Centre for Ecology and Hydrology. *2000* Linking Earth observation and vegetation growth models: work in year 1. NERC/CEH, 13pp. (Integrating Fund 6)

IF6.

Linking Earth Observation and vegetation growth models: Work in year 1

Objectives

The activities identifies in the proposal are:

1. New algorithms will be developed to link the growth model with remote sensing products.

2. Earth Observation data over the study regions will be processed to quantify spatial variability, seasonal cycles and interannual variability.

3. This dataset will be compared with output from the vegetation model. Further development of the vegetation model will be required to reproduce phenological effects found in semi-arid regions.

4. The coupling of MOSES_II with NWP and water resource models will be further investigated.

5. The use of satellite products to expand the study persistence of rainfall patterns into the Kalahari and longer periods.

Introduction

Work in the first year of the project has focused on review of the literature relevant to the HAPEX SAHEL experiment, the development of the dataset, and implementing and testing methods for handling the remote sensing data. Familiarization, sensitivity and testing of the MOSES SVAT and TRIFFID phenology models was also undertaken.

There have been staffing problems with this project. The main originators at Monks Wood, Steve Plummer and Peter North, both left in the first few months. This has inevitably delayed progress and changed the focus somewhat. In particular we now plan to focus in more detail on the Sahel, rather than the Kalahari and on AVHRR rather than ATSR. Despite these problems good progress has been made and the majority of the year one milestones achieved. In terms of integration significant advances have taken place, specifically:

- the Monks Wood group have been thoroughly familarised with the HAPEX-Sahel experiment and data.
- A set of relevant data has been extracted – which will be of use to both groups.
- The mixture modeling techniques have been thoroughly discussed between the groups and will be made use of at both sites.

The interchange has also been of considerable benefit to the development of the EO center of Excellence bid (CLASSIC) – although unsuccessful in the last rou this was judge alpha 4 and invited to reenter the current round.

AVHRR data and processing

Initial work has focused on an existing NOAA AVHRR dataset. The Advanced Very High Resolution Radiometer (AVHRR) is a five-channel scanning radiometer capable of providing global daytime and nighttime sea-surface temperature and information about ice, snow, and clouds. These data were obtained on a daily basis for use in weather analysis and forecasting. The AVHRR data collected for the HAPEX project were from instruments on board NOAA-11 and 12 polar orbiting platforms. The radiometer measured emitted and reflected radiation in two visible, one middle infrared, and two thermal channels.

Geometric and radiometric corrections were applied to the imagery (Kerr et al., 1992). Atmospheric corrections were based on the SMAC method (Rahman and Dedieu,1993), which is based on the 5S radiative transfer code (Tanre et al., 1990). Atmospheric corrections take into account Rayleigh molecules) and Mie (aerosols) scattering effects as well as water vapor, ozone, oxygen and carbon dioxide absorption.

It is now well established that a ratio index of satellite measurements in the red and near-infrared bands is related to changes in vegetation biomass amount and characteristics, including leaf area index (LAI), a critical factor in land surface hydrological processes. The Normalized Difference Vegetation Index (NDVI) is one such ratio index. A generalized NDVI temporal profile for vegetation rises as plant cover increases, reaches a peak, or a plateau, and falls off with plant senescence (Vivoy et al., 1992). Thus NDVI profiles can provide a means of describing vegetation phenology. Further, the relationship between NDVI and plant cover is known to vary between vegetation types and so different biomes can have different NDVI profiles. The NDVI profiles for a given vegetation type can vary from area to area and year to year depending on the prevailing weather.

