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Measuring Weather Impact on Crop Yield Using Aridity Index: Evidence from Odisha

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Abstract

Rainfall and temperature are the two important weather factors that affect crop yields due to their direct and indirect influences on agricultural practices. This study has negated the method of direct use of meteorological factors (either monthly or seasonal), in multiple regression analysis to measure weather impact on crop yield where rainfall and temperature are incorporated in the model as increasing monotonic functions of yield. With evidences from Odisha, where agriculture is rainfed and weather-dependent, the study has advocated the incorporation of 'aridity index' variable in the regression model. The use of composite aridity index variable in econometric model has made the analysis more easy and logical. More importantly, the use of aridity index saves the 'degrees of freedom' which is very crucial in econometric analysis. In addition, the ambiguity of using the linear trend to proxy for technological progress is taken care of adequately by using cubic function of time. The testing of hypothesis of changing rainfall dependency has established the fact that the dependence of agriculture on rainfall in Odisha has declined slightly possibly because of the developments in irrigation and other facilities.

Key words: Agriculture, weather, regression, modelling, aridity index

JEL Classification: Q18, C51

Introduction

Weather is a critical factor influencing the production of crops in any region. It is viewed by agronomists and meteorologists as a dominant climatic element influencing yield and acreage behaviour of crops while agricultural economists look at the levels of technology and other measurable inputs (Offutt *et al.*, 1987). The weather, like other inputs such as land, labour, high-yielding variety (HYV) seeds, fertilizers, pesticides, etc. is also a direct input to agriculture. While both sets of factors are crucial, measurable inputs are controllable, weather is not. More specifically, in a state of backward agriculture where the technology adoption and diffusion are very slow or nearly nil, the weather factors count more than others because of their direct and indirect effects on crops. The functional relationship between weather and yield is as much complicated as the term 'weather' itself. In a broad definition of the term, many factors can be included in 'weather'. However, the complexity of the term 'weather' gets resolved as only precipitation[1] and temperature are mostly considered in many studies as the important factors out of many others like wet days, humidity, sunshine, wind velocity, storm, snowfall, etc. due to lack of data availability on all those factors (Stallings, 1961). The functional relationship between weather factors (like rainfall and temperature) and the crop yield remains the most elusive and mysterious till today and a matter of intense debate, though research in this area dates back to 1900s (Tannura *et*

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[1] Both precipitation and rainfall are used as synonyms.

al., 2008). In spite of the daunting efforts being made by the research community to study the nature of relations existing between these two sets of variables, the problem continues to remain unresolved.

The point that gives more impetus to initiate fresh research is that understanding of the precise linkage between weather and crop yield could provide potential implications of the effects of climate change on food security and consequently, it can facilitate some kind of institutions for securing crops from the vagaries of weather.

In India, research in the area of crop-weather relations has been relatively very little[2]. Some studies (Cummings *et al.*, 1969; Rao, 1964; Sreenivasan, 1973; Shaha and Banerjee, 1975; Ray, 1981; Arif, 1988; Parthasarathy, 1992; Kumar *et al.*, 2011) have used the simplest way of linear model wherein the meteorological factors are directly included in a linear fashion. In the present paper, we have used airidity index in the econometric model to measure the impact of weather on crops. The specific objectives of the study were: (i) to examine the impact of weather on rice yield in Odisha since rice is the staple food and covers about 70 per cent of cultivated area in this state, (ii) to show both theoretically and empirically the superiority of aridity index approach over the complicated weather index developed by Doll[3] (1967) or the simplest way of linear regression model by taking the individual meteorological factors, (iii) to verify the hypothesis of changing rainfall dependence of rice yield through this aridity index approach for three different periods, and (iv) to construct a new weather index for examining the favourableness of weather each year. The aridity index approach is based on the works of Lang (1920), Köppen (1936), De Martonne (1926), Ängstrom (1936) and Thornthwaite (1948) as discussed in Oury (1965) in his study and others like Selyaninov (1928) and Ped (1975). These indexes were obtained by combining monthly data on precipitation and temperature.

Theory of Crop-Weather Modelling: Concepts of Aridity, Moisture and Technology[4]

Most of the researchers like Oury (1965), Stallings (1961) and Shaw (1964) have rejected the direct use of meteorological variables like rainfall and temperature primarily on the ground that the functional relationship between these variables and yield is not known.

