Greenhouse Gas Observation
& Climate-Smart Agriculture

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Climate system-related observation networks in Africa, and the variables needed for a comprehensive system

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Funded by the
European Comission
under the Horizon2020
Work Programme

Project: 730995 - Supporting EU-African Cooperation on Research Infrastructures for Food Security and Greenhouse Gas Observations (SEACRIFOG)

Work package number: 3

Work package title: Developing a common research agenda to promote Carbon, GHG and aerosols observations in Africa to fill gaps in a global observation system

Deliverable number: 3.1

Deliverable title: (in original proposal) Report about existing network and perspective for further development (revised title suggested for this report) Climate system-related observation networks in Africa, and the variables needed for a comprehensive system

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Submitted by: Veronika Jorch

Place, Date of submission: Potsdam, 31.08.2018

Executive Summary

This report is Deliverable 3.1 of the SEACRIFOG project, and reports on subtasks 3.1.1 and 3.1.2 of Work Package 3, which set out to document the current climate-system relevant observation networks in Africa, and the variables which would be required for a comprehensive system to estimate net climate forcing over the continent of Africa, with an accuracy comparable to that achieved in the rest of the world.

A web-based tool was used to solicit information from SEACRIFOG partners or other interested parties regarding existing observation nets which could potentially be useful for the purposes of observing the net climate forcing from Africa; either in their own right since they already collect required variables, or because they could be enhanced with instruments to collect missing variables. As of July 2018 47 such networks, collectively comprising hundreds of sites, were documented. The total will likely continue to grow somewhat as new networks are discovered or come on stream. The survey covered all observation domains: the land, atmosphere, freshwater, coastal and marine, and included surface-based, airborne and satellite platforms. While a good start, the existing networks are deficient for a comprehensive system in several regards: some key variables are missing; the spatial density or distribution may be inadequate; the data are not routinely and reliably available in the public domain; the achieved accuracy may be insufficient; and some observation domains are less developed than others.

The variables actually being collected, and those required for a comprehensive and sufficient climate forcing observation system, were solicited through the networks identified above, through various global observation system design documents, and through a top-down design exercise carried out by SEACRIFOG. The prioritised list for an operational system comes to about 40 variables. The available technologies, their costs and performance characteristics were documented, as an input to SEACRIFOG Tasks 3.2.1 and 3.2.2, which set out to design an optimised system for the future.

1 Introduction

SEACRIFOG Task 3.1 involves information gathering regarding the stations and systems involved in measuring Greenhouse Gas (GHG) emissions over Africa, and the variables they collect and methods used.

> **Subtask 3.1.1** gathers information about existing and planned carbon cycle and other environmental observation networks in Africa, by reviewing the published and grey literature and conducting web searches, guided by the knowledge of SEACRIFOG participants. For each network, it records the start date, current status, spatial footprint, sensors deployed and variables captured. http://seacrifog-tool.sasscal.org
>
> **Subtask 3.1.2** surveys the technical literature to establish the price and performance specifications of the various sensor approaches applied in Africa and elsewhere to the measurement of key carbon cycle variables.

This deliverable, *D3.1, reports on the above two subtasks.*

Task 3.2, which follows on from these tasks designs an optimized future network for GHG monitoring in Africa over the next two decades. It will be reported in Deliverable 3.2 due in 2019.

2. SEACRIFOG Task 3.1.1: The existing networks and variable specifications

This task was executed by the creation of the web-based SEACRIFOG Collaborative Inventory Tool (http://seacrifog-tool.sasscal.org/) by the partner Southern African Science Service Center for Climate Change and Adaptive Land Management (SASSCAL), in service of tasks related to SEACRIFOG WP1, WP3 and WP4. The SEACRIFOG Collaborative Inventory Tool allows the systematic capturing of information on variables, observation networks and infrastructures, as well as existing data products relevant to the objectives of SEACRIFOG, i.e. the design of a future Africa-wide greenhouse gas observation system. All consortium partners were invited to use the tool to contribute their knowledge of existing networks. They were further asked to recommend external contributors who may bring in additional expertise. The web site is currently password-protected to avoid corruption by spurious entries. Permission to access it can be granted by Johannes Beck at johannes.beck@sasscal.org. The tool may be turned into an open-access public resource at a later stage of the SEACRIFOG project.

The purposes of the web tool are as follows:

1. identifying potentially relevant variables to be considered in the context of SEACRIFOG. (Task 4.1a)
2. prioritizing the resulting ideal set of potentially relevant variables in order to identify a set of essential variables to be considered in the context of SEACRIFOG (Task 4.1b)
3. creating an inventory of existing and planned research infrastructures relevant to SEACRIFOG (Task 3.1.1)
4. creating an inventory of available data products for the relevant variables in order to identify needs, gaps and opportunities (Task 4.2, Task 1.3)

The tool consists of four interactive tabs:

Variable Classes: The list in this tab contains all variables and variable classes of potential relevance to SEACRIFOG. The tab is titled 'variable classes' because it can contain variables which consist of several sub-variables. All contributors were requested to contribute to the completion of this 'long-list' by adding potentially relevant variables and corresponding information.

Variable Rating: In analogy to the identification process of the 'Essential Climate Variables', all contributors were requested to rate the variable classes in the long-list (see above) according to their SEACRIFOG-specific relevance, feasibility and cost. The ultimate outcome of this survey-style exercise is a measure of 'essentiality' for each variable in the long-list, which would allow for defensible decision-making with regards to the set of 'mandatory' or 'essential' variables to be considered by SEACRIFOG.

Observation Networks/Infrastructure: The list in this tab contains all existing and planned observation networks and infrastructure potentially relevant to SEACRIFOG. All SEACRIFOG consortium partners and external contributors were requested to help making this inventory as complete as possible. As a result, the spatial coverage of the networks could be be established, allowing for a comprehensive spatial analysis and spatial network design.

Sub-Variables and Data Products: The list in this tab contains all sub-variables or data products for the essential variable classes to be considered under SEACRIFOG. For example, consider the essential climate variable (ECV) 'Anthropogenic GHG Emissions': This is listed as a single variable in the ECV list, but consists of various sub-variables, e.g. CO_2 emissions, CH_4 emissions and N_2O emissions. This tab captures the more granular sub-variables and the corresponding data products associated with the broader 'variable class'.

The following report on outcomes of this data-gathering approach is based on the situation captured by the Inventory Tool as of early July 2018. The tool will remain accessible through the web, and open for input by authorized persons, throughout the duration of SEACRIFOG, in order to remain as current as possible and provide a place for the capture of newly-formed or newly-discovered networks.

Figure 1 contains a screenshot of the tool section "Observation Networks/Infrastructure", through which relevant existing and planned observation networks are captured. The section contains a searchable list of networks on the left side. When a user selects a network from that list, detailed information on that network is provided on the right. If applicable and available, an interactive map further visualizes the individual sites of that network against different base layers. Registered users can add new networks, edit existing ones and upload site-specific information in the form of csv-files.

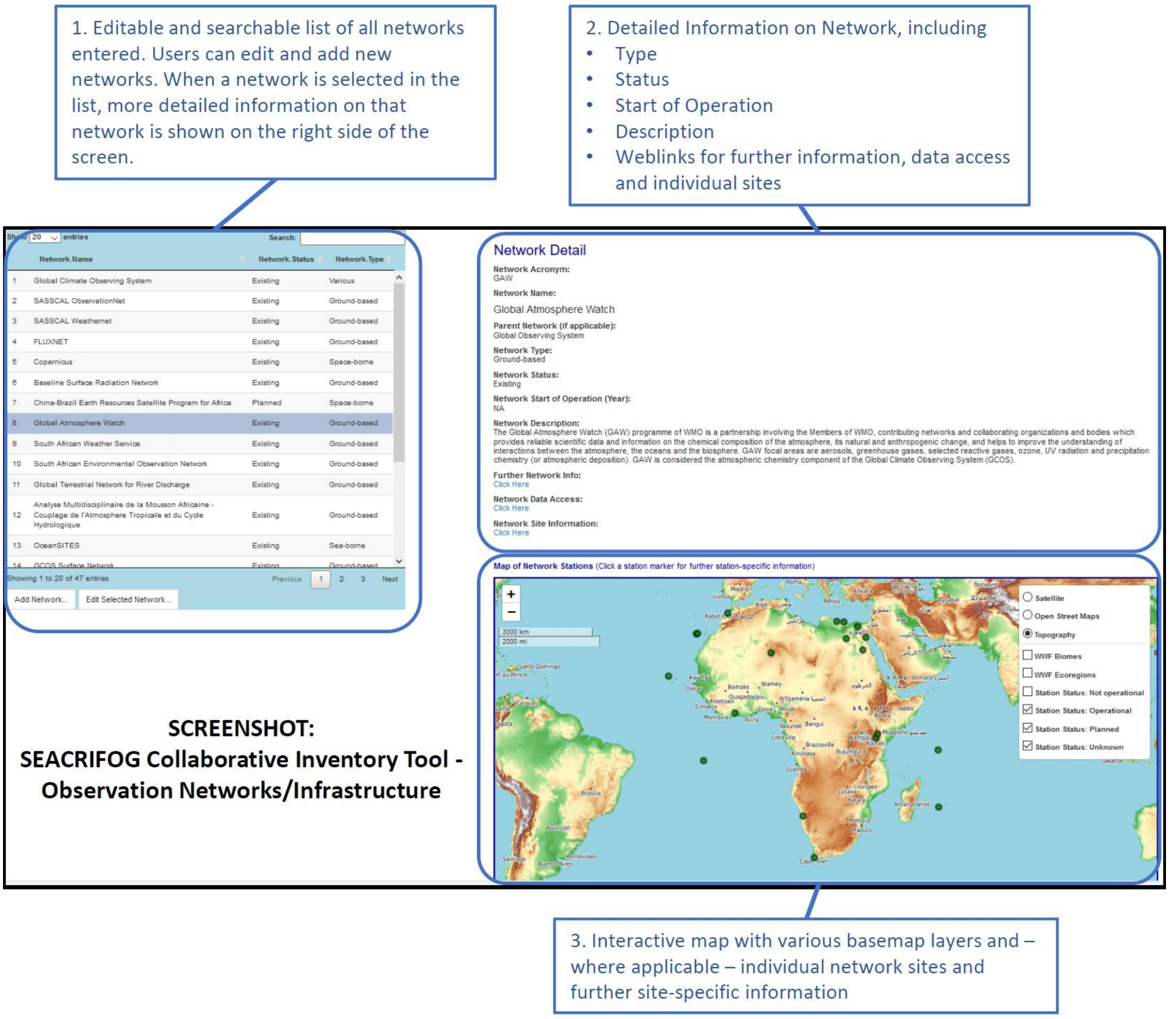

Figure 1: Screenshot of the tab "Observation Networks/Infrastructure" of the SEACRIFOG Collaborative Inventory Tool (http://seacrifog-tool.sasscal.org/).

As of early July 2018, more than 200 contributors were given access to the web-tool and invited to provide their input. Only a small fraction of these actually provided information by July 2018.

2.1 Observational networks relevant to greenhouse gas observations relating to Africa

As of July 2018, 47 relevant networks had been identified, with a combined total of hundreds of observation sites. The inventory is not considered exhaustive, so it is likely that this list will continue to grow. The networks currently captured are summarized in Table 1, and selected locations of sites for the main observational domains (atmosphere, land, ocean and rivers) are shown in figure 2.

Table 1. African and circum-African observational networks relevant to the quantification of greenhouse gas fluxes, as collated by SEACRIFOG in July 2018.

