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The availability of renewable energies in a changing Africa

Assessing climate and non-climate effects

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Cover Pictures: Top left: Kakira Sugar Ltd (Masindi District, Uganda), Top right: Khayelitsha township solar water heating project www.kuyasacdm.co.za (Western Cape, South Africa), Bottom left: Soitec 36MW Concentrating PV plant at Touwsrivier (Western Cape, South Africa)

Pictures by Umberto Tromboni and Wim Zaaiman, JRC - IET.

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Foreword

In 2011, the JRC published a report on Renewable energies potential in Africa summarising the current technical knowledge of the availability and exploitability of African resources for renewable energies generation. A first assessment of the main geographical pattern of raw resources for the generation of renewable energies is provided in the report together with elements for discussions on the social and economic framework in which the renewable potential has to be deployed.

This report once again deals with renewable energies in Africa providing a deeper analysis of some of the issues involved in the actual exploitability of renewable energies such as, for example, technological evolution of production devices, changes in fossil fuels prices or a more detailed view of the complexity of bioenergy resources in the African context.

Moreover, following a need for further investigation already stated in the previous report, the expected renewable resources evolution in the changing African climate is also addressed for the next decades: forecasts of key climate parameters such as sun radiation, wind speed, precipitation, ground temperature and others were provided by robust climatic models. Climate evolution is then interpreted in terms of changes in the expected availability of renewable resources.

Nevertheless, climate change is only one of the several forces that drive the socio-economic and geographical changes in the African continent. The actual exploitation of renewable energy options is well known to depend not only on the availability of raw resources but on a complex mix of social and market effects not always related to climatic issues.

For this reason, climate related impacts on renewable energy availability have been quantitatively compared or completed whenever possible with the expected effects of other non-climate changes, like e.g., technological development (see e.g., chapter 2) or the pressures arising from population increase and displacement (see e.g., section 4.5).

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Executive summary

Climate science has provided indications on the climatic change taking place in Africa: according to forecasts, higher temperature values are expected in the whole continent, with sharper increases in the dry belts just north and south of the tropics. Precipitation should increase in the tropic areas while it is expected to decrease in the northern and southern extremes of the continent. This already happening climatic change could have an impact on the raw resources available for renewable energy production, even if scientific literature on this aspect is somewhat limited and IPCC has pointed out that "Climate change will have impacts on the size and geographic distribution of the technical potential for Renewable Energy sources, but research into the magnitude of these possible effects is nascent".
Nevertheless, the issue is relevant for both policy makers and private investors needing to understand if and to what extent energy policies or investments in infrastructure should be tuned in response of changing climate conditions.
For this reason, in this report, a first quantitative estimation of climatic effects on renewable energy resources availability has been attempted on the basis of the analysis of the output of climate models on the African region.

Chapter 1 introduces the context of energy and climate change issues in the African continent. Future availability of renewable energies is evaluated based on several meteorological indicators calculated applying the global ECHAM-HAM aerosol-climate model. Results are provided on the statistically significant changes of the most relevant meteorological variables (ground temperature, solar radiation and precipitation) in a 30-year time span, to be used as a basis for the analyses described in the following chapters.

In **Chapter 2** PhotoVolatic electricity production under climate variability is assessed, together with the effect of technological improvements already leading to a substantial decrease of PV system costs.

Chapter 3 deals with wind and provides a forecast of major changes of typical wind energy production indicators. Given the resolution at which the climate modelling has been developed (1.75ºx1.75º degrees), the analysis focuses on synoptic scale effects.

Chapter 4 first discusses the complexity of bioenergy in the African context. Several key messages were provided regarding the opportunities and the caveats to be considered when planning biomass-to-energy exploitation chains. A quantitative assessment of threats posed by excessive fuelwood exploitation for cooking is also presented, combining the analysis of both climate and demographic pressures.

In **Chapter 5** a quick continent-wide estimation of climate change impact on hydro-power resources was performed, based on variables that describe hydrological characteristics, and which resulted by using the already cited climate model.

The report is completed by **Appendix A** describing in more detail the seasonal variability of the key meteorological parameters and by **Appendix B** setting the basis for an assessment of the theoretically total potential of methane as Landfill Gas, derived from Municipal Solid Waste, a potentially relevant resource in the African context.

1. Africa and its climate in next decades – main issues.

M. Gaetani, L. Pozzoli, E. Vignati, F. Monforti

1.1 Africa, a changing continent in a changing climate

1.1.1 Climate and non-climate pressures. An overview

According to (Conway *et al.*, 2009) that has analysed in detail the impacts of a number of long-term (100 years) simulations based on IPCC scenarios, the climate in Africa is going to move towards diffusing higher temperature values at all latitudes with peak increase in the dry belts just north and south of the tropics. Precipitation will increase in the tropic areas while it is expected to decrease in the northern and southern extremes of the continent. Moreover, a general trend towards more concentrated rain events is also clearly visible, with droughts and flooding becoming stronger and more and more frequent. This change in climate forcing will end up in pressures on the environment, human health and several other human and non-human activities.

One of the sectors most severely affected is the agriculture. Changes in temperature and precipitation can put agriculture under stress or relieve cultivations from water or temperature stress, depending on the pattern of the change. Following the climate evolution described here, agriculture is expected to become more stressed in the two northern and southern belts of the continent, while in the tropical zone agricultural suitability can be expected to increase for certain crop types. Nevertheless, these zones are today the areas which highest amount of remaining forest land and corresponding ecosystems services, biodiversity and carbon storage and should therefore no considered as areas for agricultural expansion.

Human health will be generally under pressure on the whole continent, both directly (e.g. because of the increasing temperature especially in urban areas which has a significant impact on mortality), and indirectly through the enlargement of the areas potentially suitable for infectious disease like e.g. malaria and dengue.
Animal as well plan live will also be strongly affected by changed climate conditions, this will include world-known African National Parks, unique ecosystems and biodiversity hotspots.

Sea level is expected to increase because of the thermal expansion of the oceans, even if this prediction is subject to a high grade of uncertainties. It has been shown that a one metre rise in sea level, whenever confirmed, would have an severe impact on the densely inhabited areas on the Nile delta and the West Africa coast.

Nevertheless, a changing climate is not the only pressure on the African environment as UNEP has also recently summarised (UNEP, 2008). The impressive population growth in Africa has reached an estimated annual rate of 2.27% for the period between 2010-2015 (2.45% in the Sub-Saharan area) to be compared with the world figure of 1.1% (UNDESA, 2012)
Even if about 60% of the African population is still living in rural area (64% in the Sub-Saharan area), Africa has also the fastest growth of urban population in the world reaching a growth rate of 3.2% per year in 2010-2015 (3.6% in Sub-Saharan Africa). This rate is a consequence of people looking for better living conditions (including a perceived better access to energy), and jobs in urban and peri-urban areas. Through the intrinsically very high

urban birth the urban African population is expected to increase from 288 million in 2000 to 744 million in 2030 (with 85% of this development taking place in Sub-Saharan countries).

Such noticeable growth rate implies that, whatever progress technology could provide to cultivation efficiency in the next decades, more and more land will be devoted to agriculture on the continent. This is a difficult task for countries with agriculture already under stress or where agriculture is likely to be negatively affected in coming decades. The need of providing food to such a fast growing population results in pressures on the arable land, a finite resource not evenly distributed across Africa. Additionally, the strong reliance on traditional biomass and the its unsuitable use cooking and heating is putting forest and bush lands at risk in many regions of the continent.
If not properly managed, the increasing need for land and wood is going to finally end up in land degradation, deforestation and the potentially desertification of dry lands.
Finally an increasing population needing freshwater for daily life[1] is expected to put water resources under pressure, even more so considering that the potential water pollution related to rapid urbanisation, intensive agriculture and industrialisation is expected to limit more and more the share of water ultimately available for human uses.

However, technological development is expected to play a key role in the next decades to address and solve some of the potentially harmful developments on the African continent. For instance, the intensification of agriculture through mechanisation, and improved farming methods will lead to a decreased need for additional land, further, supporting highly efficient cooking stoves and the transition to modern cooking fuels would ideally counteract the fast depletion of wood resources. Obviously, benefits from technology will be exploited only if technological development is able to reach the African communities, to provide them with feasible solutions for their specific needs. An increased access to energy, will play a crucial role for reaching such a goal.

1.1.2 Renewable energy and climate nexus

The energy and climate nexus is often studied from the perspective of the relevant benefits provided by the introduction of low carbon and/or renewable energy generation technologies to the overall emissive carbon balance. (see e.g., UNECA, 2011) and results are especially useful for designing an appropriate convergence between climate change and renewable energy policies.

In this report a different perspective will be taken and the impact of both climate and non-climate changes on the renewable energy availability, exploitability and sustainability will be studied for the African continent, and compared with each other to the largest possible extent.
Scientific literature on this aspect is somewhat limited and IPCC has pointed out that "Climate change will have impacts on the size and geographic distribution of the technical potential for Renewable Energy sources, but research into the magnitude of these possible effects is nascent" (IPCC, 2011). Even more scarce is the literature dealing with this problem from an African perspective, also considering the relatively small number of climatic simulations dealing specifically with this continent.

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[1] According to UN standards, access to less than 1000 m^3 of potable water per person per year define the status of "water scarcity", while "water stress" is defined when a person has access to less than 1700 m^3 of potable water per year.

The next two paragraphs describe the climate model and scenario used for providing data to the analyses on availability detailed in Chapters 2, 3 and 5 on solar power, wind energy and hydro resources respectively, while for the analysis of woody biomass evolution described in Chapter 4 a different approach has been taken (see paragraph 4.5 for details).
It also has to be noted that JRC is currently involved in CORDEX (COordinated Regional Downscaling EXperiment) in which Africa was selected as the main focus. The project aims to perform a dynamical downscaling of different global models, by means of regional high resolution models forced with climate change scenarios with the first results are expected to be available in the course of 2013.

1.2 Present-day and future climate simulations

1.2.1 The global model

Future availability of renewable energies is evaluated based on several meteorological indicators calculated applying the global ECHAM-HAM aerosol-climate model (Stier et al., 2005). The model is coupled to an ocean model (Roekner et al., 1995) to perform equilibrium climate simulations.
The sulphur chemistry is calculated on-line (Feichter et al. 1996), while fields of oxidant concentrations are used off-line. The aerosols are composed of sulphate, organic and black carbon, mineral dust, and sea salt (Vignati et al., 2004, Stier et al., 2005). The calculation on-line of the aerosol fields is important for the evaluation of the variation of the solar radiation arriving on the ground: aerosol particles scatter and absorb the radiation and their distribution changes in time and space. Particles interact directly with the radiation, but are also responsible for cloud formation and lifetime, being indirectly responsible for the variation of the solar radiation due to cloud presence and properties. The model considers also the radiation interaction of the greenhouse gases (e.g., carbon dioxide, ozone, methane), as well as the cloud water and ice.
In this study a resolution corresponding to ca. 1.75°x1.75° degrees (i.e., about 195 km at the equator latitude) is used with 31 vertical levels from the surface up to 10 hPa.

1.2.2 Simulation of the present-day and the year 2030

The present-day simulation was performed over a 100 years with present-day (2000) greenhouse gas concentrations and present-day aerosol and aerosol precursor emissions (Kloster *et al*, 2009). A future (2030) simulation was performed making assumptions on anthropogenic aerosol and aerosol precursor emissions and greenhouse gas concentrations. The 2030 simulation was performed for 60 years and analysed for the last 30 years in which an equilibrium state was reached. Statistical significance of the simulated differences is evaluated before the calculations of the energy potential.
The inventories of anthropogenic air pollutant emissions for the present day (2000) and future scenarios for 2030 were developed by IIASA (International Institute for Applied System Analysis) and consider two possible future developments: current legislation (CLE) and maximum feasible reduction (MFR) (Cofala *et al* 2007). CLE accounts for presently decided and full compliance of control legislations for future developments in nations where there is legislation. MFR assumes a full implementation of today's most advanced technologies worldwide and it implies a stronger emission reduction than the CLE scenario.

In the 2030 simulation, the assumption is that Europe implements the MFR scenario in 2030, but that the rest of the world follows the Current Legislation Emission scenario. The MFR

scenario used in this study, although it describes the larger reductions that could be achieved, is probably not completely unrealistic in Europe, where new regulations impose that air pollutant emissions are effectively abated to almost 70% of MFR.
Natural emissions are simulated interactively in the model. Biomass burning emissions are assumed to be the same as for the year 2000. For greenhouse gas concentrations the SRES B2[2] scenario is used (IMAGE, 2001): the scenario describes a world in which local solutions to economic, social and environmental sustainability are found (Table 1.1).

Table 1.1. *Greenhouse gas concentrations prescribed in the model for present-day and 2030 simulations according to the SRES B2 scenario*

	Carbon dioxide (ppmv)	Methane (ppmv)	N2O (pptv)
2000	373	1.82	314
2030	452	2.49	340

In the equilibrium climate simulations the ECHAM5-HAM model is allowed to fully adjust to a change in radiative forcing due to different aerosol and/or GHG concentrations.
More details on emissions, greenhouse gases concentrations, and oxidant concentrations used in this study can be found in Kloster *et al.* (2008; 2009).

1.3 Scenario results for climatic key variables on the African area.

Figures 1.1. to 1.3 show on the left the ensemble yearly mean for 2000 for the set of key climatic variables: precipitation, net solar radiation at the surface and air temperature at a height of to metres. On the right, differences between 2030 and 2000 ensembles are shown for the same key climatic variables. White areas correspond to not statistically significant differences ($p<0.05$) according to a Student's t-test (von Storch and Zwiers, 1999).

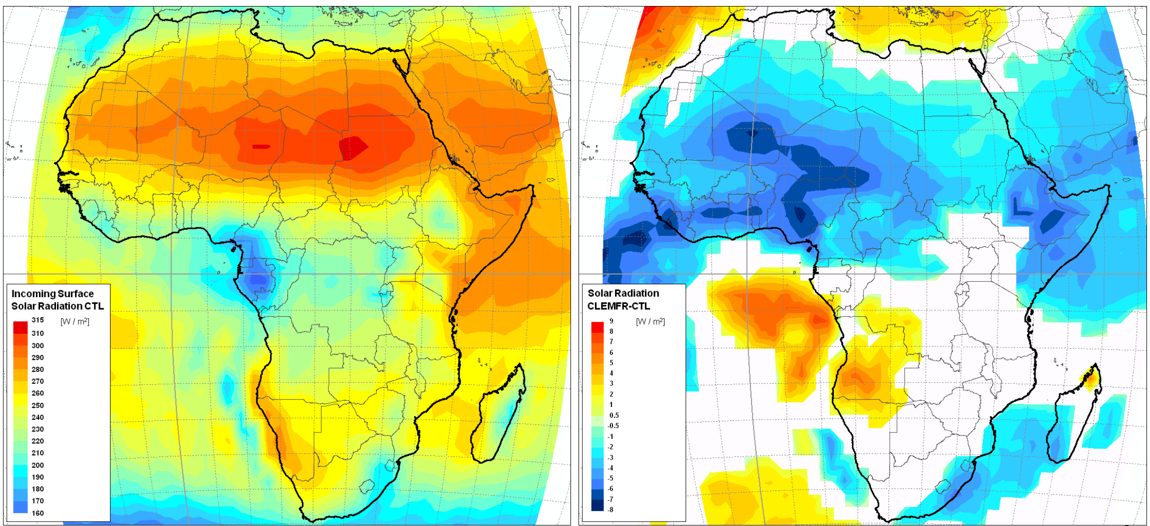

Figure 1.1. Ensemble yearly mean of the net solar radiation at the surface (left – W/m^2) in 2000 and its change between 2030 and 2000 (right – W/m^2). Positive changes imply an increased radiation amount, while negative changes imply a decrease in solar radiation. White areas correspond to not statistically significant changes ($p<0.05$).

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[2] The B2 IPCC emission scenario describes a world looking for solutions to economical, social and environmental challenges mostly at the local level.

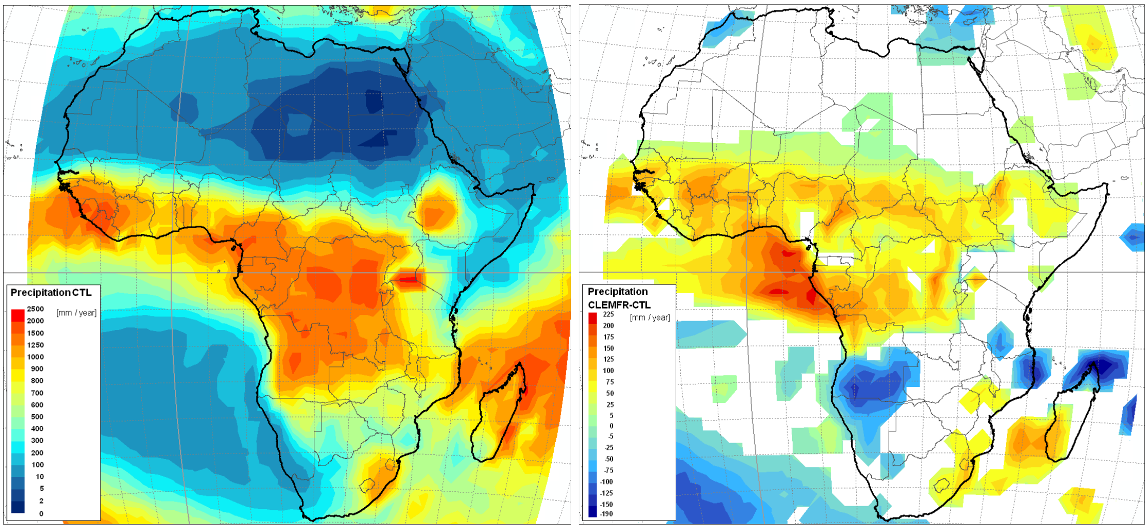

Figure 1.2. Ensemble mean of the annual precipitation (left – mm/year) in 2000 and its change between 2030 and 2000 (right – mm/year). Positive changes imply an increased amount of precipitation while negative changes imply a decrease in precipitation. White areas correspond to not statistically significant changes ($p<0.05$).

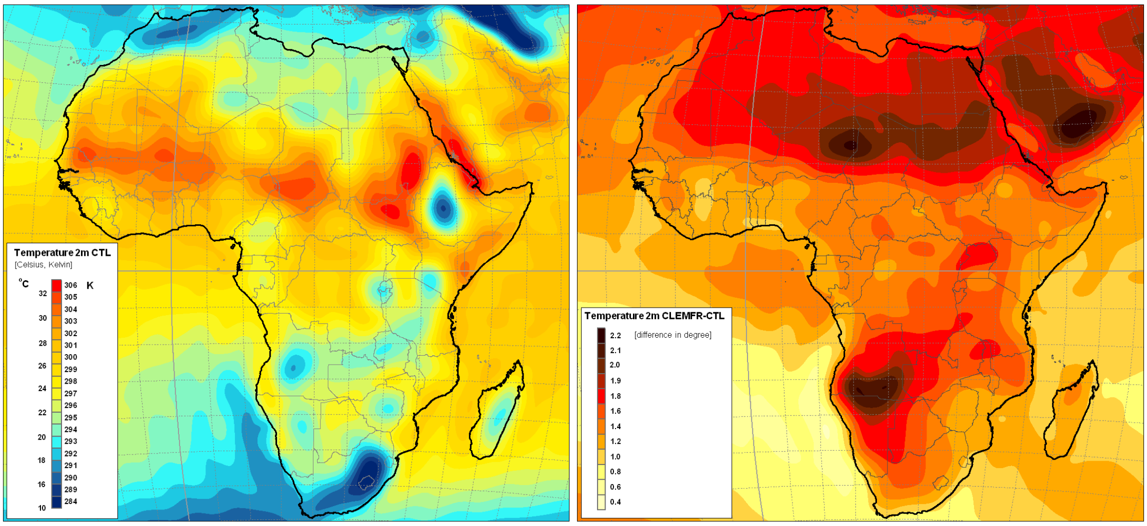

Figure 1.3. Ensemble yearly mean of the air temperature at two metres (left – C) in 2000 and its change between 2030 and 2000 (right – C). Temperature is found to increase everywhere in the area studied showing everywhere statistically significant changes ($p<0.05$).

The 2030 solar radiation reduction over the Sahara Desert (Fig. 1.1) can be explained through the dynamical response to the changes in air temperature. The general future warming shows larger anomalies in the northern hemisphere (Fig. 1.3), producing an anomalous northward displacement of the Intertropical Convergence Zone (ITCZ) and the associated precipitation belt. Specifically, the rainfall anomalies located over the Sahelian belt (Fig. 1.2) are associated to intense convergence and surface winds over the Western Sahara, favourable to the extraction and uplift of desert dust (not shown), which is the main factor responsible for the solar radiation suppression observed. It is also worth noting that the yearly rainfall anomalies result from the composition of different seasonal responses to thermal patterns

showing larger anomalies in the northern hemisphere even at seasonal scale (see Appendix A for a detailed view of seasonal data).

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2. Solar resources and their exploitation. Climate and technological changes compared

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2.1 Impact of climatic issues on PV production

Climate variability can influence the actual production of solar panels through two main mechanisms: the net surface radiation changes will affect the PV panel output per square metre, while changes in ambient temperature can have an influence on the efficiency of the PV system with PV power decreasing by about 0.5% for each additional temperature degree for current reference technologies, with all other factors constant.

The climate simulation results described in Chapter 1 were used for assessing the expected changes in PV productivity in the African continent in the next 30 years. In the calculation, PV modules were assumed to be mounted in a fixed position (i.e., do not move during the day or year), with modules facing the Equator and mounted at the local optimum angle[3] for maximum yearly energy yield. The calculation was then performed for a typical day in the month, using the monthly average irradiation values, calculated for the plane of the modules (Šuri *et al.*, 2005). The PV productivity algorithm requires both global and diffuse horizontal irradiation, whereas the climate model output only provides the global horizontal irradiation. For this reason it was decided to use the ratio of diffuse to global radiation D/G, obtained from existing satellite data (Huld et al. 2012) and assume that this ratio remains constant also in the future. The uncertainty introduced by this assumption is small since any decrease in D/G would mean that the reduction in diffuse radiation would be accompanied by a corresponding increase in direct radiation with only a small impact on the global radiation on an inclined plane. However, this argument does not hold if we consider only the direct radiation, which would be needed to estimate the change in output from concentrating solar power installations or concentrating PV. In this case the assumption of constant D/G would introduce a significant extra uncertainty. For this reason we have chosen not to consider CSP or CPV systems in this work.

The PV power output depends, in a non-linear way, on the instantaneous irradiance and temperature and a model for crystalline silicon modules (the most widely used technology) was applied (Huld *et al.*, 2010) and a correction for temperature changes was also inserted, based on a fully yearly simulation to account for seasonal temperature profiles too. Furthermore, the model takes into account the effects of shallow-angle reflectance (Martin and Ruiz, 2001), though this effect is unlikely to change much between the scenarios. Other losses in the system, such as inverter losses, resistive losses in cables, snow and dirt cover etc., are assumed to remain constant and therefore have not been included in the calculation which focuses on the change in PV output from 2000 to 2030.

The overall pattern of change in PV energy yield, moving from 2000 to 2030, shows a general decrease in PV energy yield in much of Africa north of the Equator. Even statistically significant, the effect is not especially large, with a decrease generally of around 2% in yearly output (see Figure 2.1).

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[3] The map of the optimum angle has been taken from the calculation performed in Huld et al., 2012

South of the Equator the picture is less clear, with some areas showing a decrease, while others show only a slight decrease, which is generally not statistically significant.

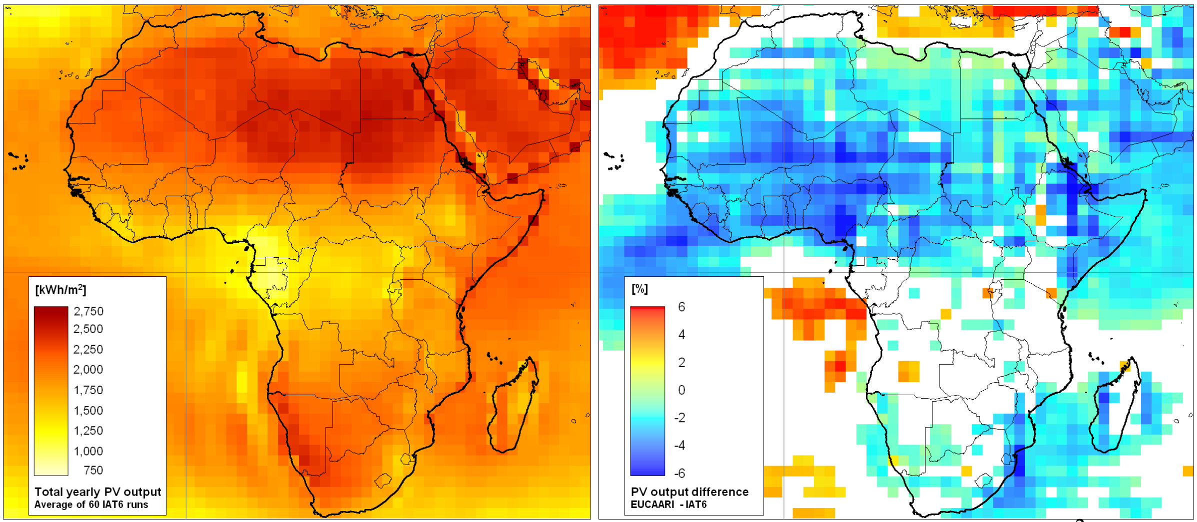

Figure 2.1 Ensemble mean of the PV potential power output in 2000 (kWh/m^2) and its change between 2030 and 2000 (right – %). White areas correspond to not statistically significant changes ($p<0.05$).

Increased PV output is generally due to an increase in annual irradiation which overcomes the general decreasing effect of the ubiquitous temperature increase (see Figure 1.2), which would tend to dump the PV output. On the contrary, in other areas, negative changes in solar radiation are reinforced by temperature increase in order to induce a decreased PV output.

Bearing this in mind and comparing Figure 2.1 with Figures 1.1 and 1.3, the results are not surprising. Europe sees a general increase in irradiation which in some places overwhelms the increase in temperature. Africa north of the Equator has a slight decrease in irradiation, which, in combination with the temperature rise, causes a decrease in PV output, while Southern Africa sees a slight increase in irradiation which counteracts the increase in temperature, so the overall effect in most places shows little change in the PV output, and is mostly not statistically significant.

2.2. Comparison of the changes in the solar energy potential due to the rapid global cost decrease of PV modules

In this section the above-mentioned analysis of climatic effects on solar radiation production is compared with an economic assessment that makes it possible to visualise to what extent the changes in the solar production potential due to climatic change are significant compared to the changes in the cost development driven by market and technological development forces.

2.2.1. The significant PV modules cost reduction induced by technology learning effects

Technology learning had been a well-known and described phenomenon in the energy technology literature (see Table 2.1) and its effect on the PV price has a fundamental influence on the actual exploitation of the solar potential in Africa.

Table 2.1 *Technology learning estimated for several energy technologies*

Technology	Country/region	Time period	Estimated learning rate (%)	R^2 [b]	Performance measure (dependent variable)	Experience measure (independent variable)	Reference/data source
Oil extraction	North Sea	—	≈25	—	sp. labor (man-hrs to construct one ton of platform jacket)	cum. cap. (construction projects)	Blackwood (1997)
Gas pipelines, onshore	US	1984–1997	3.7	0.09	sp. inv. price ($/mile-inch^2)	cum. cap. (mile-inch^2)	Zhao (1999)
Gas pipelines, offshore	US	1984–1997	24	0.76	sp. inv. price ($/mile-inch^2)	cum. cap. (mile-inch^2)	Zhao (1999)
DC converters	World	1976–1994	37	0.35	conversion losses (%)	cum. cap. (installed units)	Rabitsch (1999)
Gas turbines	World[c]	1958–1963	22	–	sp. inv. cost ($/kW)	cum. cap. (MW)	MacGregor *et al.* (1991)
Gas turbines	World[c]	1963–1980	9.9	–	sp. inv. cost ($/kW)	cum. cap. (MW)	MacGregor *et al.* (1991)
Gas turbines	World[c]	1958–1980	13	0.94	sp. inv. cost ($/kW)	cum. cap. (MW)	Nakićenović *et al.* (1998); MacGregor *et al.* (1991)
Nuclear power plants	OECD	1975–1993	5.8	0.95	sp. inv. cost ($/kW)	cum. cap. (MW)	Kouvaritakis *et al.* (2000)
Hydropower plants	OECD	1975–1993	1.4	0.89	sp. inv. cost ($/kW)	cum. cap. (MW)	Kouvaritakis *et al.* (2000)
Coal power plants	OECD	1975–1993	7.6	0.90	sp. inv. cost ($/kW)	cum. cap. (MW)	Kouvaritakis *et al.* (2000)
Lignite power plants	OECD	1975–1992	8.6	0.96	sp. inv. cost ($/kW)	cum. cap. (MW)	Kouvaritakis *et al.* (2000)
GTCC power plants	OECD	1984–1994	34	0.78	sp. inv. cost ($/kW)	cum. cap. (MW)	Kouvaritakis *et al.* (2000)
GTCC power plants	World	1981–1991	−11[d]	0.41	sp. inv. price ($/kW)	cum. cap. (MW)	Claeson (1999)
GTCC power plants	World	1991–1997	26[d]	0.90	sp. inv. price ($/kW)	cum. cap. (MW)	Claeson (1999)
Wind power plants	OECD	1981–1995	17	0.94	sp. inv. cost ($/kW)	cum. cap. (MW)	Kouvaritakis *et al.* (2000)
Wind power (electricity)	California	1980–1994	18	0.85	sp. prod. cost ($/kWh)	cum. prod. (TWh)	CEC (1997); Loiter and Norberg-Bohm (1999)
Wind	Germany	1990–1998	8	0.95	sp. inv. price ($/kW)	cum. cap. (MW)	Durstewitz (1999)
Wind turbines	Denmark	1982–1997	8	n.a.	sp. inv. price ($/kW)	cum. cap. (MW)	Neij (1999)
Solar PV modules[e]	World	1968–1998	20	0.99	sp. inv. price ($/$W_{peak}$)	cum. cap. (MW)	Harmon (2000)
Solar PV panels	US	1959–1974	22	0.94	sp. sale price ($/$W_{peak}$)	cum. cap. (MW)	Maycock and Wakefield, 1975
Ethanol	Brazil	1979–1995	20	0.89	sp. sale price ($/boe)	cum. prod. (cubic meters)	Goldemberg (1996)
Model-T ford	US	1909–1918	14	0.96	sale price ($ per car)	cum. prod. (cars)	Lipman and Sperling (1999); Abernathy and Wayne (1974)
Compact fluorescent lamps, integral-electronic type	US	1992–1998	16	0.66	sp. sale price ($ per lumen)	cum. prod. (units)	Iwafune (2000)
Air conditioners	Japan	1972–1997	10	0.82	sale price (Yen per unit)	cum. sales (units)	Akisawa (2000)
4-function pocket calculators	US	Early 1970s	30	n. a.	sale price ($ per unit)	cum. prod. (units)	Maycock and Wakefield (1975)
SONY laser diodes	—	1982–1994	23	0.95	prod. cost (Yen per unit)	cum. prod. (units)	Lipman and Sperling (1999)

The high learning rate of photovoltaics (PV) was an important factor in driving the PV support policies. As a relatively new energy technology with a low deployment rate it had a high potential for cost reduction (see Figure 2.2).

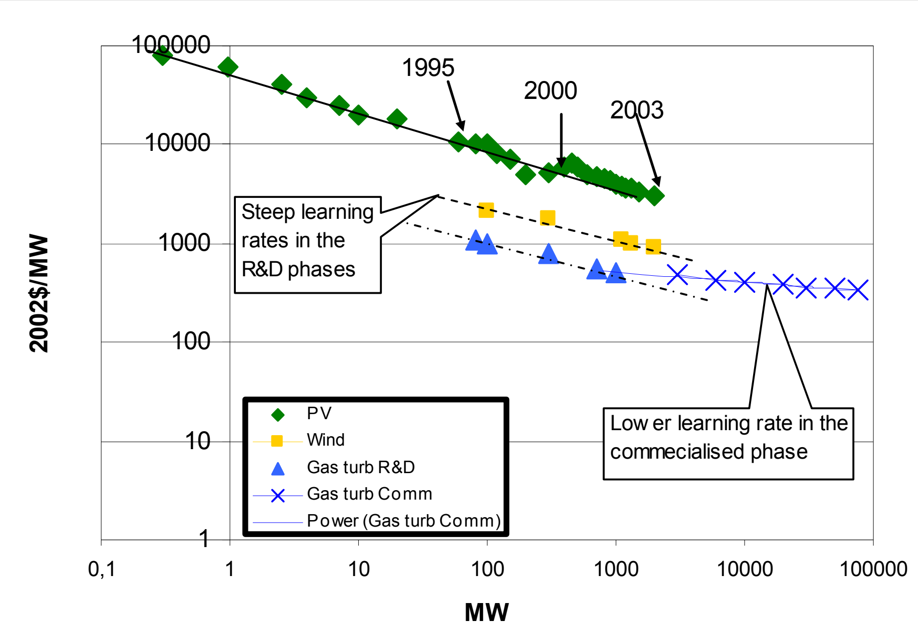

Figure 2.2. The Research & Development and the commercialisation phases of learning for some electricity generation technologies (Gritsevskyi and Nakicenovic, 2000; Surek, 2004; Neij, 1997)

The global deployment of the grid-connected PV made technological learning an important element of modelling the least-cost portfolio in the developing world. Without taking account of this, the forecasts would not have been able to project the unprecedented growth of the solar PV deployment.

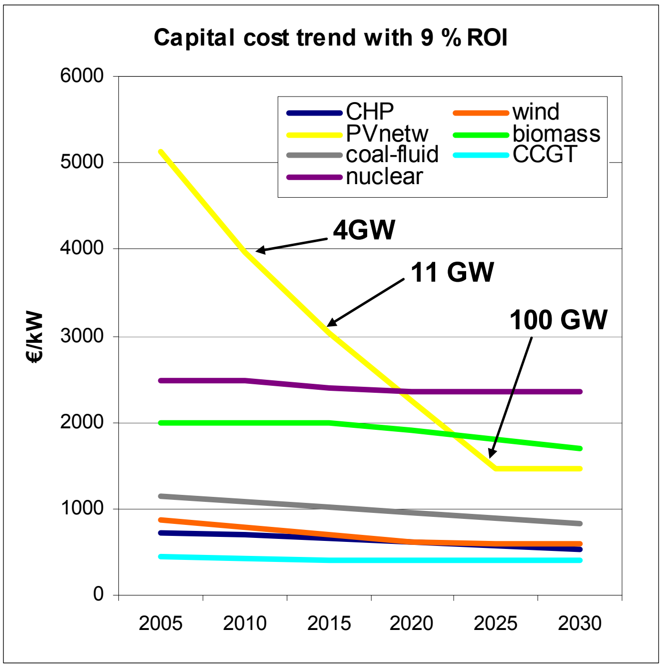

Figure 2.3 Dynamic learning forecast in the year 2008 based on a financial model (Szabó and Jäger-Waldau, 2008)

Up to 2011 the PV deployment, worldwide and in the EU, has followed the projected pathway down on the costs parallel with the upward curve of deployed PV capacity (Figure 2.4).

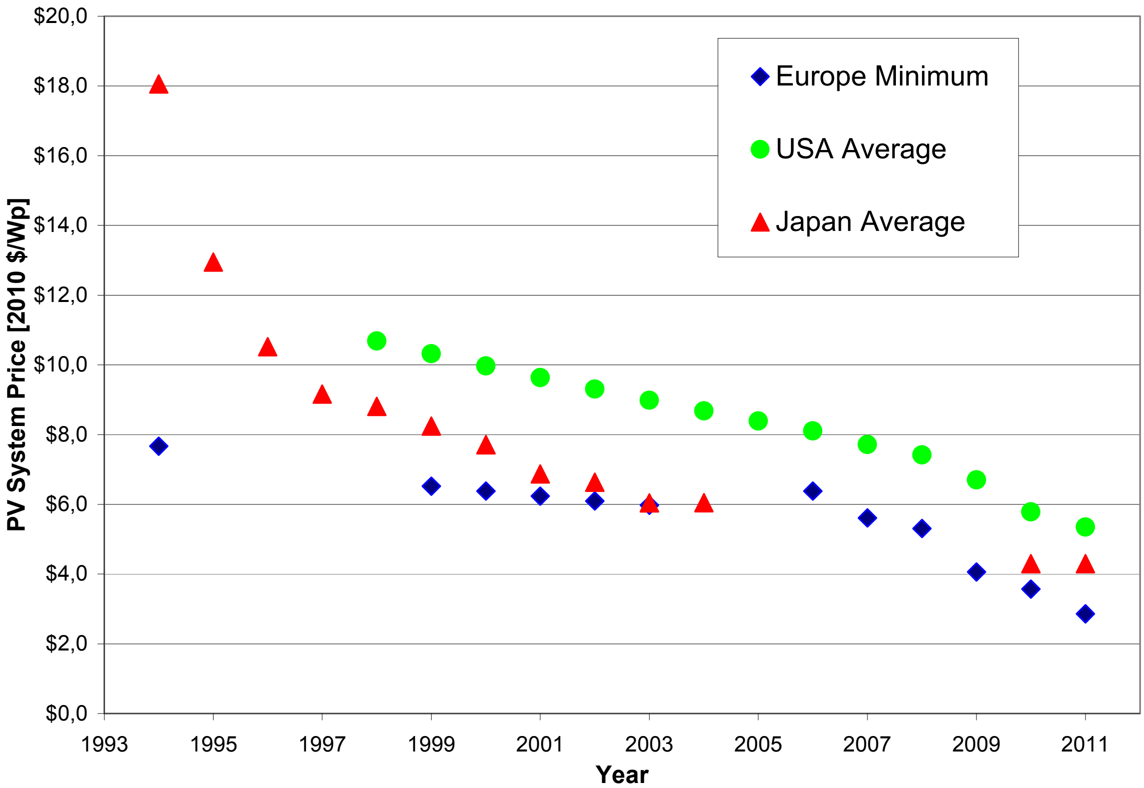

Figure 2.4 Experienced technology learning for PV technologies in USA, Europe and Japan. Experienced technological learning for PV up to 2011 was in accordance with the projection of the financial models (Data source: www.pvinsights.com).

