Greenhouse Gas Observation & Climate-Smart Agriculture

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Identification of Key Variables for Climate Change Observation across Africa

SEACRIFOG Deliverable 4.1: Ideal and Mandatory Sets of Variables and Criteria

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List of Acronyms

CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
EBV	Essential Biodiversity Variable
ECV	Essential Climate Variable
EOV	Essential Ocean Variable
EU	European Union
GCOS	Global Climate Observing System
GEOBON	Group on Earth Observations Biodiversity Observation Network
GHG	Greenhouse Gas
GOOS	Global Ocean Observing System
ICOS	Integrated Carbon Observation System
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land Use, Land Use Change and Forestry
N_2O	Nitrous Oxide
NMVOC	Non-Methane Volatile Organic Compound
OSCAR	Observing Systems Capability Analysis and Review Tool
RF	Radiative Forcing
RI	Research Infrastructure
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 Greenhouse Gas Observations
ToA	Top of Atmosphere
ToC	Top of Canopy
UNFCCC	United Nations Framework Convention on Climate Change
WMGHG	Well-Mixed GHG
WMO	World Meteorological Organization
WP	Work Package

Executive Summary

The Earth's climate and environment is undergoing fundamental changes linked to human presence and activity, above all through the emission of greenhouse gases (GHG) and land use/cover change. In the case of the African continent, there are still major observational gaps, resulting in large uncertainties for most of the key variables of climate change, above all the GHG balance. The objective of the 'Supporting EU-African Cooperation on Research Infrastructures for Food Security and Greenhouse Gas Observations' (SEACRIFOG) project is to design a continental network of joint EU-African research infrastructures (RIs) for the monitoring of climate change and other environmental changes on the African continent linked to GHG emissions and food security. SEACRIFOG is funded by the European Union (EU) through the Horizon 2020 Programme.

This report constitutes Deliverable 4.1 of the SEACRIFOG project. It was prepared under the lead of the Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL) as a part of SEACRIFOG Work Package (WP) 4. The SEACRIFOG WP4 is implemented under the lead of the Trinity College Dublin in cooperation with the contributing partner institutions SASSCAL, Uni Research and the University of Bergen.

In line with the SEACRIFOG WP4 objective of improving technical harmonisation and data quality in environmental monitoring and experimentation, this report presents 'a minimal dataset of mandatory climatic parameters and ecological and land-use assessment criteria, together with an 'ideal' set of criteria'. The primary aim is to identify the essential variables to be observed systematically in order to sufficiently capture and quantify anthropogenic climate forcing as well as its interlinkages with agricultural production and food security in Africa and the surrounding oceans.

In order to maximize interoperability and to avoid duplication of effort, the approach to identify the variables to be considered by SEACRIFOG was based on existing global frameworks such as the 'Essential Climate Variables' (ECV), the 'Essential Ocean Variables' (EOV) and the 'Essential Biodiversity Variables' (EBV), which already define a minimum common scope and requirements for the observation of the Earth's climate and environmental system. These variable sets were modified and complemented by further variables to account for the African context and the SEACRIFOG objectives. From the resulting 'ideal' variable set, a 'mandatory' subset of variables was distilled, which captures the major dimensions of climate forcing related to GHG fluxes and land use across Africa through a minimum set of essential measurements. Given the high relative importance of anthropogenic GHG emissions directly and indirectly related to land use and food production across the African continent, corresponding activities receive special attention in the design of an African observation system.

The identification of these 'ideal' and 'mandatory' variable sets was carried out in line with a comprehensive consultative process, inviting the input from numerous experts in the field of environmental observation. In analogy to other approaches to the identification of 'essential' variables (e.g. ECVs and EOVs), the 'mandatory' set was derived from the 'ideal' set through a survey-based assessment of each variable against the criteria of relevance, feasibility and cost in the African context and in consideration of the SEACRIFOG objectives. Most of this input was collected through the specifically

developed 'SEACRIFOG Collaborative Inventory Tool' (http://seacrifog-tool.sasscal.org/) developed and hosted by SASSCAL. This approach was complemented by a systemic approach based on expert judgment and existing literature, which focused on variables which are narrowly related to components and drivers of radiative forcing as described in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). This systemic approach is based on ideas and concepts which are described in more detail in the SEACRIFOG Deliverable 3.1 report.

Table 1 below lists the 58 'mandatory' variables identified. Detailed qualitative and quantitative variable descriptions are provided in the report annex. All variables are linked to either the atmospheric, oceanic or terrestrial domain. The systematic and long-term observation of these variables through a combination of *in situ* and remote sensing measurements has the potential to drastically refine transport models and improve the quantification and attribution of radiative forcing across Africa and the surrounding oceans. Numerous variables in the 'mandatory' set are relevant to the observation and projection of agricultural production and thus production-based food security. Their systematic observation will thus also contribute to the refinement of food security related early warning systems and models.

Note that some variables are provided as aggregates of various sub-variables (e.g. aerosol properties), whereas others are disaggregated down to sub-variables (e.g. 'burnt area' as part of the variable class 'fire'). In some cases, only certain sub-variables of a wider variable class were identified as 'essential' (e.g. 'cloud cover fraction' as part of the ECV class 'cloud properties'). In other cases, a higher level of disaggregation reflects a higher degree of heterogeneity within a variable class with regards to observational techniques and requirements (e.g. the distinction between 'inland water extent' and other land cover types). Further note that, while the variable sets presented here are considered to meet the intended scope and requirements at the present stage, they may undergo further iterations with increasing knowledge and evolving technologies. They should therefore not be considered as fixed, because there may be convincing reasons at a later stage to add, remove or (dis-)aggregate individual variables.

Within SEACRIFOG, the 'mandatory' set of variables constitutes the point of departure for various project tasks. The status quo in terms of available and planned observation infrastructure and data will be assessed in the context of this variable set, with the aim to identify the exact requirements in terms of additional observations and appropriate measurement parameters to reduce the uncertainty regarding anthropogenic climate forcing on the African continent to the same range as for other continents (standard deviation ≤ 15% of mean value). With the 'mandatory' variable set being largely compatible and interoperable with global climate and environmental change observation efforts, systematic observation of this set can further make a direct contribution to corresponding global initiatives.

Table 1: 'Mandatory' set of 58 variables to be observed in order to close the GHG budget and reduce uncertainty of anthropogenic radiative forcing (RF) in Africa and the surrounding oceans. The global figures for the RF components are extracted from the IPPC's Fifth Assessment Report and refer to the period 1750-2011. Where more than one RF component is associated with a variable, the figures in the table refer to the sum of these RF components. WMGHGs = well-mixed greenhouse gases. NMVOCs – Non-methane volatile organic compounds.

Variable Class	Variable	Domain	Type	Major related RF component	RF best estimate global (Wm-2)	Relevant for food security
Above ground biomass	Above ground biomass	Terrestrial	ECV	CO2	1.68	X
	Litter	Terrestrial	Other	CO2, CH4	2.65	-
Aerosol properties	Aerosol properties	Atmospheric	ECV	Aerosols	-0.76	-
Agricultural management	Area of ploughed land	Terrestrial	Other	CO2, CH4	2.65	X
	Manure Management	Terrestrial	Other	CH4, N2O	1.14	X
	Fertilizer application	Terrestrial	Other	N2O	0.17	X
	Irrigation	Terrestrial	Other	CH4, N2O	1.14	X
Animal Population	Livestock Distribution	Terrestrial	Other	CH4, N2O	1.14	X
	Wild Herbivore Distribution	Terrestrial	Other	CH4, N2O	1.14	-
Below-Ground Biomass	Below-Ground Biomass	Terrestrial	Other	CO2	1.68	-
Biosphere-Atmosphere GHG flux	Biosphere-Atmosphere CH_4 flux	Terrestrial	Other	CH4	0.97	-
	Biosphere-Atmosphere CO_2 flux (NEE)	Terrestrial	Other	CO2	1.68	-
	Biosphere-Atmosphere N_2O flux	Terrestrial	Other	N2O	0.17	-
Boundary layer height	Boundary layer height	Atmospheric	Other	-	-	-
Carbon Dioxide, Methane and other Greenhouse gases	Tropospheric CH4 mixing ratio	Atmospheric	ECV	CH4	0.97	-
	Tropospheric CO2 mixing ratio	Atmospheric	ECV	CO2	1.68	-
	Halocarbons	Atmospheric	Other	Halocarbons	0.18	-
	Tropospheric N2O mixing ratio	Atmospheric	ECV	N2O	0.17	-
Cloud Properties	Cloud Cover Fraction	Atmospheric	ECV	Albedo	-	-
Crops	Crop Yield	Terrestrial	Other	-	-	X
Economic Development	Economic Development	Various	Other	-	-	X
Ecosystem Function	Net Primary Productivity	Terrestrial	EBV	CO2	1.68	-
Fire	Active Fire	Terrestrial	ECV	CO, Black Carbon, Organic Carbon	0.58	-
	Burnt Area	Terrestrial	ECV	CO, Black Carbon, Organic Carbon	0.58	X
	Fire Fuel Load	Terrestrial	Other	CO, Black Carbon, Organic Carbon	0.58	-
Human Population	Human Population	Terrestrial	Other	-	-	X
Hydrology	Evapotranspiration	Terrestrial	Other	-	-	-
	Infiltration and Runoff	Terrestrial	Other	WMGHGs (CO2, CH4, N2O)	2.82	X
	Precipitation (surface)	Terrestrial	ECV	-	-	X
	River Discharge	Terrestrial	ECV	WMGHGs (CO2, CH4, N2O)	2.82	-

Inorganic Carbon	Inorganic Carbon	Oceanic	ECV	CO2	1.68	-
Land Cover	Land Cover	Terrestrial	ECV	Surface albedo, mineral dust	-0.25	X
	Extent of inland waters	Terrestrial	ECV	CO2, CH4	2.65	X
Land Use/Land Use Change	Land Use/Land Use Change	Terrestrial	Other	WMGHGs (CO2, CH4, N2O), Surface albedo, mineral dust	2.57	X
Nitrous Oxide	Nitrous Oxide (Ocean)	Oceanic	ECV	N2O	0.17	-
Nutrients	Marine Nutrients	Oceanic	ECV	WMGHGs (CO2, CH4, N2O)	2.82	-
Ocean Colour	Ocean Colour	Oceanic	ECV	WMGHGs (CO2, CH4, N2O)	2.82	-
Oxygen	Oxygen	Oceanic	ECV	-	-	X
Plant Species Traits	Plant Species Traits	Terrestrial	EBV	-	-	-
Precursors	Carbon Monoxide (CO)	Atmospheric	ECV	CO	0.23	-
	Dimethyl Sulfide	Oceanic	Other	aerosol-cloud interaction	-0.45	-
	Non-methane hydrocarbons	Atmospheric	Other	NMVOC	0.1	-
	Nitrogen Oxides (NOx)	Atmospheric	ECV	NOx	-0.15	-
	Sulfur Dioxide (SO_2)	Atmospheric	ECV	SO2	-0.41	-
Pressure (surface)	Pressure (surface)	Terrestrial	ECV	-	-	-
Radiation	Albedo	Terrestrial	ECV	Surface albedo	-0.15	-
	Fraction of Absorbed Photosynthetically Active Radiation (FAPAR)	Terrestrial	ECV	CO2	1.68	-
	Net Radiation at surface (SW/LW)	Terrestrial	ECV	WMGHGs (CO2, CH4, N2O)	2.82	-
Reported Anthropogenic Greenhouse Gas Emissions	CO_2, CH_4, N_2O emissions by country and IPCC sector	Terrestrial	ECV	WMGHGs (CO2, CH4, N2O)	2.82	-
Sea Surface Salinity	Sea Surface Salinity	Oceanic	ECV	-	-	-
Soil Properties	Soil Moisture	Terrestrial	ECV	WMGHGs (CO2, CH4, N2O)	2.82	X
	Soil Organic Carbon	Terrestrial	ECV	CO2, CH4	2.65	X
Stable Carbon Isotopes	Stable Carbon Isotopes	Oceanic	ECV	-	-	-
Surface Roughness	Surface Roughness	Terrestrial	Other	-	-	-
Surface Wind	Surface Wind Speed and direction	Terrestrial	ECV	-	-	-
Temperature	Sea Surface Temperature	Oceanic	ECV	-	-	-
	Temperature (surface)	Terrestrial	ECV	-	-	X
Water Vapour (surface)	Water Vapour (surface)	Terrestrial	ECV	-	-	X

1 Introduction

1.1 Document Purpose

This report constitutes Deliverable 4.1 of the 'Supporting EU-African Cooperation on Research Infrastructures for Food Security and Greenhouse Gas Observations' (SEACRIFOG) project funded by the European Union (EU) through the Horizon 2020 Programme. It was prepared in July 2018 under the lead of the Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL) as a part of SEACRIFOG Work Package (WP) 4. The SEACRIFOG WP4 is implemented under the lead of the Trinity College Dublin in cooperation with the contributing partner institutions SASSCAL, Uni Research and the University of Bergen.

The objective of SEACRIFOG is to design a continental network of joint EU-African research infrastructures (RIs) for the monitoring of climate change and other environmental changes on the African continent linked to greenhouse gas emissions and food security. More specifically, the SEACRIFOG project aims to

1) identify the essential parameters needed to develop science-based strategies to improve food and nutrition security including early warning systems and to mitigate climate change,
2) formulate a roadmap towards fully interoperable and accessible research infrastructures in agricultural and climate research in the EU and Africa that match the needs of the users, and
3) deliver a contribution to capacity building and human capital development in Africa.

SEACRIFOG is part of the INFRASUPP Work Programme 2016-2017 ('Policy and international cooperation measures for research Infrastructures') of the EU's Horizon 2020 Funding Programme. In line with the objectives of this work programme, SEACRIFOG aims to "help to develop better coordination and cooperation of European research infrastructures with their African counterparts, ensuring global interoperability and reach, and pursuing international agreements on the reciprocal use, openness or co-financing of infrastructures".

The SEACRIFOG WP4 aims at 'improving technical harmonisation and data quality in environmental monitoring and experimentation'. The WP4 sub-objective relevant to this present deliverable 4.1 is 'to identify the environmental parameters within atmospheric, terrestrial and marine systems that are essential to monitor long-term changes in climate and that can be used to predict future climatic variability'.

The present SEACRIFOG Deliverable 4.1 is directly related to this WP4 objective and presents 'A minimal dataset of mandatory climatic parameters and ecological and land-use assessment criteria, together with an 'ideal' set of criteria'. In line with the overall objectives of SEACRIFOG and the focus of other WPs, special emphasis is placed on the observation-based quantification of anthropogenic climate forcing across the African continent and the interoperability of the results with global initiatives to ensure their global relevance and complementarity. At the same time, the variable sets presented are specific to the African context and tailored to the focus of the SEACRIFOG project on GHG observation and food security.

The report authors acknowledge the inputs from the contributing SEACRIFOG consortium members, the consulted external experts as well as the wider environmental observation community.

1.2 Background

The Earth's climate and environment is undergoing fundamental changes linked to human presence and activity, above all through the emission of greenhouse gases and land use/cover change [1]. Observation-based evidence is essential to further our understanding of these phenomena, their causes, interplay, consequences and the role of human activity, with the aim to improve forecasts and develop appropriate responses [2]. As these dynamics take place and can be linked to processes at all spatial scales around the globe, they need to be considered and understood not only locally, but require systematic research and long-term observation up to the regional and global level [3]. However, projects or systems based on research funding are generally not designed for transition to sustained monitoring of variables globally and over long periods, often leading to partial, haphazard, intermittent coverage [4].

Accordingly, various global initiatives aim at streamlining existing and future observation initiatives by defining a minimum common scope and requirements to comprehensively capture the state of the Earth's climate system and related processes [5]. Examples include the Global Climate Observing System (GCOS) [6], the Global Ocean Observing System (GOOS) and – for biodiversity - the Group on Earth Observation's Biodiversity Observation Network (GEOBON). Yet, the scope and design of corresponding research infrastructures (RIs) are also determined by regional and local circumstances. In Europe, for example, the Integrated Carbon Observation System (ICOS) is a pan-European RI specifically designed to provide harmonized and high precision scientific data on the European carbon cycle and greenhouse (GHG) gas budget.