Number	Name	Status	Type
1	*Global Climate Observing System*	*Existing*	*Various*
2	*SASSCAL ObservationNet*	*Existing*	*Ground-based*
3	*SASSCAL Weathernet*	*Existing*	*Ground-based*
4	*FLUXNET*	*Existing*	*Ground-based*
5	*Copernicus*	*Existing*	*Space-borne*
6	*Baseline Surface Radiation Network*	*Existing*	*Ground-based*
7	*China-Brazil Earth Resources Satellite Program for Africa*	*Planned*	*Space-borne*
8	*Global Atmosphere Watch*	*Existing*	*Ground-based*
9	*South African Weather Service*	*Existing*	*Ground-based*
10	*South African Environmental Observation Network*	*Existing*	*Ground-based*
11	*Global Terrestrial Network for River Discharge*	*Existing*	*Ground-based*
12	*Analyse Multidisciplinaire de la Mousson Africaine - Couplage de l'Atmosphere Tropicale et du Cycle Hydrologique*	*Existing*	*Ground-based*
13	*OceanSITES*	*Existing*	*Sea-borne*
14	*GCOS Surface Network*	*Existing*	*Ground-based*
15	*Global Ocean Ship-Based Hydrographic Investigations Program*	*Existing*	*Sea-borne*
16	*Global Observing System*	*Existing*	*Various*
17	*Global Ocean Observing System*	*Existing*	*Sea-borne*
18	*Argo*	*Existing*	*Sea-borne*
19	*Cooperative Air Sampling Network*	*Existing*	*Various*
20	*Aerosol Robotic Network*	*Existing*	*Ground-based*
21	*Advanced Spaceborne Thermal Emission and Reflection Radiometer*	*Existing*	*Space-borne*
22	*Clouds and the Earth's Radiant Energy System*	*Existing*	*Space-borne*
23	*Multi-angle Imaging SpectroRadiometer*	*Existing*	*Space-borne*
24	*GCOS Reference Upper-Air Network*	*Existing*	*Various*
25	*Global Ecosystem Monitoring network*	*Existing*	*Ground-based*
26	*Global Ocean Data Analysis Project version 2*	*Existing*	*Various*
27	*Greenhouse Gases Observing Satellite*	*Existing*	*Space-borne*
28	*African Tropical Rainforest Observation Network*	*Existing*	*Ground-based*
29	*GCOS Upper Air Network*	*Existing*	*Various*
30	*Global Terrestrial Network - Hydrology*	*Existing*	*Various*
31	*Data Buoy Cooperation Panel*	*Existing*	*Sea-borne*
32	*Ship Observations Team*	*Existing*	*Sea-borne*
33	*Atlas Mohammed V (MARSU project)*	*Existing*	*Ground-based*
34	*Carbon-Ghana*	*Planned*	*Ground-based*
35	*International Soil Moisture Network*	*Existing*	*Ground-based*

36	*Surface Ocean CO2 ATlas*	*Existing*	*Sea-borne*
37	*Sea Level Station Monitoring Facility*	*Existing*	*Ground-based*
38	*ARS AfricaE*	*Existing*	*Ground-based*
39	*Orbiting Carbon Observatory-2*	*Existing*	*Space-borne*
40	*Orbiting Carbon Observatory 3*	*Planned*	*Space-borne*
41	*Total Carbon Column Observing Network*	*Existing*	*Ground-based*
42	*Trans-African HydroMeteorological Observatory*	*Planned*	*Ground-based*
43	*Network for the Detection of Atmospheric Composition Change*	*Existing*	*Ground-based*
44	*African Centre of Metereological Applications for Development*	*Existing*	
45	*Regional Ceter for Mapping of Resources for Development (East and Southern Africa Region)*	*Existing*	
46	*Global Observation of Forest and Land Cover Dynamics*	*Existing*	*Remotely sensed (space and airborne) plus ground calibration*
47	*Eddy Covariance Flux Station Inventory for Africa*	*Existing and campaign*	*Ground-based*

Notes to table 1:

*‘**Status**’ includes networks which are ongoing (‘existing’), those which are planned with reasonable probability of coming into existence by 2022; and those which were executed in ‘campaign’ mode and subsequently closed. The latter sites may be suitable for future infrastructure, and the data relating to the campaigns exist and are in the public domain.*

*‘**Type**’ refers to the dominant way in which the data in the network is obtained: from space-based or airborne remote sensing, ground observations, sea-borne or various. Often the dominant type is supplemented by other types.*

While acknowledging that figure 2 is certainly incomplete, given the fragmented and ever-changing landscape of observations, several important points are already clear. Firstly, Africa and its surrounding oceans are far from ‘*terra incognita*’. The sampling network, particularly for atmospheric and land components, is less dense than in some other world regions, but exists as a useful starting point. Secondly, some observation domains are rather patchily represented: notably the river domain, especially on the eastern seaboard and for the Nile basin; for all observation domains in central equatorial Africa, where access is logistically difficult and personnel and equipment are unsafe; and the southern hemisphere ocean domain in general, since it is very extensive and sees few volunteer ships because it has few traversing trade routes.

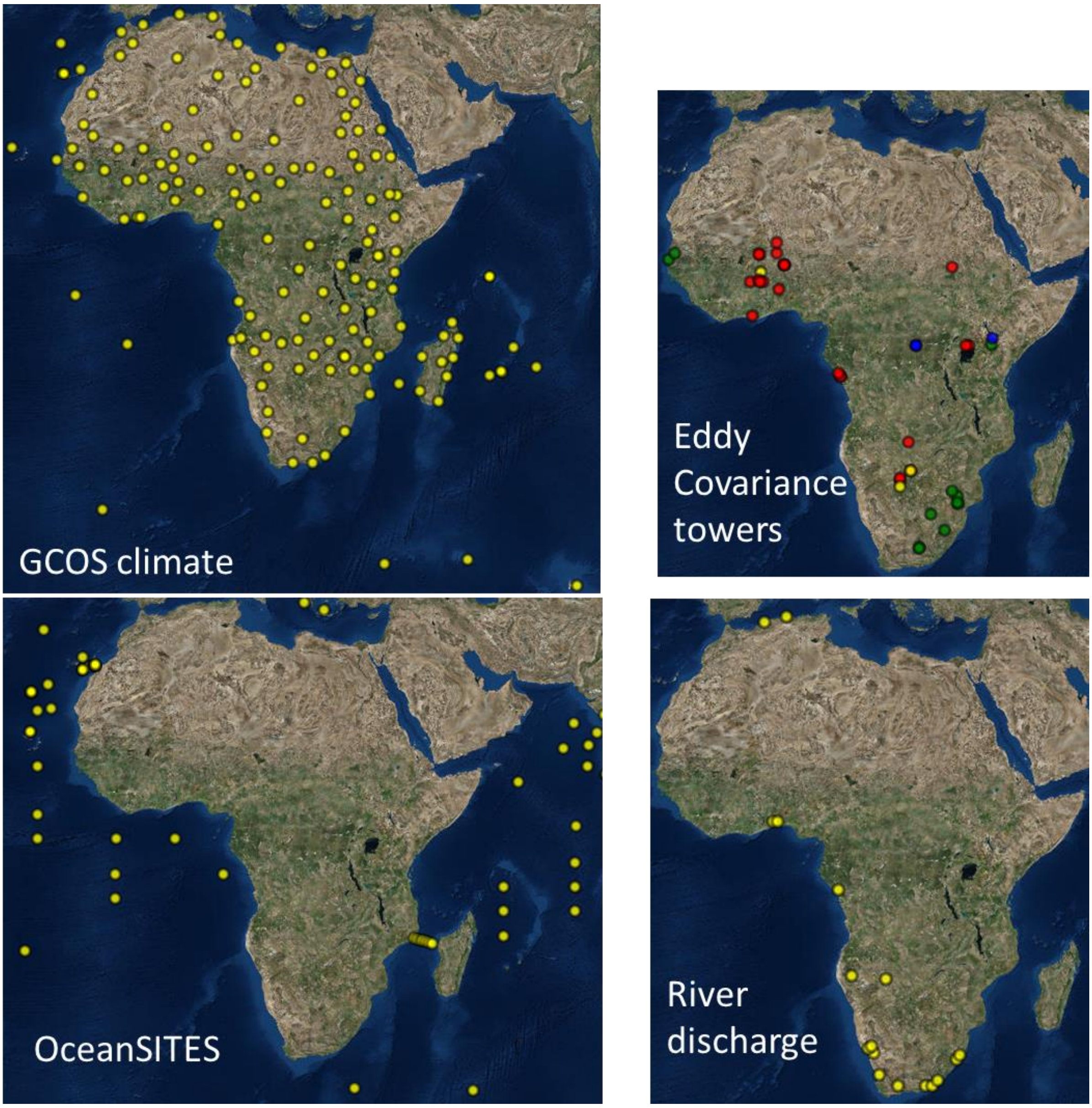

Figure 2 A selection of site networks in various observation domains as of July 2018. The station status is encoded in the symbol color (green – active; yellow – status unknown; red – inactive; blue - planned). In the atmospheric domain, in addition to the Global Climate Observing System (GCOS) sites where climate variables are collected there is also a network of nine cooperative air quality sites (in the Africa region) which include the Global Atmosphere Watch (GAW) sites, and several dozen AERONET robotic aerosol measurement sites. On land, the eddy covariance sites shown here contain a subset that are Fluxnet sites. In the oceans there are several networks, including hundreds of drifting Argo floats that happen to be in the Africa domain, and various volunteer ships which have typical tracks but not fixed stations. In addition to these surface site locations there are numerous satellite-based products with complete Africa coverage, with variables relevant to all domains, at various time and space resolutions

2.2 Variables identified as relevant to greenhouse gas observation systems

A comprehensive list of potentially relevant variables was collected through the SASSCAL tool in line with the task 4.1 (work package 4). It includes variables collected by the various contributing networks, but also a comprehensive collation extracted from a range of mandated variable-identifying processes, including the GCOS essential climate variables, the GEOBON essential biodiversity variables, and the IOC essential ocean variables. The result is a list of 110 variables, some of which are ‘compound variables’ (such as ‘clouds’: which actually consist of a cluster of variables, including cover fraction by altitude for a range of cloud types, each with descriptive variables such as temperature, droplet size and droplet density). A 'crowd-sourced' variable ranking process, involving a within SEACRIFOG volunteer expert-based scoring of relevance and practicality was then conducted, via the web tool, which prioritized the list.

From this sorted list a subset identified by expert judgement was extracted, consisting of those variables which are **directly** and fairly **narrowly**-related to the estimation of anthropogenic climate forcing. The experts were from within the SEACRIFOG team, and were guided by a simultaneous top-down design exercise for a greenhouse gas observation system (Task 3.1.2). The result is a list of 40 variables (Table 2). This list is not yet definite. It should be considered dynamic and undergoing further iterations in the course of the project, but probably captures the main elements.

The columns in table 2 relating to spatial resolution, temporal resolution and required accuracy are all expert judgments, based on how the variable is used and the error propagation involved in getting to a final African climate forcing estimate that is no worse than the estimates for similar continental-scale regions worldwide, which are currently at around ± 15% (where the ± stands for one standard deviation; Global Carbon Budget 2017). The design intent of a future observation network is that it be able to spatially resolve nation-sized entities, since these are the units with international treaty obligations, and is thus the scale at which reporting to the UNFCCC is done. In this context, it is noteworthy that the IPCC is currently drafting the '2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories' where comparisons with atmospheric measurements and inverse modelling are discussed as a verification method. Achieving greenhouse gas budget closure at national scale using a 'top-down' inversion method is a more difficult target to meet than budgeting at the whole-continent scale (which is in turn harder than budget closure at global scale, which has been possible for several years already). African countries vary greatly in both size and emission-generating activity. But since the biggest emitters are also large countries, a target spatial resolution in the order of 500 km x 500 km (which totals about 120 grid cells for complete coverage of Africa) is used, with a target accuracy of about ±20% at this scale. Furthermore, the requirement is guided by what is currently possible using existing, best-practice technology which is neither excessively expensive nor experimental. These estimates, and the main technologies used to obtain them, are explained further in Task 3.1.2. under section 'Variables and observation technologies', later in this report.

Table 2. Variables considered essential for an observation network for quantifying anthropogenic climate forcing over the domain of Africa and surrounding oceans. This network would be able to estimate sources and sinks of greenhouse gases, but also direct forcing due to changes in surface reflectivity. 'int' means interpolated from some other scale; AGB =aboveground biomass; EC=eddy covariance; RUE=radiation use efficiency; TSU=tropical stock unit (~250 kg steer);LCCS=Land Cover Classification System;GDP=Gross Domestic Product; PSU=practical salinity unit; DM=Dry Matter.