Oury (1965) has recommended the inclusion of aridity index into the econometric model of crop weather relation. He has argued that the term 'weather' includes many components and it is very difficult to limit only to one factor since they are interrelated. Again, it is also unrealistic to select one of them. Secondly, inclusion of several weather factors in an additive relationship runs the risk of assuming an inaccurate mathematical relationship among them. It also consumes too many degrees of freedom in variance analysis in small samples. He was the first to suggest the use of aridity indexes which were basically developed to classify the climate of different regions. It was assumed that the composite index which is used to distinguish dry climates from moist climates geographically at one point of time can be used historically. Thus, an index differentiating excess moistures to dry or insufficient moistures from one location to another during a particular year can be used to reflect weather variation over the years and it provides an operational tool for the production analysis. He has cited such indexes in his study starting with Thornthwaite. Thornthwaite (1948) had emphasized the importance of evaporation as a weather factor and had discovered the process of 'evapotranspiration' which combines both evaporation from soil and transpiration from plants. It represents the reverse of precipitation. An increase in water supply leads to rise in evapotranpiration to a maximum limit in such a way that depends only on the environmental climate. The maximum is called potential evapotranspiration, different from actual evapotranspiration. However, it is very difficult to measure this potential evapotransipiration directly. But experimentally it can be determined. Nevertheless, it is an important climatic element. He had also discovered the growth rate of evapotranspiration depending on four elements:

[2] Vaidyanathan (1980) reviewed some studies on crop weather relations in India which mostly used either the multiple linear regression models or the curvilinear model or sometimes Fisherian integral technique which is similar to curvilinear technique. But, there have been no studies using the index method so far to our knowledge.

[3] Doll (1967) too included directly the rainfall in his analysis and also ignored the temperature which is a crucial factor influencing crop growth.

[4] The development of this section is drawn from Oury (1965), Thornthwaite (1948), Ångström (1936) and Meshcherskaya and Blazhevich (1997).

climate, soil moisture supply, plant cover and land. The equation is based on von't Hoff Law[5] and written as Equation (1):

$$v = a\frac{bce^{ct}}{\left(e^{ct}+b\right)^2} \quad \ldots (1)$$

where, 't' is the temperature (°C); a, b, and c are constants; and e is the base of natural logarithm and v is the optimum growth rate. Here, the numerator represents the growth stimulating factor and the denominator shows the growth inhibiting factor. The equality between these two leads to optimum temperature. Unfortunately, Thornthwaite index is not available for operational purpose as cited by Oury (1965).

Recognizing temperature as the major factor for evaporation, Lang (1920) had suggested one simple method. He used a coefficient of humidity which is defined as the ratio of precipitation or rainfall of a year to the sum of mean temperatures of the frost-free months divided by twelve. It is written as Equation (2):

$$I_L = \frac{P}{\frac{1}{12}\sum T > 0} \quad \ldots (2)$$

where, P is the sum of the precipitation of a year and T is the annual mean temperature. The ratio is related directly to precipitation and inversely to temperature. De Martonne (1926) modified the Lang's method and used it as a coefficient of humidity which is simply the ratio of precipitation to temperature by adding 10 in the denominator to avoid negative values of the ratio, i.e.

$$I_M = \frac{P}{T+10} \quad \ldots (3)$$

De Martonne applied a similar coefficient for characterizing various months, in which case the coefficient takes the form of Equation (4):

$$I_M^I = \frac{P.12}{T^I+10} \quad \ldots (4)$$

where, P is the precipitation and T^I is the mean temperature of the month. However, as Oury (1965) mentioned that the index can be for any number of cumulated months, it can be written as Equation (5):

$$I_M^{II} = \frac{\sum_{i=1}^{n} P_i.12}{n} \Bigg/ \frac{\sum_{i=1}^{n} T_i}{n} + 10 \quad \ldots (5)$$

Here, P_i is monthly precipitation of the i^{th} month (in millimeters), T_i is the average monthly temperature (°C) for the i^{th} month and n stands for the number of months[6].

Ångström (1936) suggested a modification in De Martonne's index of aridity. He found that the index of aridity was proportionate to duration of precipitation, which, in turn, was directly proportionational to the amount of precipitation and inversely proportionational to an exponential function of temperature. His humidity coefficient is written as Equation (6):

$$I_A = \frac{P}{1.07^T} \quad \ldots (6)$$

In this method, the denominator of the fraction doubles with each rise of 10 °C in temperature, in accordance with von't Hoff's law. Ängstrom (1936) states that this function coincides for the positive values on 'T' closely with the humidity factor of De Martonne (1926). For the negative values on 'T', it possesses the advantage to be continuous. Consequently, it is applicable to such conditions where the temperature goes below -10 °C. Further, he states that 'it is proportional to the time of precipitation, with which it in fact may be brought to coincide, if the unit of time is chosen properly'.