In the case of the African continent, there are still major observational gaps [7], resulting in major uncertainties for most of the key variables of climate change, above all the GHG balance [8, 9, 10]. Consequently, it is currently not known whether the African continent constitutes a net sink or source of atmospheric carbon. The 'Supporting EU-African Cooperation on Research Infrastructures for Food Security and Greenhouse Gas Observations' (SEACRIFOG) project (www.seacrifog.eu) aims to develop a roadmap towards a network of joint EU-African RIs for the systematic long-term observation of anthropogenic GHG emissions across the continent and their links to agricultural production and food security. This network is to be tailored to the African context by ensuring that continent-specific ecosystems and anthropic developments as well as their interactions with the local and global climate system be captured with sufficient accuracy.

The primary focus of the resulting continental observation system will be to determine the anthropogenic and natural contributions to climate forcing across Africa with the same level of accuracy as for the rest of the world. Such a system will make a significant contribution to the improvement of GHG accounting in line with the implementation of the Paris Agreement by contributing to both improved top-down and bottom-up GHG emission estimation methods and by providing independent cross-checks. Given the high relative importance of anthropogenic GHG emissions directly and indirectly related to land use and food production across the African continent [11, 10], corresponding activities need to receive special attention in the context of an African observation system. Africa comprises 20% of the global land area and currently accommodates about 14% of the world population. Williams et. al. [9] found that, in the 1990s, carbon fluxes from Africa associated with land use contributed 21% and biomass burning 37% to the respective global total estimates. Both these components are closely related to food production on the continent.

Given the mismatch between African continental GHG emissions and the relative climate change burden [12], adaptation measures are likely to take priority over GHG mitigation across Africa. However, since emissions related to land use, land use change and forestry (LULUCF) – above all through agriculture and biomass burning - are major contributors to Africa's GHG budget, possible mitigation co-benefits should not be ignored in the development and promotion of adaptation measures and vice versa. The scope for carbon sequestration through land management is large in Africa and so is the potential for many African nations to participate in global mitigation efforts [13] and benefit from corresponding mechanisms for financial and technological transfers [9]. An improved understanding of the impact of agricultural activities on anthropogenic climate forcing is thus in the interest of identifying sustainable ways for food production across Africa. Systematic and more accurate observation of relevant variables will further have the co-benefit of supporting corresponding early-warning systems.

In order to make a meaningful contribution at the continental and global level, the RIs to be proposed by SEACRIFOG need to be interoperable and compatible among each other and with other existing and planned observation initiatives in and beyond Africa. A fundamental condition for a harmonized observation system is to have consensus about the exact variables to observe and how, i.e. to agree on systematic observation of a limited set of critical variables and corresponding measurement requirements. With regards to monitoring of climate change globally, the GCOS has defined the Essential Climate Variables (ECV), a set of physical, chemical or biological variables (or groups of variables) which provide the empirical evidence needed to understand and predict the evolution of climate [4]. The ECVs are considered feasible for global implementation and are closely aligned with the requirements of the UNFCCC and IPCC. The ECV concept further served as a blueprint for the development of the Framework for Ocean Observing [14] and the corresponding Essential Ocean Variables (EOV) [15] and the development process of Essential Biodiversity Variables (EBV) by the GEOBON, working towards a harmonized global observation system to track biodiversity [16].

In analogy with these concepts, the objective of SEACRIFOG WP4 is to improve technical harmonization and data quality in environmental monitoring and experimentation for the RI network to be designed. More specifically, Task 4.1 under WP4 comprises the identification of key environmental observational parameters required to capture both short-term variability and monitor long-term change within atmospheric, marine and terrestrial systems. The primary aim is to identify the essential variables to be observed systematically in Africa and the surrounding oceans to sufficiently capture and quantify anthropogenic climate forcing as well as its interlinkages with agricultural production and food security.

Summarizing, just as the ECVs, EOVs and the EBVs distil complex fields into a manageable list of priorities and related actions at the global level, the SEACRIFOG WP4 partners are doing the same with a focus on the African continent and in the context of the SEACRIFOG project. The resulting mandatory set of variables serves as the central point of departure for numerous tasks of SEACRIFOG.

This report presents the work done in line with task 4.1 and constitutes Deliverable 4.1 of the SEACRIFOG project. It presents and describes the 'ideal' and 'mandatory' sets of variables to be considered by the RI network to be designed in line with SEACRIFOG. Note that, while the variable sets presented here are considered to satisfy the project's scope and requirements at the present stage, they may undergo further iterations with increasing knowledge and evolving technologies. They should therefore not be considered as fixed, since there may be convincing reasons at a later stage to add or remove individual variables.

The following Section 2 describes the methodology applied to identify the variable sets. Section 3 presents the actual variable sets. Section 4 puts these results into context by discussing their validity and describing their linkages to other SEACRIFOG activities, which build on this deliverable. Finally, detailed information on all variables considered can be found in the annex to this report.

2 Methodology

2.1 Identification of an 'Ideal' Set of Variables

The aim of compiling an 'ideal' variable set for the SEACRIFOG project is to identify all variables potentially relevant for the comprehensive description of anthropogenic climate forcing as well as related direct and indirect drivers across the African continent. In order to maximize interoperability and to avoid duplication of effort, the approach to identifying this variable set was based on ongoing global initiatives which already define a minimum common scope and requirements for the observation of the Earth's climate and environmental system. A highly relevant initiative in this context is the Global Climate Observing System (GCOS) of the World Meteorological Organization (WMO). The existing, widely accepted and

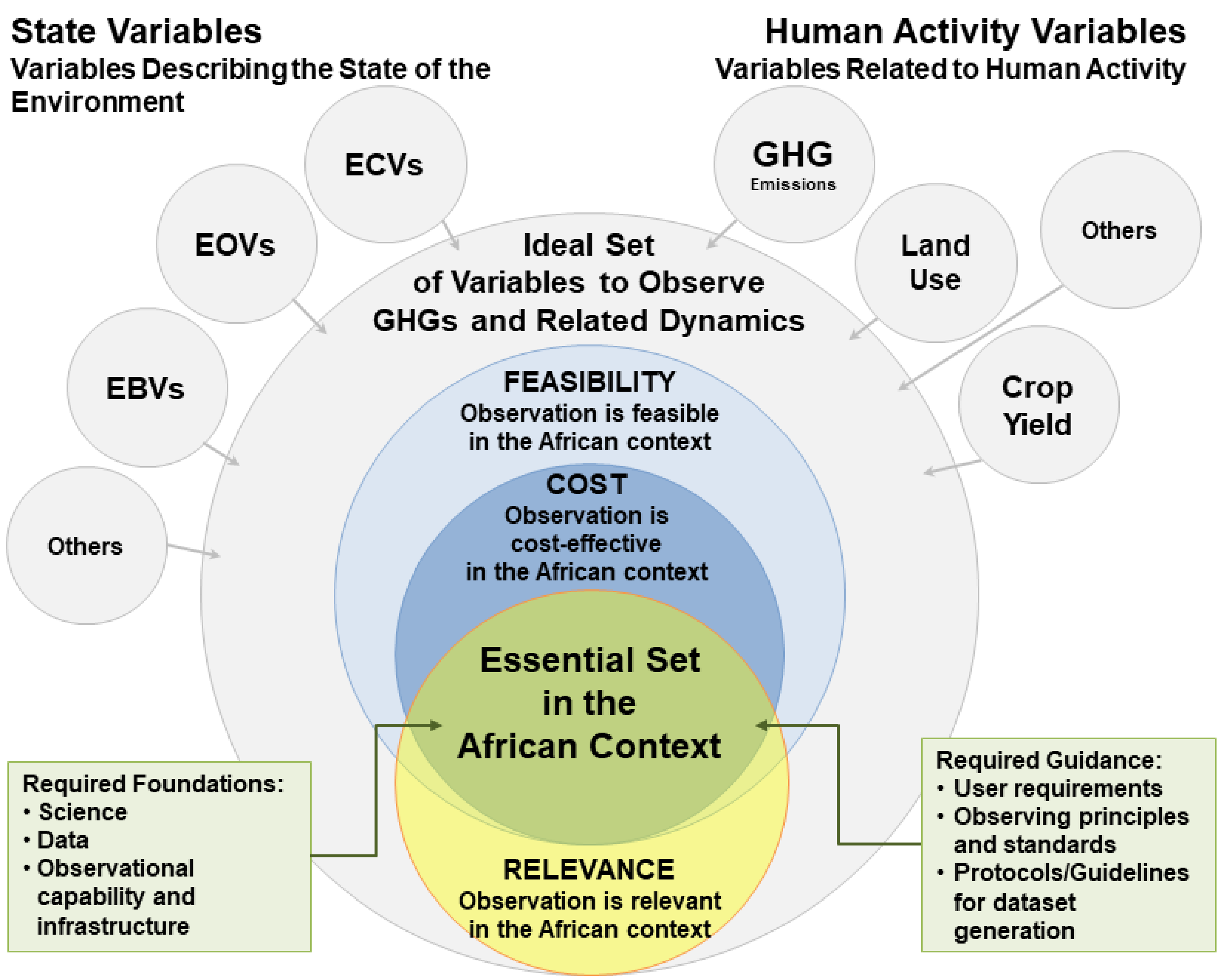

Figure 1: Schematic illustration of the concept for identifying essential environmental change variables in Africa in the context of SEACRIFOG. Adapted from Bojinski et. al. [4]

relatively well-defined set of the ECVs developed in line with the GCOS [1] thus served as the point of departure for the ideal set of SEACRIFOG variables. On one hand, through the exclusive focus on the African continent and adjacent oceans, the scope of SEACRIFOG is narrower than the scope of the ECVs. On the other hand, considering any possible direct and indirect drivers and manifestations of anthropogenic climate forcing in Africa, the SEACRIFOG scope may comprise aspects which are not captured by the global ECVs. The EOVs [2] and EBVs (https://geobon.org/ebvs/what-are-ebvs/) were thus added and the resulting set of variables was further complemented by anthropic factors, i.e. variables which are related to human activity and impact, as well as other ancillary variables. Unlike the existing global sets of 'essential' variables, which primarily focus on state variables, the 'ideal' SEACRIFOG set thus also includes variables related to anthropogenic pressures and drivers of change (see Figure 1). The resulting set is 'ideal' in the sense that it does not only contain variables which are absolutely essential to sufficiently quantifying the African GHG budget, but also additional variables which provide information that goes beyond the scope of the project objectives.

The compilation of the 'ideal' variable set was carried out through a comprehensive consultative process, inviting the input from the SEACRIFOG consortium partners and experts in the field of environmental observation. This input was collected through the 'SEACRIFOG Collaborative Inventory Tool'. This interactive webtool is hosted by SASSCAL on a cloud server and accessible online at http://seacrifog-tool.sasscal.org/. The tool was developed by SASSCAL based on the Shiny package of the R software environment and was specifically developed to integrate the work done in line with various SEACRIFOG WPs by facilitating the systematic collection of relevant information and sharing of corresponding outcomes. Concerning WP4, the tool served to capture and assess potentially relevant variables (see Figure 2) and prioritize them (see section 2.2.1). Registered users can add, edit and retrieve information on variables and corresponding data products.

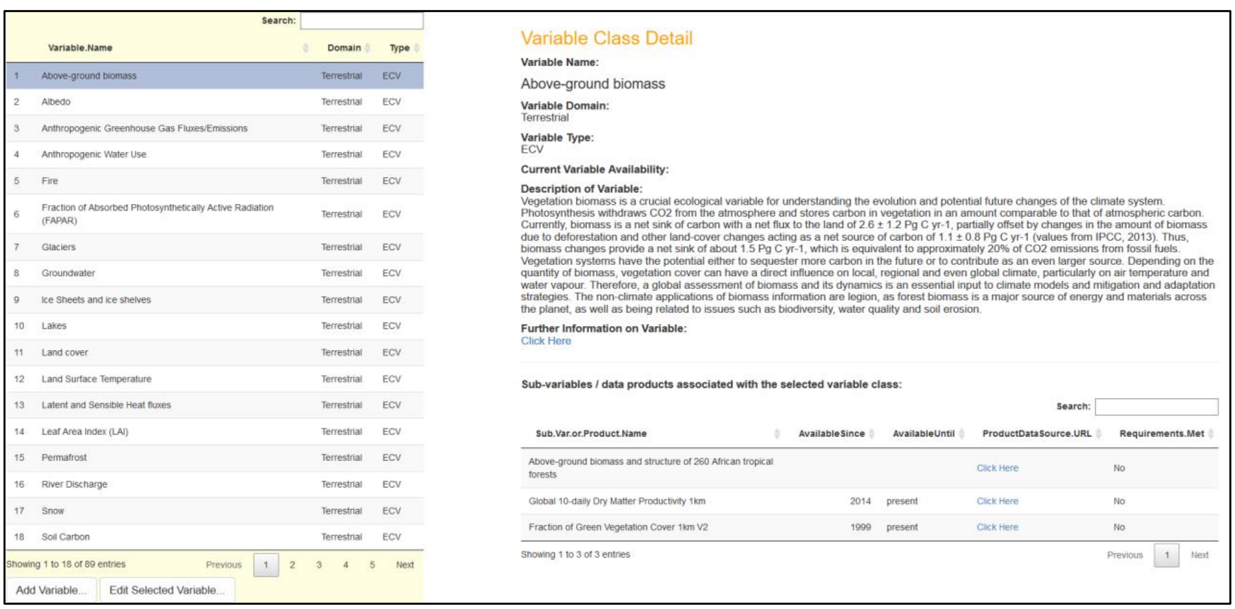

Figure 2: Screenshot of the tab 'Variable Classes' of the 'SEACRIFOG Collaborative Inventory Tool' developed by SASSCAL. The tool is accessible at http://seacrifog-tool.sasscal.org/ (full access only for registered users).

[1] https://www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix
[2] http://www.goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114

The tool was deployed online in February 2018. Since then, full access has been granted to more than 200 potential contributors from the environmental observation community. These were invited to add potentially relevant variables/variable classes and review the existing list of variables. The resulting 'ideal' variable set contains 93 variables or variable classes, respectively (see Figure 6 in section 3). Note that some variables are listed as variable classes (in accordance with the ECVs), whereas others are rather individual variables. Where applicable, further disaggregation of these variable classes took place in line with the identification of the 'mandatory' variable set (see section 2.2 below). However, note that throughout the remainder of this document, unless specified otherwise, the word 'variable' can refer to both variable classes and individual variables.

2.2 Identification of Mandatory Set of Variables

The aim of distilling a 'mandatory' set of variables from the 'ideal' set is to sufficiently capture the major dimensions of anthropogenic climate forcing in the terrestrial, atmospheric and oceanic domain through a minimum set of essential measurements. Systematic long-term observation of this 'mandatory' set of variables would enable the African GHG budget and the corresponding role of human activities related to agricultural production and food security to be determined with appropriate accuracy (i.e. at least in the same range as other continents and according to global standards). The 'mandatory' set was identified through the combination of two different approaches: A survey-based assessment in analogy of the approach taken for the identification of the ECVs (see section 2.2.1) and a systemic top-down approach narrowly focusing on the different sources of climate forcing in Africa (see section 2.2.2). The former approach yields a rather continuous and relative measure of 'importance' of a variable in the SEACRIFOG context, which is useful for prioritization of the variables. The latter approach, in turn, allows for a more binary discrimination of whether a variable is 'essential' or not, based on whether the respective variable is arguably related to the estimation of drivers or components of climate forcing. The findings of both approaches were combined and the resulting set was then further refined through targeted consultations with experts in various relevant fields (e.g. terrestrial carbon stocks, oceanic sinks and emissions, etc.).

2.2.1 Measure of Essentiality I: Bottom-Up Survey-Based Assessment

Based on the concept developed and applied in line with the identification of the ECVs, EOVs and EBVs (see Figure 1), a survey-based rating exercise was conducted among identified members of the environmental observation community. The purpose of this exercise was to establish a measure of the importance of each variable in the context of SEACRIFOG from the triangulation of numerous ratings. This measure, i.e. the variable score, allows for prioritization of the variables. In analogy to the above global concepts, each variable in the 'ideal' set was assessed against the following criteria in consideration of the African context and the SEACRIFOG objectives.