Variable	Domain	Units	Spatial resolution	Temporal repeat	Main Technology	Addnl technology	Reqd accuracy
Boundary layer height	Atmospheric	m above surface	20 km	daily	sondes	lidar	500m
Stable Carbon Isotopes	Oceanic	^{13}C, ^{14}C	3 transects	seasonal (3 mo)	mass spectrometer	cavity ring-down	1%
Species Traits	Various	Various, by % of vegetation cover	biome	once	manual measurment	expert judgement	for all species, up to 90% of cover
Litter	Terrestrial	gDM m^{-2}	1 km	seasonal (3 mo)	collect & weigh	modelled	10%
Below-ground biomass	Terrestrial	gDM m^{-2}	1 km	5 annual	root core	expansion factor to AGB	10%
Ecosystem Function	Various	NPP in gC m^{-2} y^{-1}	1km	monthly	RUE model	increment, harvest, EC	10%
Nitrous oxide (N_2O) flux	Terrestrial	mmol N_2Om^{-2} s^{-1}	points	hourly	Chamber	EC	5%
Methane (CH_4) flux	Terrestrial	mmol CH_4 m^{-2} s^{-1}	points	hourly	EC	chamber	5%
Runoff	Terrestrial	mm	1 km	monthly	modelled	runoff plot	10%
Anthropogenic Greenhouse Gas Emissions	Terrestrial	TgGas y^{-1}	national	annual	Inventory	modelled	10%
River Discharge	Terrestrial	$Mm^{-3}d^{-1}$	river basin	monthly	River gauge	modelled	10%
Carbon dioxide (CO_2) flux	Terrestrial	mmol CO_2 m^{-2} s^{-1}	points	hourly	EC	chamber	5%
Soil Organic Carbon	Terrestrial	gC m^{-2} to 1m	1 km	10 yearly	core	modelled	5% (100 gCm^{-2})
Surface Roughness	Terrestrial	m (Z_0)	1 km	5 annual	lidar	Met tower	1 m
Soil Moisture	Terrestrial	mm	1 km	daily	passive radar	modelled,in situ sensor	10% relative
Ocean Colour	Oceanic	Spectral function	1 km	8 daily	Multi spectral satellite		10 nm, 5%
Albedo	Terrestrial	MJ MJ^{-1}	300 m	monthly	Satellite	albedometer	5%
Sea Surface Salinity	Oceanic	g kg^{-1} (PSU)	1 km	8-daily	Satellite	Electro-conductivity	1%
FAPAR	Terrestrial	MJ MJ^{-1}	300 m	8 daily	Satellite	ceptometer	5%
Pressure (surface)	Atmospheric	Pa	20 km, int	hourly	Transducers	modelled	100 Pa (1%)
Lakes and impoundments: extent	Terrestrial	ha	20 m	seasonal (3 mo)	Satellite	depth sensor	1%
Water Vapour (surface)	Atmospheric	g m^{-3}	20 km, int	hourly	RH sensor	satellite, surface t	5%
Surface Wind Speed	Atmospheric	m s^{-1}	20 km, int	hourly	anemometer	satellite, model	10% (2 ms^{-1})
Livestock Population	Terrestrial	TSU km^{-2}	20 km	5 yearly	census	modelled	15%
Net Radiation (SW+LW)	Terrestrial	W m^{-1}	1 km	once	net radiometer	Satellite	5%
Crop Yield	Terrestrial	kg DM ha^{-1} $crop^{-1}$	national	annual	natl ag stats	farm survey, modelled	10%
Fire burned area	Terrestrial	km^{-2}	300 m	8 daily	Satellite	airborne	5%
Land cover	Terrestrial	ha by LCCS class	300 m	5 yearly	Satellite	ground calval	85% correct
Economic Development	Terrestrial	GDP	Nation	Annual	Natl stats	Global stats	5%
Above-ground biomass	Terrestrial	gDM m^{-2}	1 km	5 yearly	Lidar, radar	Ground plots	15%
Precipitation (surface)	Atmospheric	mm	1 km	daily	rainguage	Radar	10%
Sea Surface Temperature	Oceanic	°C	1km	daily	Satellite	temp sensor	0.1° C
Temperature (surface)	Atmospheric	°C	1 km	hourly	weather station	satellite	0.1 °C
Human Population	Terrestrial	people km^{-2}	20 km, int	5 yearly	Census	lights at night	5%
Fire date of burn	Terrestrial	yyyymmddhh	20 km	daily	satellite	ground observer	1 hour
Carbon dioxide mixing ratio, boundary layer	Atmospheric	mmol mol^{-1}	~ 10 sites	daily	chamber ring-down	IRGA	0.1 ppm
Methane mixing ratio, boundary layer	Atmospheric	mmol mol^{-1}	~ 10 sites	daily	chamber ring-down	IRGA	1 ppb
Cloud cover fraction	Atmospheric	fraction by type	2.5 km	hourly	Satellite	ground sensor	10% abs
Chlorophyl _a in surface water	Oceanic	mg kg^{-1}	1 km	8 daily	Satellite	ship/UAV sensor	5%
Land Use	Terrestrial	Action calendar	1 km	annual	Expert	model inference	80% correct
Marine nutrients	Oceanic	N, P and micro-nutrients mg l^{-1}	biochemical province	seasonal (3 mo)	ship-board analysis	inference from marine biome	20%

3. SEACRIFOG Task 3.1.2: Specifications of variables

Subtask 3.1.2 surveys the technical literature and consults experts in observation technologies - in particular those with experience in Africa - to establish the price and performance specifications of the various sensor approaches applied in Africa and elsewhere to the measurement of key carbon cycle variables.

3 Subtask 3.1.2 Terms of reference: Performance characteristics of observation technologies

The task terms of reference are as follows: *Develop a costing and technical performance model for key observation infrastructures, based on particular observation technologies for key variables identified in task 4.1 (see table 2 above) in order to build effort versus accuracy curves for each. In general the costs to make an observation or series of observations at a location can be calculated: these include equipment acquisition and operation costs, personnel costs for both making the observation and post-processing, and infrastructure support costs. These costs per observation show a relationship (typically exponentially declining) with effort (ie, number of observations taken and number of locations sampled) due to economies of scale and learning curves. The accuracy per observation is intrinsically determined by the technology used, but the accuracy of the system as a whole broadly improves as a function of 1/n, where n is the number of independent observations (for spatially and temporally auto correlated observations the relationship is also declining, but at a lower rate). This information can be used to construct accuracy vs effort (where effort is denominated in total cost terms) curves for the various technologies that can be applied to each key variable. These are then inputs to the model used to design an optimal mix, given an existing infrastructure and future needs. Wits to lead the subtask (2 person months), with interaction with task 5.*

3.1 The spatial domains

The following spatial domains are defined, along with their spatial resolutions. Domain refers to the extent of coverage, while resolution is the scale of the smallest detail which can be observed.

<u>All of Africa and adjacent oceans</u>

The extremes of this domain are defined by the oceanic GAW stations around Africa, which constrain the transport modelling domain covering the continent of Africa: Cape Verde Islands to the west, Amsterdam Island to the south and east, Izana to the north. The west boundary is 25° W, the east 77 °E, North 37 °N and south 38 ° (see ***Fehler! Verweisquelle konnte nicht gefunden werden.*** *3*). This corresponds approximately to the CORDEX region, but extend a little to the south and east to include Amsterdam Island. The resolution is set by the grid spacing of Global Circulation Models, which is quite variable and uses different projections, but the CLIVAR ensemble and the CMIP5 and CMIP6 models typically generate output at 1 degree latitude and longitude or better, with the most-resolved models at **0.25 degree**. Downscalings are possible at virtually any resolution using the CCAM stretched grid configuration as run by the CSIR, but with exponentially-increasing computational effort and accompanying uncertainties.

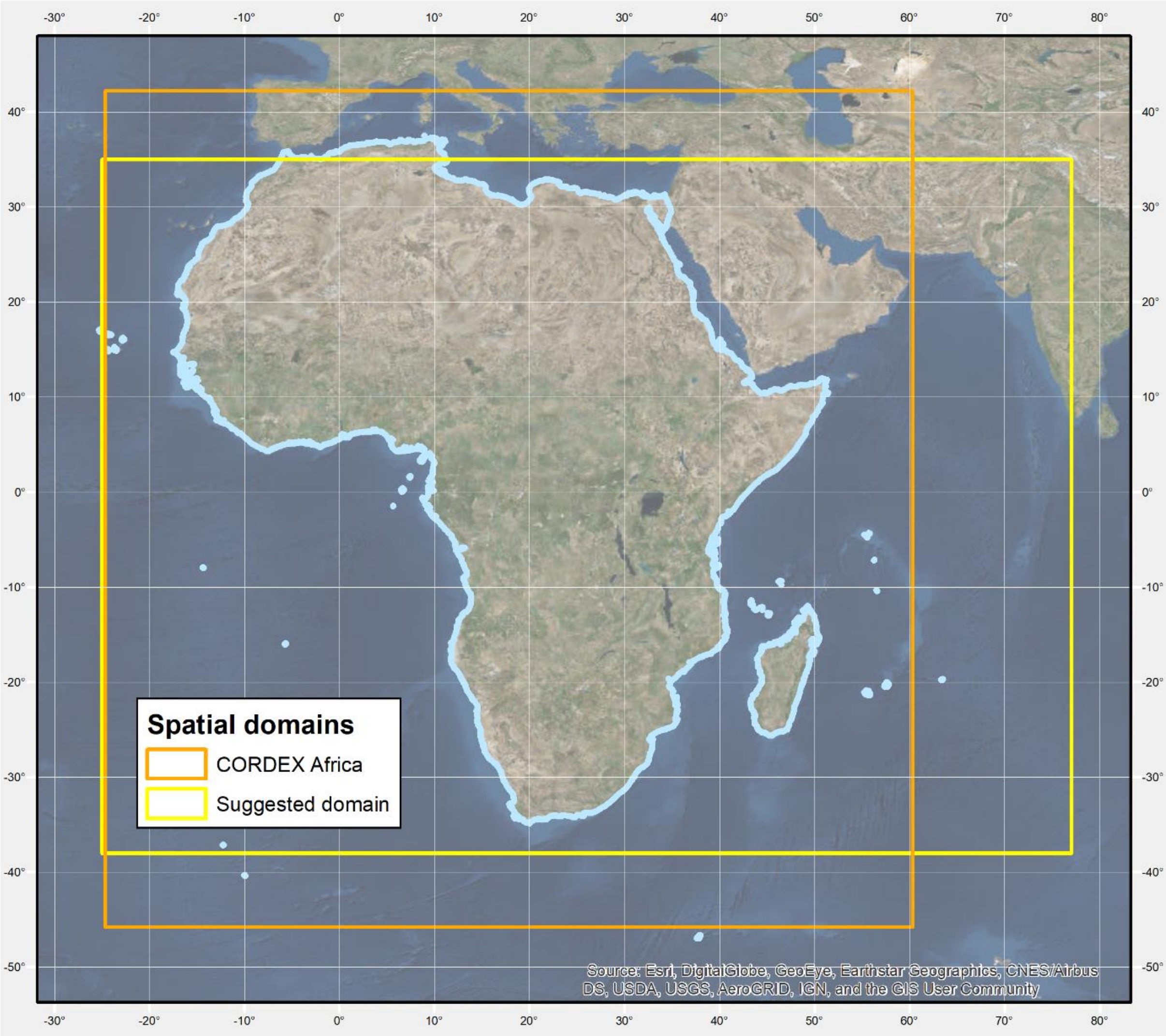

Figure 3 Spatial domain for Africa and the surrounding oceans.

