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**Modelling the Effects of Climate Change on Agriculture in South Africa:
The Case of the Western Cape**

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**Modelling the Effects of Climate Change on Agriculture in South Africa:
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Abstract

Two different methodologies are linked to determine the effects of climate change on the Western Cape farm sector in South Africa. First, it uses a general circulation model to model climate change. Second, a sectoral mathematical programming model is used to determine these effects on key variables of the farm economy. Results indicate that less water will be available to agriculture. This will have a negative overall impact, with both producer and consumer welfare decreasing. Total employment in the farm sector will also decrease as producers switch to extensive farming. The total decline in welfare falls disproportionately on the poor.

Key words: Climate change, South African agriculture, mathematical programming

1. Introduction

At any one location, year-to-year variations in weather can be large, but analyses of meteorological and other data over large areas and over period of decades or more have provided for some evidence for some important systematic changes in weather over the past century (IPCC, 1995a). For example, global mean surface air temperature has increased by between 0,3 and 0,6 degrees centigrade, with some regional variations, since the late 19th century.

Considerable progress has been made in the 1990s in the modelling of climatic change¹. Three advances are of particular interest. First, in order to distinguish between natural and anthropogenic influences on climate, the inclusion of effects of sulphate aerosols in addition to greenhouse gases have led to more realistic estimates of human-induced radiative forcing. Second, simulations with coupled atmosphere-ocean models have provided important information about decade to century time-scale natural internal climate variability. Third, there has been a shift of focus from studies of global-mean changes to comparisons of modelled and observed spatial and temporal patterns of climate change (IPCC, 1995a). Two results from these models are important: The balance of evidence suggests that there is a discernible human influence on global climate, and climate is expected to continue to change in the future.

A range of future scenarios, incorporating future greenhouse gas and aerosol precursor emissions based on assumptions concerning population and economic growth, land-use, technological changes, energy availability and fuel mix during the period 1990-2100, have been developed. Global circulation models (GCMs) use these emissions to develop projections of future climate by linking the global carbon cycle and atmospheric chemistry (IPCC, 1995b). However, the limitations of these GCM results should be recognised when quantifying effects of climate change. Due to the complex nature of atmospheric conditions giving rise to precipitation, there is more confidence in temperature predictions than in hydrological predictions. Confidence is also higher in broad scale (global and hemispheric) climate predictions than in regional predictions. In spite of these limitations, these results remain important, as they provide the only indication of the potential effects of climate change, particularly precipitation, on regions that are to a large degree dependent on favourable climatic conditions for securing livelihoods for the inhabitants. One such region is the Western Cape, where agricultural production based largely on irrigation, provides the backbone of the regional economy.

Against this background, the objectives of this paper are twofold. First, it uses a general circulation model (GCM) to model future climate change in the Western Cape, particularly with respect to precipitation. Second, a sector mathematical programming model of the Western Cape farm sector is used to incorporate the predicted climate change, specifically rainfall, from the GCM to determine the effects on key variables of the regional economy. Ideally, each farm in a region should be modelled independently, with its own unique set of production conditions. However, this is hardly feasible and not necessary when production conditions are broadly homogeneous over an area. For both the GCM and sector mathematical programming model, the Western Cape has been divided into ten relatively homogeneous regions. This demarcation follows the Statistical Regions constituting the former Development Region A of South Africa, but includes a new Region 10 and leaves out the districts which were incorporated into the new Northern Cape Province. The Western Cape region modelled here thus closely approximates the Western Cape Province as defined in the 1997 Constitution.

¹ See Dinar et al (1998) for a comprehensive discussion of the literature on the measuring and modeling of the impact of climate change in agriculture and other sectors.

The paper is organised as follows: The modelling of climate change in the Western Cape, using a GCM, is discussed next (Section 2). This is followed by a description of the regional mathematical programming model of the Western Cape farm economy in Section 3. The modelling of the effects of future climate change on the Western Cape farm economy is done in Section 4. Some conclusions follow in Section 5.

2. Modelling climate change in the Western Cape

2.1 General

There are a host of GCM models developed by various meteorological offices world-wide. The model used to predict climate changes for the Western Cape region was developed by the Hadley Centre for Climate Prediction and Research of the United Kingdom Meteorological Office. The model gives pessimistic but robust predictions and is generally accepted as reliable. It is currently being used in the South African Country Studies Programme on Climate Change.

