cf(\text{water})$  index coincided with the decline in biomass increase.

## 4. Discussion and Conclusions

Following the results and discussions presented so far, this section presents the conclusions reached from this study. Subheadings of main discussion points are used to present conclusions for each subject raised.

### Atmospheric Stability

Parameterizations of  $r_{ah}$  by Jacobs, Jackson and Thom were able to perform relatively well (  $\text{adj } r^2 > 0.60$  ) in estimation of H in unstable conditions. Better performance (  $\text{adj } r^2 > 0.90$  ) was even realised when the parameterizations were applied to less unstable conditions  $\{(T_s - T_a) < 5K\}$ . Conversely, the performance under strongly unstable conditions  $\{(T_s - T_a) > 5K\}$ , was poor for all three parameterizations. We therefore concluded that while the influence of atmospheric stability cannot be ignored (Brutsaert , 1982), these relatively less complex parameterizations of  $r_{ah}$  by Jacobs, Jackson and Thom can be used without stability correction as long as conditions are not yet strongly unstable.

### Enhancement with LAI

The effect of LAI, though already proven to be a strong influence by previous studies (e.g. see Schaudt and Dickinson, 2000; Lindroth, 1993), could not be captured significantly well by this study. Possible reasons for the failure include absence of further crop and field management details such as plant populations and soil nutrient information. We have resolved that for this study, the results pertaining to the effect of adding LAI to parameterizations cannot be used as basis for conclusive claim.

### Choice of parameterizations

It has clearly been demonstrated that different parameterizations of  $r_{ah}$  will give different estimates of sensible heat flux and thus evapotranspiration. Essentiality of accuracy in evapotranspiration estimation has been discussed especially when applied in models for yield simulation and drought stress detection.

## 5. Recommendations

From continuous reviews of literature and continuous questions raised during the research period, we are convinced that much more research into this interesting subject area. In that line, there are also improvements which can be made towards achievement of better results.

- The use of meteorological data remains a major concern due to uncertainties of interpolation. Future studies may consider the use of satellite data.
- Where overlaps of observed data sources occur, further methods to extract the best or true value may be considered for instance employ of a weighted mean with weights depending on the conditions of the case.
- In use of the PS<sub>n</sub> model, the need for calibration cannot be over emphasised as this has an effect on the ultimate performance of the model, For Zimbabwe, the calibration for PS<sub>1</sub> was well done but there is need for calibration for PS<sub>2</sub>.
- Studies researching into combination effect of rah and other factors may also be considered towards the ultimate goal of better crop stress detection.

## References

- American Meteorological Society, 1997. Policy statement-‘Meteorological Droughts’. *Bulletin of American Meteorological Society*, **78**(5): 847-849.
- Bailey, W.G. and Davies, J.A., 1981. The effect of uncertainty in aerodynamic resistance on evaporation estimates from the combination model. *Boundary-Layer Meteorology*, **20**(2): 187-199.
- Boken, V., Cracknell, A. and Heathcote, R. (Editors), 2005. *Monitoring and Predicting Agricultural drought: A Global Study*. Oxford University Press, New York, 472 pp.
- Breda, N.J.J., 2003. Ground-based measurements of leaf area index: a review of methods, instruments and current controversies. *J. Exp. Bot.*, **54**(392): 2403-2417.
- Byun, D.W., 1990. On the Analytical Solutions of Flux-Profile Relationships for the Atmospheric Surface Layer. *Journal of Applied Meteorology*, **29**(7): 652-657.
- Byun, H.-R. and Wilhite, D.A., 1999. Objective Quantification of Drought Severity and Duration. *Journal of Climate*, **12**(9): 2747-2756.
- Choudhury, B.J., Reginato, R.J. and Idso, S.B., 1986. An analysis of infrared temperature observations over wheat and calculation of latent heat flux. *Agricultural and Forest Meteorology*, **37**: 75-88.
- Dabrowska-Zielinska, K., Kogan, F., Ciolkosz, A., Gruszczynska, M. and Kowalik, W., 2002. Modelling of crop growth conditions and crop yield in Poland using AVHRR-based indices. *International Journal of Remote Sensing*, **23**(6): 1109 - 1123.
- De-Wit, C.T. and Penning-de-Vries, F.W.T., 1985. Predictive models in agricultural production. *Philosophical Transactions of the Royal Society of London*, **310**( Series B): 309-315.
- Di, L., Rundquist, D.C. and Han, L., 1994. Modelling relationships between NDVI and precipitation during vegetative growth cycles. *International Journal of Remote Sensing*, **15**(10): 2121 - 2136.
- Dorenboos, J. and Kassam, A.H., 1979. *Yield Response to Water*, Roma.
- Driessen, P.M. and Konijn, N.T., 1992. *Land Use Systems Analysis*. 230 pp.
- FAO, 2002. *Food insecurity: when people must live with hunger and fear starvation, State of Food Insecurity in the World - 2002* Food and Agriculture Organization of the United Nations Viale delle Terme di Caracalla, 00100 Rome, Italy, Italy.