In line with Koppen (1936) and Lang (1920), Selyaninov (1928) suggested one index commonly known as 'Hydrothermal Coefficient' (HTC) and Ped (1975) suggested the dryness index 'S_i'. Both these indexes use monthly precipitation and temperature data. The HTC index is written as Equation (7):

$$HTC = \sum_{i=1}^{n} P \Bigg/ 0.1\sum_{i=1}^{n} T \quad \ldots (7)$$

[5] The von't Hoff law of physics states that the velocity of a chemical reaction is an exponential function of temperature. It has been applied by biologists to physiological processes. The procedure usually adopted is to determine a temperature coefficient as the quotient of two growth rates separated from each other by a 10 °C interval of temperature.

[6] Koppen (1936) modified De Martonne's Index and developed three different but related indices as follows:

$$I_{K1} = \frac{8P}{5T+120},\ I_{K2} = \frac{2P}{T+33},\ I_{K3} = \frac{P}{T+7}$$

where, ΣP is the summation of precipitations and ÓT is the summation of temperatures higher than 10 °C for some time period (months and vegetation season). The value of HTC less than 0.5 (HTC< 0.5) shows desert like drought, equals to 0.6 ((HTC= 0.6) shows a weak drought; and less than or equal to 0.7 ((HTC ≤ 0.7) depicts a dry condition. The value more than or equal to 1 (HTC ≥ 1) implies sufficient moistures. This method is somewhat similar to Lang's formula except that the denominator is multiplied with 0.1.

The Dryness Index 'S_i' suggested by Ped (1975) can be written as Equation (8):

$$S_i = \frac{\Delta T}{\sigma_{\Delta T}} - \frac{\Delta P}{\sigma_{\Delta P}} \quad \ldots(8)$$

where, ΔP and ΔT are precipitation and temperature anomalies, respectively and $\sigma_{\Delta P}$ and $\sigma_{\Delta T}$ are their respective standard deviations at the i^{th} station, calculated from long-term series of data. The procedure involved in calculating these anomalies is quite complicated since one needs to consider the total area and corresponding area of the i^{th} administrative region. Details can be found in Ped (1975).

In general, these aridity index formulae show that when rainfall/precipitation is higher and temperature is lower, it leads to high aridity index and subsequently, high moisture and vice versa. On a comparative scale, if the De Martonne index value lies below 20 (I_M < 20), then drought characterizes, and if it is less than 10 (I_M < 10), then it is desert-like situation. Similarly, a comparative scale can be drawn for Angstrom index. However, the fact to be noted here is that the same amount of precipitation does not have the same meaning in all the seasons because it depends on the evaporation which varies from season to season; it is substantial in summers and less in winters. Thus, the aridity index will have a negative or positive effect on crops depending upon its biology and phonological growth period (Oury 1965).

Among other works in this area, Sazonov (1991) drought indices, Meshcherskaya and Blazhevich (1977) index and Palmer (1965) drought index are worth mentioning. The indices suggested by Sazonov are the differences in the number of stations (in tens) at which dry and surplus moisture conditions are observed, as determined by the graphic joint analysis of precipitation and temperature series. The disadvantage of these indexes is the artificial restriction of the range of their variations (Meshcherskaya *et al.*, 1989). In another paper, Meshcherskaya and Blazhevich (1977) have suggested two indices: a drought index and an excessive moisture index, which for the first time in explicit form included the areas of distribution of precipitation and temperature in the given gradations. These are very complicated indices and are beyond the scope of this paper to discuss.

The study on the influence of weather on crop was initiated long before the study of trend representing the technological progress or technology effect on yield. It was not a matter of much interest to the researchers before 1940s (Shaw, 1964). Earlier, the yield was perceived to be a function of weather and some direct measurable inputs. However, later on it was realized that a substantial part of variation in yield has been due to technology and it needs to be removed before analyzing the weather impact on crop yield. Since then many studies have incorporated trend variable in a linear fashion in crop-weather models showing that yield is a monotonic increasing function of technology (*see* Morgan, 1961; Thompson, 1969; 1970; Parthasarathy *et al.*, 1992; Lobell *et al.*, 2007; Tannura *et al.*, 2008; Kumar *et al.*, 2011). However, Shaw (1964) categorically rejected the use of linear trend because it first systematically underestimates and then overestimates the yield effect of changing technology.