<u>All of Africa land</u>

This includes the land area of continental Africa (29.78 million km^2) and Madagascar (587 044 km^2), including the wetlands, lakes and rivers within the land mass. The small fringing islands are excluded, except where they constitute nations reporting to the UNFCCC and have an area greater than 100 km^2. For most space-based observational purposes a spatial resolution of **1 km** is achievable everywhere, since it represents ~10-16 moderate resolution satellite pixels (250-300m, with 1 to 16 day return periods) or several thousand high resolution pixels (20m, with ~ annual return periods, though declining to ~ 3 days due to the availability of constellations of compatible satellites, such as the Landsat and Sentinel 2 series). A resolution of 1 km captures the main land cover and topographic features with sufficient fidelity to allow within-nation disaggregation with acceptable precision, even for small countries. Many land datasets are available at much higher resolution (e.g. digital elevation models (DEMs) and land cover, both at 30 m), but these often have greater uncertainty than the coarser products and impose 100 times higher data burdens. Assimilated climate data (i.e., a combination of weather stations and satellite data, assimilated via a climate model which fills in the missing points in space and time) has been available for Africa, since about 2000, to a resolution of about 10 km (3 arc minutes). From that resolution, rainfall and temperature data can be downscaled using DEM-derived altitude as a covariate, in principle to around 30 m. For the purpose of GHG net emission estimations, 1 km would be sufficient to match the other datasets, if downscaling is needed at all – all 100 1 km pixels within a 10 km climate grid could simply be assigned the same value, or a smoothed spline could be applied at 1 km resolution.

Some datasets - for instance, GHG emissions as reported to the UNFCCC by treaty signatories - are only available at **national** resolution, and 5 yearly (though in some cases 10-yearly is more realistic, and the latency (delay) is often 5 years). The returns are meant to be disaggregated per year over the reporting period; often this is simply a linear interpolation. There are 54 countries in Africa, the largest being 2.4 million km^2 and the smallest 451 km^2, with the median at 342 000 km^2, i.e. about 600 x 600 km.

Another important resolution is that of the **drainage basin** (also called a 'watershed' or 'catchment' in some literature or disciplines). Drainage basins can be defined at a range of nested resolutions – first order is the entire area draining out at the mouth of the river to the ocean - down to the fundamental limit imposed by the accuracy of the DEMs used to determine the drainage pattern. In practice, for computational reasons, the so-called 3rd order (~500 x 500 km) or 4th order (~100x100 km) catchment is often selected for Africa-wide work, while national work goes to 5th order (~ 20 x 20 km).

3.2 Temporal domains

Temporal domains have a **duration** for which the observational record is available, and a **timestep**, the frequency of observation.

Africa-focused data with acceptable accuracy over the historical period and for the present

Gridded data at 0.5 degree resolution are available annually for historical climate back to 1900, based on data-constrained reanalysis models. They have very large uncertainty over much of the area of Africa, since they contain few actual observations over Africa until around 1960. Climate trend data at monthly or annual time resolution (e.g. point data from selected weather stations) is of acceptable accuracy for many regional-scale purposes from about 1960 onward, but only really becomes reliable at fine resolution (5 -15 km) after about 2000, with the advent of dedicated geostationary weather satellites, polar-orbiting Earth observation satellites (ENVISAT, TERRA, Aqua around 2000, and after 2015 the Sentinel series) and data assimilation models. 'Since 2000' is a sufficient period to encompass, for instance, COP21 goals including a baseline period, but misses the start of the international climate treaty period (UNFCCC, 1992).

The scales of temporal variability of weather data are such that for purposes such as determining or modelling the daily time-course of photosynthesis, respiration and transpiration, sub-daily (typically **hourly**) data are needed, and are available either as satellite products, data assimilation products or automated weather station outputs. Otherwise they can be interpolated from daily maximum-minimum values (e.g. for temperature and RH), or from solar geometry (e.g. radiation). Geostationary weather satellites (Meteosat Second Generation, in the case of Africa) provide data every 15 minutes, for the entire continent and surrounds, at around 2.5 km spatial resolution.

The next logical temporal scale is **daily**, which is a fundamental natural scale which ties in well with synoptic-scale air movements, rainfall events and plant phenology. Capturing sub-annual **seasonal** variation (e.g. summer vs winter, or more pertinently for Africa, rainy season vs dry season, bearing in mind that much of Africa has monsoonal climates with two rainy seasons and two dry season per year) is usually done monthly or in 3-monthly bins (DJF, MAM,JJA, SON). Moderate resolution (300 m) satellite products are often composited to 8 or 16-day products, even if in principle the platform passes over daily, in order to fill in areas obscured by cloud on a single pass. Much land surface modelling makes use of this time resolution, linearly interpolating to the daily timescale if necessary.

The **annual** timescale is the next logical reporting resolution – it ties in with much economic activity data, which is typically reported annually, and automated land cover products.

Some variables are slow-changing and expensive to measure (such as soil variables and plant biomass), so 5-yearly or **decadal** (10 year) resolution is specified. Some are so slowly-changing (soil depth and particle size distribution, elevation) that for this purpose they are treated as 'one-off'.

The effect of future technology on attainable space and time resolutions

It would be desirable to collect some variables at finer time and space resolutions and greater accuracies than are currently or historically available. In particular, this relates to variables which support model-based estimates of rapid-response land- or ocean-based fluxes of CO_2, CH_4 and N_2O. An example is soil moisture, which varies daily, often at a space scale of around 100 m. There is good reason to believe that advances in observation technology (new sensors and data assimilation models) will make some of these variables observable at a spatial scale compatible with land surface modelling at around 1 km, from around 2020 onward. Continued improvements in both observation and computational power may make the 1 km spatial resolution obsolete by about 2030.

New satellite-based aboveground biomass estimates using a combination of LiDAR, Radar and optical sensors are likely to yield biomass values at around 30 m spatial resolution, but realistically with a repeat period of only about 5-years, since some of the sensors are on research platforms such as the international space station, rather than on operational platforms where there is a commitment to long-term operation.

The latest generation of satellite-based atmospheric composition sensors, such as the Orbiting Carbon Observatory, promise continental-wide coverage of whole-column CO_2 with 2x2 km resolution and 1 ppm resolution at regional scales, and repeat frequencies of around a week. This is about an order of magnitude less precise than the ground-based technologies, but many thousands of times more spatially resolved, so potentially this type of observation (and similar ones for CH_4 and N_2O) could be used in conjunction with a relatively small set of ground stations to achieve greater spatial resolution in the emission estimates. The equipment located at the ground stations must be thoroughly planned if it is to achieve full interoperability with the satellite products. In addition to high-temporal resolution time series of CO_2, CH_4 and N_2O concentrations near the Earth surface, they should also measure selected isotopes and tracer gases, in order to distinguish for instance between fossil fuel-derived emissions and ecosystem-derived emission sources, or to split biomass burning sources from soil sources. The direct comparison to the satellite measurement is an upward-looking ground-based total column measurement, performed using sun spectrophotometers or Fourier Transform Infra Red (FTIR) instruments.

4 A top-down analysis of the required variables for a climate forcing observation network

4.1 The need to include all substantive sources of contemporary climate forcing

The 'modern' period of Anthropogenic climate forcing is variously defined as having started around 1750 with the Industrial Revolution and its adaption of fossil fuels as a dominant energy source; or around 1850 with the beginning of the first standardized observations of the climate; or 1950 with the enormous acceleration of economic activity and emissions of all sorts following World War 2. In terms of quantifying the role of Africa in the global trends, very little actual data is available prior to about 1960, but by general consensus, the role of Africa globally was small (~1%) up to the start of the period of contemporary climate concern, marked by the UNFCCC treaty in 1990. Currently Africa contributes around 3.8% of the global total forcing (Brookings Institute 2016). The projections are for a rapidly increasing population in Africa over the 21st century, accompanied by increasing emissions of GHG as a result of technological development and urbanization. This will be accompanied by widespread land use change, currently a dominant driver of African GHG emissions. Therefore by the second half of the century, Africa may be contributing 20% of global emissions, more in line with its fraction of the global land area and population. Currently a large *fraction* (~35%) of the African anthropogenic GHG emissions are associated with Land Use, Land Use Change and Forestry (LULUCF). The high contribution of LULUCF is true at national level too, for all but a few individual African countries (the exceptions are South Africa, Nigeria, Angola, Egypt, Algeria and Libya, all with large fossil-fuel-based industries). The contributions by the various GHGs to the combined forcing are in the same *order* as in other parts of the world- CO_2 makes the biggest contribution, followed by CH_4 then N_2O, but because of the importance of agriculturally-related emissions a relatively bigger fraction of the total is contributed by CH_4, than the global average, and because nitrogenous fertilization and vehicle traffic is low, N_2O emissions are a smaller fraction, though projected to grow.

There is a tendency in policy circles to think of climate forcing as being entirely due to the 'major GHGs' carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (or to make the even more radical simplification of only considering carbon dioxide fluxes, or just an easily observed subset of them, such as those from changes in aboveground biomass). For comparison purposes in the following discussion, the **global** climate forcing in 2010 by the main gases was as follows: CO_2 =1.7, CH_4 =1.0, and N_2O =0.2 Wm^{-2}, for a combined total of 2.9 Wm^{-2} *acting over every square meter of the Earth's surface* (Figure 4). The tendency to focus only on the major gases is reinforced by the fact that all African countries belong to the non-Annex 1 category under the UNFCCC, which have less-onerous reporting requirements, usually restricted to just these three gases. In reality, substantive contributions to climate forcing (i.e. contributions approaching or exceeding the desired accuracy specifications for the climate forcing observation system proposed here, of $\pm$10%) are made by 'minor' GHG, including aerosols, and by the direct biophysical effects of changes to the land surface, mediated by its reflectivity to solar radiation (the 'albedo' effect).

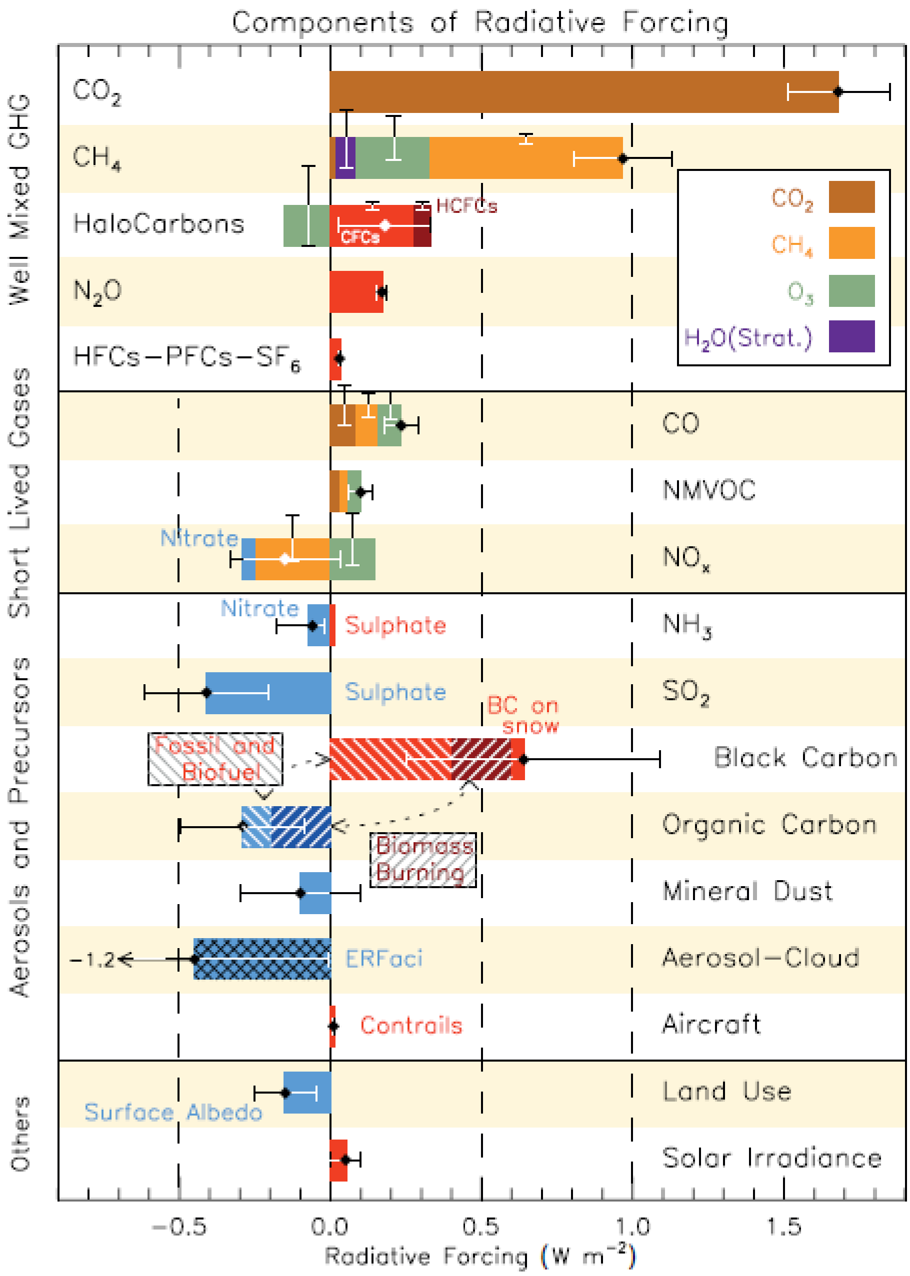

Figure 4 The components of climate forcing at global scale. Source: IPCCAR5 WG 1 fig 8.7 (Myhre et al 2013)

The 'minor' GHG include gases with no natural source (i.e. they are entirely human-made) such as the halocarbons, chlorofluorocarbons and SF_6. Together they provide a net forcing globally of about 0.25 W m^{-2}, about the same as N_2O. Since these gases are entirely synthetic, their estimation is usually based on production (by just a few suppliers worldwide) and trade statistics. Africa is a small source of these minor GHGs, and not likely to grow much as a source now that the production of these gases is restricted because of their effects on the climate and ozone depletion. Often the GAW-type atmospheric composition stations used for CO_2, CH_4 and N_2O monitoring also measure one or more of these constituents, which are useful as air mass tracers. These observations can provide a check on the self-reported emissions by countries.

