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Analysis of the in-situ and MODIS albedo variability at multiple time scales in the Sahel

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Abstract

The variability of the Sahelian albedo is investigated through the combined analysis of five years of in situ radiation data from the AMMA northernmost sites (Agoufou 1°28'W, 15°20'N and Bamba 1°24'W, 17°06'N Mali) and remotely sensed albedo from seven years of MODIS data. Both datasets are found to be in good agreement in terms of correlation and bias. The drivers of albedo variability are identified by means of in situ measurements of biological and physical properties of the land surface collected over a network of 25 long-term survey sites. Short-term variability is dominated by changes in the spectral composition of incident radiation, which reflects aerosol optical depth and integrated water content, and changes in soil moisture, which have a short-lived effect (1 day). Bush fires cause a marked decrease of albedo of the order of 10 days, whereas a dry season storm event is suspected to have increased albedo through litter and soil surface abrasion. Seasonal plant growth causes the largest changes in rainy season albedo, and displays a large interannual variability: Because of the 2004 drought, albedo increases steadily from late 2003 to

early 2005 at latitude 15°N. Dry season albedo is controlled by the amount of litter and standing dead phytomass hiding the bright soils. Grazing pressure is found to impact albedo mostly in the dry season, through the pace of dry phytomass decay. EOF analysis and Hovmüller diagrams (10°W to 0°, 10°N to 20°N) show these effects to be present on a large scale. Above average rainfall thus have a direct effect on albedo through plant growth but also a lagged effect caused by above normal amounts of dry phytomass that can persist until the arrival of the next monsoon. This provides positive feedbacks at both the intra-seasonal and inter seasonal scales. Surface albedo in the Sahel exhibits a strong variability at different timescales caused by external forcing and internal dynamics of land surface, which should be included in climate models.

1. Introduction

Surface albedo is central to surface/climate interactions in the Sahel. Many investigations have studied the possible link between changes in albedo and the severe droughts that affected West Africa during the 70's and 80's. The main hypothesis, introduced by Otterman et al. (1974) and developed by Charney et al. in 1975, is that a decrease in the vegetation cover caused by drought, over-grazing, extensive clearing for cropping, deforestation or land degradation triggers an increase of the albedo. This in turn tends to reinforce subsidence in the Sahel and weaken convective activity, resulting in less precipitation and thus further decline in vegetation cover. The Charney's mechanism has been extended to account for other surface properties like the release of latent heat (Eltahir and Gong 1996), and questioned as the sea surface temperature was recognized to drive the West-African monsoon (Gianini *et al.*, 2003). Nevertheless, the importance of the surface feedbacks to the atmosphere has been demonstrated, the current view being that this feedback acts more as a strong amplifier of ocean driven variability than as the initial trigger of monsoon variability (Lamb, 1983, Folland *et al.*, 1986, Nicholson et al., 1998, Nicholson, 2000, Fontaine and Janicot, 1996, Zeng *et al.* 1999, Gianini et al.2003).

Numerical climate models showed that important land cover changes can lead to climate change in West Africa (Xue and Shukla, 1993, 1996, Lofgren, 1995, Dirmeyer and Shukla, 1996, Claussen, 1997, Xue, 1997, Clark *et al.*, 2001, Notaro et al 2007). However, the magnitude of albedo changes caused by a reduction of vegetation cover is thought to have been overestimated (Nicholson 2000, Taylor *et al.*, 2002). Notaro et al 2007 even suggested that the land surface feedback may be negative, an hypothesis at odds with most results so far. More precise studies are required to analyze the history of albedo changes that actually occurred in the Sahel in the last decades. In particular, it is necessary to accurately assess the contribution of the albedo feedback to

the recent droughts in West Africa. There is also a need for realistic scenarios of potential future albedo variations associated to land cover changes.

Given the recognized importance of the land surface energy budget, surface albedo has been the subject of several studies, most of them based on remote sensing data. Norton *et al.* (1979) investigated the signature of the 1973 drought by means of green reflectance measured by the Applications Technology Satellite (ATS) 3 sensor from 1967 to 1974. They suggested that the drought caused an increase in spectral albedo in the green wavelength during the wet season, and a smaller increase in the dry season, which they attributed to a reduction in vegetation cover and soil wetness. However, the authors were careful in their conclusions because of the poor quality of the data. Using a series of Landsat images, Courel *et al.* (1984) bridged the time gap between ATS 3 and Meteosat 1 data. Despite limitations due to the combination of spectrally and geometrically different datasets, they were able to conclude that dry season albedo in Ferlo (Senegal) and Gondo (Mali) decreased from 1973 to 1979, which they considered was at odds with Charney's hypothesis, according to which such a dry period should have displayed a steady high albedo. More recently, Ba *et al.* (2001) provided a comprehensive climatology of surface albedo from Meteosat data, showing that the largest gradients occur between latitude 13 to 18°N, with the largest seasonal variability being at 15°N. They found that north of 13°N, albedo decreases during the wet season, whereas it increases south of 13°N. Nicholson *et al.* (1998) stated that surface albedo in the Sahel had shown relatively small year-to-year changes during the 1983-1988 period, which were probably within the margin of error of satellite measurements, despite the major droughts of 1983 and 1984. Nicholson *et al.* (1998) concluded that albedo is a complex problem, adding that a reduction of vegetation cover does not always result in higher albedo. Fuller and Okkte (2002) investigated albedo derived from the Pathfinder dataset of the AVHRR sensor. While 30-year averaged rainfall and ecosystem properties like tree cover were found to explain spatial albedo gradients, rainfall had a rather weak impact on albedo on a monthly time scale, even when lags of 1-12 months were considered.

Being uniquely based on remote sensing data, these studies could not trace the changes in albedo back to their primary drivers. Surprisingly few studies investigated albedo changes in the Sahel by means of in situ data. The Sahelian Energy Balance Experiment (SEBEX) provided the longest dataset (Allen *et al.* 1994) spanning over 15 months and two rainy seasons for a tiger bush site and a fallow site in Niger. In addition to providing reference albedo values, the Allen *et al.* study insisted on the role of soil wetness and leaf development. The Hydrologic and Atmospheric Pilot Experiment (HAPEX) in the Sahel and Niger expanded the number of measurement sites

adding millet fields to already studied tiger bush and fallow (e.g. Bégué *et al.* 1996) but this experiment was mostly focused on the transition period from the wet season to the dry season of 1992. As a result, there is a clear lack of analyses dealing with multi-site, multi-year in situ data, as well as quantitative relationships between albedo changes and their drivers. Up-scaling of in situ data to a significantly large area has not been considered so far. The remote sensing based studies reviewed above shed invaluable light on the plausibility and strength of Charney's mechanism as well as on the extent and reality of 'land degradation'. They suffer however from non ideal data - incomplete spectral range, directional effects, orbital drifts, incomplete atmospheric corrections, difficulties of sensor inter-calibration - which may bring precise characteristics of inter-annual variability and trends close to the noise level. Recent datasets and new generation sensors are greatly improved in these respects. The Moderate Resolution Imaging Spectroradiometer (MODIS) derived albedo dataset (Schaaf *et al.* 2002), for instance, benefits from a very good sampling of the solar spectrum, intensive calibration monitoring, orbit control and progress in albedo derivation algorithms. Similar improvements are applied to current re-processing of the Meteosat archive (Govaerts and Lattanzio, 2007). This is especially important because the results of recent studies have displaced the emphasis from a drastic change in albedo caused by historical droughts towards more subtle variations at the intra-seasonal to inter-annual time-scale. Indeed, albedo variations at such time scales have the potential to amplify the monsoon variability by providing positive land surface / rainfall feedbacks. Modelling studies suggest that multi-year memory effects of the surface are necessary to explain the persistence and intensity of ocean-driven droughts over several years (e.g. Zeng *et al.*, 1999).

To improve the parameterization of albedo in climate models, the drivers of albedo variability need to be identified based on observations at the relevant scales. This requires significant instrumental deployment in areas where field data are scarce. Intensifying observations networks in West Africa was a strong motivation of The African Monsoon Multidisciplinary Analysis (AMMA, Redelsperger *et al.*, 2006). This paper aims to describe the main sources of albedo variability in the Gourma Sahelian region, in Mali, at different time scales, ranging from daily to inter-annual variations, combining a set of in situ measurements over a network of sites and MODIS derived albedo data.

2. Data and methods

2.1. Study area and ground measurements

The region under study is the Gourma, extends over 90 000 km² on the right bank of the Niger river to the south of the large loop made by the river between Mopti and Gao (Ag Mahmoud, 1992). Within this area, located in Mali, a mesoscale site has been more intensively instrumented within the framework of the AMMA project. Ranging between latitude 14.5° N and 17.5° and longitude 2° W to 1° W, it covers a large part of the Sahelian bioclimatic conditions, with precipitation ranging from 100 to 500 mm (Figure 1). This region shows a strong spatial albedo gradient (Norton *et al.*, 1979, Ba *et al.*, 2001), and therefore it is expected to display significant albedo sensitivity at different timescales.

Albedo variability in this study is diagnosed from ground measurements and remote sensing estimates. As opposed to controlled experiments, albedo variability in the real-world is caused by distinct processes operating at different spatial and temporal scales. Therefore, different time scales and phenomena have to be extracted from the albedo time series, and correlated with ancillary data. Such an approach is demanding in terms of in situ measurements, which range from radiation to multi-site vegetation properties, but it has the advantage of documenting real albedo variability.

Automatic weather stations were installed near Agoufou (15°20'40", -1°28'45") in April 2002 and near Bamba (17°05'56", -1°24'06") in April 2004. In addition to the standard parameters (rain / SBS Campbell, air temperature, humidity / Vaisala HMP45C probe, wind speed/ A100R Vector anemometer and wind direction / W200P Vector wind vane), these two stations have been recording soil moisture and temperature profiles (TDR and thermistors) and the four components of the radiation budget with a CNR1 (Kipp and Zonen) installed 2.5 m above ground level. To investigate possible effects of field of view, a second device was installed at 0.7 m above ground level. Photosynthetically active radiation (PAR, 0.4 to 0.7 micron) was measured by a BF2 device (DeltaT) in 2003, and a BF3 (DeltaT) since 2004. Both total and diffuse PAR were measured. All these data were averaged over 15 minutes and stored with Campbell CR10X data loggers. Routine sensor cleaning was performed but occasional failures due to the harsh environment led to a few gaps in the datasets, mostly in the dry season. Shortwave radiation data were accumulated over 24 h periods to compute the daily albedo values used in this study. An automatic sun-photometer was installed in Agoufou in 2002 and provides Aerosol Optical Thickness (AOT) and Integrated Water vapor Content (IWC) according to the AERONET algorithm. AOT and IWC values were averaged between 10 h and 14 h local solar time.

