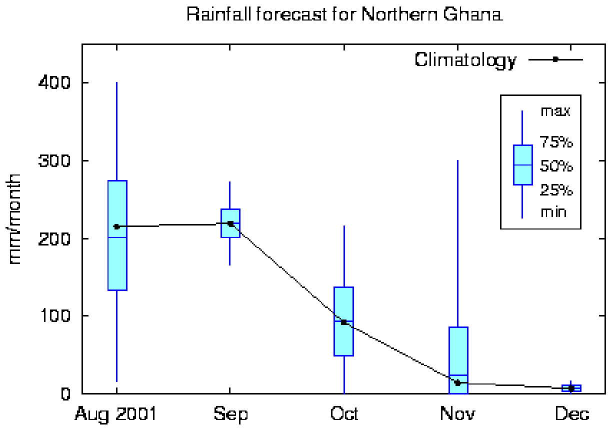
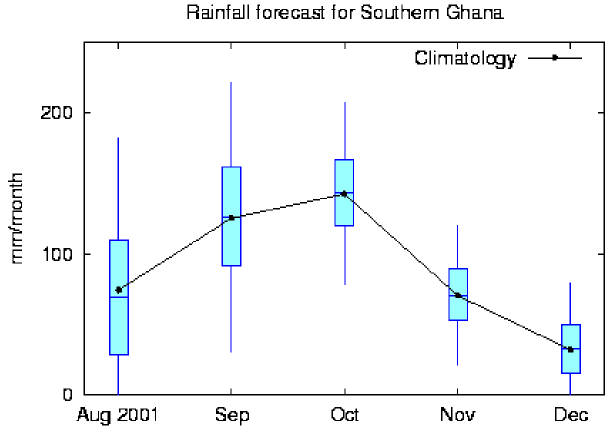
Danish Climate Centre

DMI, Ministry of Transport

Application of seasonal climate forecasts for improved management of crops in Western Africa

J. H. Christensen[1], J. E. Olesen[2], H. Feddersen[1], U. J. Andersen[1], G. Heckrath[2], R. Harpøth[3], and L. Wester-Andersen[1]





1. Danish Meteorological Institute
2. Danish Institute of Agricultural Sciences
3. Institute of Geography, University of Copenhagen

Report 03-02

Application of seasonal climate forecasts for improved management of crops in Western Africa

J. H. Christensen, J. E. Olesen, H. Feddersen, U. J. Andersen, G. Heckrath, R. Harpøth, and L. Wester-Andersen

Danish Climate Centre, Report 03-02

ISSN: 1398-490-x (Print)
ISSN: 1399-1957 (Online)
ISBN: 87-7478-483-8

Danish Meteorological Institute
Lyngbyvej 100
DK-2100 Copenhagen Ø
Denmark

Phone: +45 3915 7500
Fax: +45 3927 1080
www.dmi.dk

Contents

Summary

Climate variability, drought and other climate related natural disasters have a direct impact on both quality and quantity of the agricultural production. In many developing countries with limited technology the sustainability and productivity of the agricultural system is negatively affected by this climate variability. Seasonal climate prediction models have improved substantially over the last decade, and the predictions in many parts of the tropics are now sufficiently accurate that agricultural production planning can benefit from them. However, seasonal climate predictions are, in contrast to ordinary weather forecasts, probabilistic in their nature, and so interpretation and communication of the seasonal climate predictions require a substantial effort before they can be of practical use.

The objective of the present project has been to explore the possibilities of adjusting crop management practice for a selected agricultural crop (groundnut) in two regions in Ghana in Western Africa, making use of the best available seasonal climate predictions. The crop and geographical area has been selected in collaboration with the Department of Soil Science, University of Ghana. The PNUTGRO crop model of the DSSAT software system has been applied to evaluate scenarios for modified crop management strategies, including choice of sowing time and crop cultivar. The seasonal climate predictions have been calibrated and validated against observed climate variables, which have been collected in collaboration with the national meteorological service of Ghana.

The effect of using seasonal rainfall forecasts were analysed using actual seasonal forecasts from ECMWF for the period 1987 to 2000. In most cases the use of seasonal rainfall forecasts resulted in changes in simulated optimal sowing dates. However, this did not result in any marked changes in yields obtained. The starting date of the rainy season is very constant in Northern Ghana, and this may be the reason for the small response here. There should be more possibilities for use of the forecasts in the coastal regions. However, the current seasonal forecasts seem to be too uncertain for choosing sowing time. There will probably be more use for seasonal forecasts for selecting short- or long-season cultivars, which depend on total season rainfall. However, this was not analysed in detail in the current project.

This project was only made possible due to financial support by RÅDET FOR ULANDSFORSKNING (RUF) for a period of two years (01-01-2001to 31-12-2002). Part of the work documented in this report has been finalised in 2003.

1. Project idea

The overall objective of the present study has been to investigate the sensitivity in yield to climatic variations for groundnuts in Ghana, and to investigate the possibility for adapting planting and crop management practices based on seasonal climate predictions.

2. Background

The climate exerts crucial influences on soils, vegetation, water resources and land use. The growing awareness of the importance of population development, degradation of natural resources and the importance of sustainable development makes it essential to increase the understanding of the interaction between climate and agriculture, and to use this understanding for improving cropping strategies. The climatic variability, drought and other natural disasters directly influence both quantity and quality of agricultural production. In many developing countries with limited technology, climatic variability negatively affects the ability of the agricultural systems to sustain an adequate food production. The use of reliable seasonal weather forecasts may contribute to reducing the negative consequences of climatic variability.

The use of numerical models for producing long-term or seasonal forecasts with a lead-time of up to half a year is currently being intensively investigated in several parts of the world. The currently best numerical model is probably the one used at "European Centre for Medium-Range Weather Forecasts" (ECMWF), where DMI has direct access to all details of the forecasts. For this and other models it has been shown that the most reliable forecasts are obtained in tropical regions (Stockdale *et al.,* 1998; Shukla, 1998). However, such seasonal forecasts are not widely used in practice, in particular not in developing countries. For this project it has been necessary to verify whether the model gives sufficiently reliable predictions for practical use, and it has been one of the aims in the project to use the knowledge of the project participants to test this for a selected crop in West Africa.

There is still an obvious need for an interdisciplinary effort in this area. In most countries where the current quality of seasonal forecasts should make a practical use possible, there is not the necessary collaboration between climate researchers and agricultural researchers. In Australia where the relationship between El Niño/Southern Oscillation (ENSO) and the yields obtained are just as strong as between ENSO and rainfall (Rimmington & Nicholls, 1993), there are already a number of examples of successful agricultural applications of seasonal weather forecasts. This is primarily due to agricultural production in Australia being predominantly determined by lack of water and thus rainfall. Similar results have been obtained in Southern Africa (Mason, 1998; Martin *et al.*, 2002; Phillips *et al.*, 2002) and West Africa (Adiku & Stone, 1996; Ingram *et al.*, 2002). Results from use of models for simulating crop production shows that there are considerable potentials under tropical conditions to better adapt cropping strategies to the climatic conditions in a given year (Lal *et al.*, 1993). With the better predictions of climatic conditions during the growing seasons it is therefore important to investigate the possibilities of including seasonal weather forecasts in planning of agricultural production.

Hansen (2002) listed a number of prerequisites for successful use of seasonal weather forecasts in agriculture, and he suggested three phases in the attempts to apply seasonal weather forecasts: an investigation phase to increase the understanding and to assess the potential, a pilot phase characterised by a mutual learning between researchers and decision makers, and an operational phase focused on the involvement and equipment of the relevant institutions. This project has just initiated the first phase, and there are in general very few places in the world where the last phase is currently being initiated for selected crops (Everingham *et al.*, 2002; Nelson *et al.*, 2002).

3. Methodology

3.1 Seasonal climate forecasts

As a very first priority, the climate (monthly averages of precipitation, temperature, humidity, etc.) for the selected region in West Africa was described in details for a period of at least 15 years. The regions in concern – representative for the northern and southern Ghana are characterised by variations in precipitation, which have a profound impact on crop production (Osafo, 1976; Adiku *et al.,* 1997) – were selected in collaboration with University of Ghana (Dr. Samuel Adiku).

The collection of climatic observations was performed in prolongation of an already existing collaboration between DMI and Ghana Meteorological Services Department (Deputy Director Frank P. Mote). Knowledge about the observed climatic variations in the selected areas during a longer period was then used to drive a crop model in order to assess the potential in using seasonal forecasts, as the observed climate is a perfect proxy for a perfect seasonal forecast. Conversely, the minimal usage of a seasonal forecast can be assessed by knowledge of the normal climatic variability, e.g. no access to a seasonal forecast at all. The real value of a seasonal forecast in the form of increased yield and reduced risk will be somewhere in between what can be obtained without any seasonal forecast (but with knowledge about the observed climate variability), and what can be obtained using a perfect forecast. In the present study, it turns out to be difficult to elude on the unique value of seasonal forecasts (see Section 5 on seasonal forecasts)

The modelled seasonal forecasts could not be used in their raw form. Firstly, the horizontal resolution of the seasonal forecast model is too coarse (app. 200 km); secondly, the forecast results need to be converted into a probabilistic measure. It is essential to be able to provide an uncertainty measure along with the prognosis itself; otherwise the potential user will not be able to assess the risks associated with decisions made based on the forecast. For this reason a downscaling procedure was developed. This allowed the coarse resolution forecasts to be calibrated and produced for local applications. In turn the downscaled information could be used as representative climate predictions for the local area with the crop model. The downscaling and calibration of this has been made using statistical relations between modelled variables (i.e. the precipitation over a larger area) and observed variables in the region of interest (i.e. the precipitation measured at a specific site) according to Feddersen *et al.* (1999). Probabilistic forecasts are furthermore based on ensembles of individual forecasts, which have been calculated using different atmospheric initial conditions from several different climate models.

3.2 Seasonally adapted crop management strategies

Initially the cropping practices in the selected areas in Ghana were characterised, and a single crop (groundnut) was selected for further study. The sensitivity of the current cropping systems with respect to yield levels, yield variability, drought, flooding, erosion, nutrient leaching etc. was also described. This was done based on existing reports from the areas and by interviewing agricultural experts in the areas. This last part was performed in collaboration with Geographical Institute at Copenhagen University (see the section on collaboration in Denmark). Groundnut was selected as a suitable crop as this crop is also included in the DSSAT model system (Decision Support System for Agrotechnology Transfer) for simulating crop production (Tsuji *et al.*, 1994). There is a growing use of DSSAT in the region and contact was established to these groups. Both climatic and crop data were collected for this crop in the region. This has primarily concerned data from field experiments performed by universities and research institutes. Such datasets are scarce and have dominated the choice of crop for the investigation.

