Concept paper for an adapted observation system for Africa including special and sectoral observational requirements to integrate multiple Grand Challenges in Africa

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SEACRIFOG Deliverable 3.2

Contents

Executive Summary

This report is Deliverable 3.2 of the SEACRIFOG project and reports on subtasks 3.2.1 and 3.2.2 of work package 3.

All the necessary elements of the comprehensive climate forcing observation system for Africa, as specified in SEACRIFOG Deliverable 3.1, are optimised and costed in this report. The design goal was to bring the African climate forcing observation system to the standard where it is no longer the ‘weakest link’ in a global evaluation of trends in greenhouse gas emissions and other climate-relevant processes. At the same time, it must provide the necessary operational information for African countries to evaluate progress towards meeting their Nationally Determined Contributions under the Paris Agreement, and eventually collectively moving from Tier 1 towards Tier 3 IPCC reporting procedures. The key elements required for the system involve an integrated set of remotely-sensed products, modelled products, in situ observations of atmospheric mixing ratios of key gases, ecosystem fluxes, and weather conditions. Also required are a number of campaigns to adapt emission factors to unique African situations, ongoing national greenhouse gas emission inventories in accordance with the requirements of the UN Framework Convention on Climate Change, and some ancillary socioeconomic datasets. The system could be incrementally implemented, and is designed with a 30-year horizon. About 30 million (M) euros (€) are required initially for establishment in the first three years. Annual operational costs are estimated at an initial 5 M€, rising to 10 M€ after every development phase to allow for system upgrade and maintenance. The whole budget of around 450 M€ over 30 years includes the personnel costs needed for the system in Full Time Equivalent (FTE) at about 250 M€, that would go hand in hand with the research infrastructure growth at later phases. Considering future modular extensions to accommodate potentially atmospheric measurements, it is wise to estimate a 500 M€ cost for the future GHG observation system for Africa.

1. Introduction

SEACRIFOG task 3.2 designed an optimized future network for greenhouse gas (GHG) monitoring over Africa and its surrounding coastal oceans, for implementation over the next two decades. It had two subtasks:

Subtask 3.2.1 associated experientially-tested costs with the set of 'essential variables', identified in deliverable 3.1 as necessary for an Africa-scale GHG observation system that meets both national and international requirements. Many of the variables can be observed in several different ways. The task proceeded by adding least cost technologies to the existing African and global observational network, while satisfying given performance requirements. For instance, there is often an optimum mix of many low-cost but relatively imprecise sensors, with a small number of high-cost, high-accuracy sensors. The approach was applied to all the key variables associated with net anthropogenic climate forcing from the African continent, now and over the next three decades, noting any interactions and observational synergies involved. For instance, some infrastructural elements can deliver more than one variable at smaller incremental cost when measured simultaneously than if considered independently. This is also a part of the logic for building on observation systems that already exist in Africa, rather than starting with a completely blank slate; the second part is based on the necessity for building capacity and a sense of ownership in African countries and institutions.

Subtask 3.2.2 asked where new sensors should be located in and around Africa, while making best use of established infrastructure, in order to reduce the uncertainty in the overall system by the largest amount. It ran models of carbon dioxide, methane and nitrous oxide fluxes and transport in reverse (a technique known as 'inverse modelling'), constrained by existing observations and their locations, and prior estimates of the emission fields from both anthropogenic and natural sources. This allowed the task to identify the best location for each additional sensor, in order that it reduce overall uncertainty the most. The process was continued until a saturation effect set in for the uncertainty reduction achieved by adding further sensors. The target level of accuracy was that which resulted in the uncertainty associated with net emissions from Africa no longer being the factor most constraining to the overall global greenhouse gas uncertainty. In other words, until an additional investment in an African observation system is no longer the place where additional observation investment can be assumed to most effectively reduce global uncertainty. A set of 54 existing or likely locations were provided to the model, rather than asking it to search everywhere. Some locations were excluded as being impractical or otherwise unsuitable.

This deliverable D3.2 reports on the above two subtasks.

2. SEACRIFOG Task 3.2.1: Designing a GHG monitoring system for Africa

This subtask sets out to design an optimised, fit-for-purpose climate forcing observation infrastructure for Africa by adding least cost technologies to the existing network. The existing network elements and the essential variables for a balanced and comprehensive system for measuring anthropogenic climate forcing in Africa were identified in SEACRIFOG task 3.1.1.