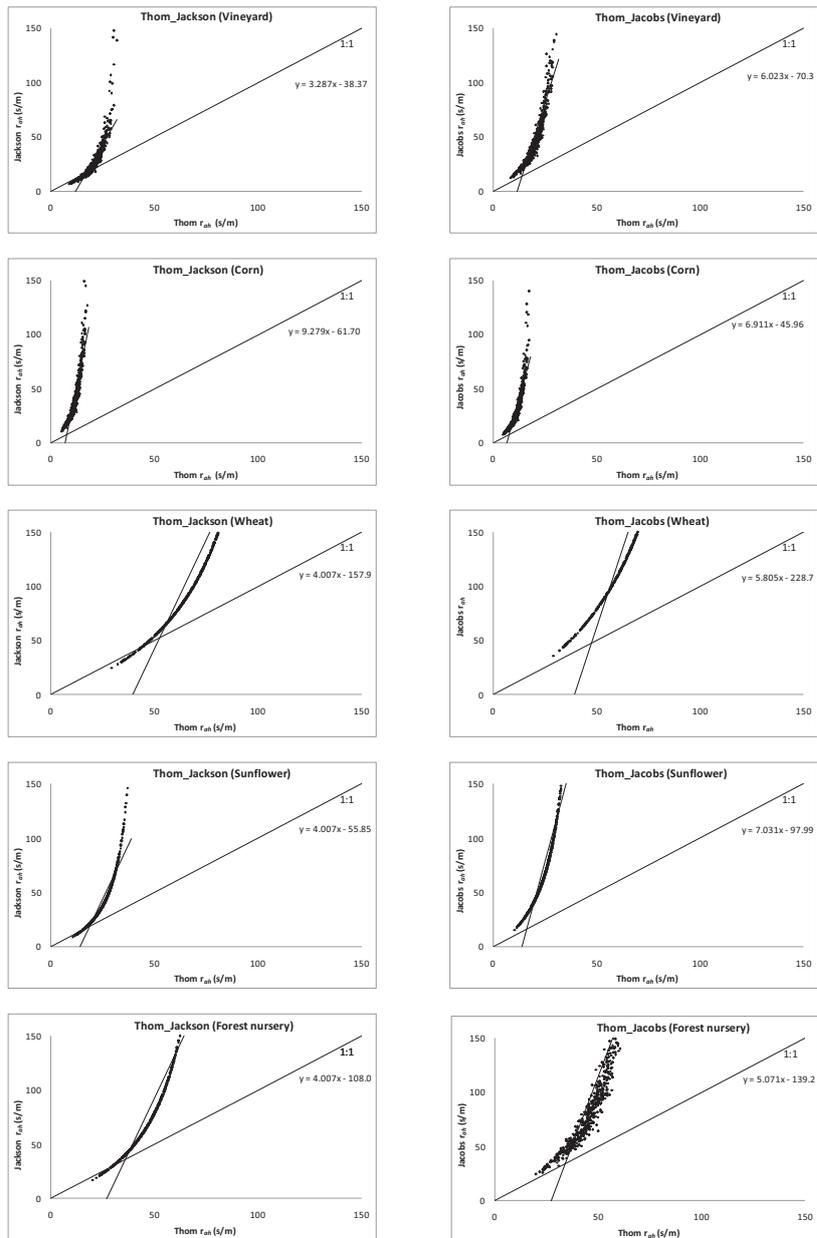
- Gouveia, C., Trigo, R.M. and DaCamara, C.C., 2009. Drought and vegetation stress monitoring in Portugal using satellite data. *Natural Hazards and Earth System Sciences*, 9(1): 185-195.
- Hatfield, J.L., Perrier, A. and Jackson, R.D., 1983. Estimation of evapotranspiration at one-time-of-day using remotely sensed surface temperature. *Agric. Water Manage*, 7(341-350).
- Itier, B., 1980. Une Méthode Simplifiée pour la Mesure du Flux de Chaleur Sensible. *J. Rech. Atmos*, 14: 17-34.
- Jackson, R.D., Kustas, W.P. and Choudhury, B.J., 1988. A REEXAMINATION OF THE CROP WATER-STRESS INDEX. *Irrigation Science*, 9(4): 309-317.
- Jacobs, J.M., Myers, D.A., Anderson, M.C. and Diak, G.R., 2002. GOES surface insolation to estimate wetlands evapotranspiration. *Journal of Hydrology*, 266(1-2): 53-65.
- Ji, L. and Peters, A.J., 2004. A spatial regression procedure for evaluating the relationship between AVHRR-NDVI and climate in the northern Great Plains. *International Journal of Remote Sensing*, 25(2): 297 - 311.
- Kalluri, S.N.V. and Townshed, J.R.G., 1998. A Simple Singlelayer Model to Estimate Transpiration from Vegetation using Multi-spectral and Meteorological Data. *International Journal of Remote Sensing* 19: 1037-1053.
- Kalma, J.G., 1989. A comparison of expressions for the aerodynamic resistance to sensible heat transfer. CSIRO Division of Water Resources Technical Memorandum, 6(89): 11.
- Kogan, F.N., 1998. A typical pattern of vegetation conditions in southern Africa during El Nino years detected from AVHRR data using three-channel numerical index. *International Journal of Remote Sensing*, 19(18): 3688 - 3694.
- Li, L., Yu, Q., Su, Z. and Tol, C.v.d., 2009. A simple method using climatic variables to estimate canopy temperature, sensible and latent heat fluxes in a winter wheat field on the North China Plain. *Hydrological Processes*, 23(5): 665-674.
- Liu, W.T. and Juárez, R.I.N.n., 2001. ENSO drought onset prediction in northeast Brazil using NDVI. *International Journal of Remote Sensing*, 22(17): 3483 - 3501.
- Mahrt, L. and Michael, E.K., 1984. The influence of atmospheric stability on potential evaporation. *J. Clim. Appl. Meteorol*, 23: 222-234.
- McKee, T.B., N. J. Doesken, and J. Kleist. . . , 17-22 January 1993, , 1993. The relationship of drought frequency and duration to time scales, In *Proceedings of the 8th Conference of Applied Climatology*