The data collected have been used for calibrating and validating the crop model prior to use with the seasonal forecasts. The data have also been used to define the controlling conditions for model calculations, including soil conditions, irrigation, nutrient applications, crop varieties etc. Initial model runs together with data collected on real farms have been used to clarify the primary reasons for lower productivity on actual farms compared with simulated results. This has been used for defining restriction in the scenarios for possible cropping strategies.

The sensitivity of the current cropping systems in groundnut to climatic variability was investigated using the crop model by simulating the climatic variability with a weather generator (Semenov and Barrow, 1997). The weather generator has been calibrated using data from climate stations in the selected regions in Ghana. The scenarios for planting time and varieties were subsequently tested with the crop model using the climate forecasts for each growing season. The weather generator was also used to downscale the seasonal weather forecasts, because the crop model requires daily data for temperature, rainfall and global radiation. The simulated results were used to estimate a risk profile (frequency distribution for yields) for each of the scenarios. This was used to determine the possible benefits from seasonal weather forecasts, because these profiles can be compared with risk profiles for the baseline scenario.

4. Experience gained during the project

4.1 Acquiring of meteorological data from Meteorological Service Ghana

Since 1997, DMI has had collaboration with Meteorological Services Department, MSD of Ghana as part of project on water resources. The project has been supported by DANIDA and has the title: Strengthening of Water Resources Information Services (WRIS). The primary goal of the WRIS-project has been to increase the amount of and accessibility to meteorological data. This has been obtained via a general re-establishment of meteorological stations, improvement of data collection, data bases, and handling of data. It is important to stress that data in most cases are collected manually and later digitized after they have arrived at the main office of MSD in Accra.

On the basis of the connection between DMI and MSD via the WRIS project, the data for the present project has been more easily available than otherwise. Even so, the delivery of data has been much delayed, which is basically due to the lack of digitalization of the most recent data, data was available in different units (Fahrenheit and Celsius), the staff in the unit processing the data was busy on many other tasks, and finally, the head of unit went on a longer visit to the UK.

4.2 Field work in Ghana

Two visits were made to Ghana by Jørgen E. Olesen, each visit lasting 2-3 weeks. The base for the visits was University of Ghana, Legon, and the visits were carried out in April 2001 and April 2002.

During the first visit to Ghana the possibilities of using crop models in Ghana was investigated. The use of such models has been very modest, but there is an increasing interest in this at University of Ghana in Legon (Dr. Samuel Adiku) and an emerging use at Savannah Agricultural Research Institute (Dr. Jesse Naab). The use of crop models has concentrated on groundnuts in Northern Ghana, and the PNUTGRO model of DSSAT has been calibrated for this. The varieties used in Northern Ghana, however, deviates from the varieties used in the coastal savannah region, and there was thus a need to adapt the model for this part of Ghana.

After the initial discussions with the collaboration partners in Ghana (primarily Dr. Adiku and Dr. Naab), the groundnut crop was selected for the project. Groundnut is an important crop in Ghana, and is used in many national dishes. Also it can be roasted and eaten as a dessert or as a snack. The roasted groundnuts can also be further processed for food oil and confectionary. It is also an important protein source for both human and animals. The straw from the groundnut production is used for cattle feed during the dry season, and is even sold on the local markets. Groundnut production is most widespread in the northern part of Ghana, including Upper West Region, but there is also a significant cultivated area in the eastern coastal savannah region, including the Akatsi district. Groundnuts are primarily grown for use on farm, but it is not uncommon for households to sell a part of the production on the local markets.

The possibilities of performing field trials at the university and investigations on farmers' fields were looked into during the first visit to Ghana. The university farm was visited and so were selected farms in the Akatsi district. Additionally the possibilities of supporting research and education on crop models at the University of Ghana were discussed. During the last part of the project a M.Sc. student at University of Ghana has been associated with the project. This student has performed his own field experiments with groundnut and applied the models in the DSSAT system. The project has also been a contributing factor to courses on crop modelling at the University of Ghana. Finally Ghana Meteorological Service was visited.

The first visit to Ghana resulted in a memorandum of understanding between Danish Institute of Agricultural Sciences, University of Ghana and Savannah Agricultural Research Institute. This included conducting a field experiment on the university farm in Legon, which could form the basis for calibrating the model for use in the coastal savannah region. Also a characterisation of the current cultivation patterns of groundnut in the coastal savannah (Akatsi District) and the Upper West Region (5 districts: Wa, Nadowli, Jirapa/Lambussie, Lawra and Sissala) was initiated.

The second visit in April 2002 was primarily a follow-up on the agreements and the initiated studies. The characterisation of groundnut production had been performed at all sites, but only reported for the Akatsi district, because the data and the report from Northern Ghana was lost on a PC that had a disk crash. This report has later been recreated. The cultivation experiment at the university farm was conducted according to the plan, but the crop was severely damaged by root disease some time before harvest. However, the first comparisons between the model and data showed a good agreement, and it was therefore decided to repeat the experiment in 2002 and to take samples of crops at selected farmers in the Akatsi region for comparison with the model simulations.

4.2.1. Field experiment at Legon

Two field experiments with groundnut were performed at the university farm at University of Ghana, Legon (5°36'N, 0°10'W) on an Acrisol. The first experiment was carried out during the minor rainy season in 2001, and the second experiment was carried out during the major rainy season in 2002. The previous crops were okro and maize for 2001 and 2002, respectively, and the sites were left fallow at least two months before the groundnut experiments. The soil was ploughed and harrowed before sowing. PK fertilisers were supplied at emergence, with 13 kg P and 17 kg K per ha in 2001 and 30 kg P and 20 kg K per ha in 2002. Weeds were controlled by manual weeding.

The experimental treatments in 2001 were two varieties, with/without irrigation and with/without fungicide control. The experimental treatments in 2002 were two varieties, two plant densities and two sowing times. In 2001 the entire experimental area was attacked by root disease about 4 weeks before harvest, and it was not possible to control this disease with the available fungicides. In 2002 data from the late sowing time had to be discarded due to poor emergence. Plant samples were taken at bi-weekly intervals for characterising crop development and growth (Figure 1).

As there were problems in obtaining climate data in electronic form from Ghana Meteorological Service, University of Ghana had to buy these data in paper format from Ghana Meteorological Service. The climate data was then entered in a spreadsheet and used for calibrating the crop model using data from the field experiment.

Photo 1. Establishment of the field experiment at University of Ghana.

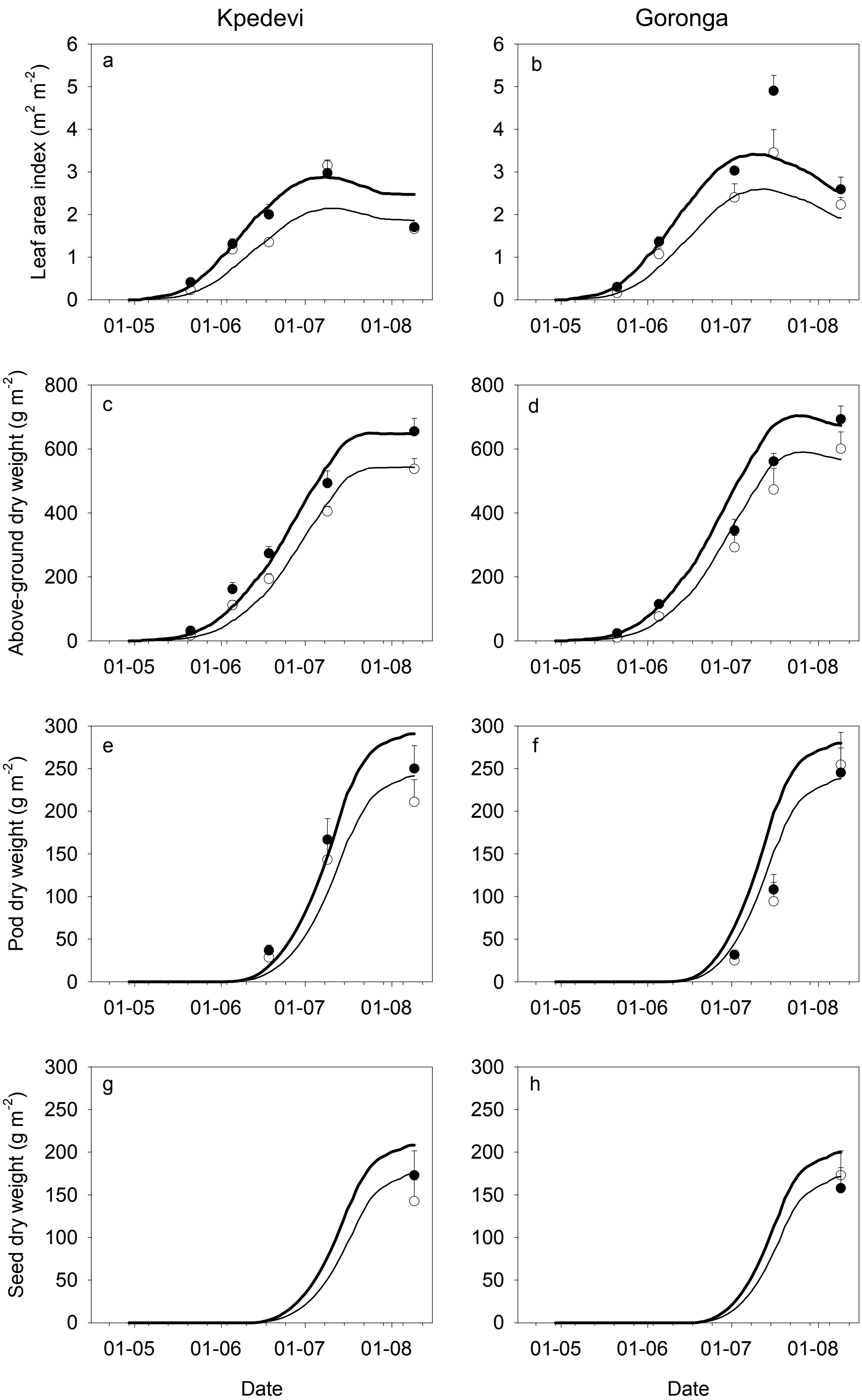


Figure 1. Observed and simulated time course of leaf area index, above-ground biomass, weight of pods and seeds for two varieties (Kpdevi and Goronga) and two plant densities in the field experiment at University of Ghana in 2002. The vertical bars show standard error of the observations.

4.2.2 Overview of current groundnut crop management

In the autumn 2001 interviews were carried out with groundnut farmers in the Akatsi District in the coastal savannah region and in five regions in the North West Region of Ghana. Yield measurements were taken on a number of groundnut farmers' fields, in the autumn 2001 in all districts and in the summer 2002 in the Akatsi district.

The majority of the groundnut farming in the Akatsi district was located on farms with an area of less than 1 ha (Adiku et al., 2001). Very few of the farmers had more than 10 year of formal education. There was little emphasis on increasing the soil fertility, and most of the farmers had only very limited knowledge on the importance of nodulation for N-uptake and yield, and they did therefore not inoculate the seeds before planting. The yields were generally small, less than 1 ton/ha. Higher yields would be obtainable through better choice of planting date and plant density and through better control of soil fertility.