Suppose that there are two technological spurts which stimulate more crop production at two different points of time, as shown in Figure 1. Assume that the

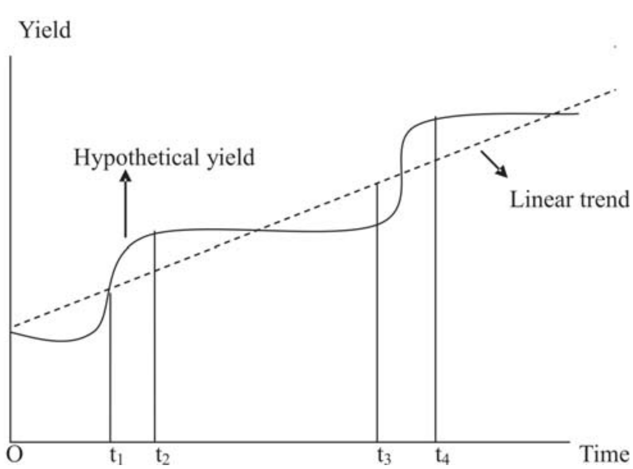

Figure 1. Linear and hypothetical trend of yield

Source: Taken from Shaw (1964)

first one is due to fertilizer at time t_1, after which the hypothetical yield (representing actual yield here) curve becomes steep upwardly, showing the sudden rise in crop yield.

After it reaches t_2, assume that it becomes flat because every farmer adopts this technology. Again, assume that at t_3 the HYV seeds technology comes and there is a rise in yield, making the hypothetical yield curve steeper upwardly. However, the linear trend shows a constant rise of yield. Therefore, within the range Ot_1, the trend yield is more than the actual yield and in the range $t_1 t_2$, the linear trend yield is less than the actual yield. Same thing happens if we see the impact of HYV seeds technology. Thus, the linear trend sometimes underestimates and sometimes overestimates the yield effect of technology variation. More importantly, the actual trend resembles more like a logistic curve than a linear curve.

Aridity Index and Econometric Modelling of Weather Impact on Crops

To estimate variations in yield due to weather and technology, we rely on econometric models where crop yield is considered as a function of aridity index for the measure of weather and a trend acting as technological change. Here, the average rainfall and the average of daily maximum temperatures of June, July and August are taken as the growing period meteorological factors. This study intended to examine the impact of weather on rice yield in Odisha, an important agricultural state of India. The inclusion of aridity index in the model also strengthens the argument that the yield response of precipitation 'P' is not constant, rather a function of temperature 'T' and vice versa (Oury 1965). Because the same amount of precipitation will have different effects if accompanied by varying levels of temperature and vice versa (Stallings, 1961). Thus, the response functions of two factors are interrelated. Here, we incorporated the aforementioned aridity indexes into the econometric models. The cubic function of time t as a technological progress, following Doll (1967), was included into the econometric models. As pointed out by him, the linear trend cannot capture the substantial part of yield fluctuations. It is because the linear trend assumes a constant rate of upward technological change, but the one which comes closer to reality is the logistic shape of the trend which can be written as a cubic function of time. The quadratic-term of time is assumed to retain a negative sign theoretically as the yield curve becomes flat or declines, once a particular technology is adopted completely. Similarly, the cubic function captures the fact that due to progress in technology again, viz. shifting cultivation to better soil, increased managerial abilities and other systematic phenomena, the yield curve may turn convex from below leading to 'technological explosion' (Doll, 1967). This cubic-term is assumed to be positively related to yield.

For establishing the relative strength of aridity index models empirically we also included the linear model where both weather factors were modelled in an increasing monotonic fashion. The final models over the time t (= 1950-51 to 2009-10) were:

$$Y = \alpha_0 + \alpha_1 P + \alpha_2 T + \alpha_3 t + \alpha_4 t^2 + \alpha_5 t^3 + \varepsilon \quad \ldots(9)$$

$$Y = \beta_0 + \beta_1 \left(\frac{P}{T}\right) + \beta_2 t + \beta_3 t^2 + \beta_4 t^3 + \varepsilon^{I} \quad \ldots(10)$$

$$Y = \mu_0 + \mu_1 \left(\frac{P}{T+10}\right) + \mu_2 t + \mu_3 t^2 + \mu_4 t^3 + \varepsilon^{II} \quad \ldots(11)$$

$$Y = \theta_0 + \theta_1 \left(\frac{P}{1.07^{T}}\right) + \theta_2 t + \theta_3 t^2 + \theta_4 t^3 + \varepsilon^{III} \quad \ldots(12)$$

$$Y = \pi_0 + \pi_1 \left(\frac{P}{0.1T}\right) + \pi_2 t + \pi_3 t^2 + \pi_4 t^3 + \varepsilon^{IV} \quad \ldots(13)$$

where, Y is the yield of crop per hectare; P is the average precipitation during the selected period (growing period) in mm; T is the temperature of the same period (°C); α_0, β_0, μ_0, π_0 and θ_0 are the constant intercept terms; β_1, μ_1, θ_1 and π_1 are the coefficients of different aridity indexes; other parameters are coefficients of trend variable; and ε^{I}, ε^{II},…., ε^{IV} are error-terms.