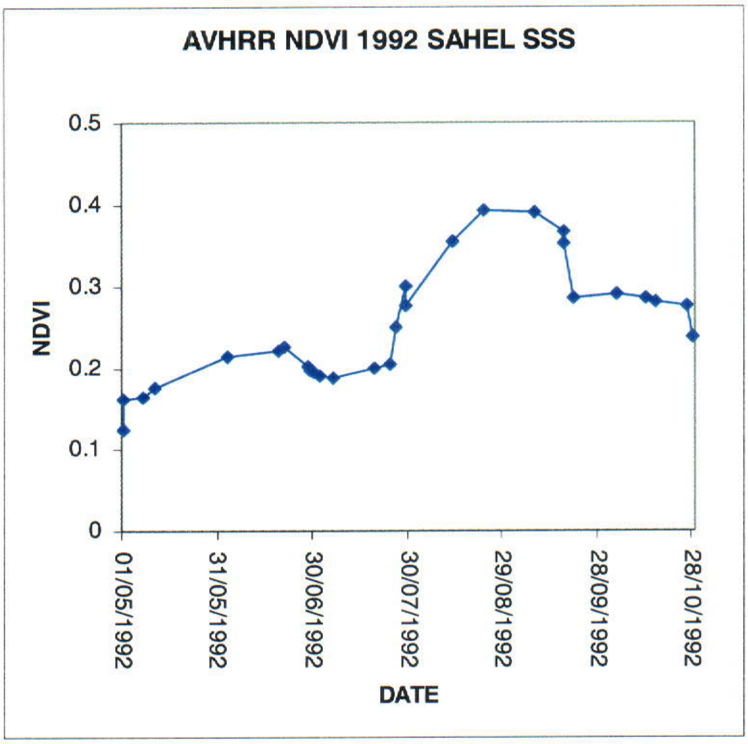
Changes in AVHRR NDVI profiles should be indicative of changes in surface conditions, principally in the vegetation. However, there are nearly always changes in these profiles caused by cloud contamination, atmospheric variability (even if atmospheric corrections have been applied) and bi-directional effects (Gutman 1991); these changes are considered undesirable noise in vegetation studies. In order to reduce these effects the Best Index Slope Extraction (BISE, Viovy et al., 1992) was applied to the time profiles of AVHRR data. This method helps to remove errors in the data due to sensor noise, cloud contamination and atmospheric variability, and bi-directional effects.

The result for a fallow test area located in the HAPEX SAHEL Super Southern Site (SSS) is shown in Figure 1 for 1992. The stage of vegetation growth can clearly be estimated from the NDVI profile, in July, as can the period of vegetation senescence, in

September. This provides the possibility of estimating some of the phenological information required by MOSES. The key growth stage is related to the onset of the seasonal rainfall.

Three separate sub-sites for the SSS were available, each dominated by one of the three main cover types (fallow, bush, and millet). However, all three sets of measurements looked very similar, and there did not appear to be any obvious difference between them. This may be due to a number of reasons, including pixel edge effects or environmental contamination of the reflectances. It seems likely that spectral mixing at the sub-pixel (< 1 km) level is also a factor, since the land cover fractions are known to vary at a sub-pixel scale. This may present difficulties in the extraction of phenological information, since, the NDVI profile includes the responses of multiple vegetation types. It may thus be necessary to use higher spatial resolution remote sensing imagery such as SPOT to estimate the land cover fractions within each AVHRR pixel. Current work is looking at the NDVI temporal profiles for different sites and cover types.

Figure 1
NDVI temporal profile for the fallow test site, extracted from the daily AVHRR data using the BISE algorithm.



Spectral mixture modeling
Due to the existence of sub-pixel mixing of land cover fractions in the test area, spectral mixture modeling was evaluated in order to assess whether or not this could provide a method for estimating the different land cover phenology within an 1 km AVHRR pixel.

The method assumes that the composite AVHRR reflectance is a linear sum of each of the individual sub-pixel land cover type reflectances, weighted by their relative fractions within the pixel. A principal use of mixture modeling has been to derive data on sub-pixel proportions of specified ground cover components, thereby providing more detailed information on the spatial distribution of resources within an area than is achievable using traditional classification procedures (e.g. Cross *et al.*, 1991). Linear mixture modeling requires definition of the end-member spectra. These are the spectral responses for the specified cover types under conditions of complete coverage of a pixel ('pure pixels'). Once derived, the model can be inverted to estimate the pixel proportions of the ground cover classes, assuming no variation in the spectral responses of the different cover types. However, in many sites, it is difficult to find suitable pixels due to sub-pixel mixing. In addition, the number of ground components that can be solved for is restricted by the dimensionality of the image data.

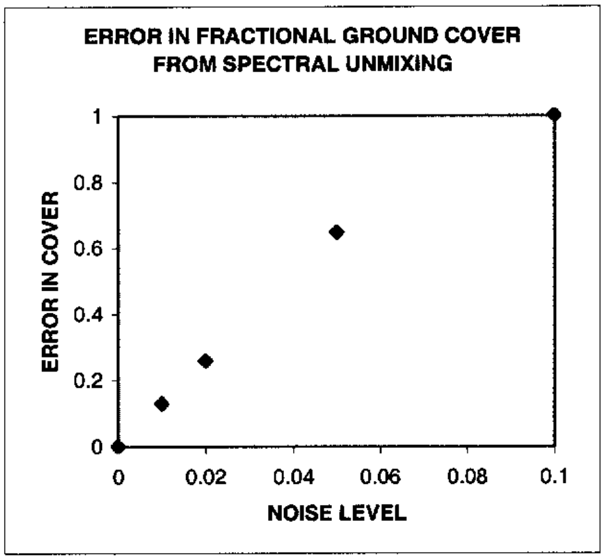
An alternative approach, which may avoid the requirement for pure pixels, is to specify the different cover fractions within the AVHRR pixels, and then to invert the model using the AVHRR NDVI measured for a number of separate pixels. The individual reflectance components of the different land cover types may thus be obtained. This method also provides the possibility of estimating for a greater number of classes.