Following this period, the support levels of the previous subsidy schemes have diminished and the PV market became a production-driven market: the built-up capacities tried to find new consumers by reducing their margins, which have lead to a very strong price competition inducing an experienced price drop even bigger than predicted by model.

During 2012 the international PV module prices have further decreased to a level never seen before. The dramatic price reduction of PV systems surpassed 50% over the 2009-2012 period. In the second quarter of 2012, the average system price for systems smaller than 100 kWp was in the range of 1.78 €/Wp (2.3 $/Wp) in Germany, while prices for large systems are already much lower: turnkey system prices as low as 1 €/Wp (1.3 $/Wp) have been reported for projects to be finished in 2013 (Bloomberg, 2012)

2.2.2. Updating PV competitiveness change in Africa due to cost development of the technology

In the JRC 2011 analysis, the cost calculation of the PV, diesel and the mini-hydro rural electrification options was based on the PV system costs in 2010 and the prevailing national diesel prices of 2009 (latest figures available). As the above described significant costs reduction took place in the period, and concurrently important changes were observed in the

diesel prices as well, the previous analysis was repeated using the latest input parameters available in order to point out what consequences can be concluded on the PV competitiveness due to these changes. Table 2.2. shows the actual updates of the off-grid PV system component costs.

***Table 2.2** PV system component cost changes between 2010 and 2012*

	PV module cost	Rest of the system	Battery price	O & M costs
Analysis based on 2010 data	2500€/kWp	1000€/kWp	1.5€/Ah	2.5 %/year of PV array
Analysis based on 2012 data	1100€/kWp	800€/kWp	1.5€/Ah	2.5 %/year of PV array

The other previous assumptions on the 15kWp PV system modelled did not change:

- **1/3** energy consumption during day and **2/3** during night
- Operation maintenance costs **2.5 %/year** of the PV array
- PV lifetime: **20 years**
- Battery lifetime: **5 years** (required battery size changes with PV output)
- Discount rate: **5 %.**

Figure 2.5 shows the changes calculated in PV electricity costs estimated for a stand-alone PV system of about 15kW with enough battery capacity to assure reliable and continuous electricity availability following the changes summarised in Table 2.2 from 2010 (left) to 2012 (right) while Figure 2.6 shows the same data in terms of Cost 2012/Cost 2010 ratio.

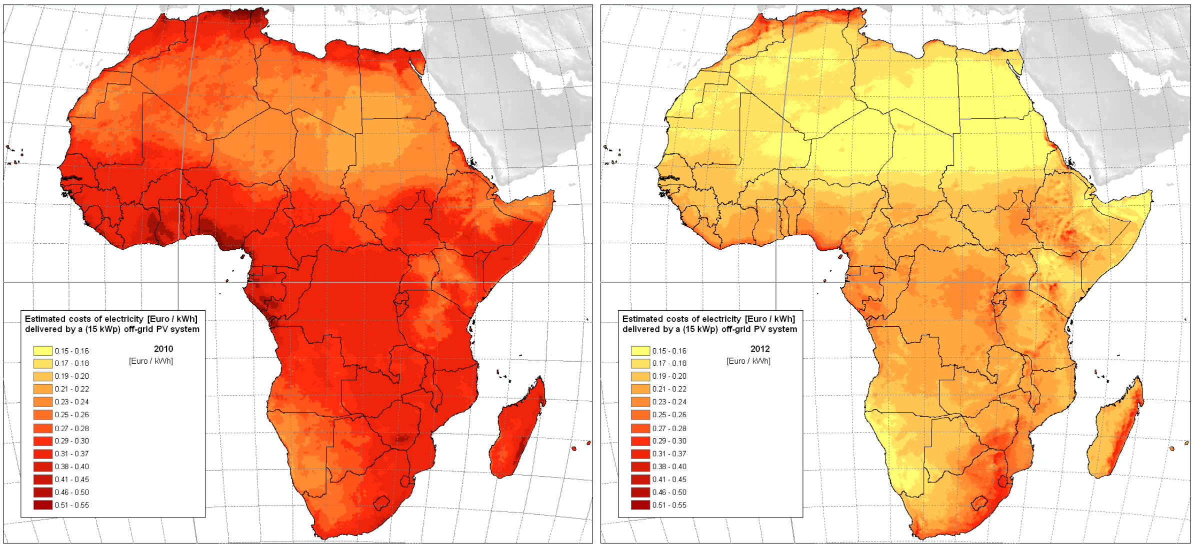

Figure 2.5 Cost (Euro/kWh) of PV electricity produced by a stand-alone 15 kW system estimated on the basis of component costs in 2010 (left) and 2012 (right).

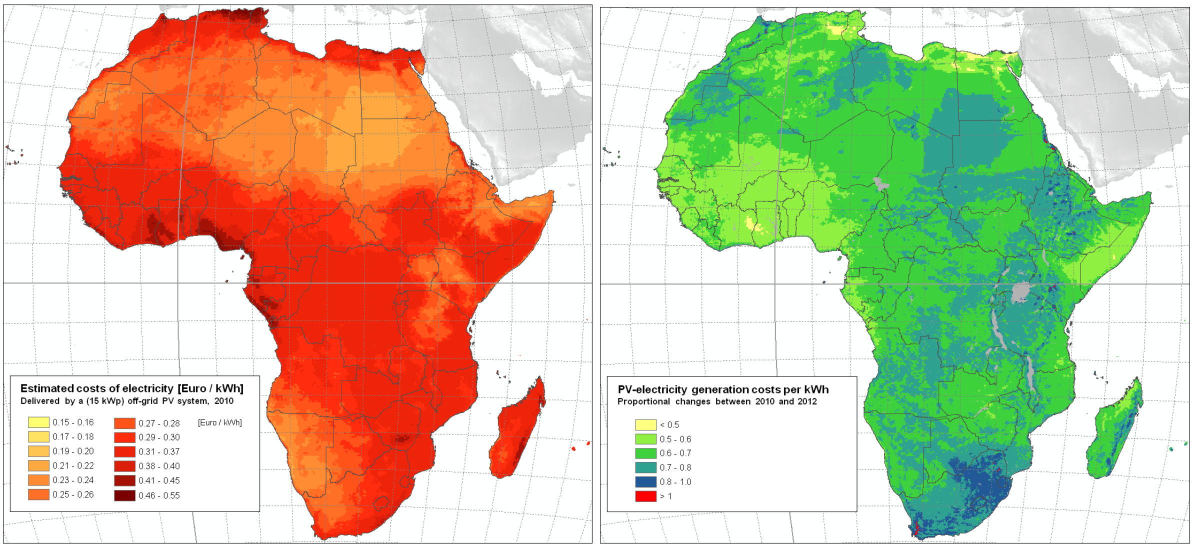

Figure 2.6 As Figure 2.5, with cost changes in relative values (Cost 2012/Cost 2010).

As in JRC, 2011 PV has been compared with other technologies. For diesel the 2010 November diesel cost data (latest available) from GIZ replaced the 2008 data (Figure 2.5).

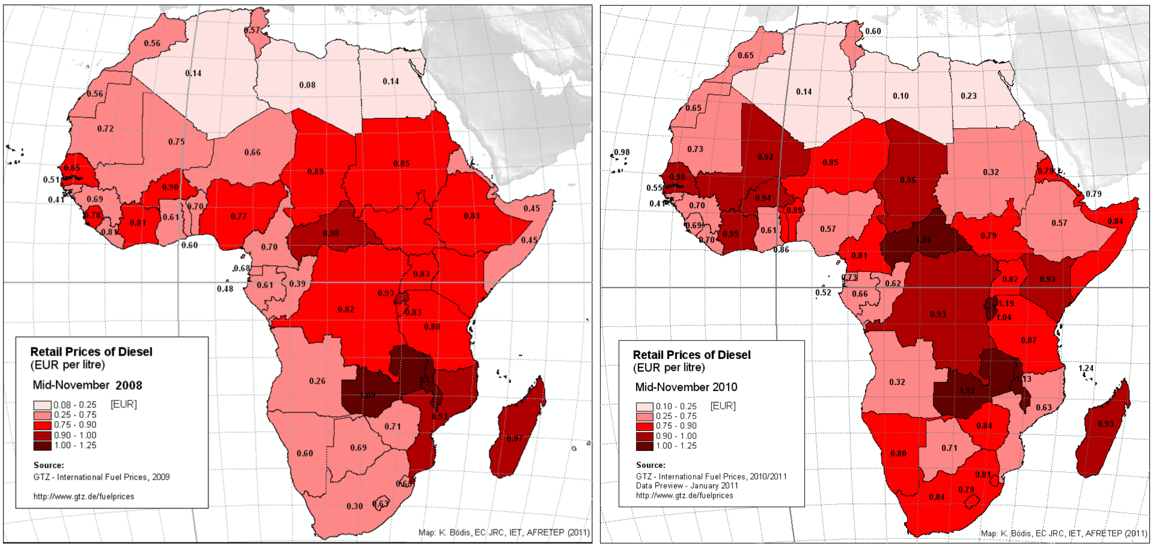

Figure 2.7 Diesel Cost (Euro/litre) in Africa in 2008 (left) and in November 2010 (right).

Figure 2.7 shows a generalised increase in the diesel cost caused also by the policies of progressive removal of subsidies followed by many African countries.

For the other two technologies analysed in (JRC, 2011) i.e., grid extension and mini-hydro, no changes were introduced in prices, while in two countries (Kenya and Burkina Faso) new data for additional grid-lines were added.

The changes in PV and diesel technology and fuel cost, during this short period, have lead to notable changes in the projected distribution of the population that could be served by the modelled least-cost energy technology that can be seen in Figure 2.8.

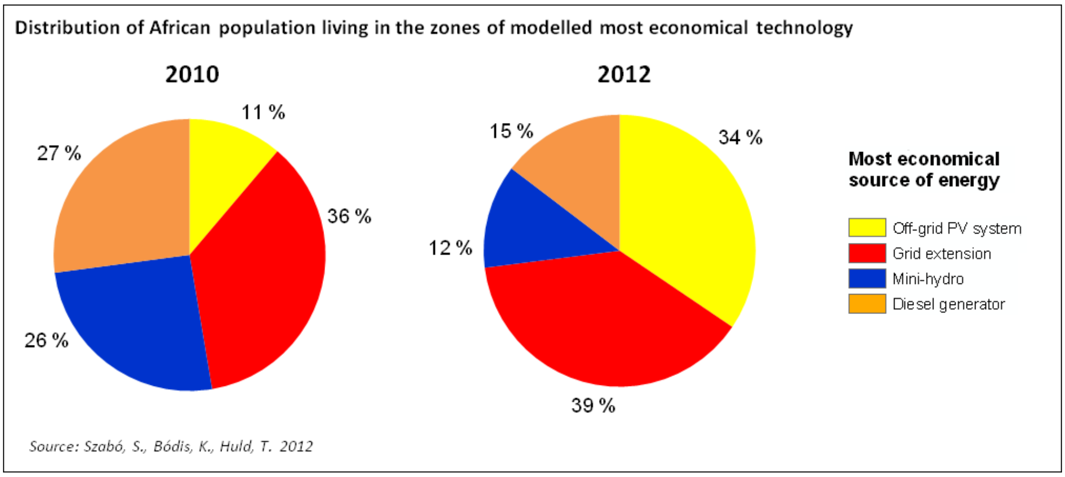

Figure 2.8 Distribution of Africa population living in the zones of the modelled most economical technology in 2010 (left) and 2012 (right) analysis.

While the biggest part of the population that could be most economically served by the extension of the existing electricity grid still dominates the distribution, the size of population for whom the off-grid PV technology option is calculated to be the cheapest option has tripled from the previous analysis. Parallel to this, the size of the population for whom the diesel genset off-grid option was calculated as the cheapest has been halved.

The projected decrease in the population for whom the mini-hydro option was the cheapest is solely due to the more competitive PV option: mini-hydro remained the least-cost option in the areas close to the river bodies, but PV outcompeted this option further away from the rivers. Nevertheless, the 12 % still represents an enormous market potential for mini-hydro technology.

The developments described above in the modelled off-grid electricity options mean that the renewable energy sources will play an increasing role in the energy portfolio of Africa, and the PV potential has become a really attractive option in rural electrification. The favourable technology prices, and the increased awareness of governments in Africa, could assist the African countries to rely more on their own domestic renewable resources for energy service.

The calculations clearly show that these developments, driven by socio-economic factors, would offset the comparably negligible negative effects of a few percentages decreased production projected in some regions by the climate effects (Figure 2.1). Moreover, the time-span of the technological learning and climate influence are also very different (a few years versus some decades).

In summary, with the present knowledge of the climate-change effects this renewable energy technology can be considered as a win-win technology.

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3. Wind energy in Africa – climate effects in short and medium term

S. Russo, M. Gaetani, J. Thielen

3.1 Climatic impacts on wind energy–scales of analysis and modelling tools

Winds are strongly influenced by general circulation pattern, weather, as well as topography, and are the result of complex processes that require high resolution modelling to be accurately reproduced in a theoretical framework. Currently, the General Circulation Models (GCMs) used to calculate the effects of climate change are too coarse to capture these processes in sufficient detail. In particular variables such as peak wind intensity, which is a key driving factor in wind energy production, require downscaling techniques to be applied for a meaningful potential estimation.

However, before going into these details, a broader analysis of main changes in wind patterns in a changing climate and their effect on some parameters quantifying the wind power potential (e.g., the Wind Power Density, WPD; Hennessey, 1977) can be performed. In this way, indications on the expected order of magnitude of the potential evolution can be provided.

The methodology to be applied for such analysis of the potential impact of climate change on wind energy in Africa has been tested by means of the ECHAM5 global model outputs forced with two different emission scenarios (A1B and B2).

3.1.1 Model simulations description

In order to take into account the combined radiative impacts of anthropogenic greenhouse gases (GHGs) and aerosol emissions on the wind patterns, the 6-hourly 10 metre wind speed from the ECHAM-HAM experiments forced by the B2 scenario described in Chapter 1 were analysed. Changes in the probability distribution of mean and maximum wind speed were estimated and a corresponding Wind Power Density indicator developed.

Moreover, a second climatic dataset developed in the ESSENCE Project, taking into account only the radiative impact of anthropogenic greenhouse gases under the A1B scenario, was also analyzed[4] in order to provide additional hints on the sensitivity of wind energy availability to a different hypothesis on future climate evolution.
Based on the 3-hourly 10 metre wind speed data generated in the project for two selected periods (current climate 1980-2010 and mid-term future climate 2021-2050), changes in the probability distribution of yearly mean and maximum wind speed were investigated, the latter being also directly relevant for the production of wind power.

[4] In the ESSENCE project a 17-member ensemble of climate change simulations in response to the SRES A1B scenario has been carried out using the ECHAM5/MPI-OM climate model. It has a spatial resolution of 1.875 degree in latitude and longitude. Model runs start in 1950 and end in 2100 (for details see Sterl et al. 2008, Russo and Sterl 2011, Russo and Sterl 2012).

3.1.2 Data analysis

In order to test whether future wind speed is significantly different from that in the reference period, i.e., whether or not they are drawn from the same distribution the Kolmogorov-Smirnov (K-S) test (Von Storch and Zwiers, 2003) was applied at the 5% level of significance ($p<0.05$) on both data sets described in Section 3.1.1

In case any significant differences between the distribution of the current and future wind speed data are detected, downscaling techniques should be applied and the higher resolution fields compared with the results obtained with ERA-Interim data for the first report on Africa.

3.2 Preliminary results on the large scale

3.2.1 Base case analysis (2000-2030)

First results of the analysis of the ECHAM-HAM climate scenarios described in Chapter 1 shows that for 50th percentile of the annual mean wind speed the changes are within the range ± 0.2 m/s, thus very small (Figure 3.1).

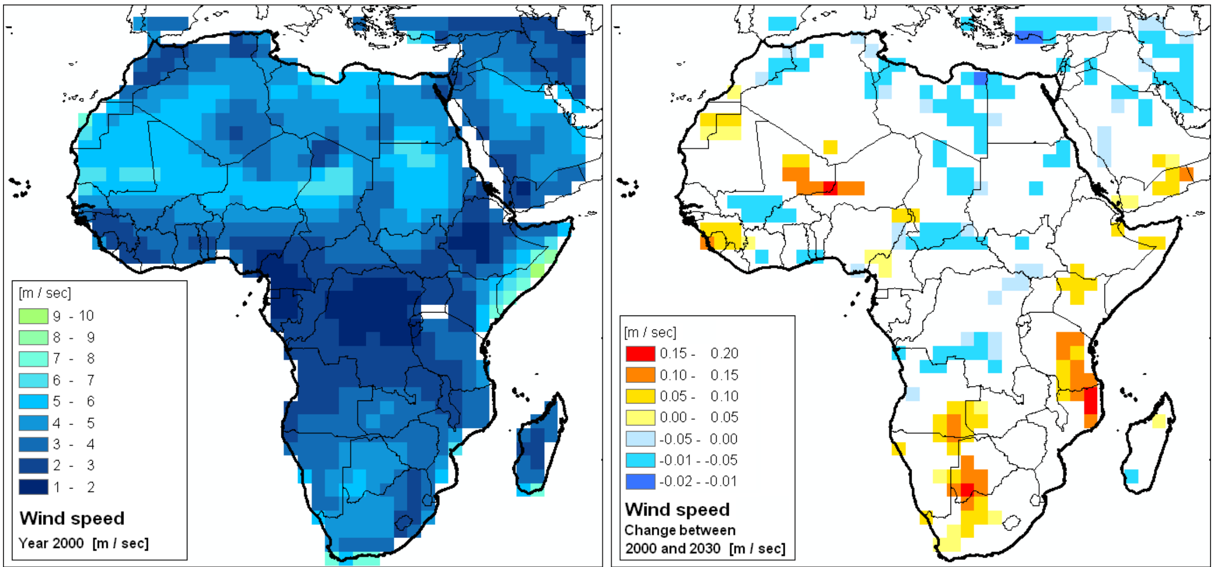

Figure 3.1: 50th percentile of annual mean wind speed (left – m/s) in 2000 its change between 2030 and 2000 (right – m/s). Positive changes imply an increased wind speed, while negative changes imply a decrease in wind speed. White areas correspond to not statistically significant changes ($p<0.05$).

Similar behaviour is detected for the annual maximum wind speeds. Although the overall changes are somewhat larger, they still range within ± 0.6 m/s.

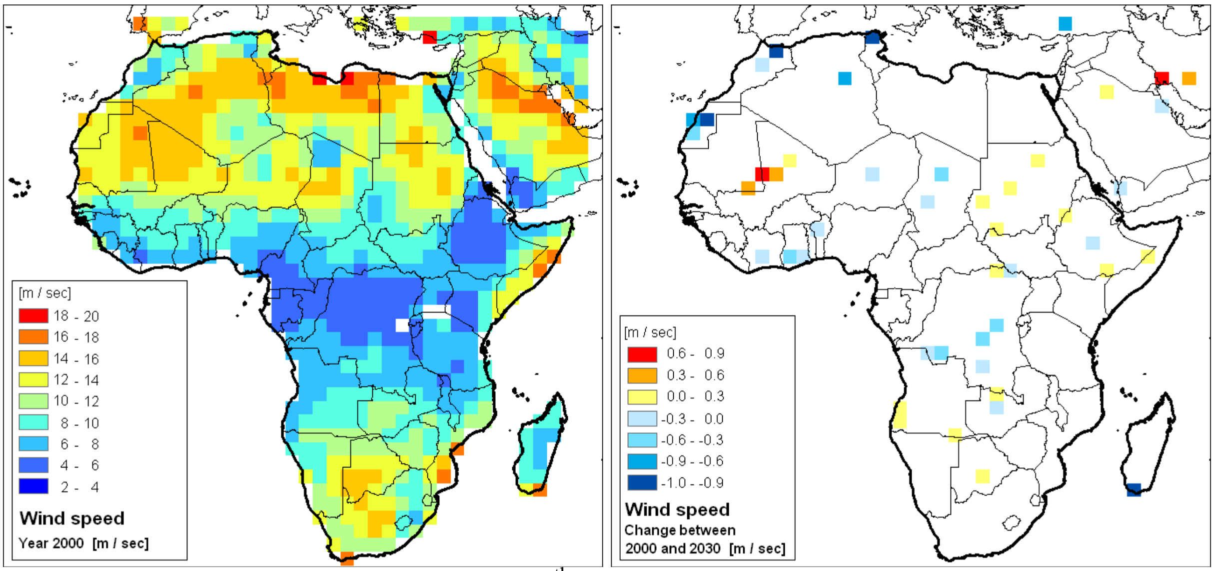

Figure 3.2: As Figure 3.1 but for the 90th percentile of the annual maximum wind speed. White areas correspond to not statistically significant changes ($p<0.05$).

The wind power density (WPD) indicator has been also calculated: following Hennessy (1977) WPD is defined as:

$$WPD = \frac{1}{2} \rho V^3,$$

where V is the wind speed and ρ is the air density defined as $\rho = 1.225 - (1.194 * 10^{-4} * z)$, with z the location's elevation above sea level in metres.
In his study, WPD has been computed at the height of 10 m a.g.l. (a typical wind speed measurement height and small turbine height) averaging the monthly values obtained as the mean of the cubed 6-h V provided by the model.
Moreover, the suitability of a certain area for wind power exploitation is usually also described by means of the associated "wind class" ranking, rather than the WPD values or mean wind speeds. Class 3, or greater ones, are suitable for most wind turbine applications, whereas Class 2 is marginal and Class 1 is generally not suitable (Elliott *et al*. 1986). The ranges of WPD at 10-m height above ground and the associated classes are shown in Table 3.1.

Table 3.1: *Wind Power Classes definition (NREL, 2012)*

Class	**WPD [W/m2]**	**Resource Potential**
1	<100	Not suitable
2	100-150	Marginal
3	150-200	Fair
4	200-250	Good
5	250-300	Excellent
6	300-400	Outstanding
7	>400	Superb

Significant positive changes in WPD between 2000 and 2030 are found over the Eastern Sahara, East Africa and Southern Africa, with values up to 40 W/m^2 (Figure 3.3). However, analysing the data with regard to Wind Power Classes (Table 3.1) it results that only limited

areas over the Eastern Sahara and Southern Africa show a shift to the adjacent higher or lower class, whereas most of the continent is unaffected by any change (Figure 3.4).

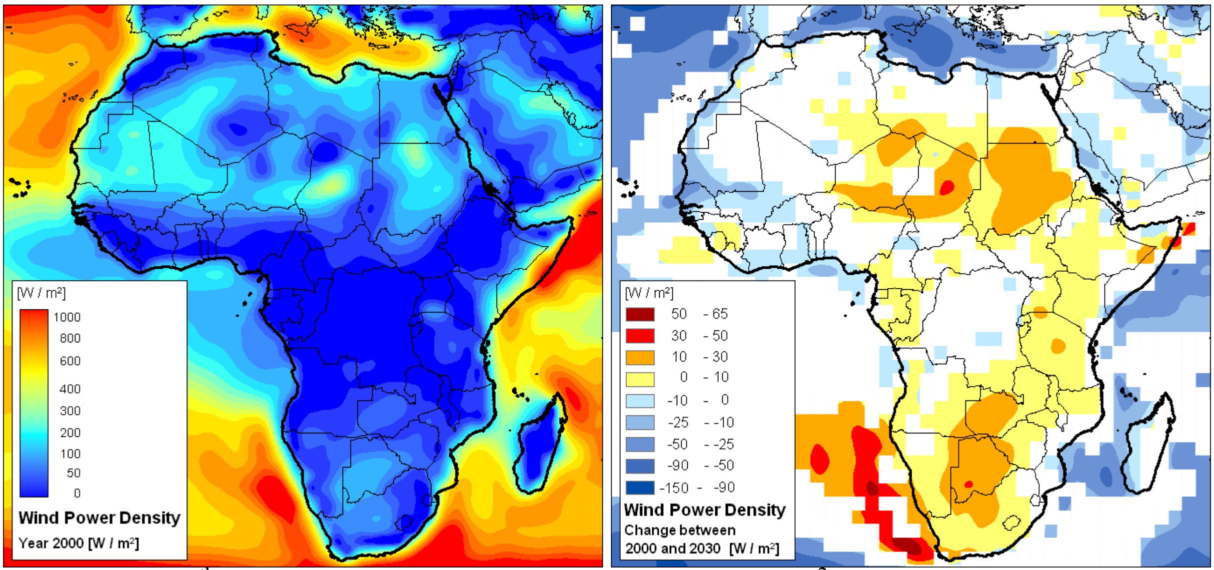

Figure 3.3: 50th percentile of annual mean WPD (left – W/m^2) in 2000 its change between 2030 and 2000 (right – W/m^2). White areas correspond to not statistically significant changes ($p<0.05$).

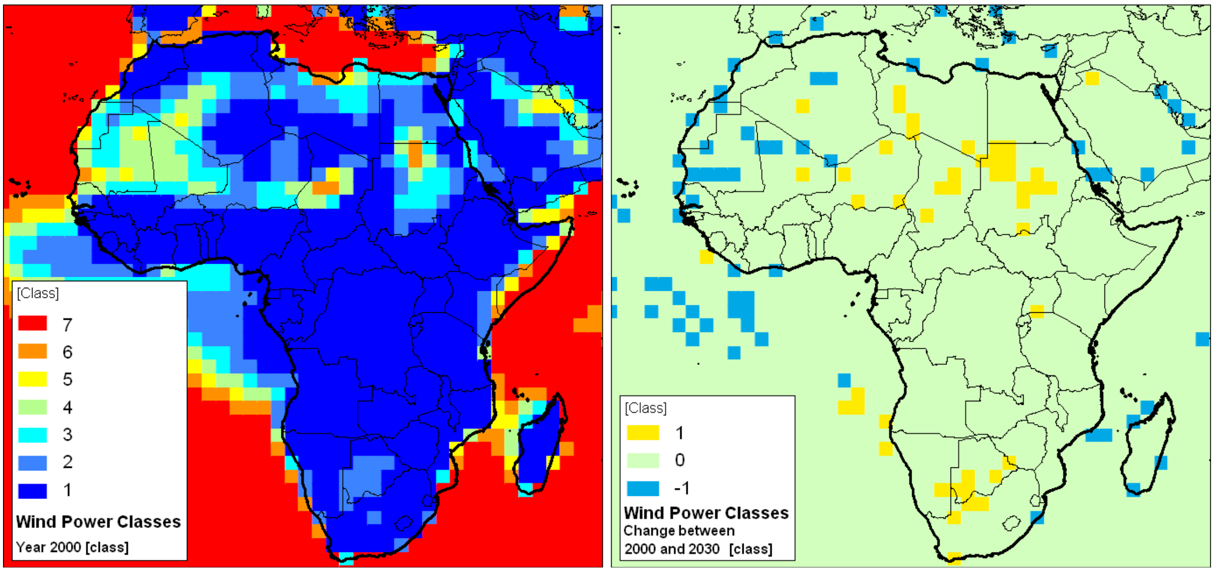

Figure 3.4: As Figure 3.3, but for Wind Power Classes.

These results imply that an assessment of the future wind energy can be robustly based on the evaluation of the present-day data e.g., following the methodology suggested in (JRC, 2011) at least up to 2030.

3.2.2 Additional analysis (1981-2050)

In order to investigate the robustness of the findings from the previous section 3.2.1 additional analysis was performed on data coming from the ESSENCE Project (see section 3.1.1) taking into consideration the two 30-year periods 1981-2010 and 2021-2050. Figures 3.5 and 3.6 show the results of the analysis based on the same indicators of Figures 3.1 and 3.2.

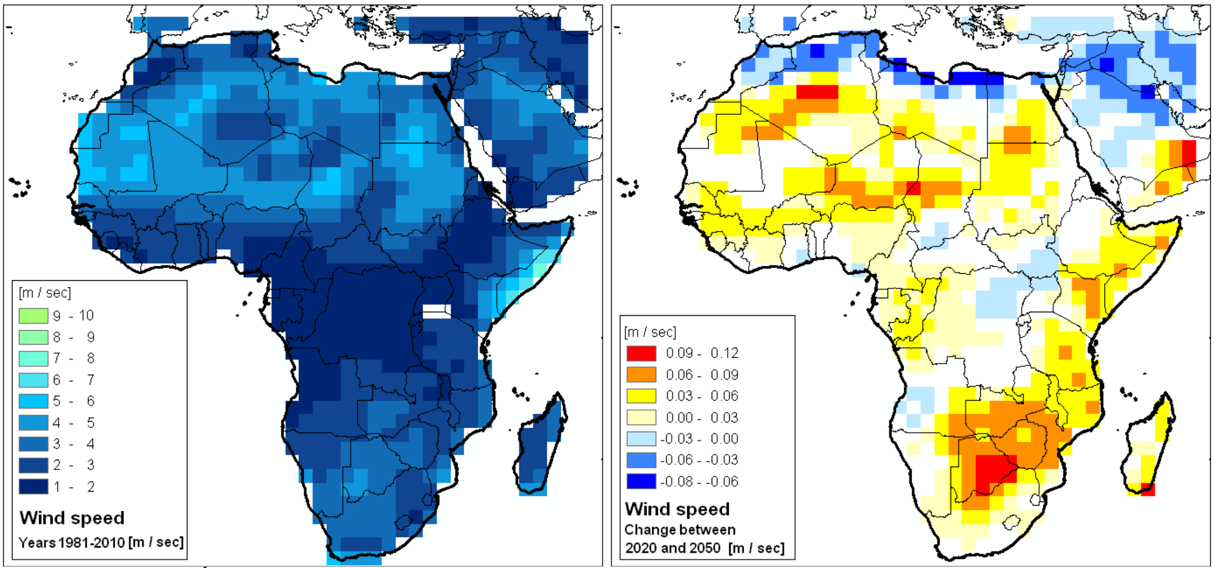

Figure 3.5: 50th percentile of annual mean wind speed (left – m/s) in the 1981-2010 period and its change in the period 2020-2050 (right – m/s). White areas correspond to not statistically significant changes ($p<0.05$).

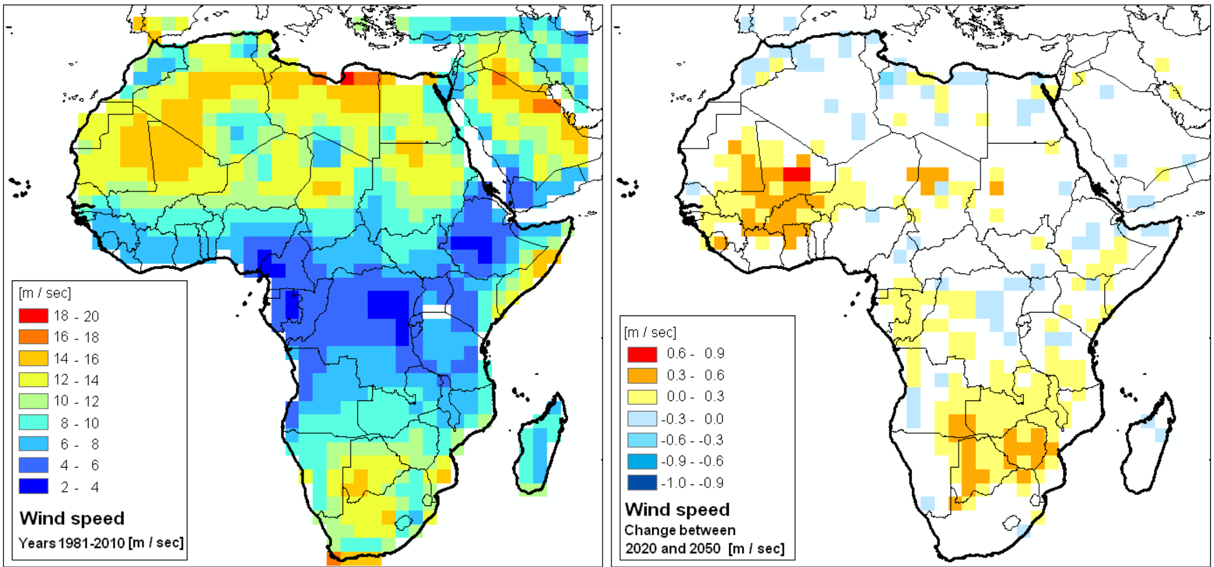

Figure 3.6: As in Figure 3.2, but for the 90th percentile of the annual maximum wind speed. White areas correspond to not statistically significant changes ($p<0.05$).

Results from this second data set also show very small variations of 50th percentile of annual mean wind speed (± 0.1 m/s), even if a tendency towards a slight but statistically significant increase in wind speed localised in North West Africa and in Southern Africa can be noticed.

3.3 Conclusions

The analysis here, performed by using wind data from a robust global model applied to two scenarios, demonstrates that in the near future almost over the whole African continent very little significant wind speed changes are expected, meaning that the future wind power can be assessed at the synoptic scale discussed here, through the evaluation of the present climate data as reported in (JRC,2011)

Nevertheless, these preliminary results, even if they are based on two models used in ensemble mode and forced with two different scenarios, assume a more limited meaning when transposed on a more local scale, given low resolution (synoptic scale) and have not yet been downscaled. As already mentioned, JRC is currently involved in CORDEX (COordinated Regional Downscaling EXperiment) that is expected to develop regional high resolution models forced with climate change scenarios in the close future.

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4. Bioenergy complexity in Africa and its changing climate.

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Bioenergy is an intrinsically complex energy resource involving several kinds of feedstock and deeply interconnected with several other non-energy uses of the same resources in agriculture, forestry, industry uses or as an environmental services provider. Technological issues of bioenergy are also complex, involving mobilisation, transformation and distribution steps, each with specific features depending once again on the feedstock, the geographical context and several other drivers. In this chapter some key messages on the bioenergy resources currently available and exploited in Africa will be provided together with highlights on some key feedstock for future deployment. Forces driving expected future changes in bioenergy will be also discussed, including the climate-driven changes, and will be compared with each other.

4.1 Key messages regarding bioenergy in Africa

Africa is a continent extremely rich in natural resources, including biomass suitable for energy production. Bioenergy development in Africa can take place for domestic purposes, for exports (or both) and addresses the electricity, heating and cooling or transport sectors. The feedstock categories which can be used include various types of waste, as well as biomass from agriculture and forestry.

Africa as a continent corresponds to very different realities depending on the country. Bioenergy status and development perspectives must be addressed at national or regional levels, as land availability and suitability but also energy access and costs as well as food security issues vary considerably between locations. A geographic approach is essential for bioenergy in order to identify sub-continental areas sharing similar properties and problems. Such an approach can be based on agro-ecological zoning (such as Agro-Ecological Zoning, AEZ) and can result in maps (e.g. sub continental level, national and regional levels) of biomass potential taking into account the natural capital, socio-economic aspects as well as geopolitics. For West Africa, a large experience on biomass resource estimation and digital cartography production is available at ECOWREX (See ECOWAS Observatory for Renewable Energy & Energy Efficiency on sweet sorghum land suitability mapping at http://www.ecowrex.org/mapView).

With the exception of Northern African Countries, the demography in Africa is still in the transition phase: the total population is expected to pass from 1 billion in 2010 to 1.5 billion in 2030 (see UNDESA population statistics) while the situation is quite varied among countries. The population growth rate in a number of West African and Central African countries is such that the population is expected to almost double between 2010 and 2030 in the region. However, such a population growth is instead expected to slow down in Southern Africa because of the high level of prevalence of HIV/AIDS in this region. In general, the proportion of population living in urban areas is expected to increase significantly.

The demographic evolution in Africa will have a major impact on land-use requirements for crop production, as well as on the need for fuelwood, and will be associated with a possible change in consumption habits, in particular in cities. Related to the strong population growth, agricultural land is expected to reach saturation in an increased number of regions in Africa.

This can be stated even if the exact assessment of the level of pressure on land resources and competition between various possible uses is difficult, because of the insufficient level of accuracy and detail of the information about the extent of land reserves and their agronomic suitability. Currently, the agriculture is characterised by low yields and efficiencies which leave potential scope for intensification and releasing pressure on future required land resources, nevertheless such transition is linked to considerable changes in production methods and for example increased energy, fertilizer and water input.

In this respect, the water footprint of bioenergy, at the stages of biomass production or conversion, has also to be taken into account, since many parts of Africa are already experiencing water shortage with about one-third of Africa's productive area already classified as dry-land. In some cases, irrigation may be required for the production of biomass to be used for biofuels for transport or other bioenergy purposes. Even if there is often a potential for increasing irrigated surfaces and thus agricultural production, such developments are often difficult to implement in environmentally vulnerable ecosystems and would need significant investments. This is very unlikely to take place for energy purposes alone.

Currently, general trend towards deforestation takes place in many regions in Africa, therefore the creation of protected zones and areas is an important step towards securing biodiversity, maintaining valuable ecosystem services such as soil and water conservation. Forest also plys a critical role as climate regulators and carbon sequesters. Therefore, as a general rule it is recommended not to use biomass from protected zones for bioenergy purposes. Even if in some tropical forest ecosystems, some biomass quantities could be collected in a sustainable way, protected zones should be considered for their environmental role, or for the provision of ecosystem services and not for energy purposes.
In many parts of Africa, forest residues play a central role in providing household energy, often being the sole largest energy source in the country. Forest residues are to a certain extent already used as firewood in peri-urban areas, as well as to provide energy to isolated industrial plants (e.g., sawmills). In addition, there might be a potential unused resource in managed/planted forests, as well as in equatorial forests where a number of "low-value" trees need to be cut in order to access the few valuable trees available per ha. A transition towards modern household fuels could reduce pressure on those resources making them available for higher efficiency use in the industrial sector or for electricity generation.

Bioenergy developments also require investments, which are in many cases lacking in Africa. Several large bioenergy projects are starting to be developed in various parts of Africa. There is an urgent need to identify the potential sources of conflicts between domestic uses of biomass (including the use of land areas for domestic food production) and exports. Biomass production for export might bring significant improvement in rural development, job creation, local economy. On the other hand, local needs for land and biomass should be considered as well. A careful assessment of all sustainability issues should be performed (including resource conflicts and impact on social structure), especially for large projects, and in this context carbon trade and REDD could play a role to increase economic attractiveness of bioenergy development.