There are two options when implementing this model: with and without the potential mitigating effects of sulphate aerosols. Climate change values for this paper were derived by implementing the Hadley Centre Unified Model with no sulphates (http://www.metogovt.uk/sec5/NWP/NWP_sys.html). The model was implemented by the Computing Centre for Water Research (CCWR) and the resultant values represent a worst case scenario for South Africa (Hewitson, 1998). This GCM predicts a temperature rise of 2,5-3,0 degrees centigrade for South Africa by the time that atmospheric CO₂ levels have doubled from their pre-industrial levels. Erring on the side of caution, this means that significant climate change can be expected at latest by the year 2050 (and quite possibly earlier) (Hewitson, 1998).

Precipitation data used in the model consisted of annual and monthly means from the past 30 years. These data at 1 minute resolution were re-sampled to a quarter degree resolution since predictions at the 1 minute resolution were considered as unreliable because of modelling limitations (CCWR). Predicted changes in monthly precipitation were provided for each quarter degree grid square by the CCWR. The annual change for every quarter degree grid square was derived by adding up the changes for each of the 12 months. These precipitation data were then spatially intersected with the ten homogenous regions of the Western Cape to arrive at a map where every region is assigned a mean precipitation value based on the values of all the quarter degree grid squares intersecting that specific region.

Previous experience with analyses of these data (Erasmus, Kshatriya, Mansell, Chown & Van Jaarsveld, in review) has shown that temporal variability is a dominant feature. Annual means therefore tend to disguise seasonal effects of climate change. In order to account for this, seasonal data were represented by values for February and August. These months were chosen because a factor analysis (Statsoft Inc, 1995) of the 12 monthly rainfall shows that February rainfall contributed most to Factor 1, explaining 56% of the variance in rainfall data, and August rainfall contributed most to Factor 2, which explained 37% of the variance in the data.

2.2 Results

Table 1 contains a summary of the future changes in precipitation that can be expected in the Western Cape. All the sub-regions have lower predicted precipitation values in February and August, as well as mean annual precipitation, compared to present values. There is a relatively wide range in the predicted decrease in mean annual precipitation from just over 3 per cent in Sub-region 2 to 27 per cent in Sub-region 10. Generally, it seems that the drier areas will be much more affected.

/Table 1/

3. Modelling the farm sector in the Western Cape²

3.1 Basic considerations

The theory for the construction of sector mathematical programming models has been applied to South African agriculture on a number of occasions³. In this paper, these procedures are used to model the Western Cape farm sector to determine the effects of climatic change, particularly the effects of rainfall. Due to time and other constraints, Western Cape agriculture is modelled using 1988 census reports (CSS, 1993), which appeared in June 1993, as basis. A number of more recent features of the economy are, however, modelled onto this base.

The construction of the model was done in three phases. First, the basic model with costs and fixed prices only was assembled. Next, risk was included by the mean absolute deviation method (MOTAD). Finally, variable product and input prices were modelled by using stepped demand functions, respectively.

In this model the Western Cape has been divided into ten relatively homogeneous regions, as described above. Two import and export 'regions' were also included, namely Cape Town for international imports and exports and Beaufort West for domestic trade with the rest of South Africa. Farm commodities can be produced in any of the ten resource regions, or imported from the international market or the rest of South Africa. Similarly, commodities are either consumed in the region (on the consumption side no differentiation is made between the regions), or exported to the international market or to the rest of South Africa.

It is important to identify those commodities that compete for land and other resources so that the alternative production possibilities that face the farmer are also specified in the computer model. In this way, substitution in supply is included in the analysis. The 20 major agricultural commodities produced in the Western Cape were selected as production alternatives in this particular application. These commodities were selected on the basis of their contribution to gross farm income, as well as the land allocated to them. The selected commodities account for more than 90 per cent of the total agricultural land used in the region, and more than 85 per cent of the gross value of agricultural production.

Because there is a constraint for land in each area the model generates shadow prices for land if all the land is used. It is assumed that farmers employ a resource until its marginal revenue equals its price within a given set of physical, financial and institutional constraints. Therefore, the shadow price of land serves as a check on the model, because these shadow prices can be compared with the rental value of land. Labour and credit were assumed to be freely available, albeit at an increased cost for increasing amounts. Supply elasticities of 5 and 6, respectively, were assumed.