Experiments with simulated reflectances were undertaken in order to explore the possibility that the spectral signatures of three different covers could be estimated, if the composite reflectances (e.g. from AVHRR) and the fractional covers were known (e.g. from SPOT). A wide range of fractions and signatures were included. It was found that, if the simulated AVHRR reflectances were free of noise, the original signatures could be obtained from measurements of three different areas of ground, each containing the three cover types in different proportions.

Different levels of error were then added to the 'AVHRR' reflectances and the experiments repeated. However, quite small errors (e.g 0.01) added to the reflectances lead to significant errors in the retrieved signatures (Figure 2). However, this problem may be reduced to an extent by applying the BISE noise filter described above.

The next step in this work is to test the method with real AVHRR data. For this purpose it will be necessary to obtain information on the different land cover fractions, from a higher spatial resolution 20 m SPOT image classification. Currently work is focused on the image processing to obtain this information.

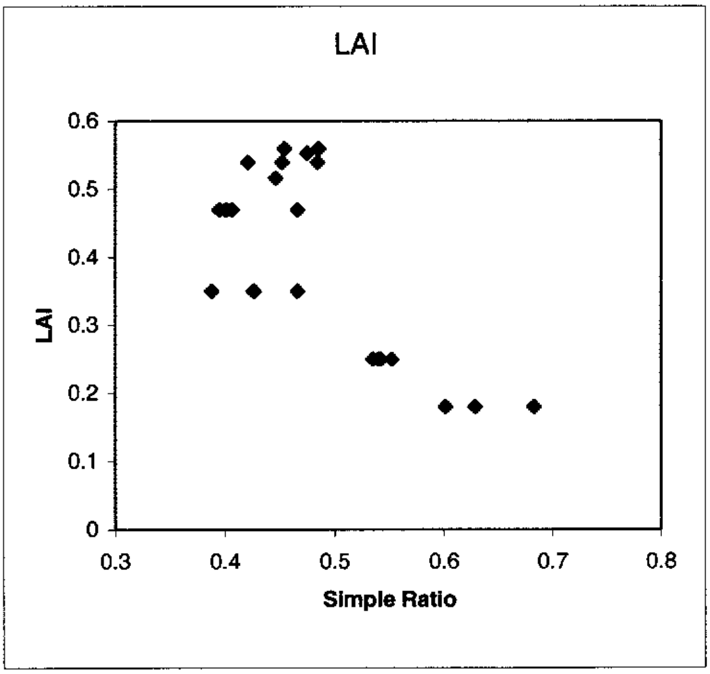
Figure 2
Errors in spectral unmixing using simulated data.



Airborne reflectance measurements
The HAPEX SAHEL database also contains aircraft measurements of reflectance through the summer 1992. These profiles showed some quite distinct differences between covers. These should be useful in two ways. First these could serve as a ground reference for signatures extracted from the AVHRR; and second, these measurements may potentially be calibrated them for LAI.

Figure 3 shows an attempt to calibrate the aircraft measurements of the red/near-infrared simple ratio for the fallow cover type LAI. The plot shows the actual LAI measurements, versus the predicted ones from a regression with the simple ratio data. This is a first approximation, but there was quite a bit of scatter in both spectral and LAI data. While the LAI increased right through to October, the simple ratio leveled out. This might be related to a gradual change in the spectral characteristics of the foliage, which did not affect the overall LAI. Current work is attempting to find similar LAI measurements for SSS millet and bush.

Figure 3
Red/near-infrared ratio and LAI measurements for fallow.



Land surface modelling activities

The Met. Office Surface Energy Scheme version 2 (MOSES2) incorporates a dynamic global vegetation model (DVGM) in order to simulate the climate-vegetation feedbacks. The DVGM is based on a "top-down" approach in which the relevant land surface characteristics, such as leaf area index, are modelled directly. It defines the state of the terrestrial biosphere in terms of soil carbon, and the structure and coverage of five plant functional types (broadleaf tree, Needleleaf tree, C_3 grass, C_4 grass and shrub). The areal coverage, leaf area index and canopy height of each plant functional type are updated based on the carbon fluxes which are derived using a couple photosynthesis-stomatal conductance model (Cox *et al.*, 1998).