Tropospheric ozone is a powerful but short-lived GHG, which thus has predominantly regional effects on the climate. It is thus hard to express in CO_2 equivalent terms, but contributes about 0.1 Wm^{-2} globally. Tropospheric ozone is predominantly generated indirectly, through an extremely complex interaction in the lower atmosphere between a large number of trace gases, including non-methane volatile organic carbons (NMVOC), carbon monoxide (CO) and oxides of nitrogen (NOx), in the presence of sunlight. These tropospheric ozone precursors are conventionally thought of as having predominantly industrial or transport system sources, notably as byproducts from high temperature combustion. It was therefore a surprise when seasonally-high concentrations of tropospheric ozone were observed over Africa and surrounding oceans by satellite sensors such as MOPPIT (Thompson et al 1996). Vegetation wildfires producing CO, NOx and NMVOC, soil processes generating NOx and emissions of NMVOC from vegetation are all important sources of ozone precursors in Africa. The reporting of tropospheric ozone and its precursors is not a requirement of UNFCCC, and it is generally not included in efforts to control climate change. It is of scientific interest, and is an important pollutant, since it causes human health issues (respiratory distress) and decreases in crop production. The general network designed by SEACRIFOG provides much of the information needed to estimate tropospheric ozone generation and disappearance, and could be enhanced to measure ozone and its precursors directly. Column ozone can be observed by satellites in a variety of ways.

Aerosols (tiny droplets or particles, suspended in the atmosphere) can either cause global cooling or warming, depending on their nature, properties and location in the atmosphere. They also have a powerful indirect effect through nucleating the formation of clouds. The climate effects globally range from -0.4 W m^{-2} for cloud nucleation and sulphate aerosols, to -0.3 for organic aerosols, -0.2 for mineral dust and +0.6 for black carbon. The overall effect is thought to be about -0.8 W m^{-2} – close to, but opposite in sign, to the forcing by methane. Africa is a major source of mineral dust and vegetation-fire generated aerosols worldwide, accounting for over half of the total.

Worldwide, the total climate forcing also includes a component which is the result of the direct radiative effects of changing the reflectivity of the land surface (i.e., in addition to the effects mediated through the changes in GHG emissions or uptake which result from such changes). The global contribution is estimated as a net cooling of -0.15 Wm^2; compared to sum of major GHG warming of +2.9 Wm^{-2} (Myhre et al. 2013). This forcing has not been disaggregated over Africa, but given the large role which land use change is likely to play in Africa during the 21st century, no observation system aimed at managing the climate changes of the world would be adequate without its inclusion. The forcing from this source is best compared with that from GHGs by expressing both in units of Wm^{-2}, but can also be done by converting the albedo-based forcing to the more familiar CO_2 eq units. The conversion, either of CO_2 eq to Wm^{-2} or vice versa, is not straightforward, and is accomplished using a relatively complex model embodying a number of assumptions.

In summary, a comprehensive climate-forcing observing system for Africa would have the structure depicted in figure 5.

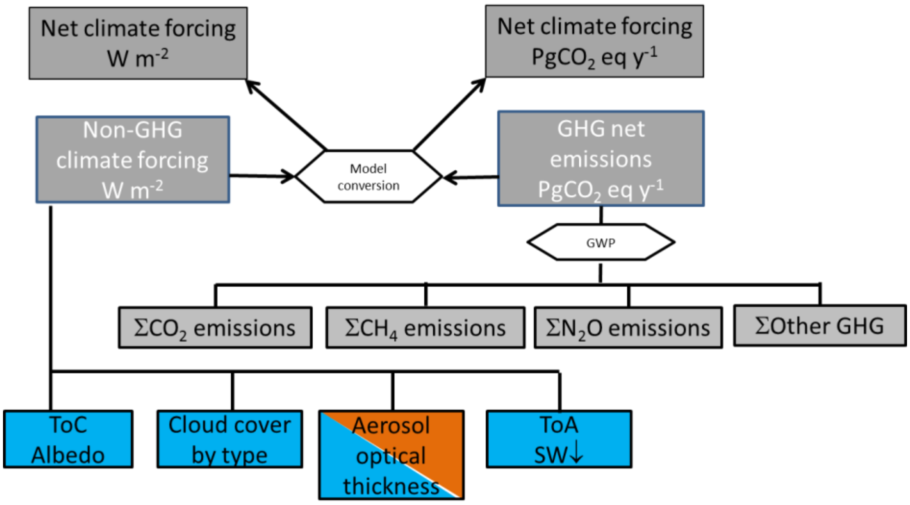

Figure 5 The top-level components of an anthropogenic climate forcing observation system from Africa. Shades of grey are observationally-constrained model products. Sky blue is for space-based observations, orange-brown is for land-based observations. Abbreviations are tabulated at the end of the report.

4.1.1 Carbon dioxide sources, sinks and stocks

The elements of a carbon dioxide observation system, a key subcomponent of figure 5, are shown in figure 6.

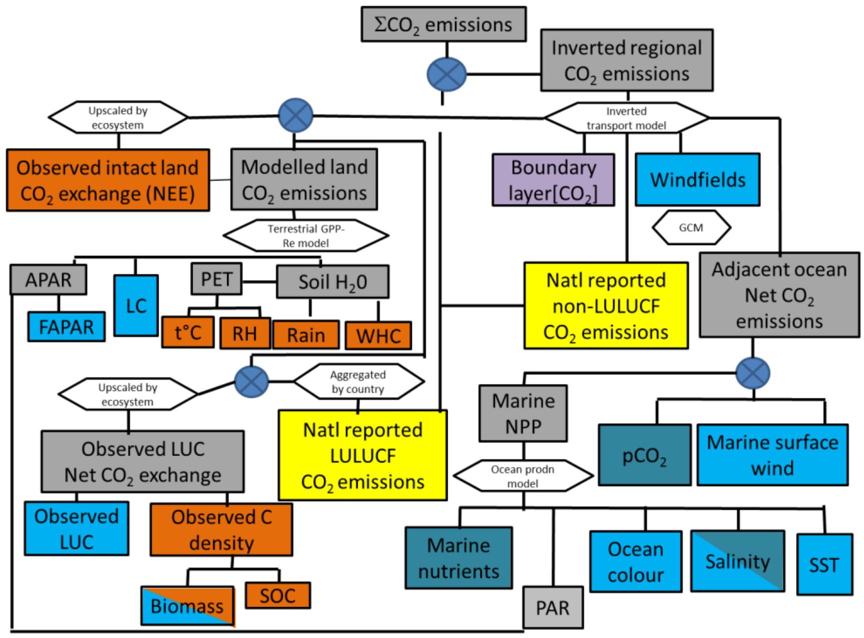

Figure 6 The components of a carbon (CO_2) net emissions observation system for Africa. Shades of grey are observationally-constrained model products. Sky blue is for space-based observations, orange-brown is for land-based observations, dark blue for ocean observations, purple for ground-based atmospheric measurements, and yellow for national inventory reports to the UNFCCC. The hexagons are complex model algorithms. The circles are opportunities for cross-checking data from different sources, and to combine them using Bayesian approaches to synthesize them into a more robust product with lower variance.

All of the variables in this scheme are included in Table 2, with the exception of the nationally-reported (usually inventory-based) anthropogenic emissions. These are reported to the UNFCCC by all signatory countries, approximately every 5 years for African countries, with annual detail provided or interpolated.

4.1.2 Methane sources and sinks

The elements of a methane observation system for Africa are depicted in figure 7. It shares many approaches, observations, datasets and sites with the carbon observing system, improving the cost-efficiency of the combined system. All of the variables are included in table 2, and the methods are described the section below.

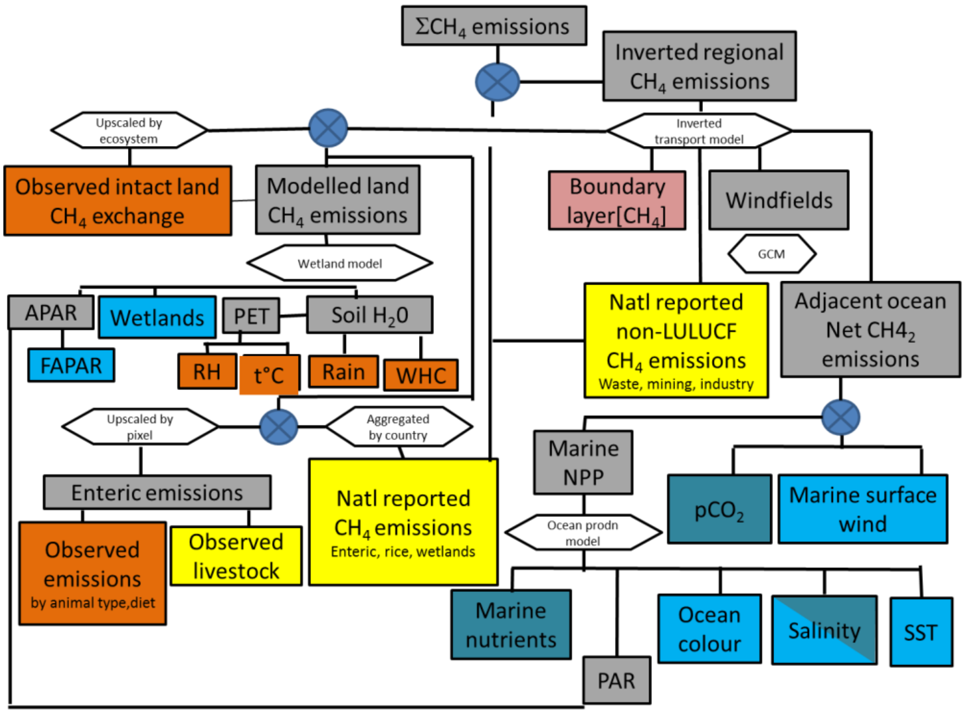

Figure 7. The components of a methane (CH4) net emissions observation system for Africa. Shades of grey are observationally-constrained model products. Sky blue is for space-based observations, orange-brown is for land-based observations, dark blue for ocean observations, purple for ground-based atmospheric measurements, and yellow for national inventory reports to the UNFCCC. The hexagons are complex model algorithms. The circles are opportunities for cross-checking data from different sources, and to combine them using Bayesian approaches to synthesis synthesize them into a more robust product with lower variance.

4.1.3 Nitrous oxide sources and sinks

The elements of an observation system for N_2O from Africa are shown in figure 8. Since N_2O comprises a small part of the current African climate forcing, and its measurement requires different instrumentation to CO_2 and CH_4, it is suggested to take a less-detailed approach than that for those gases, while making use of common infrastructure as far as possible. All the variables are included in Table 2.