Water is included as a conventional input into irrigation farming at existing price levels, while the total availability of irrigation water is set as the outer limit to irrigation use. This allows manipulation of both the price of water (the tariff) as well as the total availability of irrigation stocks. In the former case a change in water tariffs will affect net farm income, and therefore the objective function of the model. In the latter case the model optimises using a different total availability of water as a binding constraint.

² This section describes a model of the Western Cape farm sector developed by Vink and Van Zyl (1998).

³ The model construction is described in a report to the Development Bank of Southern Africa by Van Zyl (1995) which summarises much of the relevant theoretical literature. South African applications include Ortmann, 1985; Frank, 1986; Van Zyl, 1987; 1989a; 1989b; Howcroft, 1991; Van Zyl *et al*, 1991; Meyer and Van Zyl, 1992; Vink *et al*, 1996.

Since Freund's (1956) article on the inclusion of risk in a programming model, rapid developments have occurred in techniques for incorporating risk, particularly in single-period optimisation models (Hazell, 1982). Evidence suggests that farmers behave in a risk-averse manner (Young, 1979:1065). Neglect of risk can lead to considerable overstatement of the size of risky enterprises. Risk can be considered as a cost, namely the additional expected return that farmers want as compensation for taking risk (Barry & Fraser, 1976:288). Risk associated with various enterprises may be taken as the deviations of gross income per hectare from the mean or from the trend line over time (at least six years) as the enterprise price elasticities relate price and yield variability to income variability. The mean absolute deviation method (MOTAD), first proposed by Hazell (1971) and later developed by Hazell & Scandizzo (1974), was used in this application. Income variations during the six year period 1982 to 1988 were used to model the production risk associated with production of each of the commodities in each of the ten regions.

Transport opportunities/activities link the supply and demand sections of the model. Each of the thirteen resource regions or two import 'harbours' can supply any of the three consumption points, namely the Western Cape as a whole, and the two export 'harbours' (Cape Town and Beaufort West). Supply and demand for each region is treated as if it is coming from a specific point rather than from all over a region. This is done to make the representation of transport costs between and within resource regions easier. Consumption and production points were subsequently developed to facilitate this treatment. This is in line with the assumption that production practices, yields, risk and prices are the same within each of the regions.

The final model has 200 production activities (20 commodities in 10 regions); 24 import activities (12 commodities with two import points); 624 transport activities (200 production activities transported to 3 consumption areas, and 24 import activities); 42 demand schedules (of which 24 consist of 10 steps each), and 6 years of risk data for each commodity in each region. In addition, the model was structured to allow for the easy measurement of producer, consumer and total welfare, which form part of the different objective functions, depending on the scenario followed.

3.2 *Model validation*

Validation of the model is a process that leads to: (1) a numerical report of the model's fidelity to the historical data set; (2) improvements to the model in the case of imperfect validation; (3) a qualitative judgement on the reliability of the model in terms of its stated purposes; and (4) a conclusion (preferably explicit) concerning the kinds of uses that it should not be used for (Hazell and Norton, 1986). Validation begins with a series of comparisons of model results with the reported actual values of the variables.

Production is the variable most commonly used in validation tests, and for a number of agricultural models there are reported validation results that can be used for comparative purposes. Typically, there is considerable variation in the closeness of the fit to the historical data across different products, and the model builder may be willing to accept greater deviations in minor products if the predictions are good for the major products. There is no consensus on the statistic to be used in evaluating the fit, but in most cases a simple measure such as the mean absolute deviation (MAD) or the percentage absolute deviation (PAD) have been used.

The testing of the model was done by imposing all of the relevant policies which were current in 1988, specifically the marketing and pricing regime for each product, credit policy and other on-farm policies, in order to see how well it simulated the existing (1988) situation. The better the current situation is represented by the model, the more reliable the model. The values generated by the model correspond

fairly well with the actual values for the Western Cape as a whole, although this is not necessarily true for the 13 sub-regions.⁴ If a deviation of 15 per cent is deemed acceptable as a general rule of thumb (as suggested by Hazell and Norton, 1986), all the generated production quantities for the Western Cape are within this limit. A PAD of 8.19 per cent across all commodities for the Western Cape (as a whole) is obtained, which is adequate for this type of model.