The land-atmosphere fluxes are calculated at a sub-daily time step (60 minutes in this case) by MOSES2, using meteorological driving data and land surface parameters. These fluxes are time-averaged and passed to the DVGM at a daily time step. Leaf phenology (bud-burst and leaf drop) is updated using accumulated leaf turnover rates that are a function of the surface temperature and the soil moisture deficits. The land surface parameters, e.g. albedo, roughness length, are then in turn updated on the basis of the new vegetation state. These parameters are calculated as a function of the plant functional type, height and leaf area index of the vegetation. The DVGM is also capable of allocating the average net primary productivity, over a longer time step, between the growth of the existing vegetation (leaf, root and wood biomass) and competition between the different vegetation types on the proportions of the land surface each occupies, but this option has been switched off for the purposes of this study.

The leaf mortality rate of each vegetation type, γ_{lm}, is assumed to be a function of the surface temperature, T, and the fractional soil moisture content, θ. It increases from a minimum, γ_0, as the leaf temperature drops below a threshold value, T_{off}, and/or the soil moisture availability factor, β, rises above a threshold value, β_{off}:

$$\gamma_{lm} = \gamma_0 \qquad \beta < \beta_{off} \text{ and } T < T_{off}$$

$$\gamma_{lm} = \gamma_0 \left(1 - \frac{d\gamma}{dT}(T_{off} - T)\right)\left(1 - \frac{d\gamma}{d\beta}(\beta_{off} - \beta)\right) \qquad \beta \geq \beta_{off} \text{ or } T \geq T_{off}$$

The soil water availability factor is calculated for each layer of the soil water model as:

$$\beta = 1 \qquad \theta \geq \theta_c$$

$$\beta = (\theta - \theta_w)/(\theta_c - \theta_w) \qquad \theta_w < \theta < \theta_c$$

$$\beta = 0 \qquad \theta \leq \theta_w$$

where θ_c is the critical fractional soil water content (the soil water content above which stomata are not sensitive to the soil water content) and θ_w is the fractional soil water content at the wilting point (the soil water content below which stomata close). The soil water availability factor for each layer is multiplied by the proportion of roots in each layer. They are then summed to give an average value for the whole soil profile

The rate of change of the phenological status, *dp/dt*, is updated on a daily basis assuming:

- leaves are dropped at a constant absolute rate, $\gamma_p L_b$, when the daily value of leaf turnover, exceeds twice its minimum value, and
- "budburst" occurs at the same rate when γ_{lm} drops back below this threshold, and "full leaf" is approached asymptotically thereafter:

$$\frac{dp}{dt} = -\gamma_p \qquad \gamma_{lm} > 2\gamma_0$$

$$\frac{dp}{dt} = \gamma_p(1-p) \qquad \gamma_{lm} \leq 2\gamma_0$$

where γ_p is the rate of leaf growth. The phenological status, p, is updated as:

$$p = p + \frac{dp}{dt}$$

p is the ratio of the actual leaf area index, L, and the balance-growth leaf area index, L_b. For vegetation of height h, the balance-growth leaf area index is:

$$L_b = \left(\frac{a_{ws}\eta_{sl}h}{a_{wl}}\right)^{1/(b-1)}$$

where a_{ws} is the woody biomass as a multiple of the live stem biomass, η_{sl} is the live stem wood coefficient (kg C/m/LAI), a_{wl} is the target woody biomass and b is an allometric exponent given the value $^5/_3$. Thus the value for the actual leaf area index is updated using:

$$L = pL_b$$

Driving data and land surface parameterisation

The study has concentrated on the area covered by HAPEX-Sahel (Goutorbe et al., 1997) to exploit the considerable amount of data and knowledge available from this experiment. Driving meteorological data for the East Central Super Site (ECSS)were obtained from the Hydrological-Atmosphere Pilot Experiment (HAPEX-Sahel) database. A continuous time series of hourly data is required for the model and it was decided to use data covering the whole of a year in order to allow the model to spin-up during the months without rainfall at the beginning of the year. Data for 1992, the year of the experiment, was obtained. Unfortunately there were a number of gaps in the time series for periods of several days, although these were mainly at the very beginning or end of the year. These gaps were infilled using data from 1991 on the assumption that, being the dry season, there would be some variability on a day to day basis but the 'average' conditions would not change from year to year.