Nevertheless, the development of bioenergy in a given country, whether it is for domestic use or exports, needs a stable policy and socio-economic framework in order to allow the shift to multi-use agriculture or forestry at mid-term and trigger the necessary investments, both in infrastructures and research. On the contrary, several parts of Africa are presently subject to unrest due to a combination of local and international factors. This situation does not easily

allow sustainable infrastructure development in the short-term and thus limits the development of bioenergy potential, even in regions with a high level of biomass availability . The experience in Brazil with sugarcane-derived ethanol, produced at competitive prices compared to fossil energy shows that research is needed at all stages, from biomass production with species and varieties adapted to the environment, to production facilities making use of adapted, yet efficient, technologies.

The use of bioenergy in Africa should be considered simultaneously with other complementary renewable energy sources, especially solar, wind and hydro. Drawing up Renewable Energy Strategies, including Renewable Energy Action Plans, with targets according to the availability of various energy sources would contribute to the development of the renewable energy production in Africa. This will contribute to a better mobilisation of biomass resources under sustainable conditions.

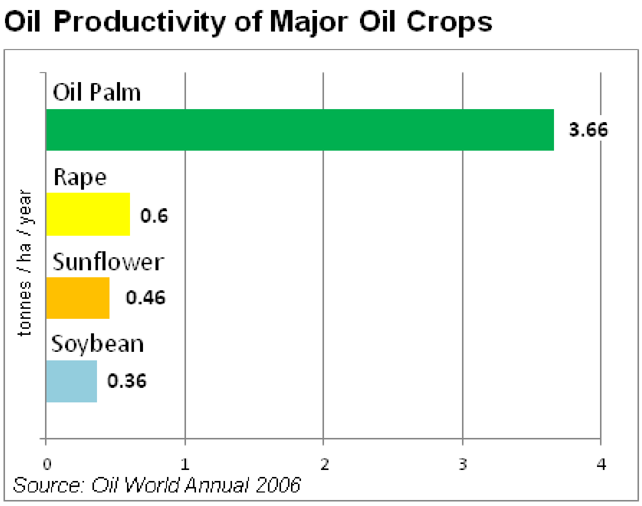
4.2. Promising bioenergy feedstock in the African context.

4.2.1. Energy from waste

In Africa, there is a huge potential, unused at this stage, available from the organic fraction of municipal waste in urban zones. Urban population increases rapidly, but efficient waste management is missing in most cities, leading to land filling or uncontrolled dumping. In the case of Africa, priority should be given to the production of clean energy from organic waste, since this biomass category is produced constantly, needs to be managed properly and is not in competition with food production. It does not require extra land or reduce the role of forests as carbon sinks. In addition to the use of organic municipal waste, there are also benefits related to the use for energy of manure or residues generated by intensive animal breeding (e.g., chicken). Waste to Energy technologies are thus an option to handle municipal waste and produce electricity while, at the same time, reducing negative environmental impacts such as the pollution of water bodies. It also reduces the health hazard of waste and the amount of fossil fuel needed (in many cases imported) for power generation.
In the case of Ghana, it was estimated (Ohene and Lohmueller), that each citizen (out of 18 million) produces 0.5 kg of solid waste every day. The fraction of biodegradable components from the solid waste was estimated at approximately 60%, with a heating value of 17MJ/kg and a moisture content of 50%. This means that 5610 tons of the organic fraction could be provided every day to produce energy for the national grid. With a power output of 1.66 MWh/ton, a total of 3320 GWh of energy could be produced annually. Waste disposal in Ghana is to a large extent performed by open dumping, since primary collection of waste from households is limited to high income communities which represent only 11% of the population, while secondary collection from transfer points to the disposal facilities is inefficient.
Waste produced in large urban areas offers a suitable energy source that can be used in the specific case of Africa. Additional data, if available from different parts of Africa, would be valuable in order to make better estimates of the waste production, since the waste production and composition might be quite different from place to place.
A more detailed analysis is presented in Appendix B.

4.2.2 Palm oil

Palm oil is being used globally mainly for food, cosmetics and industrial applications and so far only to a limited extent for bioenergy purposes. A possible future development of palm oil production driven by bioenergy has raised concern about environmental impact in Asia, Latin America and Africa. There has been a significant growth of the palm oil sector at worldwide level (All uses) in the past three decades, with the planted area of palm-tree growing from 1.55 million ha in 1980 to about 12.2 million hectares in 2009, i.e., corresponding to an eightfold increase. Simultaneously, over this 29-year period, global production has increased tenfold, from 4.5 million tons in 1980 to about 45 million tons in 2009. Palm oil was the first vegetal oil consumed at worldwide level, which was very competitive in terms of production costs, before oils from soya, rapeseed and sunflower also in terms of productivity and energy balance (see Figures 4.1 and 4.2).



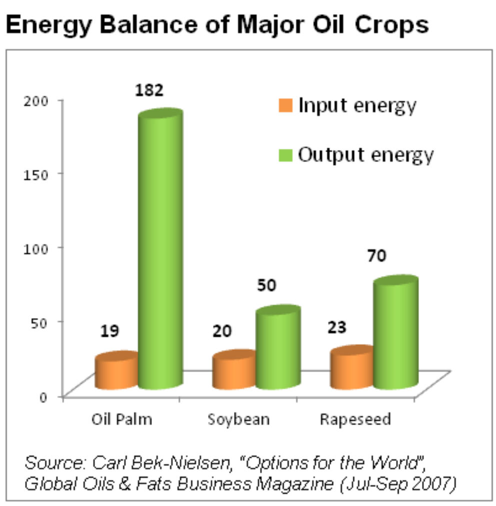


Figure 4.1 Typical oil productivity (left – tonnes/ha yr) and energy balance of the major oil crops.

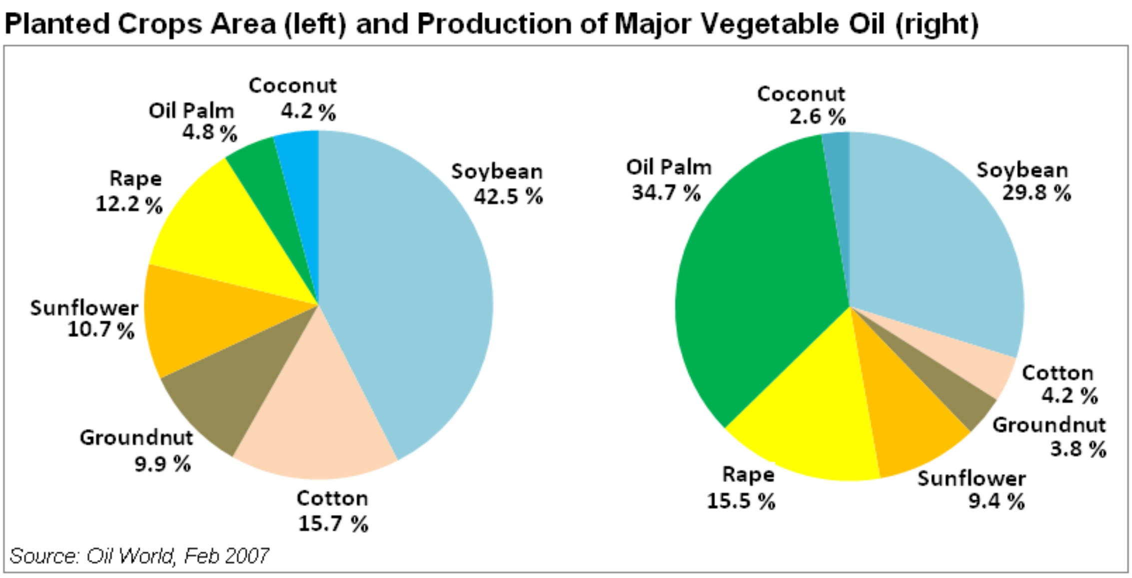


Figure 4.2 Planted crops area (left) and production of major vegetable oil (right) – world shares

Even if Africa is the place of origin of the plant Elaeis Guineensis and if palm has been used traditionally in Africa for cooking purposes, as a beverage and also for industrial applications, the evolution into an international commodity, with a wide range of food and non-food applications, took place recently mainly due to the contribution from Asia, with Malaysia and Indonesia covering about 90% of the exports.
In Africa, oil palm can be found in the tropical rainforest belt of West Africa, including Cameroon, Ivory Coast, Ghana, Liberia, Nigeria, Sierra Leone and Togo, or in the equatorial region (parts of Angola and Democratic Republic of Congo), where a strong historical experience in palm oil production and soap manufacturing is present.

Large scale projects (200000 to 300000 hectares) are now in phase of preparation, or starting the implementation, for example in Cameroon, Ghana and Gabon. Nigeria has presently about 350 000 hectares of oil palm plantations (Boyfield & Ali), but mainly associated to inefficient production methods, with about 80% of palm oil production collected from 2.3 million hectares of wild or semi-wild sources, often on not very productive land.

Africa's current average *per capita* consumption of oils and fats is presently estimated at 11 kg a year, the global average being 24 kg. There is thus a real gap between the continent's relatively low production levels of palm oil and the rising trend in consumption, even without taking into account possible bioenergy uses. Africa is presently a net importer of palm oil, independently of possible future bioenergy development.

The main challenges to be addressed regarding a possible palm oil expansion in Africa are:
- policy and regulatory environment ensuring, for example, the respect of the rights of local communities. This part of identification and possible transfer rights is sometimes extremely complex to handle, since part of the claims on land are not always based on formal land titles and there is a deficit in transparency or governance;
- sharing of economic benefits;
- ensuring sustainable private sector investment;
- codes of sustainable practice, with in the case of biofuels' implementation of sustainability certification schemes, such as the Roundtable on Sustainable Palm Oil (RSPO), the Roundtable on Sustainable Biofuels (RSB) or others.

4.2.3 Sugarcane

There is a huge interest regarding the use of sugar cane for bioenergy. Traditionally used, over centuries, for sugar production, the example of Brazil has demonstrated the possibility to use sugar cane for bioethanol at large scale and at production costs competitive against fossil fuels. Brazil is the first producing country in the world for bioethanol from sugar cane. Brazil has a long tradition in sugarcane production and already started its ethanol industry about 30 years ago, initially mainly for energy security reasons. Sugar cane provides the 4Fs (Food, Fiber, Feed and Fuel) and also generates large quantities of straw or bagasse which can be used for energy purposes.

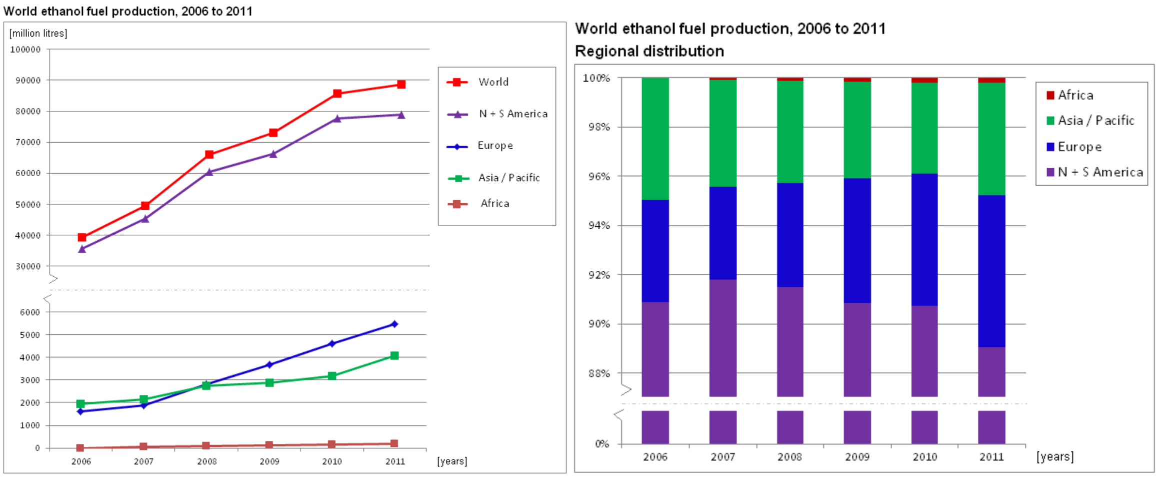
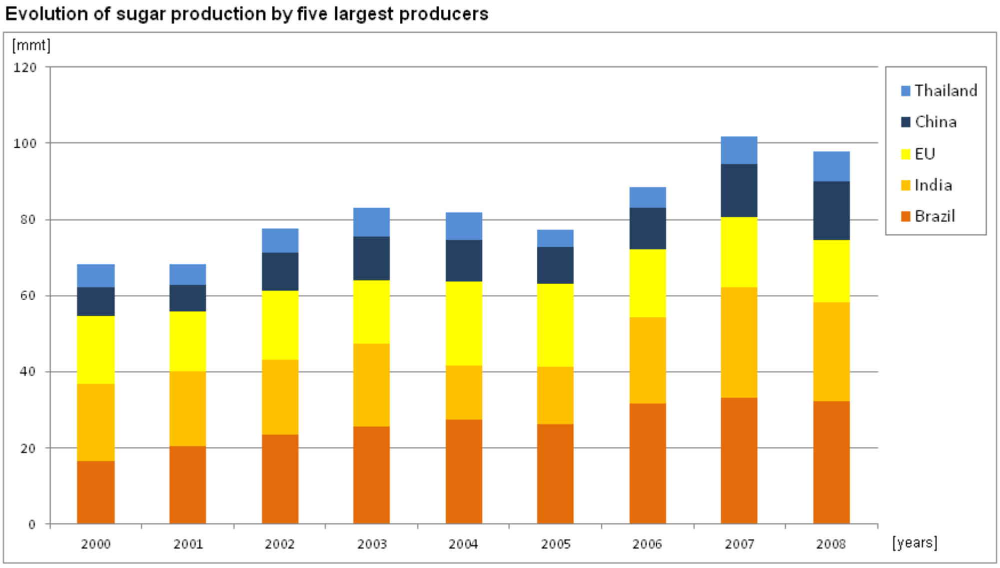


Figure 4.3 World ethanol fuel production, 2006 to 2011 (left – million litres; right – regional shares). Data source: Bioenergy for sustainable development and international competitiveness, 2012 (Eds.: F. X. Johnson, V. Seebaluck), Graphs: JRC REMEA

Figure 4.3 shows, as in Africa, that a very small share of the current world ethanol fuel production (about 0.2%) takes place in a market largely dominated by American producers. Nevertheless, production of sugar is not negligible at all in the African continent in comparison with the major production players in the world sugar market (see Figure 4.4). Moreover, under sustainable conditions, an important potential of expansion of sugar cane cultivation in some of tropical and sub-tropical regions of Sub-Saharan Africa exists, even if the estimates of land availability for sugar cane cultivation under rain-fed conditions vary. Nevertheless, it should be noted that such a development is expected to depend on several factors, including:

- output of research in breeding improved varieties,
- cultivation of sugar cane in marginal areas,
- improvement of agricultural efficiency and agricultural modernisation,
- shift from cane burning to mechanised harvesting, as in the case of Brazil, thus with improved consequences on air quality and the collection of residues,
- co-generation of electricity from bagasse,
- development of value-added products in addition to sugar,
- competitiveness of African production on global markets, related to economic policies of subsidies on oil.



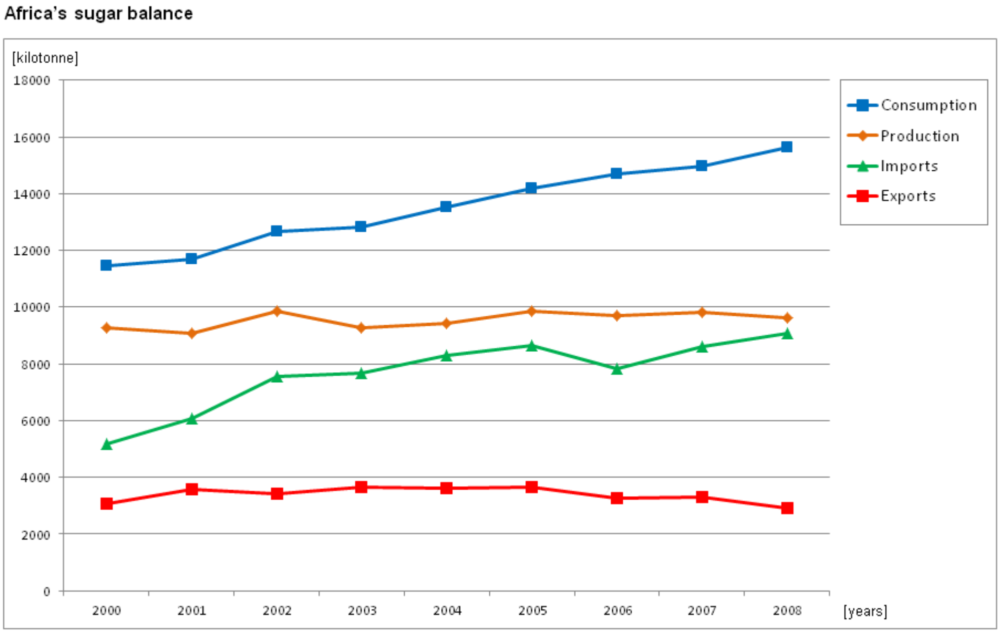


Figure 4.4 Recent evolution of sugar production in the five top producer countries/economic areas of the world (top panel) and in Africa (bottom panel). Imports, exports and consumption data are also reported for Africa. Data source: Bioenergy for sustainable development and international competitiveness, 2012 (Eds.: F. X. Johnson, V. Seebaluck), Graphs: JRC REMEA

The main drivers for market diversification from sugar, only for food to the renewable energy market, are also related to uncertainties in oil and sugar prices, land and the availability of resources, power supply conditions, environmental and economic policies. Sustainability certification schemes are also necessary to implement and several are already in the advanced phase like RSB, Bonsucro or others.

Moreover, there is the need for identification and mapping the no-go areas (primary forests, high biodiversity value areas, protected areas, high carbon stock areas) in relation with suitability areas (for oil palm and sugar cane), since these issues are especially sensitive in Africa. There is a danger of using forest areas for sugar cane cultivation as current agricultural land is used for food and cash crop production. The issue of competition for natural resources

(land, water) is also important to consider, as well as the customary rights for land. and potential conflicts.

Figure 4.5 shows estimates for land potentially suitable for rain-fed sugar cane production while Figure 4.6 and Table 4.1 show how these estimates can change once some of the previously listed constraints are applied to five test countries.

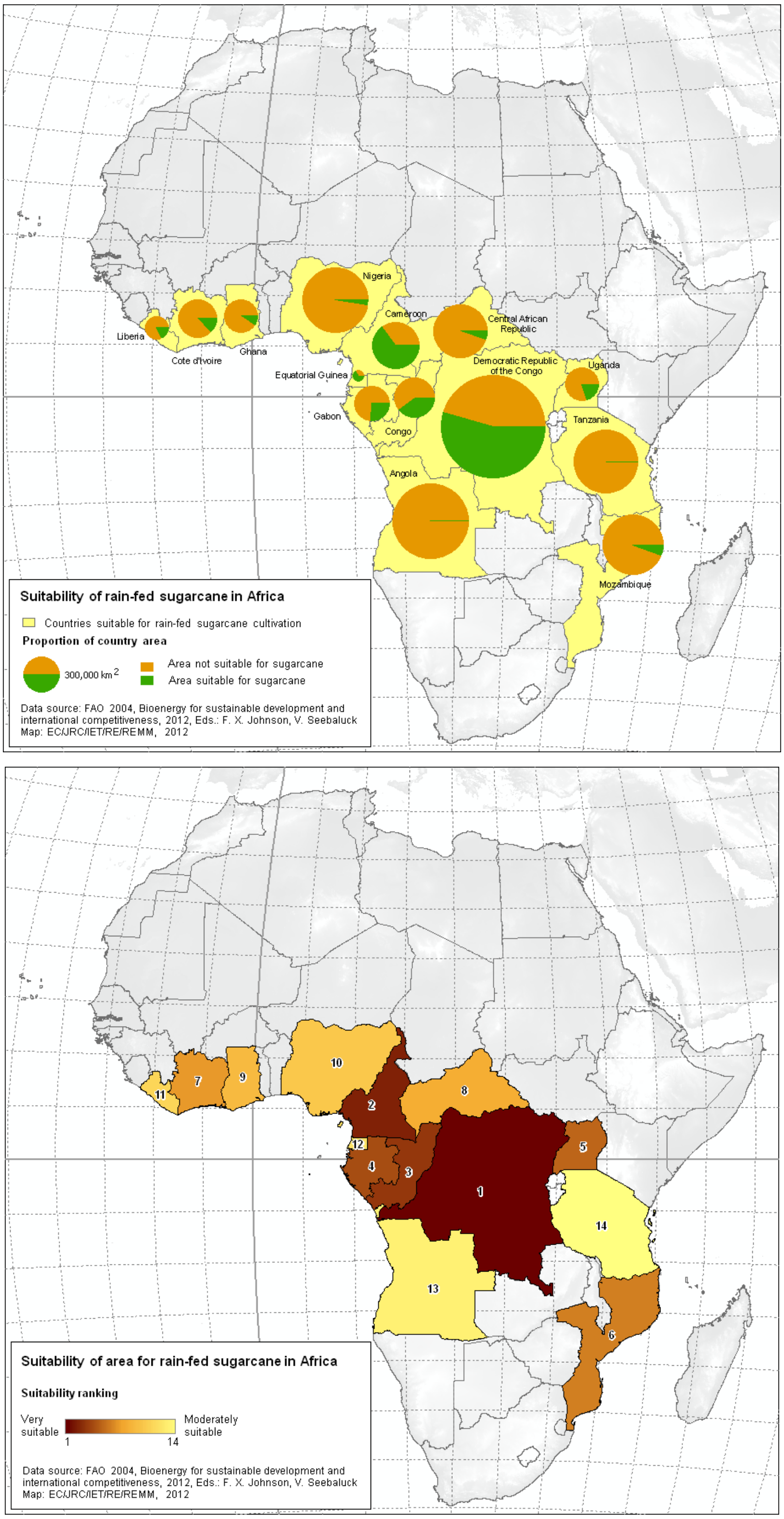


Figure 4.5. Areas very to moderately suitable for rain-fed sugar cane in Africa (left) and overall country suitability for sugar cane cultivation expansion (right) (FAO, 2004)

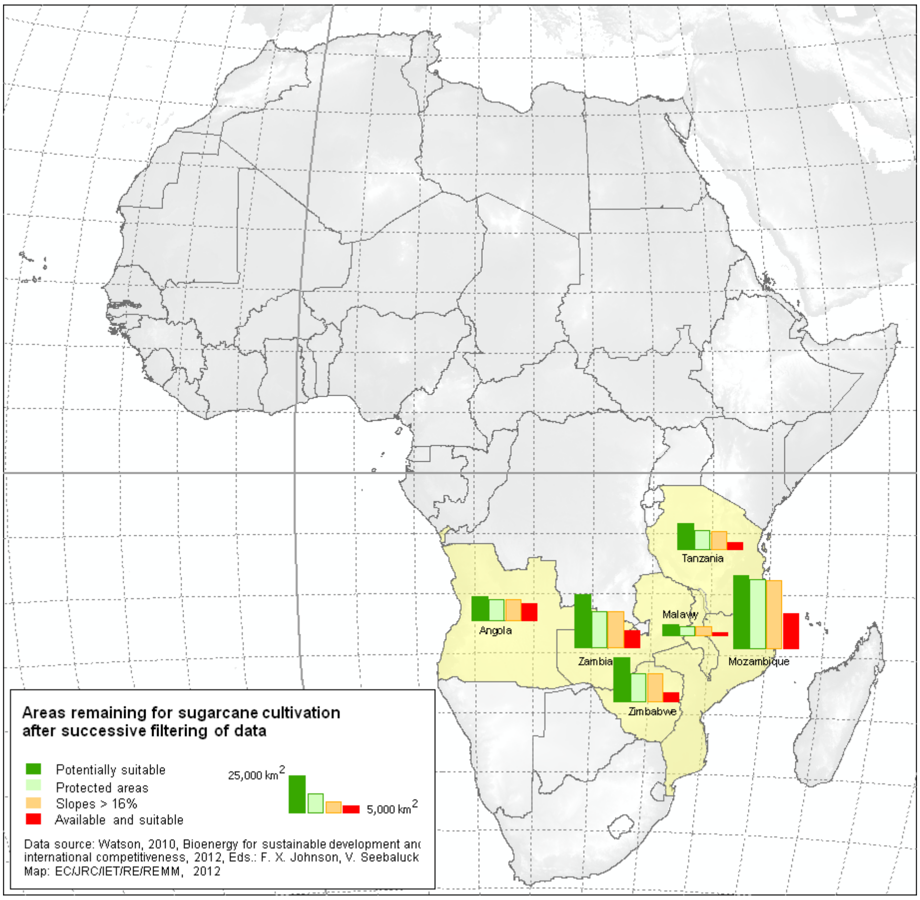


Figure 4.6. Areas remaining for sugarcane cultivation after successive data filtering in five African countries (Watson, 2010 in Bioenergy for sustainable development and international competitiveness, 2012 (Eds.: F. X. Johnson, V. Seebaluck)

Table 4.1 *Detailed analysis of the application of successive constraints to sugar cane potential in five test countries.*

	Angola	**Malawi**	**Mozambique**	**Tanzania**	**Zambia**	**Zimbabwe**
Country land area	1246700	94080	784090	878690	743390	386670
Potentially suitable	16260	7420	49060	16940	35460	29350
Protected areas	13950	5950	46020	12230	24330	18600
Slopes > 16%	13890	5800	45300	12170	24270	18550
Available and suitable	11270	2060	23380	4670	11780	6200
% of country land area potentially suitable	1.30	7.89	6.26	1.93	4.77	7.59
% of country land area available and suitable for sugarcane	0.90	2.19	2.98	0.53	1.58	1.60

Source: Watson, 2010, Note: [a] excluding Zanzibar and Pemba

4.3. Towards a sustainable bioenergy exploitation. Risk and opportunities for the continent

4.3.1 Degraded and marginal land

The production of devoted energy feedstock on degraded and marginal land is an option which allows avoiding some possible negative effects related to land use change, since these areas are considered as largely unsuitable and often economically unattractive for crop production. Perennial bioenergy production on degraded and marginal land can sequester carbon, improve soil fertility and reduce soil degradation and soil erosion processes. In addition, perennial bioenergy crops cultivated on degraded and marginal land can improve biodiversity, especially if large fields are avoided and a mixture of species planted.
Nevertheless some challenges have to be faced, for example:
- difficult growing conditions,
- social situation of poor rural communities for which degraded land is a "common use" resource, often without property title.
- lack of mechanisation/industrialization of the full bioenergy chain.

Subsistence farming and livestock farming are important parts of the social fabric in rural Africa which can be strongly affected by large scale farming transitions, even on so-called marginal land. In large areas of Africa, the areas in question are used as grazing grounds and therefore are only to be seen as marginal, especially when considering transhumance and nomadic grazing.

Even if some important R&D issues are still to be addressed (bioenergy potential of degraded and marginal lands, as well as economic balance and environmental impact), it is commonly accepted that this is a resource which, if used in a sustainable way, can give a positive contribution to rural development and access to energy.
In the case of sub Saharan Africa, for example, in semi arid and arid regions, candidate bioenergy systems can be based (Wicke, 2011) on cassava, jatropha and fuelwood (e.g., acacia). The land available for bioenergy production is estimated at 2% (1.3 Mha) of the total semi-arid and arid area in South Africa and 21% (12Mha) in Botswana, after taking into account limitations due to land use, steep slopes and biodiversity protection.

The share of available land in relation to the total area is estimated at 10.7% in Burkina Faso, 14% in Mali and 10.8% in Senegal. Nevertheless, at this stage, fuelwood, jatropha oil and cassava ethanol have production costs in most arid regions of sub Saharan Africa above average national market prices of gasoline or diesel. Even if the financial fluxes and the economic return to local level should also be taken into account, this raises the issue of public support mechanisms for renewables and also the issue of removing subsidies for diesel & petrol.

For jatropha, it is necessary to intensify the work of genetic selection and improvement for region-specific plant material before going large scale, for example using the experience from India. Presently, there is a high variability of yields and it is difficult to define an average yield (See Jongshaap et al.) or to quantify the yield according to the genetic type and climatic zone.
Moreover, bioenergy production from biosaline forestry, for example with acacia, is also an option to be considered for salt-affected soils (83 Mha in West Africa and 56 Mha in East Africa out of 831 Mha worldwide according to FAO). This would allow benefits such as an improvement of soil conditions, an income from previously low productive or unproductive land and an increased soil carbon sequestration.

4.3.2 Land acquisition from outside Africa

Biofuels and bioenergy are sometimes criticised as a source of additional pressure on African land resources. There is presently an increase of land acquisition by various non-African public and private partners for both; crop production as well as for bioenergy (see Cotula et al.).
The 2012 Land Matrix Project (http://landportal.info/landmatrix) provides a data base of large-scale land deals for agriculture in Africa and other continents, defined as the Global South. This project allows a realistic assessment of transnational farmland acquisitions by covering, since 2000, transactions which involve 200 ha or more. Even if the global land rush is still ongoing, it appears that it has slowed down after a peak in 2009 and it involves a large number of target countries associated to very different investment conditions, actors and investment drivers.

Regardless of the complexity and the several delicate implications of this phenomenon, there is a deficit of transparency on land governance issues, more specifically regarding planning and decision-making processes, contractual agreements, community involvement and compensation.

In any case, Africa is the most targeted region with 754 land deals covering 56.2 million ha, compared to 17.7 ha in Asia and 7 million ha in Latin America. Reported land deals in Africa during the period of the study correspond to an area equivalent to 4.8% of Africa's total agricultural area, mainly in Eastern Africa, followed by Western Africa.

The majority of the reported acquisitions is concentrated in a few countries, with 70% of the reported targeted surface in 11 countries. From these 11 countries, 7 are African: Sudan, Ethiopia, Mozambique, Tanzania, Madagascar, Zambia and Democratic Republic of Congo. According to Land Matrix data, food production corresponds to 34% of investments, non-food crops 26%, flax crops 23% and multiple uses 17%. The flax crops include soybean, sugarcane and oil palm of special interest for biofuels. The importance of flax crops and multiple uses category makes it difficult to quantify the real split between food and non-food production of the acquired land and, on the other side, it also shows the importance of flexibility for investors to address market risks and price volatility. Export markets are the target of most projects.

4.3.3 Fuelwood and cook stove improvement

There has been strong pressure in African ecosystems during the last decades. According to Brink and Eva (2009), there has been a 57% increase in agriculture area at the expense of natural vegetation, which has itself decreased by 21% over the period 1975-2000, with nearly five million hectares forest and non-forest natural vegetation lost per year. This study is based on the assessment of changes in four broad land cover changes (forest, natural non-forest vegetation, agriculture and barren) by using high spatial resolution Earth observation satellites, with stratified random sampling techniques at 1% sampling rate.

The main driving force for agricultural expansion would appear to be the population increase, reported to nearly double over the 1970-2000 period from under 250 million (rural population estimated at 196 million) to over 570 million (rural population estimated at 371 million). Thus

the average amount of agricultural land per head of rural population fell by 20% from 1.09 ha to 0.91 ha, even if in certain zones the situation is far more dramatic.

The decreased natural forest areas have in turn resulted in an increased scarcity of fuelwood, and called for a more sustainable use of this resource. Additionally, the negative impacts on health through indoor pollution have led to the understanding that the use of improved stoves has become a necessity in many situations. This resulted in a large number of countries having started Improved Cook Stove (ICS) programmes since the 1980s.

These programmes are at an operational stage and count on the support of various players, such as development agencies, governments, NGOs, as well as from the private sector. Different technologies can be used, such as, for example, direct combustion, small-scale gasification, small-scale anaerobic digestion, direct use of a liquid fuel (ethanol), or a combination of these technologies. This can result in a noticeable improvement of the combustion efficiency compared to alternative open fires. The cost of the stoves ranges from less than 10 US$ for the simpler models to more than 100 US$ for more sophisticated equipment and 100 to 300 US$ for institutional stoves for collective use, for example, targeting schools and hospitals (2007-2009 data). Fuel savings range from 30 to 60% in real conditions to more than 90%, with measurements in pilot testing of the most advanced models. A significant reduction in GHG emissions and indoor pollutants is also associated to this technological shift: it was estimated (see Bioenergy in IPCC Special Report on Renewable Energy Sources and Climate change Mitigation, 2011) that by 2008, 820 Million people in the world (i.e., around 30% of the 2.7 Billion people which rely on traditional biomass for cooking) were using improved cook stoves for cooking, with more than 160 stove programmes in place worldwide.

The UN Foundation-led Global Alliance for clean cook stoves started in 2010 to promote the dissemination and adoption of advanced cook stoves with the aim of reaching 100 million stoves by 2010. The two main lines of technology development that have been followed are mass scale production with some companies producing more than 100 000 stoves per year, or developing regional capacity and local employment, with stoves built on site.

The main factors pushing for the adoption of improved cooking stoves are considered to be:

- cooking conditions where users feel smoke is a health problem and annoyance,
- short consumer pay-back time, for example of a few months,
- donor or government support over a period of at least five years,
- financial support to local institutions and to the development of local expertise, with in some cases a role for public institutions in technical advice and quality control.

Among the barriers identified, there is a need for more R&D (for example on equipment evolution after years of use or small-scale gasification), customisation and field testing, product specification and certification.

Data, as robust and detailed as possible, are needed on the present use of fuelwood and other biomass sources, in order to quantify the benefits from the dissemination of improved biomass cook stoves.

In the medium to long term, improved traditional cook stoves could be seen as a transitional step towards modern energy services based on electricity and clean gas. The available wood resources would in such a scenario be used under highly improved efficiencies in large scale applications in the industry or for electricity production.

4.3.4 Irrigation in agriculture

With the increase of population and the need to develop agricultural production, the future development of agricultural-based bioenergy will be to a certain extent related to the capacity of Africa to increase its currently very low crop yields. One of the possible options to increase crop production is, for example, through the improvement of current irrigation schemes or the development of new irrigation schemes. The perspectives are different for the forestry-based bioenergy or the waste-to-energy sectors which are less dependent, or even independent from irrigation.

According to Faurès *et al.* (2010), in 1998, irrigation at worldwide level was covering 272 Mha, i.e., about 18% of cultivated land. In Africa, only 12.5 Million ha were irrigated, out of a total of 202 Mha of cultivated land, i.e., 6.2%. In the case of Sub Saharan Africa, this proportion is even more reduced, since only 5.2 Mha were irrigated, which corresponds to only 3.3 % of the cultivated land. Nevertheless, irrigation plays a key role for agricultural production and food security. It is estimated that the 18% of irrigated land provides 40% of the world agricultural production. Especially in Africa, irrigation can be an important part of the solution to increase agricultural yields as many regions suffer from strong inter and intra annual changes in precipitation. Sound water management and irrigation can help in these areas to reach higher stable and predictable yields and may also lead to less vulnerability to extreme weather events such as draughts and flooding.

At African continental level, about 85% of water use is related to agriculture, but with strong regional variation. As expected, arid zones, where irrigation plays an important role withdraw more for agriculture while on the other hand, regions with more rainfall such as the countries of the Gulf of Guinea have a lower rate of use in agriculture (62% or 43% in Central Africa). In this latter case, it corresponds to the same percentage as the urban use.

UN FAO is now the main reference for data on irrigation with national statistics on the extent of irrigated areas in FAOSTAT and AQUASTAT databases. At country level, or in existing studies, some statistics refer to areas actually irrigated in a specific year, irrigable area (which could be potentially equipped with irrigation tools) or to harvested irrigated crop area (two or more harvests per year).

There are differences in the irrigation methods used, for example, irrigation *stricto sensu*, flood management, equipment of low wetlands. In the 1990s, five countries (Egypt, Sudan, South Africa, Morocco and Madagascar), corresponding to 19% of the total area of Africa, had more than 60% of land with water control, while 28 countries corresponding to 30% of the continent area had only 5% of the total of the irrigated land.

For the future, the potential of irrigation was estimated by Faurès et al. (2010) taking into account land quality, water resources and economic aspects at 42.5 Mha at continental level, i.e., more than three times the size of the irrigated area of reference. Despite high uncertainties, it appears that seven countries (Angola, Sudan, Egypt, RD Congo, Ethiopia, Mozambique and Nigeria) correspond to 60 % of this potential.

Irrigation is used mainly for rice, but also for other cereals, such as wheat and corn, in Egypt, Morocco, Sudan and Somalia. Sorghum is cultivated with flood management techniques in the Sudano-Sahelian zone. Vegetable cultivation is present in most regions or countries and is estimated at 8% of irrigated acreage. Tree cultivation corresponds to 5% of the total and is

mainly concentrated in the Northern countries (citrus trees). Depending on the region, cotton and sugar cane are also important irrigated crops.

In addition to the extent of the equipped area, an important point to be considered is the rate of use of the perimeters equipped for irrigation. For the future, the costs of initial investment necessary are also a key factor, ranging from a few hundreds US$ for small-scale vegetable family production to about 25.000 US$ per ha for large perimeters in some parts of the Sudano-Sahelian region. Such costs are much larger than the costs in Asia for similar hydro equipment in agriculture. This is thus a problem for investments in large-scale irrigation in Africa, due to possible problems of cost effectiveness, while small-scale private irrigation is sometimes less costly and more productive. In West Africa, since the 1980s there has been an increase in the deficit in the production of cereals in the region, with only 63% of the rice consumption produced in the region in 1995.

According to FAO (2000), in its analysis of the perspectives of agriculture at the horizon 2015-2030, irrigated zones are not expected to increase significantly, but the rate of intensification is expected to grow substantially, due to an increased demand of agricultural products. This general framework in relation to irrigation in agriculture will affect possibilities of bioenergy development in Africa, whether considering energy crops, multi-use agriculture (e.g. from sugar cane, oil palm, rice and other cereals, cotton….) or the mobilisation of crop residues. Specific perspectives for biofuels have been discussed by FAO in 2008.

4.3.5 Protected zones

The Figure 4.7 shows the protected areas in Africa.

