PRACTICE PAPER

Development of a Climate Forcing Observation System for Africa: Data-Related Considerations

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In the case of the African continent, the estimates of most climate forcing components are associated with large uncertainties, above all the greenhouse gas budget. The EU-funded SEACRIFOG project is designing an observation network which aims at reducing these uncertainties. In this practice paper, we present the various steps towards the design of this network and discuss the data-related implications. This includes the formulation of appropriate observational requirements for each variable considered essential to quantify Africa-wide climate forcing as well as an assessment of corresponding available observational infrastructures and data in order to determine data gaps, needs and priorities. The results are intended to inform the design of an interoperable African data infrastructure for environmental observations.

Introduction

The Earth's climate system is undergoing fundamental changes linked to human presence and activity, above all through the emission of greenhouse gases (GHG) as well as changes in land use and land cover (IPCC, 2014). In order to attribute and quantify these changes and develop appropriate responses, the availability of and access to long-term data from environmental observations is essential. In the case of the African continent, the availability of in situ observational data is low, resulting in large uncertainties for most of the key variables of climate forcing, above all the GHG balance (Valentini, et al., 2014; Williams, et al., 2007; Kim, et al., 2016). Consequently, there are still significant uncertainties whether the African continent constitutes a net GHG sink or source on an annual timescale. At the same time, Africa's role in global climate forcing is growing, given the continent's considerable carbon stocks (Williams, et al., 2007) and the high direct dependency of a fast-growing population (UN, 2017a) on natural resources as well as major changes driven by urbanization (UN, 2017b) and the continental development agenda (AU, 2015).

The 'Supporting EU-African Cooperation on Research Infrastructures for Food Security and Greenhouse Gas Observations' (SEACRIFOG) project (www.seacrifog.eu) is developing the roadmap for a network of environmental research infrastructures (RI) for the systematic long-term observation of variables relevant to climate forcing across the continent and the surrounding oceans. This network, covering the atmospheric, oceanic and terrestrial domains, is to be tailored to the African context by considering those processes which contribute most to the continent's radiative forcing and those that propagate the greatest uncertainty in continental-scale GHG reporting. The aim is to quantify the continent's anthropogenic and natural contributions to climate forcing at least at the same level of accuracy as is available for the rest of the world. In accordance with global estimates for the main GHGs (Le Queré, et al., 2018; Saunois, et al., 2016), the corresponding target uncertainty for the overall African radiative forcing estimate is set to ±15% at a ±1 sigma (68%) confidence level.

In line with the definition adopted by the EU (2013), the term RI here refers to a wide range of facilities, resources and related services that are used by the scientific community and comprise equipment and instruments, knowledge-based resources and computing and data infrastructures. Possible elements of, and contributors to the envisaged RI network include the full spectrum of in situ and remotely sensed environmental observations and corresponding platforms, thus ranging from individual ground-based observation sites to national (e.g. the South African Environmental Observation Network (SAEON), regional (e.g. the EU's Integrated Carbon Observing System or the SASSCAL WeatherNet) and global networks (e.g. Global Atmosphere Watch, Argo or Fluxnet) up to remote sensing missions with global coverage (e.g. ESA's Copernicus or NASA's Earth Observing System). A major aim of the SEACRIFOG project is to improve technical harmonization and interoperability of existing and planned environmental RIs, both within Africa and between Africa and Europe as well as other world regions.

The first outcomes of the corresponding work were presented by López-Ballesteros et al. (2018). This includes the identification of a set of 58 variables considered essential to quantify African radiative forcing as well as a first inventory of existing and planned observation infrastructures. Further work included an inventory of existing methodological protocols for the observation of relevant variables and an assessment of the applicability of these protocols in the African context López-Ballesteros et al. (2019). These outcomes, together with the results presented in this paper, feed into the ongoing design of an optimized spatial network of locations for in situ GHG observations by applying inverse Bayesian modelling methods as described by Nickless et al. (2018) at the continental scale.

In this paper, we present additional results from this ongoing conceptualization process with a particular focus on the data-related considerations. In a first step, we briefly describe the overall conceptual framework for the observation system. From this framework, a set of essential variables and corresponding observational data requirements were derived. These clearly define the system's overarching observational targets and thus have direct implications for data generation, processing and management. We then assessed the coverage of existing and planned observations and related data products against these requirements in order to identify gaps and needs in terms of data coverage and quality. All data and information feeding into these results were captured using a publicly accessible web-based tool (https://seacrifog-tool.sasscal.org/). This tool was developed to facilitate the SEACRIFOG design work and can be considered a first iteration of a more advanced and comprehensive data infrastructure for environmental observations across Africa and the surrounding oceans.