The land surface flux component of the model was parameterised using values given by C. Taylor (pers. comm.) who had tested the MOSES2 model against measurements of soil moisture and the atmospheric fluxes, using measured values of the vegetation canopy, with data from the area. These modifications included:

- the vegetation parameters of canopy capacity, rooting depth and the absorption of shortwave radiation;
- using measured values of soil hydraulic properties;
- introducing an albedo for soil depending on the top layer soil moisture and for C^4grass and trees that depends on canopy height.

The impact, on the phenology, of making these changes is illustrated by Figure 4, which compares the phenological status of C^4 grass predicted by MOSES2 using the 'standard' parameterisation with that using the modifications described above. The parameters of the DVGM are kept the same. The effect of the modifications is to advance the phenological cycle by about ten days.

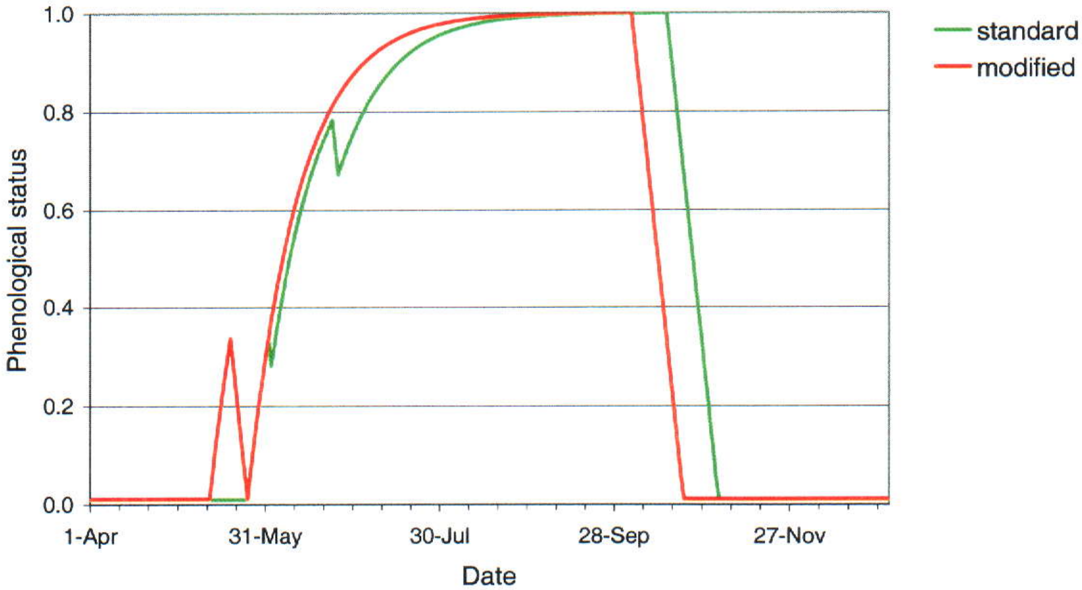


Figure 4 Impact of modifications to the land surface energy model on the phenological status

Sensitivity to model parameterisation

The surface temperature is not going to have any impact on phenology in the Sahel as the temperatures never fall low enough to have an impact. Therefore the phenological part of the DVGM is controlled essentially by three factors: the threshold of the fractional soil water (β_{off}), the green leaf turnover rate ($d\gamma/d\beta$), and the green leaf growth rate (γ_p). A literature search revealed very few studies of these parameters. In terms of the soil moisture, this is understandable since it is the water potential that is a control on the leaf turnover. Thus there are numerous papers describing the plant water potential and a few on the impact of soil water potential. The two remaining parameters are also rarely described in the literature, which tends to be more concerned about the details of the processes. Thus these parameters must be regarded as requiring calibration. A sensitivity analysis on these parameters has been carried out to understand how they effect the predicted phenological status, and thus the predicted LAI. Each of the parameters was varied in turn whilst the two other parameters were left at "standard" values ($\beta_{off} = 0.7$, $d\gamma/d\beta = 4.0$, $\gamma_p = 20$ yr^{-1}). The analysis has been confined to the plant functional type C^4 grass, parameterised as maize (the dominant crop in the HAPEX-Sahel area).