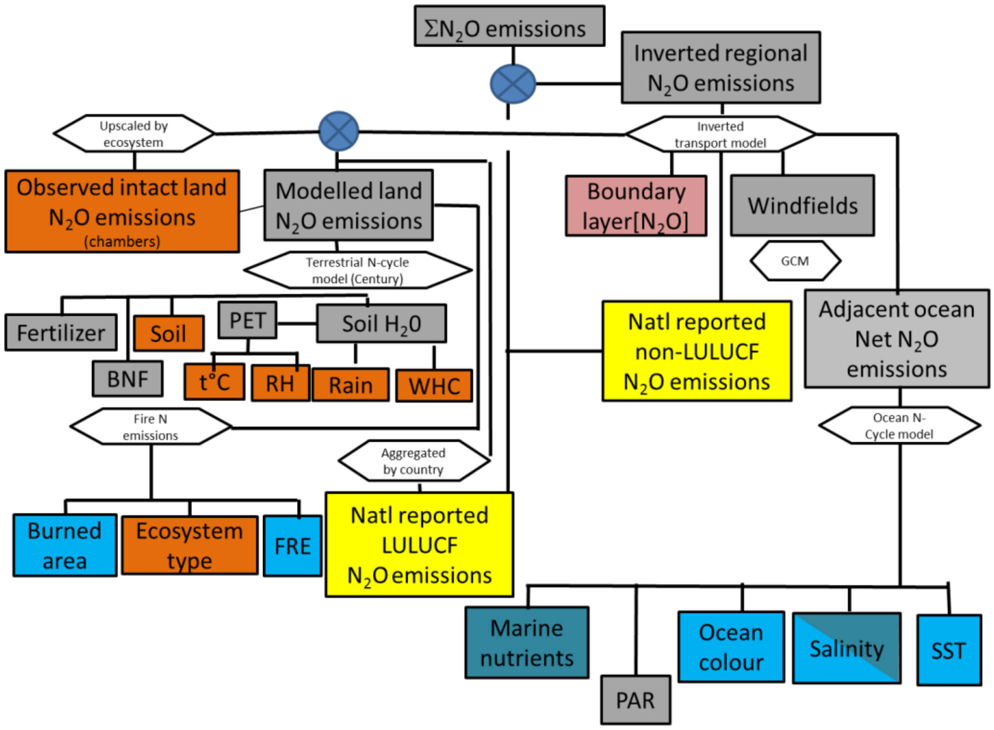

Figure 7 the components of a nitrous oxide (N2O) net emissions observation system for Africa. Shades of grey are observationally-constrained model products. Sky blue is for space-based observations, orange-brown is for land-based observations, dark blue for ocean observations, purple for ground-based atmospheric measurements, and yellow for national inventory reports to the UNFCCC. The hexagons are complex model algorithms. The circles are opportunities for cross-checking data from different sources, and to combine them using Bayesian approaches to synthesize them into a more robust product with lower variance.

4.1.4 An observations system for minor greenhouse gases and aerosols

The necessary elements of an observing system for the emissions of minor GHGs (ozone precursors, Chloroflurocarbons etc.) and aerosols from Africa are shown in figure 9. It has rather different elements, but similar design principles, to the systems for the major GHGs, but could benefit from integration and colocation with those systems. Some of these variables are not listed in Table 2, since that table emerged ‘bottom-up’ from a series of sources, none of which were considering aerosols or minor GHG.

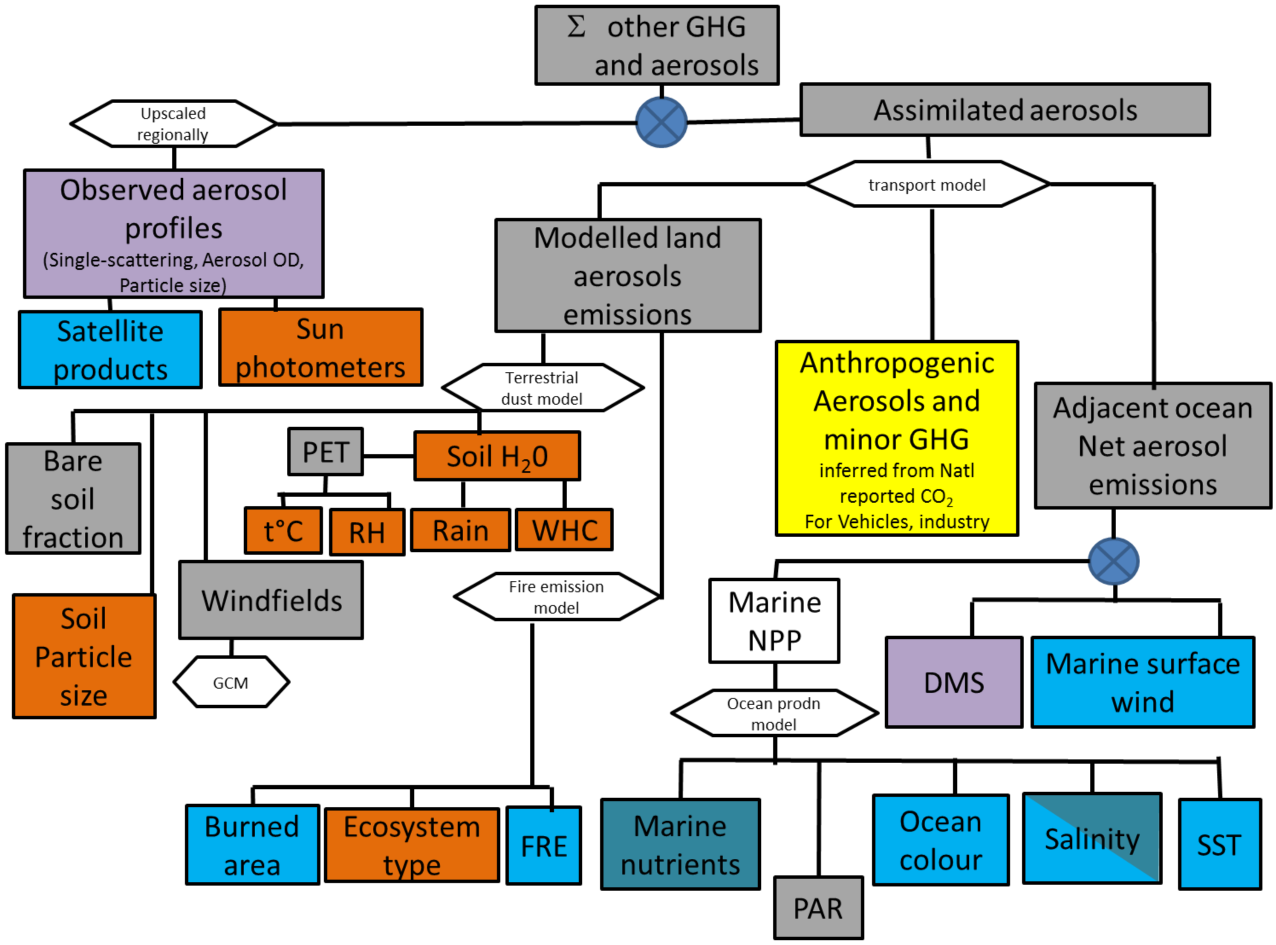

Figure 8 The components of a minor GHG and aerosols observation system for Africa. Shades of grey are observationally-constrained model products. Sky blue is for space-based observations, Orange-brown is for land-based observations, dark blue for ocean observations, purple for ground-based atmospheric measurements, and yellow for national inventory reports to the UNFCCC. The hexagons are complex model algorithms. The circles are opportunities for cross-checking data from different sources, and to combine them using Bayesian approaches to synthesize them into a more robust product with lower variance.

5 Variables and observation technologies

Each of the necessary variables for a greenhouse gas observation system, identified through the above process and listed in table 2, is described in more detail below. The accuracy estimates (± x%) refer to the standard deviation as a percentage of the average value (or in some cases, as a percentage of the absolute value of the expected maximum or minimum, where for instance the average is small because it is the sum of a large source and a large sink), for a standard off-the-shelf instrument, calibrated and well-maintained with a best-practice level of replication at a site.

Boundary layer height: Traditionally this is measured with a weather sonde ('weather balloon'), but there are very few locations in Africa which routinely launch sondes, because of the expense of doing so. The modern technique is to use a ground-based Lidar, or sonar technology; but that is also expensive and not routinely implemented in Africa. Commercial aircraft fitted with temperature-altitude loggers can provide the atmospheric profiles used to estimate boundary layer height in the vicinity of their ascent and descent paths. There are ways to infer the boundary layer height from satellite-based sounders. The default is to infer the information from weather data assimilation models, which run over Africa at about 0.25°

horizontal resolution, and vertical resolutions which increase with height, but are seldom better than ±500 m at the typical boundary layer height.

Stable Carbon Isotopes: These are measured using a mass spectrometer. In the case of ^{13}C, which is present at relatively high abundance, the cost per analysis is relatively low (~Euro 20 per sample), but for ^{14}C, Accelerator Mass Spectrometers are needed, which are at least an order of magnitude more expensive. In both cases the accuracy achieved is better than ±1%.

Species Traits: The main plant traits are J_{max} and V_{cmax}, G_s, SLA, leaf dimension, leaf nitrogen content, wood density, mean maximum height (especially of the perennation organs), root-shoot. These are measured with basic ecophysiological equipment, such as leaf-chamber IRGA, fluorescence meters, porometers, Carbon-Nitrogen-Sulfer analyzers, leaf area meters, at relatively low cost per sample and high accuracy. With this information the assignment of the species to a plant function type is accurate. However, there are close to 50 000 plant species in Africa, and this information has only been collected on perhaps 100. For the rest, inferences are made from the family or genus, often quite inaccurately.

Litter dry mass: This is collected with very basic equipment – a 0.5x0.5 m quadrat, 2 mm sieve, drying oven, balance accurate to 0.1 g and a combustion oven for ash correction. Measurement is relatively labor intensive and this variable is therefore only routinely collected at a handful of long-term ecological research sites. Accuracy, with about 30 samples per site, is better than ± 10%, but there is large within-year variation, so litter mass is collected at least twice a year, and preferably more often. An alternative is to model litter mass using a comprehensive ecosystem/plant production model with litter decomposition rates calibrated to African vegetation.

Below-ground biomass: This variable is probably the stock with the largest associated absolute inaccuracy. It is collected using extremely labour intensive excavation, sieving, washing and sorting techniques. Even with the expenditure of 100 person-days per site, the accuracy is around ±10%. This variable has only been measures for perhaps 10 sites in Africa, very unevenly distributed. Most studies simply assume an 'expansion factor' which is applied to the aboveground biomass. The factor varies from 0.2 for forests to about 1.1 for arid land grasses or shrubs, and is very poorly calibrated in Africa or elsewhere - thus the errors using this approach are likely to be in excess of ±50%. They could probably be reduced to ±20% if more primary data were collected, and a calibrated, systematic model were developed.

Ecosystem Function (NPP): This is a fundamental variable for many diagnostic purposes – ecosystem degradation, productive capacity for crops or timber – but is not actually directly used for carbon assessment (the NEE, which is equal to GPP+Re, is used; sometimes NPP is used to estimate GPP). NPP is traditionally measured by repeated biomass harvest, at huge effort (300 person days per site per year), but with low accuracy (±20%) because of the many hidden losses. It has been measured this laborious way at several hundred sites in Africa, but few on an ongoing basis. NPP can be inferred from eddy covariance methods with an accuracy of about ± 10%, if the various respiration terms are known, which adds perhaps 50 person days per site per year to the standard EC costs, plus a once-off equipment cost of about Euro 20000. NPP is routinely modelled using ecosystem models, generally driven by satellite-observed chlorophyll or FAPAR observation, and site-based climate, plant functional type, soil data, with accuracy which cannot exceed that of the calibration data (i.e. about ± 15%).