The relevant technologies were described in SEACRIFOG task 3.1.2. Both the above subtasks were reported in deliverable D3.1 (Climate system-related observation networks in Africa, and the variables needed for a comprehensive system, Thünen Institute, October 2018).

Currently, the net CO_2 exchanges from the African domain to the atmosphere are about 232 Tg $CO2.y^{-1}$, when estimated by 'top-down' methods (Valentini et al. 2014). The associated uncertainty, defined as the 'one σ' level (i.e. the standard deviation), is in the order of 760 Tg $CO2.y^{-1}$, calculated as the standard deviation of 6 different inversion models, each looking at slightly different periods of time. The interannual variability within the longest of the inversion periods (11 years) was 3,300 Tg CO_2. Noting that net exchange is the sum of two large terms, a downward flux of Gross Primary Productivity (by convention given a negative value, since it is out of the atmosphere) and an upward flux of ecosystem respiration and anthropogenic emission, including from land use change. Their two fluxes are of the order of 120,000 Tg $CO2.y^{-1}$ each, which is why it is quite remarkable to be able to detect their net outcome at all, and why it is so hard (but imperative) to tease apart the anthropogenic part of this, which is only 2% of the gross fluxes, but 90% of the net flux. The 'bottom-up' anthropogenic greenhouse gas emissions from Africa as a whole, calculated by summing national GHG inventories for the year 2014, comes to 2,600 Tg CO_2e, of which about 80% are as CO_2. The difference between the top-down and bottom-up estimates could be explained by the African continent as a whole being a net sink of around 2,370 Tg $CO2.y^{-1}$. The uncertainty associated with the bottom-up estimate is not explicitly known, but since most of the African countries apply 'Tier 1' estimation methods, is widely thought to be around 30% at the 2σ level, or 400 Tg CO_2e at 1σ. The task sets as its target the need to reduce the top-down uncertainty to around 400 Tg $CO2.y^{-1}$, similar to the uncertainties on other major regions and the bottom-up flux to around 200 Tg $CO2.y^{-1}$ or about 10% of the anthropogenic flux.

This subtask (3.2.1) estimates the optimal design mix of observational technologies, based on accuracy-effort curves per technology (from 3.1.2), and constrained by locational feasibility (from 3.2.2) and the existing and planned network (3.1.1). The concept is that there are typically several ways to measure the desired variables identified in tasks 3.1 and 4.1, and new methods will continue to appear as technology advances. Each method has an associated cost, which scales in a particular way with the number of repetitions in different places. Each method also has an associated accuracy, with its own scaling rules in terms of bias and precision, and a characteristic domain of observation in time and space. Furthermore, there may be negative or positive interactions with the rest of the variables in the observational system. Thus, there are many conceivable ways to build an observation system for a particular purpose, and each version will have different total costs for a given level of accuracy. The task for the system designer is to choose the mix which reliably delivers the desired accuracy at the lowest cost, while bearing in mind issues of robustness, feasibility and adaptability. A deliberate level of redundancy was designed into the system. The redundancy prevents the system from collapsing if spatial or thematic subsets of the variables drop out or fail to materialise. This allows an observation system for the *whole* of Africa to be implemented nearly immediately, albeit with a fairly large uncertainty. The uncertainty can then be reduced over time by incremental investment. The system would not thereafter be hostage to the success or failure of individual sites or elements. To achieve this designed-in redundancy, most variables are specified to be estimated in two ways: typically, through an approximate but spatially-comprehensive way (using, for instance, remote sensing or observation-constrained modelling techniques) and an exact, but localised way, such as through direct measurement at a site. In order to calibrate the models and remotely-sensed approaches, a category of accurate, but spatially-and-temporally *discontinuous* variables are also necessary, generally obtained through limited-period, targeted measurement campaigns. Many of the models and indices used in support of the climate forcing observation system require ancillary socioeconomic driver data, such as population densities and income levels, typically collected on an ongoing basis by national statistical offices.