Decreasing the value of the threshold of fractional soil water, β_{off}, has the effect of greening up occurring earlier and senescence occurring later, i.e. making the growing season longer, Figure 5. Values less than 0.4 would appear to be unlikely as the would result in leaf die back occurring late in the year. Values greater than 0.8 as the vegetation does not achieved the balanced LAI. Values between 0.4 and 0.8 have little impact on the date of leaf die back but the date of leaf growth beginning is more sensitive, suggesting that it is in this period that any procedures for calibrating this parameter should concentrate.

The value of the rate of change of green leaf turnover, $d\gamma/d\beta$, also has an impact on the length of the growing season, Figure 6. The sensitivity to values greater than 5 is low so this may represent an upper bound, whilst values less than two would lengthen the growing season too much so a value between 2.5 and 5 seems reasonable.

Increasing the value of the leaf growth rate, γ_p, has the effect of increasing the date at which the balanced LAI is achieved during growth and the date at which leaf die back is complete but it has no effect on the date of start of growth or of leaf die back, Figure 7. The model is not particularly sensitive to values above 25 whilst values less than 15 and so a value within this range would seem likely.

A consequence of using the phenological sub-model is that the modelled soil water content never falls to the wilting point. This is because the leaf die back increases, and thus evaporation is reduced, as the soil water content approaches the wilting point.