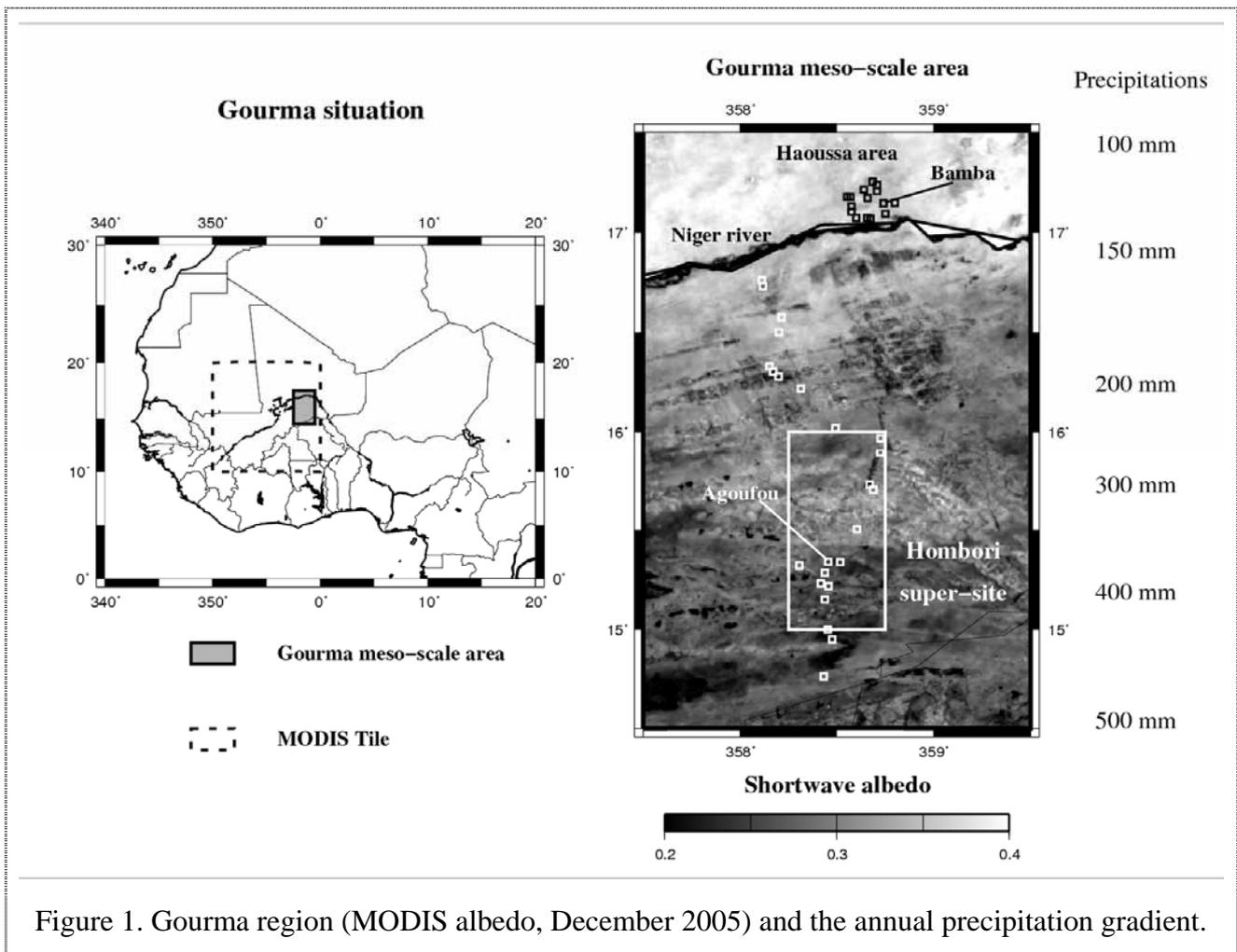


Figure 1. Gourma region (MODIS albedo, December 2005) and the annual precipitation gradient.

A set of 29 field sites sampled along the bioclimatic gradient in the Gourma (Figure 1) has been surveyed since 1984. They were selected in order to represent the surface diversity in terms of vegetation cover and pattern, soil texture, hydrology, and land use (Hiernaux and Justice, 1986). Sandy soils resulting from wind erosion/deposition during the arid periods of the quaternary extend on 55% of the Gourma. 17 of the sites are covered with an almost continuous low herbaceous layer and sparsely distributed trees and shrubs. They are distributed along the bioclimatic gradient, covering four classes of grazing intensity, and constitute the main sources of forage with grazing pressure depending on the distance to water points. 4 sites are composed of shallow soils with very sparse vegetation over sandstone and schist outcrops cover 30% of the Gourma. The remaining 8 field sites are distributed in the loamy and clay soils that occupy 15% of the Gourma as depressions gathering water run-off from shallow soils. Some of these sites support dense cover of tree species standing seasonal floods.

Systematic observations were carried out during the past 23 years to estimate standing herbaceous mass, litter, density of trees, floristic composition, surface properties (crusts, flood, and wind erosion), and land use (grazing intensity, fire frequency). The sampling protocols to assess

herbaceous and woody plant vegetation along 1 kilometer lines can be found in Hiernaux and Justice (1986). From the beginning, the sites have been selected to be homogeneous at the 1 km scale, to allow monitoring with the Advanced Very High Resolution Radiometer (AVHRR) sensor onboard the National Oceanic and Atmospheric Administration (NOAA) series. They are then particularly well adapted for the validation and the use of remote sensing products.

The Agoufou intensive site is grassland on sandy soil which receives an average of 350 mm of rain per year. It is the most instrumented site of the AMMA experiment in the Gourma. Vegetation consists of an herbaceous layer dominated by annual grasses with scattered trees making 3 % canopy cover (see picture in Baup et al 2007). The commonest species are widespread throughout the Sahel and dominant in Sahelian grasslands. The Bamba site is also a sandy soil site with lower precipitation (about 100 mm on average). The sparse herbaceous layer is a mix of scattered tussock perennials and short cycle annual grasses. Woody population is more scattered than in Agoufou with canopy cover of only 0.9 %.

2.2. *Satellite data*

For this study, we used the MODIS albedo product (version 4) at 1 km and 16 days resolution (Schaaf *et al.* 2002). The relatively low temporal resolution is due to the necessity to collect a sufficient number of observations with different viewing geometries to retrieve the surface Bidirectional Reflectance Distribution Function (BRDF). We used principally the broadband “white-sky” or bi-hemispherical albedo that is available for three spectral intervals: Visible [0.4-0.7 μ m], Near Infra-Red (NIR) [0.7-2.5 μ m] and shortwave [0.4-2.5 μ m]. Broadband albedos are obtained using a combination of the 7 narrow-band albedos corresponding to each spectral channel of the instrument. The MODIS product uses the formula provided by Brest and Goward (1987), initially established for the Landsat Thematic Mapper spectral bands. Until 2004, the BRDF and albedo are processed by using the MODIS data from the Terra satellite. For 2005 and 2006, they are processed using the data from both Terra and Aqua. Using two sensors instead of one increases the number of observation and thus reduces the gaps caused by the lack of clear-sky observations for cloudy regions. In the case of the Gourma, the cloudiness is not really an issue, but south of 10° N, clear-sky observations become irregular during the monsoon in summer. When a daily temporal resolution was necessary, we also used the daily MODIS directional reflectance in the red and Near Infrared (NIR) spectral bands which are available at a resolution of 250 m. Formosat-2 images (8 m resolution) were used to evaluate the spatial heterogeneity.

3. Comparison between in situ and satellite albedo

Figure 2 shows the comparison between the MODIS white-sky albedo time series and the in-situ albedo from Agoufou and Bamba stations. The in situ albedo is calculated by integrating the downward and upward radiative fluxes over the whole day. Because the sun is close to zenith at these latitudes, the value resulting from this integration is very close to the white-sky albedo definition: Simulations using the SAIL radiative transfer model (Verhoef, 1984) for typical Sahelian surfaces showed that the theoretical difference between the bi-hemispherical albedo and the station albedo is lower than 1% of the signal. Daily in situ albedo time series were filtered using a sliding mean to smooth the short-term variations in order to facilitate the direct comparison with the 16-day MODIS product.

For Agoufou, the overall albedo evolution is strongly related to the vegetation seasonal cycle, which itself is driven by the precipitation. The albedo is usually maximal at the end of the dry season, in June, and minimal during the wet season, when the vegetation is fully developed. The role of the vegetation is less important at Bamba. The albedo seasonal cycle is thus weak, even in 2005, a year of significant rain and vegetation growth.

Generally there is good agreement between the MODIS and in-situ albedo for both Agoufou and Bamba: The seasonal variations are consistent between the two sources with a very good timing match at the onset of the wet season, when the albedo abruptly decreases. The agreement between the two datasets can also be seen in Figure 3 where the MODIS albedo is plotted against the station albedo for all dates in both sites. The MODIS products exhibit a slight positive bias of 0.0121 and the dispersion (standard deviation after removal of the bias) between the two time series is 0.0263. The bias is mainly due to the lowest albedo values, for which the MODIS data stands higher than field measurements. Time series reveal that this discrepancy systematically occurs during the wet season (Figure 2). At that time, the minimum albedo reached at the Agoufou station is lower than the MODIS albedo, with a maximum bias of about 0.04. In 2002, the difference persists until the next rainy season. Instrument calibration is not likely to be the cause of this bias, as the same phenomenon occurs at the Bamba site in 2005, although albedo values are still high compared to Agoufou.

Given the difference in field of view between the satellite and the ground instrumentation, we performed two additional comparisons. First, we compared the in situ albedo measured at 2.5 m and 0.7 m. The CNR1 sensors have an hemispheric field of view and a cosine response (Kipp and Zonen). For the 2.5 m sensor, 90% of the signal comes from a 7.5 m radius area, with 55% coming from the fenced area. The fenced area makes 95% of the signal for the sensor at 0.7 m. The two

sensors result in very similar daily albedo, with a correlation coefficient r^2 of 0.94 and a RMSE of 0.014. Second, we compared spectral data from FORMOSAT-2 at 8 m resolution (bands in the blue, green, red and NIR domains) at four dates during the season. The 4 pixels corresponding to the Agoufou station were compared to the average of the 15365 pixels located in the 1 km by 1 km MODIS pixel. The RMSE was 0.0066, reaching a noticeable level only in the red band at one date in early august (reflectance of 0.11 for the 1km site and 0.13 for the station). This difference is dampened when all bands are combined to give an average short-wave reflectance. This is in line with results from Garrigues et al. 2006, who used variograms from high resolution SPOT data to characterize satellite-derived LAI validation sites world-wide. For these reasons, spatial heterogeneity is not responsible for the difference between MODIS and in situ albedo and **some residual inaccuracies in** satellite data processing can not be ruled out. However, the difference in the seasonal minimum albedo between in situ and MODIS data does not impair the consistency of the two datasets, as inter annual variability is very coherent. For instance, 2004 and, to a lesser extent, 2002 stand out in the two Agoufou time series, showing a small decrease or almost no decrease of albedo in the wet season in both in situ and MODIS data in relation to poor rainfall and vegetation growth.