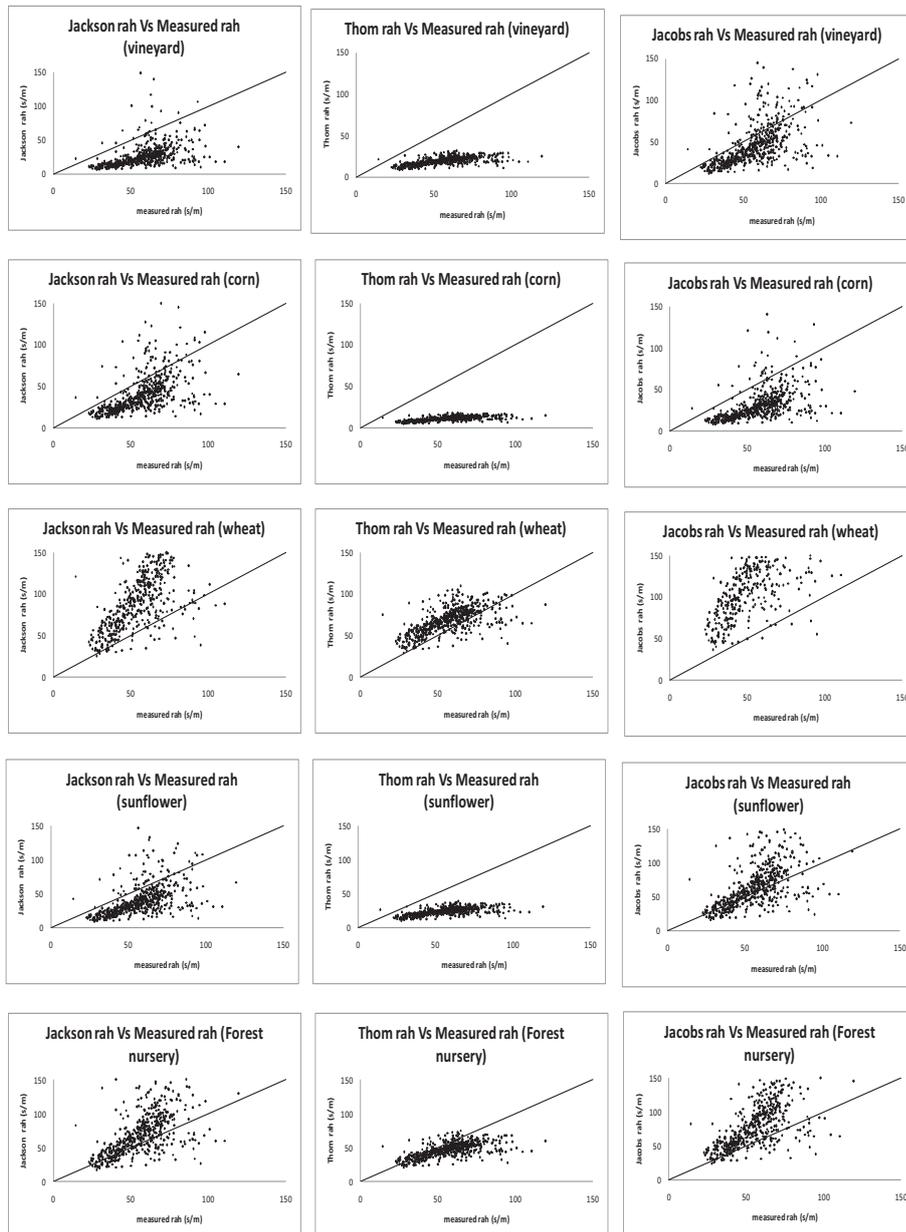
- American Meteorological Society, Anaheim, CA., pp. 179-184.
- Monteith, J.L. (Editor), 1973. Principles of Environmental Physics, London, 241 pp.
- Oke, T.R., 1987. **References**, Boundary Layer Climates, 2nd Edition. Routledge, pp. 406 - 416.
- Palmer, W.C., 1968. Keeping track of crop moisture conditions, nationwide: The new crop moisture index. *Weatherwise*, **21**: 156-161.
- Roberts, C.R., 2002. Drought management in the Río Guadalhorce region of Andalucía, southern Spain. *Land Degradation & Development*, **13**(2): 151-163.
- Rugege, D. and Driessen, P.M., 2002. Combining remote sensing and crop growth modeling for early warning applications. *Innovative Soil-Plant Systems for Sustainable Agricultural Practices*: 24-28.
- Singh, R.P., Roy, S. and Kogan, F., 2003. Vegetation and temperature condition indices from NOAA AVHRR data for drought monitoring over India. *International Journal of Remote Sensing*, **24**(22): 4393 - 4402.
- Stanhill, G., 1969. A Simple Instrument for the Field Measurement of Turbulent Diffusion Flux. *Journal of Applied Meteorology*, **8**(4): 509-513.
- Szeicz, G., Endrődi, G. and Tajchman, S., 1969. Aerodynamic and Surface Factors in Evaporation. *Water Resour. Res.*, **5**.
- Tanner, C.B. and Pelton, W.L., 1960. Potential Evapotranspiration Estimates by the Approximate Energy Balance Method of Penman. *J. Geophys. Res.*, **65**.
- Thom, A.S., Stewart, J.B., Oliver, H.R. and Gash, J.H.C., 1975. Comparison of aerodynamic and energy budget estimates of fluxes over a pine forest. *Quarterly Journal of the Royal Meteorological Society*, **101**(427): 93-105.
- Venus, V. and Rugege, D., 2004. Combined use of polar orbiting and geostationary satellites to improve time interpolation in dynamic crop models for food security assessment. *International Archives of Photogrammetry Remote Sensing and Spatial Information Sciences*, **35**: 212-219.
- Verma, S.B., Rosenberg, N.J., Blad, B.L. and Baradas, M.W., 1976. Resistance-energy Balance Method for Predicting Evapotranspiration: Determination of Boundary Layer Resistance and Evaluation of Error Effects. *Agron J*, **68**(5): 776-782.
- Wan, Z., Wang, P. and Li, X., 2004. Using MODIS Land Surface Temperature and Normalized Difference Vegetation Index products for monitoring drought in the southern Great Plains, USA. *International Journal of Remote Sensing*, **25**(1): 61 - 72.