A further point is that there is a linear relationship between the phenological status and the actual LAI. Thus it is reasonable to expect the shape of the predicted phenological status time series to match the observed variations in LAI. The latter is shown in Figure 8 which, when compared with all the predicted phenological status time series shown in Figure 5 to 8, it is clear that the observed growth occurs much later in the year than predicted by the model. It is difficult to foresee how any combination of the model parameters will reproduced the measurements. Further work is required and it may be necessary to include as additional process in the model.

Future Plans

1. the MOSESII model will be modified to produce a convincing simulation of the observed LAI patterns at the HAPEX_Sahel Supersites (figure 8) and the EO derived patterns at these sites.
2. Mixture modeling techniques will be further developed by identifying pixels that have a predominant single land cover.
3. The MOSES model will then be run for the 50+ raingauges across the HAPEX_Sahel area – the resulting simulated vegetation pattern will be compared with the EO derived LAIs for the pixels surrounding the gauges and, in particular, with the date of greening up observed from EO. This will be done for each of the land covers in 2.
4. The analysis will be repeated for 1991 – which had a significantly different seasonal pattern.
5. More recent years (1999 and 2000) and ATSR product will be investigated.

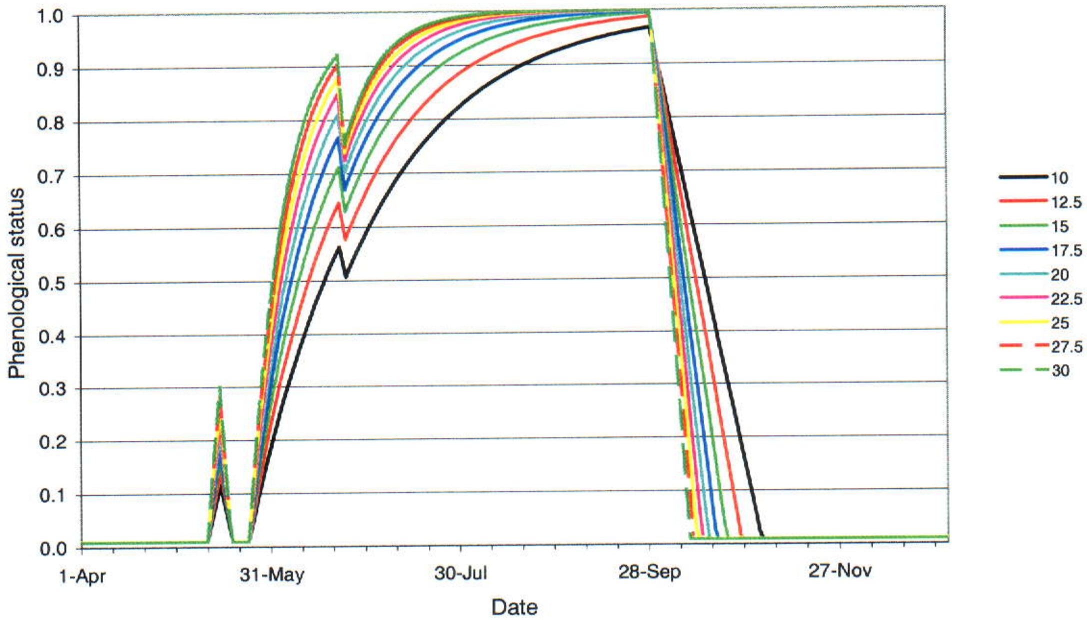
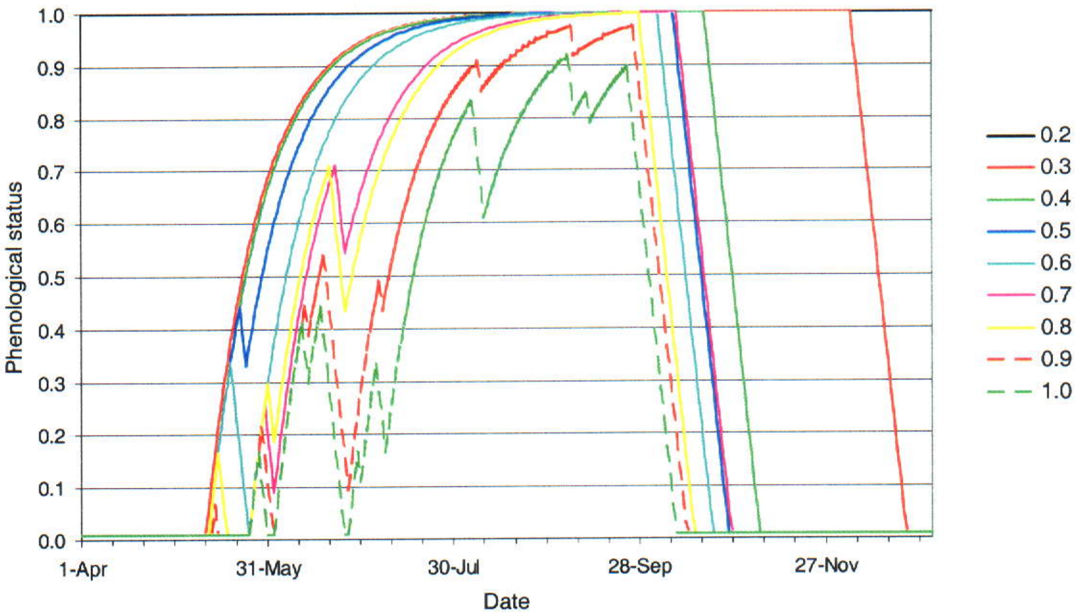