The results of response to precipitation and temperature are given in Table 1. Two points can be observed from the above models and Table 1. First, the response function of one factor as argued before is also a function of the other factor. Second, the response function of temperature is negative in sign (for positive coefficient of aridity index), showing that as temperature rises, yield declines after the optimum

Table 1. Response to precipitation and temperature

Equation No.	Response to precipitation	Response to temperature
9.a	$\frac{dY}{dP}=\alpha_1$	$\frac{dY}{dT}=\alpha^2$
10.a	$\frac{dY}{dP}=\beta_1\frac{1}{T}$	$\frac{dY}{dT}=-\beta_1\frac{P}{T^2}$
11.a	$\frac{dY}{dP}=\mu_1\frac{1}{T+10}$	$\frac{dY}{dT}=-\mu_1\frac{P}{(T+10)^2}$
12.a	$\frac{dY}{dP}=\theta_1\frac{1}{1.07^T}$	$\frac{dY}{dT}=-\theta_1\frac{P\log 1.07}{1.07^T}$
13.a	$\frac{dY}{dP}=\pi_1\frac{1}{0.1T}$	$\frac{dY}{dT}=-\pi_1\frac{P}{0.1T^2}$

level. Thus, it reflects the fact that instead of taking the quadratic term to allow for diminishing returns to weather factor, we can solve this problem by taking the aridity index[7]. In this way, it serves two purposes; first, it allows the diminishing returns to weather variable, and second, it saves the degrees of freedom by not taking one more variable. Moreover, the index is free from units of measurement of variables.

Model Evaluation

The models using different aridity indexes and direct meteorological parameters were compared by using two techniques, viz. root mean squared error (m_r) and efficiency of prediction (n_p) following Adekalu and Okunade (2008) and Pirmoradian and Sepaskhah (2006). These statistics reveal the efficiency of the estimated models. These measures are defined as follows:

$$m_r=\sqrt{1/n\sum_{i=1}^{n}(M_i-P_i)^2} \quad \ldots(14)$$

$$n_p=\frac{\left[\sum_{i=1}^{n}\left(M_i-\bar{M}\right)^2-\sum_{i=1}^{n}\left(M_i-P_i\right)^2\right]}{\left[\sum_{i=1}^{n}\left(M_i-\bar{M}\right)^2\right]} \quad \ldots(15)$$

where, M_i is the observed yield, P_i is the predicted yield, and $\bar{M}$ is the mean of observed yields. The value of m_r shows the accuracy of the model; lower the value, more accurate is the model. The value of n_p indicates the ability of the model to predict the measured values. The maximum value of n_p is unity, which indicates the perfect prediction ability of the model.

Empirical Verification of Models

The econometric models discussed above have been empirically verified in this section. The data of sixty years from 1950-51 to 2009-10 were compiled from various issues of Centre for Monitoring Indian Economy. Meteorological data are taken from Indian Meteorological Department, Pune. We started with the linear model where both the factors, rainfall and temperature, were monotonically and additively modelled. The estimated model results were:

$$Y = 18.08 + 0.873P - 50.53T + 30.46t - 0.715t^2 + 0.009t^3 \quad \ldots(16)$$

(0.87) (1.16) (-0.77) (1.83) (-0.97) (1.01)

$R^2=0.68$, df=54, DW =1.67, m_r = 172.12, n_p= 0.6352

The figures within the brackets below each coefficient are student-t statistic values of respective coefficients. Except the trend variable t, all estimated coefficients are statistically not significant. This implies that when weather variables like rainfall and temperature are modelled linearly, their influences on the rice yield are not significant statistically. While the rainfall or precipitation P has a positive sign, the coefficient of temperature has a negative sign. The technological progress, reflected in t variable, shows that only the linear term is significant at 10 per cent level, but the theoretical signs of quadratic and cubic-terms of t are intact, saying that course of progress is very much like logistic curve.