Photo 2. Visit at groundnut farmer in the Akatsi district 2002.

Northern West Region (NWR) was surveyed by interviewing 100 groundnut farmers. The average farm size was ca. 1 ha. However, the Wa and Lawra districts had farms up to 4 ha, primarily because of lower population densities here. Only 21% of the farmers had attended primary school, and the rest were thus illiterate. This occurred despite a large spread in age of farmers and an average age of 45 years. 77% of the farmers cultivated groundnuts for both on-farm consumption and for sale, whereas 19% cultivated for sale only. Only 57% of the farmers received assistance from advisors on groundnut cultivation.

Most farmers indicated that the area with groundnut had been increasing over some time. This was primarily a consequence of declining soil fertility and less financial resources for buying fertilisers for cereal production. Groundnut does not require fertiliser and needs fewer pesticides, and is therefore more attractive than cereals. In cases where groundnut cultivation had been declining, this has mainly been caused by bottleneck problems with labour.

Groundnuts in NWR were sown between April and July with the majority of sowings occurring in May and June, but still with a very large variation. Five main types of groundnut were cultivated. Two of these are improved varieties (Chinese, a 90 day variety, and Manipinta, a 120 day variety), and three are local varieties. 73% of the farmers grew Chinese and 17% Manipinta. 71% of farmers used their own harvested crops for seeds, and only 11% bought certified seeds. Groundnut was intercropped with other crops in about half of the cases to increase yield stability. The observed plant densities varied from 5 to 20 plants m^{-1} with a recommended plant density of 10 plants m^{-2} for the variety Chinese. The yields varied considerably between farms, but generally yields were about 1 t ha^{-1}.

The growers in NWR were asked which factors were the most limiting for groundnut production (Table 1). Infrequent rainfall was specified as the most limiting factor. However, declining soil fertility was also seen as an important issue.

Table 1. Limitations in groundnut production in Upper West Region (number of replies).

Constraint	Rank 1	Rank 2	Rank 3	Total
Infrequent rainfall	19	3	4	26
Declining soil fertility	20	3	1	24
Lack of credit	9	-	1	10
Weeds	1	6	2	9
Labour	1	3	-	4

The observed yields from the farmers' surveys were supposed to form the basis for validation of the crop model. However, climate data from Ghana Meteorological Service was not acquired before May 2003 and it was thus not possible to use these data within the project period.

4.3 Collaboration within Denmark

The present project was initiated due to a number of more or less formalized initiatives taken in order to try to combine the well established Danish expertise on weather and climate modelling on the one hand with similar established expertise within agriculture, crops modelling and management in particular. Since the early phase of the project interests in the project was indicated by the Institute of Geography, University of Copenhagen. Connections between the present project, and other projects with focus on Ghana were identified. In particular, these initiatives developed into a master thesis project drawing heavily on some of the meteorological data, which have been acquired by the present project. Similarly, the crop model which has been used was also applied in the master's work. For these reasons, we have also included a description of the master thesis project in this report (see Section 8).

In order to ensure a smooth management of the project, a series of small working meetings were arranged with participants from DMI, DIAS, and the Institute of Geography. In the early phase of the project an informal meeting was also head with the Director of the Meteorological Service Ghana, who was visiting DMI in connection with another project. This meeting in particular was very instrumental in getting the access to meteorological data initiated. Unfortunately, it was not easy to maintain this contact as a stronghold, but individuals from DMI, who were visiting MSG were able to assist in making progress in data the delivery.

5. Seasonal forecasts

5.1 The climatological rainfall in Ghana

Climatically Ghana can be divided into four zones (Opoku-Ankomah and Cordery, 1994): (a) A rainforest region in southwest with large annual rainfall amounts, falling mainly in two rainy seasons in May-June and around October; (b) a southern coastal zone with less rain falling also mainly in May-June and around October; (c) central Ghana with one long rainy season from May-October; (d) northern Ghana with one rainy season in July-September. The climatological rainfall distribution is shown in Fig. 3 for 17 synoptic stations in Ghana shown in Fig. 2.

As indicated in Fig. 3 the rainfall amount can vary substantially from year to year. Rainfall in the southern part of the country is to some extent related to the sea surface temperature (SST) in the Gulf of Guinea, while the position of the West African monsoon trough is more important for the interannual rainfall variation in the northern part of Ghana. It has been shown that there is a statistical link between El Niño and rainfall in the Sahel region (Rowell et al., 1995). This may possibly also affect northern Ghana.

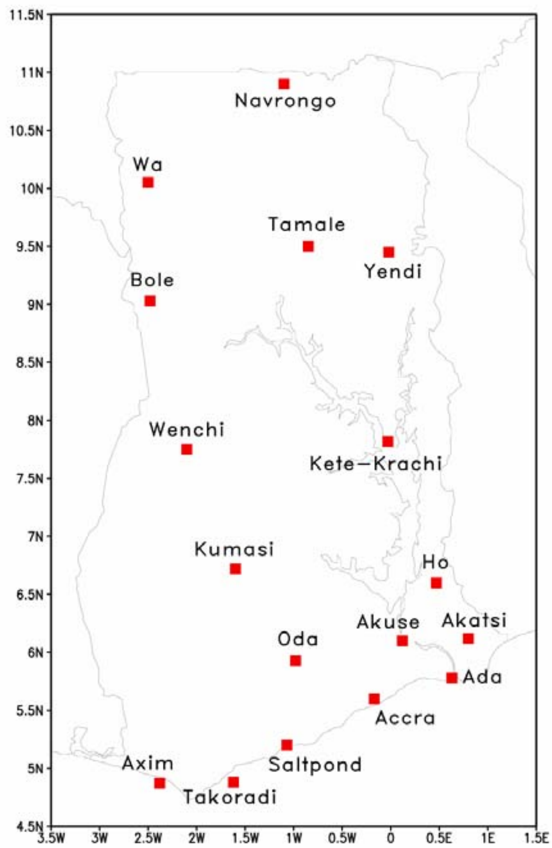


Figure 2. Ghanese synoptic weather stations used in this project.

5.2 The concept of seasonal forecasting

A seasonal forecast is traditionally a forecast for the coming season(s). In the following we consider forecasts up to six months ahead. The forecasts are based on calculations in a climate model that includes the physical laws that determine circulation, temperature, etc. in the atmosphere and oceans. Such a climate – or general circulation – model is complicated and computationally expensive to run, and so the details that can be described with such a model, are limited. The climate model that has been used in this project has a horizontal resolution of approximately 200 km.

The atmospheric part of the climate model is very similar to the models that are used for operational numerical weather prediction. Like in numerical weather predictions, the accuracy of the forecasts drops quickly during the first few days of the forecast.

Numerical weather prediction is a typical example of an initial value problem: The state of the atmosphere is known at a given time (or at least we assume it is known) from an analysis of meteorological observations, and the evolution in time of the initial state is computed using the numerical weather prediction model. In seasonal forecasting we have an initial value problem for the oceans (and, in theory, also for other relatively slowly varying variables, e.g. soil moisture), while predictability of the weather becomes a boundary value problem, where the lower boundary condition is given by the sea surface temperature (Shukla, 1998).

Thus, seasonal forecasting is based on the notion that slowly varying SST modulates the weather, and the key to accurate seasonal forecasts is the ability to make accurate SST forecasts. But even with perfect SST predictions we would not be able to predict the atmospheric day-to-day variability ("the weather") months ahead. At most, we can expect forecast skill for statistics about the weather, e.g. the accumulated rainfall in a three-month period. This limited predictability is not only due to shortcomings in the models. It is also a consequence of the chaotic nature of the climate system, especially the atmospheric component. In applications of seasonal forecasts it is therefore important to take into account a substantial forecast uncertainty. In practice the uncertainty is estimated by considering an ensemble of forecasts where each member of the ensemble represents a possible development. If the individual ensemble members *a priori* are equally likely, then the ensemble mean is an estimate of the most likely forecast.

The forecast skill for Ghana was estimated by validating five-member ensemble hindcasts for the period 1987-2001. Together with observed rainfall for the same 15-yr period, these hindcasts were used to derive a statistical relationship between climate model output and observed rainfall which subsequently was used to downscale the climate model output.

The model forecasts that we used, are state-of-the-art seasonal forecasts from the European Centre for Medium-Range Weather Forecasts (ECMWF). The forecasts are based on a system that analyzes the state of the oceans and the atmosphere at the beginning of the forecast and computes the evolution in time using a coupled ocean-atmosphere general circulation model (Stockdale et al., 1998). The forecasts are made once a month when an ensemble comprising 40 members is generated, and the model is integrated six months ahead in time for each ensemble member.