2.1. Categories of observation products

In principle, *all* the 'essential variables' identified in deliverables 3.1 and 4.1 are needed for a robust, comprehensive and integrated GHG observation system for Africa. They have gone through a rigorous systems-analysis process to identify the minimum set, along with a comprehensive 'bottom-up' solicitation of requirements from many other associated systems. All signatories to the UN Framework Convention on Climate Change and its associated agreements, which includes all African countries, undertake to conduct national bottom-up inventories of anthropogenic greenhouse gas emissions, presently at a time resolution of about one year, but reported only every five years in most African cases, and with a relaxed set of accuracy requirements appropriate to countries with currently-small emissions and limited technical capacity. As those circumstances change, the expectations for accurate and verifiable GHG inventories from African countries are likely to converge with the requirements imposed on developed countries.

Typically, the following categories of climate forcing system variables have different cost characteristics, so they are treated separately. In order to provide an integrated cost estimate, it is principally distinguished between basic data services (storage, transfer, computing capacities), scientific and technical higher-level product generation (data processing, data analysis, modelling) and in situ observations. While the in situ observations assumes a relatively constant network that will not increase over time, it is assumed that data services and higher-level product generation grow exponentially over time with more data (new satellite constellations) and new scientific and societal demands and possibilities occurring. An integrated financial concept for these tasks is presented in the Chapter 2.2.

2.1.1. Africa-wide remotely-sensed products

The first category of knowledge products for a continental-scale, national-resolution GHG observation system is based on remote sensing (see D3.1 for a complete explanation of the many ways these products are used in a GHG observation system). Most of them require a spatial resolution no better than about 1000 m[1], which is substantially coarser than the typical resolution delivered by modern operational environmental satellites such as the Sentinel 1, 2 and 3 series. Some observational needs – for instance the mapping of individual farmers' fields or small wetlands within the landscape – require much finer resolutions, in the order of 1 m to 10 m. This level of spatial detail can already be satisfied by existing satellite sensors and platforms, but at a computation, transmission and storage cost that will be increased by a factor of 10,000 to 1 million times relative to the coarser products. So better-and-better spatial resolution does not necessarily lead to better products; the expenditure is often more usefully spent in improving the signal-to-noise ratio and in more precise calibration of the coarser resolution sensors, or even in completely different parts of the observation system.

The approach for this study is based on open data available from satellite providers and examines the costs for data flow, processing and storage that are needed for providing Africa-specific products.

In the contemporary era, many satellite-based data products are treated as 'global public goods', and are therefore often characterised as being 'cost free'. In reality, of course, they are not without cost – they required billions of euros of investment in satellite development, launch and operation, over a period of decades, plus an equivalent sustained investment in the 'ground sector', consisting of processing, product development and testing, archiving and serving the data to users. However, both of the space and ground sector activities are amortised over very many possible products and services, and are 'sunk costs' (i.e. the bulk of the expenditure already incurred, which can only be retrospectively justified by maximisation of the use of the resultant information). Although the absolute costs are high, because the instruments operate over the whole world and continuously, the cost per hectare for a regular and frequent observation is relatively low, even if the full and true costs are included.

The cost-recovery model for national and super-national (e.g. European Space Agency) investment in space-based remote sensing has swung several times between viewing them as a social investment and considering them to be a commercial investment. It is likely to swing again within the lifetime of the observation system designed here. At present, for the category

[1] Higher spatial resolution than this may lead to better estimates of that sub-variable, but other factors in the observation system are more limiting to the overall accuracy.

of satellite-based observation described here, there is not yet a viable commercial market, so for now the products identified here are ‘open access’ products. With the privatisation of space and the commercialisation of information delivery systems, this may not always be the case.

Even if the remotely-sensed base product, typically processed to ‘level 4’ (i.e. the raw signal has been radiometrically and geometrically corrected, sampled to a given scheme, and manipulated or combined with other data sources to yield a derived product for a defined use), is in principle supplied without cost to the user, that still does not mean that it is cost-free. One or more institutions need to equip themselves with servers, storage capacity, bandwidth and computational capacity in order to extract an African subset of the global product, quality-check it, often recalculate and combine it with other data-streams to make a purpose-built product, re-project the data to the desired resolution, and provide the information to the observation system users in an easily accessible and comprehendible form. This includes not only high investments in computational infrastructure (including power and redundancy), but also strong scientific interpretation and modelling capacities. The institution needs to hire and train and retain a skilled workforce to perform these tasks in a rigorous and adaptive way. Some of the abovementioned costs are amortised over several functions of the institution and therefore not completely attributable to the GHG observation system, but mostly they do represent ’incremental costs’, which scale to some degree with the additional workload taken on.