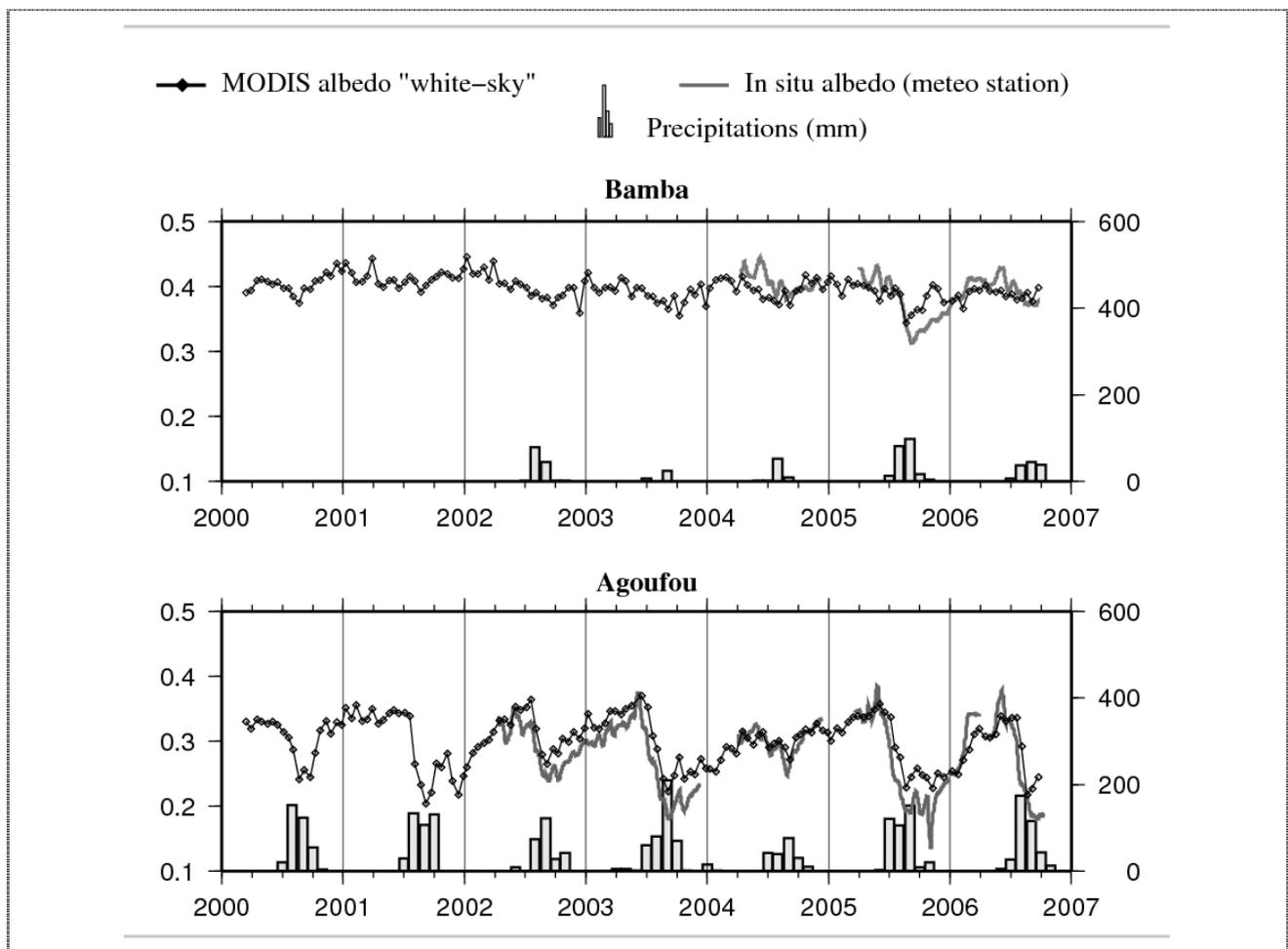


Figure 2. Albedo from MODIS and field station data for Agoufou and Bamba (left scale) and monthly precipitation (right scale).

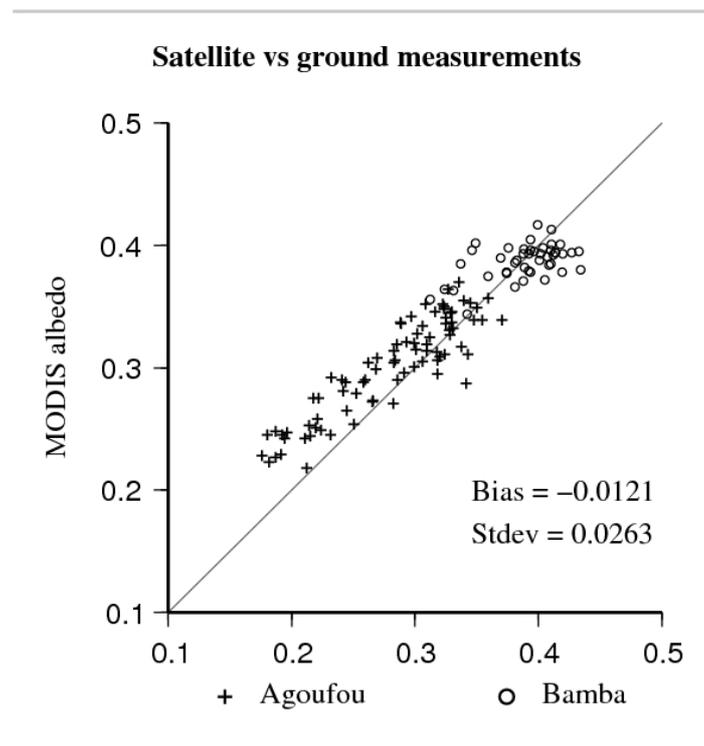


Figure 3. MODIS albedo versus field station measurements of daily albedo. Data for Agoufou (+) and Bamba (o).

The temporal and spatial consistency of MODIS albedo at both intra and inter annual time scales allows the use of MODIS data to diagnose the drivers of albedo variability over longer time series acquired on a broader range of ecological situations in the Gourma survey sites.

4. Albedo variability

4.1. Short term variations

In this section we use principally the daily albedo from the Agoufou station, as it offers a better temporal resolution than the MODIS products for the analysis of short term events.

a) Surface soil moisture effects on albedo

The effect of soil wetness on albedo has been already well documented (e.g. Lobell and Asner, 2002) and is often included in modeling studies of Sahelian climate. The darkening of the surface color is thought to typically reduce the albedo by as much as 50% of the dry surface albedo. In Figure 4, time series of the 2003 monsoon season rainfall events is superimposed to the short-term albedo variations from day of year 150 (30 May) to 260 (17 September).

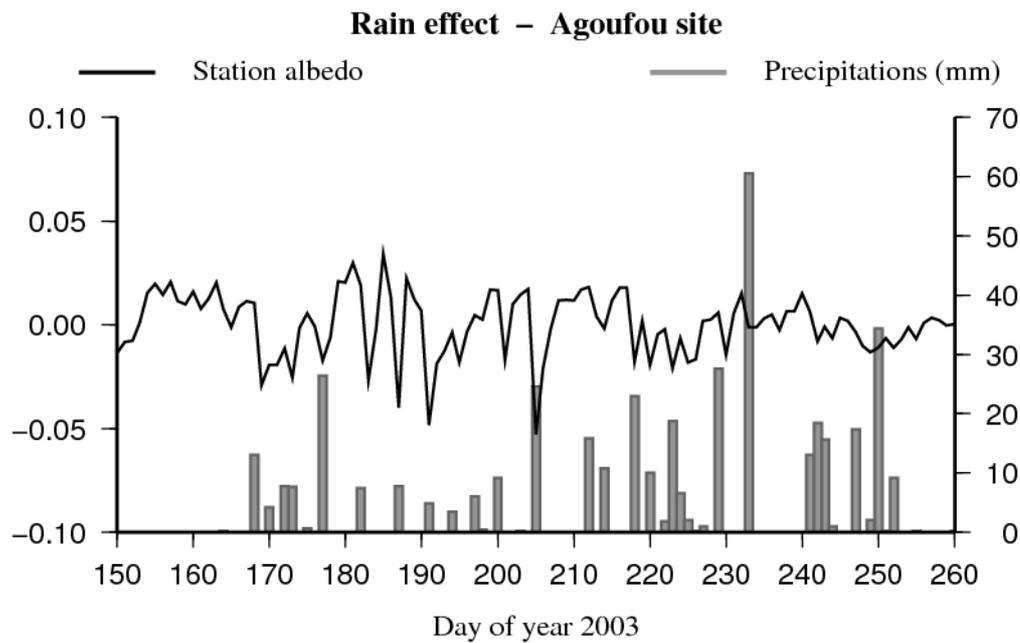
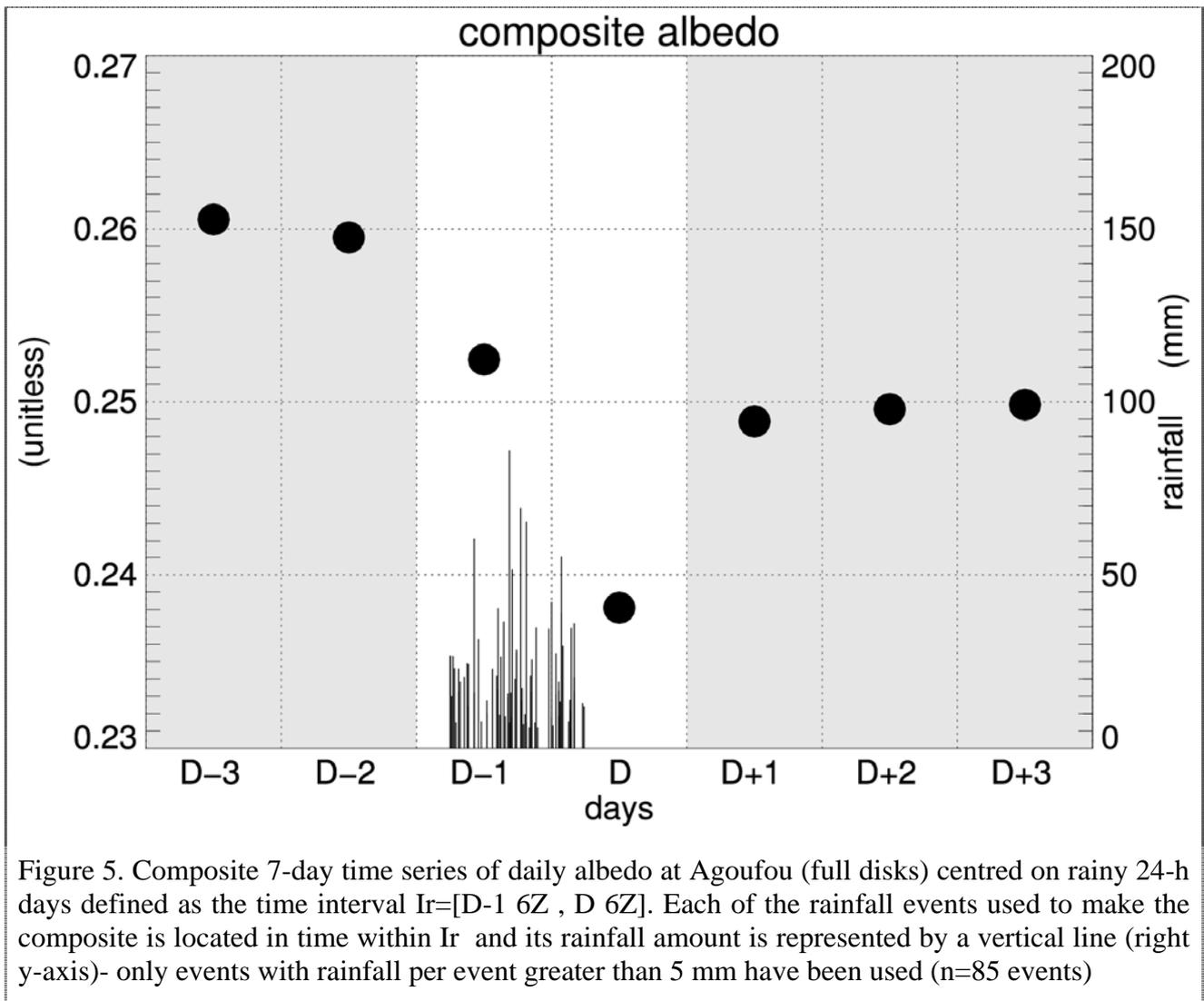


Figure 4. Albedo short term variations from Agoufou station superimposed to rainfall events for the 2003 monsoon season.

Negative albedo peaks generally correspond to rainfall events. Short-term decreases of typically one day are caused by soil moisture. However, the soil moisture effect is clearly more pronounced at the beginning of the rainy season whereas the amplitude of albedo variations is much smaller later in the season. This is because the soil is progressively hidden by the growing vegetation, whose spectral response is not directly affected by the precipitation. In addition, albedo does not seem to be very sensitive to the amount of precipitation but rather to the hour of the day at which they occur. Indeed, rainfalls are more likely to affect the daily albedo if they occur in the morning than if they occur during the afternoon, because the soil surface has time to drain and dry during the night.