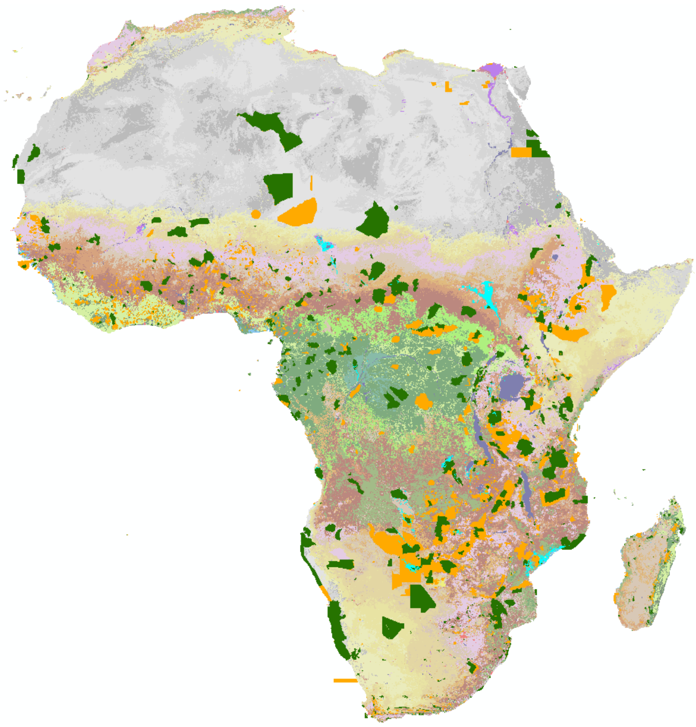


Figure 4.7 Protected Areas in Africa (Dark green = Highly Protected Areas), Source: JRC-IES

The future development of bioenergy in Africa is generally assessed taking into account two conditions:

- high rate of biomass sustainability certification, at least for export-oriented bioenergy;
- need to maintain the protection of natural areas presently under protection schemes.

In order to protect the huge biodiversity richness of the African continent, a network of protected areas has been continuously developing since 1925, the date of the creation of the Kruger National Park in South Africa. The current coverage of areas with the most protective conditions (i.e. the National Parks and the Wildlife Reserves) is 164 Million hectares (in dark green on the map), or 5.6% of the land, while an additional area of 80 million ha for less strictly protected areas (like game reserves, in orange on the map). But this overall figure hides national differences and also differences from one ecosystem to the other. About 8% of the humid rainforests, and of the shrublands, are under a strict protection status, while only 4% of the deserts are protected.

In the frame of Convention of the Biological Diversity of Nagoya (2010), the CBD parties decided to set up a new target of 17% of the land covered by terrestrial protected areas. The rationale behind this decision is the provision by protected areas of very important ecosystem services in terms of regulation of the climate, water cycle or long-term provision of goods such as medicines, pollination… that improve the overall management of natural resources at local, regional and global scale. This increase of the protected surfaces will prevent in these areas the development of bioenergy crops or the biomass mobilisation.

4.4. Climate change and bioenergy in Africa: facts and uncertainties

Geographical distribution of biomass is mainly controlled by climate (Woodward, 1987) and climate changes imply change in vegetation patterns which will follow quite closely. In turn, changes in spatial distribution and composition of terrestrial vegetation end up in a feedback altering the climate through modifications of heat and water fluxes, atmospheric gas and aerosol composition.
The main interaction pathways involve long-term photosynthesis effects on the CO_2 concentration, the vegetation control of ground to atmosphere water flux through stomata, physical water interception of runoff by vegetation canopies and the effect on albedo and many others. (Brovkin, 2012)

In other terms, biomass, and bioenergy, in consequence, is an intrinsically complex system (as described in previous sections) interacting with the climate. The detailed climate-biosphere integrated models allowing a deep understanding of these relations are being developed in the main research climate institutions, but are mostly still far from reaching a level of analysis detailed enough for guiding practical exploitation policies.

For this reason, it is extremely difficult at this stage to give a complete overview of the current situation and possible scenarios regarding the future evolution of bioenergy in Africa on the basis of results of climate models, especially considering that several relevant parameters are not included in the most common scenario elaborations such as, e.g., the forecast of demographic data, even if reasonably reliable. Even worse are some other crucial parameters, like the already mentioned figures on available land for agriculture and/or the production of bioenergy, which are still quite far from being reliable at the current stage.

4.4.1 Climate versus non- climate impacts for next decades

Taking a long term perspective and limiting to the broad view allowed by the current development models, climate change and global warming are expected to affect agricultural and non-agricultural biomass production in the African region through several both direct and indirect pressures.

Following (Conway, 2009) some possible likely trends for the next 100 years could be identified:

- drier subtropical regions will warm more than the moister tropics,
- Northern and Southern Africa will become much hotter (as much as 4 °C or more) and drier (precipitation falling by 15% or more),
- wheat production in the north and maize production in the south might then be affected in a negative way,
- sea levels to rise, perhaps by half a metre, in the next 50 years with serious consequences in the Nile Delta and certain parts of West Africa,
- Incidence and severity of droughts, floods and other extreme events is expected to increase.

Results presented in Chapter 1 (see especially Figures 1.2 and 1.3 and the seasonal analysis in Appendix A) confirm whether these expected long-term trends will become evident even in the very next decades, starting with temperature increase followed by a slower but noticeable change in precipitation patterns.
It has to be noted, however, that not all changes are necessarily going to imply a negative impact on bioenergy. As an example, the visual comparison of Figures 1.3 and 4.5 shows how the countries, already considered suitable for rain-fed sugar cane cultivation, are not going to see this suitability eroded by a decreasing rain availability. Moreover, if Figure 5.7 on expected runoff evolution is compared with the land irrigation situation described in Section 4.3.4, it can be seen how future water availability is not always expected to represent an increasingly limiting factor, especially in the western equatorial belt.

Nevertheless, biomass use as a modern and efficient source of bioenergy is extremely limited at the present stage. As a consequence, at short-term and mid-term (i.e. a few decades) and taking into account the uncertainty previously discussed, we retain that the impact of climate change on bioenergy development in Africa is expected to play a relatively small role when compared with:
- the impact of national and international policies (in the field of energy, agriculture, rural development) to support biomass resource mobilisation in all the three main biomass categories (waste, agriculture and forest),
- the possible agriculture modernisation leading to yield improvement.
Setting the right incentives and policies in place can thus bring large benefits through the use of bioenergy on the African continent.

4.5. Assessing wood availability in future climate. A modelling approach

Being aware of the complexity of the bioenergy sector depicted in the previous sections, a quantitative analysis of one of the issues described in the previous sections, namely fuelwood consumption and its impact on biomass availability are presented in this section.

4.5.1. Climatic parameters and life-zone

In principle, changes in climate variables, forecasted by models, are expected to induce a pressure to the natural environment that could end up in a changed pattern of natural biomass density and availability.

A possible approach, linking climate features with biomass classes, was developed in (Holdridge, 1947), where three key climatic variables are identified to be:
- Mean annual precipitation (*P*)
- Mean annual biotemperature[5] (*B*)
- Ratio of mean annual Potential EvapoTranspiration[6] to mean annual precipitation (*PETR*)

The value of these three variables in a certain point define the local life-zone, as described in Figure 4.8

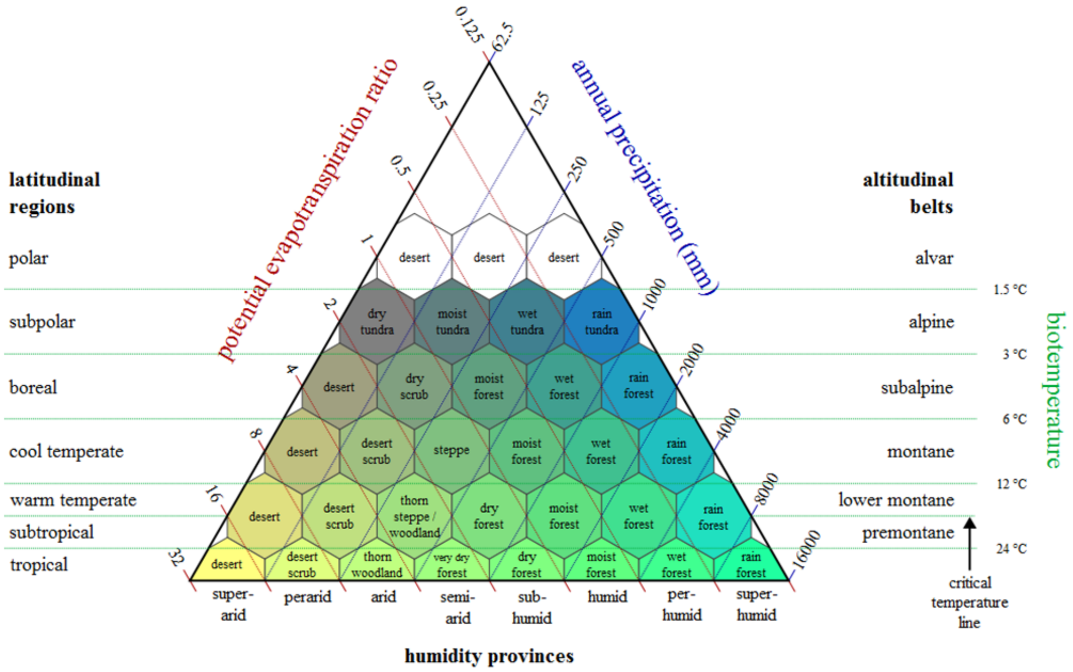


Figure 4.8 . Holdridge’s life-zones as a function of the climatic variables P (precipitation), B (biotemperature) and PETR (potential evapotranspiration ratio) (Holdridge, 1947)

On the basis of this analysis, a relationship between the local elevation, the cited climatic variables and the local production of biomass can be assumed.

In the present study such a relation was supposed to have the following quantitative form:

$$\log(C) = \frac{a}{PETR} + bB + c\log(P) + \log(H) \qquad \text{Eq. (1)}$$

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[5] Biotemperature is the annually averaged temperature after replacing all temperatures below the freezing point with zero values, assuming that plants are dormant at lower temperatures.
[6] PET is obtained from the Thorntwaite equation (Thorntwaite, 1948)

where *C* is the amount of biomass per hectare, and *H* is the elevation, and *P,B* and *PETR* have been already defined.

4.5.2. Climatic pressure on biomass (2000-2080)

Equation (1) contains the three parameters a, b and c that have to be fixed on the basis of available current biomass density data and current climate by means of a multiple regression procedure. For this goal, biomass density data were obtained from the reference map of current forest carbon stocks in tropical regions developed by (Saatchi *et al.*, 2011) and shown in Figure 4.9. The maximum carbon stock from Saatchi *et al* (2011) was also used as an upper limit to the modelled biomass in the regression model.

In order to correctly train the regression model ideally only areas where the land-cover is natural should be used. As a practical solution for this, the carbon stock values from inside the protected areas were selected, assuming that these areas have been less affected by deforestation of different types.

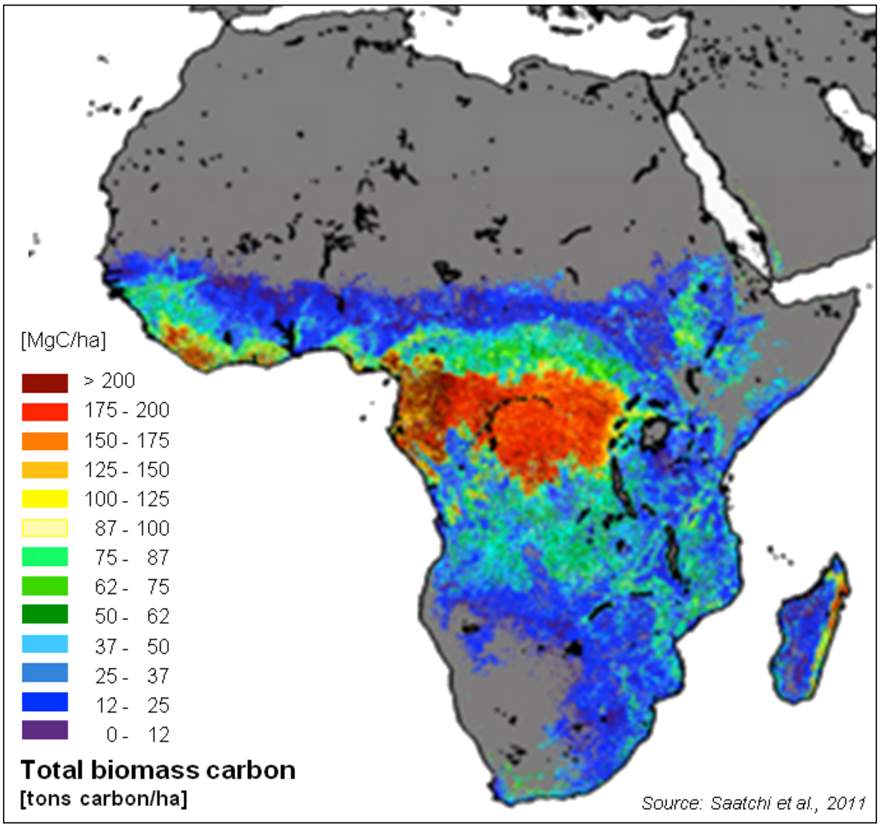

Figure 4.9. Reference map of current forest carbon stocks in tropical regions (Saatchi *et al.*, 2011). Units are MgC/ha or tons carbon/ha.

Current values of the climatic variables *P,B* and *PETR* were obtained from the WorldClim data base. (Hijmans et al., 2005). This data base provides gridded maps of current and future climate variables at different lat-long resolutions, i.e., 10 minutes, 5 minutes, 2.5 minutes and 30 seconds. The 30 sec grid corresponds to cells of 0.86 km^2 at the Equator, often referred to as the 1 km grid map. The data set for the current climate (average of period 1950-2000) has been produced by interpolating the records from climate stations with a spline interpolation method.

The results of the regression are shown in Figure 4.10, both as a scatter plot and in a map format.

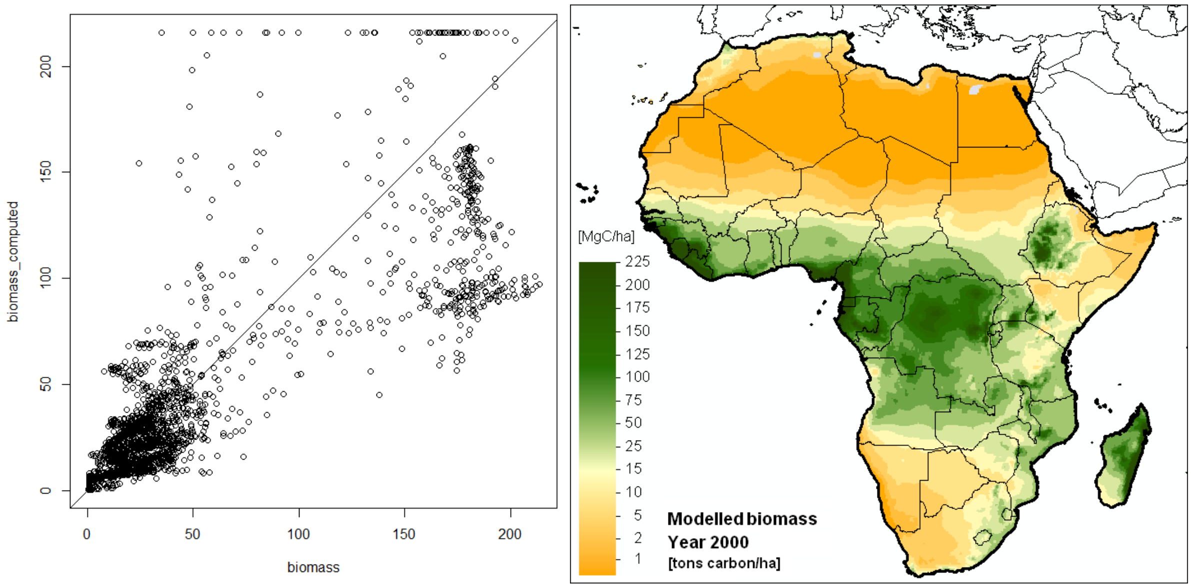

Figure 4.10. Left panel: Scatter plot of biomass from the Saatchi (horizontal axis) vs. computed biomass (vertical axis). Right panel: estimated potential biomass from the regression model. Units are MgC/ha or tons carbon/ha.

Although the regression approach provides the best-fit parameters for Equation (1), the scatter plot in Figure 4.10 shows an underestimation of biomass for densely forested areas, also visible when comparing the two maps in Figures 4.9 and 4.10. Nevertheless, an area in Ethiopia where biomass is most likely overestimated is also visible.

Applying the trained regression model to forecasts of future climatic data, the future potential biomass for Africa for different climate scenarios can be estimated. Future climate data were again obtained from the WorldClim data base, where the forecast data set for different climate scenarios of different global circulation models has been downscaled to the same resolutions of the current climate data base, assuming that the spatial patterns within each grid cell is constant (Ramirez and Jarvis, 2010).

Future biomass estimations obtained in this way are expected to have a bias pattern similar to the ones found for the current climate shown in Figure 4.10, so instead of using the predicted biomass from these maps, the predicted percent changes were subtracted from or added to the estimate of the current biomass. In this way, the effect of the pure climate change on the biomass stock could be captured.

The result will of course differ for different scenarios. In this preliminary report we include the average results from the three models HADCM3, CSIRO and CCCMA for the A2a scenario (often referred to as business as usual-emissions). The biomass is forecast for the years 2030 (interpolated from the years 2020 and 2050), 2050 and 2080 and the results are shown in Figure 4.11

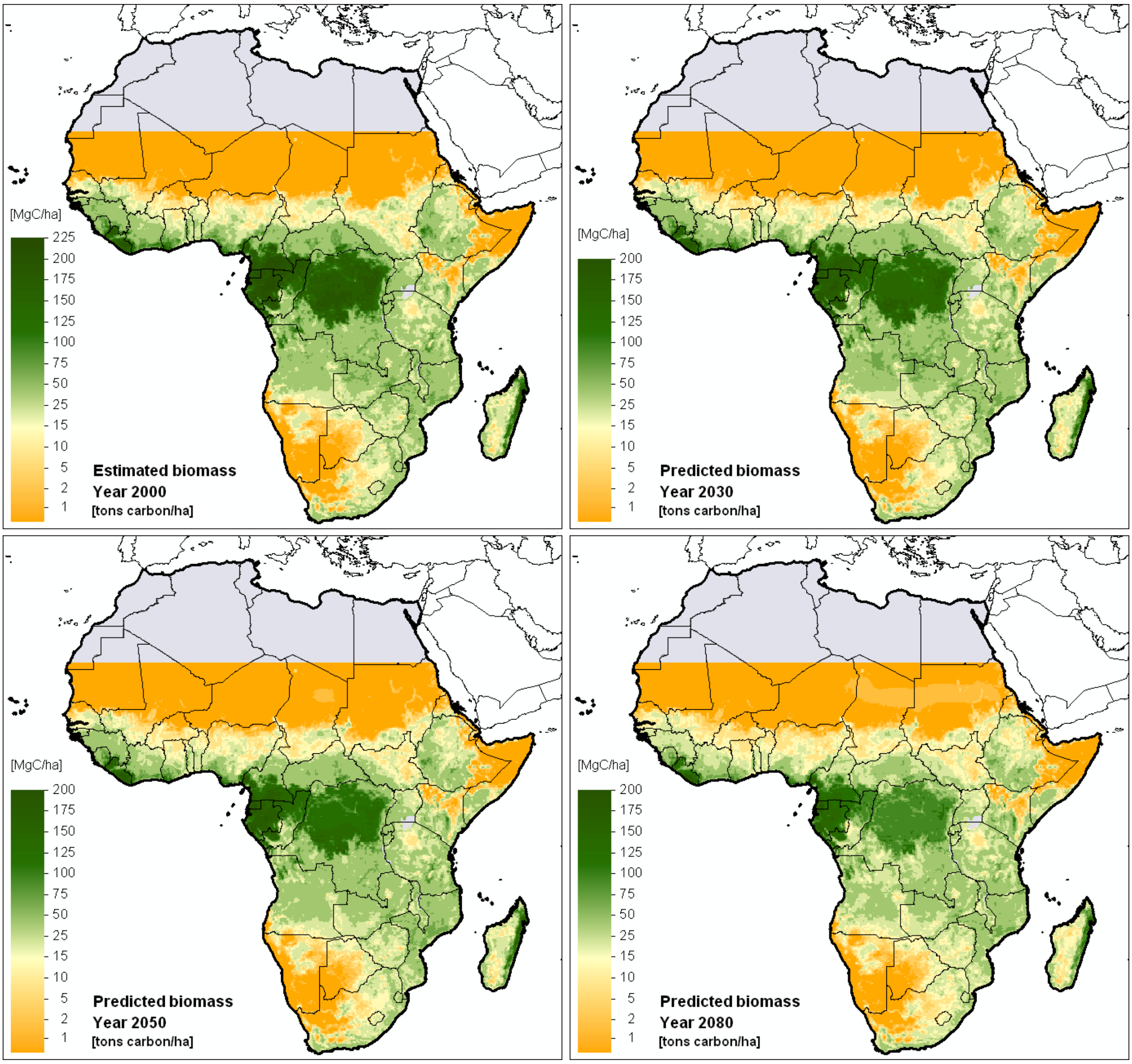

Figure 4.11 Estimated biomass stocks in the years 2000 (top left), 2030 (top right), 2050 (bottom left) and 2080 (bottom right). Data are provided in tons of carbon/ha

The statistical significance of changes shown in Figure 4.11 for biomass stocks with this model will depend on two factors:

- The variance between the different climate forecasts (CCCMA, CSIRO and HADCM3)
- The variance from the regression model.

The two errors were assumed to be uncorrelated, and their joint variance has been computed as the sum of the two variances. Assuming a simple normal distribution and drawing a few samples, the significance of the results could then be estimated. Figure 4.12 shows maps of changes in biomass stocks that are estimated to be statistically significant ($p < 0.05$) for the three forecast years.

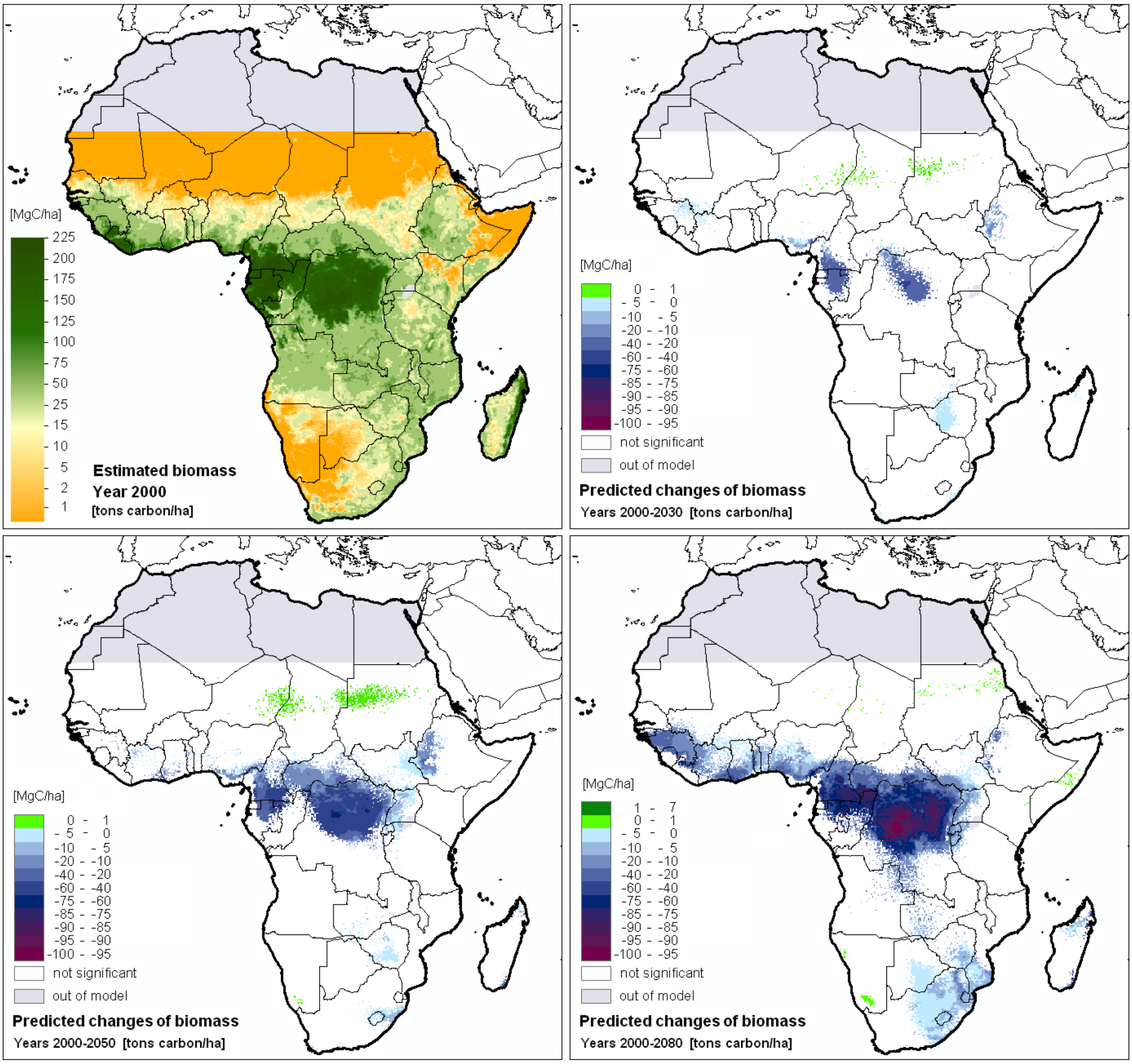

Figure 4.12 Estimated biomass stocks in 2000 (top left), and its estimated change in 2020 (top right), 2050 (bottom left) and 2080 (bottom right). Data are provided in tons of carbon/ha and are shown only for statistically significant values ($p < 0.05$).

Figure 4.12 clearly shows how in 2030 the predicted changes are mainly significant for the rain forest in Central Africa and some other areas in Eastern and Southern Africa, while the area of significant changes increases considerably in 2050 and 2080.

Moreover, Figure 4.12 shows a relatively strong decrease in biomass. Nevertheless it has to be clearly stated that the method for computing the availability of biomass described here is highly simplified. Its most important limitation is that it does not take into account the increase of bio-accessible CO_2 in the atmosphere. This increasing availability of carbon dioxide will most likely act as a fertiliser and will ultimately lead to an increase of biomass, which might counteract some, or all, of the negative growth shown in Figure 4.12. On the other hand, the reduction of land available for biomass was not taken into account, which will further reduce the potential. In paragraph 4.5.4 a more detailed discussion of these and other missing effects will be provided.

4.5.3. Fuelwood consumption

Data from FAO (FaoStat 2012) for historic consumption of fuelwood for the period 1965-2010 were coupled with UN data on population (UNDESA, 2012) to give the *per capita* consumption of fuelwood. Data show that while the total fuelwood consumption has been increasing, the *per capita* consumption has decreased in most countries. An example for some countries is shown in Figure 4.13 (black lines).
The *per capita* consumption of fuelwood can also be fitted to a regression model with population with years as the predictor, even if the results can be expected to have a relatively high uncertainty, as many of the annual reports on fuel consumption are most likely erroneous.

Therefore several different regression models were tested:

1) A) Linear regression (can give extremely high consumption for countries which for some reason have an increasing trend currently, or a negative consumption in the future)
   B) Linear regression with the relative decrease for Africa for each country
   C) Constant consumption.

2) A) Exponential regression
   B) Exponential regression, constant consumption countries (future) with apparent increasing consumption (past data, 1965-2010)
   C) Exponential regression, relative decrease for Africa (future) for countries with apparent increasing consumption (past data, 1965-2010).

Observed values from FAO are plotted together with the regression models for a few example countries in Figure 4.13. Observations and regression models for all countries are in the Appendix. It is relatively easy to model the observations for some countries, whereas it is more challenging for other countries. In the examples below, we can see that the fuelwood consumption of Ethiopia is well modelled with all regressions except for constant consumption. For Gabon it is not clear which one is best. The observations from Ghana indicate that there has been a strong increase in the *per capita* consumption, which will lead to extremely high forecast fuelwood consumption if we use regression models 1A or 2A directly. For Guinea, the linear regression models reach zero in 2050. Considering these effects, we have chosen to use regression model 2C in the further analyses, as this is a model with an exponential decay, and where we assume that increases like the observations from Ghana are likely to be reporting errors or a temporal increase. We do not have information that can confirm this assumption at the moment.

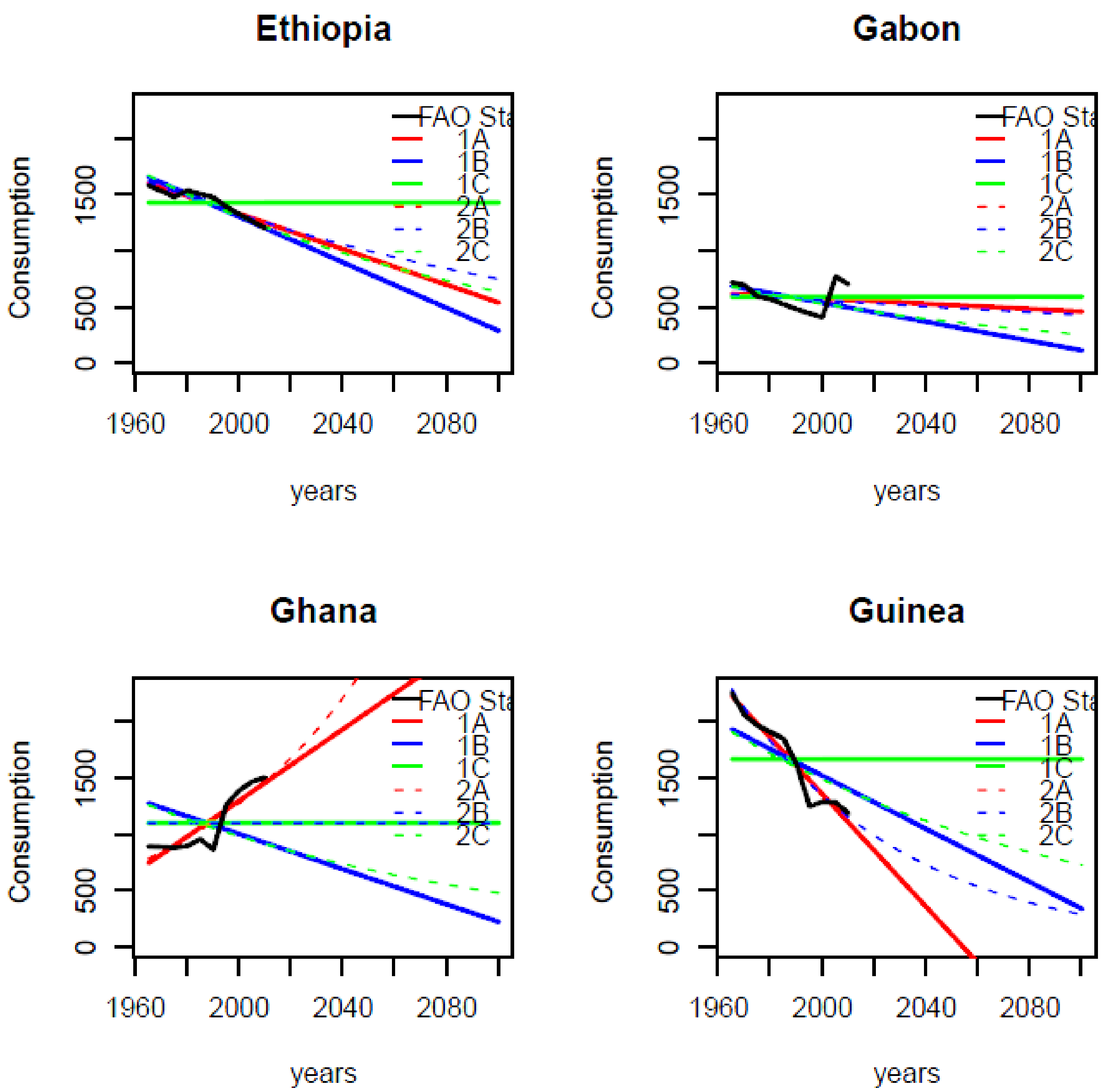

Figure 4.13. Annual per capita consumption of fuelwood in some African countries (m^3/1000 inhabitants ~ kg/inhabitant), observations in black, other lines represent different regression forecasts (see text for details).

Figure 4.14 shows the projections on fuelwood consumption up to 2080 for the countries with the highest estimated consumption, using the 2C) regression model when UN medium population forecast (UNDESA 2012) is employed. We can see that there will be a considerable increase in the fuelwood consumption even with the relatively conservative assumptions taken here (Use of 2C model previously described and medium population forecast). The model indicates an increase in fuelwood consumption for most countries in this period.

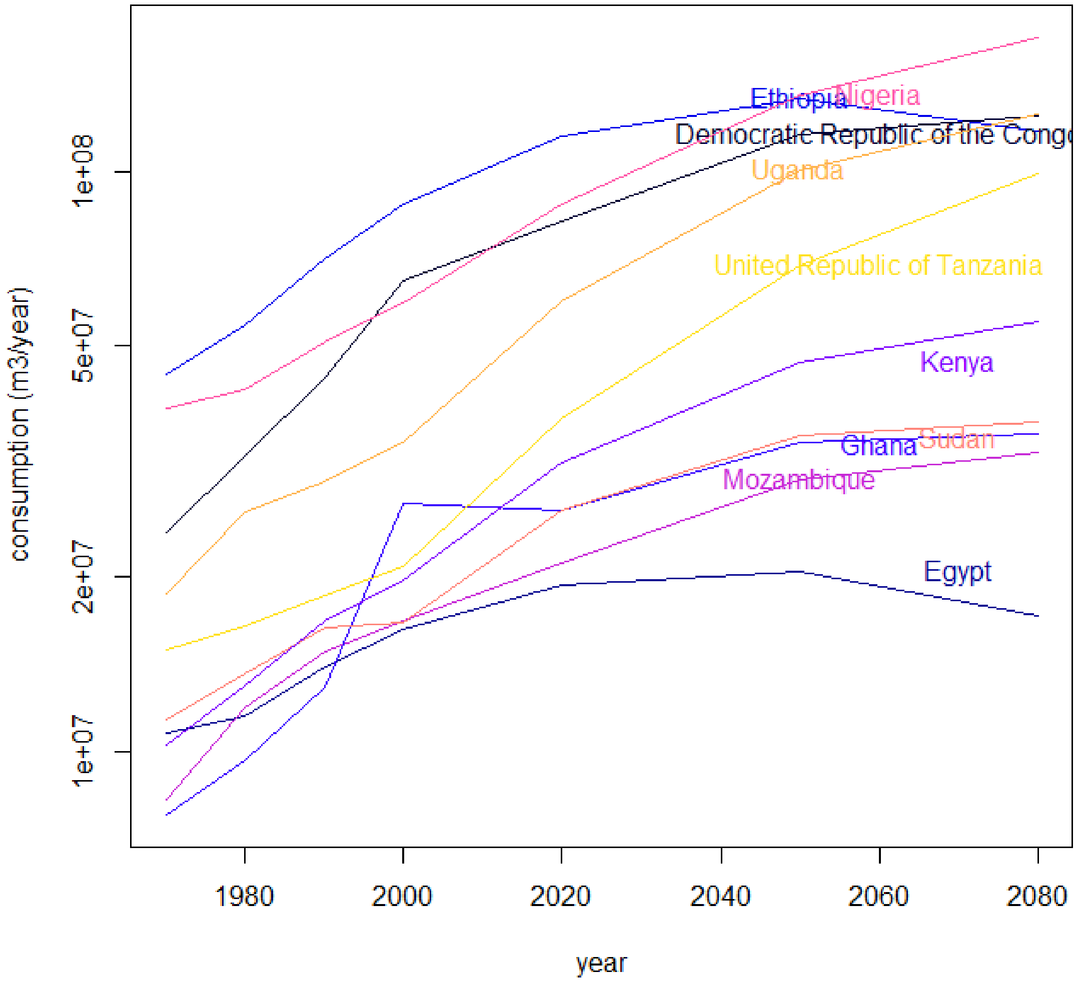

Figure 4.14. Estimated and forecasted fuelwood consumption (m^3/year)for some African countries up to year 2080. (1e+07 = 10 million)

The forecasted fuelwood consumption data shown in Figure 4.14 are year specific (not cumulative) and can be put in relation with the potential biomass for each country as the ratio between the potential biomass and the annual fuelwood consumption. This indicator can be referred to as the depletion time, i.e., the time before all biomass is consumed if there were to be no regrowth, and it is presented on a country basis in Figure 4.15.

This number can again be related to the typical source of biomass in a country, such that a depletion time of 50-100 years, where much of the biomass is bushes, is likely to be sustainable, whereas the same depletion time in a country with more slow growing rain forest and moist forest cannot be seen as sustainable, but the fact that the regrowth time depends also on the use of the soils following the forest cut (e.g., if the soils are successively used for pasture or agriculture) and on the age of the forest cut must also be considered.
Broadly speaking, a depletion time below 20-50 years could be surely considered a threat to the biomass resources, while a depletion time above 200 years is not likely to put the overall stock at risk, while the consequences of intermediate values depend on the local biomass features of each country. The depletion time is rather low also for some small countries (e.g., Lesotho, Swaziland), but the sustainability is most likely not a problem, as much of the fuelwood can be, and probably already is, imported from South Africa.