Methods
Observation system scope and framework
The design scope of a comprehensive Africa-wide climate forcing observation network is defined by the observations required to directly quantify or estimate the major components of climate forcing as reported by the IPCC (Myhre, et al., 2013), which include the major GHGs carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), minor GHGs (e.g. ozone-precursors and chlorofluorocarbons) and aerosols as well as non-GHG components such as incoming solar radiation and albedo (see **Figure 1**).

In **Figure 1**, each of the grey boxes depicting the different GHG observation components can comprise numerous observations, model products and other inputs for an aggregate estimate of net emissions at the continental level (Scholes, 2018). For example, in the case of CO_2, the corresponding component includes subcomponents estimating the contributions from the terrestrial and marine carbon cycle as well as anthropogenic CO_2 emissions, each depending on a possibly high number of environmental variables. The set of variables that are currently considered essential for the depicted climate forcing observation system are presented in **Table 1** in the results section. The following paragraphs describe their identification.

Identification of essential variables to be observed
The environmental variables to be observed were identified in the course of 2018 through a two-stage iterative process. In a top-down analysis departing from the framework described above, all environmental variables were identified which, according to the current state of knowledge, are of immediate relevance for the quantification of the major African climate forcing components as well as their respective sources, sinks and stocks. An initial list of variables was compiled by experts from within the SEACRIFOG consortium. This list was then consolidated through consultative discussions with seven external experts from the relevant research disciplines (e.g. experts in atmospheric chemistry, terrestrial and marine carbon cycle, terrestrial biodiversity, etc.).

In a parallel bottom-up process, a survey was conducted among 40 European and African researchers from the environmental sciences, each having specific expertise in the atmospheric, oceanic and/or terrestrial
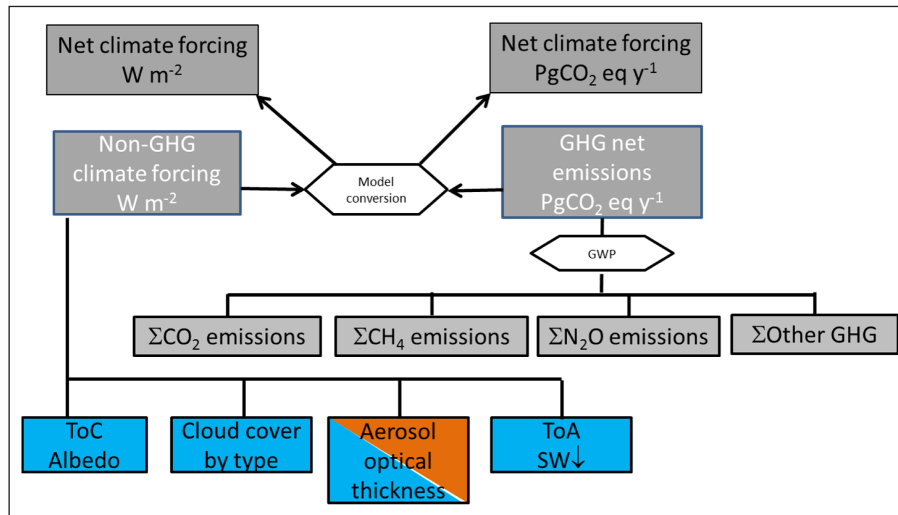
Figure 1: The top-level components of a climate forcing observation system for Africa. The global warming potential (GWP) is measured in units of CO_2 equivalent (CO_2 eq) and is derived from the net flux of the different GHG observation components. Non-GHG climate forcing components include top-of-canopy (ToC) albedo, cloud cover, aerosols and top-of-atmosphere (ToA) downward short-wave (SW) irradiance. Grey boxes illustrate observationally-constrained model products. Blue is for space-based observations, orange is for land-based observations.

domain (Beck, et al., 2018). In analogy with the approach described by Bojinski et al. (2014), the respondents rated a larger set of 110 potentially relevant variables against the criteria of relevance, feasibility and cost of their systematic observation in the African context. This set of potentially relevant variables included the essential climate variables (ECV) (WMO, 2016), essential ocean variables (EOV) (Task Team for an Integrated Framework for Sustained Ocean Observing, 2012), essential biodiversity variables (EBV) (Ferrier, et al., 2013) as well as other variables (e.g. variables specific to Africa such as wild herbivore distribution) nominated by the participating researchers.