Figure 5 shows the average albedo response to a rainfall event (composite). It is built by extracting 7-days albedo time series, centered on rain events larger than 5 mm. The center day (D) is selected so that rain events fall between 6 am the day before (D-1) and 6 am (D). Rainfall of the previous afternoon thus partly affects D-1. Compositing during the whole rainy season, when albedo is decreasing (Figure 2), creates the overall downward trend. The results show that rainfall, via soil moisture, has an effect which is limited in duration and amplitude. On average the albedo is reduced by about 0.017 (7 %) and the effect does not last longer than 24 hours because the uppermost soil layers dry and drain very quickly. Since precipitation is of convective nature in the

Sahel, with an average of around 25 rainfall events per year in Hombori, near Agoufou (35 km apart), the effect of soil moisture on surface albedo is mostly significant during periods of repeated events, while isolated rainfall have a very limited –in time- impact.



b) Atmospheric effects on incident shortwave radiation and albedo

During the dry season (November to early June), albedo is affected by variations in the spectral composition of the incident radiation and from the proportions of diffuse versus direct irradiance. Because the surface spectral albedo is lower in the visible domain (400-700) than in the NIR domain, an increase of the visible fraction of incident radiation results in a decrease in broadband albedo (400-2500 nm). Such a change of the spectral composition can be caused by variations of the Aerosol Optical Thickness (AOT). Even if dust and Sahelian aerosols are not among the most selective aerosols in terms of spectral diffusion because of their size, they have a strong effect on the incoming radiation spectrum at the surface. It can also be related to the Integrated atmosphere

Water vapor Content (IWC), since it absorbs more the light in the NIR domain.

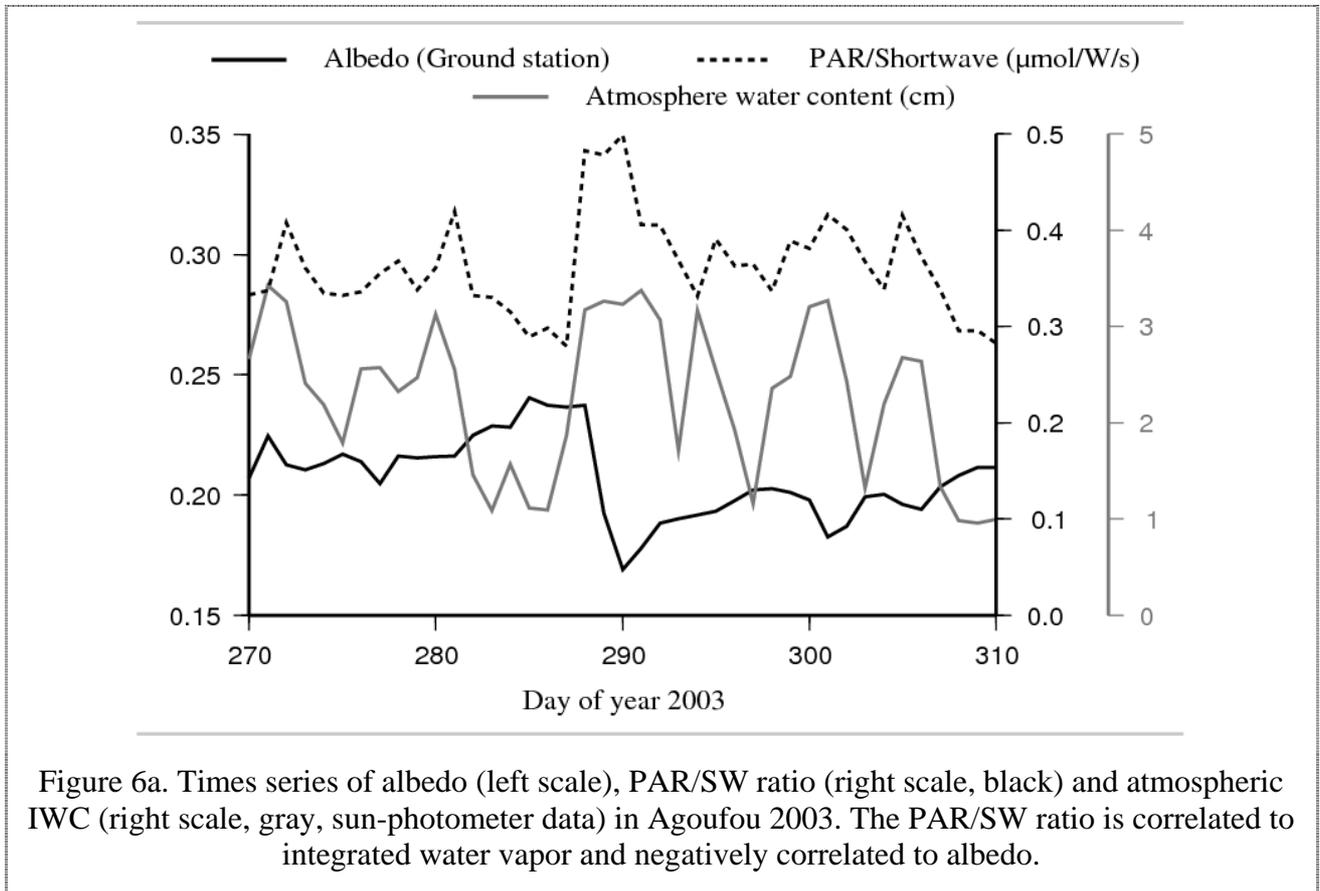
Consequently, high aerosol events, which are common in winter and spring in the Sahel, will cause an increase of in situ albedo measurements, while high water vapor content will shift broadband albedo towards lower albedo values.

Changes in the spectral composition of incident radiation can be traced by plotting the ratio of PAR to total shortwave (PAR/SW), a quantity sometimes called ‘conversion factor’ or ‘climatic efficiency’. As the PAR sensor is a quantum sensor, the units are micromoles of PAR photon per second per watt of broad-band irradiance (see Ross and Sulev, 2000). The conversion factor is usually highest in the rainy season ($2.1 \mu\text{mols}\cdot\text{1W}^{-1}$, which translates to 0.4934 using a standard conversion coefficient of $.235 \text{ W}\mu\text{mol}^{-1}$) and lowest in the spring (as low as $1.8 \mu\text{mols}\cdot\text{1W}^{-1}$ or 0.423) during high aerosol and dust events.

Figure 6a and 6b illustrate this effect for two periods in autumn 2003 and 2004, where the relation between albedo and the PAR/SW ratio is particularly clear, with correlation coefficients of -0.63 and -0.97, respectively. It can be seen in addition that in the first case (Figure 6a), the dependency is mainly due to the IWC, whereas in the second case (Figure 6b), it is mainly due to the AOT. The global impact of the PAR/SW ratio on albedo has been also assessed for the whole 2003-2006 period, while removing the wet season (June to September), because the albedo variation are there too much dependant on the precipitation and vegetation changes. Dates where the PAR/SW variations are below 0.015 were also removed to exclude situations where albedo varies for other reasons. The short term albedo variations plotted against the PAR/SW variations on Figure 7 reveals a significant dependency with a correlation coefficient of -0.62.

For the 2003-2006 period, the PAR/SW ratio was also compared to the AOT (Figure 8a) and the IWC (8b). On the first figure, the data are pooled for IWC values higher than 2 cm or lower than 2 cm in order to isolate the AOT variations from the IWC ones. Indeed, water vapor content has two main modes, as the inter-tropical convergence zone moves during the year: one ‘dry’ mode during the so called Harmattan period and a moist mode during the monsoon season, during which it remains relatively constant. On the contrary, during the transition periods, strong fluctuations occur. For both modes, the PAR/SW ratio is drastically decreased when AOT is high (correlation coefficients of $r=-0.69$ and $r=-0.65$). High aerosol loadings occur mainly from January to June. In addition to the change in the spectral composition of incident radiation, high aerosol loading also increases to ratio of diffuse to total irradiance (there is a strong relationship between AOT and diffuse PAR to total PAR measured by the BF2 and BF3, not shown), which in turn further

increases surface albedo. This strengthens the control of aerosol on the short term variability of albedo. On Figure 8b, the data are polled similarly for clear days and for AOT values lower than 0.5 to isolate situations where IWC is the only fluctuating variable. Although less spectacular than for the AOT effect, the IWC has a clear impact on the PAR/SW ratio, with correlation coefficients of $r=0.67$ and $r=0.5$ for the clear and dust cases).



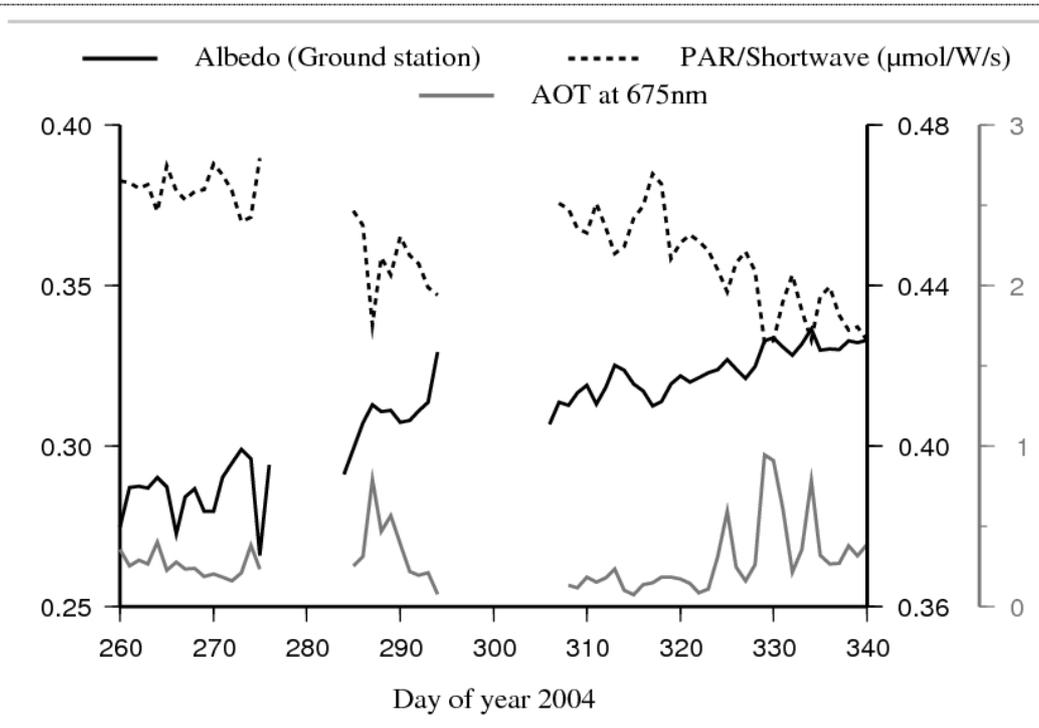


Figure 6b. Time series of albedo (left scale), PAR/SW ratio (right scale, black) and AOT (right scale, gray, sun-photometer data), in Agoufou 2004. The PAR/SW ratio is correlated to the AOT and negatively correlated to the albedo.