When combined into one variable, due to concomitant interactions, weather variables may have significant effect on the crop yield. For testing this, we examined all models with the aridity indexes discussed above. The estimated models with various aridity indexes for the period 1950-51 to 2009-10 in Odisha are given below:

Model with Lang Index:

$$Y = 224.01 + 2.41\left(\frac{P}{T}\right) + 29.22t - 0.61t^2 + 0.007t^3 \quad \ldots(17)$$

(1.08) (2.21) (1.88) (-1.07) (1.02)

$R^2=0.68$, df =55, DW= 1.71, m_r = 170.81, n_p =0.7292

[7] Doll (1967) used the quadratic-term of his weather index having negative sign to allow for diminishing returns to the weather variable. But in the case of small sample using too many variables consumes many degrees of freedom rendering inefficient estimates of the parameters.

Model with De Martonne Index:

$$Y = 300.28 + 2.36\left(\frac{P}{T+10}\right) + 29.16t - 0.61t^2 + 0.007t^3 \quad \ldots(18)$$

(1.07) (2.51) (1.88) (-1.06) (1.02)

R^2 =0.68, df=55, DW =1.71, m_r = 170.63, n_p = 0.7298

Model with Ångström Index:

$$Y = 295.73 + 4.93\left(\frac{P}{1.07^T}\right) + 29.21t - 0.61t^2 + 0.007t^3 \quad \ldots(19)$$

(1.31) (2.23) (1.88) (-1.09) (1.02)

R^2 =0.68, df=55, DW= 1.70, m_r =169.88, n_p = 0.7321

Model with Ped's HTC Index:

$$Y = 227.3 + 2.35\left(\frac{P}{0.1T}\right) + 29.12t - 0.61t^2 + 0.007t^3 \quad \ldots(20)$$

(1.24) (2.42) (1.88) (-1.09) (1.02)

R^2 =0.68, df=55, DW =1.71, m_r =170.56, n_p=0.7287

Some important points observed from the results cited above are: First, the estimated coefficient of aridity index variable in each model was positive, as expected theoretically. Coefficient values varied between 4.93 and 2.35, which denoted high influence of aridity index variable on yield of rice crop. Moreover, on collapsing the precipitation (P) and temperature (T) variables into one aridity index by their physical relationship, each regression equation came out to be more suitable since the coefficients were significant statistically at 5 per cent level of significance.

Compared to these index-based model results, the linear model did not render satisfactory results as the coefficients were not statistically significant. Second, the estimated coefficient of trend variable t in each model was also positive and statistically significant at 5 per cent level. It is seen that when the net influence of weather variables was allowed, the coefficient estimates of trend t did not change from model to model. As stated above, in a paradigm shift in technological progress, negative sign and positive sign respectively of coefficients of quadratic and cubic-terms of t can be expected in a given yield function. Here, though the quadratic and cubic-terms of t were not statistically significant, their coefficient signs were theoretically ensured. Thus, the trend and weather variables were orthogonal. These results (the linear trend term t being significant and non-significant quadratic and cubic terms) also showed that the technological transformation was in its initial phase where the yield was linear monotonic function of trend variable t, a proxy for technological progress. It ascertains the fact that technological transformation has been very low in the agriculture of Odisha.

Going deeper into the comparison of models, we could observe that though the R^2 values were almost similar to that of the linear model, statistics for model accuracy and prediction improved in the aridity index based models as the number of variables declined. The values of root mean squared error (m_r) and efficiency of prediction (n_p) ensured that the aridity index approach was better than the direct use of variables in the linear model. The values of m_r were relatively lower in the case of aridity index models than the linear model where both precipitation and temperature were modelled directly. Again, among aridity index models, it was found that the Angstrom index model performed better than other index models, because the value of m_r was 169.88, the lowest among values of other index models and the value of n_p was 0.7321, the highest among other index models. Moreover, the Durbin-Watson (DW) statistics for serial correlation among the residuals improved in the aridity index models compared to that in the linear model.

Testing the Hypothesis of Changing Rainfall Dependency of Rice Yield

Since independence the agriculture in India has experienced three phases of development so far as policy implementation is concerned. The first phase was of the period 1950-65 when the agricultural sector was quite underdeveloped and the country was the net importer of food grains under the schemes like PL 480 from the U.S. (Dantwala, 1991). Many western scholars apprehended that India will not be able to feed its growing population. Thus, it was suggested that the triage principle should be applied in the case of India since it is beyond redemption (Padock and Padock, 1968). During this phase, agriculture was more dependent on rainfall since there was not much development in irrigation facilities. Then the second phase started from 1965 which marked the onset of 'Green Revolution' in Indian agriculture. There was widespread adoption of HYV seeds of rice and wheat with strong government support in the form of input

Table 2. Estimated yield equations for three sub-periods of agricultural development in Odisha

Sub-period	Constant	Ångström Index	t	t^2	t^3	R^2	D.W.
1950-65	68.86**	7.38**	-43.84**	22.97	-0.84	0.74	1.72
1966-90	-64.72**	5.54*	20.04**	-8.57*	0.11	0.65	1.78
1991-2008	-50.07**	4.31	28.95**	-3.06	0.21	0.57	1.25

Note: ***, ** and * denote significance at 1 per cent, 5 per cent and 10 per cent levels, respectively.