- Relevance: What is the relevance of the variable in the SEACRIFOG/African context? This criterion ensures that variables which are not of high relevance for the African continent (e.g. variables related to the cryosphere) be omitted from the mandatory set.
- Feasibility: To which degree is it technically feasible to systematically capture the variable in the long term in the SEACRIFOG/African context?
- Cost: What is the (relative) cost associated with the systematic long-term observation of the variable in the SAECRIFOG/African context?

The same group of contributors as for the identification of the 'ideal' variable set was invited to contribute to this variable assessment, again using the web-based 'SEACRIFOG Collaborative Inventory Tool'. Through the corresponding tab 'Variable Rating', contributors could rate each variable/variable group against the above three criteria on an ordinal scale comprising the levels 'Low', 'Medium' and 'High' (see Figure 3). From these ratings, a composite score was computed for each variable. First, the ordinal rating values were translated into numeric values according to the following rules:

Rating level	Relevance numeric	Feasibility numeric	Cost numeric
High	3	3	1
Medium	2	2	2
Low	1	1	3

For each variable, the arithmetic mean of the numeric rating values was then calculated for the three criteria from all ratings given. The composite score was then calculated as the simple unweighted sum of these arithmetic means, with a theoretical minimum of 3 and maximum of 9. The composite score for each variable is expressed in percent (%) of the range between these two extremes, with a higher score indicating a higher composite adherence to the three assessment criteria.

The online rating process took place between February and May 2018. Ratings from a total of 40 contributors were collected. Of these contributors, 18 (45%) indicated that they are either from Africa or have conducted extensive research in/on Africa. Eight (20%) contributors indicated that they have special expertise in the atmospheric domain, 26 (65%) in the terrestrial domain and 14 (35%) in the oceanic domain.

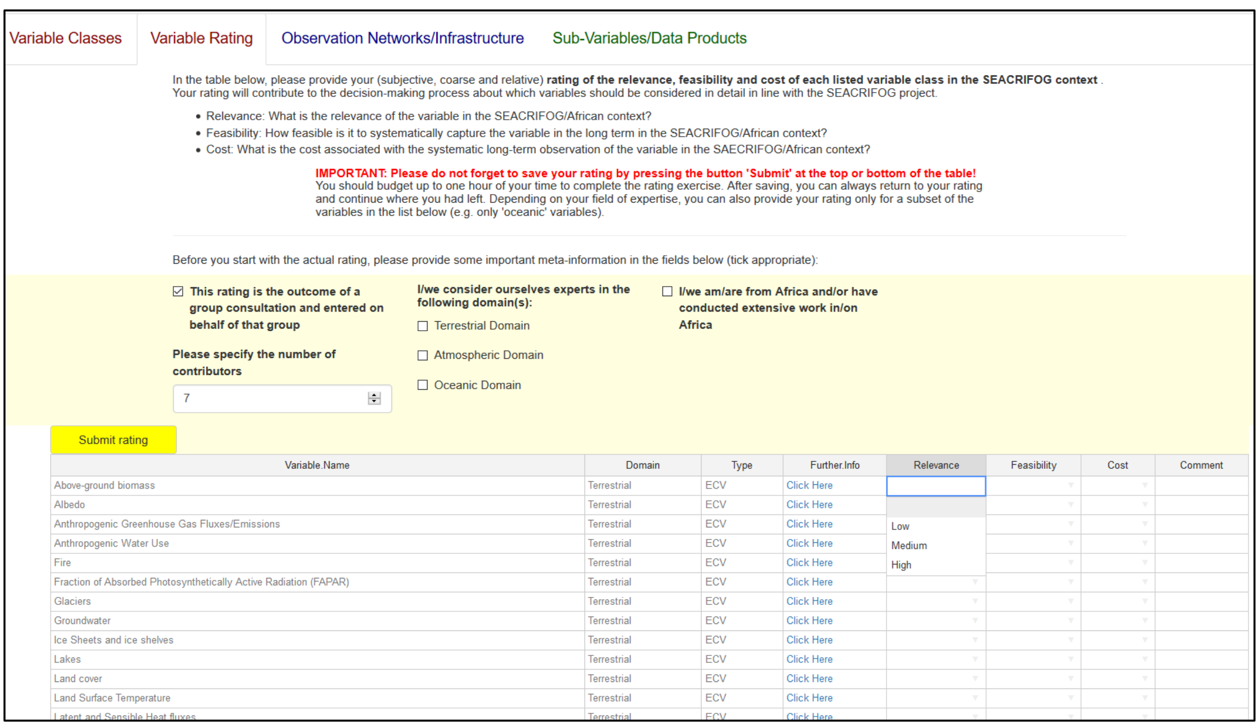

Figure 3: Screenshot of the tab 'Variable Rating' of the 'SEACRIFOG Collaborative Inventory Tool' developed by SASSCAL. The tool is accessible at http://seacrifog-tool.sasscal.org/ (full access only for registered users).

The result of the rating process applied to the 'ideal' variable set is presented in Table 2, providing the survey score as well as the averages for the criteria relevance, feasibility and cost for each variable. For more detailed information on each variable, refer to the report annex.

2.2.2 Measure of Essentiality II: Systemic Top-Down Analysis of Required Variables

This second approach is based on ideas and concepts laid out in detail in SEACRIFOG Deliverable 3.1 ('Report about existing network and perspective for further development'). It applies a narrower focus than the survey-based approach by limiting itself to known direct and indirect components and drivers of anthropogenic radiative forcing as described and quantified in the IPCC's Fifth Assessment Report [17], see Figure 4.

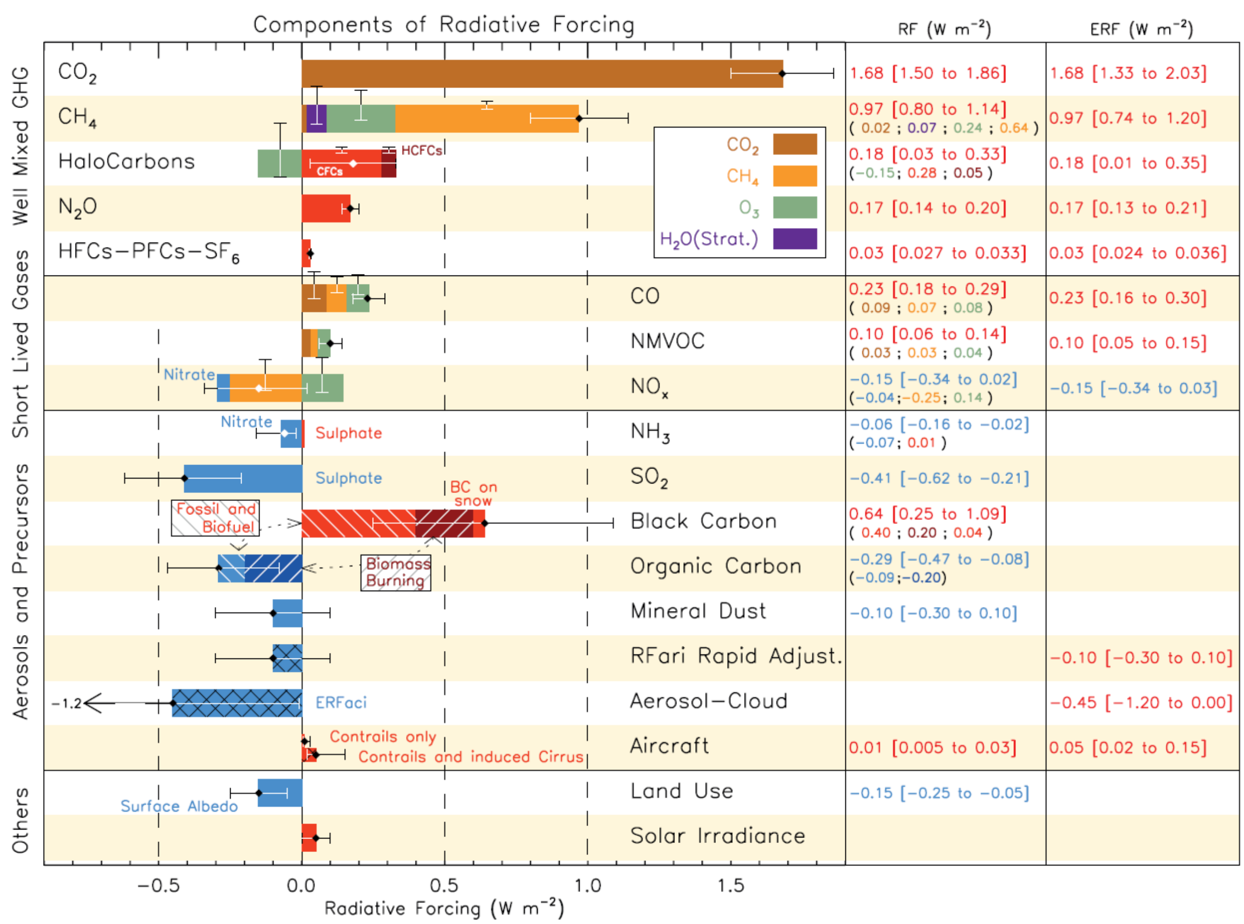

Figure 4: Global radiative forcing (RF) of climate change during the Industrial Era shown by emitted components from 1750 to 2011 [16].

Since there is no absolute and objective measure of 'essentiality', expert judgment was applied to identify the variables which, according to the current state of knowledge, are of immediate relevance for the quantification of the main components of radiative forcing in Africa. The top-level components of a corresponding observation system are illustrated in Figure 5. Starting off from this top-level, the requirements for observation of the main components of anthropogenic radiative forcing (CO_2, CH_4, N_2O, 'minor' GHGs, aerosols and precursors, land surface albedo change) were identified, including the variables which are required for their estimation either directly or related to indirect drivers. The resulting list was further refined based on expert judgement in order to ensure that no major aspects were omitted.

For a detailed description of the various components of such a system specific to the African continent as well as a first iteration of a corresponding list of variables, refer to SEACRIFOG Deliverable 3.1.

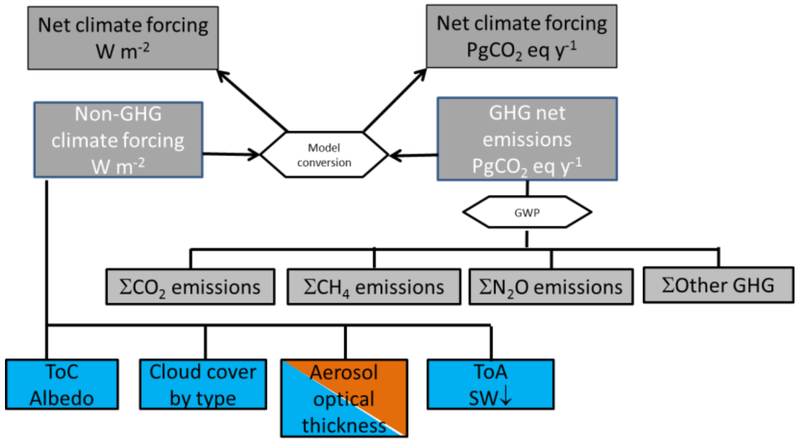

Figure 5: Top-level components of an observation system for anthropogenic climate forcing, copied from SEACRIFOG Deliverable 3.1. For more detailed information, refer to the corresponding deliverable report.

2.2.3 Consolidation of the Two Approaches

The ‘mandatory’ set of variables was derived from the ‘ideal’ set by consolidating the two approaches described in sections 2.2.1 and 2.2.2 in the following way: The variables identified as ‘essential’ in line with an observation system for anthropogenic climate forcing in Africa formed the first iteration of the ‘mandatory’ variable set (see SEACRIFOG Deliverable 3.1).

In a second iteration, these variables were then compared with the outcomes of the survey-based approach and amended accordingly. While there was generally a good agreement between the two approaches (i.e. variables ranked high in the survey generally were among the variables independently identified as essential by the systemic analysis), there were a few ‘outliers’ for which the two approaches were not in accordance. For example, the ECV “sea level” received a high score in the survey (84/100), but is arguably not required to estimate anthropogenic climate forcing (because it is a global effect and not a cause thereof). Similarly, the oceanic variable ‘stable carbon isotopes’ was rated very low (25/100), but observations thereof are essential for the estimation of the oceanic carbon cycle and the anthropogenic fraction of dissolved inorganic carbon. By comparing the results of the two approaches, such ‘outliers’ were identified and reconsidered in detail before a founded decision was made on whether to include or exclude a variable from the ‘mandatory’ set.

The result of this second iteration was then shared with experts from relevant fields of environmental science (e.g. experts on terrestrial carbon stocks, oceanic GHG emissions, biodiversity, etc.) to obtain a final round of feedback and ensure that no fundamental aspects had been omitted and that the ‘mandatory’ set would not contain any redundant variables. This third iteration resulted in a further refinement of the set, mainly by further breaking down some variable classes and explicitly listing the relevant sub-variables (e.g. under the variable class ‘agricultural management’). The ‘mandatory’ variable set resulting from this third iteration is presented in the following section 3.

3 Results: Ideal and Mandatory Variable Set

Figure 6 presents the outcomes of the variable identification process described in sections 2.1 and 2.2 in form of both the 'ideal' and the 'mandatory' (variables in bold font) set of variables/variable groups to be taken into account for the design of a pan-African RI network in line with SEACRIFOG. For detailed information on the mandatory variables, refer to the annex to this report.

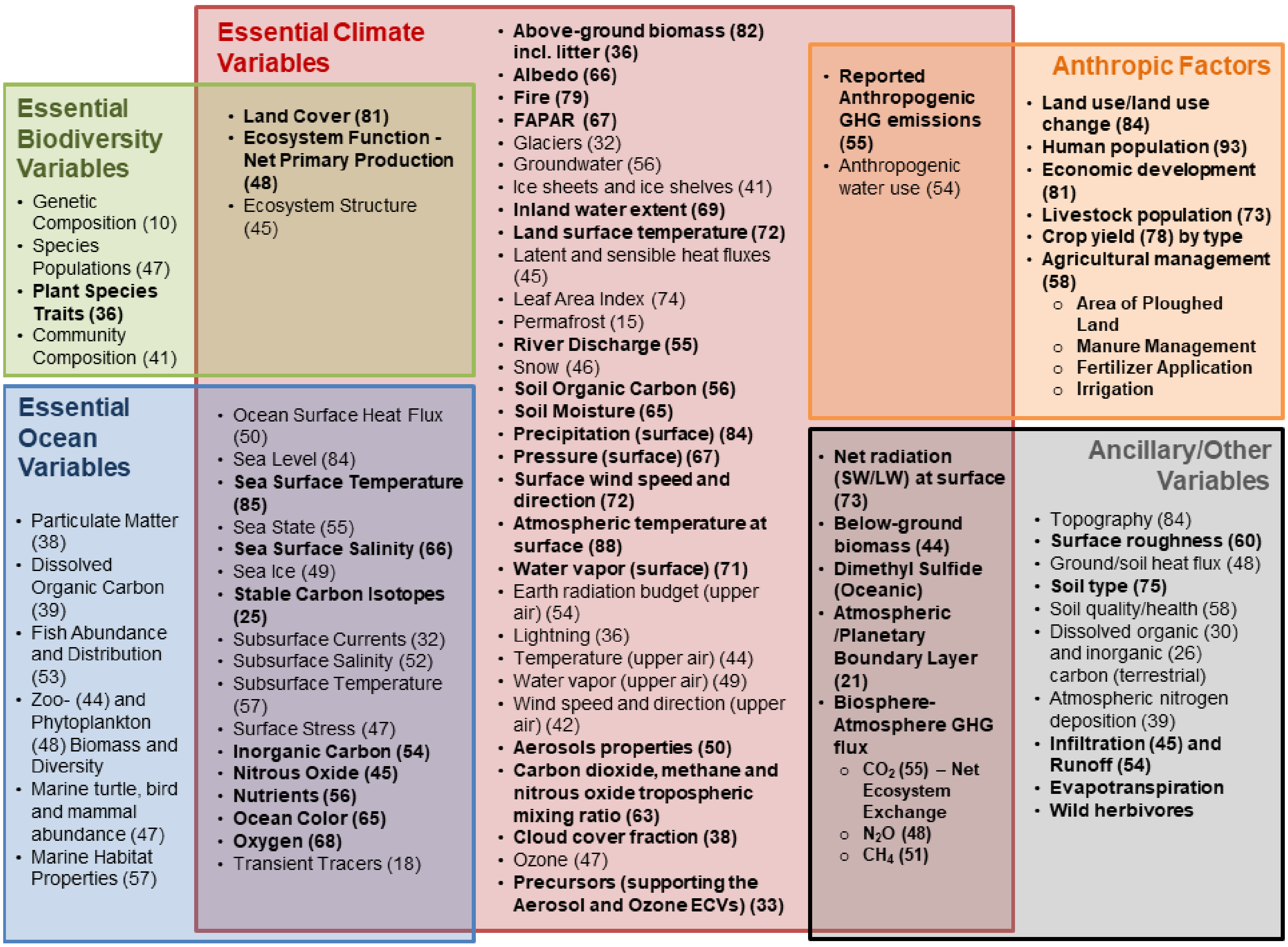

Figure 6: 'Ideal' and 'mandatory' (bold font) set of variables to be considered in the context of the SEACRIFOG project. Each variable's rating score (see section 2.2.1) is provided in parentheses.