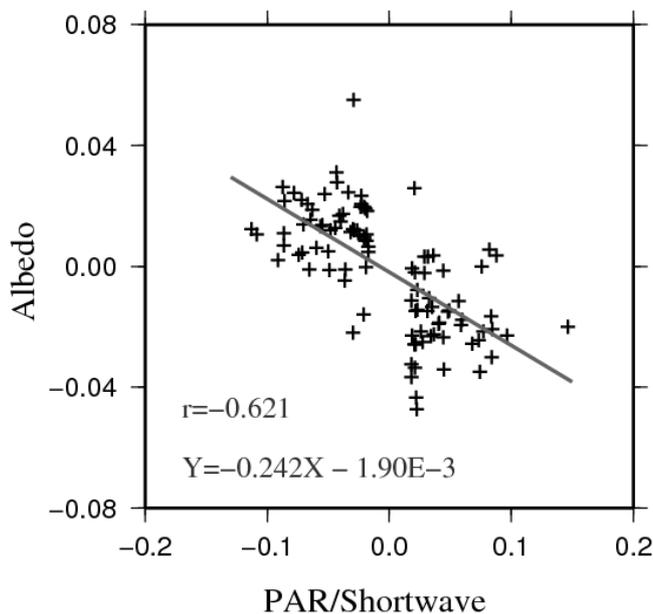


Figure 7. Relation between albedo and PAR/Shortwave variations for the 2003-2006 dry periods in Agoufou.

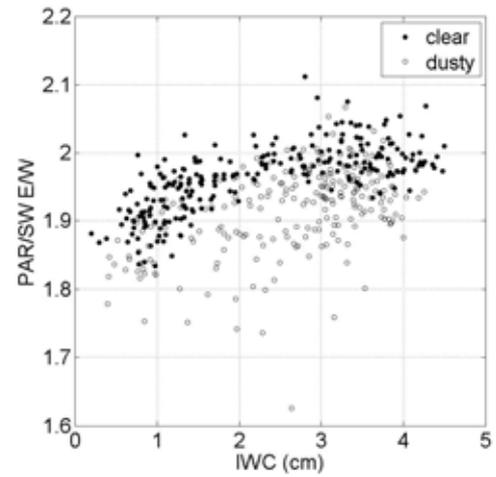
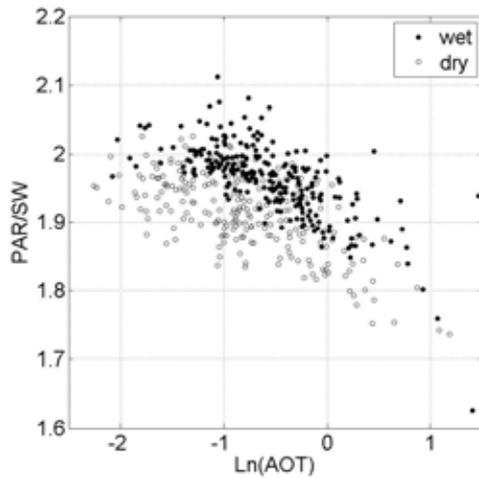


Figure 8a. Ratio of PAR to short-wave irradiance ($\mu\text{mol PAR/W}$) versus AOT at 440 nm measured by a sun-photometer, (log scale) pooled for IWC > 2 cm (open symbol) and IWC < 2 cm (full symbol).

Figure 8b. Same as 8a for PAR/SW against IWC, pooled according to AOT < 0.5 for clear days.

Since long-lived continuous cloud cover rarely occurs in the Gourma, no effects of clouds on daily albedo was found, as opposed to what is found in many albedo studies (Roesch et al 2002 and references therein). Surprisingly, such ‘atmospheric’ effects on in situ measurements of albedo are rarely discussed except for snow albedo response to cloud cover and NIR depletion. We conclude that these effects are important in the Sahel, but mainly because of the variations in aerosols and water vapor contents of the atmosphere.

4.2. Disturbances

a) Fire

Although bush fires are less frequent in the Sahel than in the Soudanian zone south of the 800mm isohyet, they do occur occasionally, especially when the grass cover is more or less continuous over the uncropped sandy area. The effect of a fire can be seen on Agoufou data as the station burned in 2005 on November 1st (the instruments, however, continued to function). It corresponds to the last albedo negative peak in 2005 on Figure 2. The effect of fire is best observed by using the MODIS daily reflectance instead of the 16-day composite albedo. Figure 9 and 10 show series of images before and after bushfire occurring near Agoufou in December 2001 and November 2005. Since MODIS reflectances are not corrected for directional effects, we applied a normalization so that the reflectance of unburned areas stays constant throughout the series.

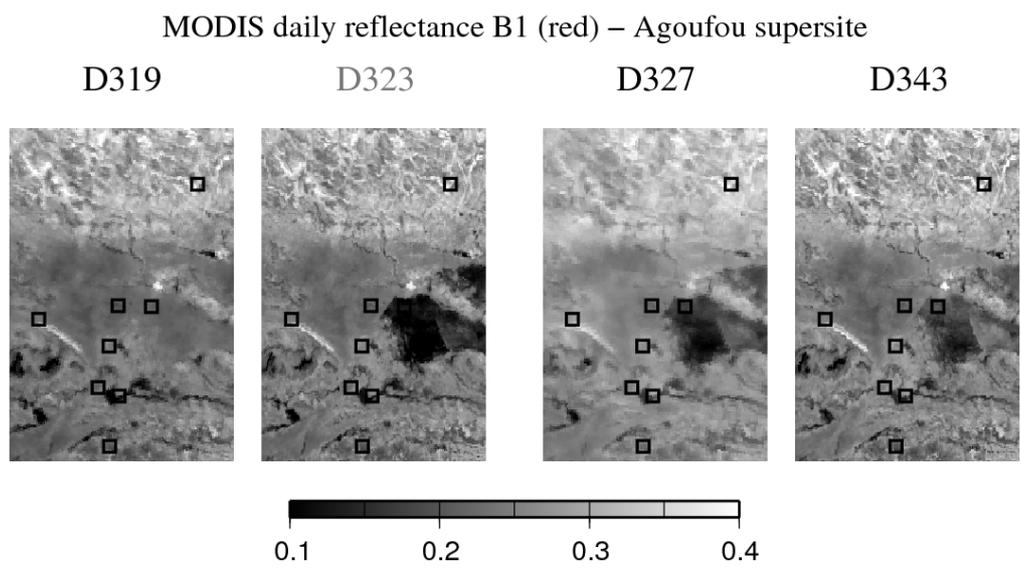


Figure 9. Evolution of MODIS surface reflectance, normalized for directional effects, after a bush fire (December 2001). The fire scar is significantly attenuated after ten days.

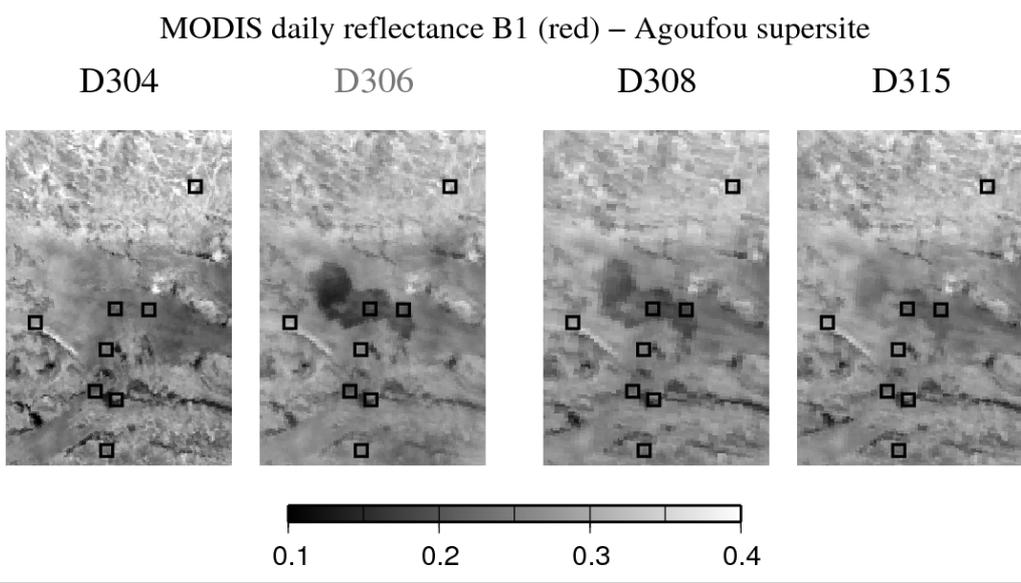


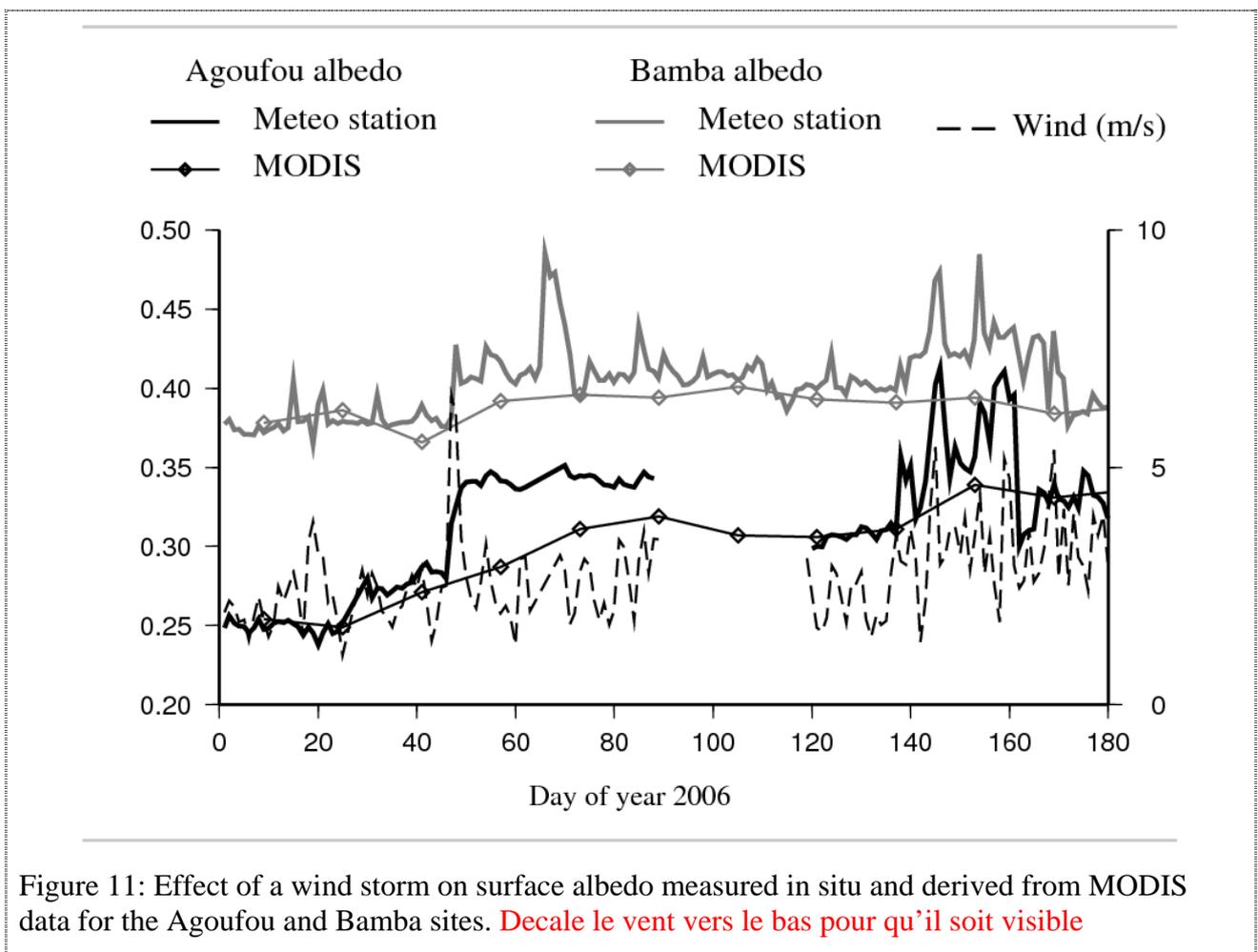
Figure 10. Same as 9, but for the November 2005 fire.