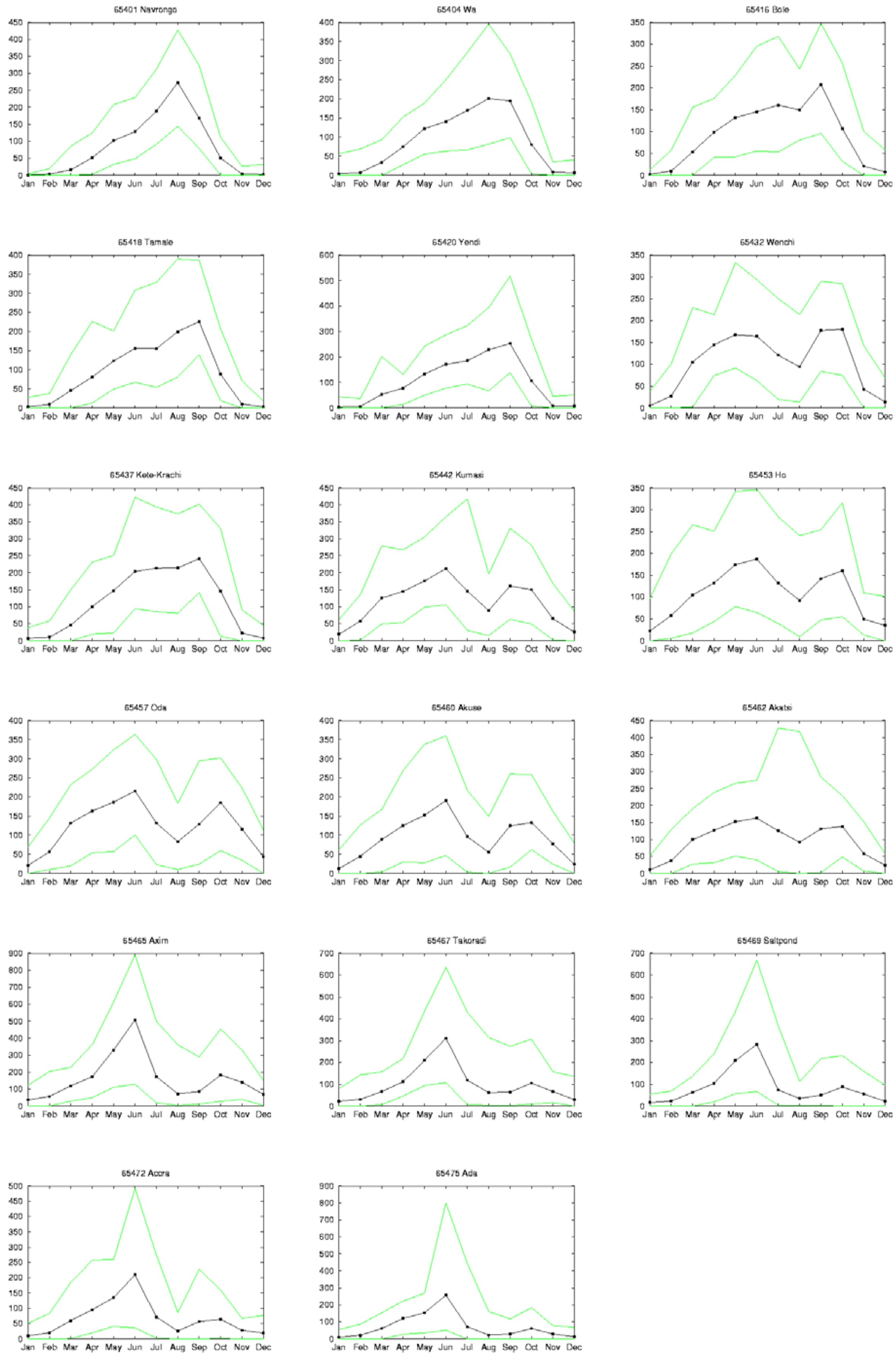


Figure 3. 1961-2000 rainfall climatologies in mm for the stations shown in Fig. 2. Black lines show 40-yr average; green lines show 5% and 95% quantiles.

5.3 Downscaling Predicted Rainfall

Even if the seasonal forecasts were perfect, we would expect significant differences between predicted and observed rainfall at the weather observing stations, due to the relatively coarse horizontal resolution of the seasonal forecast model. With a resolution of approximately 200 km the model does not include many local features, including details of the orography which may be important for local rainfall. In addition, the horizontal resolution of the model is so low that one model grid box may include several weather stations. In order to compensate for these limitations, the model output is downscaled, whereby model simulated rainfall is transformed to rainfall for the individual weather stations, using a statistically derived relation between model output and observed rainfall.

Statistical downscaling can be done using a number of different methods (von Storch and Zwiers, 1998). In addition, downscaling can be done dynamically, using a regional climate model (Giorgi and Mearns, 1999), but dynamical downscaling is computationally expensive, and it is not clear that better results will be obtained. In the present project we used a downscaling technique that is based on statistical specification of seasonal total rainfall from large-scale rainfall patterns that are assumed to be well-simulated by the models. Recently, several variations of this technique have been successfully applied to seasonal simulations (Feddersen et al. 1999; Gershunov 2000; Kharin and Zwiers 2001; Widmann et al. 2003; Tippett et al. 2003). The large-scale patterns that are used as predictors for the statistical downscaling are determined as the singular vectors of a singular value decomposition (SVD) of the cross-covariance matrix of model output seasonal total rainfall and observed seasonal total rainfall at the synoptic weather stations in Ghana. The downscaling uses a Model Output Statistics (MOS; Wilks 1995) approach where the 15-yr period 1987-2001 is divided into a training period and a validation period. The SVD analysis is applied to model output and corresponding observations in the training period, and subsequently seasonal rainfall is specified by linear regression based on a few significant SVD time series.

The main advantage of using a MOS-type downscaling is that systematic errors are automatically corrected for; not only constant biases, but also flow-dependent systematic errors such as, e.g., a rainfall pattern that is systematically displaced during El Niño episodes. We note that although the downscaling is linear, the coupled ocean/atmosphere models are nonlinear, and so the downscaled predictions are in general still nonlinear in nature.

The downscaling results are verified against station observations using cross-validation (Michaelsen 1987). Typically, the training period includes all years, except one. A prediction is made for the excluded year and stored. This is repeated for all years, and the predictive skill is estimated from the stored predictions. By using cross-validation the predictions are verified against independent data. The relation between model predicted and observed rainfall is seasonally dependent, so each season was treated separately, thus reducing the training data available for the statistical downscaling.

A general problem associated with predictions that are based on linear regression, is that the variance of the predictions is unrealistically small, particularly when the correlation between predictor and predictand is small. In order to compensate for this the downscaled predictions were inflated to ensure that the variance of the predictions matches the observed variance (Karl et al., 1990).

5.4 Results for Ghana

Figure 4 shows cross-validated correlations between downscaled seasonal predictions and verified observed rainfall for the two seasons March-April-May (MAM) and June-July-August (JJA) for forecasts initiated on 1 March. For most stations the correlations are positive, but for no stations exceeding 60%. The relatively low correlations between predictions and observations that are typical for seasonal predictions (Palmer et al., 2003), are caused, primarily, by the inherent limited predictability for seasonal predictions. However, the correlations are relatively uncertain estimates of the predictive skill, due to the short period (15 years in total) available for training and validation of the statistical downscaling model.

The correlations are in most cases higher for the first three months than for the last three months, and they tend to be higher near the coast, presumably due to a direct influence from the sea surface temperature.

Figure 5 shows monthly and seasonal downscaled predicted rainfall, as well as observed rainfall, for Accra which is the station with the best correlation between observed and predicted rainfall. Although the correlations for the first three months are low (−0.04, −0.04 and 0.16, respectively), the correlation for the total three-monthly seasonal rainfall is 0.43.

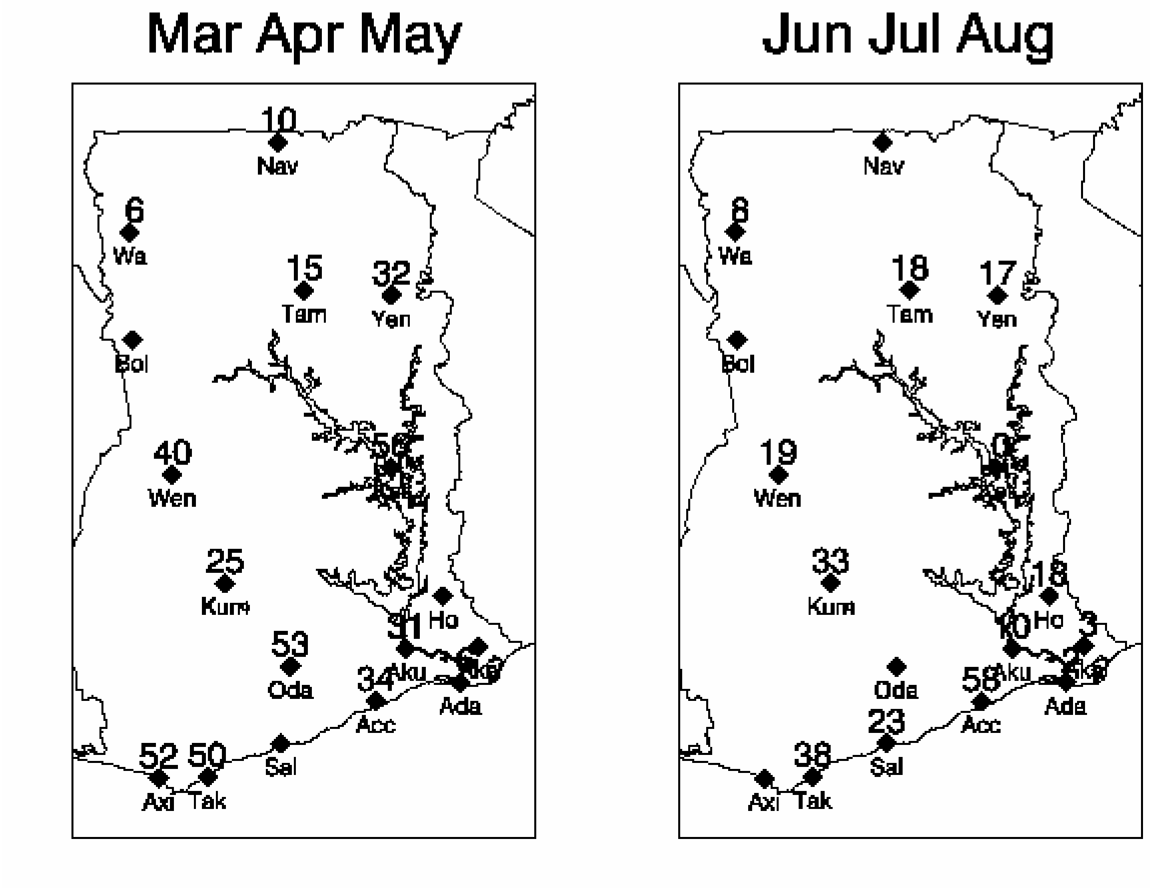


Figure 4. Correlations in % between predicted and observed rainfall anomalies for 1987-2000. Only positive correlations are shown. Seasonal forecast initiated on 1 March. Left: correlations for the first three months (March, April, May). Right: correlations for the following three months (June, July, August). Correlations are calculated for the downscaled value of the ensemble mean.