The 'ideal' set comprises a total of 91 variables or variable groups (in total corresponding to at least 201 individual variables when considering all the sub-variables) which were identified to be of potential relevance to describe the state of the climatic system and related developments and processes in the context of SEACRIFOG with its focus on GHG observation and food security in Africa. These variables cover the terrestrial, atmospheric and oceanic domain and include both state variables as well as pressures and drivers of change. While the central focus is clearly on climatic variables (ECVs), it is not limited to climatic aspects in order to capture all dimensions which possibly contribute directly or indirectly to climate forcing in Africa. The ECVs are therefore complemented by anthropic factors, i.e. variables which are related to human activity and impact, as well as the EOVs, the EBVs and other ancillary variables.

The 'mandatory' set comprises a total of 58 variables (depicted in bold font in Figure 6) covering the terrestrial, atmospheric and oceanic domains. The systematic and long-term observation of these variables through a combination of in situ and remote measurements has the potential to drastically improve the quantification and attribution of radiative forcing in Africa and refine corresponding models. The exact degree of improvement is dependent on the network design, i.e. the number, location, frequency, duration and accuracy of observations.

Note that some variables are provided as aggregates of various sub-variables (e.g. aerosol properties or species traits), whereas others are disaggregated down to sub-variables (e.g. 'burnt area' as part of the variable class 'fire'). In some cases, only certain sub-variables of a wider variable class were identified as 'essential' (e.g. 'cloud cover fraction' as part of the ECV class 'cloud properties'). In other cases, a higher level of disaggregation reflects a higher degree of heterogeneity within a variable class with regards to observational techniques and requirements (e.g. the distinction between 'inland water extent' and other land cover types). Numerous (sub-)variables are defined by existing frameworks such as the ECV framework. Others were added and/or modified in order to account for particularities of the African continent.

Table 2 below provides the set of the 'mandatory' variables together with information on the respective RF component(s) (for comparison see Figure 4 on page 13). The table further indicates which variables are related to food security and thus of possible relevance for the refinement of corresponding models, early-warning systems and adaptation measures. The survey score and the mean rating outcomes, finally, provide a measure of prioritization according to the three assessment criteria. Further details, including qualitative descriptions of the 'mandatory' variables, are provided in Annex A1.

Annex A2 provides for the 'mandatory' variables the best estimates and uncertainties for the associated radiative forcing component(s) at global scale as well as – where available – estimates and uncertainties of the fluxes or stocks related to the respective variable in Africa. These could be used for further prioritization of the 'mandatory' variables based on quantitative information, e.g. in order to focus on the variables related to the radiative forcing component with the highest uncertainty on the African continent or the variables associated with the highest stocks and/or fluxes in Africa. Note, however, that the figures provided in Annex A2 are indicative only. In case of radiative forcing, the figures refer to global estimates, which possibly differ significantly when exclusively considering the African domain. Flux and stock estimates were compiled from various sources, which have possibly used different methodologies. Estimates given in different units were translated into units of CO_2 equivalent, which may not necessarily the most appropriate measure for the different stocks and/or fluxes under consideration. These figures should thus be treated as a very rough first approximation in need of further refinement.

Table 2: 'Mandatory' set of 58 variables to be observed in order to close the GHG budget and reduce uncertainty of anthropogenic radiative forcing (RF) in Africa and the surrounding oceans. The global figures for the RF components are extracted from the IPPC's Fifth Assessment Report and refer to the period 1750-2011. Where more than one RF component is associated with a variable, the figures in the table refer to the sum of these RF components. The survey score is derived from the mean ratings of the relevance, feasibility (1 – Low, 2 – Medium, 3 - High) and cost (1 – High, 2- Medium, 3 - Low) for each variable. WMGHGs = well-mixed greenhouse gases [3]. NMVOC – Non-methane volatile organic compounds.

Variable Class	Variable	Domain	Type	Major related global RF component	RF best estimate global (Wm-2)	Survey Score (% of max)	Relevance (survey mean)	Feasibility (survey mean)	Cost (survey mean)	Relevant for food security
Above ground biomass	Above ground biomass	Terrestrial	ECV	CO2	1.68	82	3	2.6	2.3	X
	Litter	Terrestrial	Other	CO2, CH4	2.65	36	2.1	1.7	1.4	-
Aerosol properties	Aerosol properties	Atmospheric	ECV	Aerosols	-0.76	50	2.4	2.1	1.5	-
Agricultural management	Area of ploughed land	Terrestrial	Other	CO2, CH4	2.65	58	2.9	1.8	1.8	X
	Manure Management	Terrestrial	Other	CH4, N2O	1.14	58	2.9	1.8	1.8	X
	Fertilizer application	Terrestrial	Other	N2O	0.17	58	2.9	1.8	1.8	X
	Irrigation	Terrestrial	Other	CH4, N2O	1.14	58	2.9	1.8	1.8	X
Animal Population	Livestock Distribution	Terrestrial	Other	CH4, N2O	1.14	73	3	2.2	2.2	X
	Wild Herbivore Distribution	Terrestrial	Other	CH4, N2O	1.14	-	-	-	-	-
Below-Ground Biomass	Below-Ground Biomass	Terrestrial	Other	CO2	1.68	44	2.3	1.8	1.6	-
Biosphere-Atmosphere GHG flux	Biosphere-Atmosphere CH_4 flux	Terrestrial	Other	CH4	0.97	51	3	1.9	1.2	-
	Biosphere-Atmosphere CO_2 flux (NEE)	Terrestrial	Other	CO2	1.68	55	3	1.9	1.4	-
	Biosphere-Atmosphere N_2O flux	Terrestrial	Other	N2O	0.17	48	2.8	1.9	1.2	-
Boundary layer height	Boundary layer height	Atmospheric	Other	-	-	21	1.4	1.6	1.3	-
Carbon Dioxide, Methane and other Greenhouse gases	Tropospheric CH4 mixing ratio	Atmospheric	ECV	CH4	0.97	63	3	2.1	1.7	-
	Tropospheric CO2 mixing ratio	Atmospheric	ECV	CO2	1.68	63	3	2.1	1.7	-
	Halocarbons	Atmospheric	Other	Halocarbons	0.18	-	-	-	-	-
	Tropospheric N2O mixing ratio	Atmospheric	ECV	N2O	0.17	63	3	2.1	1.7	-
Cloud Properties	Cloud Cover Fraction	Atmospheric	ECV	Albedo	-	38	1.8	1.7	1.8	-
Crops	Crop Yield	Terrestrial	Other	-	-	78	3	2.4	2.2	X
Economic Development	Economic Development	Various	Other	-	-	81	2.6	2.4	2.8	X
Ecosystem Function	Net Primary Productivity	Terrestrial	EBV	CO2	1.68	48	2.5	1.8	1.7	-

[3] The well-mixed greenhouse gases have lifetimes long enough to be relatively homogeneously mixed in the troposphere. In contrast, GHGs like O_3 and the non-methane hydrocarbons are gases with relatively short lifetimes and are therefore not homogeneously distributed in the troposphere.

Variable Class	Variable	Domain	Type	Major related global RF component	RF best estimate global (Wm-2)	Survey Score (% of max)	Relevance (survey mean)	Feasibility (survey mean)	Cost (survey mean)	Relevant for food security
Fire	Active Fire	Terrestrial	ECV	CO, Black Carbon, Organic Carbon	0.58	79	2.7	2.7	2.3	-
	Burnt Area	Terrestrial	ECV	CO, Black Carbon, Organic Carbon	0.58	79	2.7	2.7	2.3	X
	Fire Fuel Load	Terrestrial	Other	CO, Black Carbon, Organic Carbon	0.58	79	2.7	2.7	2.3	-
Human Population	Human Population	Terrestrial	Other	-	-	93	3	2.8	2.8	X
Hydrology	Evapotranspiration	Terrestrial	Other	-	-	-	-	-	-	-
	Infiltration and Runoff	Terrestrial	Other	WMGHGs (CO2, CH4, N2O)	2.82	54	2.6	2	1.6	X
	Precipitation (surface)	Terrestrial	ECV	-	-	84	3	2.6	2.5	X
	River Discharge	Terrestrial	ECV	WMGHGs (CO2, CH4, N2O)	2.82	55	2.3	2.2	1.8	-
Inorganic Carbon	Inorganic Carbon	Oceanic	ECV	CO2	1.68	54	2.7	2	1.5	-
Land Cover	Land Cover	Terrestrial	ECV	Surface albedo, mineral dust	-0.25	81	3	2.6	2.2	X
	Extent of inland waters	Terrestrial	ECV	CO2, CH4	2.65	69	2.4	2.4	2.3	X
Land Use/Land Use Change	Land Use/Land Use Change	Terrestrial	Other	WMGHGs (CO2, CH4, N2O), Surface albedo, mineral dust	2.57	84	3	2.7	2.4	X
Nitrous Oxide	Nitrous Oxide (Ocean)	Oceanic	ECV	N2O	0.17	45	2.3	1.6	1.8	-
Nutrients	Marine Nutrients	Oceanic	ECV	WMGHGs (CO2, CH4, N2O)	2.82	56	2.7	1.9	1.7	-
Ocean Colour	Ocean Colour	Oceanic	ECV	WMGHGs (CO2, CH4, N2O)	2.82	65	2.1	2.6	2.2	-
Oxygen	Oxygen	Oceanic	ECV	-	-	68	2.7	2.4	2.1	X
Plant Species Traits	Plant Species Traits	Terrestrial	EBV	-	-	36	2.1	1.7	1.4	-
Precursors	Carbon Monoxide (CO)	Atmospheric	ECV	CO	0.23	33	2	1.8	1.2	-
	Dimethyl Sulfide	Oceanic	Other	aerosol-cloud interaction	-0.45	33	2	1.8	1.2	-
	Non-methane hydrocarbons	Atmospheric	Other	NMVOC	0.1	33	2	1.8	1.2	-
	Nitrogen Oxides (NOx)	Atmospheric	ECV	NOx	-0.15	33	2	1.8	1.2	-
	Sulfur Dioxide (SO_2)	Atmospheric	ECV	SO2	-0.41	33	2	1.8	1.2	-

Variable Class	Variable	Domain	Type	Major related global RF component	RF best estimate global (Wm-2)	Survey Score (% of max)	Relevance (survey mean)	Feasibility (survey mean)	Cost (survey mean)	Relevant for food security
Pressure (surface)	Pressure (surface)	Terrestrial	ECV	-	-	67	2	2.6	2.4	-
Radiation	Albedo	Terrestrial	ECV	Surface albedo	-0.15	66	2.1	2.5	2.4	-
	Fraction of Absorbed Photosynthetically Active Radiation (FAPAR)	Terrestrial	ECV	CO2	1.68	67	2.3	2.4	2.3	-
	Net Radiation at surface (SW/LW)	Terrestrial	ECV	WMGHGs (CO2, CH4, N2O)	2.82	73	2.5	2.5	2.4	-
Reported Anthropogenic Greenhouse Gas Emissions	CO_2, CH_4, N_2O emissions by country and IPCC sector	Terrestrial	ECV	WMGHGs (CO2, CH4, N2O)	2.82	55	3	2	1.2	-
Sea Surface Salinity	Sea Surface Salinity	Oceanic	ECV	-	-	66	2.3	2.4	2.3	-
Soil Properties	Soil Moisture	Terrestrial	ECV	WMGHGs (CO2, CH4, N2O)	2.82	65	2.8	2.2	1.9	X
	Soil Organic Carbon	Terrestrial	ECV	CO2, CH4	2.65	56	2.8	2	1.6	X
Stable Carbon Isotopes	Stable Carbon Isotopes	Oceanic	ECV	-	-	25	1.9	1.5	1.1	-
Surface Roughness	Surface Roughness	Terrestrial	Other	-	-	60	2	2.3	2.3	-
Surface Wind	Surface Wind Speed and direction	Terrestrial	ECV	-	-	72	2.3	2.6	2.4	-
Temperature	Sea Surface Temperature	Oceanic	ECV	-	-	85	2.8	2.7	2.6	-
	Temperature (surface)	Terrestrial	ECV	-	-	88	3	2.8	2.6	X
Water Vapour (surface)	Water Vapour (surface)	Terrestrial	ECV	-	-	71	2.5	2.5	2.3	X

4 Discussion

4.1 Relevance of Results

The variables in the 'ideal' set presented in this report cover a relatively broad spectrum of environmental observations, not only covering climatic aspects of the atmospheric, oceanic and terrestrial domains, but also aspects of biodiversity and human activities across Africa. Some variables in the 'ideal' set are thus not of immediate relevance for SEACRIFOG. The 'mandatory' set, in turn, was carefully distilled from this broader set and comprises those variables which are arguably narrowly related to the improved estimation of the African GHG budget, particularly through observations related to land use and agricultural production. While the 'mandatory' set is not exhaustive for the comprehensive monitoring of food security and all aspects of environmental change, its systematic and long-term observation through a combination of appropriate in situ and remote measurements is expected to drastically enhance the quantification and attribution of anthropogenic climate forcing in Africa and to improve our understanding of the current and future role of food production therein.

Many of the variables in the 'mandatory' set are relevant to the observation and projection of agricultural production and thus production-based food security. Their systematic observation will therefore contribute to the refinement of food security related early warning systems, prediction models and climate-smart policies. While covering many important aspects on the biophysical side of food production, it is important to note, though, that this variable set does not cover many other crucial dimensions related to food security, such as food distribution, access, prices, nutrition, etc. However, future studies, networks and early-warning systems focusing on food security across Africa would without doubt benefit from and build on the systemic observation of the SEACRIFOG 'mandatory' variable set.

The 'ideal' set contains existing global sets, which themselves have already previously undergone assessments and prioritization processes involving a wide range of experts. The 'mandatory' set is the result of further prioritization and thus constitutes a subset which was found to be appropriate and sufficient for the observations required in the context of SEACRIFOG. It was defined through a series of iterative processes involving a diverse range of experts from the environmental observation community and is thus the result of careful triangulation of different arguments and priorities. Since there is no absolute and objective measure of 'essentiality', the 'mandatory' set contains variables which are arguably of immediate relevance for the quantification of the main components of anthropogenic climate forcing in Africa (either directly or as indirect drivers).

With regards to interoperability and compatibility with global and other regional observation networks, existing variable definitions and requirements were adopted where applicable and appropriate. The variables were largely directly derived from globally agreed variable sets, for most of which (relatively) robust conventions, definitions, requirements and measurement protocols already exist. Where necessary, variable specifications were further refined or amended to be appropriate for the African continent. The 'mandatory' set is largely compatible and interoperable with global climate and environmental change observation efforts and systematic observation of this set can thus make a direct contribution to global initiatives.