Table 1. The remotely-sensed products required for the African GHG observation system are described in table 2 of D3.1, along with their spatial and temporal resolution specifications. The spatial coverage of these products, or their equivalents, is the rectangle between 38 N / 35 S latitude and 25 W / 58 E longitude, an area of 84 Mkm^2 (in some cases only the land part – about 30.3 Mkm^2 need be observed, others only the sea part, and others both). This rectangle includes the whole of continental Africa, including Africa-associated adjacent island nations such as Madagascar, Mauritius, Cape Verde islands and Seychelles. For climate modelling purposes, CORDEX adds a buffer around this area, for a rectangle 42N / 46S, 25W / 60E. The coverages are required for the period 2020, onward indefinitely (nominally, for planning purposes, to 2050) at the specified frequency. The total estimated data flow is about 0.5 TB/year.

Product	Spatial resolution	Repeat frequency	Data flow (MB.y^{-1})
Surface roughness	1 km	5 yearly	6
Soil moisture	1 km	Daily	11,060
Net primary productivity	1 km	Monthly	1,008
Ocean colour	1 km	8-daily	2,450
Albedo	300 m	Monthly	4,040
Net radiation	1 km	Daily	30,660
Sea surface salinity	1 km	8 daily	2,450
Extent of lakes and impoundments	20 m	3 monthly	303,000
Fraction of Absorbed Photosynthetically Active Radiation	300 m	8 daily	15,360
Fire burned area	300m	8 daily	15,360
Land Cover	300 m	5 yearly	67
Aboveground biomass	1 km	5 yearly	6
Sea surface temperature	1 km	Daily	19,601
Date of fire	20 km	Daily	28
Cloud cover fraction	2.5 km	Hourly	117,734
Chlorophyll a	1 km	8 daily	19,601
Wind direction and speed at various atmospheric levels	20 km	Hourly	1,840

2.1.2. Model-assimilated meteorological products

In some ways, these observation-based products have very similar characteristics to those described above for remotely-sensed products. The distinction between them is somewhat arbitrary, since both are in practice hybrids of observations and computations, to varying degrees. However, they have their origins in different institutions, with different cost models. In particular, only a few countries worldwide are wealthy enough to operate space agencies, whereas even the poorest African countries have some form of meteorological agency.

Table 2. The model-assimilated meteorological observation products required for the Africa-wide GHG Observation System described in Deliverable D3.1. The associated cost is not the total cost, but the incremental cost to bring them up to the standard required for a GHG observation system, and to convert them to the form needed for such a system. The total estimated data flow is 0.2 TB per year at a storage cost of 54€ a year. Deliverable D5.4 gives a detailed explanation of the data infrastructure components as well as requirements.

Product	**Spatial resolution (km)**	**Repeat frequency interval (year)**	**Data flow ($MB.y^{-1}$)**
Boundary layer height	20	0.003	76.7
River discharge/runoff	1	0.083	30,660
Soil Organic C	1	10.000	30,660
Soil moisture	1	0.003	30,660
Surface pressure	20	0.001	76.7
Wind speed and direction, surface and upper	20	0.001	76.7
Water vapour, surface and upper	20	0.001	76.7
Net Radiation	1	0.003	30,660
Air temperature, surface and upper	1	0.000	30,660
Crop yields	20	1.000	76.7
Precipitation, surface	1	0.003	30,660

2.1.3. Site-based observations

These are observations which, from the perspective of the whole of Africa, are taken at a point location. The location may in fact be observing an area rather than an exact point. The continental information arises from networks of site-based observations covering the most important areas or biomes.

Often the cost of observation associated with them is much more due to the infrastructural costs of gaining access to the location and sustaining sensitive instruments there, rather than the acquisition and operation of the instruments themselves.

We identified three basic networks: in situ atmospheric composition observations ('mixing ratios'); greenhouse gas flux measurements at all important ecosystems; and an improved network of weather stations. Together, they would require an investment of 163 M€ over 30 years including personnel costs.