The resulting list of (currently) 58 essential variables (see **Table 1** in the results section) is the union of the variables identified through the two processes.

Data requirements for the essential variables

The overarching requirement for the observation network is to produce reliable estimates of the net climate forcing over the African continent and the surrounding oceans at an accuracy that is comparable to, or better than the one achieved for other continents. This roughly corresponds to limiting the maximum uncertainty of the relevant climate forcing components to ±15% at the continental scale and ±20% at the national scale (approx. 500 × 500 km). This target uncertainty guided the specification of data requirements for each essential variable in terms of spatial and temporal resolution as well as maximum uncertainty (see **Table 1**). For numerous essential variables, requirement specifications had already been formulated by existing global initiatives such as the Global Climate Observing System (GCOS; 33 out of the 58 essential variables are ECVs), the Global Atmosphere Watch (GAW; requirement specifications for in situ observations of atmospheric mixing ratios) or the Global Ocean Observing System (GOOS; for the oceanic variables). Based on expert judgement by researchers from the atmospheric, oceanic and terrestrial domains within the SEACRIFOG consortium, these requirements were reviewed in the context of the SEACRIFOG project and either adopted or amended. The primary focus for requirement formulation was laid on in situ observations, which are required to complement or improve upscaled model- or RS-based data products. In case of overlapping requirement definitions by various initiatives for a given variable, the stricter requirement (i.e. the higher resolution or accuracy) was adopted. Requirements for variables for which no prior specifications from global initiatives existed were set by the SEACRIFOG consortium.

Assessment of data availability

In a next step, we assessed the availability of observational data for the essential variables in Africa. After compiling an inventory of existing and planned observation infrastructures, we assessed the spatial coverage of in situ observation sites and infrastructures in order to identify understudied African terrestrial biomes and ecosystems (López-Ballesteros, et al., 2018). Information on individual observation sites was

compiled directly from the respective network websites or from sources such as the WMO's Observing Systems Capability Analysis and Review Tool (OSCAR). In case of the eddy covariance (EC) flux sites (see **Figure 2** in the results section), we compiled an inventory for the African continent based on data from FLUXNET, the European Fluxes Database Cluster as well as direct consultations with the EC flux research community.

For a broad analysis of RS-based observations, we considered the database of the Committee on Earth Observation Satellites (CEOS; http://database.eohandbook.com), which links all current and planned missions to the respective environmental variables observed. We further assessed the ECV Inventory by the CEOS/CGMS Working Group on Climate (http://climatemonitoring.info/ecvinventory/), which keeps track of existing and planned data records from space agency sponsored activities for the ECVs, considering the number of such data records as a proxy for the maturity of corresponding RS-based data products (see **Table 2**). Through the above analyses, we prioritized the essential variables according to the design needs for systematic in situ data generation across the African continent (Beck, et al., 2019). Corresponding in situ observational data can be used to crucially support and refine continental scale RS and model-based data products.

Results

The set of essential variables identified according to the described methodology as well as the respective observational data requirements are presented in **Table 1** below. This table defines the concrete targets in terms of observational data generation in order to quantify the major Africa-wide components of radiative forcing as found by the SEACRIFOG initiative.

Table 1: Set of 58 essential variables as identified by SEACRIFOG and respective data requirements. Underlined variables can largely be observed from space with complementary land-based/in situ observations. Conversely, variables in bold font were found to have particularly high design needs in terms of systematic in situ data generation across Africa. Note that uncertainties correspond to ±1 standard deviation from the actual value in percent, i.e. the percentual margins of a 68% confidence interval. The column 'Defined By' indicates the initiative from which the respective requirement specifications originate. A – Atmospheric; O – Oceanic; T – Terrestrial.