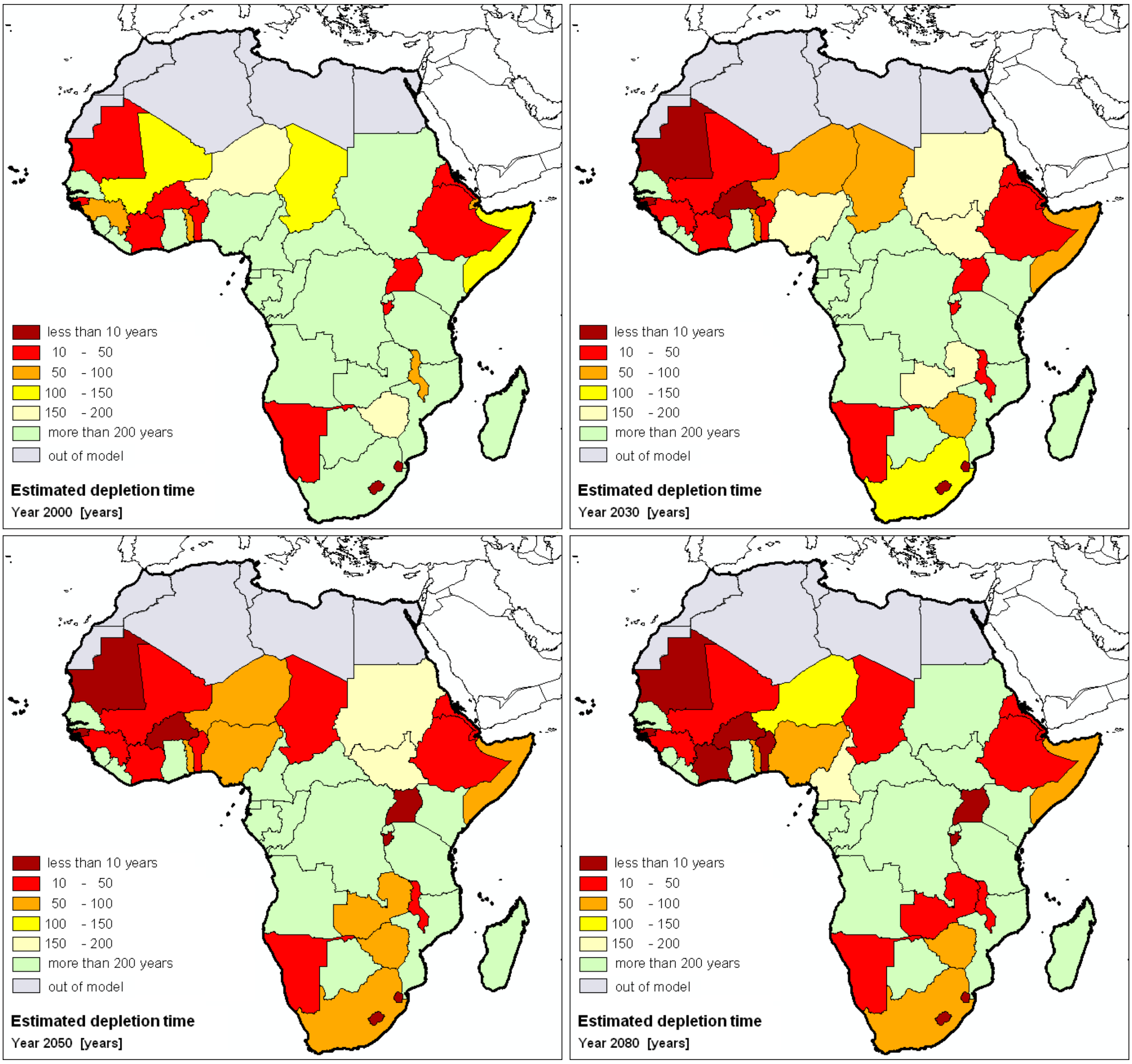

Figure 4.15. Categories of Estimated Depletion Time (years) of biomass resources in Sub-Saharan Africa in 2000 (top right), 2030 (top left), 2050 (bottom left) and 2080 (bottom right). Depletion time here is computed as the ratio between available biomass (see Figure 4.10) and fuelwood consumption and is estimated without taking into account regrowth (see Figure 4.13).

Figure 4.15 shows also that the depletion time is expected to decrease, moving from 2000 to 2080 estimations, because of the combination of an increased wood consumption, following population evolution (see Figure 4.14) and a decrease in biomass availability caused by the changed climate conditions (see Figure 4.12). So, even if in 2000 in several countries the depletion time can be seen as sustainable, or not posing an immediate threat, picture changes in future scenarios, with several countries (like e.g., Zambia) moving from a relatively safe position to a more dangerous one.

The rate at which the depletion time decreases can be very impressive. Figure 4.16 shows the "acceleration"[7] of biomass depletion in 2030 (top right), 2050 (bottom left) and 2080 (bottom right) as forecasted by the model: in front of very few countries where depletion is expected to slightly slowing down in the next decades (e.g., Mozambique and Sierra Leone) in most of the countries the biomass depletion is expected to become faster, with several countries having a depletion time in 2080 even five to ten times shorter than in 2000 and then a resource depletion five to ten times faster. The analysis of this indicator shows that there are countries like e.g., Congo-Brazzaville where biomass exploitation is expected to remain sustainable according to data shown in Figure 4.15, in which nevertheless the biomass depletion is expected to accelerate up to ten times in the next decades, potentially putting even this country in a risky situation in a longer term.

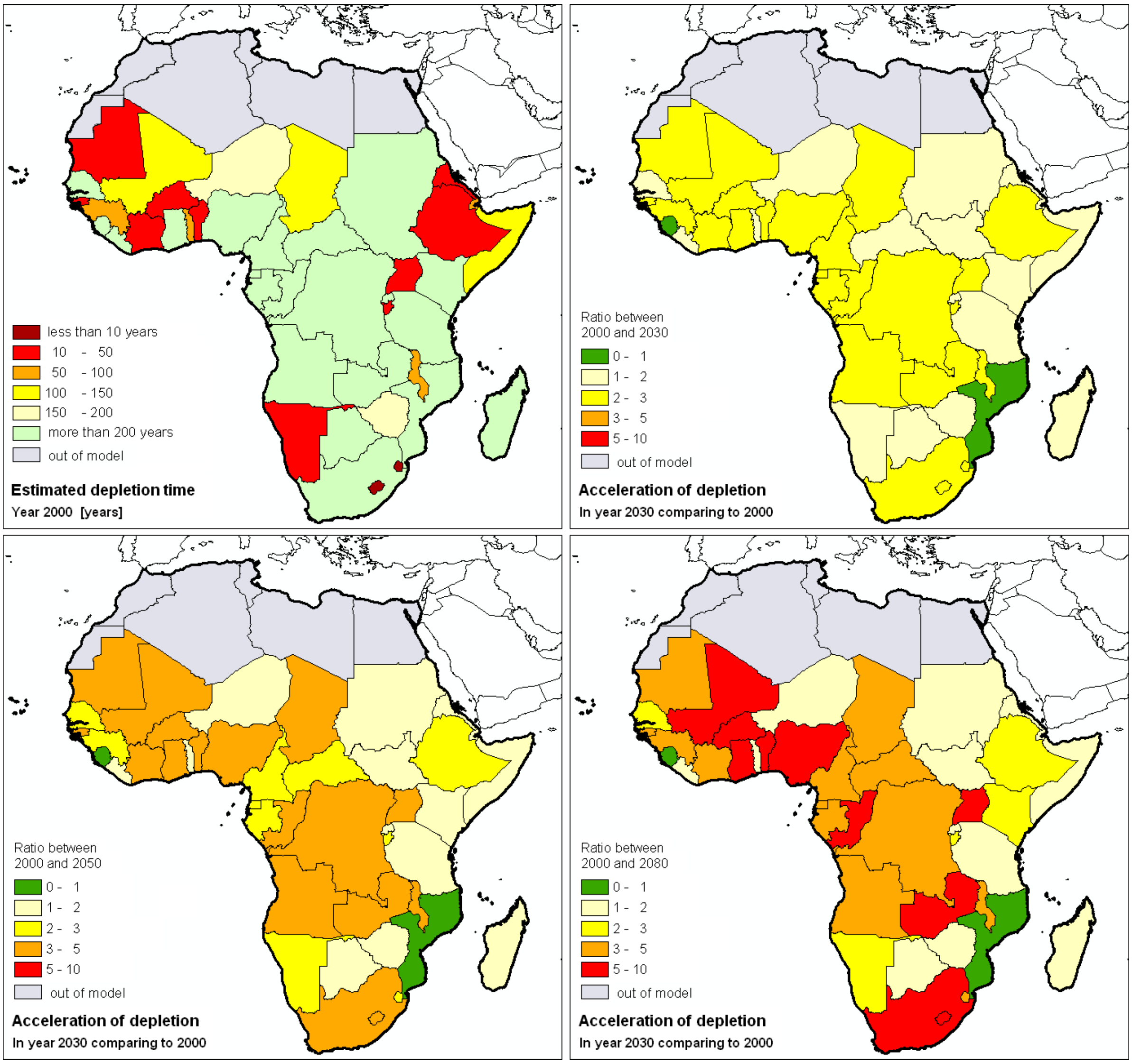

Figure 4.16. Top left: estimated depletion time (years) of biomass resources in Sub-Saharan Africa in the year 2000. Other panels: ratio between estimated depletion times: 2000 over 2030 (top right), 2000 over 2050 (bottom left) and 2000 over 2080 (bottom right). Values higher than one imply accelerating biomass depletion.

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[7] Depletion acceleration is defined here as the depletion time in 2000 divided by the depletion time in a given year. A value of acceleration larger than one implies that in the given year the depletion time is shorter than in 2000 and then depletion is faster.

Finally, it has to be noted that values shown in Figures 4.15 and 4.16 are country averages: whereas biomass collection is an essentially local phenomenon, strongly linked with the distribution of rural population. Local variations in biomass depletion time are expected to be very strong, and strategies for biomass protection (e.g., identification of protected areas) could be locally necessary also in countries where the overall national depletion rate is not particularly worrying.

4.5.4 Conclusions

A fairly simple method has been applied to evaluate the sustainability of current and future fuelwood consumption in Africa, using regression models to forecast the potential biomass, based on climate change and the fuelwood consumption based on population forecasts. The method indicates that fuelwood consumption might be less sustainable in the future than it is today.

There is a range of weaknesses in the methodology presented in this report that is likely to influence the final result. These are mentioned below, together with a short discussion of their expected magnitude and possible effect.

- Not taking increased CO_2 into account. This is likely to increase the potential biomass, which will again increase the depletion times. Our method indicates that the forest biomass will be reduced by about 30% due to climate change, whereas other studies suggest that the biomass will rather increase by up to 100% (Scheiter and Higgins, 2009). Much of this increase of biomass due to increased CO_2 is supposed to take place from the conversion of grasslands to savannah and from savannah to deciduous woodlands, and is therefore not spatially homogeneous.
- Error in biomass regression equation for the rainforest. The equation did not perform well for the rainforest, but it is not obvious what effect this will have on the depletion times.
- Error in forecasts of fuelwood consumption. We have estimated that the fuelwood consumption will almost double in the period 1990-2030, whereas FAO has predicted this increase to be around 50%, according to Mead (Mead 2005). Reduced fuelwood consumption will increase depletion times. The cited paper does not give the assumptions behind their estimates.
- The analyses have been done with forest biomass and do not include bushes, which is likely to be a major contribution to the biomass in some areas. This will most likely increase depletion time.
- Land cover change is not taken into account. Most countries will in the future contain less biomass, as forested areas are urbanised or converted into agricultural areas. This will reduce depletion times. On the other hand it is also possible that more dedicated fuelwood plantations will produce faster growing biomass, which will increase depletion time for the natural forest.

Further studies will be necessary to estimate the overall effect of these methodological weaknesses, although it can be assumed that the CO_2 error will dominate, and there are also other uncertainties that are more likely to increase depletion time than to reduce it. Our estimates can in that case be seen as worst-case scenarios.

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5 Expected changes in hydropower resources

K. Bódis, S. Szabó

This chapter gives a quick overview on the role of hydropower in electricity generation in the continent, exploited hydro power resources and estimates on technically and economically feasible potentials. Climate and socioeconomic changes should be taken equally into account, predicting the future theoretical potentials. The geographical distribution of permanent and non-permanent river network in Africa, the physical availability of hydro power resources and estimates on economically viable mini-hydro resources for rural electrification were described in the previous report on renewable energy in Africa (JRC, 2011). In the current study, a continent-wide estimation of climate change impact on hydro-power resources was performed, based on variables that describe hydrological characteristics, and which resulted by using the global ECHAM-HAM aerosol-climate model (Stier *et al*., 2005), detailed in Chapter 1.

5.1 Background

Compared to other developing countries, the level of access to electricity in Africa is very low, despite the continent's rich resources. However, the middle of the African continent has a particularly favourable hydro-geographic situation for hydropower development, due to adequate water resources, both perennial and non-perennial, over 90% of rural population relies on other energy resources (e.g., traditional biomass for cooking and heating, candles and kerosene for lighting). Among other renewable energy sources hydropower has a huge potential to provide energy services which need to be utilised for socio-economic development (FAO, 2008). While hydropower accounts for about 16% of global electricity generation, and over 90% of electricity from renewable sources (IEA, 2010), potentials are very poorly exploited in Africa (Figure 5.1).

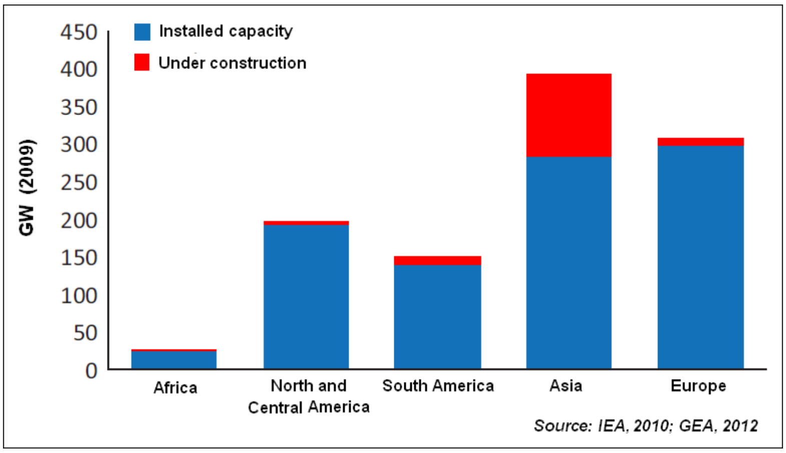

Figure 5.1 Global hydropower capacity in 2009. Source: GEA, 2012

5.2 Hydropower potentials

Assessment methods on hydropower potentials for electricity production give estimates on different levels, i.e. gross theoretical potential, technically feasible potential, unexploited economic potential and potential used at present (GEA, 2012). Africa has about 10% of the world's theoretical hydropower potential (FAO, 2008; GEA, 2012), most of which is located

in the sub-Saharan part of the continent (Klunne, 2011), but currently uses only a fraction of this potential. Africa's gross theoretical hydropower potential is estimated at 4 000 000 GWh/year, and the current production of hydropower in Africa is only about 20% of the total potential (FAO, 2008). The technically feasible hydropower potential of Africa is around 1,750 TWh, which is about 12% of the global technically feasible capacity. Only 5% of this technically feasible potential is exploited (UNIDO, 2009; FAO, 2011). The continental distribution of the estimated, technically feasible potential is showed in Figure 5.2.

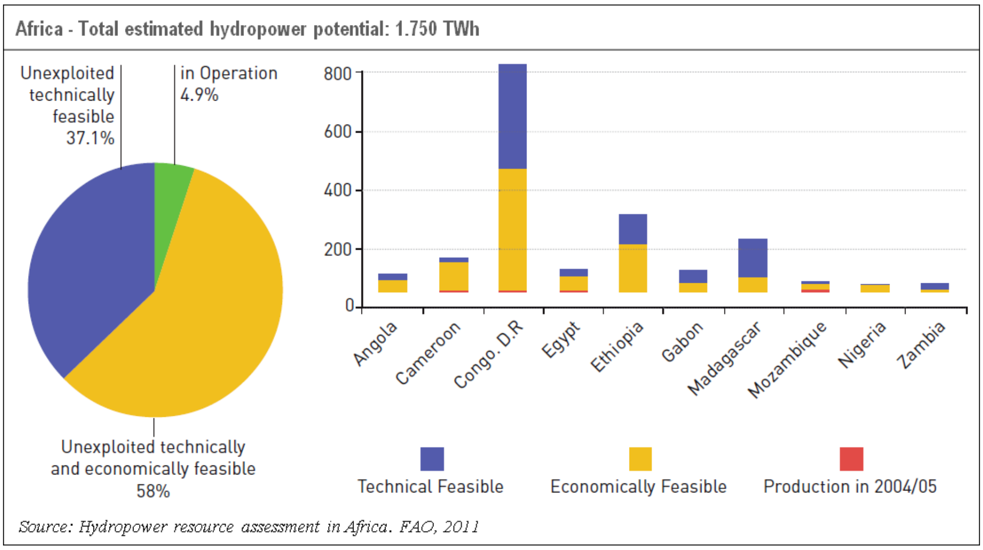

Figure 5.2 Estimated hydropower potential in Africa

Figure 5.3 shows the contribution of hydropower to net electricity generation in the case of the larger producers. Hydropower projects can be classified by applied generating methods. However, there were no statistical data available on hydropower production, differentiating among different technologies.

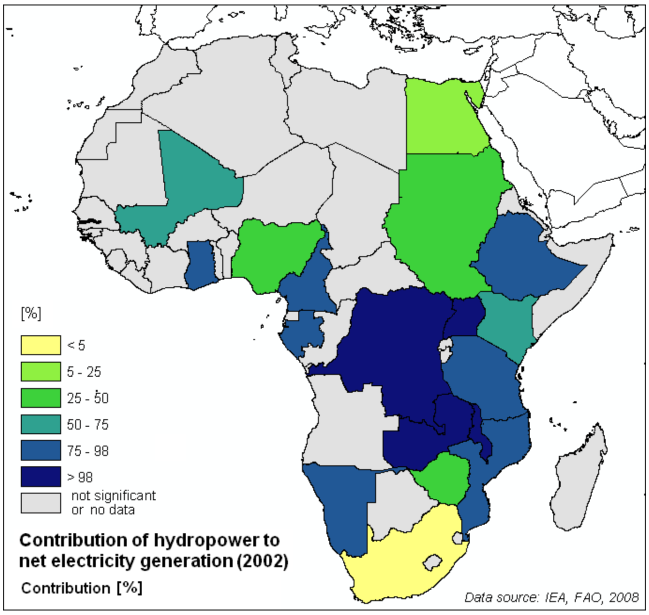

Figure 5.3 Contribution of hydropower to net electricity generation

Run-of-river projects generate electricity according to the available hydrological fluctuations of the site. Reservoir-type projects involve damming water and creating reservoirs with

significant storage capacity, which allows for the regulation of water flow and electricity production (GEA, 2012). Efficiency of both technologies may be exposed to changing hydro-meteorological circumstances driven by changing climate. Classification of hydropower plants can also be done by generating capacity.

5.2.1 Large hydropower

Large-scale hydropower plants can provide more than 100 MW and usually feeding into a major electricity grid. In Africa, the total installed capacity is 21 000 MW, 90% of which is concentrated in eight countries. The Democratic Republic of the Congo has the highest technically and economically feasible potential, followed by Ethiopia and Madagascar, then Egypt, Gabon, Nigeria, Zambia and Mozambique. Countries with installed capacity of more than 1 000 MW have a total installed capacity of about 13 GW, comprising 65% of the total hydropower installed capacity of Africa. The remaining 45 countries account for 35% of the total installed hydro capacity (FAO, 2008). Besides the undoubtful contribution of large hydropower to net electricity generation in Africa, there are uncertainties in the use of large-scale projects which still leave the local population "in the dark".

An example is the 40 GW Grand Inga hydropower project on the Congo River, under an agreement between the Democratic Republic of the Congo and South Africa. It will be the world's largest installation by a wide margin (96 m drop, mean discharge of 42,476 m^3/s) and shall increase Africa's electricity generating capacity by one-third; the plans include a 205 m-high dam, 15 km-long reservoir and a plant with a capacity to produce 320 terawatt hours of electricity annually. Nevertheless, some analysts say that like many big-push style projects in the developing world, the local people will probably get little of the electricity produced by the Grand Inga (expected to begin operating between 2020 and 2025). Instead, the power transmission lines are expected to privilege the electricity use for mining and industrial facilities, the big cities in South Africa and Egypt, as well as possibly being exported to Europe (BBC, 2008; Palitza, 2011), because of the well known problem of the questionable return of investments of the grid extension solution for rural electrification (see also the discussion of this topic in Chapter 2).

5.2.2 Small hydropower

Small hydro is the development of hydroelectric power on a scale serving a smaller, local community, or industrial activity. The definition of a small hydro project varies, but the usual generating capacity does not exceed 10 MW. Harnessing the optimal hydrographical characteristics of the affluent rivers of the continent, the focus in many African countries has been on large-scale hydropower projects for decades. Recent studies have shown that small hydropower (SHP) plays an important role in the African rural renewable energy market; the local electricity generation, using small hydropower, is advancing due to its shorter realisation period, lower investment and environmental impacts (Paish, 2002; Mtalo, 2005; FAO, 2008; Omojolaa and Oladejib, 2012). Studies on electrification strategies claim that local renewable energy production and small off-grid systems provide a better solution for rural Africa – where up to 92% of the population lives without electricity – than the national grid model (e.g., Klunne, 2009, 2010; Szabó *et al.*, 2011).

Africa has one of the lowest contribution (about 0.5%) to global SHP installed capacity, less than 240 MW comparing to the global app. 48 000 MW SHP total (FAO, 2011). In the case of some countries, theoretically rich in hydropower resources, the actual figures indicate that

only 1% is exploited of the SHP potentials. Figure 5.4 shows the country-based distribution of installed generation capacity in both scales.

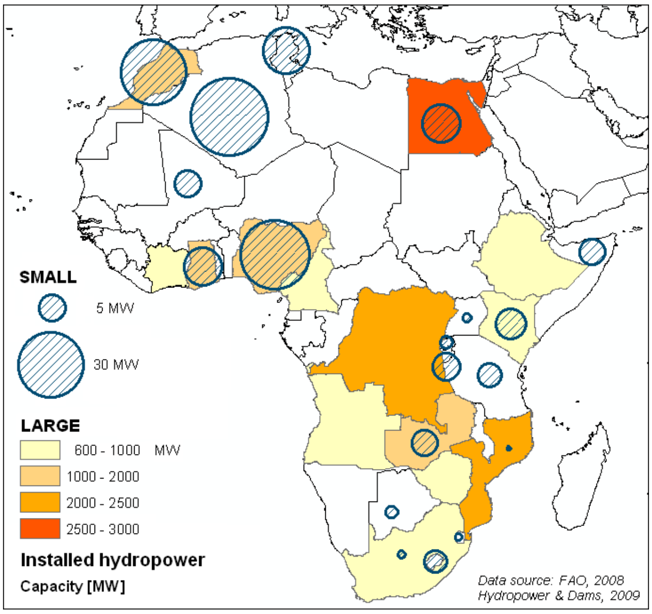

Figure 5.4 Capacity of installed large and small hydropower by countries

5.2.3 Barriers to the development of SHP in Africa

According to several studies the main, current obstacles to hydropower in Africa could be grouped into the following categories:

a) Financing, policy and regulatory background: lack of funds and regulations governing the development. Customers' willingness and ability to pay for energy services is still an important factor to be determined (Moner-Girona, 2009; Klunne, 2010; Szabó *et al.*, 2011).
b) Infrastructural and knowledge-based background in the design and manufacture of turbines and other components, site installation and operation employing local technical assistance.
c) Technological challenges: lack of access to appropriate technologies (small head, high river discharge / high head, low discharge) in the mini, micro and pico hydro categories (Klunne, 2010).
d) Missing essential information on potential locations, lack of high resolution hydrological data and hydro-geographical descriptions, difficulties of site measurements (FAO, 2008).

The listed hindering circumstances did not consider impacts due to estimates on changing climate.

5.3 Hydropower and climate change

The interrelationship between electricity generation using hydropower and the phenomena of changing climate can be investigated from two directions. Theoretically, electricity production using hydro-energy does not lead directly to the emission of greenhouse gases and therefore does not contribute significantly to global warming (FAO, 2008). The options with the lowest emissions are run-of-river hydropower (1-3 kt eq. CO2/TWh), wind power and nuclear (Gagnon, 2003; FAO, 2008). Hydropower, with reservoir, has a slightly higher

emission rate (10-15 kt eq. CO2/TWh), because the construction of dams (e.g., blasting, excavation, displacement of material, cement manufacturing, transport, etc.), depending on their type and size, emits significant amounts of greenhouse gases (Svensson, 2005). The impact assessment of climate change on hydropower potentials is a challenging problem. A model-based analysis of possible effects of global change on Europe's hydropower potential indicates severe future alterations in discharge regimes, leading to unstable regional trends in hydropower potentials (Lehner *et al*., 2005). A significant (25% or more) decrease and increase could equally be expected, depending on the geographical location and the current climatic zones.

5.3.1 Analysing the hydropower potential of Africa

Research on long-term African climate change indicates that the climate of Africa is warmer than it was 100 years ago, and model-based predictions of future greenhouse gas-induced climate change for the continent suggest that this warming will continue (Hulme *et al.*, 2001). A warming climate will place stresses also on water resources, whether or not future rainfall is significantly altered (Hulme *et al.*, 2001). Scenarios and modelled variations in temperature and precipitation are described in Chapter 1.

Natural components of hydropower generation are the kinetic energy of falling or flowing water and the volume of water that can be used for energy generation. The gross hydropower potential (GP) can be defined as $GP = m \times g \times h$; where m is the mass of runoff; g is the gravitational acceleration and h is the height (e.g., the elevation above sea level, the head of turbine). Supposing that the main morphological characteristics of water courses are not changing, the differences in the mass of runoff give an estimate about the change in hydropower potential.

5.3.2 Data preparation

Two variables of the climate model (Roeckner *et al.*, 2003) called "drainage"[8] and "surface runoff[9] and drainage"[10] and were further processed in order to estimate changes in water resources. After data format conversions, monthly averages were calculated from each realisation (60 for 2000 and 30 for 2030), in each of the three model-runs (IAT6, IAT8, EUCAARI). Statistical significance has been defined on a monthly basis using Student's t-test (two-tailed, unequal sample sizes, unequal variance). Changes in monthly average surface runoff and drainage ($kg \times m^{-2} \times s^{-1}$) between the 2000 scenarios (IAT6) and the 2030 (IAT8, EUCAARI) scenarios are presented in the Annex. Additional GIS datasets, such as administrative borders, water drainage network and water basins (Lehner *et al.*, 2006; Bódis, 2009) were integrated and involved into the spatial analysis.

[8] Drainage is the removal of excess surface or sub-surface water. It is usually measured in [$kg \times m^{-2} \times s^{-1}$] or given in millimetre per year.
[9] Surface runoff is water, from rain, snowmelt, or other sources, that flows over the land surface, and is a major component of the water cycle. It is usually measured in [$kg \times m^{-2} \times s^{-1}$] or given in millimetre per year.
[10] The complex variable is defined in the description of the climate model (Roeckner *et al.*, 2003).

5.4 Changes in water resources

The climate model has no output on river discharge[11], but provides two variables that could be indirectly applied for estimating surface runoff. The variable called "surface runoff and drainage" is the output of the complex soil hydrology scheme, indicating contribution to overland flow from rain, snowmelt, or other sources (surface runoff), and base flow (drainage). Distributed water balance models (e.g., Van der Knijff and De Roo, 2008) consider this hydrological parameter a main component of river channel discharge, thus the modelled changes of this variable can also be indicative of variations in derivative resources.

Figure 5.5 shows the mean annual surface runoff and drainage in the 2000 scenarios as an average value, based on the monthly means of 60 realisations, and the changes between 2000 and 2030 scenarios.

The dimensional unit of results of the applied climate model is expressed in the water volume (or mass) per unit of area per unit of time (in the ECHAM-HAM model: $kg \times m^{-2} \times s^{-1}$). For mapping purposes, and in order to have results comparable with precipitation values, the estimated values of surface runoff and drainage are given in mm/year. Figure 5.6 shows the aggregated changes between the 2000 and 2030 scenarios in two classifications; first using the naturally delineated drainage area of main river basins (changes are indicated in mm/year), then the changes are also given for the countries as a percentage of the initial values of the 2000 scenarios.

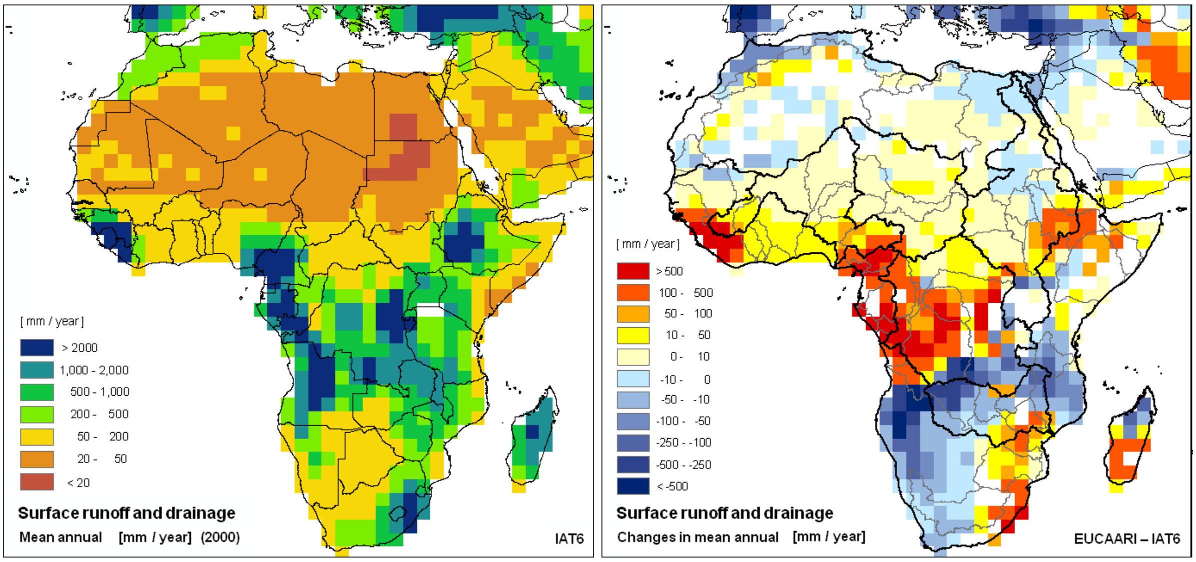

Figure 5.5 Annual average surface runoff and drainage in the 2000 scenarios (left), and the changes between the 2030 and 2000 scenarios (right). Positive values (yellow-red colours) mean an increase, negative values (dark and light blue) indicate a decrease between 2000 and 2030. White areas show water bodies, or statistically not significant ($p < 0.05$) changes over the year. The black and grey borderlines show the country borders (left) or delineate the main river basins (right).

[11] River discharge is the volume of water which flows through it in a given time. It is usually measured in cubic meters per second.

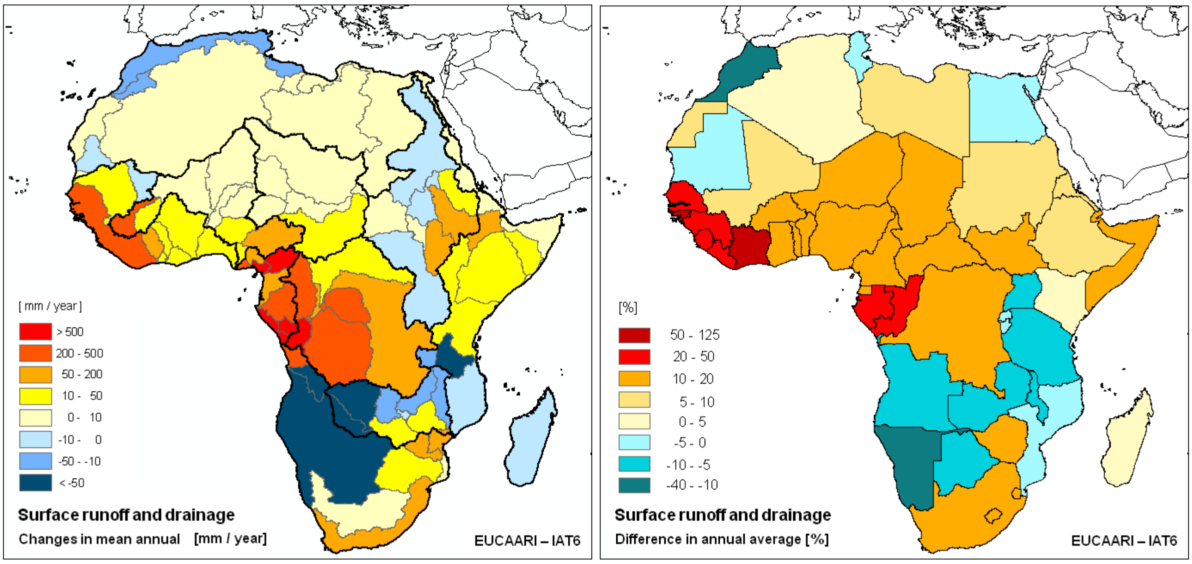

Figure 5.6 Changes in surface runoff and drainage between the 2000 and 2030 scenarios. The map on the left shows the main river (drainage) basins and the aggregated average changes in mm/year within the basin. The map on the right shows the country-based changes in percentage, comparing to the annual average values of the 2000 scenarios. Positive values (yellow-red colours) mean an increase, negative values (dark and light blue) indicate a decrease between 2000 and 2030. Areas characterised by statistically not significant ($p < 0.05$) changes have been taken out from both data series.

The "surface runoff and drainage" variable presented indicates the potential changes in water resources for general purposes. Taking only the "surface runoff" (the excess water flowing over the land when soil is infiltrated to full capacity) as the difference between "surface runoff and drainage" and "drainage" variables into account, a more realistic estimation on hydropower potential could be obtained. Similarly to the previous maps, Figure 5.7 shows the mean annual surface runoff in the 2000 scenarios, and the changes between the 2000 and 2030 scenarios, and Figure 5.8 shows the aggregated changes between the 2000 and 2030 scenarios by main river basins and countries.

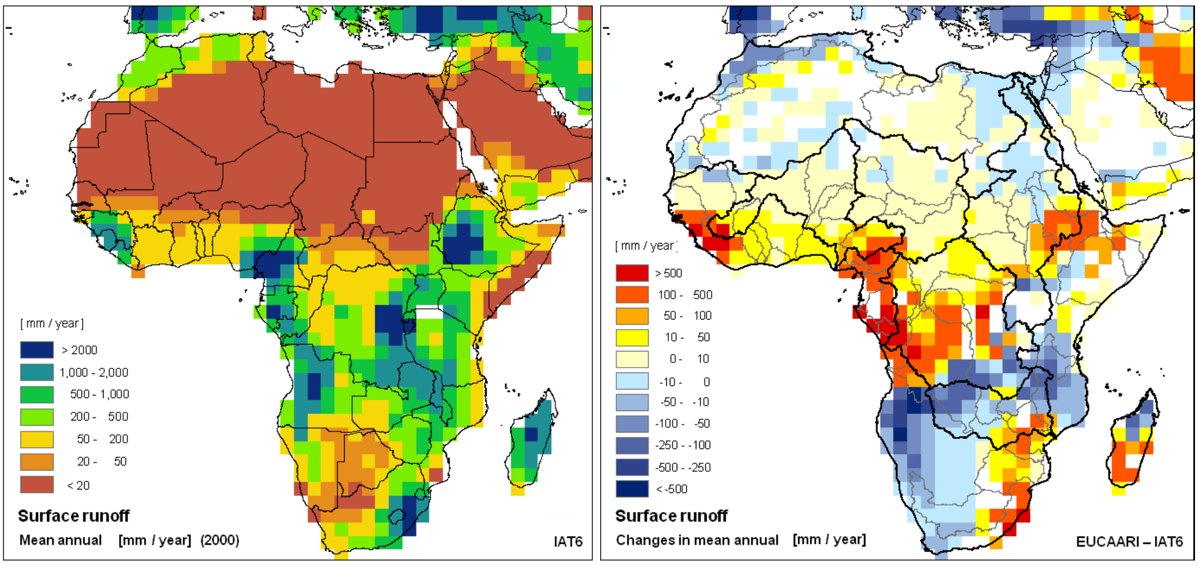

Figure 5.7 Annual average surface runoff in the 2000 scenarios (left), and the changes between the 2030 and 2000 scenarios (right). Positive values (yellow-red colours) mean an increase, negative values (dark and light blue) indicate a decrease between 2000 and 2030.

White areas show water bodies, or statistically not significant ($p < 0.05$) changes over the year. The black and grey borderlines show the country borders (left) or delineate the main river basins (right).

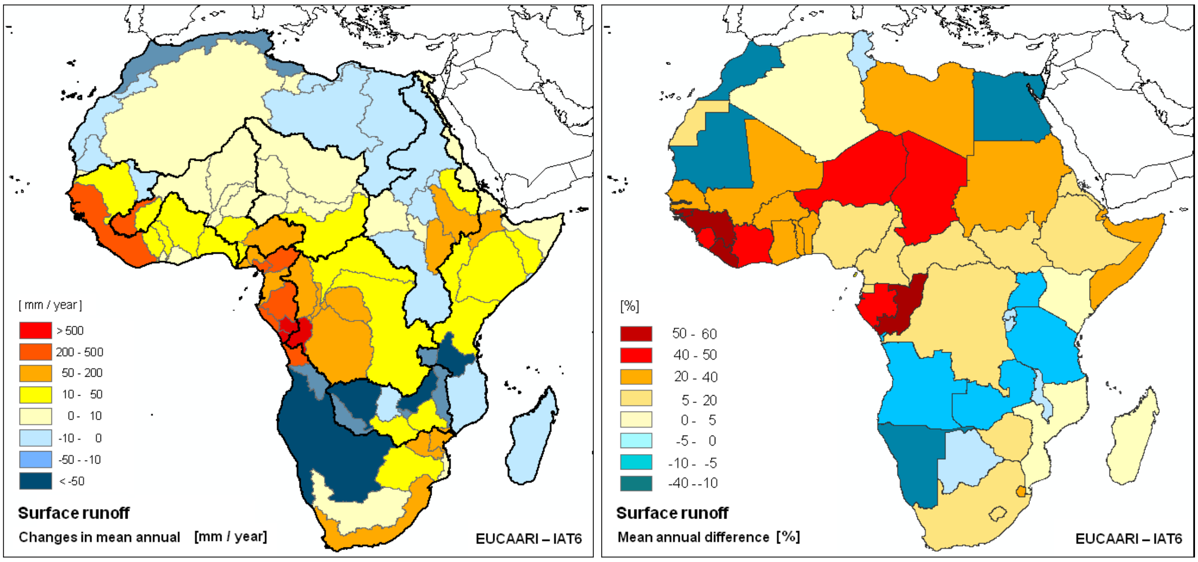

Figure 5.8 Changes in surface runoff between the 2000 and 2030 scenarios. The map on the left shows the main river (drainage) basins and the aggregated average changes in mm/year within the basin. The map on the right shows the country-based changes in percentages comparing to the annual average values of the 2000 scenarios. Positive values (yellow-red colours) mean an increase, negative values (dark and light blue) indicate a decrease between 2000 and 2030. Areas characterised by statistically not significant ($p < 0.05$) changes have been taken out from both data series.