2.1.3.1. Atmospheric composition measurement stations

The greenhouse gas concentrations in the troposphere integrate all natural and anthropogenic fluxes, atmospheric chemistry and transport processes. The goal is to establish a continental network of tall towers and mountain stations where data on greenhouse gas concentrations in the atmosphere are collected that allow for, for example, inverse modelling approaches describing the continental sources and sinks of greenhouse gases. An atmosphere composition station is an observatory established to continuously measure the dynamics in the concentration of greenhouse gases (CO_2, CH_4, N_2O) and other trace gases indirectly involved in climate forcing (for example CO), which are the result of regional and global fluxes as well as of complex atmospheric transport mechanisms.

A site chosen for installing an atmosphere station will typically be representative of a footprint area of more than 10,000 km^2. The stations are equipped with commercially available instruments integrated into a digital control system. They have modular character allowing for various configurations. Atmospheric composition measurement stations can also be used for measurements of aerosols and short-living atmospheric compositions (e.g. NH_3 or NO_x).

The sites which are required (see Section 3) are concentrated in the interior of the continent, in the tropical zone. This means that they need relatively tall towers to sample the well-mixed free troposphere. Most of the existing sites are coastal or oceanic, where the long fetch over a relatively flat and homogenous area of sea means that the tower can be quite short (20 m) and still sample well-mixed free troposphere. Over land, particularly where the vegetation is rough and highly productive, the tower needs to be much taller (up to 300 m) to sample the free troposphere uncontaminated by very local effects. The cost of the tower scales roughly with height. The necessary height can be reduced by siting the tower on a high, bare mountain, such as Mt. Kenya, but this typically increases the access costs. In addition, drones or balloons with air core technology to sample the atmospheric profile may be applied discontinuously. Since continuous stations will be few, they should be supplemented by a combination of total column measurement from satellites combined with a calibration network of ground based

FTIR sensors or similar technology. This approach can currently only be seen as a supplement due to low temporal coverage and high cloudiness in tropical areas.

Table 3. The cost components associated with atmospheric composition (mixing ratio) measurements at a single location in Africa. It is assumed that the lifetime of the physical infrastructure is 30 years; that access infrastructure (roads, telecommunications, power in some instances) already exists; and the lifetime of the measurement sensors and instruments is 10 years. Initial costs include the instrument and any special valves needed for it to operate, as purchased in Africa including import costs. Operating costs include calibration gas, and consumables. The levelised cost is expressed in one-year values of the operational and data processing costs for a thirty-year period and after adding the initial cost, this is reduced to back to the annual value. The large range in tower costs is due to the uncertainty associated with the required tower height; for inland towers it will generally be towards the upper end unless 'towers of convenience' (e.g. FM or TV broadcast towers) are available. The incremental cost for N_2O is higher than for CH_4, because typically a dedicated instrument is needed for the former, while the latter is typically a second channel on the CO_2 instrument.

Item	Initial cost (k€)	Annual operating cost (k€.y^{-1})	Related data services (k€.y^{-1})	Levelised cost over 30-year period (k€.y^{-1})
Tower, piping, pumps, filters, dataloggers	100–200	10		**13 – 17**
Air-conditioned container for instrumentation, power supply	50	25		**27**
Basic Instrumentation (CO_2, climate)	125	20	5	**30**
Flask sampling	50	20	3	**25**
Incremental cost for CH_4 measurement to 1 ppb and N_2O to 10 ppt	125	5	3	**12**
Total	**450–550**	**80**	**11**	**107–111**

The initial costs for a comprehensive atmospheric composition measurement site with the full spectrum of measurements and including the construction of a tall tower are about 550 k€. Operating costs will be about 80 k€.y^{-1} not including personnel costs for at least 1 FTE. Considering an average between a national and international technician, we consider 30 k€ annually per site. Related data services are estimated to be 11 k€.y^{-1}.

With a runtime of 30 years, a comprehensive atmospheric composition measurement site means a total investment of 3 M€ – 3.5 M€ plus 1FTE.

The number of additional atmospheric composition measurement sites (over and above the 6 which already exist in the Africa domain) is thought to be about 10 for a halving of uncertainty

(See task 3.3.2); beyond that, incremental reductions in uncertainty become very small. The total costs of a comprehensive atmospheric network would therefore be 30 M€ – 35 M€ excluding personnel cost.