Fire has an immediate effect in reducing the reflectance by about 0.1 in the red (645 nm band) and 0.15 in the near-infrared (858 nm band), which is consistent with the results of Myhre et al. (2005). Although the impact of fire can be noticed on in situ vegetation cover and soil surface several months after, it does not last long on MODIS images: In December 2001 (Figure 9), the burned area is still visible after 20 days but both the affected surface and the contrast with the surrounding zones are largely reduced. In November 2005 (Figure 10), the fire impact disappeared almost entirely after just 10 days. In fact, the reduction of the reflectance is mainly due to the ashes

that are quickly dispersed by the wind. Furthermore, the removal of herbaceous litter and standing tissues over bright soil sometimes leads to an increase in albedo after dispersion of ashes. This was particularly obvious in the case of a bush fire occurring in April 2007, which produced a strong contrast with the surrounding areas supporting large amount of dry plants mass (not shown, see the role of biomass/litter below).

b) Wind storms

A remarkable wind event occurred on the 16th of February in 2006, with surface winds blowing southward at 8 m/s for about 36 hours in Agoufou, 10 m/s in Bamba (2 meters height, 15 min average). As represented on Figure 11, this coincided with a sudden and step-like increase of the albedo measured at both the Bamba and Agoufou stations.



Strong wind episodes produce a blend of soil erosion and dust deposition resulting in a smoothing of the surface roughness and sweeping out of litter, which could explain the overall increase in surface albedo. Indeed, rugged soils with protrusions or creeks have a lower albedo because more shadows are visible from the sensor. A deposit of a fine sand layer on the ground may also be involved in this albedo change, although this is mostly speculation. Such storm-driven

effects, which are known to change the albedo on planet Mars (e.g. Szwasst *et al.*, 2006), need to be further investigated in Sahelian landscapes.

4.3. *Seasonal to inter-annual variations*

In this section, time series of MODIS albedo are extracted for each of the 25 long-term survey sites to investigate the effects of land cover, vegetation growth and decay, and that of grazing. Times series of MODIS images for the whole Gourma mesoscale area (see Figure 1) and the whole 10°x10° MODIS tile provide extension to larger scale.

a) Albedo and biomass

Seasonal albedo variations in the Gourma are mainly driven by the seasonal course of vegetation growth and decay (Figure 2). The development of vegetation canopies over a bright soil reduces the broad-band visible albedo because of the chlorophyll absorption but it can decrease also the broad-band NIR albedo. Because of soil brightness, the reflectance of bare soil and grass canopy are similar in the Gourma. However, in the Short-Wave Infrared (SWIR, 1200 to 2500 nm), bare soil reflectance is significantly higher than grass canopy reflectance. The relation between albedo and vegetation mass is quantified for the Agoufou site, where frequent measurements of the herbaceous plants mass have been carried out at the kilometer scale, covering different stages of the vegetation cycle each year. Figure 12 shows the correlation between the green standing mass of herbaceous and MODIS albedo for the 2000-2006 period. A linear relation can be established with a correlation coefficient of -0.855 and a slope of -0.421 albedo units per kg/m².

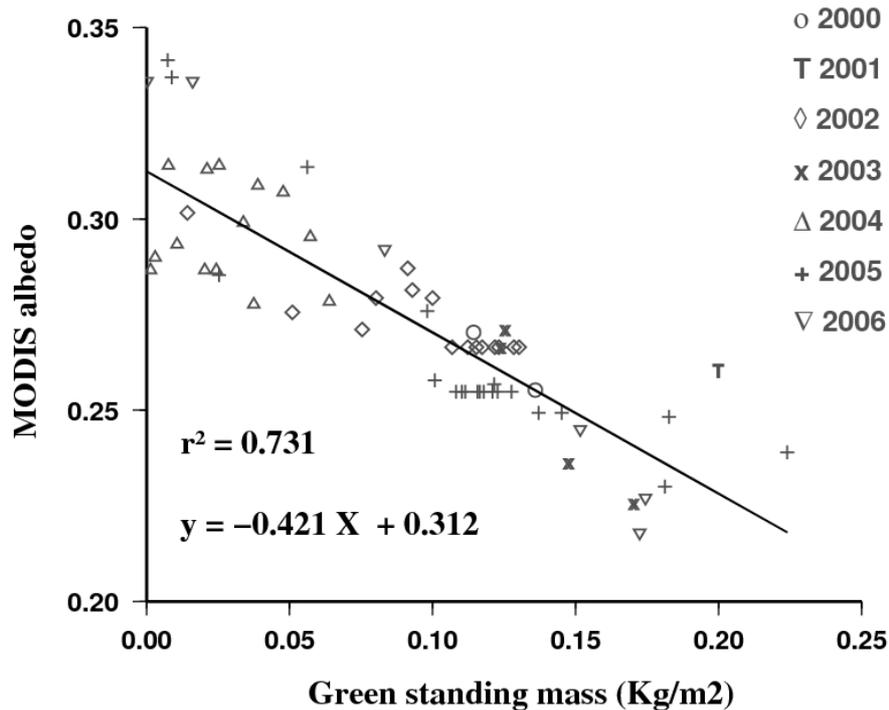


Figure 12. Relation between green herbaceous mass and albedo for the Agoufou site.

Albedo is expected to depend primarily on plant leaf surface modulated by canopy architecture. Biomass proved to be a good proxy for these combined variables, as far as seasonal and inter-annual variations are concerned. This relation is fairly robust, despite the fact that dominant herbaceous species, which are annuals, may vary from year to year and even within a season. Data for the different years follow the same line, with maximum value of green standing mass being severely reduced in drought years like 2004.

b) Effects of land cover and grazing pressure

The long term survey sites network was designed to sample land cover types as well as grazing pressure by selecting sites on sandy or gravel soils, clay depression, close to or far from permanent water bodies which are associated to high or low grazing pressure.

Figure 13 shows the seasonal profiles for the different surface types that are encountered in the Gourma. The profiles are normalized relatively to the maximum albedo value to compensate for the different soil colors and to focus on relative variations. All profiles show a similar timing that is driven by the vegetation cycle in the Gourma. It is characterized by a short and intense growing season during the monsoon and a rapid senescence after the end of rainfalls. The profile for seasonally flooded sites differs with the albedo remaining much longer at low values. Persistent

liquid water that strongly reduces the NIR albedo adds to the fact that the vegetation remains green longer due to higher soil moisture availability. Highly productive and lightly grazed vegetation sites, located in the southern part of the Gourma, display time profiles of broadband albedo similar to those of the flooded areas, albeit resulting from different contribution of the visible and NIR domains.

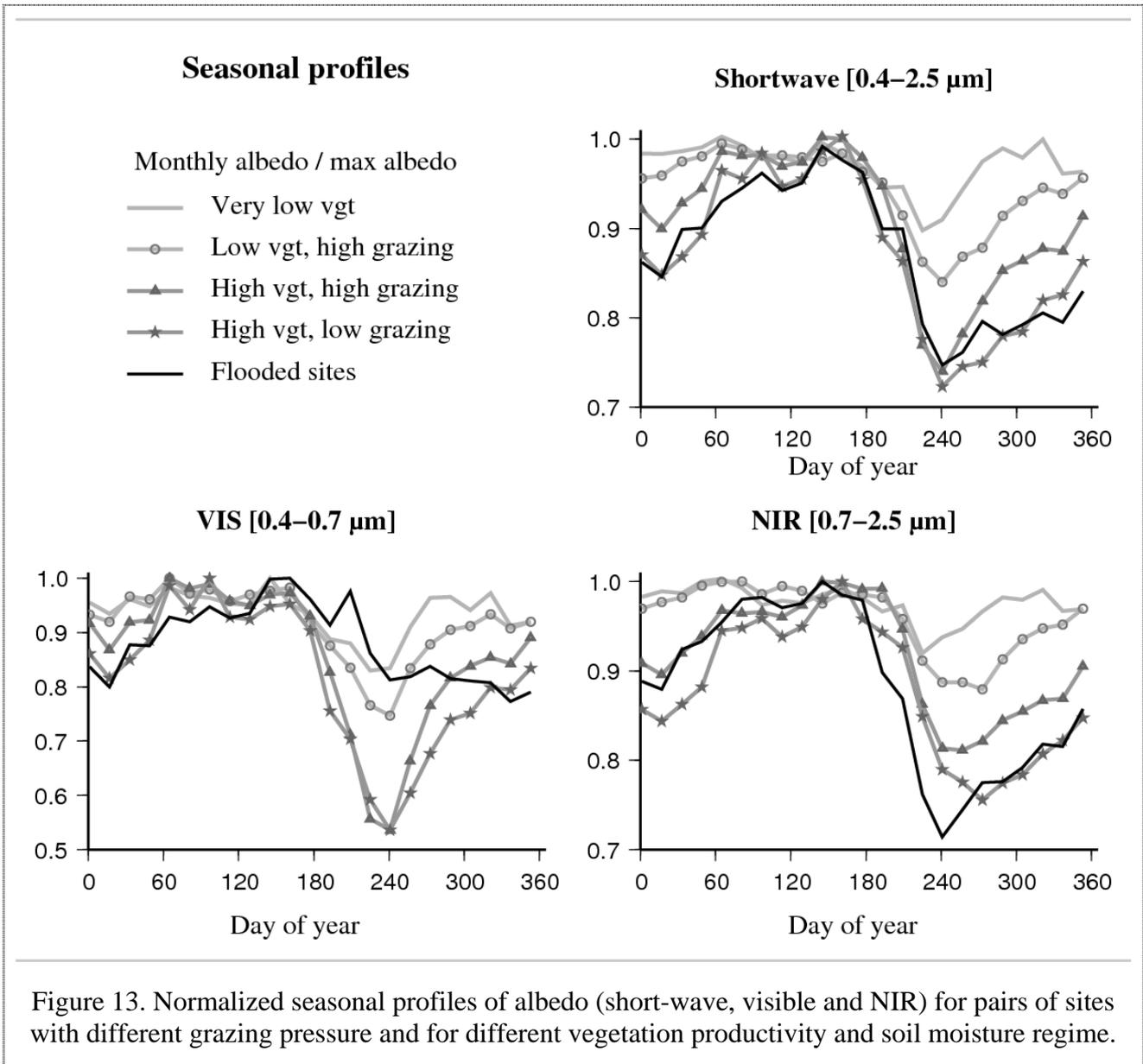


Figure 13. Normalized seasonal profiles of albedo (short-wave, visible and NIR) for pairs of sites with different grazing pressure and for different vegetation productivity and soil moisture regime.

Since grazing has been suggested as an important driver of surface changes in the Sahel surfaces, grazing pressure effects have been investigated. It can be noted that albedo rises more quickly following the rainy season for grazed sites compared to non-grazed. This is particularly true in the NIR (0.7-2.5 μm) domain. Grazing however does not affect much the albedo during the growing season and the minimum albedo value is close to what is observed for non-grazed sites (not shown). This can be explained by an adaptation of the plants to grazing (activated grass

tillering and stimulated regrowth productivity at the short term, and selection of species more resistant to defoliation or avoided by grazers at longer term) so that the total biomass is eventually not much affected. A lower height of the herbaceous layer with a more planophile orientation of the leaves, which results from grazing by cattle and small ruminants, may also produce a more efficient absorption of light and consequently a lower albedo value compared to a higher and more erectophile ungrazed plants of comparable standing mass.

c) Effects of straws and litter on albedo

The optical properties of straws (standing dead herbaceous) and litter (dead plants and debris on the soil surface) are not very well known and the effect of straws and litter on albedo has been poorly documented. Both the albedo seasonal cycle and the large increase of albedo following some of the bush fires indicate a strong control of dry season albedo by the variations of dry tissues and litter. Because straws and litter in the Gourma grasslands are darker than the underlying soil, the gradual decomposition of dead plants leads to a gradual increase in albedo during the dry season. This is particularly clear during the 2004 drought, as shown by Figure 14 for the Agoufou site: Albedo steadily increases from mid-2003 to mid-2005 while both the green biomass and the amount of litter decrease.