River sections belonging to areas showing a positive (increasing) or negative (decreasing) tendency in terms of annual surface runoff can be classified by the estimated changes. Our analysis indicates that permanent watercourses (and their catchment areas) are mainly (62.3 %) in the slightly or moderately altering (either increasing or decreasing) zones (± 20 % change in surface runoff) and about 30% of the river courses belong to zones where the modelled increase exceeds 20%. The calculation was based on the small-scale (1:1,000,000) Vector Map Level 0 (VMAP0) geo-spatial data, which includes the most important descriptive hydrographical information of river courses. Figure 5.9 shows the proportional length of permanent river sections connected to the classes of surface runoff changes, based on the ECHAM-HAM model. It should be noted that the analysed model results are indicating the changes in surface runoff, and not showing the potential changes of river discharge.

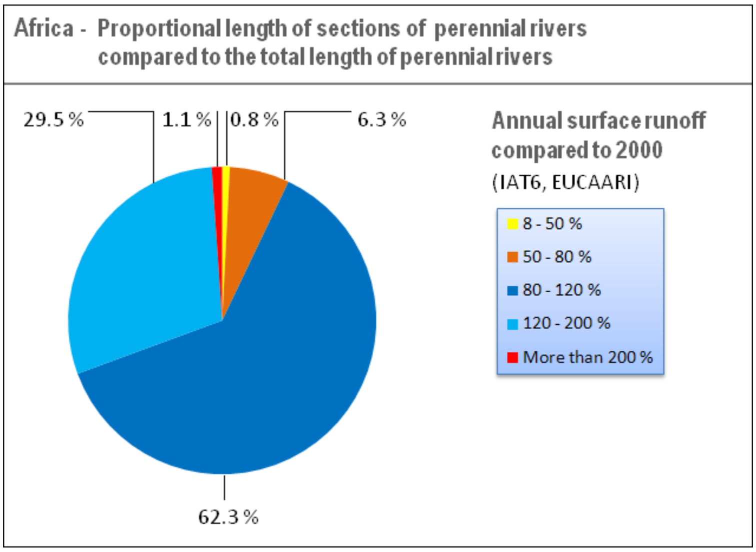

Figure 5.9 Distribution of permanent watercourses based on expected changes in surface runoff between the 2000 and 2030 scenarios. Based on the model, 62.3 % of the total length of current perennial rivers is within the zone characterised by a ± 20 % change in surface runoff. Approximately 7 % of the river sections belongs to areas expecting a decrease (8-80 % of surface runoff compared to 2000), and about 30% of the river courses belongs to zones where the modelled increase exceeds 20% (120-200% of surface runoff compared to 2000).

5.5 Conclusions

The results suggest that the huge, and only fractionally exploited, continental hydropower potential is not altering significantly, and rather, rising. Most of the areas characterised by decreasing tendencies are already poor in permanent watercourses. Following also the pattern of increasing precipitation, countries of the Gulf of Guinea and the south-eastern coasts of the continent could experience an increase, but the main drivers for continental hydropower development are most likely hidden in socio-economic circumstances. Barriers listed in paragraph 5.2.3 should be overcome first. A detailed technological and economical analysis, feasibility assessment involving hydrological modelling, in order to obtain high resolution river discharge (flow rate) data, would give a more direct answer on potential hydropower production on continental, and also on country level.

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6. Conclusions and outlook

This second JRC report on Renewable Energies in the African continent has started to address some questions posed by the previous JRC report "Renewable Energies in Africa". In particular, the issue of climate change has been addressed and a first idea of the future tendency of renewable resources availability has been discussed.

An additional effort has been put in covering the information gaps still making detailed analyses quite difficult. For this reason, a more detailed picture of the opportunities provided by some resources like e.g., biomass from agriculture and forestry, organic waste from households and hydro power has been also provided.

The analysis shows how climatic changes in the mid-term period investigated here are not expected to induce relevant changes in the theoretical potential of several Renewable Energies resources, and the exploitation opportunities described in the previous JRC report are not expected to change substantially in the next few decades, a mid-term time frame relevant for both energy policy design and investments in energy infrastructures.

Wind patterns are not foreseen to change in the mid-term, at least at the large synoptic scale investigated here and the areas currently interesting for deeper exploitation of this resource are not expected to be put at risk by mid-term climate evolution. For hydro power generation, the results suggest that the huge, and only fractionally exploited, continental hydropower potential is not altering significantly, and rather, rising. Solar power generation is expected to more than compensate the slight efficiency decrease caused by the rising temperature with the already experienced decrease in costs.

For biomass, the issue of sustainability will remain crucial in the next decades as it is now. For instance, in some countries excessive exploitation of the fuelwood resources could combine with climate effects and decrease the depletion time of the biomass stock. The improper use of biomass derived fuels like charcoal in unsuitable facilities will continue to create relevant health problems. On the other side, carefully managed exploitation of both forest and agricultural biomass and organic waste remains a huge opportunity for the local energy needs of African communities.

The main results obtained in this report have been based on climate scenarios elaborated by the ECHAM-ham climatic model. Considering the well known variability of climate results, an "ensemble" approach should be taken for more robust investigations or for assessing longer time horizons in future research. Higher resolution, long-term, multi-model analyses are expected to become available also for the African region in a short time thanks to the CORDEX: (COordinated Regional climate Downscaling Experiment): the assessment methodologies and the indicators developed in the present report could be easily and meaningfully applied to the CORDEX results.

Appendix A. Seasonal analysis of relevant climate parameters.

M. Gaetani, L. Pozzoli, K. Bódis

The seasonal analysis of some of the key parameters provided by the climate model described in Chapter 1 is shown in Figures A.1 to A.8. The use of these data in the analysis performed for assessing changes in solar and hydropower potential is described in Chapters 2 and 5 respectively.

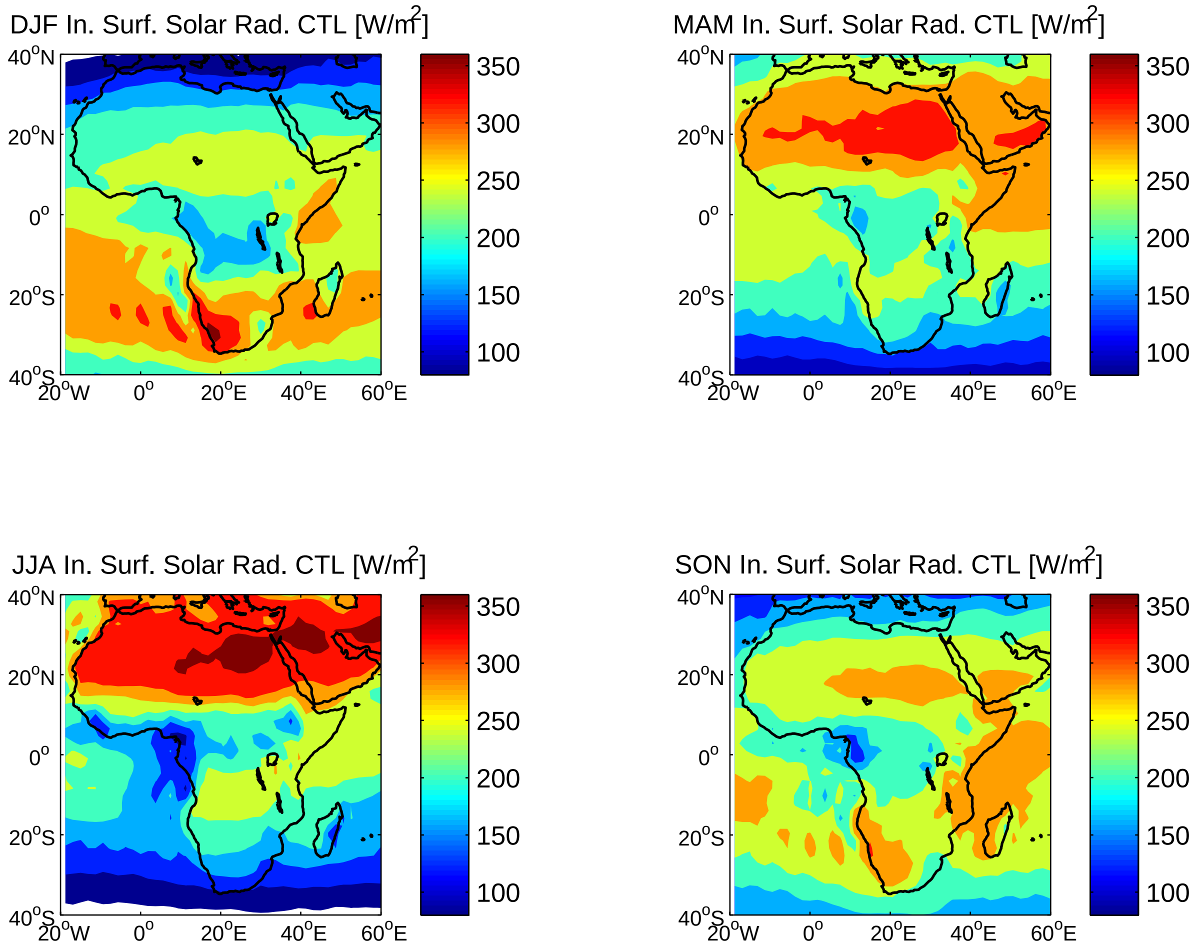

Figure A.1. Seasonal values of net surface sun radiation in W/m^2 (top left – December, January and February; top right – March, April and May; bottom left – June, July and August; bottom right – September, October and November)) in the 2000 scenarios.

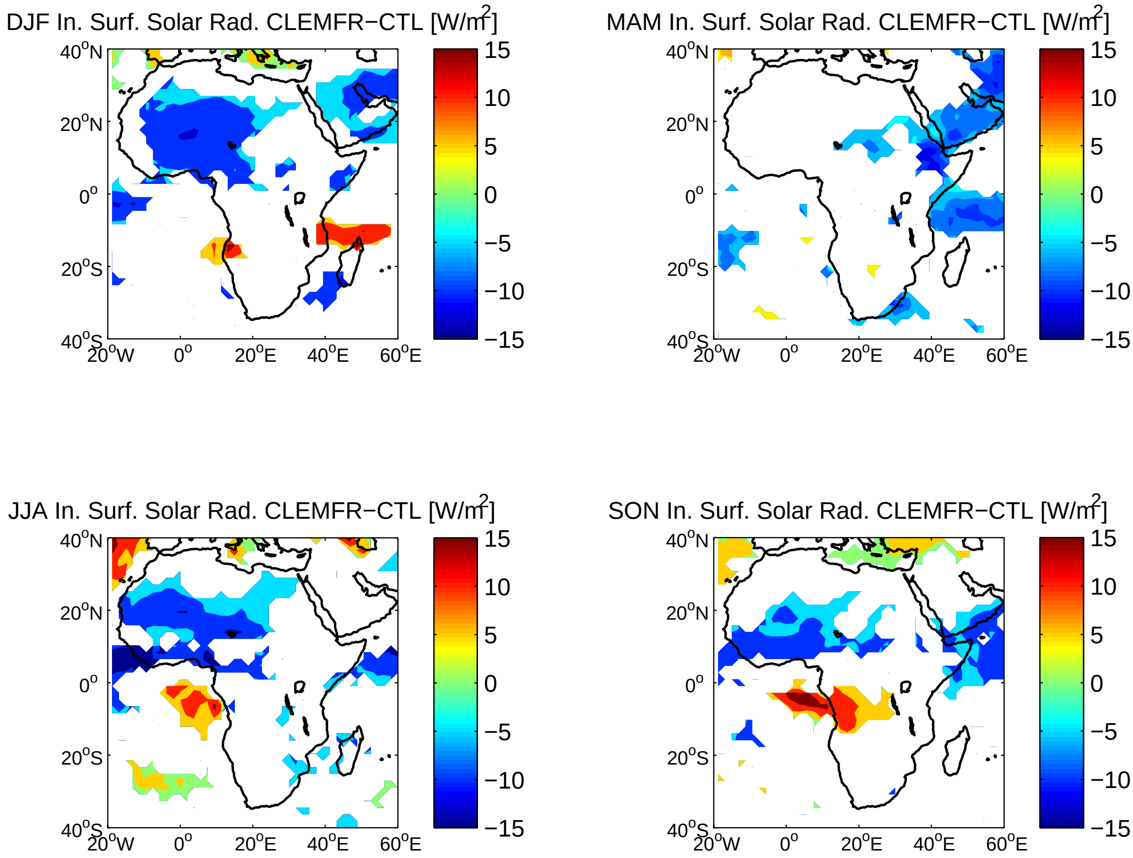

Figure A.2. Seasonal variations of net surface sun radiation in W/m^2 (top left – December, January and February; top right – March, April and May; bottom left – June, July and August; bottom right – September, October and November) between the 2030 and 2000 scenarios. White areas identify not statistically significant ($p < 0.05$) changes.

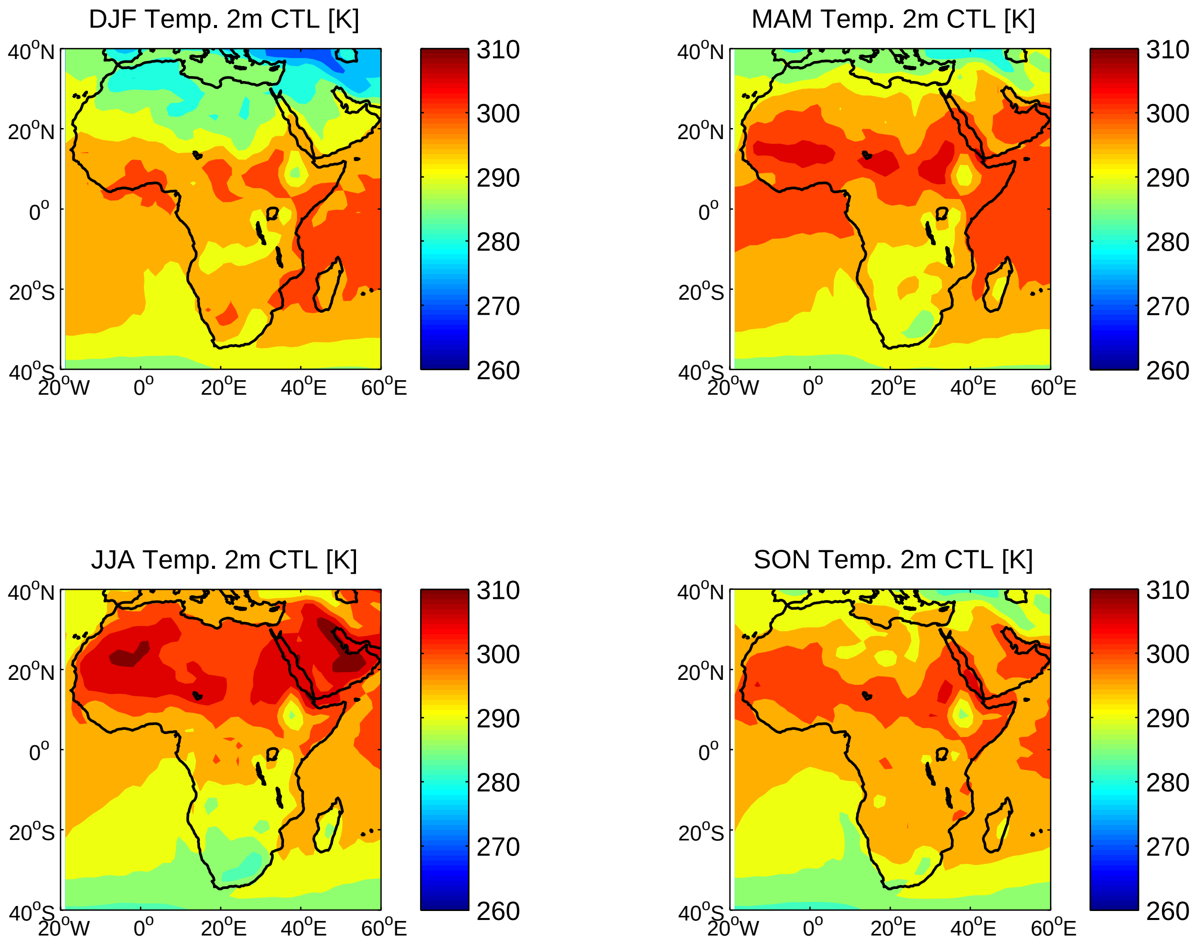

Figure A.3. Seasonal values of average surface temperature in K (top left – December, January and February; top right – March, April and May; bottom left – June, July and August; bottom right – September, October and November)) in the 2000 scenarios.

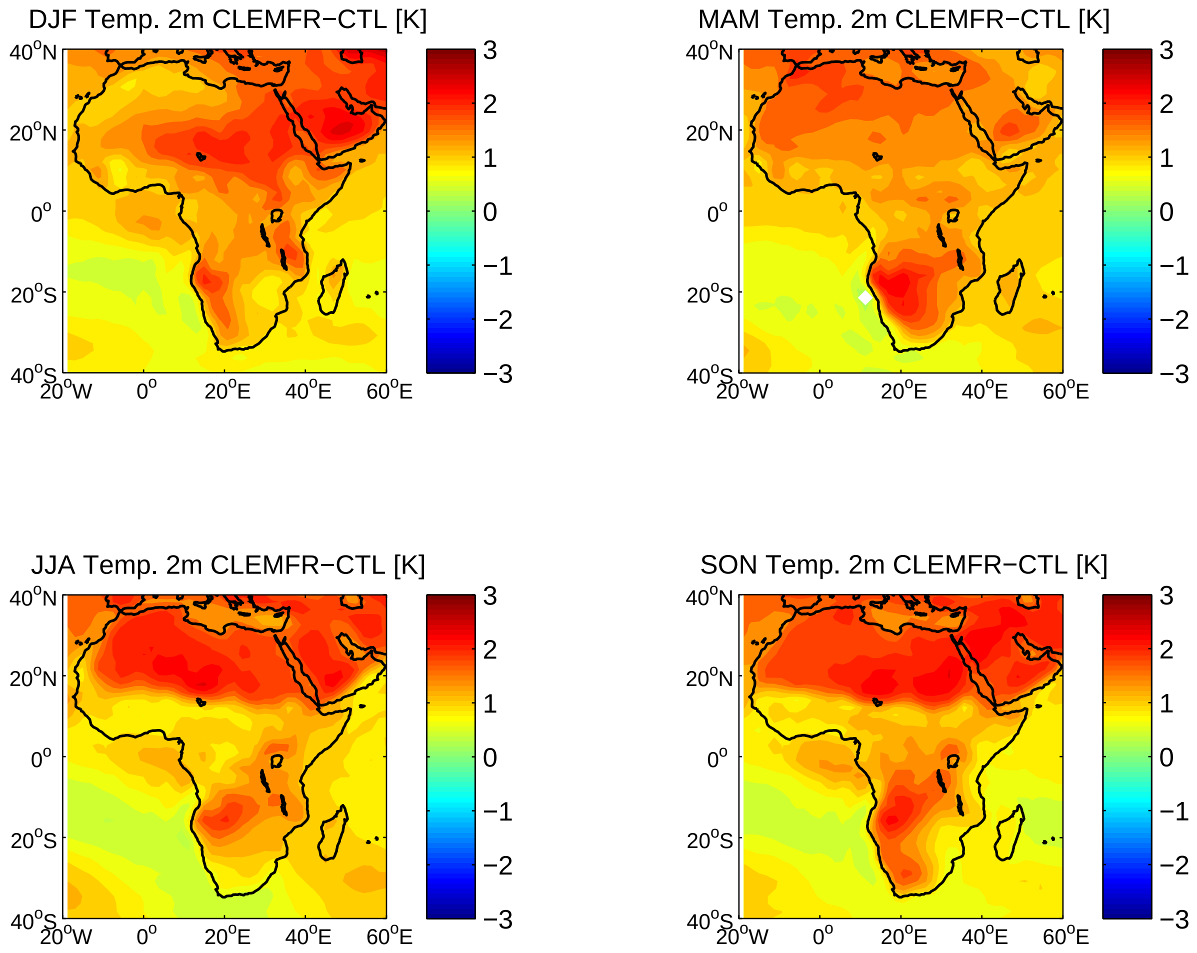

Figure A.4. Seasonal variations of average surface temperature in K (top left – December, January and February; top right – March, April and May; bottom left – June, July and August; bottom right – September, October and November) between the 2030 and 2000 scenarios. All grids showed a significant temperature increase ($p<0.05$).

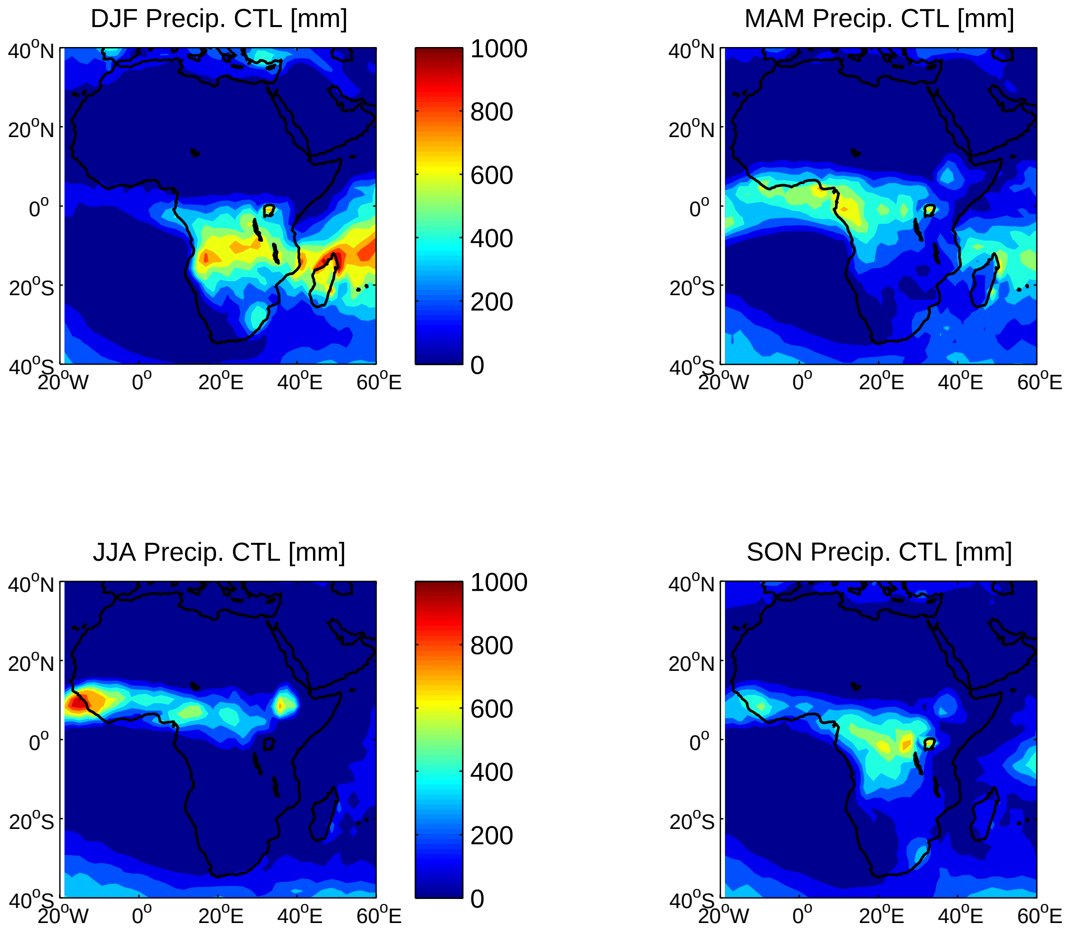

Figure A.5. Seasonal values of average precipitation in mm/year (top left – December, January and February; top right – March, April and May; bottom left – June, July and August; bottom right – September, October and November)) in the 2000 scenarios.

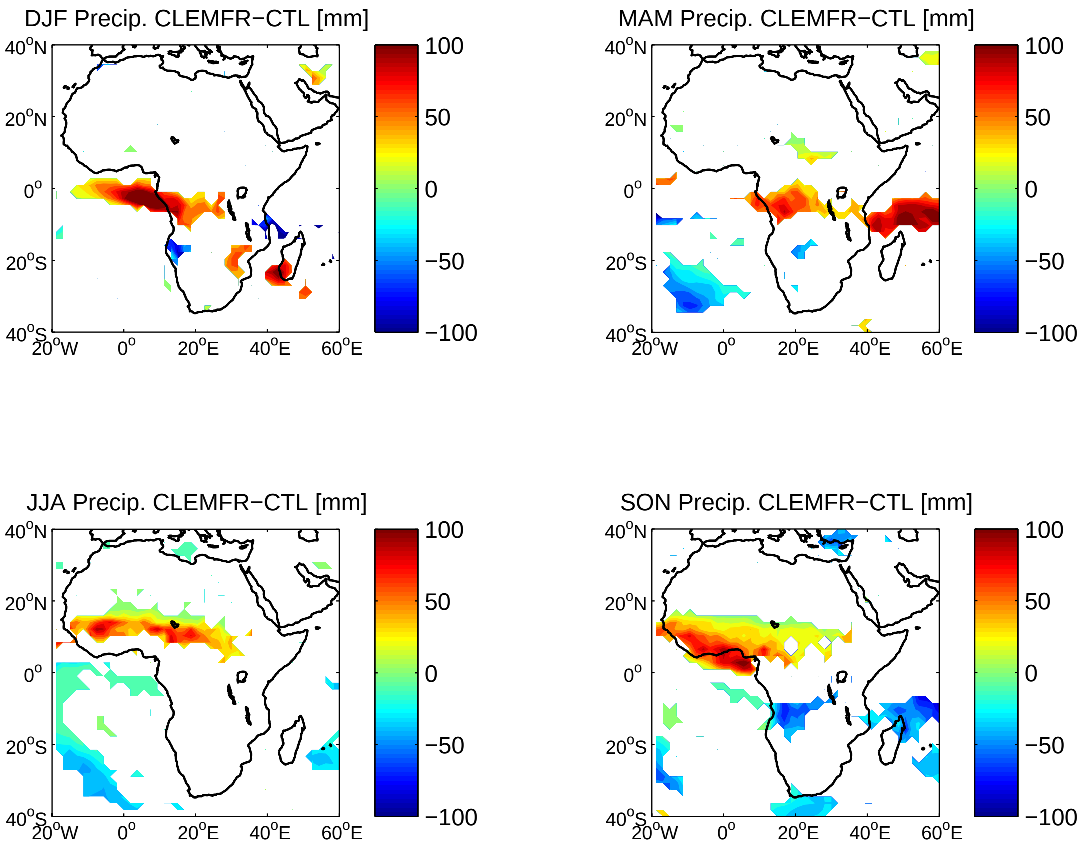

Figure A.6. Seasonal variations of average precipitation in mm/year (top left – December, January and February; top right – March, April and May; bottom left – June, July and August; bottom right – September, October and November) between the 2030 and 2000 scenarios. White areas identify not statistically significant ($p < 0.05$) changes.

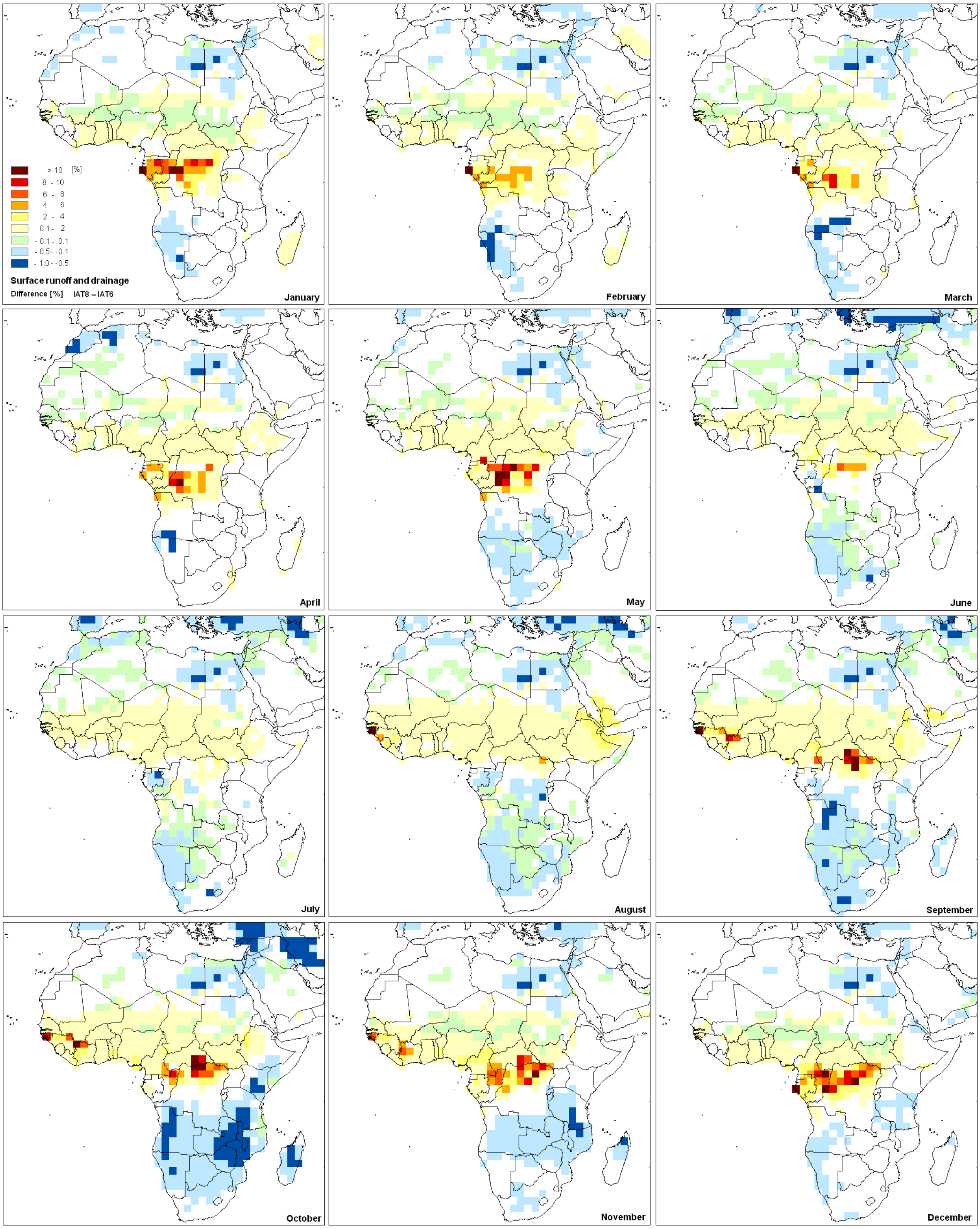

Figure A.7 Changes in monthly average surface runoff and drainage (kg × m^{-2} × s^{-1}) between the 2000 scenarios (IAT6) and the 2030 (IAT8) scenarios. Positive values (yellow-red colours) mean an increase, negative values (dark and light blue) indicate a decrease between 2000 and 2030. White areas identify water bodies or statistically not significant ($p < 0.05$) changes.

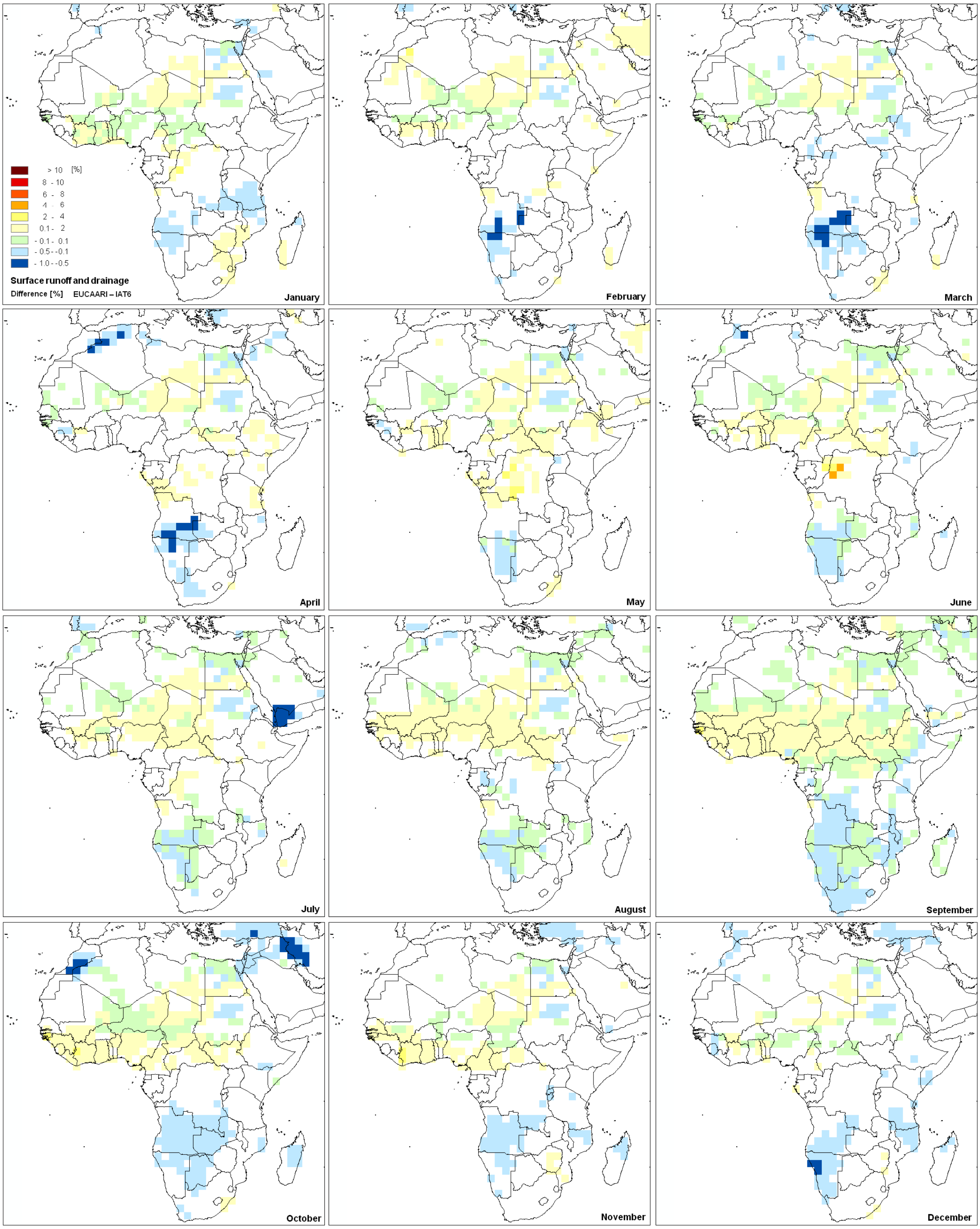

Figure A.8 Changes in monthly average surface runoff and drainage (kg × m^{-2} × s^{-1}) between the 2000 scenarios (IAT6) and the 2030 (EUCAARI) scenarios. Positive values (yellow-red colours) mean an increase, negative values (dark and light blue) indicate a decrease between 2000 and 2030. White areas show water bodies or statistically not significant ($p < 0.05$) changes.

Appendix B. Preliminary gross Evaluation of CH4, volume and energy, derived from Municipal Solid Waste (MSW) in African urban areas if disposed in managed landfills

V. Motola

Abstract

According to Couth *et al.* (2011) data on waste management in Africa are poor. There is uncertainty over the quantity of greenhouse gas (GHG) emissions from waste management, notably from waste disposal.

Nevertheless, it is clear that GHG emission rate from waste disposal in African territories will increase leading to further climate change as the population increases and becomes more urbanised, with the corresponding increasing risk of water and soil pollution.

For this reason there is a need, at the African level, for an assessment of waste management country per country with the objective to elaborate specific recommendations for a sustainable and energy recovering waste strategy.

As a starting point, this study assesses the theoretically total potential of methane as LFG (Landfill Gas), derived from MSW (Municipal Solid Waste) when disposed in managed Landfill. This potential is expressed in Volume and Energy and allocated spatially for the whole Africa continent with a resolution of 25 Km^2.

B.1 Introduction

Landfill gas (LFG) is generated by the decomposition of the organic fraction of waste, disposed in a landfill under anaerobic conditions, and can be recovered through the operation of gas collection and control systems that typically burn the gas in flares. Alternatively, the collected gas can be exploited as energy source and LFG uses may include upgrading to pipeline quality methane gas (if there is sufficient quantity and quality to support gas processing costs), or more often its use as fuel in energy recovery facilities, including internal combustion engines, gas turbines, microturbines, steam boilers, or other types of facilities that can use LFG for electricity or heat generation.

When waste is landfilled, the organic matter in the waste is converted to landfill gas. Landfill gas is a mixture of methane (45% to 60%), carbon dioxide (40% to 60%) and trace components (H_2S, mercaptanes, organic esters and other volatile hydrocarbons, all of them giving landfill gas its characteristic smell). The time scale of the gas generation depends on waste composition, landfill management, climate but generally, it can be divided into four phases (see figure B.1):

Phase I – Aerobic;
Phase II - Anaerobic Non-Methanogenic;
Phase III Anaerobic Non-Methanogenic Unsteady;
Phase IV Anaerobic Non-Methanogenic Steady.
Phase IV is usually reached in less than one year, see Figure 1.