Nitrous oxide (N_2O) flux: This is generally measured using chamber methods (bottle incubations in the ocean), with analysis by gas chromatograph. The accuracy is high and the cost per sample is fairly low. But the scale of measurement is small (<1 m^2) and spatial and temporal heterogeneity is high, thus large numbers of samples are needed; N_2O measurements are therefore usually done in campaign mode. It is technically possible to measure **N_2O flux** using EC methods, but the fast response N_2O instrument required is expensive and seldom installed in standard towers. Since the contribution by N_2O to climate forcing is quite low (but likely to rise in Africa as nitrogen fertilizer and BNF crops increase), this is a case where a model-based approach is suggested to be justified for the medium-term future, both for the ocean and land. There is no reason to believe that the underlying processes of N_2O generation are different in Africa than elsewhere; but this assumption needs to be tested with several Africa-based measurement campaigns.

Methane (CH_4) flux: These fluxes originate predominantly from wetlands (including rice paddies), wet soils) and ruminants, are conventionally measured using a combination of chamber and micrometeorological methods. Dry soils oxidize methane, and are therefore a small but extensive sink. Some invertebrates (termites are abundant in Africa) emit CH_4 from methanogenic microorganisms in their gut; the quantities are thought to be small and included in the chamber and micrometeorological methods mentioned above The equipment acquisition and operation cost for CH_4 flux is of the same order of magnitude as for CO_2 flux, and the achievable accuracies are similar ($\pm$10%). The CH_4 and other trace gas emissions from wild fires (N_2O, NMVOC, aerosols etc) are typically modelled, based on the extensive measurements made during the SAFARI 2000 campaign, and extrapolated using satellite-measured burned area and fire radiative power measurements.

Runoff is measured in runoff plots, traditionally 20 m long by 2 m wide; or alternatively in micro-catchments of a few hectares, equipped with a flume gauge. This is relatively cheap and simple technology, which has been widely deployed in Africa to quantify both infiltration and sediment yield under different land uses, with accuracy around +15% for replication of about 5 plots, each costing about Euro 500 to install, but requiring ongoing maintenance. Thus few places have ongoing, continuous measurements. The key problem is high spatial variability. The runoff plot data is used to parameterize models. Ongoing measurement is required under new forms of land use to keep these models relevant, but only at any moment in a few specialized institutions in Africa.

Anthropogenic Greenhouse Gas Emissions: These are reporting requirements at national scale by all UNFCCC signatories (which includes all the countries in Africa), for CO_2, CH_4 and N_2O. Non-Annex One countries are required to report about every 5 years, with annual detail, broken down by IPCC-defined sector. The accounting is done by inventory, and typically in Africa by applying very simple ('tier 1') models involving an estimate of an activity level multiplied by an emission factor from a lookup table. The accuracy of these models is unlikely to be better than about $\pm$25%. In some cases – for instance the emission of CO_2 from the burning of fossil fuels, the emissions can be constrained by trade data relating to oil products, coal and gas, and is often assumed to be around $\pm$ 5%. An Africa-wide GHG observation system could not only verify this self-reporting, but could also improve its accuracy by fine-tuning the emission factors, or replacing them with tier 2 (quasi mechanistic) or even tier 3 (mechanistic, situation-specific) models.

River Discharge: This is the large-scale manifestation of runoff, described above. It is needed in GHG budgets to correct for lateral fluxes of dissolved and suspended carbon; and as a driver of CH_4 and N_2O emissions from wetlands, all of which are relatively small components of the Africa-wide emissions. River discharge is also needed for many other national and international developmental reasons, including freshwater supply and hydroelectric power. The developmental needs generally have a greater accuracy requirement than the emission estimates. In small rivers it is measured using gauging weirs. Large rivers are usually measured by recording the river level and calculating the flux through the area of a surveyed profile, using a knowledge of the flow velocity. Accuracies are around +10%, but the big gauging structures cost in the order of Euro 1 million and upward.

Carbon dioxide (CO_2) flux: This is measured as NEE. On land NEE is measured using eddy covariance towers costing around Euro 50 000 each to establish and a similar amount per year to operate, with achievable accuracy of around ±10% . The problem is high spatial variability at ecosystem scale, and temporally. It would be infeasible to sample every ecosystem type with the prerequisite density, so a reduced number of towers (~15 per large and broad ecosystem type, such as forest, savanna and shrubland in Africa) is used to calibrate a terrestrial ecosystem carbon cycle model, constrained with satellite observed FAPAR, ground observed soils and vegetation parameters, and model-assimilated climate. With such a hybrid approach, ±10% absolute accuracy is achievable (noting that NEE is typically close to zero, since it is the sum of two large fluxes with opposite sign- GPP downward into the land, and R_e upward to the atmosphere). Chamber methods have historically also been used to measure CO_2 fluxes, but their scale is limited, so achieving ecosystem-scale measurement would require multiple replication and would thus be very expensive. The oceanic NEE is inferred from measurements of ocean surface water pCO_2 plus the near-surface wind velocities. pCO_2 is measured while underway by oceanographic research vessels, and potentially by autonomous oceanographic robotic floats, buoys or gliders. The track data are then up scaled using models, driven by satellite-observed ocean colour, temperature, salinity and marine nutrients. Achievable accuracy with this combination of techniques are similar to those achievable on land.

Soil Organic Carbon: This is the largest terrestrial C stock, so small relative errors have large consequences. The area-density of soil organic carbon (SOC) to specified depth (gCm^{-2}) is calculated from the SOC of dried, sieved soil ($gC\ kgsoil^{-1}$) and the in situ (undisturbed) bulk density ($Mgsoil\ m^{-3}$), corrected by the gravel content (%), for several soil horizons to the specified depth. Errors can occur SOC determination, but these are typically<1% for a CNS analyzer (but up to 20% using older techniques, such as mass loss on ignition or Walkley-Black wet digestion). More typically, the largest errors (15%) are in in bulk density estimation; and the failure to correct for gravel content, SOC is measured by Carbon-Nitrogen-Sulphur (CNS) analyzer, the bulk density using weighed samples of known volume, and the gravel content by sieving and weighing. These are all very standard measurements, performed in soil labs in virtually every African country, with achievable accuracy of the calculated area-density of soil carbon of ±10%. However, spatial variability is high, at scales of 10- 100 m, and the shared pool of African soil data is small, especially for the potentially high-C but poorly accessible equatorial regions. Temporal variability in undisturbed ecosystems is small, so sampling frequency can be low (decades). In ecosystems recently converted to agriculture (the main source term) the change is relatively rapid (years). Therefore a comprehensive effort to increase the density of samples with known SOC and particle size distribution from Africa is called for, followed by a lower-level ongoing sample effort tracking changes in areas subject to recent land use change. The numbers of samples needed to bring the knowledge on soil carbon in Africa to the same level as in Europe would be in the order of 100 000; the ongoing effort thereafter would be around 1000 samples per year. The co-benefits in terms of agricultural planning and management would be large. The AfSIS project is an example of such an effort. It has cost Euro 30 million to date, which amounts to around 20% of the required effort.

Surface Roughness is directly measured using micrometeorological towers fitted with profiling anemometers, or backed out of the data provided by the 3-D sonic anemometers on EC towers. Adding such equipment to EC towers costs about Euro 5000 each. Once a set of measurements are taken, the surface roughness can be extrapolated with adequate accuracy using satellite observations of canopy height and cover. Regional scale climate is not very sensitive to surface roughness at the vegetation-canopy scale; but is sensitive to topographic roughness, which is why climate models downscaled to a few kilometers pick up and represent much more valuable detail than GCMs.

Soil Moisture is the key controller of the emissions of all GHGs from the soil, in Africa and elsewhere. It is relatively cheap and easy to measure at a site, using arrays of soil moisture sensors costing a few Euros each, but spatial and temporal variability is high, so this approach is impractical for general landscape-wide coverage. There are ground-based instruments which measure large are soil moisture through the interaction with cosmic rays; sensitivity is good, but the sampled area is unclear. Satellite-based soil moisture detection has been the holy grail for several decades, but despite great improvements, is generally still far from the required accuracy for whole-profile soil moisture; for surface wetting in places without a dense vegetation canopy the measurements may be acceptable. The accuracy (particularly for water deeper than a few centimeters below the surface) improves when radar-based observations are assimilated with rainfall and evapotranspiration drivers and soil water-holding capacity (WHC) into soil water balance models. The models can be further constrained using vegetation cover type, FAPAR, and 'canopy temperature' (from satellites with thermal bands), along with drainage measurements (see above), probably to about ± 15% on a large-area basis.

Ocean Colour: The measurement is made from space by a variety of platforms, including the Sentinel 2 and 3 instruments, with high accuracy, coverage and frequency. Ocean bio-optical observatories and cruises are used to calibrate the space observations using local area spectrophotometers and analyses of phytoplankton populations and their pigments.

Albedo: is measured from space using a range of instruments. A hemispherical, broad-band (SW) integrated albedo measurement is required, which best performed by a multi-angular, multi-spectral instrument such as MISR. The accuracies are in the order of ±5%. The measurements can be validated from tall towers using albedometers, but this is not necessary to do specifically in Africa (cal-val sites are distributed globally).

Sea Surface Salinity: is routinely measured by electroconductivity sensors, which are accurate to about ±1%, on board oceanographic vessels and autonomous floats, buoys and gliders. It is extrapolated using satellite measurements, where the accuracy degrades to around ±10%, adequate for the main purpose it is used for in GHG estimation, which is as a driver of ocean productivity models and a discriminator of oceanic biogeochemical provinces.

Fraction Absorbed Photosynthetic Radiation (FAPAR): is measured by several satellite platforms equipped with multispectral sensors in the VIS and NIR. Most products estimate it as a linear function of a greenness index such as NDVI. A more robust and accurate approach is the inversion of a radiation transfer model. The achievable accuracy is about ±10%. Since FAPAR is linearly related to GPP, this sets the fundamental accuracy of most carbon cycle models. FAPAR can be validated at ground level, but with some difficulty (for instance by measuring leaf area, leaf distribution, and soil and leaf spectral properties), and so is seldom done. It is not necessary to measure LAI *in addition* to FAPAR, since the main reason to measure LAI is to estimate FAPAR following some assumptions about leaf orientation. It is better to estimate FAPAR directly, then back-calculate LAI if needed, for instance in evapotranspiration models.

Pressure (surface): is a fundamental constraint in all GCMs, used here as data assimilation models to generate a variety of necessary variables such as wind fields, rainfall, temperature and humidity. It is measured in first-order weather stations using pressure transducers, at several hundred locations in Africa. The instruments have an accuracy of around ±1%, and a relatively sparse sample can be extrapolated using elevation as a covariate. Pressure is also used in instrument corrections and in various GHG emission models.

Lakes and impoundments extent: The surface area of lakes, rivers and dams is used in its own right as a land cover, but also as a proxy for stored volume and depth of water, given a bathymetric model. Detection by satellites, especially in the radar wavelengths which penetrate cloud is accurate to within about 30 m, ie for the larger dams and lakes (>100 ha), to within 1%.

Water Vapour (surface) is usually measured by a RH sensor, which is cheap (Euro 300 each) and accurate to around $\pm$5%. Other technologies (IRGA, wet bulb/dry bulb aspirated psychrometers, krypton hygrometers) can be used and may be more accurate and have less drift over time, but in practice are seldom deployed except for calibration purposes. Simultaneous temperature measurements (and pressure, but this can be inferred from altitude) are needed to convert the RH to the appropriate units of absolute water vapour content ($gH_2O\ m^{-3}$)or vapour partial pressure (kPa). All first order and most second order weather stations record RH. There are thousands of these in Africa, but this is still far less than the scale of spatial variability. Therefore the daily temperature range, obtainable from many more stations (tens of thousands in principle, those many do not report) is often used as an extrapolator. Satellite-derived estimates of atmospheric column water content (in mmH_20 equivalent) are routine, but not directly related to surface RH measurements. Water vapour is a GHG in its own right (though not considered to be a direct anthropogenic one). Its main use in GHG estimation systems is via its effects on potential evaporation, which controls stomatal aperture and soil moisture, and in correcting the results instruments where it water vapour is an interference.