Variable	Domain	Temporal Resolution (Target)	Spatial Resolution (Target)	Max. Uncertainty (Target)	Defined By
Aerosol properties	A	4 h	5 km	10%	GCOS
Boundary layer height	A	1 h	20 km	20%	SEACRIFOG
<u>Cloud Cover Fraction</u>	A	1 h	25 km	10%	SEACRIFOG
Halocarbons	A	1 week (flask)	1 site	5%	SEACRIFOG
Nitrogen Oxides (NOx)	A	4 h	5 km	20%	GCOS
Non-methane hydrocarbons	A	1 h	1 site	10%	WMO GAW
Sulfur Dioxide (SO_2)	A	4 h	5 km	30%	GCOS
Tropospheric Carbon Monoxide (CO)	A	1 h	1 site	1% (1 ppb)	WMO GAW
Tropospheric CH_4 mixing ratio	A	1 h	1 site	0.05% (1 ppb)	WMO GAW
Tropospheric CO_2 mixing ratio	A	1 h	1 site	0.25% (0.1 ppm)	WMO GAW
Tropospheric N_2O mixing ratio	A	1 h	1 site	0.05% (0.1 ppb)	WMO GAW
Economic Development	O	1 year	1 country	5%	SEACRIFOG

(Contd.)

Variable	Domain	Temporal Resolution (Target)	Spatial Resolution (Target)	Max. Uncertainty (Target)	Defined By
Inorganic Carbon (Ocean)	O	1 month	250 km	10%	GOOS
Marine Nutrients	O	3 months (seasonal)	100 km (marine biochemical province)	20%	GOOS
Marine Oxygen	O	1 month	100 km (marine biochemical province)	10%	GOOS
Nitrous Oxide (Ocean)	O	1 day	1 km	1%	GOOS
Ocean Colour	O	8 days	1 km	5%	SEACRIFOG
Oceanic Dimethyl Sulfide (DMS)	O	1 month	10 degrees	10%	SEACRIFOG
Sea Surface Salinity	O	8 days	1 km	1%	SEACRIFOG
Sea Surface Temperature	O	1 day	1 km	0.03% (0.1 K)	SEACRIFOG
Stable Carbon Isotopes	O	3 months (seasonal)	100 km	10%	GOOS
Above ground biomass	T	1 year	500 m	20%	GCOS
Active Fire	T	1 h	250 m	5%	GCOS
Albedo	T	1 month	300 m	5%	GCOS/SEACRIFOG
Area of ploughed land	T	5 years (resolve seasons)	1 ha	20%	SEACRIFOG
Below-Ground Biomass	T	5 years	1 km	10%	SEACRIFOG
Biosphere-Atmosphere CH_4 flux	T	1 h	1 site (every major ecoregions)	5%	SEACRIFOG
Biosphere-Atmosphere CO_2 flux (NEE)	T	1 h	1 site (every major ecoregions)	5%	SEACRIFOG
Biosphere-Atmosphere N_2O flux	T	1 h	1 site (every major ecoregions)	5%	SEACRIFOG
Burnt Area	T	1 day	30 m	15%	GCOS
CO_2, CH_4, N_2O emissions by country and IPCC sector	T	1 year	1 country	10%	SEACRIFOG
Crop Yield by Type	T	1 year	1 country	10%	SEACRIFOG
Evapotranspiration	T	1 day	1 km	10%	SEACRIFOG
Extent of inland waters	T	3 months	20 m	1%	SEACRIFOG
Fertilizer application	T	1 year	1 country	20%	SEACRIFOG
Fire Fuel Load	T	1 year	1 km	15%	SEACRIFOG
Fraction of Absorbed Photosynthetically Active Radiation (FAPAR)	T	8 days	300 m	5%	SEACRIFOG

(Contd.)