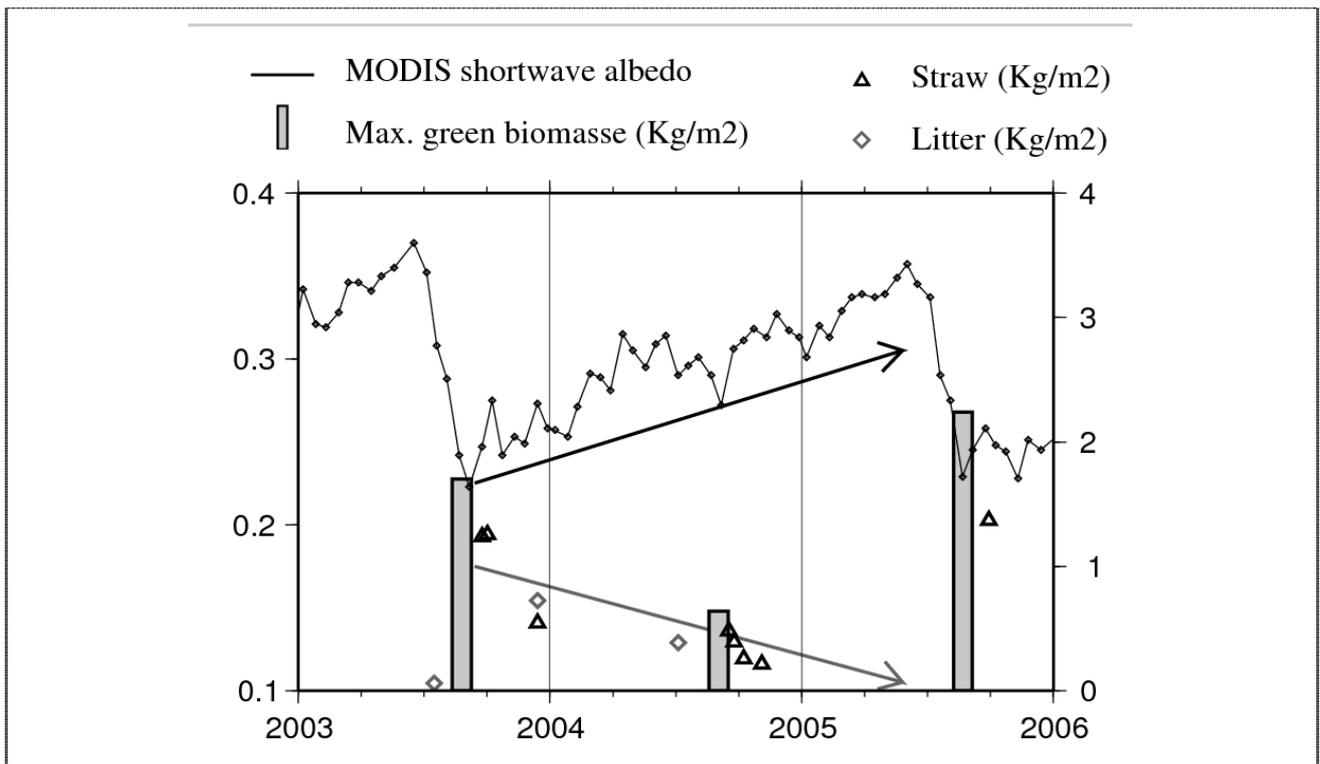


Figure 14. Effect of straws and litter decomposition on albedo during the 2004 drought. Bars are for maximum green standing mass. Triangles and diamonds are for standing straws and the litter, which both decrease from late 2003 to mid 2005.

The poor plant productivity of 2004 barely produces a drop in albedo during the rainy season and does not refuel the litter reservoir. This results in a striking ‘two-year’ cycle, portrayed by both MODIS and in situ data (Figure 2), which dramatically illustrates the strong variability of vegetation cover in the Sahel. Yet herbaceous growth in 2004 (65.3 g/m²) was not as bad as in 1984 (22.8 g/ m²) in spite of the same total annual rainfall (205 mm both years). This suggests an even stronger albedo anomaly in extremely dry years like 1984.

From this analysis, it appears that the seasonal course of albedo over the Gourma is shaped not only by the growth of green vegetation as a response to the monsoon rainfall but also by the gradual decay of senescent and dead plant tissue during the dry season.

4.4. *Spatial patterns of inter-annual variations*

In order to extend the conclusion that plant control both rainy season and dry season dynamics of albedo, which were obtained over a network of sites, the pixel time series of the MODIS tile (10 to 20°N, -10 to 0°E) were averaged along lines (longitude) to produce a time versus latitude plot (Hovmueller diagram, Figure 15). This figure illustrates both the latitude dependence of albedo, ranging from highly seasonal at latitude 10°N to mostly constant at latitude 17 to 20°N, and the inter-annual variability. As the monsoon precipitation progresses northwards, ‘tongues’ of low albedo value extend from the South to the North, whose width depends on the amount of rainfall: large in 2003 and 2005, indicating a prolonged rainy season, but narrow in 2002 and 2004, indicating a short and poor rainy season. In addition, this plot shows that, south of 17°N, the albedo in the dry season following a year of ample rain and good productivity is maintained at lower value until at least March. The southernmost latitudes, which are not in the Sahelian zone, exhibit a different seasonal cycle, with a minimum albedo shifted to the early dry season (December) because of the high frequency of bush fires uncovering darker soils (Govaerts et al., 2002). The conclusions that vegetation development imposes a fingerprint on both rainy season and dry season albedo, drawn on the basis of the network of long term sites, are therefore valid over a large area, and probably over the Sahel as a whole.

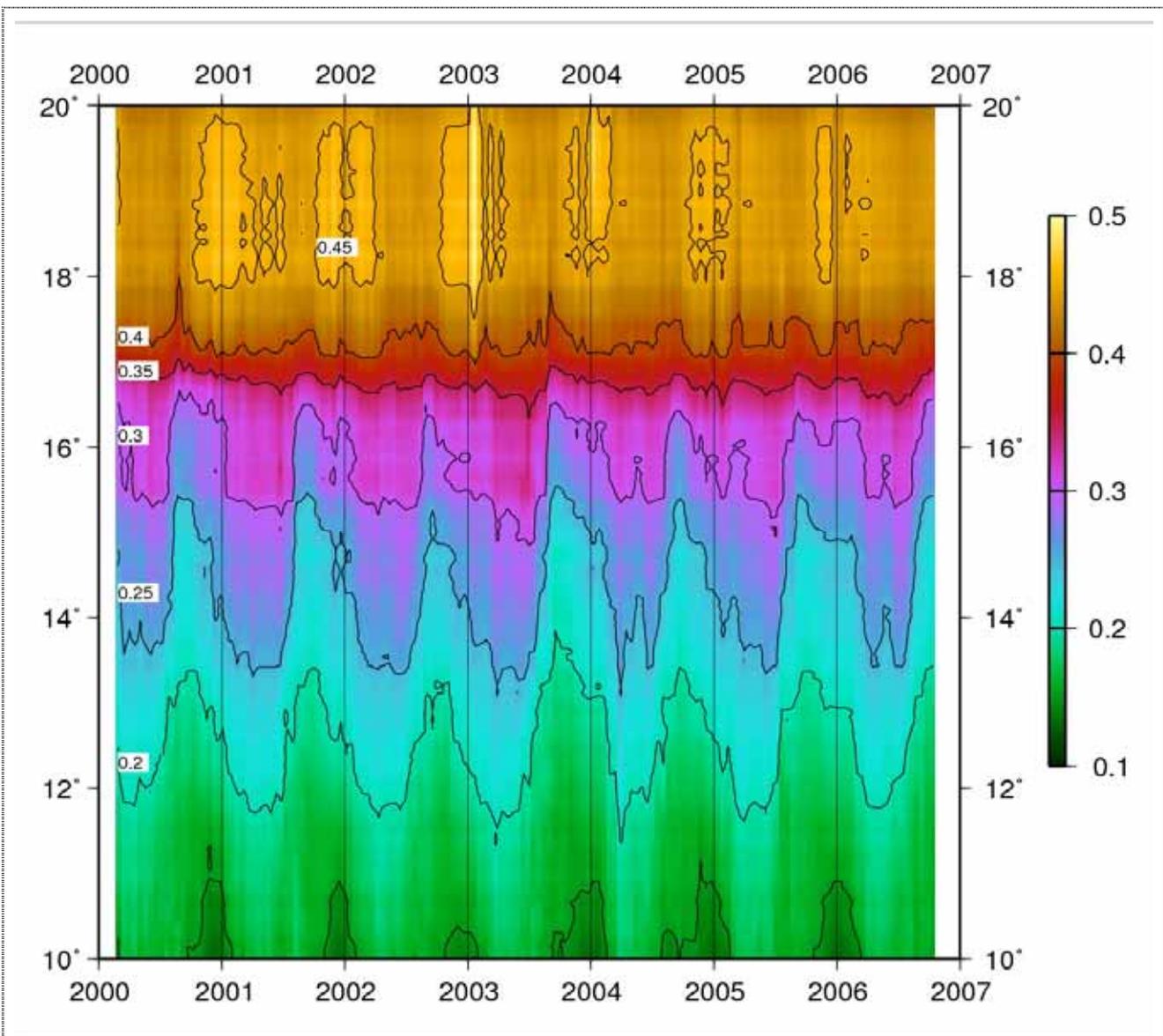


Figure 15. Time versus latitude diagram of MODIS albedo averaged over longitude -10 to 0. Years with high productivity and ample rainfall (2003, 2005) show broad tongues of low albedo values, lasting over the vegetation season (July-August) but also extending in the following dry season (eg. Until March).

4.5. *Spatial patterns of inter-annual variability*

The inter-annual albedo anomalies were calculated for each MODIS pixel of the Gourma meso-scale area by subtracting the mean albedo annual cycle from the 6 years time series. The temporal signal was analyzed using Empirical Orthogonal Functions (EOF) with the method developed by Toumazou and Cretaux (2001). Figure 16 shows the results for the first two modes, for which a physical interpretation is provided.