Table 3. Yield dependency of rice on rainfall

Period	Growing season rainfall			Yield of rice			Rainfall dependency	
	Mean	SD	CV	Mean	SD	CV	AI	ε_{yp}
1950-65	251	25.53	10.15	712	200.59	28.16	7.38	0.4127
1966-90	225	27.98	12.40	970	203.38	20.97	5.54	0.2031
1991-08	248	49.51	19.94	1361	253.11	18.60	4.31	0.1217

Notes: ε_{yp} = Yield elasticity of rainfall and AI = Coefficient of Ångström Index in the yield equation in Table 2. SD and CV denote standard deviation and coefficient of variation, respectively.

subsidies and credit for purchasing machineries etc. Efforts on irrigation were also put on high priority since fertilizer and assured irrigation were complementary to it (Kumar and Rosegrant, 1994). Even farmers responded positively to it by developing private irrigation facilities like tube-wells in large numbers (Bhalla and Singh, 1997). However, the controversy occurred regarding the rainfall dependence as empirical evidences show two counter arguments. The first says that adoption of HYV seeds along with increasing fertilizer-use leads to the rising water requirements. Its susceptibility to flood and drought has also gone up (Dastane *et al.*, 1970). The counter argument with empirical evidence was lent by Lahiri and Roy (1985) which says that since adoption of HYV seeds along with fertilizer was also accompanied by increasing irrigation facilities, the rainfall dependency has slightly declined.

The third phase started with the new economic policies of 1991[8]. The quantitative restrictions were lifted from agricultural exports and imports. The crop diversifications were encouraged towards more commercial and cash crops. The VIIIth Plan initiated one special foodgrain production programme, namely, 'Integrated programme for rice development'. Restrictions on export of common rice were lifted in 1992. More rice production was also encouraged. The total subsidies, though expected to be reduced since many experts pointed out its deleterious effects on other developmental activities (Dhawan, 1995), did not decline (Gulati and Sharma, 1997).

Considering the above facts, we tested the hypothesis of rainfall dependency by dividing the entire period into three sub-periods, viz. pre-green revolution period (1950-65), post green revolution period (1966-90) and liberalized period (1991-2008). We estimated the yield equations for these three sub-periods by using the Ångström Index (AI)[9], that is, Equation (12). Results are given in Table 2. Then, the variability of rainfall and yield, and the elasticity[10] of rice yield to rainfall were calculated using the estimated parameters of three equations (*see* Table 3).

Many inferences can be drawn from the Table 3. A look at rainfall data reveals that during the liberalized era, there have been much fluctuations in rainfall as

[8] The process of liberalization started in 1980s when the government started the initiatives to liberalize the economy. However, the liberalization as a full-fledged economic policy was adopted in 1991.

[9] Other aridity indexes can be used for this purpose. Keeping the view that this index model is better than others from the point of prediction efficiency to represent the weather components in the economic analysis of agriculture, we used this one. This index has also been used by other studies like Zhang and Carter (1997).

[10] From the Ångström Index based model (12), the elasticity was calculated as: $\varepsilon_{YP} = \frac{dY}{dP}\frac{P}{Y} = \left[\theta_1 \frac{1}{1.07^T}\right]\frac{P}{Y}$

indicated by the higher values of coefficient of variation (CV) and standard deviation (SD). But, the average figure is slightly lower in that phase than the first phase. The rice yield figure shows a wide variability in the coefficient of variation in all the three periods. However, compared to other two periods, the third period performed better, as the mean yield was 1361 kg/ha and C.V. was also 18.6. It was because after liberalization the price fluctuation in rice was less and there has been a marked development in the irrigation facilities. The rainfall dependency measured by the elasticity of yield to rainfall at the mean level, through the Angstrom index depicts a declining trend, from 0.41 during the first period to 0.20 during the second and 0.12 in the third period, respectively. This could be attributed again to irrigation facilities developed so far. It also supported our hypothesis that the rainfall dependency of yield was declining gradually because of the irrigation developments accompanied by use of HYV seeds, fertilizer and other inputs along with access to credit facilities. However, rainfall still plays a crucial role in the agricultural sector of Odisha since more than 45 per cent of the agricultural lands are not irrigated, but are rain-fed.