4. Modelling the effects of future climate change on the Western Cape farm economy

4.1 General

Different scenarios were modelled to demonstrate the effects of climate changes, particularly as it impacts on water availability, on selected key variables to determine the effects of such changes. These variables include the physical change in output (area under production for each of the commodities and livestock numbers); commodity prices; employment; and changes in producer welfare, consumer welfare and total (social) welfare. The information provided by the base scenario simulation depicting the 'before scenario' was subsequently used to compare the different climate scenarios (indicated by different amounts of water availability). It is important to emphasise that all other variables, for example transport costs, exchange rates, international prices and interest rates, stay the same for each scenario.⁵

The results obtained with the different simulations are often a function of the set of assumptions that underpin the analysis. Therefore, it is necessary to explicitly state some of the most important assumptions, which impact on the subsequent results.⁶ Also, the direction of change is often much more important than the actual magnitude of the results obtained. For this reason less emphasis should be placed on the actual results than on the direction of change, while the assumptions, which underpin the analysis, should be considered together with the analysis of the results.

⁴ In some of the individual sub-regions, relatively small quantities of some specific commodities are produced. In these areas, the model predicts a relatively large deviation (increase or decrease) of up to 75 per cent of the actual production, but in absolute terms these variations are small and insignificant. Where a specific commodity is important in a region, the model predicts both the relative and absolute production levels fairly accurately.

⁵ This restrictive *ceteris paribus* assumption allows for evaluation of the effects of the specific scenario in relative isolation.

⁶ The most limiting factors in the analysis are as follows: (1) only the farm sector is modelled, with no attention given to changes in the farm input sector (credit aside); (2) there is no scope for changing input mixes of commodities in reaction to changes in output prices -- the assumed underlying technologies and market demand guide the whole system; (3) income changes and its effects on demand are not taken into account; (4) specific transport costs, exchange rates and international prices underlie the analysis; and (5) changes are not shown in a dynamic manner, but as final results.

4.2 Results

Two different types of scenarios are used. First, the total availability of irrigation water to each of the ten sub-regions comprising the Western Cape farm sector is limited by 10 and 30 per cent of current use, respectively. Importantly, it is assumed that rainfall stays the same, which implies that this scenario is similar to irrigation quotas imposed on farmers. Second, the changes in rainfall generated by the GCM (Table 1) are used to model water availability for each of the sub-regions. Under this scenario, it is assumed that both rainfall and water availability decreases, which affects the production of irrigation and rain-fed, as well as extensively produced commodities. The availability of irrigation water was assumed to be directly related to the rainfall.⁷

New crop budgets had to be developed for each scenario. These scenarios allow for the full complementarity and supplementarity that exists with respect to water use between the different commodities within the different production sub-sectors. The production of the different commodities will be affected in different ways when water availability becomes increasingly limited, and the available water is transferred to the most profitable commodities. It was assumed that water could not be transferred between the ten relatively homogeneous sub-regions within the model. Also, water is not fully substitutable between different kinds of crops, mainly because of soil and other constraints. In addition, human consumption of water takes preference over that for agricultural use, which implies that lower water availability affects irrigation agriculture relatively negatively as it becomes a residual user. Table 2 provides a summary of the results.⁸

/Table 2/

From the table it is clear that the production of field crops and livestock products will increase with lower water availability, while vegetable, fruit and intensive livestock production will decrease. The direction of change stays the same regardless of the level of the constraint on water availability, but as expected, the magnitude of change increases the less water is available. This seemingly counter-intuitive result has important consequences for total welfare and for the level of employment in Western Cape agriculture.

The sequence of the argument starts with the availability of water. In the first example, the available stock of irrigation water is decreased by 10 per cent. The first reaction of the model is to reallocate water to its highest and best use. However, because water is less available, some amounts of other resources such as land are left idle. So, for example, one would expect that water would be reallocated from wheat under irrigation to higher value fruit. The land that was being used for the less valued irrigation crops will be left idle, as there is not enough water for it to be kept under irrigation. It is then reallocated to uses that do not require irrigation water, such as dryland field crop production and extensive livestock production on pastures.

Table 2 also shows the details of this result. All the sectors that are water-intensive (mainly vegetables, but also fruit, dairy, angoras, pigs and chickens--the livestock through feed requirements presently produced under irrigation) experience a drop in output as water is allocated away from their use. The freed land resources are allocated to wheat, barley, oats, beef cattle, and sheep. These increases and decreases are reflected in the changes in commodity prices in the lower half of the table. So, for

⁷ This assumption is clearly problematic. However, because agriculture is assumed to be a residual water user relative to human consumption, this assumption was used in lieu of better information.