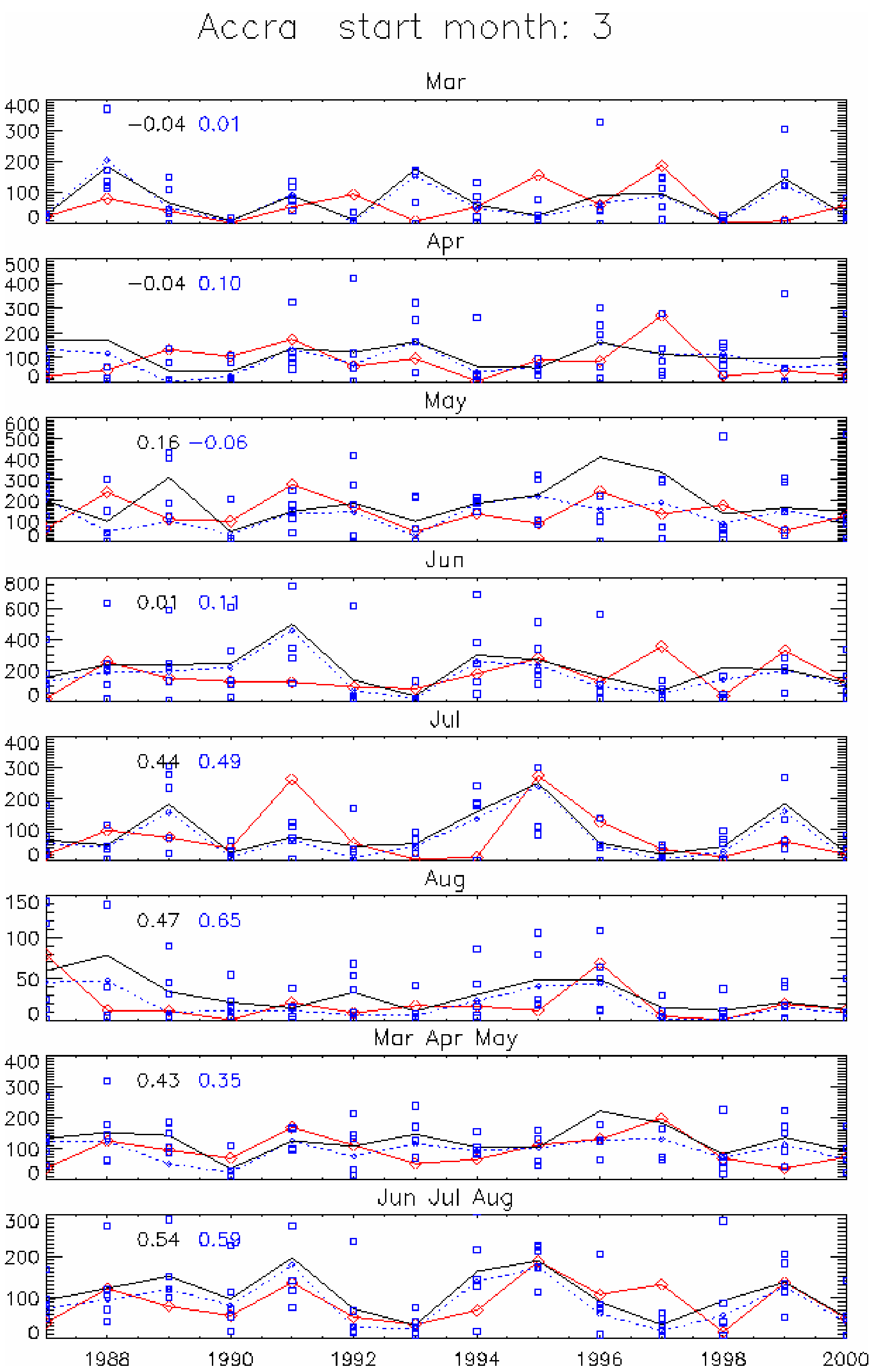


Figure 5. Predicted and observed rainfall for Accra for March-August. Observations are shown in red; downscaled rainfall for the individual ensemble members as blue squares; ensemble mean of downscaled rainfall as black line; and downscaled value of ensemble mean as blue, dashed line. Inserted numbers in black and blue show correlations between observed rainfall and black and blue lines, respectively.

6. Modelling of groundnut crops

The PNUTGRO v3.5 crop model was used to simulate development, growth and yield of groundnut under different climatic conditions and as affected by the natural variability in rainfall. PNUTGRO is a process based model for pulses, which simulates crop growth and development, water transport in soil and crop and nitrogen balance. The model is included in the DSSAT v3.5 system. The model was described by Boote et al. (1997, 1998), and it has been used in India for decision making on cropping practices under variable rainfall conditions (Gadgil *et al.*, 2002). In this project it was assumed that nutrients, weeds, pests or diseases did not limit crop growth. The crop production was thus assumed to be limited by climate and soil water holding capacity only.

The model was adapted for use in Ghana by calibration on data from the field experiments at Legon (two varieties: Kpdevi and Goronga) and by using earlier calibrations of the model on two varieties (Chinese and F-mix) in Northern Ghana. The varieties varied somewhat in growth duration, but unfortunately not as much as desirable. Goronga has a longer growing season than Kpedvi, and F-mix has a longer growing season than Chinese. These differences are seen in the simulated yields (Figure 6), where the varieties with a longer growing season under normal conditions and at optimal sowing time will give the highest yield. It should be noted that all yields shown in the graphs are net yields, where the seed weights have been subtracted from the simulated yields.

The model was applied to climate data from four sites in Ghana (Accra and Ada in the southern coastal savannah region, and Wa and Tamale in the northern savannah region). The available climate data from 1960-1990 was used to calibrate a weather generator (Semenov and Barrow, 1997). This weather generator could therefore be used to generate daily climate data with the same climatological characteristics as the original data. The yields in Figure 6 are average of model simulations using 90 years of generated weather data.

An analysis of the relationship between simulated yield and climate showed that the yield was predominantly influenced by rainfall from flowering to maturity. The average rainfall during this period is shown for different sowing dates in Figure 6. This cumulated rainfall peaks at a sowing date slightly earlier than the sowing date giving the highest yield, which indicates that the yield during early crop growth (prior to flowering) does have some influence on yield.

The highest yields at Ada and Accra were obtained for sowing around 20 April, whereas the optimal sowing dates at Wa and Tamale were ca. 20 June for F-mix and ca. 10 July for Chinese. The sowing date used in the Akatsi region is March to April, and in northern Ghana sowing occurs in May to June. The simulated optimal sowing dates were thus in both cases slightly later than the dates used in practice. There may be several reasons for this. Figure 6 shows that the yield reduction for earlier sowings compared with the optimal date is small, in particular for the variety Chinese, which is the most commonly grown variety. Earlier sowing and a variation in sowing dates in general may contribute to increasing security of crop production in any particular year, even though the average yields may become slightly lower. Additionally, actual yields may also depend on factors not covered by the crop model, including dry conditions during harvest, which may make the soil unsuitable for harvesting the pods and thus leading to crop loss.

An alternative explanation for the difference between observed and simulated sowing dates is that groundnut growers do not use the optimal sowing date, but generally sow the crop too early. One of the methods commonly employed by growers to determine the sowing date is the rainfall during the past week. Figure 7 shows the simulated yields, if this strategy is used for choosing sowing date. This approach gives a considerably larger variation in yields and the average yield is also smaller than for the average optimal sowing date (Figure 6). This analysis suggests that there is a considerable potential in further analysing the approach of groundnut growers for choosing sowing date, and to analyse whether there is a basis for recommending another strategy based on optimal sowing date rather than the amount of rainfall during the previous period. It will of course also be required to demonstrate the benefits of such an approach to farmers.

The effect of using seasonal rainfall forecasts was investigated by using actual seasonal forecasts for the period 1987 to 2000. For Accra and Ada forecasts from February and March were used, and for Wa and Tamale forecasts from May and June. In all cases the estimates of the likely average rainfall for each of the coming six months were provided in the seasonal weather forecasts. These forecasts were used to change the climatic characteristics used by the weather generator. Subsequently the crop model was run using 90 years of climate data generated by the weather generator using the new climatic characteristics. Figure 8 shows that the application of seasonal weather forecasts leads to a change in simulated yield level as well as optimal sowing date in the individual years. The crop model was also run using the observed climate data from the individual years, also with varying sowing dates (Figure 8).

Based on these results optimal sowing dates were determined for each approach for the individual years (1987 to 2000). The optimal sowing date is the sowing date giving the highest yield, which under perfect knowledge varies considerably between years. The simulated yield using these sowing dates and the observed climate in the individual year was then used to evaluate the effect of choosing different approaches for choosing sowing date. The yield at the normal sowing date is the simulated yield in the respective year at the normally best sowing date (Figure 6), and the yield from using the seasonal weather forecast is the yield at the sowing date suggested as being optimal using the climate modified by the seasonal rainfall forecast.

Figure 9 shows the frequency distribution of yields for the different methods for two selected varieties. There were only small differences in yields at the normal sowing date and at the sowing date determined by the seasonal weather forecasts. In some cases the normal sowing date gave higher yields and in other cases the seasonal forecasts were beneficial. At Tamale and Wa there were only small differences between the optimal yield under perfect knowledge and the yield obtained using normal sowing date or dates predicted by the seasonal forecasts. The seasonal forecasts therefore have very modest scope for improving choice of sowing time in Northern Ghana. This is caused by the high regularity in timing of the rainy season in Northern Ghana. The timing of the rainy season in southern Ghana (in particular at Ada in the Akatsi district) is much more irregular and here seasonal forecasts may have a role for optimising sowing date. However, the current seasonal weather forecasts are as yet too uncertain for this purpose.

The project also examined the possibility of using seasonal weather forecasts for selecting variety and planting density. In general the differences in characteristics of the varieties used in the investigation were too small to give significant results, and the interaction between amount of rainfall and the optimal plant density was also too small to be decisive for choosing plant density. There is, however, probably a potential for using seasonal rainfall forecasts for improving variety selection, since the choice of variety is more related to the amount of rainfall than to the timing of the rainfall, whereas the timing of the rainfall determines the sowing date. It may be more feasible to predict amount of rainfall than the timing, which suggests a need to further examine the potential for crop and variety choice based on amount of rainfall, including the possibilities for intercropping with other species, which may be coupled to rainfall and soil water content.