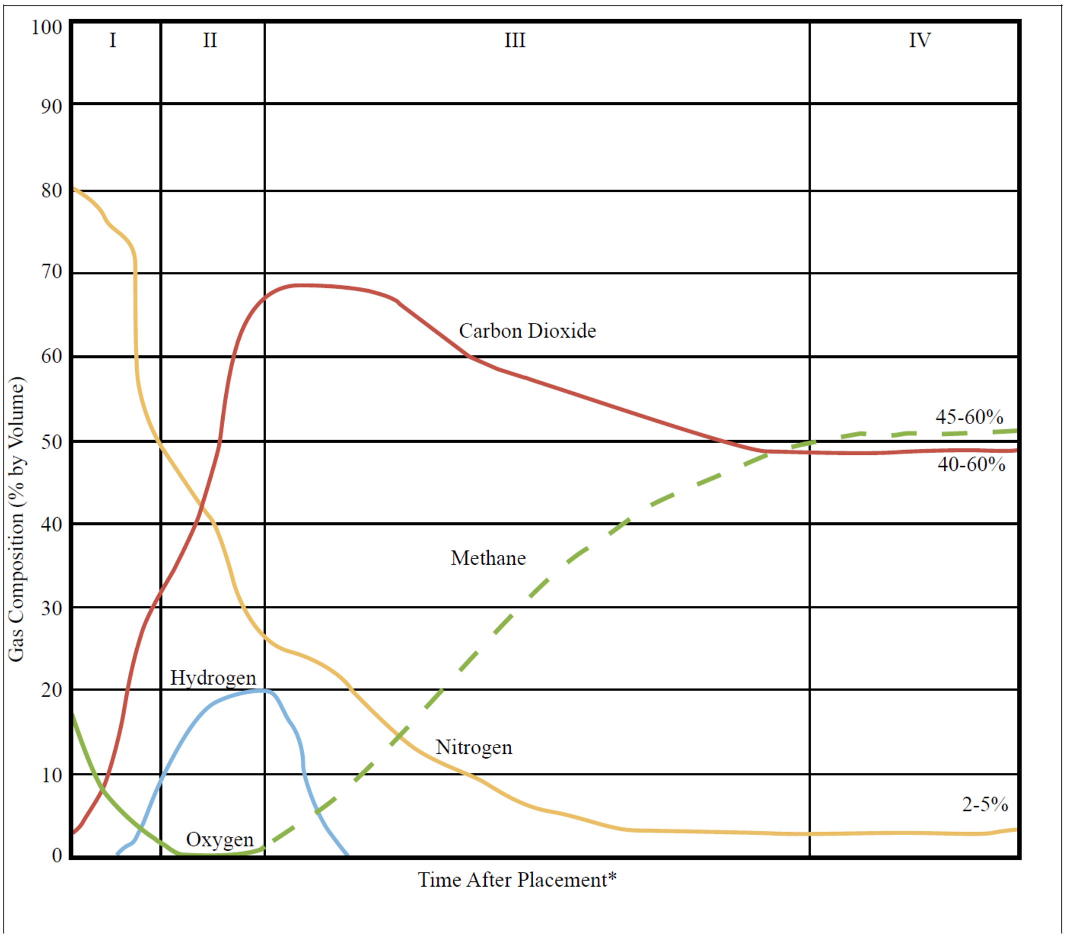

Figure B.1 Phases of MSW digestion (EPA, 2012)

LFG collection typically begins after a portion of the landfill (known as a "cell") is closed to additional waste placement. There are many methods of LFG collection, some use drilling vertical wells, others use horizontal collectors or a combination of these systems.
After collection, LFG can either be flared or used in an energy recovery system to combust the methane and other trace contaminants. Using LFG in an energy system usually requires some processing and internal combustion engines generally require minimal treatment (e.g., de-humidification, particulate filtration, and compression).
In addition to the energy benefits from the beneficial use of LFG, its collection and control helps to reduce LFG emissions that are harmful to the environment. The US EPA has determined that LFG emissions from municipal solid waste (MSW) landfills cause, or contribute significantly to air pollution that may be reasonably anticipated to endanger public health or welfare. Some of the LFG components' pollutants are known or suspected carcinogens, or cause other noncancerous health effects. Public welfare concerns include the odour nuisance from the LFG and the potential for methane migration, both on-site and off-site, which may lead to explosions or fires. The methane emitted from landfills is also a concern because it is a greenhouse gas, thereby contributing to the challenge of global climate change.
According to UNSD (2011), in Africa there is lack of statistics concerning population served by municipal waste collection (see Figure B.2). However, where statistics are available they show that only a low –medium rate of the population is generally served.

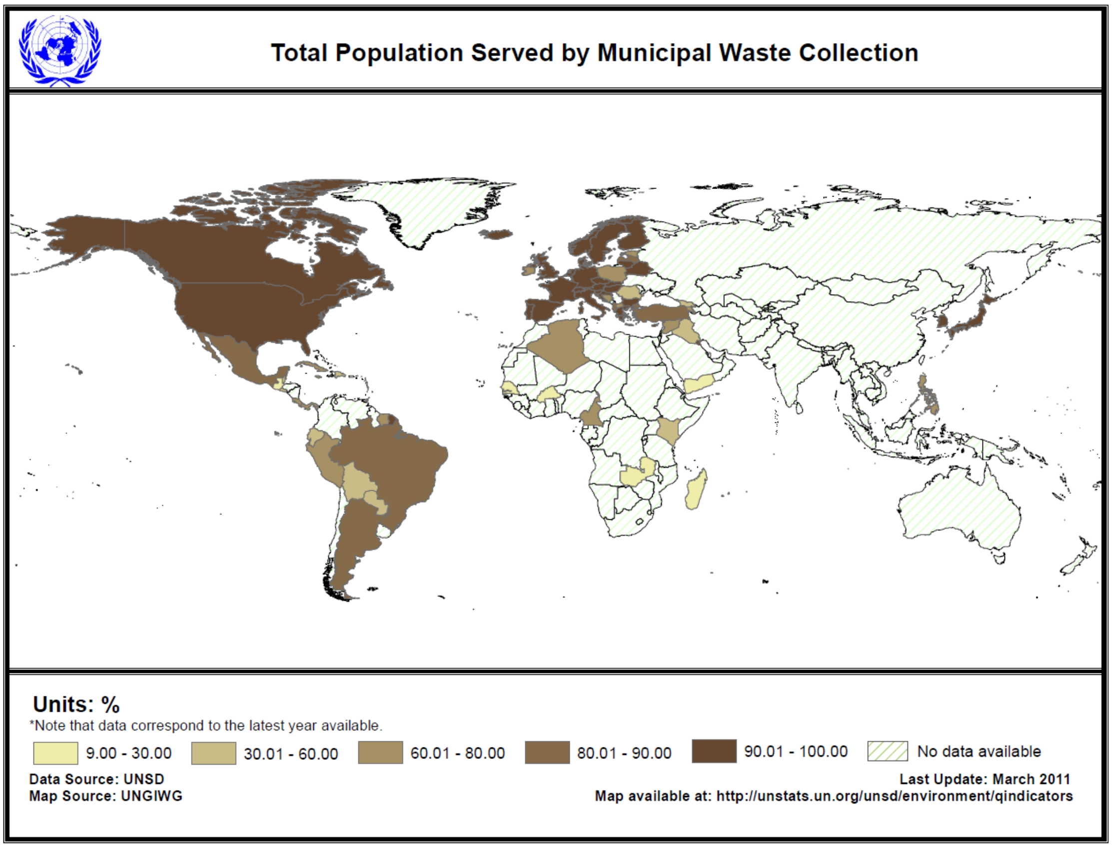

Figure B.2- Population served by MSW collection (UNSD, 2011)

Hoornweg, and Bhada-Tata (2012), confirm that in the Africa region, where investigated waste collection regards only 12 of the 48 South Sahara Countries where statistics are available, the rate is by far the lowest within the classified world regions (see Figure 3).

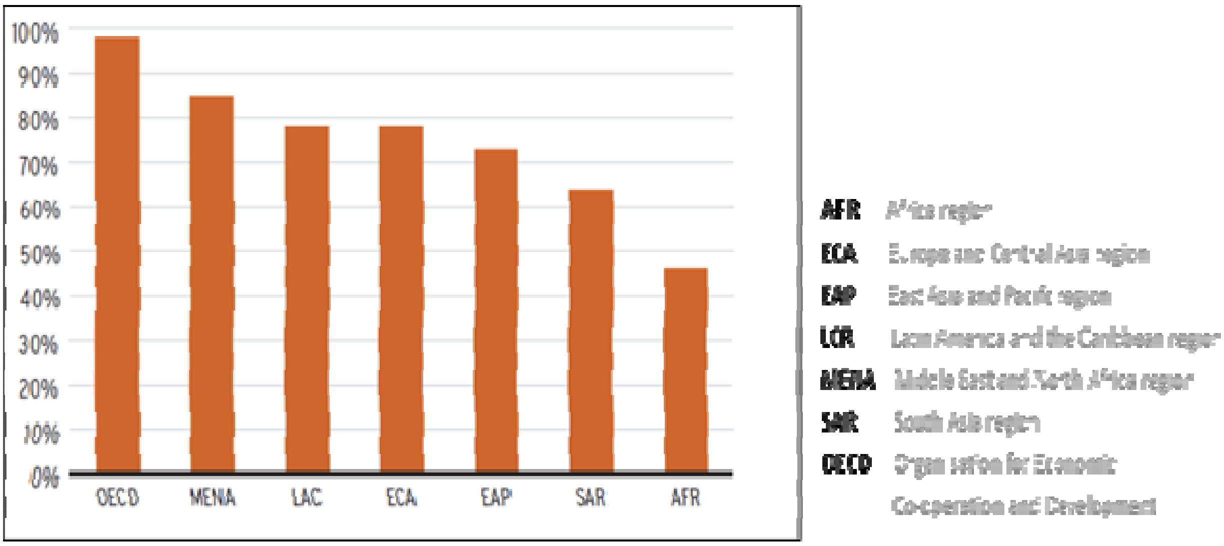

Figure B.3 Rate of Solid Waste Collection (Hoornweg, and Bhada-Tata, 2012)

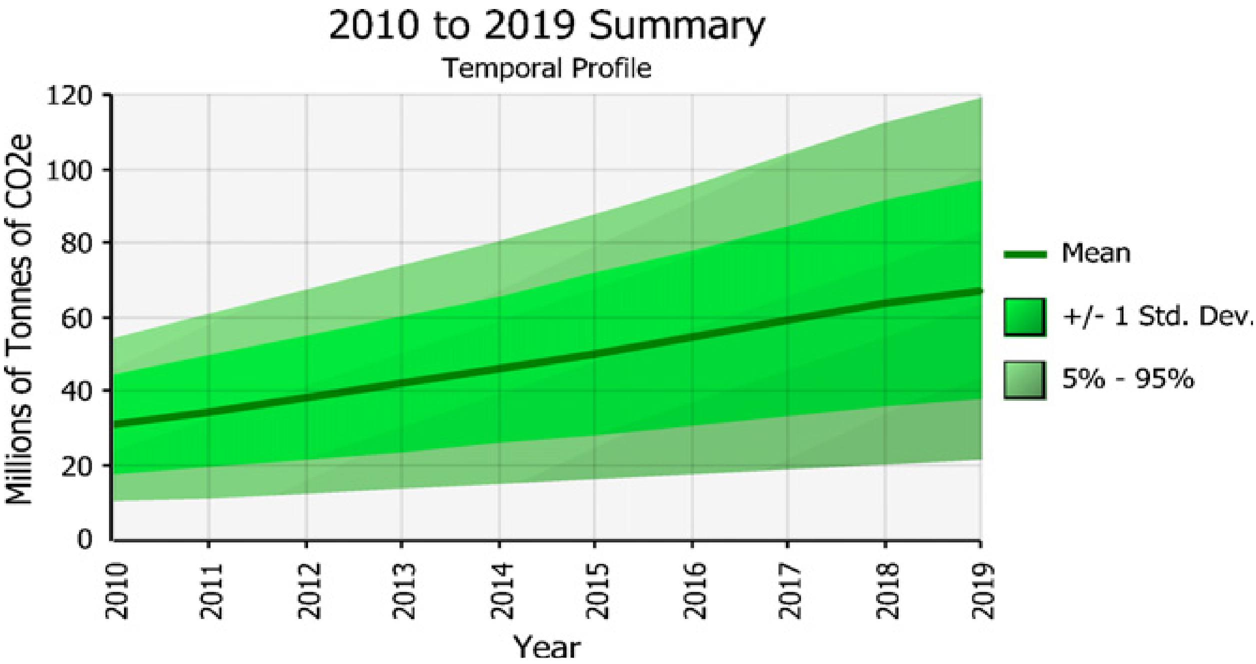

Figure B.4 Temporal profile emissions related to MSW in Africa, evaluated with the @Risk model with sensitivity to inputs analysis (Couth *et al.,* 2011).

Figure B.4 shows the temporal profile of CO_2e emissions[12] associated to MSW in the 2010-2019 time-span in Africa considering data such as MSW food fraction, fraction of CH_4 capture, urban population growth and MSW waste production, including results from sensitivity analysis. Besides the baseline scenario illustrated, the @risk model shows that the more we go towards diversion as the most preferred options (Figure B.5), the less is the CO_2e emission increase. Africa thus needs to put in place policy for waste management, implementing reliable practices, first of all avoiding uncontrolled waste dumping and dumped waste burning.

[12] CH_4 emissions associated are usually measured in CO_2e.

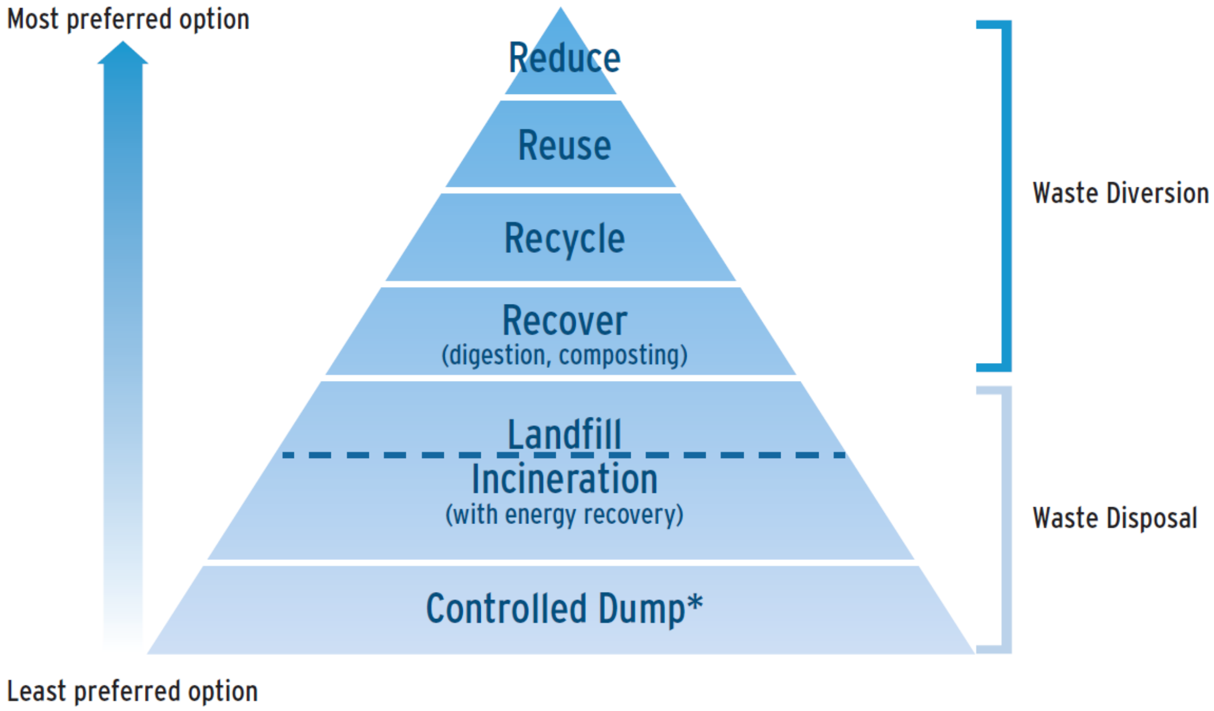

Figure B.5 MSW management options (UNSD, 2011)

Managing MSW in Africa by increasing diversion options will not only help mitigating the increase in GHG emissions: according to UN-Habitat (2011), solid waste that is not properly collected and disposed can be a breeding ground for insects, vermin, and scavenging animals, and can thus transmit air- and water-borne diseases. Surveys conducted by UN-Habitat show that in areas where waste is not collected frequently, the incidence of diarrhoea is twice as high and acute respiratory infections six times higher than in areas where collection is frequent.

In the next sections focus will be put on the recovery option, estimating CH_4 recovery potential for digestion in controlled landfill collecting MSW in the most densely populated areas of Africa where population density is more than 400 inhabitants per Km^2

B.2 Determining MSW Methane potential

In this study Ultimate Methane Generation Potential (L_0) is considered, defined as the amount of methane that is produced throughout the lifetime of the waste from biodegradation.

Except in dry climates, where a lack of moisture limits methane generation, L_0 depends almost exclusively on the type of waste present in the landfill. The higher the biodegradable organic carbon content, the higher the amount of methane. The L_0 value describes the total amount of methane gas potentially produced by a metric tonne of refuse as it decays over its lifetime, according to the chemical equation:

(CH2O)n → ½ n CH4 + ½ n CO2   (eq 1)

in which $(CH_2O)n$ is the approximate composition of organic matter in the waste, the Ultimate methane generation potential L_0 is then finally calculated:

L_0 = 1.33 *F * DOC* DOCf   (eq2)

Where the F (Fraction) is the organic product contained in the waste landfilled (W) and (DOC) is the organic carbon concentration. However, not all organic material is converted, part of it (lignin, cellulose covered by lignin) not being degradable under anaerobic conditions. Another part simply doesn't degrade because conditions in the waste are unfavorable for degradation. So when calculating L_0, a further factor DOCf is introduced to describe the part of DOC that ultimately is converted to landfill gas.

The scope of this study is the quantification of the value of L_0 spatially allocated in densely populated areas of Africa where landfill management is generally more urgent for environmental and health reasons, and also where the quantity of MSW is technically more attractive for the logistics and the economic feasibility of possible LFG collection plants.

The main parameters needed for the calculation are taken again from Couth *et al.* (2011)

In order to locate the African urban population spatially, public metadata from FAO (2012) geo portal were used. Then, only the potential methane emission from collected and landfilled MSW, theoretically produced by people living in areas where population density is more than 400 persons per square kilometre[13] were considered and used to evaluate CH_4 on the basis of the following values (Couth *et al.*, 2011):

MSW production	230 kg/capita/year
Organic Fraction (F)	58%
L_0 (CH_4 generated)	243 m^3 / MSW t

Methane volume was then converted to energy assuming a CH_4 net heating value equal to 35.8 MJ/m^3

[13] The definition of an urban area varies from country to country, but a working definition by UN, EC and the World Bank is any area where at the time of the most recent census there was a population of 1000 or more persons and a population density of 400 or more persons per square kilometre.

B.3 Results and discussion

Table B.1 shows the African overall results obtained for population over the density threshold and methane potential from MSW.

Table B.1 Overall African methane potential

Number of people living in areas where density is >400 persons/ Km²	410746906
Maximum Theoretical CH4 (L_0) Mm³/year	22.591
Maximum Theoretical CH_4 (L_0) energy content TJ/year	821.494
Maximum Theoretical CH_4 (L_0) energy content GWh/year	238.233

The calculated Methane (L_0) in terms of Energy content GWh, allocated spatially is shown for the whole continent in Figures B.6 and for some very densely populated areas in Figures B.7 and B.8.

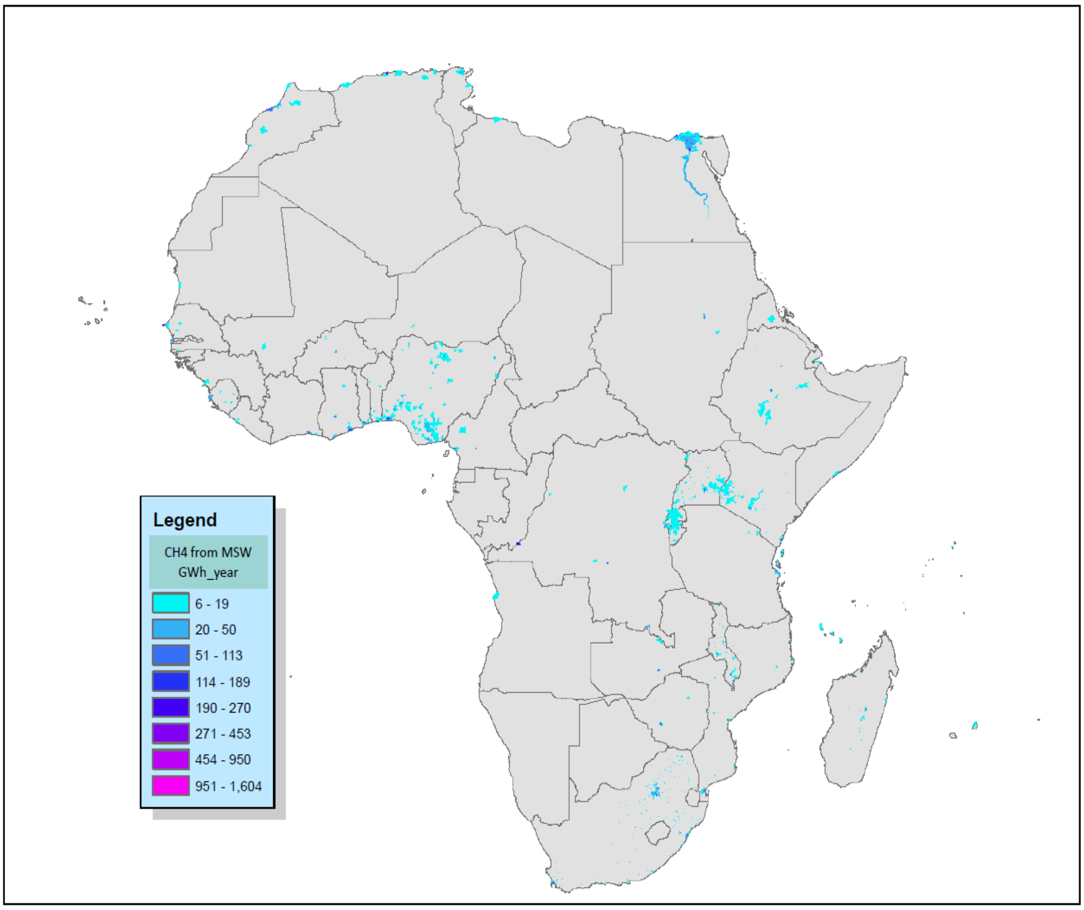

Figure B.6- Theoretical Energy content of Methane (L_0) in GWh/year – continental view

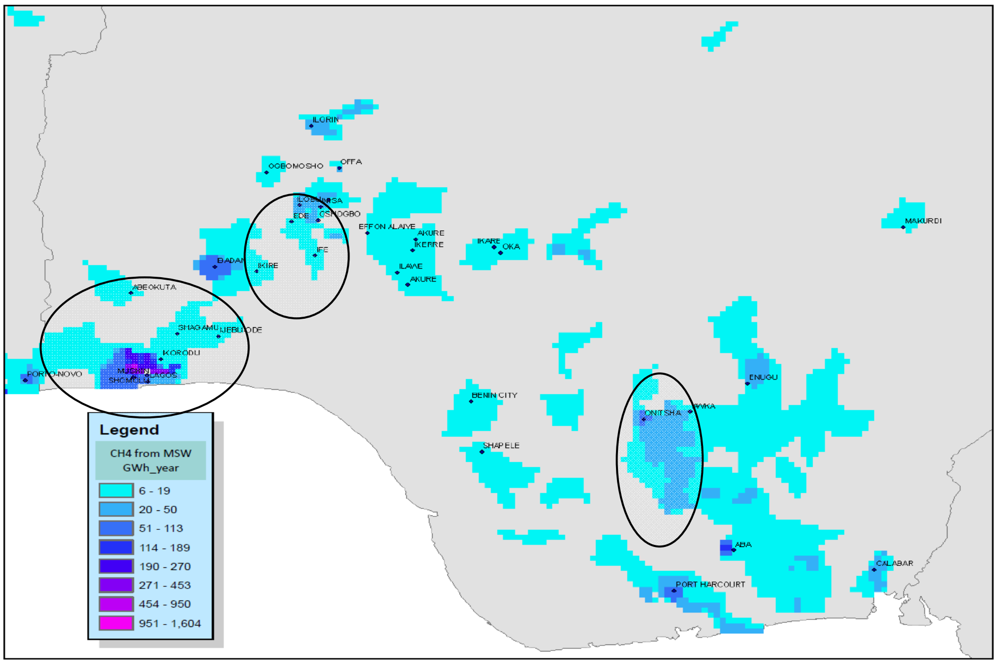

Figure B.7 Theoretical Energy content of Methane (L_0) in GWh/year - Southern Nigeria

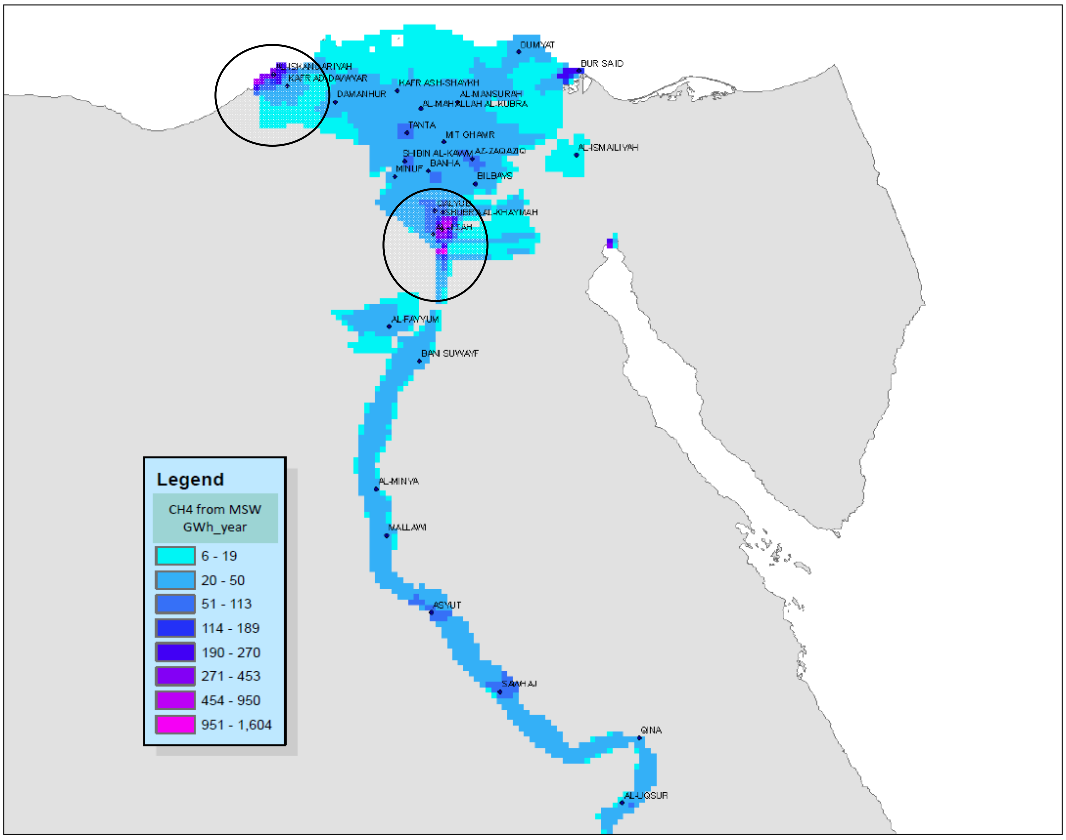

Figure B.8- Theoretical Energy content of Methane (L_0) in GWh/year - Egypt

Even if Table B.1 reports the value of L_0 from that theoretically produced by 410.7 million people living in the African areas, where population density is more than 400 persons per square kilometre (representing about the 37 % of the entire Africa population[14]), it has to be remembered that LFG energy projects are complex, their success depending crucially on optimal plant location and sizing, the presence of organised landfill logistics and that they could involve many operations such as drilling, piping, construction and the actual final potential can be sensibly different from the values presented here.

As already stated, it should be noted that the estimations from this study corresponds to the maximum yearly theoretical (L_0) in the areas studied. Practically, only a fraction of (L_0) is technically collectable and generated LFG is not released instantaneously but flowing in years as stated by the following equation (EPA):

$$Q_M = \frac{1}{C_{CH4}} \sum_{i=1}^{n} \sum_{j=0.1}^{1} k L_o \left(\frac{M_i}{10}\right)\left(e^{-kt_{ij}}\right)$$

Q_M = maximum expected LFG generation flow rate (m^3/yr);
n = (year of the calculation) – (initial year of waste acceptance)
k = methane generation rate (1/yr);
L_0 = ultimate methane generation potential (m^3/Mg);
Mi = mass of solid waste disposed in the i^{th} year (Mg);
t_{ij} = age of the j^{th} section of waste mass disposed in the i^{th} year (decimal years).
C_{CH4} = methane concentration (volume fraction).
i = 1 year time increment
j = 0.1 year time increment

For this reason, the calculated set of data and maps presented here are best suited used as input for evaluation models and could help in assessing future landfill locations, also evaluating possible methane flaring, or collection and managing existing landfills opened recently.

For these limitations, whenever local statistical data are available on MSW composition, MSW production, climate, calculating the layers could be improved and detailed, moreover, in the case of existing geo data on infrastructures, landfills, soil, geomorphology, more detailed calculations should be performed, also prospecting scenarios for composting and recycling MSW practices what are the most recommended.

Nevertheless, the broad view provided by this preliminary study allows to place the potential energy production form African landfills in a world context: according to IEA (2012) (, in 2010, Africa has produced 664 TWh i.e., 3.1% of world electricity (Figure B.9). One third of that amount was produced in one single country (South Africa) from coal.
Assuming an efficiency of 40% for power production, if all the potential LFG investigated in this study is exploited and converted to power, we have a theoretical electricity potential of 95 TWh/year, i.e., about 14 % of Africa's power production in 2010.

[14] According to CIESIN (2011), in 2015 the African population will be approximately 1.1 billion.

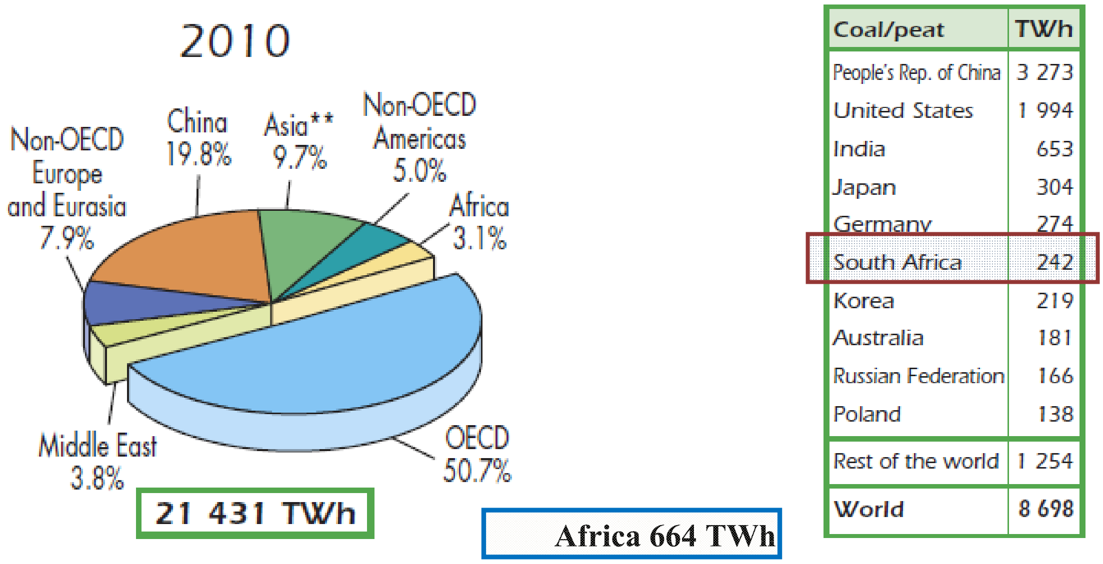

Figure B.9: Africa power production in the world context (IEA, 2012)

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Appendix C. Key maps

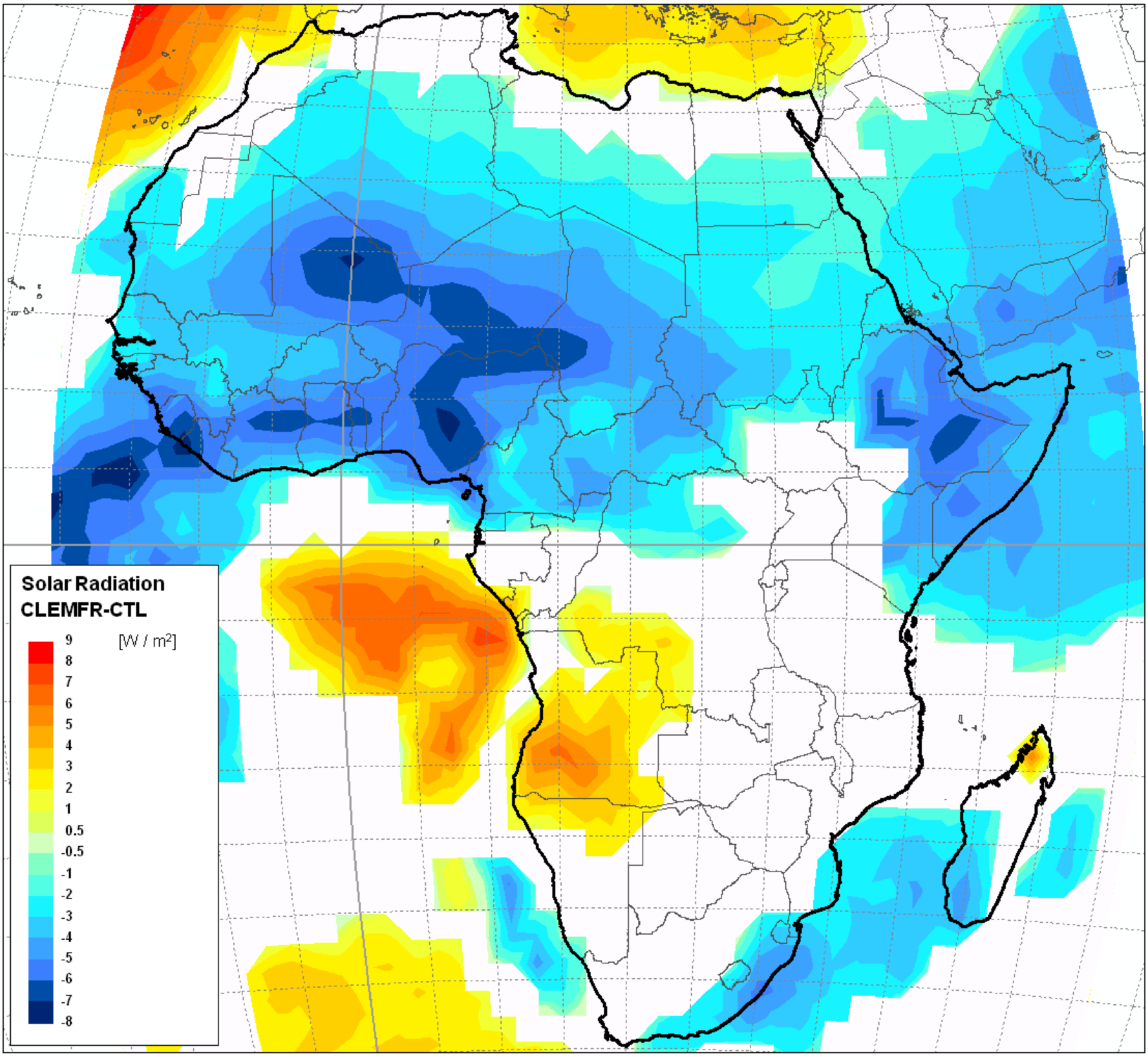

Figure C.1 Changes in the ensemble yearly mean of the net solar radiation between 2030 and 2000 (W/m^2) as predicted by the ECHAM-HAM aerosol-climate model in the scenario described in Chapter 1. Positive changes imply an increased radiation amount, while negative changes imply a decrease in solar radiation. White areas correspond to not statistically significant changes ($p<0.05$).

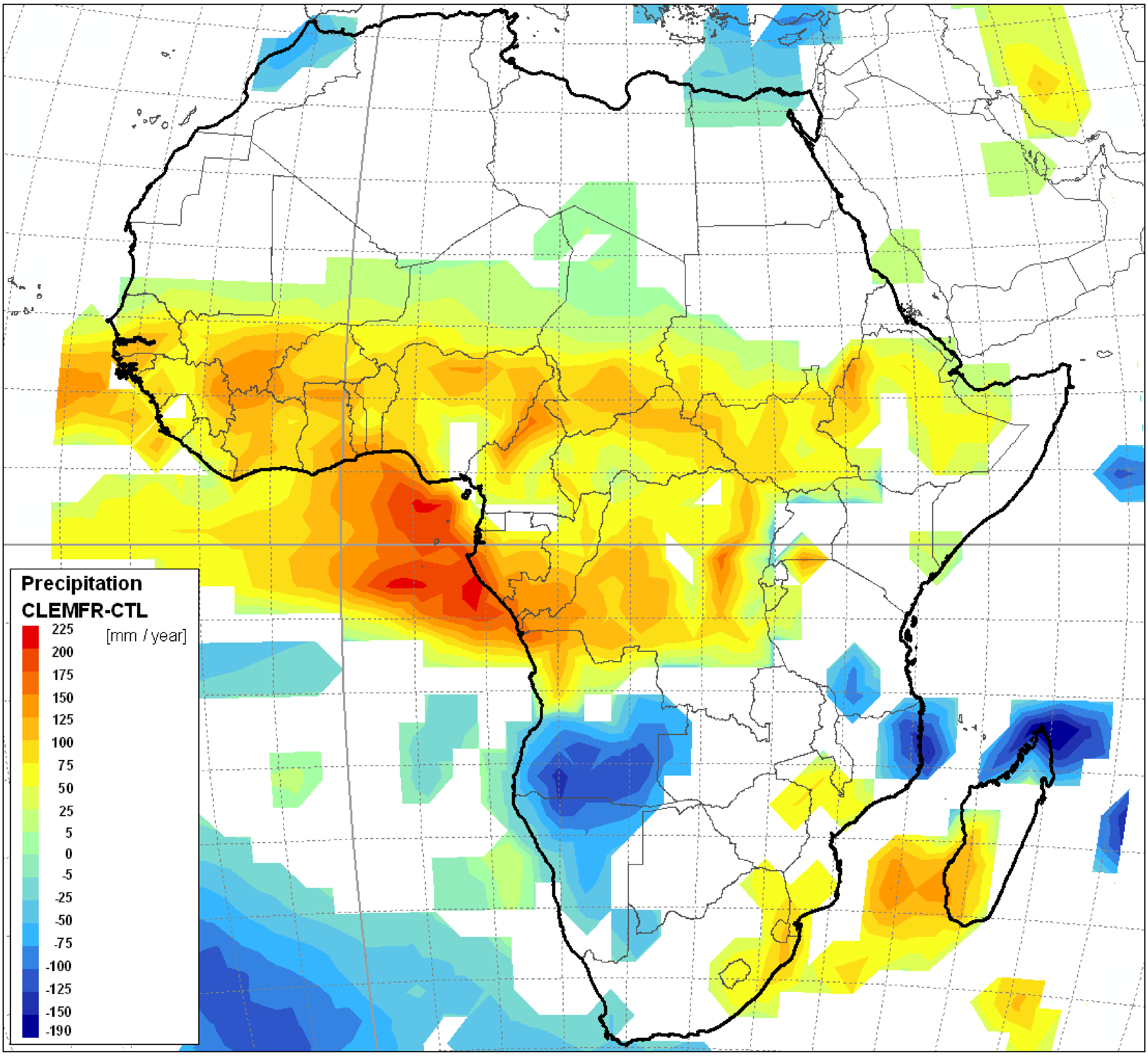

Figure C.2 Changes in the ensemble yearly precipitation between 2030 and 2000 (mm/year) as predicted by the ECHAM-HAM aerosol-climate model in the scenario described in Chapter 1. Positive changes imply an increased precipitation amount, while negative changes imply a decrease in precipitation. White areas correspond to not statistically significant changes ($p<0.05$).