4.2 Linkages to other SEACRIFOG Activities

The ‘mandatory’ set of variables constitutes the point of departure for various tasks in line with the SEACRIFOG project. As the present deliverable provides clarity on *what* is to be observed by the observation network to be designed in line with SEACRIFOG, related questions refer to the *required extent* (in response to existing needs and gaps in terms of infrastructure and data) and the *how* (i.e. specification of standardised observational requirements). The SEACRIFOG Deliverables 1.1, 3.1, 4.2 and 4.3 will directly build on the ‘mandatory’ variable set presented in this report.

4.2.1 Inventory of Existing and Planned Observation Networks

The SEACRIFOG WP3 is concerned with the development of a common research agenda to fill gaps in carbon, GHG and aerosol observations in Africa. The corresponding SEACRIFOG Deliverable 3.1 is defined as a ‘report about existing [observation] networks and perspective for further development’. This includes compiling an inventory of existing and planned observation infrastructure. With the ‘mandatory’ set of variables at hand, this inventory can be filtered specifically for the SEACRIFOG context. The inventory will then directly feed into optimal observation network design efforts [18, 19], which will provide concrete recommendations regarding additional observation sites to minimize uncertainties in observation results down to the desired level. The network infrastructure inventory has been compiled using the same web-based ‘SEACRIFOG Collaborative Inventory Tool’ as used for the identification of the present variable sets (see Figure 7).

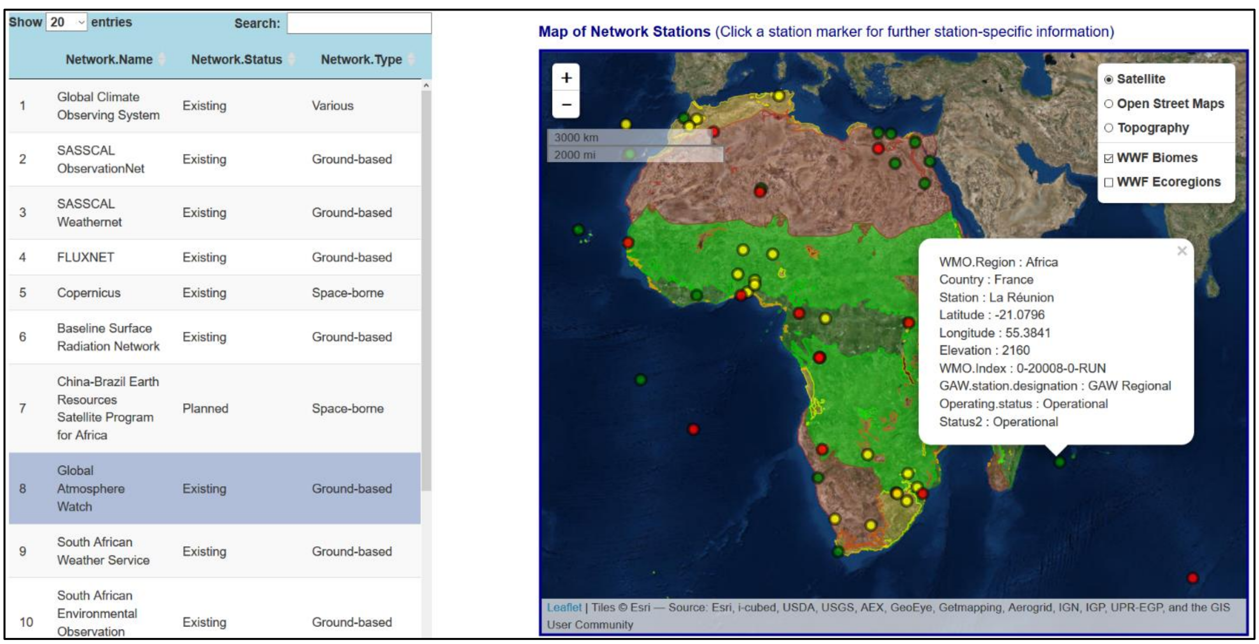

Figure 7: Screenshot of the tab ‘Observation Networks/Infrastructure’ of the ‘SEACRIFOG Collaborative Inventory Tool’ developed by SASSCAL. The tool is accessible at http://seacrifog-tool.sasscal.org/.

4.2.2 Identification of Data Needs and Gaps

Within WP4, Deliverable 4.2, which is defined as “A dataset of current measurement parameters across all systems and the spatial representation of key climatic, land use and GHG data plus a description of best practices” will directly build on the present Deliverable 4.1, since it will assess the availability, quality and spatial and temporal coverage of data for the ‘mandatory’ variables identified in line with this deliverable.

This will be implemented in cooperation with WP1, which aims to identify data needs and gaps related to observations of the 'mandatory' set of variables across Africa. Meta information on data products related to the 'mandatory' set of variables is captured via the same web-based 'SEACRIFOG Collaborative Inventory Tool' as used for the identification of the present variable sets (see Figure 8).

4.2.3 Standardised Measurement Protocols

SEACRIFOG aims at developing a 'standardised protocol to measure the environmental parameters [i.e. the present 'mandatory' set of variables] within atmospheric, marine and terrestrial systems' in line with Deliverable 4.3 of WP4. The present set of 'mandatory' variables to be observed is a direct input to this task. Since interoperability and compatibility with existing regional and global initiatives is a key requirement for the network to be designed in line with SEACRIFOG, where possible, corresponding measurement protocols will be based on existing protocols and requirements, such as the ones defined in the GCOS Implementation Plan for the ECVs [20].

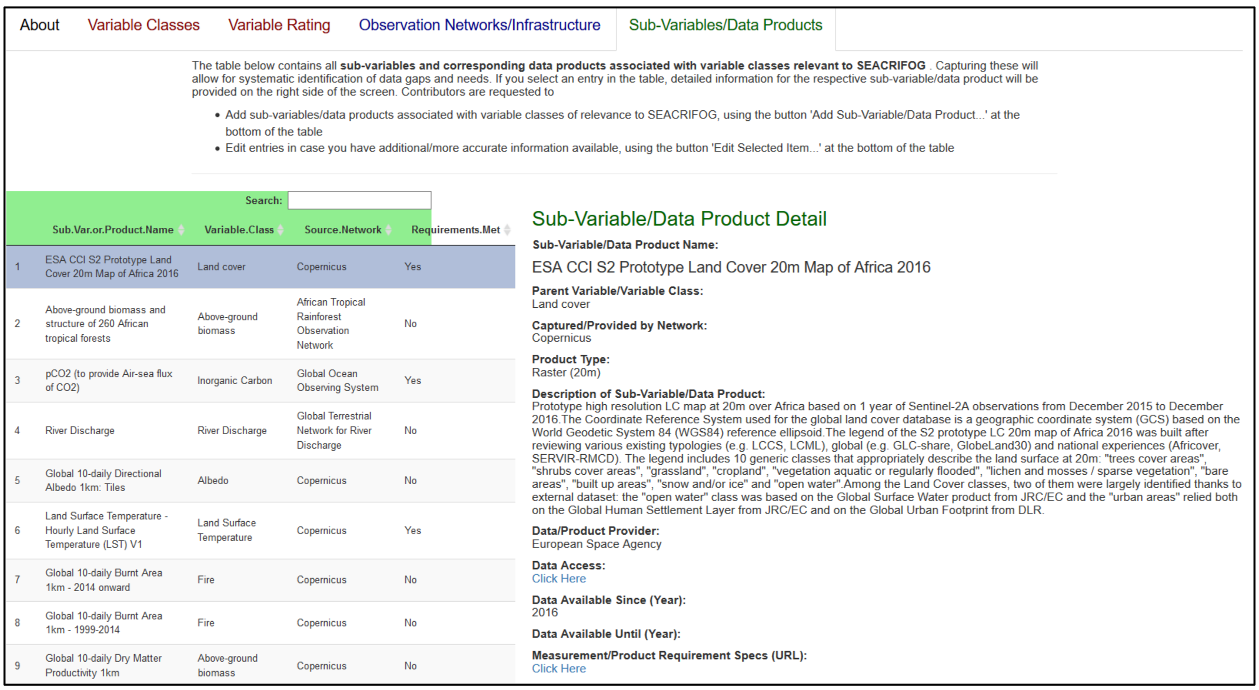

Figure 8: Screenshot of the tab 'Sub-Variables/Data Products' of the 'SEACRIFOG Collaborative Inventory Tool' developed by SASSCAL. The tool is accessible at http://seacrifog-tool.sasscal.org/.

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Annex: Detailed Variable Descriptions

A1 Qualitative Description of 'Mandatory' Variables

Table 3: Detailed qualitative information on the 58 'mandatory' SEACRIFOG variables for the quantification of anthropogenic forcing in Africa and the surrounding oceans. The column 'Domain' specifies whether a variable refers to the atmospheric (A), terrestrial (T) or oceanic (O) domain. The column 'RF role' indicates whether the respective variable is considered to be related to an indirect driver (ID) or direct driver (DD) of RF, a relevant state (S) or an ancillary (A) variable. WMGHGs = well-mixed greenhouse gases. NMVOC – Non-methane volatile organic compounds.

Variable Class	Variable	Do-main	Type	Description	Online source	RF role	Major RF com-ponent	Relevant for food security
Above ground biomass	Above ground biomass	T	ECV	Vegetation biomass is a crucial ecological variable for understanding the evolution and potential future changes of the climate system. Photosynthesis withdraws CO_2 from the atmosphere and stores carbon in vegetation in an amount comparable to that of atmospheric carbon. Currently, biomass is a global net sink of carbon, partially offset by changes in the amount of biomass due to deforestation and other land-cover changes. Biomass changes provide a net sink which is equivalent to approximately 20% of CO_2 emissions from fossil fuels. Vegetation systems have the potential either to sequester more carbon in the future or to contribute as an even larger source. Depending on the quantity of biomass, vegetation cover can have a direct influence on local, regional and even global climate, particularly on air temperature and water vapour. Therefore, a global assessment of biomass and its dynamics is an essential input to climate models and mitigation and adaptation strategies. The non-climate applications of biomass information are manifold, as biomass is a major source of energy and materials across the planet, as well as being related to issues such as biodiversity, water quality and soil erosion. Above ground biomass is traditionally measured by plot survey accompanied by the application of allometric equations. Spatial variability is high, so this approach is expensive and inaccurate at scale. Recent advances in both radar and lidar systems, airborne and satellite-based have now made these the methods of choice, calibrated against plot measurements. The achievable accuracy is around +15%, and the per hectare cost is low when applied at scale. Sub-variables are woody and herbaceous biomass.	www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix/gcos-Land-ecv-above-ground-biomass	S	CO2	X
	Litter	T	Other	Includes all non-living biomass with a diameter less than a minimum diameter chosen by the country (for example 10 cm), lying dead, in various states of decomposition above the mineral or organic soil. This includes litter, fumic, and humic layers. Live fine roots (of less than the suggested diameter limit for below-ground biomass) are included in litter where they cannot be distinguished from it empirically.	www.fao.org/docrep/009/j9345e/j9345e12.htm	ID	CO2, CH4	-
Aerosol properties	Aerosol properties	A	ECV	Atmospheric aerosols are minor constituents of the atmosphere by mass, but a critical component in terms of impacts on the climate and especially climate changes. Aerosols influence the global radiation balance by directly scattering solar radiation and indirectly through influencing cloud reflectivity, cloud cover and cloud lifetime. Africa is a major source of mineral dust and vegetation-fire generated aerosols worldwide, accounting for over half of the total. Sub-variables are aerosol optical depth, single scattering albedo, aerosol layer height and aerosol extinction coefficient profile.	www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix/gcos-atmosphere-	DD	Aerosols	-

Variable Class	Variable	Do-main	Type	Description	Online source	RF role	Major RF com-ponent	Relevant for food security
					composition-ecv-aerosols-properties			
Agricultural management	Area of ploughed land	T	Other	Soils act as sources and sinks for greenhouse gases (GHG) such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Land-use change is very important for GHG emissions from soils, particularly when forests, grass and peat lands are being converted to agricultural land. Tillage has a very important impact on soil CO_2 emissions. Tillage causes a loss of organic carbon content of about 50% due to the stimulation of aerobic processes of microbial respiration. Within the first 30 years after turning forest into agricultural land, 30–35% of the soil carbon stored in the top 7 cm is lost, while below plough depth no changes are recognizable (http://dx.doi.org/10.1016/j.chemer.2016.04.002).	http://dx.doi.org/10.1016/j.chemer.2016.04.002	ID	CO_2, CH_4	X
	Manure Management	T	Other	Since manures contain inorganic N, microbially available sources of C and water, they provide the essential substrates required for the microbial production of N_2O and CH_4. These greenhouse gases can be produced and emitted at each stage of the 'manure management continuum', being the livestock building, manure stores, manure treatment and manure spreading to land. The contribution that manure management makes to total national agricultural emissions of N_2O and CH_4 vary, but can exceed 50% in countries reporting to the UNFCCC in 2009.	https://www.sciencedirect.com/science/article/pii/S0377840111001556?via%3Dihub	ID	CH_4, N_2O	X
	Fertilizer application	T	Other	GHG emissions in Africa related to synthetic fertilizer are currently relatively small, but may increase in future.	http://dx.doi.org/10.1016/j.cosust.2014.07.010	ID	N_2O	X
	Irrigation	T	Other	Irrigation and water management is known to be a key factor on methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O) emissions from agricultural fields, especially paddy soils. Regarding GHG emission estimation, a recent review (www.mdpi.com/2077-0472/7/1/7/pdf) identified the use of emission factors calibrated using temperate conditions which do not suit tropical conditions. On location, most research on rice GHG emissions have been carried out in Asia with little input from Africa.	www.mdpi.com/2077-0472/7/1/7/pdf	ID	CH_4, N_2O	X
Animal Population	Livestock Distribution	T	Other	The estimated contribution of livestock to global greenhouse gas emissions ranges from 10 to 51% of the global emissions. The main contributors to GHG from livestock systems are land use change (CO_2), enteric fermentation from ruminants (CH_4) and manure management (N_2O). This wide range suggests significant methodological differences and uncertainties in different studies. Improving the global estimates of GHG attributed to livestock systems is of paramount importance. This is not only because we need to define the magnitude of the impact of livestock on climate change, but also because we need to understand their contribution relative to other sources.	https://www.sciencedirect.com/science/article/pii/S0167880908000121	DD	CH_4, N_2O	X
	Wild Herbivore Distribution	T	Other	In some parts of Africa, wildlife populations are large enough to require estimation (methane emissions from wild ungulates is not a UNFCCC requirement, but needs quantification for the application of the inversion of methane transport models). Not only do wildlife produce substantial methane as a by-product of microbial fermentation (Fig. 1), but at larger body masses, emissions are comparable to domesticated livestock.	https://onlinelibrary.wiley.com/doi/abs/10.1111/gcb.12973	DD	CH_4, N_2O	-