- Wu, H. and Wilhite, D., 2004. An Operational Agricultural Drought Risk Assessment Model for Nebraska, USA. *Natural Hazards*, 33(1): 1-21.
- Yang, K., Tamai, N. and Koike, T., 2001. Analytical Solution of Surface Layer Similarity Equations. *Journal of Applied Meteorology*, 40(9): 1647-1653.

# Appendices

## Appendices I: Comparison of Thom $r_{ah}$ vs Jackson $r_{ah}$ and Jacobs $r_{ah}$

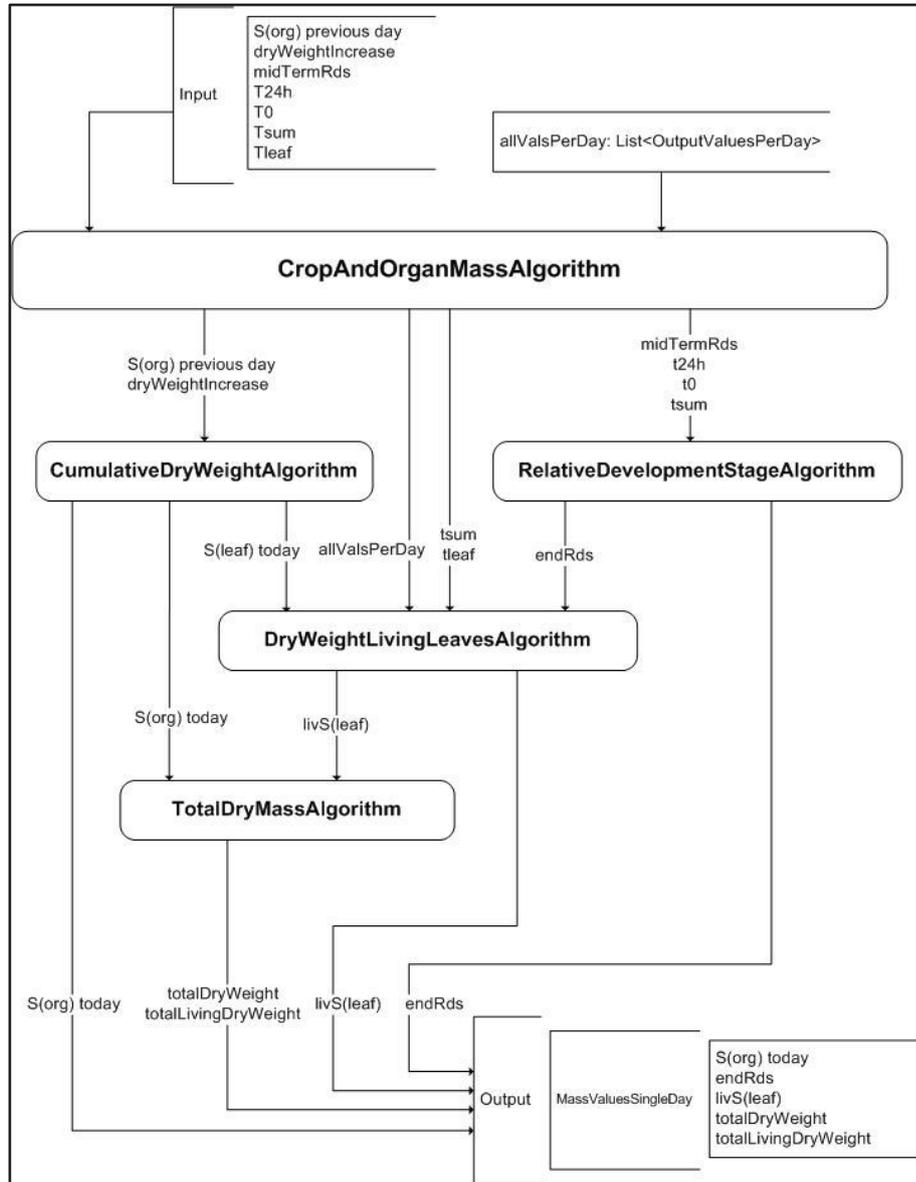




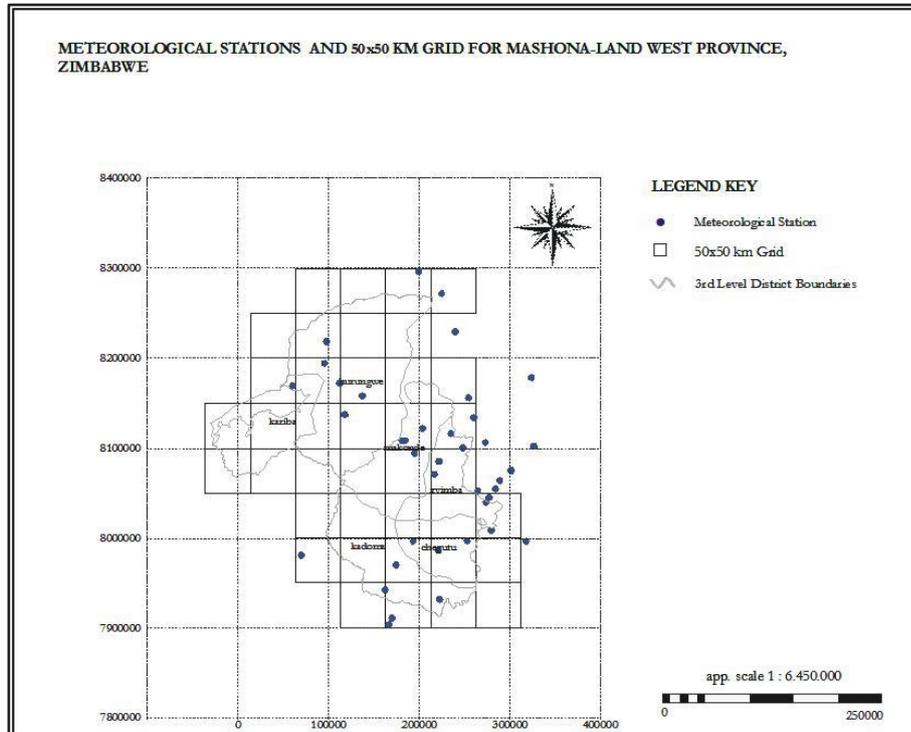
**Appendices II: Performance of various  $r_{ah}$  for H estimation**

| Xi    | Yi     | Diff= (Yi-Xi) | Abs(Diff) | Rank  | Signed Rank | T                   | -65      |
|-------|--------|---------------|-----------|-------|-------------|---------------------|----------|
| 26.89 | 25.442 | -1.44708      | 1.44708   | 1.00  | 1           | n=                  | 14       |
| 26.26 | 31.54  | 5.27806       | 5.27806   | 2.00  | 2           | $\sigma\{T\}$       | 31.85906 |
| 39.2  | 30.257 | -8.937982     | 8.93798   | 7.00  | -7          | $\alpha$            | 0.05     |
| 45.59 | 36.781 | -8.80818      | 8.80818   | 6.00  | -6          | Action(L)           | -62.4    |