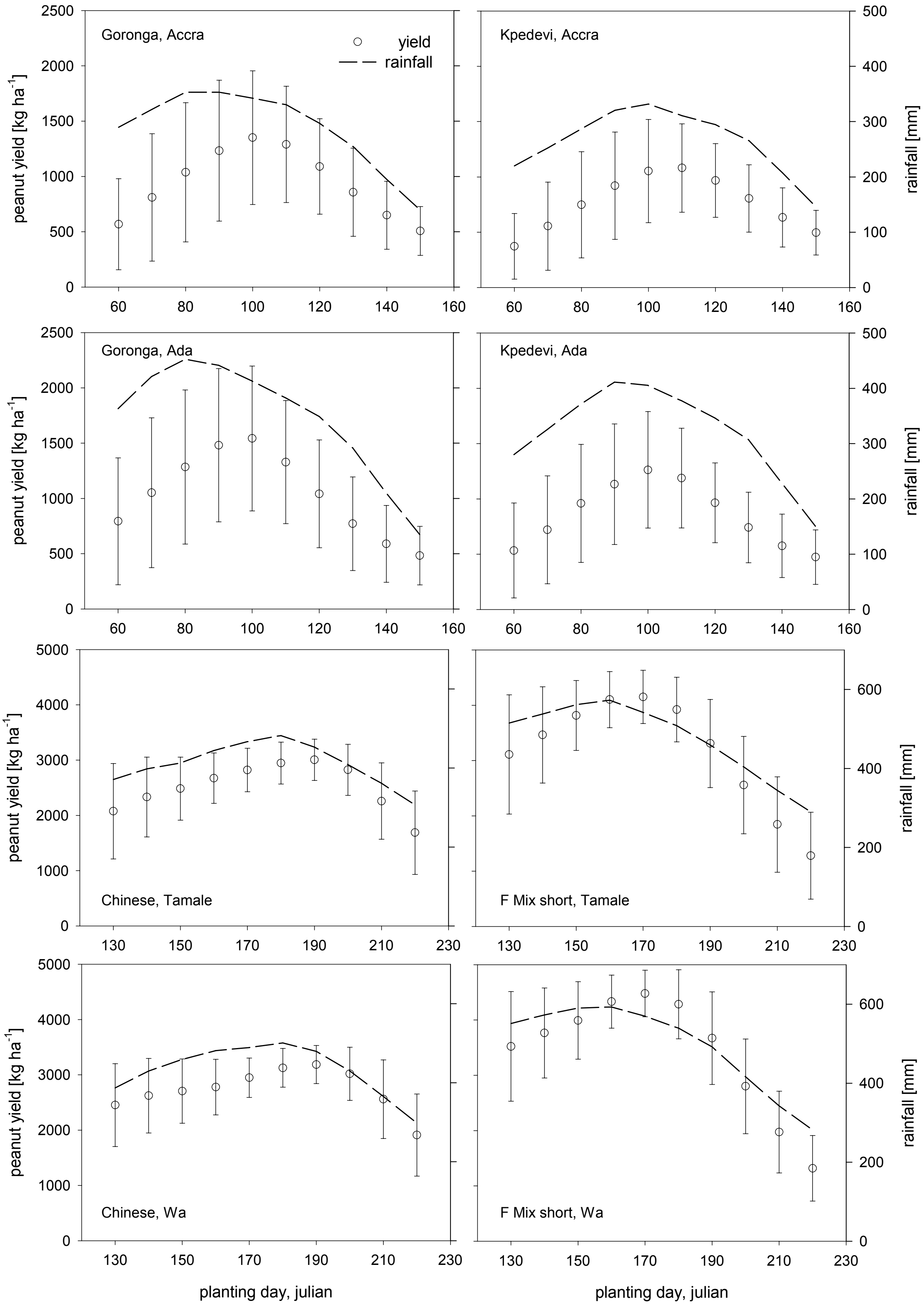


Figure 6. Effect of sowing time on yield for different varieties of groundnut at four sites in Ghana simulated for 90 growing seasons. The broken lines show the average rainfall from flowering to maturity of the groundnut crops. Error bars show the standard deviation of average yield.

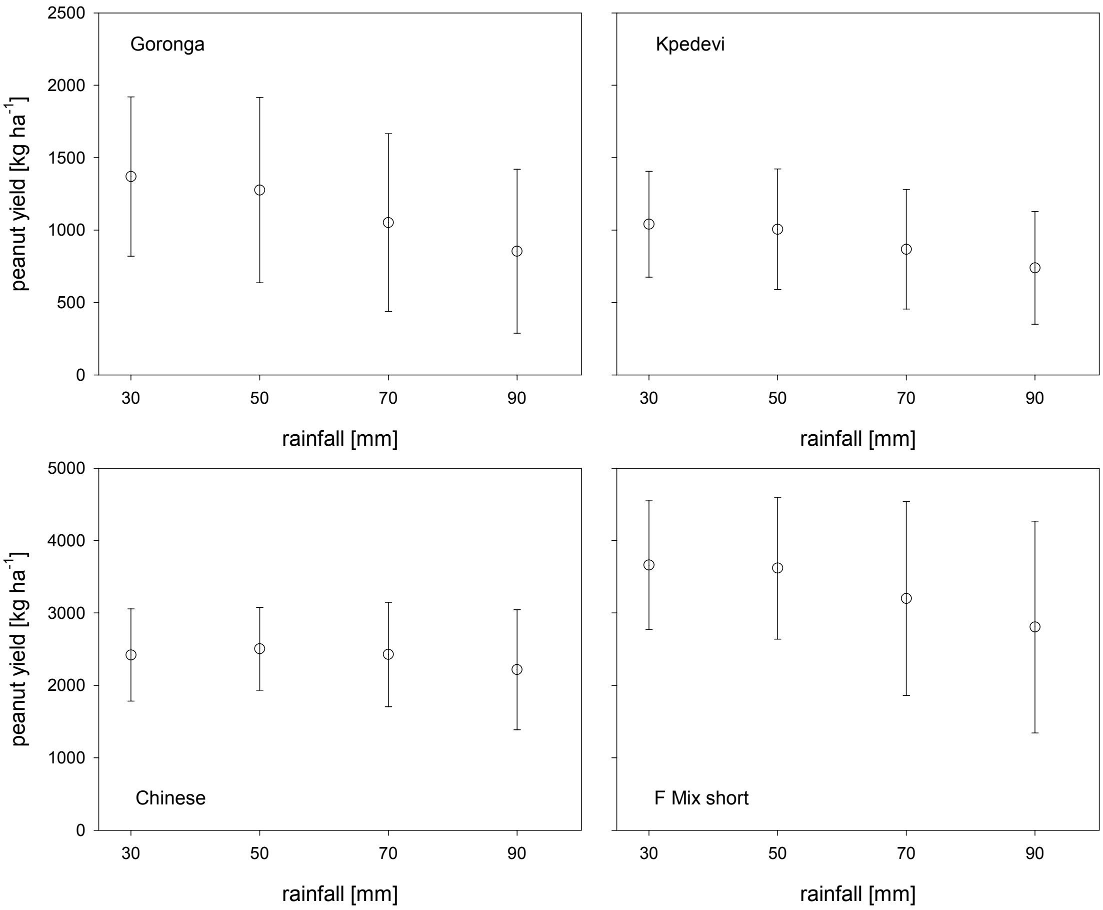


Figure 7. Average yield of groundnut at Ada (top graphs) and Wa (lower graphs) at sowing dates determined by a certain rainfall in the preceding week. Error bars show the standard deviation of average yield.

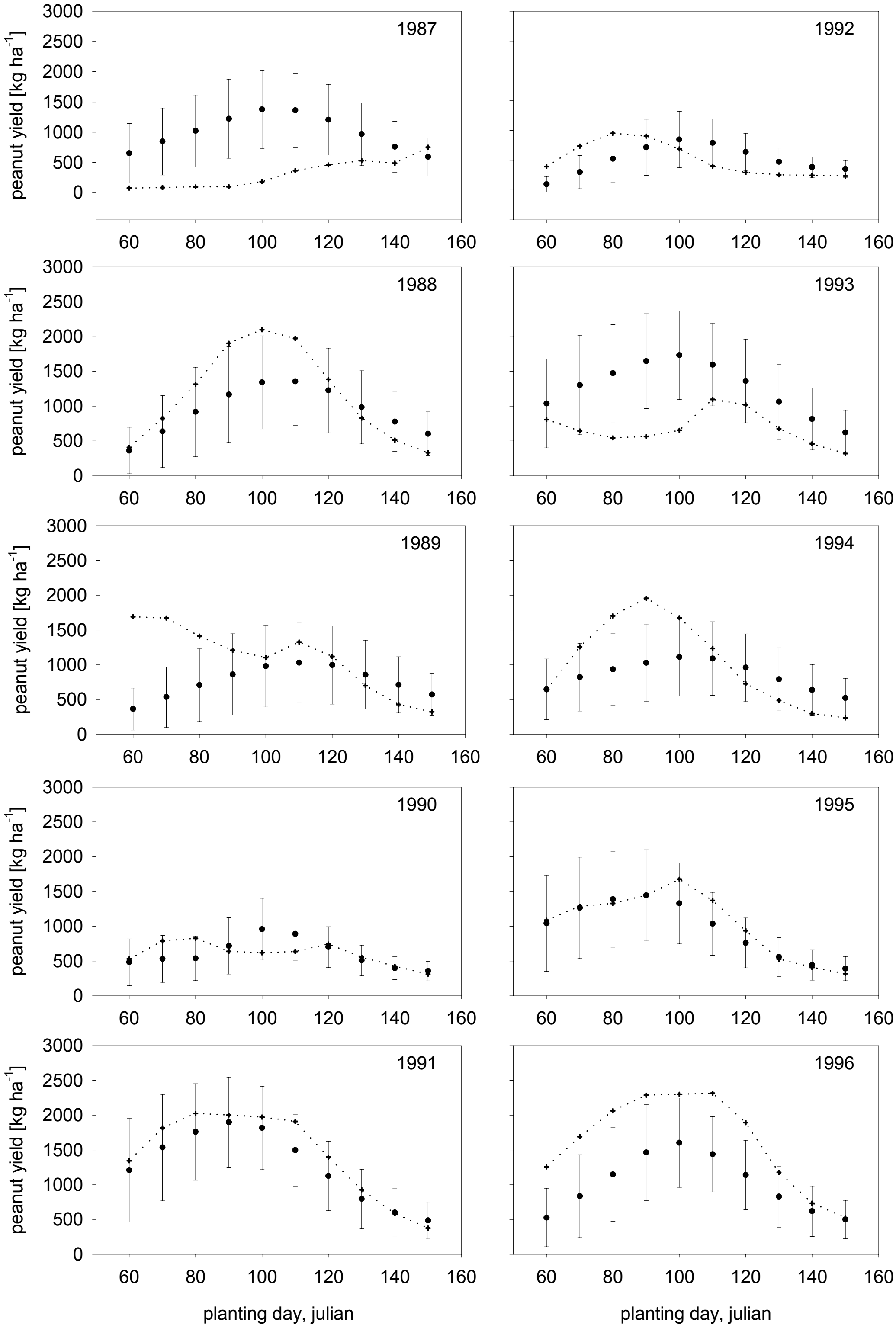


Figure 8. Simulated yields for different sowing times using seasonal weather forecasts for Ada from February 1987-1996. The dots connected with a dotted lines shown the simulated yield for the observed climate in the actual year. Error bars show the standard deviation of average yield.