Figure 5. Sensitivity of modelled phenological status to the value of the fractional soil water content threshold

Figure 6 Sensitivity of modelled phenological status to the rate of change of green leaf turnover



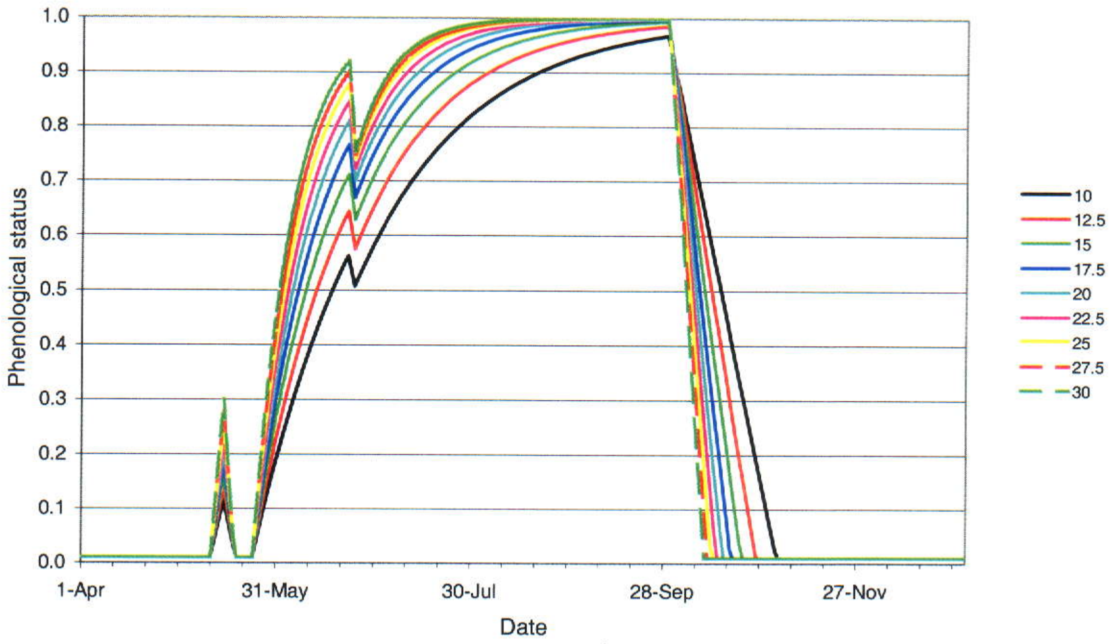
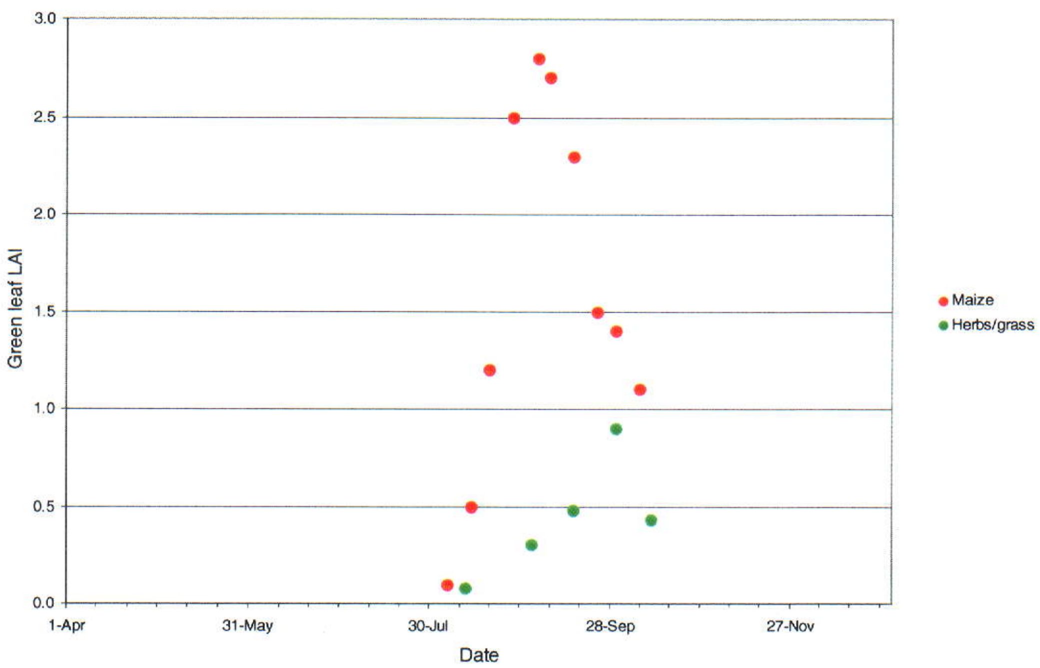


Figure 7. Sensitivity of modelled phenological status to the green leaf growth rate

Figure 8. Measured LAI at the ECSS



References

Cox, P.M., Huntingford, C. and Harding, R.J. (1998). A canopy conductance and photosynthesis model for use in a GCM land surface scheme. *J.Hydrol.* **212-213**, 79-94.

Cross, A. M., Settle, J. J., Drake, N. A., and Paivinen, R. T. M. 1991. Subpixel measurement of tropical forest cover using AVHRR data. *International Journal of Remote Sensing*, 12: 1119-1129.

Goutorbe, J.-P., Lebel, T., Dolman, A.J., Gash, J.H.C., Kabat, P., Kerr, Y.H., Monteny, B., Prince, S.D., Stricker, J.N.M., Tinga, A. and Wallace, J.S. (1997) An overview of HAPEX-Sahel: A Study in climate and desertification. *J.Hydrol.* **189**, 4-17.

Gutman, G. G. 1991. Vegetation Indices from AVHRR: An Update and Future Prospects, *Rem. Sens. Environ.* 35: 121-136.

Kerr, Y.H., Lagouarde, J.P., Imbernon, J., 1992. Accurate land surface temperature retrieval from AVHRR data with use of an improved Split Window algorithm, *Rem. Sens. Environ.*, 41: 197-209.

Rahman, H., and G. Dedieu, 1992. SMAC: A simplified method for the atmospheric correction of satellite measurements in the solar spectrum. Submitted to *Remote Sensing of Environment*. Draft available upon request.

Tanre, D., C. Deroo, P. Duhaut, M. Herman, JJ. Morcrette, J. Perbos and P.Y. Deschamps 1990. Description of a computer code to simulate the satellite signal in the solar spectrum: the 5S code. *International Journal of Remote Sensing*, 11: 659-668.

\`'ovy, N., Arino, O., and Belward, A. S. 1992. The best index slope extraction (BISE): a method for reducing noise in NDVI time series. *International Journal of Remote Sensing*, 13: 1585-1590.