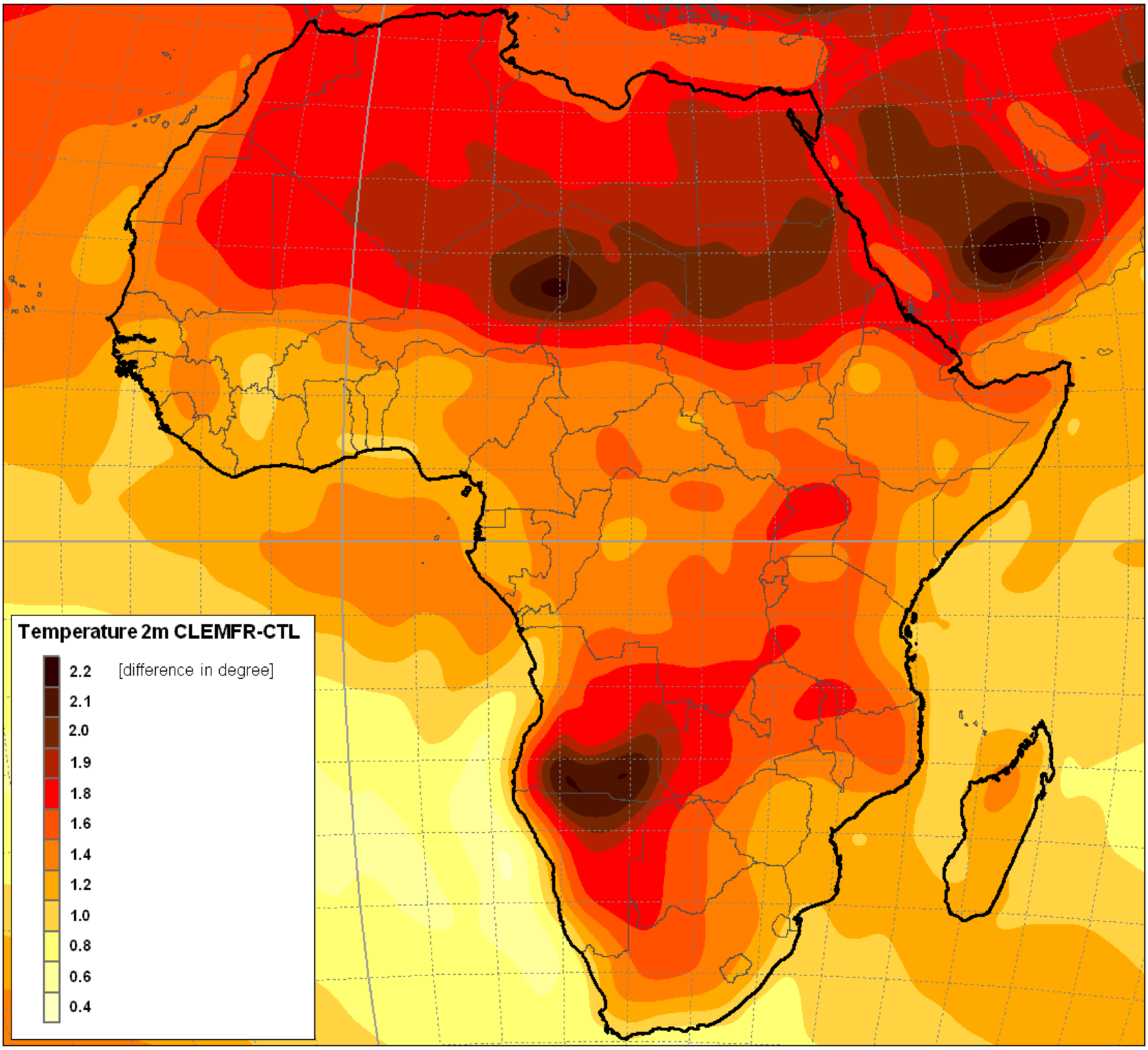

Figure C.3 Changes in the ensemble yearly mean 10m temperature between 2030 and 2000 (mm/year), as predicted by the ECHAM-HAM aerosol-climate model in the scenario described in Chapter 1. Change in temperature is positive and statistically significant ($p<0.05$) in all points of the map, implying a ubiquitous increase of the temperature.

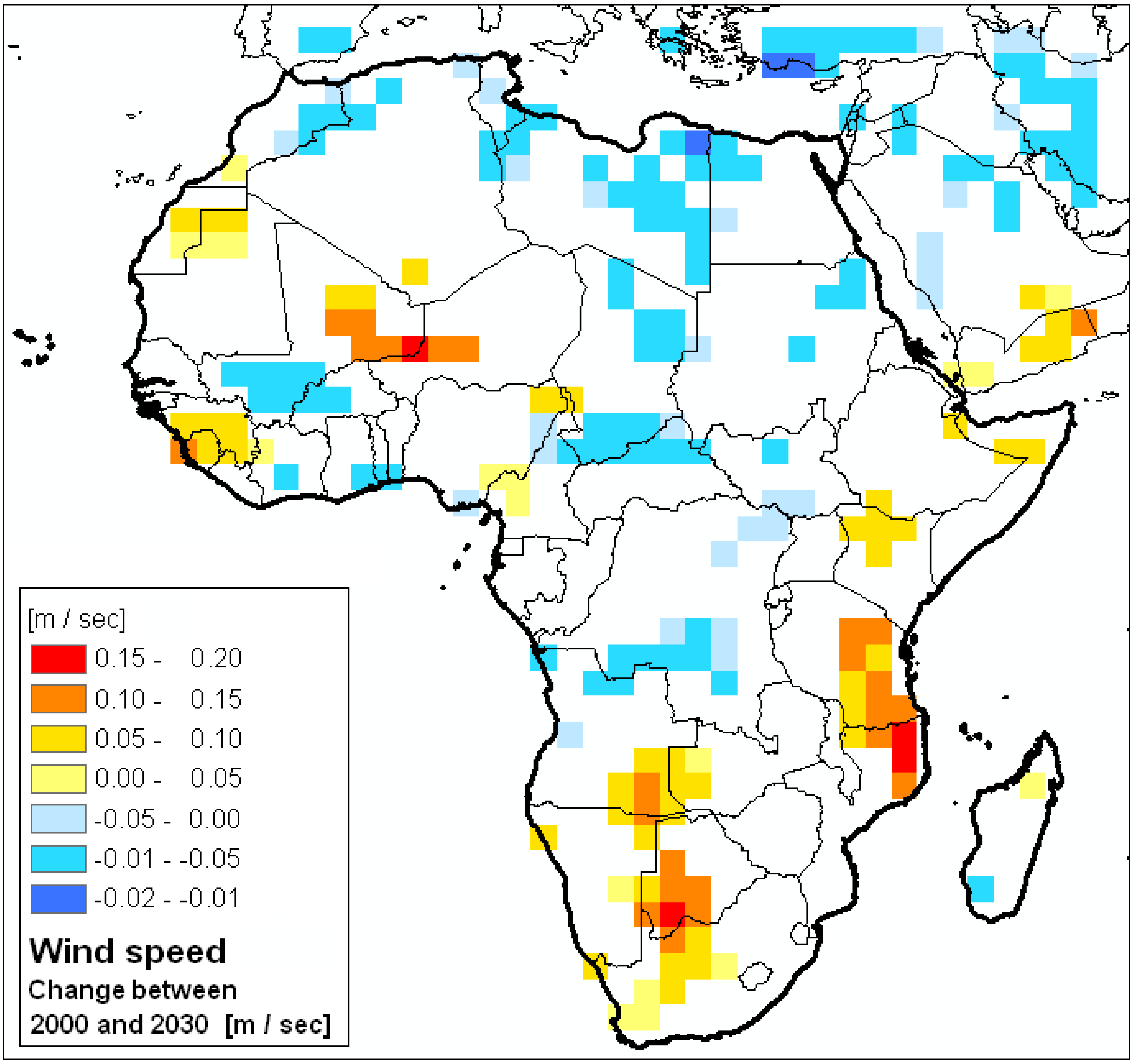

Figure C.4 Changes in the 50th percentile of annual mean wind speed between 2030 and 2000 (m/s) as predicted by the ECHAM-HAM aerosol-climate model in the scenario described in Chapter 1. Positive changes imply an increased wind speed, while negative changes imply a decrease in wind speed. White areas correspond to not statistically significant changes ($p<0.05$).

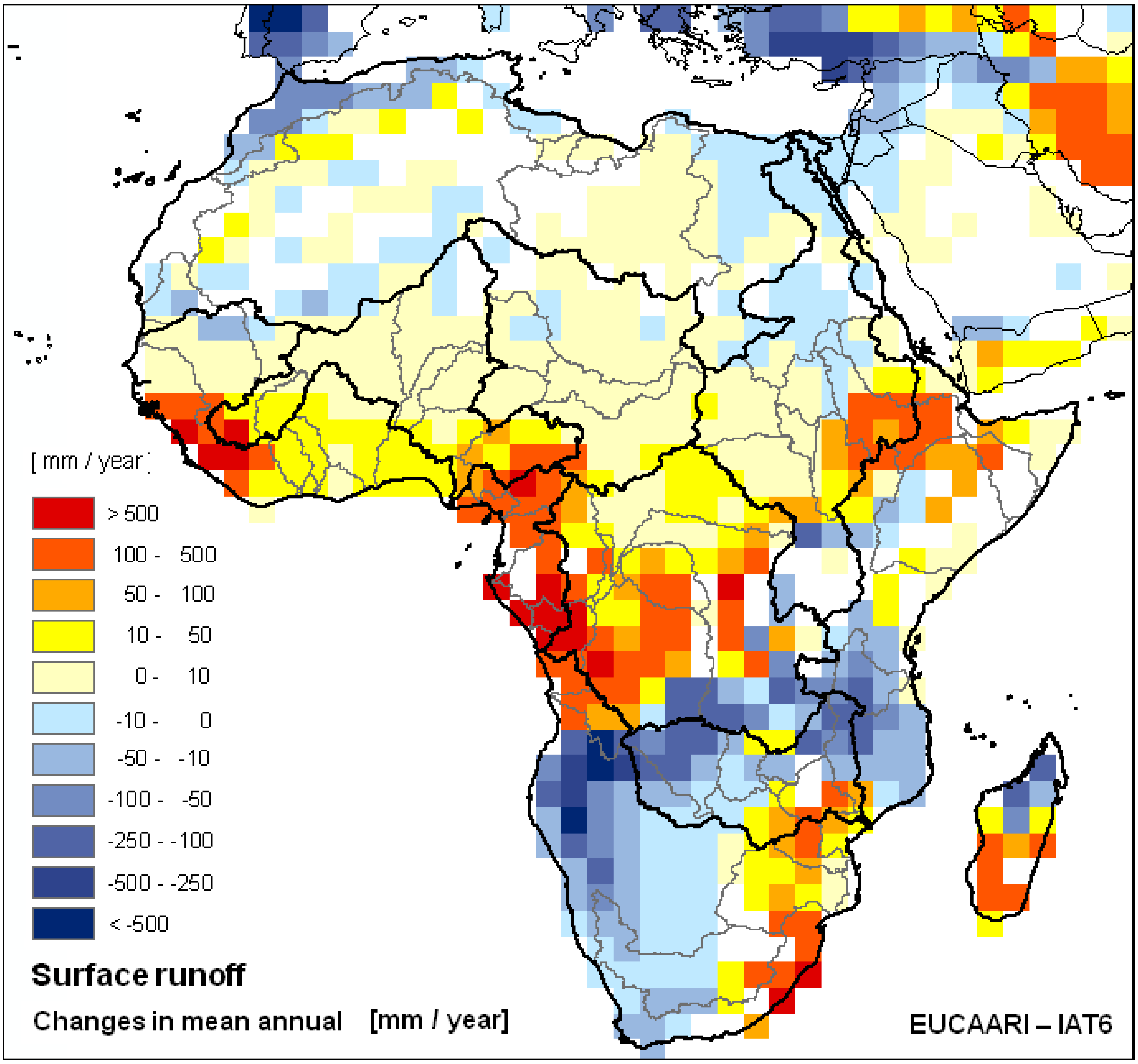

Figure C.5 Change in the ensemble annual average surface runoff between the 2030 and 2000 scenarios (mm/year), as predicted by the ECHAM-HAM aerosol-climate model in the scenario described in Chapter 1 . Positive values mean an increase, negative values indicate a decrease. White areas shows water bodies, or statistically not significant ($p < 0.05$) changes. The black and grey borderlines delineate the main river basins.

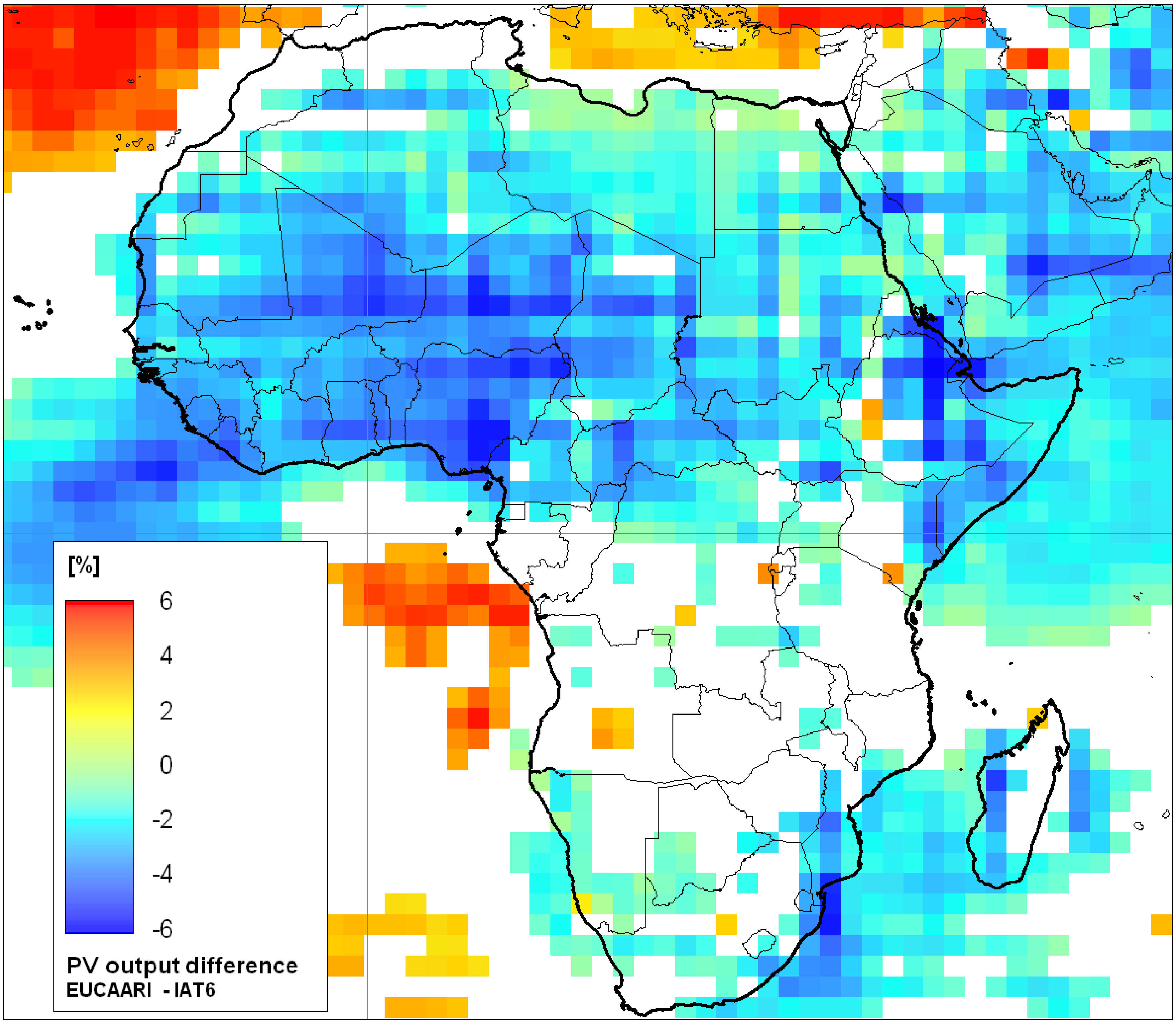

Figure C.6 Changes in the ensemble mean of the PV potential power output (kWh/m^2) between 2030 and 2000 (%). White areas correspond to not statistically significant changes ($p < 0.05$). Computations are based on solar radiation and temperature data (Figure C.1 and C.3) provided by the ECHAM-HAM model.

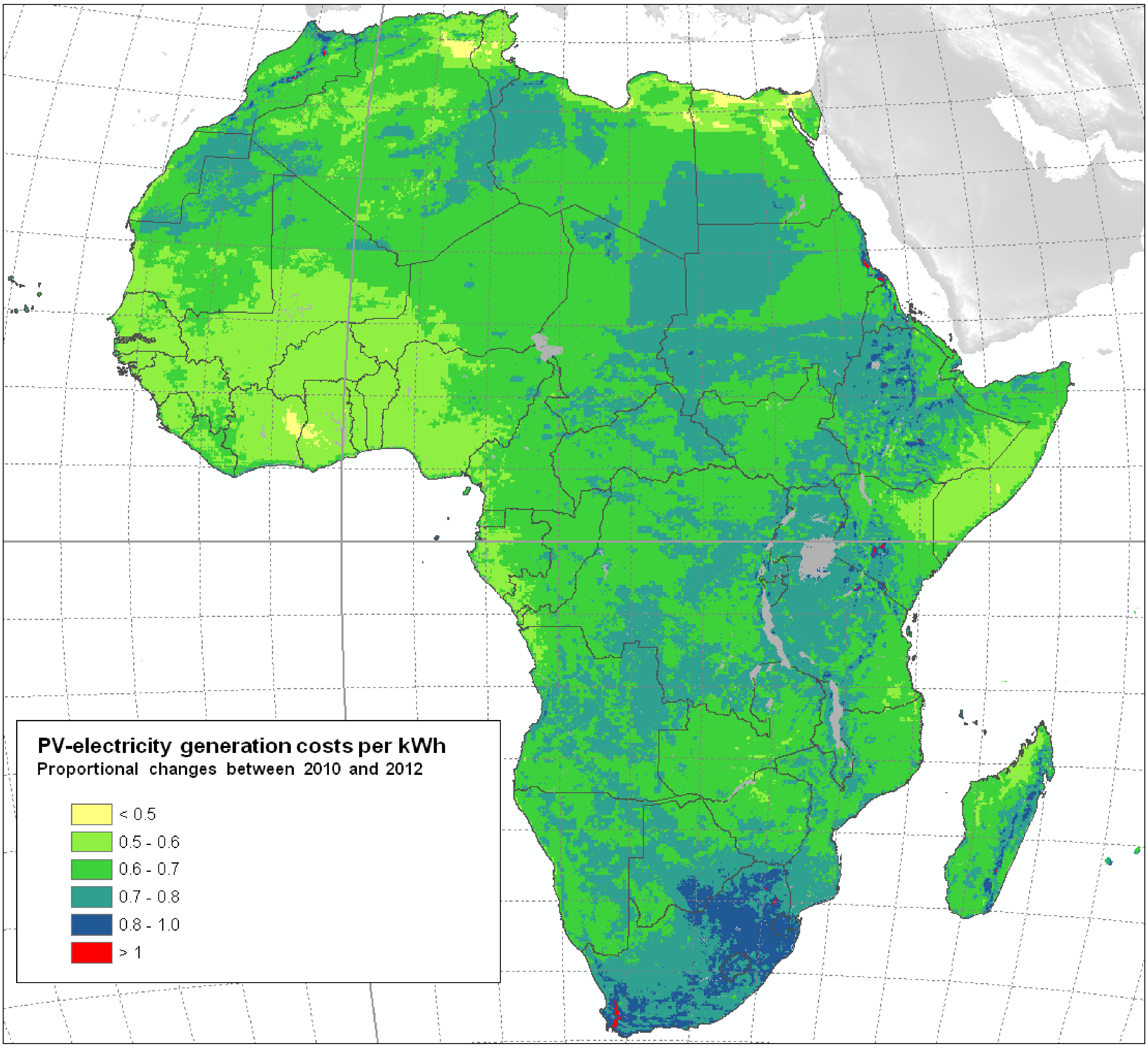

Figure C.7 Changes in the cost of PV electricity produced by a stand-alone 15 kW system between 2010 and 2012, estimated on the basis of real changes in component costs (Euro per kWh in 2012 / Euro in kWh in 2010).

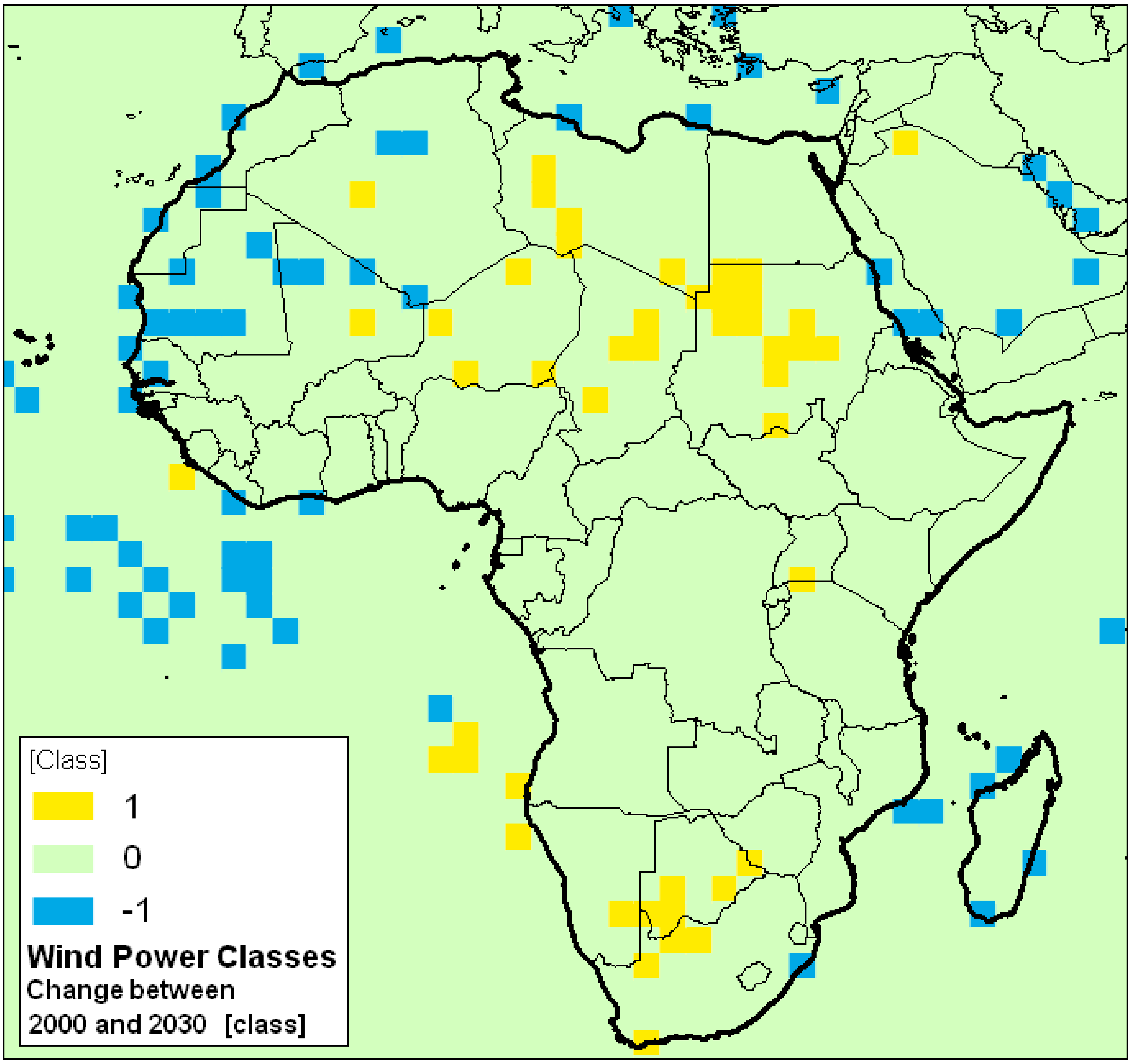

Figure C.8 Changes in wind power class between 2030 and 2000 (right – W/m^2). Computations are based on wind data (Figure C.4) provided by the ECHAM-HAM model. See Paragraph 3.2 for explanation.

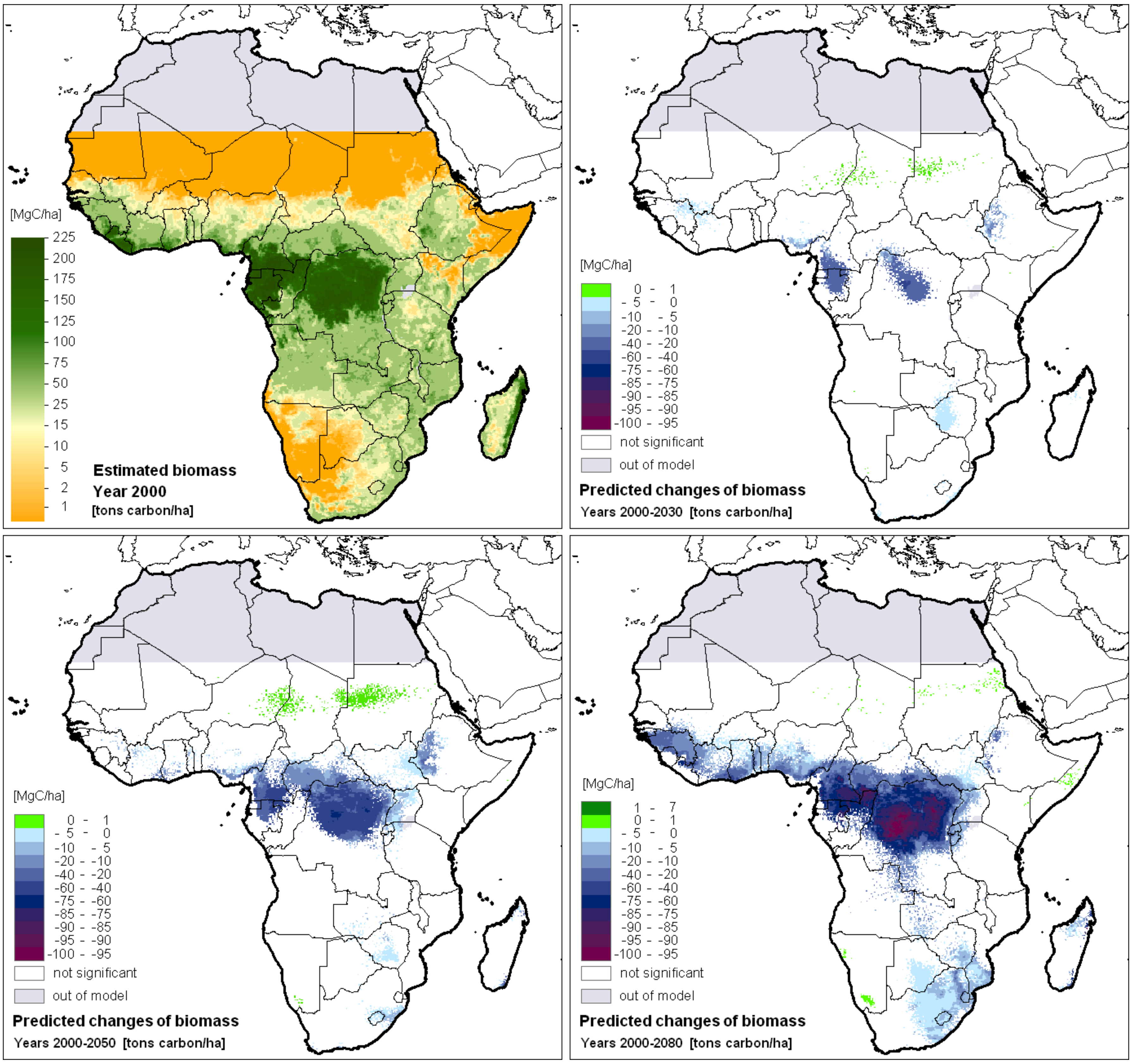

Figure C.9 Changes in the estimated biomass stocks between 2000 and 2080 in sub-Saharan Africa. Data are provided in tons of carbon/ha and are shown only for statistically significant values ($p < 0.05$). See paragraph 4.5 for details.

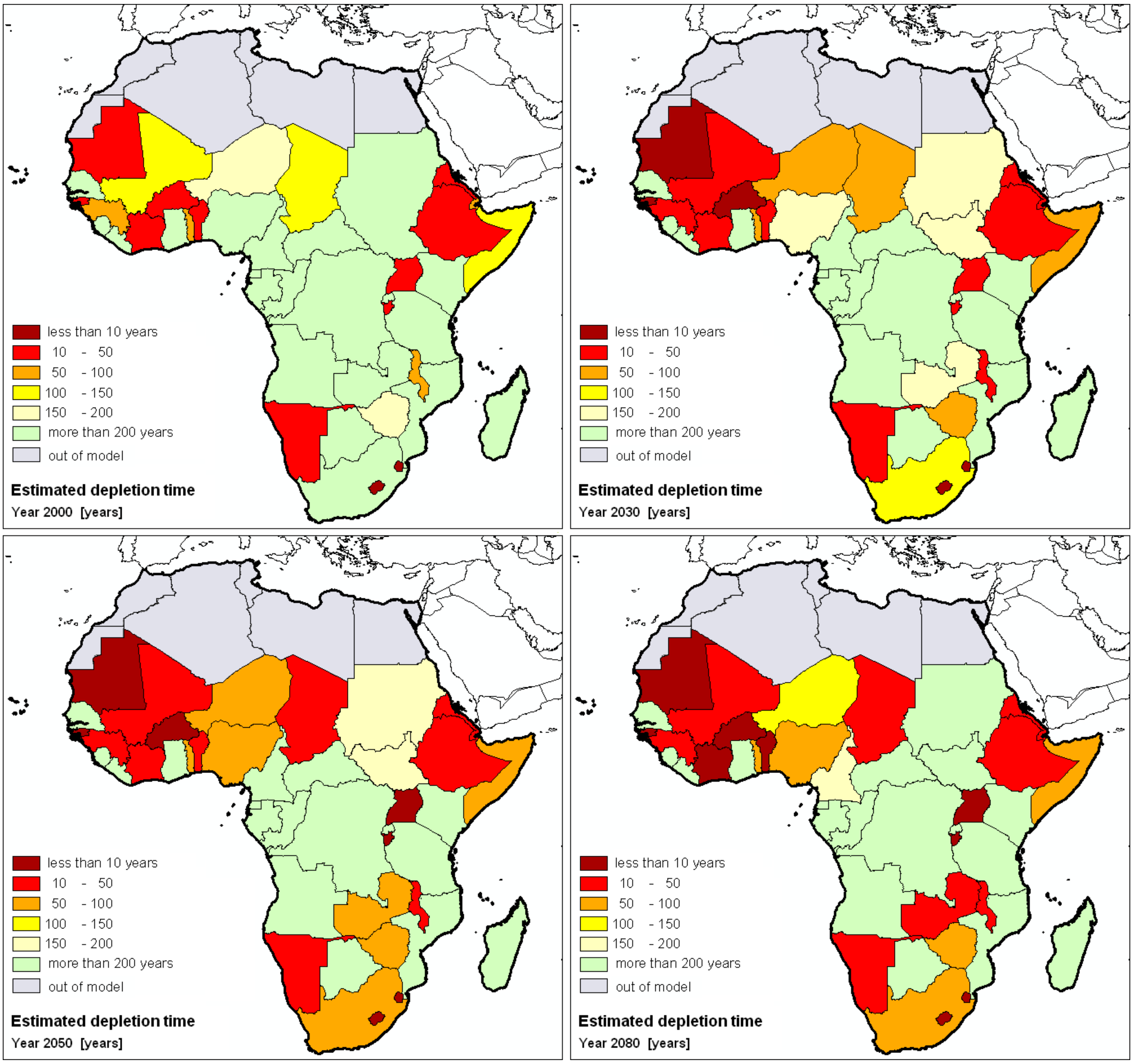

Figure C.10. Estimated depletion time (years) of biomass resources in Sub-Saharan Africa, defined as the ratio between available biomass and fuelwood consumption. See section 4.5 for extensive discussion.

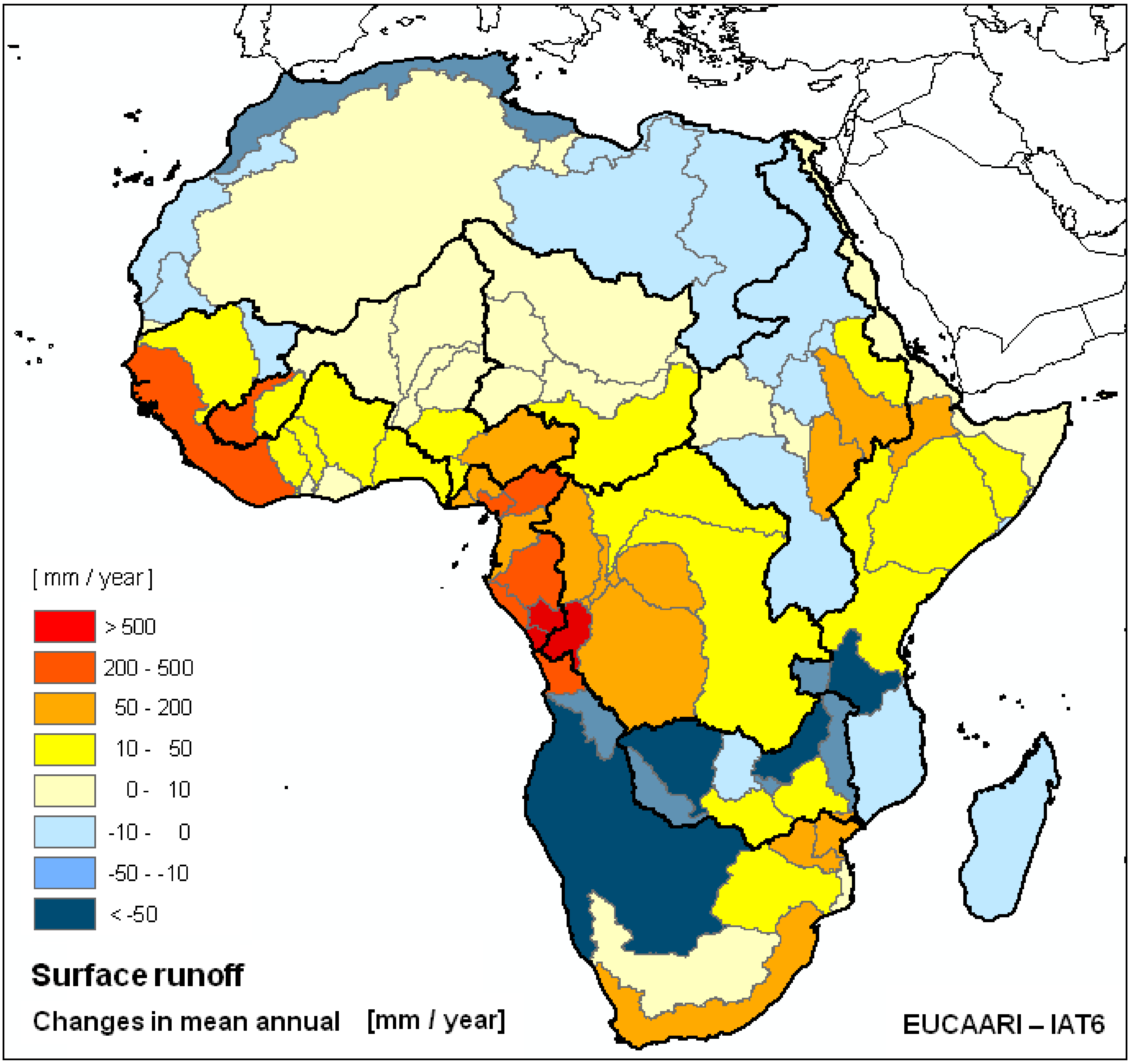

Figure C.11 Aggregated average changes in surface runoff between 2000 and 2030 (mm/year) aggregated within the main river (drainage) basins. Computations are based on runoff data (Figure C.5) provided by the ECHAM-HAM model. Areas characterised by statistically not significant ($p < 0.05$) changes have been taken out from the data series.

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Abstract
Future Renewable Energy availability under the foreseen climate evolution for the next decades in the African continent is assessed. The evolution pattern of the natural resources (solar radiation, wind, biomass and running water) providing the raw "material" for Renewable Energy is analysed following some key climate scenarios developed and analysed inside the JRC.

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