Variable Class	Variable	Do-main	Type	Description	Online source	RF role	Major RF com-ponent	Relevant for food security
Below-Ground Biomass	Below-Ground Biomass	T	Other	Below-ground biomass is defined as the entire biomass of all live roots, although fine roots less than 2 mm in diameter are often excluded because these cannot easily be distinguished empirically from soil organic matter. Below-ground biomass is an important carbon pool for many vegetation types and land-use systems and accounts for about 20% (Santantonio et al. 1997) to 26% (Cairns et al. 1997) of the total biomass. Below-ground biomass accumulation is linked to the dynamics of above-ground biomass. The greatest proportion of root biomass occurs in the top 30 cm of the soil surface (Bohm 1979; Jackson et al. 1996). This variable is probably the stock with the largest absolute inaccuracy associated.	www.fao.org/docrep/009/j9345e/j9345e12.htm	S	CO2	-
Biosphere-Atmosphere GHG flux	Biosphere-Atmosphere CH_4 flux	T	Other	These fluxes predominantly from wetlands (including rice paddies) (https://www.sciencedirect.com/science/article/pii/0045653593904277), wet soils (dry soils oxidize methane) and ruminants (https://www.sciencedirect.com/science/article/pii/S0167880908000121), are conventionally measured using a combination of chamber and micrometeorological methods. The emission from wild fires are typically modelled, based on the extensive measurements made during the SAFARI 2000 campaign, and satellite burned area and fire radiative power measurements.	http://dx.doi.org/10.1016/j.cosust.2014.07.010	DD	CH4	-
	Biosphere-Atmosphere CO_2 flux (NEE)	T	Other	This is measured as net ecosystem exchange (NEE), on land using eddy covariance towers. Net primary productivity (NPP) can be inferred from NEE with an accuracy of about + 10%, if the various respiration terms are known. The oceanic NEE is inferred from measurements of pCO2 plus the near-surface wind velocities. Furthermore, urban areas represent the dominant source of energy-related CO2 emissions and a significant share of CH4 emissions, proportions that are expected to climb as the global urban extent and the urban population grow disproportionately in the coming decades. Recent advances in observing techniques have brought the urban spatial scale within reach and offer the opportunity to create scientifically credible carbon monitoring systems to verify fluxes and therefore advance effective mitigation policies (http://dx.doi.org/10.1002/2014EF000255).	http://www.cbmjournal.com/content/2/1/3	DD	CO2	-
	Biosphere-Atmosphere N_2O flux	T	Other	Emission databases suggest that sub-Saharan Africa (SSA), home to less than 15% of the world's population, is responsible for 18% of anthropogenic nitrous oxide (N2O) emissions globally, though this includes substantial emissions from biomass burning that would occur in the absence of contemporary anthropogenic activity, and which may be over-estimated. The EDGAR inventories point to agriculture and biomass burning as the sources of the overwhelming majority of non-CO2 trace gas fluxes, and of N2O and CH4 in particular. Estimates of N2O and NO emissions from biomass burning suggest that existing databases may overestimate the area burned, and underestimate fluxes from certain types of burning. Existing data on N2O emissions from croplands in SSA suggest that emissions may remain low with fertilization rates of below 100 or 150 kg N ha 1, though this may not be true for all agroecological zones or soil types, and may change as soil N stocks increase.	http://dx.doi.org/10.1016/j.cosust.2014.07.010	DD	N2O	-
Boundary layer height	Boundary layer height	A	Other	Defined as the part of the troposphere which is directly influenced by the presence of the Earth's surface and which responds to surface forcings with a timescale of about an hour or less. It is often turbulent and is capped by a statically stable layer of air or temperature inversion. The atmospheric boundary layer (ABL) depth (i.e., the inversion	www.climate-dynamics.org/wp-content/upload	A	-	-

Variable Class	Variable	Do-main	Type	Description	Online source	RF role	Major RF com-ponent	Relevant for food security
				height) is variable in time and space, ranging from tens of meters in strongly statically stable situations, to several kilometers in convective conditions over deserts. During fair weather over land, the ABL has a marked diurnal cycle. During daytime, a mixed layer of vigorous turbulence grows in depth, capped by a statically stable entrainment zone of intermittent turbulence. Near sunset, turbulence decays, leaving a residual layer in place of the mixed layer. During nighttime, the bottom of the residual layer is transformed into a statically stable boundary layer by contact with the radiatively cooled surface. Cumulus and stratocumulus clouds can form within the top portion of a humid ABL, while fog can form at the bottom of a stable boundary layer. The bottom 10% of the ABL is called the surface layer. Boundary layer height is an important parameter with respect to budget calculations for greenhouse gases. Determination can be done by laser-based instruments (e.g. ceilometers).	s/2015/05/garratt94a.pdf			
Carbon Dioxide, Methane and other Greenhouse gases	Tropospheric CH4 mixing ratio	A	ECV	Methane (CH4) is the second most significant of the greenhouse gases that have increased in concentration in the atmosphere directly due to human activities, from the viewpoint of the radiative forcing of climate change. The tropospheric methane mixing ratio is measured in similar locations and using similar instruments to CO2 (with similar costs, but some savings when combined with CO2). The achievable accuracy is about 1 ppb. This is the fundamental input to inversion-based estimates of net continental methane emissions.	www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix/gcos-atmosphere-composition-ecv-carbon-dioxide	DD	CH4	-
	Tropospheric CO2 mixing ratio	A	ECV	Carbon dioxide (CO2) is a naturally occurring greenhouse gas, but one whose abundance has been increased substantially above its pre-industrial value of some 280ppm by human activities, primarily because of emissions from combustion of fossil fuels, deforestation and other land-use change. The tropospheric carbon dioxide mixing ratio is measured in 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. In the absence of these, tall towers (>300m) or aircraft or drone profiling can be used; FTIR and laser spectrometers are emerging technologies.	www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix/gcos-atmosphere-composition-ecv-carbon-dioxide	DD	CO2	-
	Halocarbons	A	Other	Groups of species categorised as chlorofluorocarbon (CFCs), hydrofluorocarbons (HFCs), hydrochlorofluorocarbons (HCFCs) and perfluorocarbons (PFCs). All have anthropogenic sources and none has a substantial tropospheric sink. Since these have no natural sources, their estimation is usually based on production and trade statistics, which are focused on just a few suppliers worldwide. 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 atmospheric composition stations used for CO2, CH4 and N2O monitoring also measure some of these constituents, which are useful as air mass tracers. Their observations provide a check on the self-reported emissions.	www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix/gcos-atmosphere-composition-	DD	Halocarbons	-

Variable Class	Variable	Do-main	Type	Description	Online source	RF role	Major RF com-ponent	Relevant for food security
					ecv-carbon-dioxide			
	Tropospheric N2O mixing ratio	A	ECV	Emission databases suggest that sub-Saharan Africa (SSA), home to less than 15% of the world's population, is responsible for 18% of anthropogenic nitrous oxide (N2O) emissions globally, though this includes substantial emissions from biomass burning that would occur in the absence of contemporary anthropogenic activity, and which may be over-estimated. The EDGAR inventories point to agriculture and biomass burning as the sources of the overwhelming majority of non-CO2 trace gas fluxes, and of N2O and CH4 in particular.	www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix/gcos-atmosphere-composition-ecv-carbon-dioxide	DD	N2O	-
Cloud Properties	Cloud Cover Fraction	A	ECV	The variable properties of clouds determine their profound effects on radiation and precipitation. They are influenced by and in turn influence the motion of the atmosphere on many scales. They are affected by the presence of aerosols, and modify atmospheric composition in several ways, including the depletion of ozone when they form in the polar stratosphere. The feedback from changes in cloud remains one of the most uncertain aspects of future climate projections and is primarily responsible for the wide range of estimates of climate sensitivity from models. Cloud cover fraction is required for the calculation of photosynthetically active radiation (needed in oceanic and terrestrial ecosystem models) and albedo-based forcing. The cover by itself is the most important variable, but it should be accompanied by the cloud type (cirrus, stratus, cumulus etc) and altitude, or by parameters such as temperature optical thickness, droplet density and droplet size. All of these are available routinely from satellite observations, and cane be calibrated by ground-based radiometers.	www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix/gcos-atmosphere-upper-air-ecv-cloud-properties	DD	Albedo	-
Crops	Crop Yield	T	Other	Changes in the global production of major crops are important drivers of food prices, food security and land use decisions. Average global yields for these commodities are determined by the performance of crops in millions of fields distributed across a range of management, soil and climate regimes. Crop yield by crop by harvest is not itself a GHG, but is useful as a check on production models, for lateral trade transfers of carbon, and a carbon stock for some long-lived commodities such as timber. It is essential for food security calculations.	http://www.fao.org/faostat/en/#data	A	-	X
Economic Development	Economic Development	-	Other	Economic Development is not a GHG itself, but a key underlying driver of anthropogenic emissions, as globally, economic growth is strongly correlated with growth in emissions.	http://www.worldbank.org/en/region/afr/overview	A	-	X
Ecosystem Function	Net Primary Productivity	T	EBV	Net primary productivity (NPP) is a sub-variable candidate under the EBV class of ecosystem function. NPP refers to the net production of organic carbon by plants in an ecosystem usually measured over a period of a year or more. It is gross primary production (GPP) minus the amount of carbon respired by plants themselves in autotrophic respiration. NPP is a fundamental variable for many diagnostic purposes – ecosystem degradation, productive capacity for crops or timber – but is not actually directly use for carbon assessment. More appropriate is Net Ecosystem Exchange (NEE),	https://geobon.org/ebvs/what-are-ebvs/	ID	CO2	-

Variable Class	Variable	Do-main	Type	Description	Online source	RF role	Major RF com-ponent	Relevant for food security
				which refers to net primary production minus carbon losses in heterotrophic respiration.				
Fire	Active Fire	T	ECV	Fires have impacts on several identified radiative forcing agents. While they can be a natural part of many ecosystems, they contribute to the build-up of CO2 through deforestation fires, tropical peatland fires, and areas that see an increase in the fire return interval. They also emit CH4, and are a major source of aerosols, CO and oxides of nitrogen, thus affecting local and regional air quality. Estimates of greenhouse gas emissions due to fires are essential for realistic modelling of climate and its critical component, the global carbon cycle. Fires caused deliberately for land clearance (agriculture and ranching) or accidentally (lightning strikes and human error) are a major factor in land-cover variability and change, and hence affect fluxes of energy and water to the atmosphere. Spatially and temporally resolved trace-gas and aerosol emissions from fires are the main target quantities. These can be inferred using both land-surface and atmospheric measurements, preferably in combination.	www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix/gcos-land-ecv-fire-disturbance	ID	CO, Black Carbon, Organic Carbon	-
	Burnt Area	T	ECV	Fire burned area is measured daily, cloud cover permitting, by multispectral satellites, with high accuracy (+10%) and fine resolution (20-300 m). It has been validated using airborne imagers and ground mapping, but is now a mature product that requires little further calibration.	www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix/gcos-land-ecv-fire-disturbance	ID	CO, Black Carbon, Organic Carbon	X
	Fire Fuel Load	T	Other	Estimates of fire emissions on large scale are based on a combination of burned area, combustion completeness, and fuel load. Approaches differ in the derivation of this information, which involves models and observations to different degrees. Due to the lack of highly spatially and temporally resolved observations the variability of fuel load is often not fully taken into account (https://www.sciencedirect.com/science/article/pii/S1352231015301126).	www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix/gcos-land-ecv-fire-disturbance	ID	CO, Black Carbon, Organic Carbon	-
Human Population	Human Population	T	Other	Anthropogenic greenhouse gas emissions have increased since the pre-industrial era driven largely by economic and population growth. The UN's projections are published in a biennial report called the World Population Prospects (WPP) with the 2015 revision projecting a remarkable 270% increase in the African population between 2015 and 2100. This rapid population growth has a number of potentially associated effects that could fundamentally alter the continent's landscape. These include high rates of urbanization leading to unplanned expansion of cities, the spread of informal settlements that lack basic services and degradation of natural resources as a result of over-exploitation to meet rising food demand (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5240620/). Up-to-date raster products derived from (often inaccurate) national census data and projections indicating population distribution and density are available	http://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-rev10	A	-	X

Variable Class	Variable	Do-main	Type	Description	Online source	RF role	Major RF com-ponent	Relevant for food security
				(http://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-rev10 or https://ghsl.jrc.ec.europa.eu/index.php).				
Hydrology	Evapotranspira tion	T	Other	Evaporation is the conversion of liquid or solid water into a vapor. It is the process by which water is transferred from a surface-water body or land surface to the atmosphere. Evaporation that occurs through the stoma of plants is called transpiration. In a typical terrestrial setting, it is difficult to measure plant transpiration separately from evaporation from bare soil or water bodies. Therefore, it is common for these two processes to be lumped into a single term—evapotranspiration. Evapotranspiration, when averaged over one-year periods, is usually second in magnitude among water-budget components to precipitation, representing about 65 percent of precipitation that falls on global landmasses. Evapotranspiration may not vary spatially as much as precipitation, but accurate estimates of evapotranspiration are generally more difficult to obtain. As the common link between the water and energy budgets, evapotranspiration is dependent upon the availability of both water and energy. Potential evapotranspiration (PET) is the evapotranspiration that would occur if water were plentiful and it is usually modelled. Real evapotranspiration or evapotranspiration (ET) is the evapotranspiration that occur in real-time conditions and it is equivalent to latent heat flux density measurements acquired via micrometeorological techniques or lysimeters.	https://water.usgs.gov/watercensus/AdHocComm/Background/WaterBudgets-FoundationsforEffectiveWater-ResourcesandEnvironmentalManagement.pdf	ID	-	-
	Infiltration and Runoff	T	Other	Infiltration and runoff are key variables in the carbon cycle. Both are measured in runoff plots. Few places in Africa 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.	https://pubs.usgs.gov/circ/2007/1308/	ID	WMGHGs (CO_2, CH_4, N_2O)	X
	Precipitation (surface)	T	ECV	Precipitation, translating to rainfall in the context of Africa, is the most important climate variable directly affecting humans. Through either its duration, intensity and frequency or its lack of occurrence, it influences the supply of water for personal consumption and use in agriculture, manufacturing industries and power generation, causes risks to life and the functioning of society when associated with floods, landslides and droughts, and affects infrastructure planning, leisure activities and more. Precipitation is closely related to cloud properties, a number of terrestrial ECVs and to ocean-surface salinity. It is indicative of the release of latent heat within the energy cycle, as well as being at the heart of the hydrological cycle.	www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix/gcos-atmosphere-surface-ecv-precipitation	ID, S	-	X
	River Discharge	T	ECV	River-discharge measurements have essential direct applications for water management and related services, including flood protection. They are needed in the longer term to help identify and adapt to some of the most significant potential effects of climate change. In GHG budgets, it is needed to correct for lateral fluxes of C, and as a driver of CH_4 and N_2O emissions from wetlands, all of which are relatively small components. It is also needed for many other national and international developmental reasons, including freshwater supply and hydroelectric power, with greater accuracy requirements.	www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix/gcos-land-ecv-river-discharge	ID	WMGHGs (CO_2, CH_4, N_2O)	-

Variable Class	Variable	Do-main	Type	Description	Online source	RF role	Major RF com-ponent	Relevant for food security
Inorganic Carbon	Inorganic Carbon	O	ECV	The ocean is a major component of the global carbon cycle, exchanging massive quantities of carbon in natural cycles driven by the ocean circulation and biogeochemistry. Since seawater has high capacity for absorbing carbon, the ocean also is a significant modulator of the rate of accumulation of carbon dioxide in the atmosphere. The net carbon uptake of the ocean amounts to approximately 25% of each year's total anthropogenic emissions and the ocean has sequestered ~30% of the cumulative anthropogenic emissions since 1850. Because the net ocean carbon uptake depends on chemical and biological activity, the uptake may change as oceanic conditions change (e.g., pH, currents, temperature, surface winds, and biological productivity). Due to the chemistry of the inorganic carbon in water, this uptake is causing a decline in ocean pH, also known as ocean acidification. The ecological consequences of ocean acidification are a focus for much of the present research. Sub-variables for inorganic carbon are partial pressure of CO2 (pCO2), dissolved inorganic carbon (DIC), total alkalinity and pH. In order to only measure the ocean-atmosphere CO2 exchange, it is sufficient to measure pCO2. In order to fully characterise the oceanic carbonate system, at least one other sub-variable has to be measured.	www.goosocean.org/components/com_oe/oe.php?task=download&id=35906&version=2.0&lang=1&format=1	ID	CO2	-
Land Cover	Land Cover	T	ECV	Land cover influences climate by modifying water and energy exchanges with the atmosphere and by changing greenhouse gas and aerosol sources and sinks. The amount of carbon in vegetation is roughly similar to the atmosphere; that in soils is significantly larger. Land-cover distributions are linked to regional climatic conditions, so changes in cover can be due to climate change on a regional scale as well as directly due to human activities. 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.	www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix/gcos-land-ecv-land-cover	S	Surface albedo, mineral dust	X
	Extent of inland waters	T	ECV	Inland waters (streams, rivers, lakes and reservoirs) are increasingly recognized as important sources of GHGs to the atmosphere, with global CO2 and CH4 emissions estimated at 2.1 PgC yr-1 (ref. 3) and 0.7 PgC yr-1 (CO2-equivalents; CO2e), respectively. Riverine carbon dioxide and methane emissions increase with wetland extent and upland biomass. Information on changes in lake level and area (which are surrogates for changes in lake volume) is required on a monthly basis for climate assessment purposes. The measurement requirements are thus different than for other land cover classes which do not need to be measured as frequently. Approximately 95% of the volume of water held globally in approximately 4,000,000 lakes is contained in the world's 80 largest lakes. The surface area is used in its own right as a land cover, but also as a proxy for stored volume and depth, given a bathymetric model.	www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix/gcos-land-ecv-lakes	ID	CO2, CH4	X
Land Use/Land Use Change	Land Use/Land Use Change	T	Other	Land use is "the total of arrangements, activities, and inputs that people undertake in a certain land cover type" (FAO, 1997a; FAO/UNEP, 1999). National categories of land use differ, but many have been harmonized under the influence of FAO's periodical World Census of Agriculture (http://www.ipcc.ch/ipccreports/sres/land_use/index.php?idp=45). Categories of land cover/use systems are used to illustrate the expected potential for carbon sequestration from a change in system management (e.g., intensification or	www.ipcc.ch/ipccreports/sres/land_use/index.php?idp=171	ID, DD	WMGHGs (CO2, CH4, N2O), Surface albedo,	X