Variable	Domain	Temporal Resolution (Target)	Spatial Resolution (Target)	Max. Uncertainty (Target)	Defined By
Human Population	T	5 years	20 km	5%	SEACRIFOG
Infiltration and Runoff	T	1 month	1 km	10%	SEACRIFOG
Irrigation	T	1 day	100 m	10%	SEACRIFOG
Land Cover	T	1 year	250 m	15%	GCOS
Land Use/Land Use Change	T	1 year	1 km	20%	SEACRIFOG
Litter	T	5 years (resolve seasons)	1 km	10%	SEACRIFOG
Livestock Distribution	T	5 years	20 km	15%	SEACRIFOG
Manure Management	T	5 years	1 livestock system	20%	SEACRIFOG
Net Primary Productivity	T	1 month	1 km	10%	SEACRIFOG
Net Radiation at surface (SW/LW)	T	1 month	100 km	0.25% (1 W/m^2)	GCOS
Plant Species Traits	T	Once off for all common species	All major biomes	10% (determine for 90% of cover)	SEACRIFOG
Precipitation (surface)	T	1 day	1 km	10%	SEACRIFOG
Pressure (surface)	T	1 h	1 Site	0.01% (0.1 hPa)	GCOS
River Discharge	T	1 day	1 river basin	10%	GCOS
Soil Moisture	T	1 day	1 km	4% (0.04 m^3/m^3)	GCOS
Soil Organic Carbon	T	10 years	1 km	5%	SEACRIFOG
Surface Roughness	T	5 years	1 km	20%	SEACRIFOG
Surface Wind Speed and direction	T	3 h	10 km	10% (5 m/s)	GCOS
Temperature (surface)	T	1 h	1 site	0.03% (0.1K)	GCOS
Water Vapour (surface)	T	1 h	1 site	1%	GCOS
Wild Herbivore Distribution	T	5 years	20 km	15%	SEACRIFOG

Observational coverage

In order to prioritize the essential variables in terms of their in situ observational needs (i.e. needs which are in the focus of the SEACRIFOG project), we first assessed the availability of RS-based observations for each variable, with the aim to identify variables which are already largely covered at scale and sufficient accuracy by RS methods. In late 2018, the CEOS database listed 103 active space missions capturing potentially relevant environmental data across the African continent and the surrounding oceans. The CEOS/CGMS Working Group on Climate further maintains an inventory of global RS-based data records for the ECVs. The number of existing and planned data records for the ECVs which were also identified as essential variables in the African context are presented in **Table 2**, indicating that these variables are already or will soon be covered at scale by RS methods. This does not mean that additional in situ observations are no longer required, but their function is primarily for calibration and verification purposes.

Other variables, for which mature RS data products can be expected to become available in the near to mid future include above ground biomass (notably through NASA's Global Ecosystem Dynamics Investigation (GEDI) spaceborne lidar and ESA's planned Biomass mission) as well as water runoff and river discharge

Table 2: Existing and planned data records from space agency sponsored activities for the ECVs which were identified by SEACRIFOG to be essential for observation across the African continent and surrounding oceans. The ECVs listed below are congruent with or directly related to 20 of the SEACRIFOG essential variables. Source: ECV inventory by the CEOS/CGMS Working Group on Climate.

Domain ECV	Existing	Planned
Atmosphere		
Aerosol Properties	34	13
Carbon Dioxide; Methane and other Greenhouse Gases	32	28
Cloud Properties	100	82
Earth Radiation Budget	74	53
Precipitation	11	4
Precursors supporting the Ozone and Aerosol ECVs	10	12
Surface Wind Speed and Direction	16	8
Water Vapour	59	35
Land		
Albedo	21	13
Fraction of Absorbed Photosynthetically Active Radiation (FAPAR)	2	3
Fire Disturbance	3	9
Leaf Area Index	2	3
Lakes		3
Land Cover	1	1
Land-Surface Temperature	10	18
Soil Moisture	4	24
Ocean		
Ocean Colour	8	8
Sea Surface Temperature	16	17

(notably through NASA's planned Surface Water and Ocean Topography (SWOT) mission). Those variables are underlined in **Table 1**.

Essential variables which can currently only be measured through in situ observations in a meaningful way include below-ground biomass and litter, biosphere-atmosphere GHG fluxes and tropospheric GHG concentrations. These variables are considered to have high priority in the context of the design and cooperation for continent-wide systematic observations and are highlighted in **Table 1** in bold font. With regards to in situ observations, the overall coverage for the atmospheric, oceanic and terrestrial domains in Africa is in general low compared to other continents, with exceptions in parts of southern and western Africa (López-Ballesteros, et al., 2018).