⁸ The model yields very detailed results. Space limitations prevent the presentation and discussion of these in any detail. The summary presented here serves as illustration of the directions rather than the magnitude of changes, both of which differs among the regions depending on substitutability and other factors.

example, an increase in field crop production is reflected in a lower price, while a decrease in fruit production results in a higher price. It is important to note, as stated previously, that these changes in the physical volume of production and in prices are the net result of a chain of shifts in supply and demand that take place as a result of the changing availability of water. Also, the major changes here occur in areas where there is at least some substitutability between irrigation and rain-fed activities, i.e. the Swartland.

The effect on welfare and employment are fairly predictable, and disastrous. Producers as a group lose, because production shifts away from high value crops and livestock products to extensive field and livestock sectors. Consumers (as a group) lose, even though they are paying less for basic foodstuffs. The total welfare of the Western Cape, which is the sum of the producer and the consumer surplus, therefore also decreases. Finally, as production shifts from intensive to extensive industries, the labour intensity of agriculture also declines, as can be seen by the decline in employment. This discriminates against the poor, so the conclusion can be drawn that the net effect of the changes is regressive in terms of income distribution.

5. Conclusions

This paper links two different methodologies to determine the effects of climate change on the Western Cape farm sector. First, it uses a general circulation model (GCM) to model future climate change in the Western Cape, particularly with respect to precipitation. Second, a sector mathematical programming model of the Western Cape farm sector is used to incorporate the predicted climate change, specifically rainfall, from the GCM to determine the effects on key variables of the regional economy.

In summary, results indicate that future climate change will lead to lower precipitation, which implies that less water will be available to agriculture in the Western Cape. This will have a negative overall effect on the Western Cape farm economy. Climate change will lead to a relative shift away from intensive production sectors in agriculture towards more extensive sectors. Both producer welfare and consumer welfare decrease. Total employment in the farm sector decreases as producers switch to a more extensive production pattern. The total decline in welfare, therefore, falls disproportionately on the poor in the province. These consequences could, of course be mitigated if the restriction on available water were to be matched by reactions such as a more efficient use of available water.

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Table 1: Summary of present and predicted future mean precipitation for the Western Cape sub-regions.

Sub-region	Present mean PPT	Predicted Future PPT	% Change	Present mean PPT	Predicted Future PPT	% Change	Mean Annual PPT	Predicted Future Mean PPT	% Change
	February (mm)	February (mm)	(%)	August (mm)	August (mm)	(%)	(mm)	(mm)	(%)
1	9.800	9.522	2.8	81.000	75.020	7.4	632.400	602.142	4.8
2	14.111	13.688	3.0	117.889	112.485	4.6	831.187	801.741	3.5
3	14.871	13.654	8.2	52.516	46.351	11.7	514.499	477.792	7.1
4	32.048	29.363	8.4	38.857	33.227	14.5	531.023	486.128	8.5
5	32.385	28.033	13.4	32.462	28.707	11.6	501.820	448.008	10.7
6	17.731	13.953	21.3	22.962	18.750	18.3	351.138	302.068	14.0
7	6.750	5.461	19.1	47.021	43.617	7.2	421.029	391.111	7.1
8	4.227	3.976	5.9	61.773	60.071	2.8	417.708	399.470	4.4
9	1.213	0.922	24.0	27.574	27.273	1.1	219.157	203.190	7.3
10	16.551	10.015	39.5	7.562	6.703	11.4	225.812	164.932	27.0

Table 2: Effects of different scenarios of decreased water availability to the farm sector

Measure	Item	Deviation of simulation results from base values (%)		
		10% less irrigation water only in all sub-regions	30% less irrigation water only in all sub-regions	Water availability determined from GCM
Production	<u>Production of crops (ton):</u>			
	Field crops	+	+	+
	Vegetables	-	-	-
	Fruit	-	-	-
	<u>Number of livestock:</u>			
-Extensive	-	-	-	
-Intensive	+	+	+	
Prices	Field crops	-	-	-
	Vegetables	+	+	+
	Fruit	+	+	+
	Livestock:			
	- Extensive	-	-	-
- Intensive	+	+	+	
Welfare	Producers	-4.72	-21.54	-3.61
	Consumers	-2.48	-8.49	-1.86
	Total	-2.64	-10.25	-1.98
Employment	Farm employment	-3.56	-13.40	-2.74