Variable Class	Variable	Do-main	Type	Description	Online source	RF role	Major RF com-ponent	Relevant for food security
				extensification) or upon conversion from one category to another. Africa plays a globally important role in land use carbon emissions, though the magnitudes of these terms are highly uncertain.			mineral dust	
Nitrous Oxide	Nitrous Oxide (Ocean)	O	ECV	Nitrous oxide (N2O) is an important climate-relevant trace gas in the Earth's atmosphere. In the troposphere it acts as a strong greenhouse gas and in the stratosphere, it acts as an ozone depleting substance because it is the precursor of ozone depleting nitric oxide radicals. The ocean - including its coastal areas such as continental shelves, estuaries and upwelling areas - contribute about 30% to the atmospheric N2O budget. The amount of N2O produced during water column microbially mediated processes called nitrification and denitrification strongly depends on the prevailing dissolved oxygen (O2) concentrations and is significantly enhanced under low (i.e. suboxic) O2 conditions. Thus, significantly enhanced N2O concentrations are generally found at oxic/suboxic or oxic/anoxic boundaries. Global maps of N2O in the surface ocean show both enhanced N2O anomalies (i.e. supersaturation of N2O) in coastal and equatorial upwelling regions as well as N2O near equilibrium in large parts of the open ocean.	www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix/gcos-ocean-biogeochemical-ecv-nitrous-oxide	DD	N2O	-
Nutrients	Marine Nutrients	O	ECV	The availability of inorganic macronutrients (nitrate (NO3), phosphate (PO4), silicic acid (Si(OH)4), ammonium (NH4), nitrite (NO2)) in the upper ocean frequently limits and regulates the amount of organic carbon fixed by phytoplankton, thereby constituting a key control mechanism of carbon and biogeochemical cycling. Nutrient data thus provide essential links between physical climate variability and ecosystem variability. They can provide additional information on ocean mixing and climate related phenomena such as changes in primary and export production (nutrient transports regulate new production which is correlated with export production), eutrophication and shifts in phytoplankton community composition. Therefore, it is necessary to develop accurate observations of trends in dissolved nutrients in both upper- and deep-ocean waters.	www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix/gcos-ocean-biogeochemistry-ecv-nutrients	ID	WMGHGs (CO2, CH4, N2O)	-
Ocean Colour	Ocean Colour	O	ECV	Ocean colour is measured as the ocean colour radiance (OCR). OCR is the wavelength-dependent solar energy captured by an optical sensor looking down at the sea surface. These water-leaving radiances contain information on the ocean albedo and information on the constituents of the seawater, in particular, phytoplankton pigments such as chlorophyll-a. Data analysis is not easy as satellite measurements also include radiation scattered by the atmosphere and the ocean surface. The relatively weak OCR signal is some 5-15% of the strength of the incident solar radiation. Furthermore, in-situ observations through ocean bio-optical observatories and cruises are required to calibrate the space observations using local area spectrophotometers and analyses of phytoplankton populations and their pigments. OCR products are used to assess ocean ecosystem health and productivity, and the role of the oceans in the global carbon cycle, to manage living marine resources, and to quantify the impacts of climate variability and change. OCR products, in particular chlorophyll-a, are also required by the modelling community for the validation of climate models, and for use in data-assimilation systems for reanalysis and initializing forecasts.	www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix/gcos-ocean-biogeochemistry-ecv-ocean-color	S	WMGHGs (CO2, CH4, N2O)	-
Oxygen	Oxygen	O	ECV	O2 is essential for nearly all multicellular life. Future projections indicate that oceanic O2 levels will decrease substantially, in part because of ocean warming and increased	www.ncdc.noaa.gov/gosic/gcos-	A	-	X

Variable Class	Variable	Do-main	Type	Description	Online source	RF role	Major RF com-ponent	Relevant for food security
				stratification (a process often referred to as ocean deoxygenation), but also because of increased nutrient loadings in nearshore environments that lead to eutrophication. In a business-as-usual scenario, the ocean is projected to lose nearly 20% of its O2. This could have dramatic consequences for marine biogeochemistry and marine life, as the ocean's O2 minimum zones will expand substantially, and large swaths of ocean will appear that have O2 levels that are too low for fast-swimming fish to survive, and can potentially reduce the pool of bioavailable nitrogen due to reduction of nitrate.	essential-climate-variable-ecv-data-access-matrix/gcos-ocean-biogeochemistry-ecv-oxygen			
Plant Species Traits	Plant Species Traits	T	EBV	Plant species traits refer to vegetation in the main African biomes. The main plant traits are the maximum rate of electron transport (J_{max}), the maximum rate of carboxylation (V_{cmax}), stomatal conductance (G_s), specific leaf area (SLA), leaf dimension, leaf nitrogen content, wood density, mean maximum height (especially of the perennating organs) and the root:shoot ratio.	https://geobon.org/ebvs/what-are-ebvs/	A	-	-
Precursors	Carbon Monoxide (CO)	A	ECV	CO plays a primary role in governing OH abundances in the troposphere. CO emissions into the atmosphere may have a significant impact on climate forcing due to chemical impact on CH4 lifetime, and tropospheric O3 and CO2 photochemical production.	https://www.ipcc.ch/ipccreports/tar/wg1/229.htm	ID	CO	-
	Dimethyl Sulfide	O	Other	Oceans dominate emissions of dimethyl sulfide (DMS), the major natural sulfur source. Dimethylsulphoniopropionate (DMSP), the intracellular precursor to DMS, is produced by marine phytoplankton and released during senescence, zoo-plankton grazing, and viral lysis. In oligotrophic regions (chlorophyll < 0.5 mg m-3) with shallow upper mixed layers, DMS concentration is inversely correlated with chlorophyll. In highly productive regions, however, DMS concentration becomes positively correlated with chlorophyll. DMS is important for the formation of non-sea salt sulfate (nss-SO42−) aerosols and secondary particulate matter over oceans and thus, significantly influence global climate.	https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2004GB002333	ID	aerosol-cloud interaction	-
	Non-methane hydrocarbons	A	Other	Non-methane volatile organic compounds (NMVOCs) are important precursors of tropospheric ozone (Trainer et al., 1987), secondary organic aerosols (SOA) (Claeys et al., 2004), and nitrogen oxide radicals reservoir species such as organic nitrates (Paulot et al., 2012) and peroxyacetyl nitrates (Pfister et al., 2008). NMVOCs have local and global impacts on the oxidative capacity of the atmosphere, air quality, climate, and human health. Natural sources of NMVOCs are dominated by isoprene produced in the chloroplasts of plants and released to the atmosphere via the stomata of leaves. Large sources of anthropogenic NMVOCs include energy use (e.g. fuelwood burning, natural gas flaring) and industrial processes (e.g. solvent evaporation) (Barletta et al., 2005). Field campaigns in Africa have historically focused on NMVOCs from biomass burning (Andreae and Merlet, 2001), but Africa is a large source of isoprene emissions (Stavrakou et al., 2009a) and anthropogenic NMVOCs (Hopkins et al., 2009) and has thus far received little attention due in part to limited ground-based observations (https://dash.harvard.edu/bitstream/handle/1/12274545/Marais_gsas.harvard_0084L_11313.pdf?sequence%3D1).	https://dash.harvard.edu/bitstream/handle/1/12274545/Marais_gsas.harvard_0084L_11313.pdf?sequence%3D1	ID	NMVOC	-
	Nitrogen Oxides (NOx)	A	ECV	Metric values for NOX usually include the short-lived ozone effect, CH4 changes and the CH4-controlled O3 response. NOX also causes RF through nitrate formation, and via CH4 it affects stratospheric H2O and through ozone it influences CO2. In addition, NOx	https://www.ipcc.ch/pdf/assessment-	ID	NOx	-

Variable Class	Variable	Do-main	Type	Description	Online source	RF role	Major RF com-ponent	Relevant for food security
				affects CO2 through nitrogen deposition (fertilization effect). Due to high reactivity and the many nonlinear chemical interactions operating on different time scales, as well as heterogeneous emission patterns, calculation of net climate effects of NOX is difficult. The net effect is a balance of large opposing effects with very different temporal behaviours. There is also a large spread in values among the regions due to variations in chemical and physical characteristics of the atmosphere.	report/ar5/wg1/WG1AR5_Chapter08_FINAL.pdf			
	Sulfur Dioxide (SO_2)	A	ECV	One of the most important anthropogenically sourced aerosol species is sulfate (SO4). Sulfate-containing aerosols are formed following chemical conversion of gaseous sulfur dioxide (SO2) emissions from fossil-fuel combustion, as well as natural sources such as volcanic SO2. Sulfate particles strongly scatter incoming shortwave (SW) radiation, which helps to increase the planetary albedo and cool the surface. They also act as cloud condensation nuclei, leading to additional cloud droplets forming in supersaturated conditions, which increases cloud albedo and again cools the Earth system.	www.atmos-chem-phys.net/16/11497/2016/	ID	SO2	-
Pressure (surface)	Pressure (surface)	T	ECV	Surface pressure is a fundamental meteorological variable for which observations are required for initializing forecasts and for use in reanalysis systems. It is an indicator of circulation patterns. Differences between surface pressures at pairs of stations provide traditional indices of the North Atlantic and Southern Oscillations. Other indices are based on zonal means or principal-component analyses of gridded fields. Surface pressure also provides information on the intensity of weather systems, including tropical cyclones. It has an impact on sea level.	www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix/gcos-atmosphere-surface-ecv-air-pressure	S	-	-
Radiation	Albedo	T	ECV	The albedo of a land surface is the non-dimensional ratio of the radiation flux reflected by a (typically horizontal) surface in all directions and the incoming irradiance, which is the radiation flux from the upper hemisphere. This is technically known as the bi-hemispherical reflectance factor, and both fluxes must be relative to the same spectral range. For bare soils and other solid, convex objects, the material interface between the ground and the atmosphere constitutes the reference surface. In the case of vegetation, a reference surface is typically defined at or near the top of the canopy and must be specified explicitly. This 'generic' albedo is highly variable in space and time as a result of changes in surface properties (snow deposition and melting, changes in soil moisture and vegetation cover and so on), as a function of fluctuations in the illumination conditions (solar angular position, atmospheric effects, cloud properties and so on) and with human activities (for example, clearing and planting forests, sowing and harvesting crops, burning rangeland and so on). Albedo is thus not an intrinsic surface property, but a joint property of the surface and the overlying atmosphere, since the composition (gases, clouds and aerosols) of the latter significantly affects the spectral and directional distribution of the irradiance.	www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix/gcos-land-ecv-albedo	S	Surface albedo	-
	Fraction of Absorbed Photosynthetically Active	T	ECV	Solar radiation in the spectral range 400-700 nm, known as photosynthetically active radiation (PAR), provides the energy required by terrestrial vegetation to produce organic materials from mineral components. The part of this PAR that is effectively absorbed by plants is called FAPAR. It is a non-dimensional quantity varying from 0	www.ncdc.noaa.gov/gosic/gcos-essential-climate-	ID	CO2	-

Variable Class	Variable	Do-main	Type	Description	Online source	RF role	Major RF com-ponent	Relevant for food security
	Radiation (FAPAR)			(over deserts) to 1 (for large, deep, homogeneous canopy layers observed by medium- to low-resolution sensors), although the maximum value is never witnessed in practice because some of the incoming light is always reflected back by the canopy or the underlying ground. FAPAR is related to, but different from, LAI (covered in the following subsection), which describes the amount of leaf material in the canopy. FAPAR plays a critical role in assessing the primary productivity of canopies, the associated fixation of atmospheric CO2 and the energy balance of the surface. As is the case with land-surface albedo (section 6.3.9), FAPAR depends on the illumination conditions, that is, the angular position of the Sun with respect to the vegetation layer and the relative contributions of the direct and diffuse irradiances. Both black-sky (assuming only direct radiation) and white-sky (assuming that all the incoming radiation is in the form of isotropic diffuse radiation) FAPAR values may be considered. Since FAPAR is linearly related to GPP, this sets the fundamental accuracy of most carbon cycle models.	variable-ecv-data-access-matrix/gcos-lan-ecv-fraction-absorbed-photosynthetically-active-radiation-fapar			
	Net Radiation at surface (SW/LW)	T	ECV	Net radiation refers to the difference between the incoming and outgoing radiation related to the ground (terrestrial surface). It has four components: the incoming shortwave (SW) and longwave (LW) radiation and the outgoing SW and LW radiation, which can be aggregated as net SW and LW radiation. Net radiation is the fundamental driver of potential evaporation, a controller of soil moisture, which in turn controls many soil GHG emissions.	-	ID	WMGHGs (CO2, CH4, N2O)	-
Reported Anthropogenic Greenhouse Gas Emissions	CO_2, CH_4, N_2O emissions by country and IPCC sector	T	ECV	These are reporting requirements at national scale by all UNFCCC signatories (all the countries in Africa), for CO2, CH4 and N2O about every 5 years, with annual detail, broken down by IPCC sector. The accounting is done by inventory, and typically by applying very simple (tier 1) models involving an estimate of an activity level, multiplied by an emission factor. The accuracy of these models is unlikely to be better than about +25%. In some cases – for instance the emission of CO2 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 + 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 or even tier 3 models.	www.ncdc.noaa.gov/gcos-land-ecv-greenhouse-gas-fluxes	DD	WMGHGs (CO2, CH4, N2O)	-
Sea Surface Salinity	Sea Surface Salinity	O	ECV	Salinity is the fraction of water that comprises salt and other impurities. Observations of sea-surface salinity (SSS) are needed to calculate estimates of oceanic transports of freshwater and other properties on basin to global scales. SSS also provides a good pointer to changes in the water cycle as it indicates the change in freshwater due to the difference between precipitation and evaporation. Along with coincident SST observations, it allows surface-water density to be estimated. In situ SSS data also provide important resources for evaluating numerical models, palaeological estimates and satellite observations.	www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix/gcos-ocean-physics-ecv-sea-surface-salinity	S	-	-
Soil Properties	Soil Moisture	T	ECV	Soil humidity is the single most important soil parameter for soil gas emissions, since it controls microbial activity and all related processes. It is an important variable in land-atmosphere feedbacks at both weather and climate timescales. It plays a major role in determining how the energy flux into the land from incoming radiation is partitioned into fluxes of latent and sensible heat from the land to the atmosphere, and in the	www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-	ID, S	WMGHGs (CO2, CH4, N2O)	X