As an example, here we consider eddy covariance (EC) flux observations, which play a key role in estimating GHG fluxes as well as carbon source and sink capacities at the ecosystem scale. The availability of corresponding long-term ecosystem-scale flux data is crucial for the development and refinement of accurate models and for ground-truthing of RS products. **Figure 2** depicts the location of past, current and planned EC flux observations in Africa, clearly demonstrating the large observational gaps in terms of coverage of terrestrial African ecoregions (Olson, et al., 2001). Particularly in tropical Africa, where biogenic fluxes are large, ecosystem-specific in situ flux observations are missing.
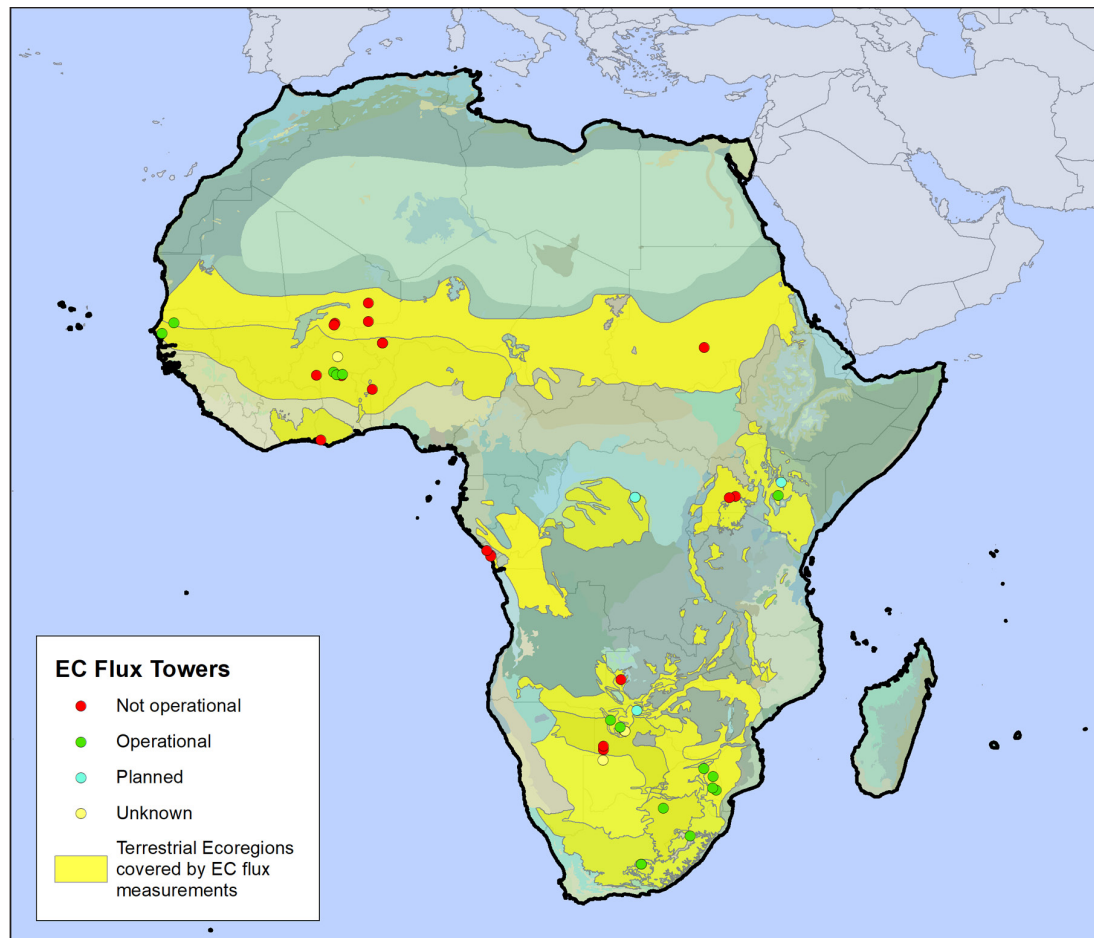
Figure 2: Past, current and planned EC flux observations on the African continent as compiled by SEACRIFOG and the African terrestrial ecoregions (Olson, et al., 2001) partially covered by these observations. Full figure legends and tabular data are provided in the supplementary materials.

Discussion

The set of essential variables and corresponding observational requirements presented above constitute the first steps towards a harmonization framework for the systematic quantification of climate forcing at the continental level in Africa. Our broad analysis of RS-based and in situ observational coverage of these variables allowed for a prioritization of variables based on whether they can largely be observed from space (i.e. mature RS products with complementary in situ observations exist or are under development) or whether there is a high need for in situ data generation in Africa.