Inter-annual albedo anomalies

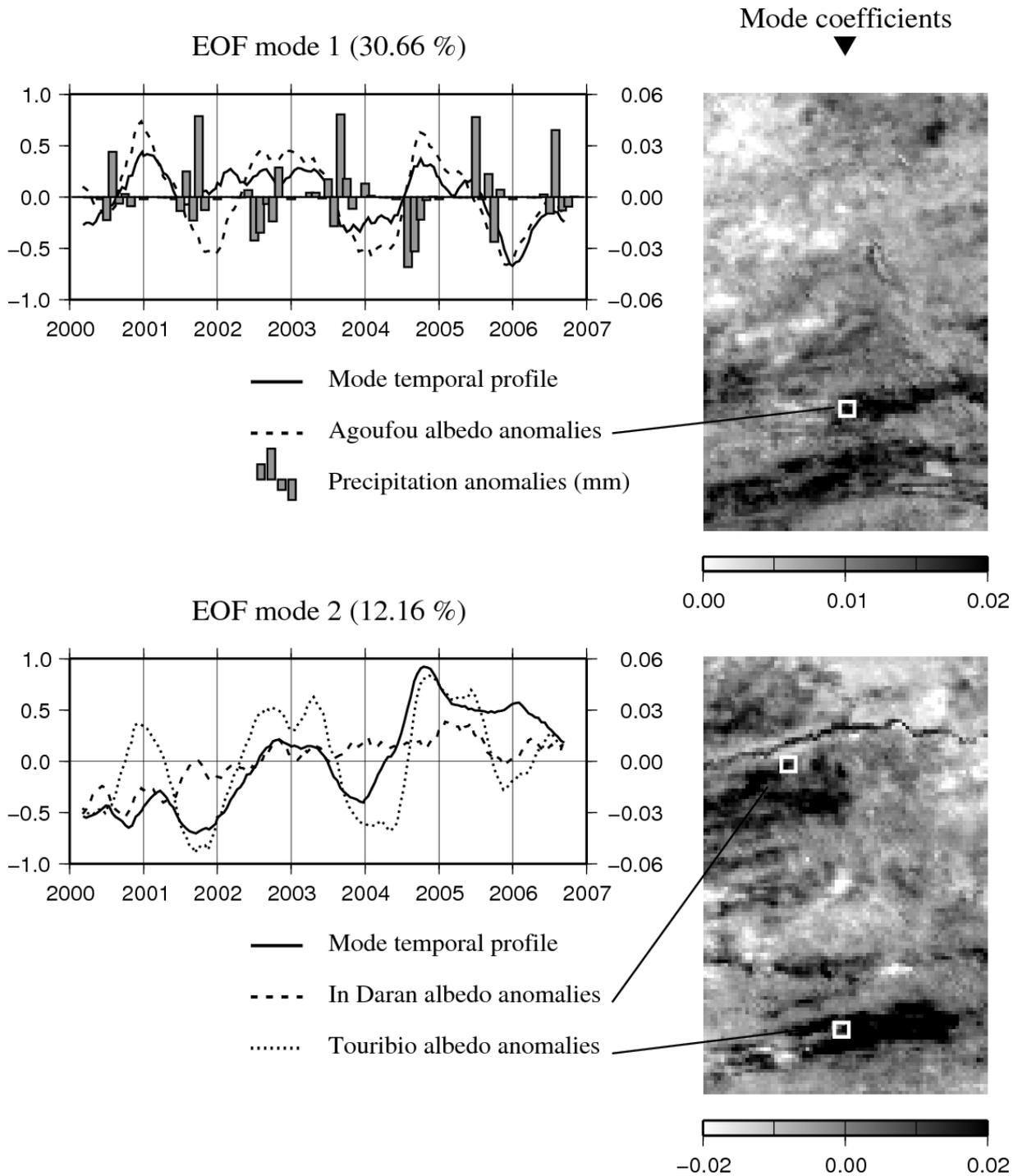


Figure 16: EOF analysis on the MODIS albedo time series (anomalies from the mean annual cycle). The mode coefficients represent the spatial distribution of the mode over the Gourma mesoscale area. The mode temporal profile (full line, left scale) is compared to the albedo anomalies of representative sites (dashed and dotted line, right scale) and with monthly precipitation anomalies (scale not represented, ranging from -100 et +100 mm).

The first mode is the time function that best represents the signal temporal variability over the Gourma, with a percentage of 30.66% of the signal variance explained. Not surprisingly, this mode is anti-correlated with the precipitation anomalies calculated for the Agoufou station (in line with the other stations in the area). This is particularly true for the years 2002 to 2005 that have marked total precipitation anomalies compared to the more neutral years 2000 and 2001. We can see, however, an important time lag between the precipitation and the albedo anomalies. As mentioned before, the amount of rainfall during the monsoon has an impact that persists until the beginning of the following year. The spatial distribution of this mode shows that sandy soils with low vegetation cover are more sensitive to such variations than other regions.

The second mode, representing 16% of the signal variance, reveals a positive trend in albedo for the area at the north-west of the study area. Inside this area, the MODIS albedo was extracted for the In Daran site, for which local measurements of biomass are available. The comparison in Figure 16 shows that the trend can be explained by a decrease of the vegetation production between 2001 and 2004. The trend for In Daran seems to reverse in 2005 which is a very good year for the vegetation due to ample precipitation. Because of the small numbers of years, such a signal should not be considered a multi-annual trend but it illustrates that some mechanisms have the capability to modify albedo in the Sahel over multi-year period of time.

5. Discussion and conclusion

The Gourma sites and the AMMA campaign offer an excellent context for the study of albedo variability thanks to a large number of field measurements over several years and a high spatial homogeneity. The good agreement between in-situ and MODIS albedo is valuable, as only a few sites are available worldwide for the validation of satellite derived albedo. It further supports the use of MODIS data for the study of inter-annual trends and anomalies over West Africa.

This study documents the observed variations of in-situ and MODIS albedo time series. Some results were qualitatively expected like the impact of surface wetness, fire or vegetation cover, although they significantly differ from what is commonly used in climate models. Here we quantify these effects by using in-situ measurements.

Albedo in the Gourma region has been found to vary significantly at scales of ranging from one day to several years. These variations are summarized in Figure 17, where albedo changes are sorted according to their approximate time scale. For each of these effects, an average range of variation is indicated as a fraction of albedo, showing that fluctuations as high as 30 to 40% are

caused by different phenomena. As a consequence, representation of albedo in climate models requires some degree of complexity for accurate simulations of the radiation balance. For instance, interactive vegetation with a representation of litter (including litter decay), spectrally resolved surface albedo and aerosol effects appears more important than for instance the effect of soil moisture, contrary to what previous modeling study have suggested (Levis et al., 2004 among other). Roesh *et al.* (2002) showed that spectrally resolved surface albedo was important for climate simulation because of cloud and water vapor spectral effect. We state that aerosols are at least as important in the Malian Sahel, given the overall climatological features of the region, such as high atmospheric aerosol amounts and relatively low cloud cover.

Remote sensing data have shown that most of the drivers of albedo variability occur on a large spatial scale. Despite the large spatial variability in rainfall, in situ and remote sensing data show that the footprint of wet versus dry years is fairly obvious over a large domain and often at the scale of the whole Sahel. Disturbances on the other hand are more localized (e.g. fires in Northern Sahel). The footprint of the dust storm was approximately 300 km x 300 km. As it has been documented for a unique event, it is not possible to conclude on the relevance of such effects on larger scale or longer term albedo changes. Other effects like crop extension or long term tree cover change are not documented because our study is focused on rangelands, where crops are almost absent (as opposed to southern Sahel like the Niamey area for instance), and the dataset is restricted to 7 years, which prevents long term changes to be assessed. Overall, the combination of in-situ and remote sensing data point towards a series of drivers, which are significant at regional to sub-continental scale.

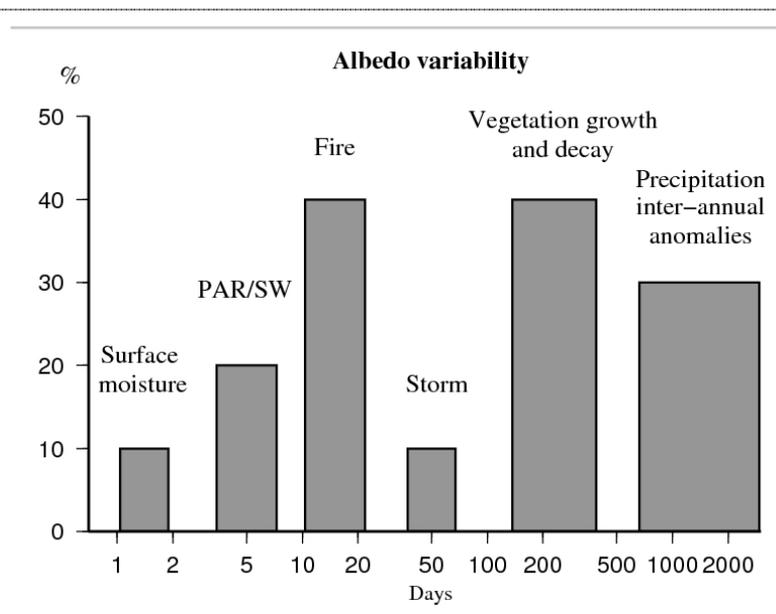


Figure 17. Schematic representation of amplitude and duration of the sources of albedo variations inferred from 7 years of MODIS and in situ data.

Of particular interest are the pathways that can lead to feedbacks in the monsoon / land surface system. Rainfall acts at different timescales through different mechanisms. The first one is the immediate response of soil albedo to surface soil moisture. Such an effect was found to be rather short-lived and its impact on the shortwave radiation budget to be rather limited. However, a second type of rainfall-induced effect, which is longer-lived, is caused by vegetation growth, which impacts albedo in the wet season and the following dry season. This provides a positive feedback at the intra-seasonal scale, with large rainfalls resulting in excess shortwave absorbed at the surface. The consequence is a net short-wave radiation excess for the relatively wet years 2005 and 2006, as shown in Table 1, which could contribute to displaced the monsoon northwards (Eltahir and Gong, 1996).

Table 1. August daily mean incoming and surface net shortwave radiation (W/m^2) and anomalies for 2002-2006 along with surface albedo. SWnet is higher for the wet years (2003, 2005, 2006) than for the dry years (2002, 2004).

	Aug - 5 year mean	2002	2003	2004	2005	2006
Swinc	259	5	-9	6	-3	2
Swnet	189	-4	-3	-6	7	6
Albedo	0.24	0.03	-0.02	0.04	-0.03	-0.02

Grazing pressure was not found to be related to change in rainy season albedo in spite of higher grazing pressure in the Gourma during that season. During the growing season, the vegetation cover is nearly identical for grazed or ungrazed sites. However, at the end of the rain season, as the grazed vegetation is not compensated by any growth, the albedo for grazed sites is observed to increase faster. Rainy season grazing pressure is spread over the whole region because of the large distribution of surface water, whereas it concentrates during the dry season. Moreover, adapted grass species respond to the defoliation due to grazing, by activated tillering and regrowth that tend to compensate for herbaceous mass removal (Hiernaux and Turner, 1996). This does not exclude grazing as an actor of long term changes of land albedo through indirect effects like modification of species composition and trends in woody plant populations (Breman and Kessler 1995, Hiernaux and Le Hou  rou 2006), or long term impact of the herbaceous mass removal and trampling by grazing on nutrient cycling and soil fertility (Schlecht *et al.*, 2004).

Much less is known about the climatic role of dry season albedo. If one can reasonably assume that winter or late autumn albedo changes in the Sahel, like the fire induced changes, do not affect

the dynamics of the West African monsoon, it is well possible that the dry-season albedo in the Sahel influences both the retreat of the rain belt southward in early autumn and the onset on the monsoon in the spring. Since they drive the amount of litter and also tend to reduce dust and aerosol events, factors like past rainfall may have an impact on the radiation budget in the spring. Whether this can impact the relationship between the heat low and the monsoon circulation remains to be investigated but there is room for surface atmosphere interactions during this period of year (e.g. Ramel *et al.*, 2006).

Last, this study has demonstrated that the dynamics of terrestrial ecosystems has the potential to prolong the effect of rainfall on timescales of the order of six months to almost a year, thus providing an amplifier effect in the monsoon/land surface system. Trends in albedo over several years and pseudo ‘two-year’ cycles, like the one caused by the 2004 severe drought, have been identified, showing that the land surface exhibits a significant plasticity of its radiative properties resulting from the response to external forcing and to internal dynamics, which ideally should be included in circulation models.

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