Surface Wind Speed is an input to oceanic gas transfer models, and a relatively weak driver of evapotranspiration on land. It is measured at site by anemometers (Euro 300 each, accurate to$\pm$5%), present on all first order weather stations, most second-order stations and on volunteer ships. It is spatially extrapolated over extensive water bodies by satellite radar scatterometry, present on several platforms. Over land near-surface wind speed can sometimes be inferred from low-level cloud movements, but is usually estimated using data assimilation GCMs.

Livestock Population is measured by local census of cattle, sheep, goats and camels, noting the breed, numbers and mean body mass, which varies considerably between breeds. Accuracy for a given herd is high ($\leq$1%), but some parts of Africa do not have frequent census coverage. In some parts of Africa, wildlife populations are large enough to require estimation (methane emissions from wild ungulates is not a UNFCCC reporting requirement, but needs quantification for the inversion of methane transport models). To cover both these gaps, empirical models of livestock carrying capacity, driven by rainfall, soil and vegetation type, have an accuracy of around $\pm$25%.

Net Radiation (SW+LW, incoming minus outgoing at top-of-canopy) is the fundamental driver of potential evaporation, a controller of soil moisture, which in turn controls many soil GHG emissions. It is measured at site with a net radiometer (Euro 1000) to an accuracy of $\pm$5%. Net radiation is extrapolated spatially using satellite measures of its main components-down welling SW and LW at the top of atmosphere, atmospheric optical thickness, upwelling SW (from albedo) and LW (from surface temperature).

Crop Yield by crop type and by harvest (many parts of tropical Africa support more than one crop cycle per year) is not itself a GHG, but is useful as a check on production models, for quantifying lateral trade transfers of carbon, and for estimating carbon stocks embodied in some long-lived commodities such as timber. It is essential for food security calculations, which is its main use. Yield is measured at plot or field level by weighing the produce from a known area and correcting for moisture content, and can be measured $\pm$5%, but farmer-volunteered estimates are notorious inaccurate. Yields are usually derived from nationally-provided whole crop production estimates, divided by the planted area, available through FAO. These regional estimates may be quite accurate, but is some cases are wildly wrong or have not been updated for a long time. Crop models can be used as a reality check, but without independent calibration are no more accurate under African conditions than $\pm$25%.

Fire burned area is measured daily, cloud cover permitting, by multispectral satellites, with high accuracy (+10%) and fine resolution (20-300 m). Burned area products have been validated using airborne imagers, ground mapping and high-resolution satellites. It is now a mature product that requires little further calibration.

Land cover is generally defined by the fractional and seasonal cover of various types of plant (described by their leaf type and canopy height). The Land Cover Classification Scheme (LCCS) is a well-established standard, widely used in Africa. It is hierarchical, and GHG estimation only requires the highest levels, which are relatively easily detectable by a range of satellites, with an overall error fraction of less than 20% (and less for the changes which really matter, such as from forest to pasture, crop or bare soil). There are routine automated LC products produced annually at resolutions of around 1 km. This operational resolution may become 20 m in the next decade.

Economic Development, expressed as GDP, is not a biophysical property , but is a key underlying driver of anthropogenic GHG emissions. It is provided annual by statistical offices in most countries, with variable accuracy, and sometimes subnational resolution. Independent estimates are available from various economic institutions.

Above-ground biomass is an important terrestrial carbon stock, and is typically the main focus of estimates of emissions associated with deforestation and sinks associated with afforestation (though even in these cases, the soil and belowground root biomass is usually larger than the aboveground biomass). It is traditionally measured by forest plot survey (where each plot is in the order of 10 m^2, though standards vary widely) accompanied by the application of species-specific allometric equations to the measurement of tree basal diameter and height. Spatial variability is high, so this approach is expensive and inaccurate at scale. Recent advances in both radar and lidar systems, either airborne or satellite-based, and increasingly mounted on drones, have now made these the methods of choice, calibrated against plot measurements made the traditional way. The achievable accuracy is around +15%, and the per hectare cost using the newer technologies is low, when applied at large scale – though the Africa-wide cost is in the order of Euro 100 000 for a single repeat.

Precipitation (surface) translates to rainfall in the context of most of Africa, since snow is uncommon, and the contribution of dew and fog, while locally important, is small in the overall budget. Rainfall is classically measured with raingauges, with an accuracy of around +15%, present in all weather stations (tens of thousands in Africa, but many no longer functioning or reporting or accessible to outside users). The spatial and temporal variability of rainfall is high at scales of 5 km and temporal intervals of one day. Therefore satellite-based passive radar sensors and cloud-top temperatures are used as estimators of rainfall, in conjunction with data-assimilation GCMs, to generate daily rainfall maps over all of Africa at 3' resolution, but with pixel-scale accuracies probably around +20%. The regional scale accuracy is much higher, since calibration is used to reduce biases. There products come at no cost to the user.

Sea Surface Temperature is measured with sensors on buoys, gliders, volunteer ships and oceanographic vessels to an accuracy of 0.1°C , and extrapolated using space-borne radiometers with an accuracy of around 1°C. It is a driver of marine production and emission models, as well as one of the diagnostics for marine biogeochemical provinces

Temperature (surface) is measured in the air just above the land or ocean surface (2-20 m, depending on the situation), by thousands of weather stations on land and hundreds of volunteer ships equipped with mercury thermometers or electronic temperature sensors, in shielded enclosures. Actual available data is much sparser; only a few hundred sites over Africa reliably available on a daily basis. Surface temperature is easily extrapolated over land using elevation as a co-variate. Satellite radiometer measurements are of 'skin temperature' (i.e. the temperature of the radiating surface, usually the soil, water surface or vegetation canopy, inferred from the radiometric measurement of emissions in the 'thermal bands' in the long-wave), which is related, but not identical, to surface temperature. The difference conveys information about evaporation, which can be a useful check on evaporation models. Temperature is a non-linear driver of many natural GHG emissions, particularly from the soil, where it is soil temperature that matters. Soil temperature can be inferred from air temperature by assuming certain lags and attenuation with depth.

Human Population is an underlying driver of most anthropogenic emissions. It is obtained by national census, which are often out of date or inaccurate. It may be available from census bureaus at subnational resolution (though seldom at resolutions approaching 1 km, since this may violate privacy conditions). As a result population is frequently spatially interpolated down to 1 km resolution using satellite-observed 'lights at night'.

Fire date of burn is extracted from the daily coverage of burned area from moderate-resolution satellites, or from one of the l active fire sensors on board several satellites. It is accurate to within a day (or an hour, for active detection), provided the surface is not obscured by clouds. Usually, in the 'fire season', there are few clouds.

Carbon dioxide mixing ratio, boundary layer is measured at dedicated, high precision stations usually located on oceanic islands, windward coasts and high mountains, to avoid local contamination by vegetation or nearby sources or sinks. An example is the eight GAW stations on or around the African continent. In the absence of oceanic or high mountain stations, tall towers (>300m) can be used, or profiling using an aircraft or drone (typically less accurate, because of weight limitations and issues of pressure compensation). Ground-based sun-viewing FTIR, or upward-looking laser spectrometers are emerging technologies. The standard instruments for ground-based precision instruments are cavity-ring-down spectrometers, accurate to 0.1 ppm or better with regular calibration against common standards. Such instruments cost around Euro 3000 to purchase and about twice that per year to operate, much of the cost is in the exchange of certified calibration gases. Satellite-based measurements with a ground resolution of 2.5 km and a total column accuracy of around 1% (ie 3 ppm) are now in operation, and could supplement a relatively sparse network of high-precision stations ground stations. Boundary-layer CO_2 mixing ratio is the fundamental input to inversion-based estimates of net continental carbon dioxide emissions.

Methane mixing ratio, boundary layer is measured in similar locations and using similar instruments to CO_2 in the boundary layer (with similar costs, but some logistic, site infrastructure and personnel savings when co-located with CO_2 measurements). The achievable accuracy is about 1 ppb. Methane mixing ratio is the fundamental input to inversion-based estimates of net continental methane emissions.

Cloud cover fraction is required for the calculation of PAR (needed in oceanic and terrestrial ecosystem models), net radiation (needed in evapotranspiration models) and albedo-based climate forcing. The undifferentiated cover fraction by clouds is the most important variable, but the utility and accuracy of the measurement is improved when accompanied by the cloud type (cirrus, stratus, cumulus etc) and altitude, or by parameters such as cloud-top temperature, optical thickness, droplet density and droplet size. All of these variables are available routinely from observations made by meteorological or earth observing satellites. Another useful source, which can be used to calibrate and validate the satellite products, is ground-based radiometers of several varieties, such as the Aeronet network of automated tracking two-channel radiometers.

Chlorophyll_a in surface water is traditionally measured by spectrometry on bottle samples (±5%). It is a key driver of ocean production models. Chlorophyll is a routine operational satellite product inferred from observations of ocean colour at 300 m, daily (±10%).

Land Use is fundamental to almost all LULCF emissions. Land Use is a complex variable, listing the calendar periods and intensity levels of a quite long set of activities, such as grazing, cultivation, fertilization, harvesting etc. In practice these is typically lumped into broad shorthand categories, such as ‘commercial short-duration crop agriculture’ or ‘extensive pastoralism’ inferred by expert judgement from land cover. However, unlike land cover, any given area can have multiple land uses. The spatial accuracy of current land use products for Africa is largely untested but probably very low. A hybridization of rural panel surveys with land cover products could dramatically improve their accuracy. Land use is an important consideration for the estimation of greenhouse gas emissions.

Marine nutrients: At a minimum, this includes dissolved inorganic nitrogen (DIN, which consists of N-NO_3^- and N-NH_4^+) and phosphate (PO_4^{2-}), but particularly away from the coastal zone also may include micronutrients such as iron and silicon. The measurement of the former from oceanographic vessels is routine, with accuracies ±5%, the latter can be very difficult because of the very low concentrations involved. The DIN species are in principle measurable using automated sensors on gliders or bouys, but drift due to bio fueling remains a problem. Generally the average values are assigned per season to leach large marine biogeochemical province (like a biome in the ocean, but with fluid boundaries), and the spatial limits of the biogeochemical provinces are determined by remote sensing of sea surface temperature, salinity and ocean colour. This approach is probably no better than + 20%.

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List of Abbreviation

APAR	Absorbed photosynthetically-active radiation
BNF	Biological Nitrogen Fixation
CCAM	Conformal-Cubic Atmospheric Model
CLIVAR	Climate and Ocean - Variability, Predictability and Change
CMIP	Coupled Model Intercomparison Project
CSIR	Council for Scientific and Industrial Research
DEM	Digital Elevation Model
DMS	Dimethyl Sulfide
EBV	Essential Biodiversity Variable
EC	Eddy Covariance
ECV	Essential Climate Variable
EOV	Essential Ocean Variable
(FA)PAR	(Fraction of Absorbed) Photosynthetically Active Radiation
FRE	Fire Radiative Energy
FTIR	Fourier-Transform Infrared Spectroscopy
GAW	Global Atmosphere Watch
GCM	General Circulation Model
GCOS	Global Climate Observing System
GEOBON	Group On Earth Observations Biodiversity Observation Network
GHG	Greenhouse Gas
GPP	Gross Primary Production
ICOS	Integrated Carbon Observation System
IOC	Intergovernmental Oceanographic Commission
IPCC	Intergovernmental Panel on Climate Change
IRGA	Infrared Gas Analyzer
LAI	Leaf Area Index
LC	Land Cover
LCCS	Land Cover Classification Scheme
LULUCF	Land Use, Land Use Change and Forestry
LW	Longwave
MISR	Multi-angular Imaging Spectral Raiometer
NEE	Net Ecosystem Exchange
NIR	Near Infrared
NMVOC	Non-Methane Volatile Organic Carbons
NPP	Net Primary Production
PET	Potential Evapo-Transpiration
Re	Ecosystem respiration
RH	Relative Humidity
SASSCAL	Southern African Science Service Centre for Climate Change and Adaptive Land Management
SEACRIFOG	Supporting EU-African Cooperation on Research Infrastructures for Food Security and GHG Observations
SLA	Specific Leaf Area
SOC	Soil Organic Carbon
SST	Sea Surface Temperature
SW	Shortwave
ToA	Top of Atmosphere
ToC	Top of Canopy
UNFCCC	United Nations Framework Convention on Climate Change
WHC	Water Holding Capacity
WP	Work Package