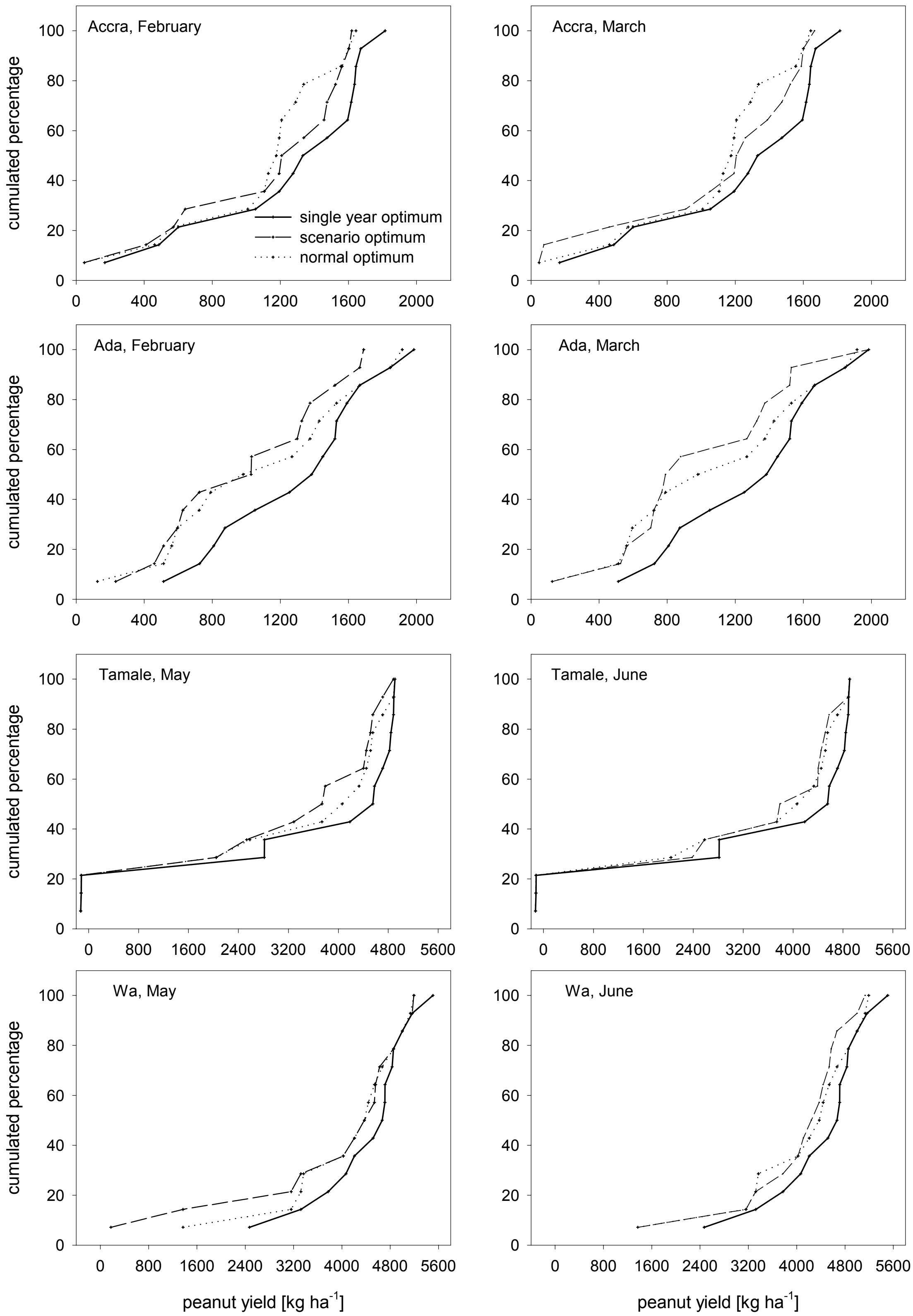


Figure 9. Frequency distribution of yields at the optimal sowing date in the individual year (solid line), at the normal optimal sowing date (dotted line) and at the sowing date predicted to be optimal from the seasonal weather forecasts (dashed line).

7. Results and perspectives

The results of the model analyses have established a framework for major changes in cropping practices that can be employed for adapting cropping practices based on seasonal weather forecasts to improve food security and increase agricultural production. However, these cropping strategies will in a later phase need to be evaluated under practical farming conditions in the various regions. This will be needed both to verify the model results and to demonstrate the results to farmers and advisors in the regions. Depending on the outcome of such a comparison, the need will emerge for simple guidelines on the use of seasonal forecasts in the planning of crop production. There will also be a large need to extend the analyses to other crops and other regions.

The project has not clearly demonstrated that the seasonal weather forecasts can be used with advantage for planning cropping strategies for groundnuts in the regions investigated. Further dissemination of the results to potential users in Ghana will therefore require considerable further analyses. Subsequently a major task will be the dissemination of forecasts and recommendations to local advisors involved with farmers to ensure a sustainable crop production. We have in the project envisaged dissemination via the internet, where the advisors could gain access to weather forecasts and to model estimates of the benefits and risks involved with different choices of crops, sowing dates etc. Within the project we have therefore designed a web-site, where the project aims and results have been published. However, it was clearly beyond the scope of the project to provide such an expert system, but this may become a key component in a later phase to ensure a successful exploitation of seasonal weather forecasts.

8. Summary of Master Thesis[1]

Crop modelling using long-term climatic forecasts - the temporal and spatial correlation between rainfall and vegetation indices measured from satellite images

Master thesis by: Rikke Harpøth, Institute of Geography, University of Copenhagen.
Supervisor: Inge Sandholt, Institute of Geography, University of Copenhagen.

Physical and agricultural data collection in developing countries such as Ghana is always a costly and a work consuming task. Often data does not even exist. Therefore the analysis of satellite images is a good alternative to using local ground data. It provides a means of improving amount and quality of data. Research conducted on local sites is time and space specific. Satellite imagery is spatially and temporally consistent. The spatial availability makes research possible in remote areas and it gives an opportunity to regionalise the results. The temporal resolution varies for different sensors, but in general the possibility of making time series is present and in physical and agricultural science seasonality is an important factor. But remote sensing data does not provide parameters directly convertible into final yield or all the parameters needed by yield models. A method for estimation of plant parameters and final yield using the available satellite data is needed.

My contribution to the main project was to regionalise the DSSAT35 output by combining it with MODIS products (remote sensing data obtained by satellites). The main objective of this sub-project was to investigate how satellite imagery can support the DSSAT35 model by delivering input data, and to test a simple algorithm for predicting regional yield based on vegetation indices (NDVI) obtained from the MODIS products using the modelled output as validation. The spatial and temporal correlation between rainfall and NDVI was investigated. It is seen from several authors that there is a correlation between rainfall distribution and soil water content and therefore with the amount of water available for the vegetation (Tucker et al. 1985, Rao et al. 1993, Ruimy et al. 1994, Running el al. 1995, Andersen et al. 2002). It is therefore expected that the correlation between the rainfall and NDVI is high. As NDVI is correlated to the yield (Knudby 2001).

NDVI time series
The curve of NDVI during one growing season for groundnut is established for 2001 and 2002 using MODIS data. Since it is expected that the NDVI curve for groundnut follows the curve for natural vegetation development, NDVI derived from MODIS images will be used for determining the yield of groundnuts, despite the relative low spatial resolution of 500 m x 500 m pixels. It is interesting to determine the time periods, where the groundnut production is highly dependent on climatic parameters (mainly rainfall, but also temperature and radiation) and when there is a strong correlation between NDVI and final yield. This will be assessed through knowledge of the phenology of groundnuts, linked to the appearance of the NDVI development curve for a growing season.

Surface temperature / NDVI
NDVI provides information on vegetation fraction. The temperature of a surface provides information on the moisture content at the surface. The relationship between the two provides information on the condition of the vegetation present. The temperature of the surface is thus closely related to the amount of vegetation present, because vegetation captures

[1] When this report was compiled the ”speciale” was not finished yet, expected mid 2004.

moisture and transpiration reduces surface temperature because of latent energy flux. Compared to rainfall data, this gives an estimate of cultivation potential and an opportunity to optimise sowing dates.

DSSAT35 (Decision Support System for Agrotechnology Transfer)

DSSAT35 simulates how the yield responses to soil, weather, and management conditions (Tsuji, 1994). The model uses photosynthesis as a function of solar radiation and availability of water and nutrients to predict the production of biomass and thus the production of seeds. Many of the parameters used by DSSAT35 are extractable from remote sensing methods (Directly: solar radiation, temperature. Indirectly: availability of water (water deficit) and production of biomass). It is attempted to use remotely sensed data for these parameters to regionalise the output of DSSAT35. The model will be used for several purposes:

1) To check the sensitivity of the crop of planting dates, rainfall regimes, radiation, temperature, soil water content. The most sensitive parameters will later be used in a regionalisation of the model output.

2) To obtain the 'true' yields of the regions by varying planting date, cultivar and plant density.

3) To create a harvest index to be used in regionalisation of yield.

Linking remote sensing and DSSAT35

The net primary production (NPP) can be obtained from satellite data in two ways: **1)** Integration of the NDVI curve gives an estimation of NPP, **2)** NPP = fAPAR x PAR x RUE. Daily fAPAR can be calculated directly from daily NDVI. These are then accumulated throughout the growing season. NPP from satellite data will be compared with the total biomass derived from the DSSAT35.

The NPP from the two methods can then be reduced by a harvest index to get the seed yield. The final yield will be obtained through three different methods and the strengths and constraints of each will be evaluated:

1) Yield is obtained directly from remote sensing by a simple equation based on integration of the NDVI curve.

2) Yield is obtained from the NPP multiplied by a harvest index simulated by the DSSAT35 model. The model calculates a harvest index automatically. The harvest index is regionalised through the climatic data.

3) Same as 2), but the harvest index is derived from satellite data. The relationship between surface temperature and NDVI provides information on drought incidents and of when during the plant development stages drought has a determining effect on the final yield. Comparing these three methods for obtaining regional yield shows the potential in the model as well as the satellite based regionalisation.

References

Adiku, S.G.K., P.W.A. Dayananda, C.W. Rose & G.N.N. Dowuona (1997). An analysis of the within-season rainfall characteristics and simulation of the daily rainfall in two savanna zones in Ghana. *Agricultural and Forest Meteorology*, 86, 51-62.

Adiku, S.G.K. & R.C. Stone (1996). Using the Southern Oscillation Index for improving rainfall prediction and agricultural water management in Ghana. *Agricultural Water Management*, 29, 85-100.

Andersen, J., Refsgaard, J. C. & Jensen, K. H., 2002. Distributed hydrological modelling of the Senegal River Basin – model construction and validation. Journal of Hydrology 247, pp 200-214.

Boote KJ, Jones JW (1998) Simulation of crop growth: CROPGRO model. In: Peart RM, Curry RB (eds) Agricultural systems modelling and simulation. Marcel Dekker Publishers, New York, p 651-692.

Boote, K. J., Jones, J. W., Mishoe, J. W. & Wilkerson, G. G., 1985. Modelling growth and yield of groundnut. Agrometeorology of Groundnut, Proceedings of an internatonal symposium, pp 243-254, Aug 1985, ICRISAT, Niger.

Boote KJ, Jones JW, Hoogenboom G (1997) CROPGRO model for grain legumes. In: Tsuji GY, Hoogenboom G, Thornton PK (eds) Understanding options for agricultural production. Kluwer Academic Press, Boston, p 99-128

Everingham, Y.L., Muchow, R.C., Stone, R.C., Inman-Bamber, N.G., Singels, A. & Bezuidenhout, C.N. (2002). Enhanced risk management and decision-making capability across the sugarcane industry value chain based on seasonal climate forecasts. Agricultural Systems 74, 459-477.

Feddersen, H., A. Navarra & M.N. Ward (1999). Reduction of model systematic error by statistical correction for dynamical seasonal predictions. *J. Climate*, 12, 1974-1989.

Gadgil, S., Rao, P.R. & Rao, K.N. (2002). Use of climate information for farm-level decision making: rainfed groundnut in southern India. Agricultural Systems 74, 431-457.