| 29.8  | 42.832 | 13.03466      | 13.0347   | 10.00 | 10          | Action(U)           | 62.4     |
| 38.88 | 15.828 | -23.04993     | 23.0499   | 11.00 | -11         | z                   | -2.0     |
| 47.14 | 23.832 | -23.30924     | 23.3092   | 12.00 | -12         | Reject Null at 0.05 |          |
| 18.36 | 9.6758 | -8.68188      | 8.68188   | 5.00  | -5          |                     |          |
| 22.45 | 29.144 | 6.693         | 6.693     | 4.00  | 4           |                     |          |
| 19.24 | 8.2377 | -11.00722     | 11.0072   | 9.00  | -9          |                     |          |
| 44    | 34.647 | -9.3527       | 9.3527    | 8.00  | -8          |                     |          |
| 24.42 | 29.836 | 5.419255      | 5.41926   | 3.00  | 3           |                     |          |
| 37.12 | 3.7548 | -33.36814     | 33.3681   | 13.00 | -13         |                     |          |
| 38.07 | 3.7548 | -34.31122     | 34.3112   | 14.00 | -14         |                     |          |

Appendices III: Wilcoxon Sign Rank Test result



Appendices IV: P<sub>Sn</sub> internal processes



**Appendices VI: Meteorological Stations**