Weather Index and Some Implications

In the previous section, we have compared the rainfall dependency of yield for the three periods. When it came to the yearly comparison, whether it was a favourable or unfavourable weather on crop, it was found that this periodic comparison did not extend much light on that issue. Therefore, it was considered useful to quantify the level of favourableness of weather on crop yield on yearly basis for which we needed to construct a single weather index number. This provided an objective measurement of how 'good' or 'bad' weather was for rice yield during a particular year. Doll (1967) has developed one weather index (W) 'as the ratio of yield predicted for the actual weather that occurs during the year to the yield predicted had average weather occurred in the year' (p. 87). The weather index can be written as Equation (21):

$$W_t = \frac{\hat{y}_t}{\hat{y}_t^{avg}}.100 \qquad \ldots(21)$$

where, $\hat{y}_t$ is the predicted yield from the regression model with actual value for weather variables, i.e., actual values of aridity index, and $\hat{y}_t^{avg}$ represents the predicted yield from the model with average values for aridity index. The strength of this method is that it assumes the weather index as the objective quantification of weather that affects crop development. This method assumes that the model is correctly specified and that the predicted yield represents the yield that would have occurred if outside factors such as diseases, insects, specific weather events and weather outside the main growing season rainfall had not affected yields (Tannura *et al.*, 2008). We used the Ångström index (AI) model for constructing the weather index, though other aridity index models could be used for the purpose of comparing yearly weather patterns but AI model has proved to be a better index in explaining weather impact.

The weather index values have been plotted year-wise in Figure 2. A perusal of Figure 2 revealed a structural break in the series at 1979 where the weather index is more than the base value. There are fluctuations in the index caused by weather but overall there is a rising trend reflecting though lately, the role new technology accompanied by development in irrigation facilities has played in the agriculture of Odisha. Going deeper into the analysis of weather index we could observe that years from 1986 to 1993 were bad crop years, followed by 2001 and 2003 so far as the impact of weather was concerned.

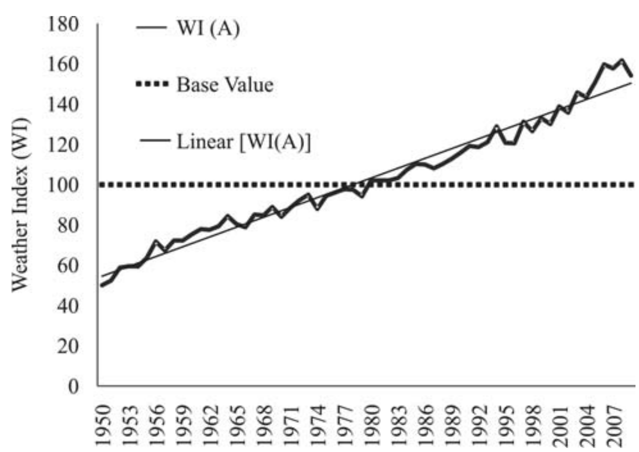

Figure 2. Weather index and rice yield of Odisha: 1950-2009

Conclusions

The arguments and comparative tests in this paper have suggested the usefulness and effectiveness of using the aridity index variable in the econometric models to measure the impact of weather on crop yields. This approach is an improvement over the direct use of meteorological factors in linear regression model, as has been evidenced from the results. This is also a better approach than Stallings' index (1961) or Shaw's index (1964) approach in the sense that Stallings' approach hypothesizes that the influence of weather on crop yields from a experimental plot can be obtained once the contribution of trend is removed assuming that all practices are held constant. The remaining variation in yield from year-to-year is the indication of influence of weather once trend is removed as soil fertility changes. Shaw's approach is also similar to Stallings' approach, except the process of trend removal. However, both the approaches are castigated on the ground that both are based on plot data approach and secondly Stallings used a linear trend while Shaw used moving averages.

In this paper, we have incorporated a cubic function of time which is an improvement over the linear trend. It instills more flexibility into the model and captures the fluctuations in yield due to different paradigms of technology transformation. Again, we have verified the hypothesis of changing rainfall dependence of yield by estimating the rainfall elasticity of yield at the mean where the elasticity depends not only on the mean rainfall but also on mean temperature based on the earlier argument that the yield is dependent on both rainfall and temperature. The model can be used universally for any crop and for any area. The concept has some relations with biophysics of plant-weather interaction. Agronomically, it also recognizes the fact that the impact of one variable is dependent on the other (Oury, 1965). Statistically, it helps to remove the built-in effect of inter-correlation between precipitation and temperature. Moreover, it consumes less degree of freedom which has a good effect on statistical significance of estimated results.

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