Gershunov, A., T.P. Barnett, D.R. Cayan, T. Tubbs and L. Goddard, 2000. Predicting and downscaling ENSO impacts on intraseasonal precipitation statistics in California: The 1997/98 event. *J. Hydrometeor.,* **1,** 201–210.

Giorgi, F. & L.O. Mearns, 1999. Introduction to special section: Regional climate modeling revisited. *J. Geophys. Res. – Atmosphere,* **104,** 6335–6352.

Hansen, J.W. (2002). Realizing the potential benefits of climate prediction to agriculture: issues, approaches, challenges. Agricultural Systems 74, 309-330.

Ingram, K.T., Roncoli, M.C. & Kirshen, P.H. (2002). Opportunities and constraints for farmers of west Africa to use seasonal precipitation forecasts with Burkina Faso as a case study. Agricultural Systems 74, 331-349.

Kharin, V.V. and F.W. Zwiers, 2001. Skill as a function of time scale in ensembles of seasonal hindcasts. *Climate Dyn.,* **17,** 127–141.

Knudby, A., 2001. Modelling spatial and temporal trends of groundnut yields in the Peanut Basin of Senegal. Master Thesis. Institute of Geography, University of Copenhagen.

Lal, H., G. Hoogenboom, J.-P. Calixte, J.W. Jones & F.H. Beinroth (1993). Using crop simulation models and GIS for regional productivity analysis. *Transactions of the ASAE*, 36, 175-184.

Martin, R., R. Washington & T.E. Downing (2002). Seasonal maize forecasting for South Africa and Zimbabwe derived from an agroclimatological model. *Journal of Applied Meteorology. In press.*

Mason, S.J. (1998). Seasonal forecasting of South African rainfall using a non-linear discriminant analysis model. *International Journal of Climatology* 18, 147-164.

Michaelsen, J., 1987. Cross-validation in statistical climate forecast models. *J. Climate Appl. Meteor.,* **26,** 1589–1600.

Nelson, R.A., Holzworth, D.P., Hammer, G.L. & Hayman, P.T. (2002). Infusing the use of climate forecasting into crop management practice in North East Australia using discussion support software. Agricultural Systems 74, 393-414.

Opoku-Ankomah, Y. & I. Cordery, 1994. Atlantic sea surface temperatures and rainfall variability in Ghana. J. Climate 7,551-558.

Osafo, D.M. (1976). Weather conditions and the growth of maize in the Kumasi area of Ghana. 1. A study of the weather. *Ghana Journal of Agricultural Science*, 9, 15-24.

Palmer, T.N., A. Alessandri, U. Andersen, P. Cantelaube, M. Davey, P. Delecluse, M. Deque, E. Diez, F. J. Doblas-Reyes, H. Feddersen, R. Graham, S. Gualdi, J.-F. Gueremy, R. Hagedoen, M. Hoshen, N. Keenlyside, M. Latif, A. Lazar, E. Maisonnave, V. Marleto, A. P. Morse, B. Orfila, P. Rogel, J.-M. Terres, M. C. Thomson. 2003, Development of a European Multi-Model Ensemble System for Seasonal to Inter-Annual Prediction (DEMETER) Submitted to BAMS.

Phillips, J.G., Deane, D., Unganai, L. & Chimeli, A. (2002). Implications of farm-level response to seasonal climate forecasts for aggregate grain production in Zimbabwe. Agricultural Systems 74, 351-369.

Rao, P. V. N., Venkatratnam, L., Rao, P. V. K., Ranama, K. V. & Singarao, M. N., 1993. Relation between root zone soil moisture and normalised difference vegetation index of vegetated fields. International Journal of Remote Sensing, 14, pp 441-449.

Rimmington, G. & N. Nicholls (1993). Forecasting wheat yields in Australia with the Southern Oscillation index. *Australian Journal of Agricultural Research* 44, 625-632.

Rowell, D.P., C.K. Folland, K. Maskell & M.N. Ward, 1995. Variability of summer rainfall over tropical north Africa (1906-92): Observations and modelling. Q.J.R. Meteorol. Soc. 121, 669-704.

Ruimy, A., Saugeir, B. & Dedieu, G., 1994. Methodology for the estimation of terrestrial net primary production from remotely sensed data. Journal of geophysical research 99, D3.

Running, S. W., Loveland, T. R., Pierce, L. L., Nemani, R. R., Hunt, E. R., 1995. A Remote Sensing Based Vegetation Classification Logic for Global Land Cover Analysis. Remote Sensing of Environment, vol. 51, pp 39-48.

Semenov, M.A. & Barrow, E.M. (1997). Use of stochastic weather generator in the development of climate change scenarios. Climate Change 35, 397-414.

Shukla, J. (1998). Predictability in the midst of chaos: A scientific basis for climate forecasting. *Science* 282, 728-731.

Stockdale, T.N., D.L.T. Anderson, J.O.S. Alves & M.A. Balmaseda (1998). Global seasonal rainfall forecasts using a coupled ocean-atmosphere model. *Nature* 392, 370-373.

Tippett, M.K., M. Barlow and B. Lyon, 2003. Statistical correction of central southwest Asia winter precipitation simulations. *Int. J. Climatol.,* **23,** 1421–1433.

Tsuji, G.Y., G. Uehara & S. Balas (1994). DSSAT version 3. International Benchmarks Sites Network for Agrotechnology Transfer. University of Hawaii, Honolulu, Hawaii.

von Storch, H. & Zwiers, F.W.,1998, Statistical Analysis in Climate Research, Cambridge University Press.

Widmann, M., C.S. Bretherton and E.P. Salathé Jr., 2003. Statistical precipitation downscaling over the northwestern United States using numerically simulated precipitation as predictor. *J. Climate,* **16,** 799–816.

The Danish Climate Centre

The Danish Climate Centre was established at the Danish Meteorological Institute in 1998. The main objective is to project climate into the 21st century for studies of impacts of climate change on various sectors and ecosystems in Denmark, Greenland and the Faroes.

The Climate Centre activities include development of new and improved methods for satellite based climate monitoring, studies of climate processes (including sun-climate relations, the greenhouse effect, the role of ozone, and air/sea/sea-ice interactions), development of global and regional climate models, seasonal prediction, and preparation of global and regional climate scenarios for impact studies.

The Danish Climate Centre is organised with a secretariat in the Research and Development Department, and it is co-ordinated by the Director of the Department. It has activities also in the Weather Service Department and the Observation Department, and it is supported by the Data Processing Department.

The Danish Climate Centre has established the Danish Climate Forum for researchers in climate and climate related issues and for others who have an interest in the Danish Climate Centre's activities.

DMI has been doing climate monitoring and research since its foundation in 1872, and the establishment of the Danish Climate Centre has strengthened both the climate research at DMI and the national and international research collaboration.

Previous reports from the Danish Climate Centre:

All reports are available on the Danish Climate Centre's list of reports on http://www.dmi.dk/dmi/index/viden/fk-introduktion/publikationer_dkc.htm.

Report 03-03	Ozonlaget over Danmark 1979-2002 (ind Danish).
Report 03-02	Application of seasonal climate forecasts for improved management for crops in Western Africa, J.H.Christensen, J.E. Olesen, H. Feddersen, U.J. Andersen, G. Heckrath, R. Harpøth and L. Wester-Andersen.
Report 03-01	Grønlands klima, temadag mandag den 16. december 2002, DMI. (In Danish)
Book	Climate Change Research – Danish Contributions. Edited by Anne Mette K. Jørgensen, Jes Fenger and Kirsten Halsnæs. DMI/Danish Climate Centre, 2001. 408 pages. Distributed by Gads Forlag.
Report 02-1	The climate of the 21st century: Transient simulations with a coupled atmosphere-ocean general circulation model. Revised version of Report No. 00-6).
Report 01-9	Klimaændringer 2001, Den videnskabelige baggrund. En rapport fra IPCC's arbejdsgruppe I, Resume for beslutningstagere: Danmarks Meteorologiske Instituts oversættelse af: Climate Change 2001 – The Scientific

Basis, A report from Working Group I of the International Panel on Climate Change, Summary for Policymakers. (translation into Danish).

Report 01-8 PRUDENCE kick-off meeting, Snekkersten, December 3-5, 2001. Jens Hesselbjerg Christensen.

Report 01-7 Detection of the Pinatubo volcanic heating signla in the lower stratosphere base don nudging assimilaiton and analysis increments. A contribution to the ACE Scientific Support Study. Eigil Kaas, Annette Guldberg and Ingo Kirchner.

Report 01-6 Using the nudging technique to estimate climate model forcing residuals. A contribution to the ACE Scientific Support Study. Eigil Kaas and Annette Guldberg

Report 01-5 Danmarks vejr og klima i det 20. århundrede. John Cappelen og Niels Woetmann Nielsen. (in Danish)

Report 01-4 Danmark, Færøernes og Grønlands Klima. DMI's afrapportering til FN's Klimakonvention UNFCCC. (in Danish)

Report 01-3 Synthesis of the STOWASUS-2100 project: Regional storm, wave and surge scenarios for the 2100 century. Eigil Kaas, et.al.

Report 01-2 Klimadag den 26. april 2001; Klimaændringer og deres virkninger - Præsentation af tværfaglig bog om danske bidrag til klimaforskningen. (in Danish)

Report 01-1 Changes in the storm climate in the North Atlantic/European region as simulated by GCM time-slice experiments at high resolution. Uffe J. Andersen, Eigil Kaas and Wilhelm May.

Report 00-6 The climate of the 21st century: Transient simulations with coupled atmosphere-ocean general circulation model. Martin Stendel, Torben Schmith, Erich Roeckner and Ulrich Cubasch. (revised version: see Report no. 02-1)

Report 00-5 A time-slice experiment with the ECHAM4 A-GCM at high resolution: The simulation of tropical storms for the present-day and of their change in the future climate. Wilhelm May.

Report 00-4 Metoder mødes: Geofysik og emner af samfundsmæssig interesse, Dansk Klimaforums Workshop 15.-16. maj 2000. (in Danish).

Report 00-3 Emissionsscenarier, Danmarks Meteorologiske Instituts oversættelse af IPCC's særrapport "Emission Scenarios, Summary for Policymakers". (in Danish).

Report 00-2 Drivhuseffekten og regionale klimaændringer. (in Danish).

Report 00-1 Forskning og Samarbejde 1998-1999. (in Danish).

Report 99-3 Luftfart og den globale atmosfære, Danmarks Meteorologiske Instituts oversættelse af IPCC's særrapport "Aviation and the Global Atmosphere, Summary for Policymakers". (in Danish).

Report 99-2 Dansk Klimaforum 12. april 1999. Workshop: Klimatisk variabilitet i Nordatlanten på tidsskalaer fra årtier til århundreder. (in Danish).

Report 99-1 Danish Climate Day 1999.

Report 98-1 Dansk Klimaforum 29. - 30. april 1998. (Opening of Danish Climate Centre and abstracts and reports from Danish Climate Forum workshop). (in Danish).