Variable Class	Variable	Do-main	Type	Description	Online source	RF role	Major RF com-ponent	Relevant for food security
				allocation of precipitation into runoff, subsurface flow and infiltration. Soil moisture is intimately involved in the feedback between climate and vegetation, as both local climate and vegetation influence soil moisture through evapotranspiration, while soil moisture is a determinant of the type and condition of vegetation in a region. Changes in soil moisture can accordingly have substantial impacts on agricultural productivity, forestry and ecosystem health.	data-access-matrix/gcos-land-ecv-soil-moisture			
	Soil Organic Carbon	T	ECV	Soil organic carbon (SOC) represents the largest terrestrial carbon pool, amounting to about two to three times the net size of the biomass pools. Carbon sinks may be explained by changes in above-ground biomass on seasonal to decadal timescales, but soil organic carbon stocks become significant on longer timescales and can be a significant source at all timescales after disturbances. Soil organic carbon is derived from plant and other decaying matter and is a significant part of the carbon cycle. About 10% of the atmospheric carbon cycles through soils each year. As SOC is the largest terrestrial C stock, small relative errors either in SOC determination, or more typically in bulk density and gravel content, have large consequences. The latter are therefore important sub-variables.	www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix/gcos-land-ecv-soil-carbon	S	CO2, CH4	X
Stable Carbon Isotopes	Stable Carbon Isotopes	O	ECV	The utility of carbon-13 isotope (13C, the carbon-13 to carbon-12 isotope ratio 13C/12C) as a tracer of the ocean's carbon cycle is observation limited. By observing the temporal development of the lightening of the oceanic inorganic carbon pool due to the uptake of CO2 originating from the burning of 13C-depleted fossil fuel carbon, a phenomenon also known as oceanic 13C Suess effect, an estimation of the anthropogenic carbon fraction of DIC is possible. Recent improvements in measuring the concentration of carbon dioxide (CO2) gas dissolved in seawater using field portable spectrometers open up the possibility of underway 13C/12C observations across large portions of the surface ocean. Such data sets would substantially improve 13C-based estimates of organic matter (OM) export rate and of the air-sea 13CO2 flux. The latter term can be compared to depth-integrated 13CO2 inventory changes in the water column to provide a separation of anthropogenic CO2 change due to air-sea CO2 flux versus change due physical transport by ocean circulation. Recent application of this approach in the North Atlantic indicates that 50% of the anthropogenic CO2 increase in this ocean basin is a result of transport from the South Atlantic as part of the meridional overturning circulation.	www.goosocean.org/components/com_oe/oe.php?task=download&id=35910&version=2.0&lang=1&format=1	S	-	-
Surface Roughness	Surface Roughness	T	Other	The geometric characteristic of a surface associated with its efficiency as a momentum sink for turbulent flow, due to the generation of drag forces and increased vertical wind shear. In micrometeorology, the surface roughness is usually measured by the roughness length, a length scale that arises as an integration constant in the derivation of the logarithmic wind profile relation. In neutral stability the logarithmic wind profile extrapolates to zero wind velocity at a height equal to the surface roughness length. Several formulas exist to parameterize this length scale as a function of the roughness element geometry (e.g., spacing and silhouette area). Source: Stull, R. B. 1988. An Introduction to Boundary Layer Meteorology. 666 pp.	-	A	-	-
Surface Wind	Surface Wind Speed and direction	T	ECV	Surface wind has substantial influence on the exchanges of momentum, heat, moisture and trace species between the atmosphere and the underlying ocean and land. It drives ocean waves, storm surges and sea ice, and provides a key forcing of the ocean	www.ncdc.noaa.gov/gosic/gcos-essential-	ID, S	-	-

Variable Class	Variable	Do-main	Type	Description	Online source	RF role	Major RF com-ponent	Relevant for food security
				circulation that is responsible for the global transport of important amounts of heat and carbon. It is a sensitive indicator of the state of the global coupled climate system, and knowledge of it is important for understanding climate variability and change, and for climate model evaluation. Data on surface wind have direct application to sectors such as transport, construction, energy production, human health, marine safety and emergency management. They are also used in metrics that characterize the strength of tropical cyclones.	climate-variable-ecv-data-access-matrix/gcos-atmospheric-surface-ecv-near-surface-wind-speed-and-direction			
Temperature	Sea Surface Temperature	O	ECV	The large-scale spatial patterns of sea surface temperature (SST) are related to large-scale weather patterns. SST plays important roles in the exchanges of energy, momentum, moisture and gases between the ocean and atmosphere. The heat and moisture exchanges are a main driver of global weather systems and climate patterns. On 25-100 km scales, strong SST gradients can contribute to vertical atmospheric circulations that transfer energy and moisture from the atmospheric boundary layer to the free atmosphere. On smaller scales, SSTs are used to diagnose adverse conditions for coral reefs. However, SST is not a good indicator of multiannual variations in the energy stored in the ocean.	www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix/gcos-ocean-physics-ecv-sea-surface-temperature	S	-	-
	Temperature (surface)	T	ECV	Surface air temperature has profound and widespread impacts on human lives and activities, affecting health, agriculture, energy demand and much more. It also has impacts on natural systems. It affects the fluxes of heat, momentum, water vapour and trace species between land and atmosphere and between ocean and atmosphere. Its monitoring provides a key indicator of climate change. Observations of it contribute to estimates of what is commonly known as "global-mean surface temperature"� and to a number of indices of extreme conditions.	www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix/gcos-atmosphere-surface-ecv-air-temperature	S	-	X
Water Vapour (surface)	Water Vapour (surface)	T	ECV	The humidity of air near the surface of the Earth affects the comfort and health of humans, livestock and wildlife, the swarming behaviour of insects and the occurrence of plant disease. Among other impacts are those that stem from the formation of fog. Along with temperature and wind, near-surface water vapour influences the surface fluxes of moisture and thus plays a role in the energy and hydrological cycles. Water vapour is a GHG in its own right (though not considered to be an anthropogenic one), but its main use in GHG estimation systems is via its effects on potential evaporation, which controls stomatal aperture and soil moisture.	www.ncdc.noaa.gov/gosic/gcos-essential-climate-variable-ecv-data-access-matrix/gcos-atmosphere-surface-ecv-water-vapour	S	-	X

A2 Quantitative Description of 'Mandatory' Variables

Table 4: In the attempt of enabling a quantitative prioritization, this table provides quantitative information on the 58 'mandatory' SEACRIFOG variables for the measurement of anthropogenic forcing in Africa and the surrounding oceans. The column 'RF role' indicates whether the respective variable is considered to be related to an indirect driver (ID) or direct driver (DD) of RF, a relevant state (S) or an ancillary (A) variable. The global figures for the RF components are extracted from the IPPC's Fifth Assessment Report and refer to the period 1750-2011. Where more than one RF component is associated with a variable, the figures in the table refer to the sum of these RF components. Estimated figures on related fluxes [F] and stocks [S] refer to the African continent and were all translated into CO2eq units. Negative numbers (in parentheses) indicate a flux from the atmosphere into the biosphere. WMGHGs = well-mixed greenhouse gases. NMVOC – Non-methane volatile organic compounds.

Variable Class	Variable	Domain	Type	RF role	Major related RF component	RF best estimate global (Wm-2)	Rel. RF uncertainty (global)	Abs. RF uncertainty range	Estimated flux/stock (Africa), Tg CO2eq y-1	Flux/stock uncertainty (Africa), Tg CO2eq y-1	Literature source for flux/stock estimate
Above ground biomass	Above ground biomass	Terrestrial	ECV	S	CO2	1.68	11%	0.36	293,333 [S]	102,667	https://cbmjournal.biomedcentral.com/articles/10.1186/1750-0680-2-3
	Litter	Terrestrial	Other	ID	CO2, CH4	2.65	13%	0.70	-	-	-
Aerosol properties	Aerosol properties	Atmospheric	ECV	DD	Aerosols	-0.76	250%	3.81	-	-	-
Agricultural management	Area of ploughed land	Terrestrial	Other	ID	CO2, CH4	2.65	13%	0.70	40,333 [F]	18,333	https://cbmjournal.biomedcentral.com/articles/10.1186/1750-0680-2-3
	Manure Management	Terrestrial	Other	ID	CH4, N2O	1.14	18%	0.40	189 [F]	-	http://edgar.jrc.ec.europa.eu
	Fertilizer application	Terrestrial	Other	ID	N2O	0.17	18%	0.06	-	-	-
	Irrigation	Terrestrial	Other	ID	CH4, N2O	1.14	18%	0.40	-	-	-
Animal Population	Livestock Distribution	Terrestrial	Other	DD	CH4, N2O	1.14	18%	0.40	578 [F]	-	http://edgar.jrc.ec.europa.eu
	Wild Herbivore Distribution	Terrestrial	Other	DD	CH4, N2O	1.14	18%	0.40	-	-	-
Below-Ground Biomass	Below-Ground Biomass	Terrestrial	Other	S	CO2	1.68	11%	0.36	-	-	-
Biosphere-Atmosphere GHG flux	Biosphere-Atmosphere CH_4 flux	Terrestrial	Other	DD	CH4	0.97	18%	0.34	-	-	-
	Biosphere-Atmosphere CO_2 flux (NEE)	Terrestrial	Other	DD	CO2	1.68	11%	0.36	44 [F]	1,071	www.pnas.org/cgi/doi/10.1073/pnas.1603956113
	Biosphere-Atmosphere N_2O flux	Terrestrial	Other	DD	N2O	0.17	18%	0.06	-	-	-
Boundary layer height	Boundary layer height	Atmospheric	Other	A	-	-	-	-	-	-	-

Variable Class	Variable	Domain	Type	RF role	Major related RF component	RF best estimate global (Wm-2)	Rel. RF uncertainty (global)	Abs. RF uncertainty range	Estimated flux/stock (Africa), Tg CO2eq y-1	Flux/stock uncertainty (Africa), Tg CO2eq y-1	Literature source for flux/stock estimate
Carbon Dioxide, Methane and other Greenhouse gases	Tropospheric CH4 mixing ratio	Atmospheric	ECV	DD	CH4	0.97	18%	0.34	-	-	-
	Tropospheric CO2 mixing ratio	Atmospheric	ECV	DD	CO2	1.68	11%	0.36	-	-	-
	Halocarbons	Atmospheric	Other	DD	Halocarbons	0.18	83%	0.30	-	-	-
	Tropospheric N2O mixing ratio	Atmospheric	ECV	DD	N2O	0.17	18%	0.06	-	-	-
Cloud Properties	Cloud Cover Fraction	Atmospheric	ECV	DD	Albedo	-	-	-	-	-	-
Crops	Crop Yield	Terrestrial	Other	A	-	-	-	-	-	-	-
Economic Development	Economic Development	Various	Other	A	-	-	-	-	-	-	-
Ecosystem Function	Net Primary Productivity	Terrestrial	EBV	ID	CO2	1.68	11%	0.36	(36,667) [F]	11,000	https://cbmjournal.biomedcentral.com/articles/10.1186/1750-0680-2-3
Fire	Active Fire	Terrestrial	ECV	ID	CO, Black Carbon, Organic Carbon	0.58	116%	1.34	3,777 [F]	807	www.biogeosciences.net/11/381/2014/
	Burnt Area	Terrestrial	ECV	ID	CO, Black Carbon, Organic Carbon	0.58	116%	1.34			
	Fire Fuel Load	Terrestrial	Other	ID	CO, Black Carbon, Organic Carbon	0.58	116%	1.34			
Human Population	Human Population	Terrestrial	Other	A	-	-	-	-	-	-	-
Hydrology	Evapotranspiration	Terrestrial	Other	ID	-	-	-	-	-	-	-
	Infiltration and Runoff	Terrestrial	Other	ID	WMGHGs (CO2, CH4, N2O)	2.82	13%	0.76	-	-	-
	Precipitation (surface)	Terrestrial	ECV	ID, S	-	-	-	-	-132 [F]	92	https://cbmjournal.biomedcentral.com/articles/10.1186/1750-0680-2-3
	River Discharge	Terrestrial	ECV	ID	WMGHGs (CO2, CH4, N2O)	2.82	13%	0.76	202 [F]	77	https://cbmjournal.biomedcentral.com/articles/10.1186/1750-0680-2-3
Inorganic Carbon	Inorganic Carbon	Oceanic	ECV	ID	CO2	1.68	11%	0.36	-	-	-

Variable Class	Variable	Domain	Type	RF role	Major related RF component	RF best estimate global (Wm-2)	Rel. RF uncertainty (global)	Abs. RF uncertainty range	Estimated flux/stock (Africa), Tg CO2eq y-1	Flux/stock uncertainty (Africa), Tg CO2eq y-1	Literature source for flux/stock estimate
Land Cover	Land Cover	Terrestrial	ECV	S	Surface albedo, mineral dust	-0.25	120%	0.60	-	-	-
	Extent of inland waters	Terrestrial	ECV	ID	CO2, CH4	2.65	13%	0.70	3,300 [F]	-	https://dx.doi.org/10.1038/ngeo2486
Land Use/Land Use Change	Land Use/Land Use Change	Terrestrial	Other	ID, DD	WMGHGs (CO2, CH4, N2O), Surface albedo, mineral dust	2.57	26%	1.36	1,320 [F]	183	https://cbmjournal.biomedcentral.com/articles/10.1186/1750-0680-2-3
Nitrous Oxide	Nitrous Oxide (Ocean)	Oceanic	ECV	DD	N2O	0.17	18%	0.06	-	-	-
Nutrients	Marine Nutrients	Oceanic	ECV	ID	WMGHGs (CO2, CH4, N2O)	2.82	13%	0.76	-	-	-
Ocean Colour	Ocean Colour	Oceanic	ECV	S	WMGHGs (CO2, CH4, N2O)	2.82	13%	0.76	-	-	-
Oxygen	Oxygen	Oceanic	ECV	A	-	-	-	-	-	-	-
Plant Species Traits	Plant Species Traits	Terrestrial	EBV	A	-	-	-	-	-	-	-
Precursors	Carbon Monoxide (CO)	Atmospheric	ECV	ID	CO	0.23	24%	0.11	133 [F]	-	https://cbmjournal.biomedcentral.com/articles/10.1186/1750-0680-2-3
	Dimethyl Sulfide	Oceanic	Other	ID	aerosol-cloud interaction	-0.45	133%	1.20	-	-	-
	Non-methane hydrocarbons	Atmospheric	Other	ID	NMVOC	0.1	40%	0.08	-	-	-
	Nitrogen Oxides (NOx)	Atmospheric	ECV	ID	NOx	-0.15	120%	0.36	-	-	-
	Sulfur Dioxide (SO_2)	Atmospheric	ECV	ID	SO2	-0.41	50%	0.41	-	-	-
Pressure (surface)	Pressure (surface)	Terrestrial	ECV	S	-	-	-	-	-	-	-
Radiation	Albedo	Terrestrial	ECV	S	Surface albedo	-0.15	67%	0.20	-	-	-
	FAPAR	Terrestrial	ECV	ID	CO2	1.68	11%	0.36	-	-	-
	Net Radiation at surface (SW/LW)	Terrestrial	ECV	ID	WMGHGs (CO2, CH4, N2O)	2.82	13%	0.76	-	-	-
Reported Anthropogenic Greenhouse Gas Emissions	CO_2, CH_4, N_2O emissions by country and IPCC sector	Terrestrial	ECV	DD	WMGHGs (CO2, CH4, N2O)	2.82	13%	0.76	3,225 [F]	-	http://edgar.jrc.ec.europa.eu
Sea Surface Salinity	Sea Surface Salinity	Oceanic	ECV	S	-	-	-	-	-	-	-

Variable Class	Variable	Domain	Type	RF role	Major related RF component	RF best estimate global (Wm-2)	Rel. RF uncertainty (global)	Abs. RF uncertainty range	Estimated flux/stock (Africa), Tg CO2eq y-1	Flux/stock uncertainty (Africa), Tg CO2eq y-1	Literature source for flux/stock estimate
Soil Properties	Soil Moisture	Terrestrial	ECV	ID, S	WMGHGs (CO2, CH4, N2O)	2.82	13%	0.76	-	-	-
	Soil Organic Carbon	Terrestrial	ECV	S	CO2, CH4	2.65	13%	0.70	40,333 [F]	18,333	https://cbmjournal.biomedcentral.com/articles/10.1186/1750-0680-2-3
Stable Carbon Isotopes	Stable Carbon Isotopes	Oceanic	ECV	S	-	-	-	-	-	-	-
Surface Roughness	Surface Roughness	Terrestrial	Other	A	-	-	-	-	-	-	-
Surface Wind	Surface Wind Speed and direction	Terrestrial	ECV	ID, S	-	-	-	-	-	-	-
Temperature	Sea Surface Temperature	Oceanic	ECV	S	-	-	-	-	-	-	-
	Temperature (surface)	Terrestrial	ECV	S	-	-	-	-	-	-	-
Water Vapour (surface)	Water Vapour (surface)	Terrestrial	ECV	S	-	-	-	-	-	-	-