In situ observations and datasets are relatively scarce for Africa, particularly those based on long and uninterrupted timeseries from land- or ocean-based observations. Accordingly, the spatial coverage of in situ observations is low and uneven. There is a need to cover the different biomes and ecosystems more homogeneously, particularly those areas in tropical Africa with potentially important GHG source/sink hotspots. While the sub-regions of Central and East Africa appear to be understudied in general, our analysis identifies the numerous ecoregions for which no specific in situ observations of key variables such as biosphere-atmosphere GHG fluxes are available (see **Figure 2** and supplementary data).

Beyond technical harmonization, the SEACRIFOG project aims at providing a design concept on how to systematically fill the major in situ observational gaps at the optimal cost. Such design primarily refers to the determination of optimal number, location, methods and harmonization of existing and additional long-term/periodic observations of a given variable required for the generation of data which meet the requirements specified in **Table 1**. These results are therefore of importance for researchers and funding institutions working on closing these knowledge gaps.

In order to maximize its impact, the SEACRIFOG design effort focuses on essential variables which are dependent on in situ observations. These variables (in bold font in **Table 1**) include biosphere–atmosphere

fluxes and tropospheric mixing ratios of the major GHGs, below ground biomass, soil organic carbon and litter, evapotranspiration, water vapor, river discharge, marine inorganic carbon, manure management as well as air temperature and pressure at surface.

The systematic long-term observation of these variables as well as their utilization in combination with RS and model-based data products does not only require the development of additional observation infrastructures, but also a well-coordinated effort towards the design of an appropriate data infrastructure which can accommodate a heterogeneous mix of data types. Given the variety of relevant observation techniques contributing to the observation system as illustrated in **Figure 1**, this infrastructure is to incorporate information on and data from both stationary (e.g. weather or atmospheric observation stations) and mobile (e.g. ships, floats and aircraft) in situ platforms as well as space-based observations. To accommodate the data and services associated with the SEACRIFOG project, an Africa-wide system of systems for environmental observations is being developed. Work is underway to integrate sources and functions of both in situ and space-based observation information systems, including WMO's Observing Systems Capability Analysis and Review Tool, (OSCAR; https://www.wmo-sat.info/oscar/), SAEON's Open Data Portal, the SASSCAL Data and Information Portal (http://data.sasscal.org), and the ICOS Carbon Portal (https://www.icos-cp.eu). Close integration with the Global Earth Observation System of Systems (GEOSS) and DEIMS-SDR (https://deims.org/) via metadata exchange is foreseen. DEIMS-SDR constitutes an existing approach towards such a system and covers in situ observations of terrestrial ecosystems globally and provides most of the required functions for the terrestrial domain, but which does not cover oceanic and space-based observations (Wohner, et al., 2019).

Given the large geographic and thematic scope of the SEACRIFOG initiative, creating awareness, buy-in and a sense of ownership among all potentially relevant stakeholders with regards to the network design methods and outcomes is a huge task. The SEACRIFOG project attempts to address this through the establishment of a permanent stakeholder dialogue platform which will bring together high-level stakeholders from the different sub-regions and thematic areas for exchange and coordination. At the time of writing, this dialogue platform is still under development.

Conclusion

The need for systematic and long-term in situ observations for the characterization and quantification of climate forcing on the African continent and the surrounding oceans is immense. The coverage of in situ observations and the availability of corresponding data is insufficient and accordingly, the GHG source and sink capacity as well as other relevant variables have not been specifically determined for most African terrestrial ecoregions. In this paper, we identified the essential variables required to quantify Africa-wide climate forcing and prioritized those for which in a systematic intensification of situ observations according to defined observational requirements is indispensable. This work therefore contributes to a continental harmonization framework under which numerous RIs can contribute towards the goal of significantly improving the quantification and spatial attribution of Africa's continental climate forcing.

This work feeds into the next development steps, which include the design of observational elements through spatial network optimization using inverse Bayesian modelling methods. Another important aspect is the development of an African data infrastructure prototype which can serve as a system of systems to integrate information management systems on different types of observation infrastructures with repositories for environmental metadata and data. Current efforts in line with the SEACRIFOG project include the conceptual design of such a system to provide full interoperability between environmental observation networks and infrastructures within Africa and globally.

Additional File

The additional file for this article can be found as follows:

- **Eddy covariance flux observations in Africa.** EC flux towers per terrestrial ecoregion in Africa. DOI: https://doi.org/10.5334/dsj-2019-042.s1

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Competing Interests

The authors have no competing interests to declare.

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