2.1.3.2. Ecosystem flux measurement sites

These measurements are direct observations of fluxes (both sources and sinks) between land surfaces and the atmosphere. The measured fluxes comprise sensible and latent heat, CO_2 and can be extended by CH_4 and N_2O fluxes. A continental network should represent a range of ecosystems in Africa, including managed ecosystems such as agriculture. As discussed in D3.1, it is simply not feasible to measure the AFOLU and natural ecosystem GHG fluxes from all possible African ecosystems by this method alone, taking into account the number of sites that would be needed for statistically valid and spatial coverage. Therefore, a strategy is proposed wherein in most cases the emissions are modelled, often driven and constrained by remotely-sensed products and meteorological products, at fine spatial and temporal resolution (1 km and daily, respectively). The role of the flux measurement sites is to develop, calibrate and validate the models. This would reduce the amount of stations required for a basic network severely.

Two main technical approaches are possible: micrometeorological approaches (generally using eddy covariance), and chamber measurements. Usually *both* are used at a single site. The eddy covariance methods measure over ecosystem scales and therefore cost-efficiently per unit area, but require fast-response sensors which can be expensive. The chamber methods sample small areas, and thus need high replication, but can be specific to certain flux components (e.g. soil respiration) and often use cheaper sensors to achieve the same flux accuracy at a point.

Table 4. Costs to establish and operate an eddy covariance site plus automated soil chambers and a comprehensive set of meteorological variables. The costs are based on ICOS estimates for Europe. The operating costs are not including human resource costs. Approximately, two FTEs are required to operate a site. The variation in equipment costs depends on the height and complexity of the vegetation – the upper estimates are for forests, and the lower estimates are for croplands, grasslands or marshes.

Item	**Initial cost (k€)**	**Annual operating cost ($k€.y^{-1}$)**	**Related data services ($k€.y^{-1}$)**	**Levelised cost over 30-year period ($k€.y^{-1}$)**
Tower, loggers, solar PV power, ancillary meteorological measurements	100–300	10		**13–20**
CO_2 fluxes (EC)	37–65	5	6	**12–13**
CH_4 fluxes (EC)	50	5	2	**9**
N_2O fluxes (EC)	125	5	2	**11**
Chamber measurements	65	5	3	**10**
Total	**377–605**	**30**	**13**	**55–63**

With a runtime of 30 years, a comprehensive ecosystem flux site means a total investment between 1.7 M€ – 1.9 M€ plus 1-2 FTE depending on the ecosystem under observation.

The number of sites required is estimated by assuming that each additional site reduces the no-site uncertainty in Net Ecosystem Exchange (NEE) by 1/sqrt (total number of sites in that ecosystem). The no-site NEE uncertainty is estimated to be $\pm$ 40%. The relative NEE of each broad ecosystem type is calculated by multiplying a mean unit area NPP by the approximate area of that ecosystem in Africa. The target is to bring the Africa-wide bottom-up NEE uncertainty to around 15% of the total NEE, since the measurement uncertainty of eddy covariance systems is in this range.

Table 5. Cost of site-based ecosystem flux measurements in Africa, for CO_2 at all stations and CH_4 and N_2O fluxes added where high fluxes are expected.

Ecosystem biome or land system (assumed NPP in $gDM.m^{-1}.y^{-1}$ – area in 10^6 km^2)	**Existing sites (N)**	**New sites needed (N)**	**Establishment cost (k€)**	**Operational cost ($k€.y^{-1}$)**	**Related data services ($k€.y^{-1}$)**	**Levelised cost over 30-year period ($k€.y^{-1}$)**
Rainforest (2,200 – 1.8)	2	3	1,500	90	30	**170**
Moist savanna (1,600 – 10.0)	5	11	3,300	275	110	**495**
Dry savanna (900 – 9.8)	6	2	500	40	20	**80**
Arid shrub land (400 – 5.0)	2	1	250	20	10	**40**
Thickets and fynbos (1,000 – 1)	3	0	0	0		**0**
Croplands (650 – 0.3)	0	2	500	50	20	**90**
Human settlement (300 – 0.1)	0	1	300	25	10	**45**
Total	**18**	**20**	**6,350**	**500**	**200**	**920**

According to these estimates, the total costs of a comprehensive ecosystem flux system would be 27,6 M€ for 30 years and 20 new sites.

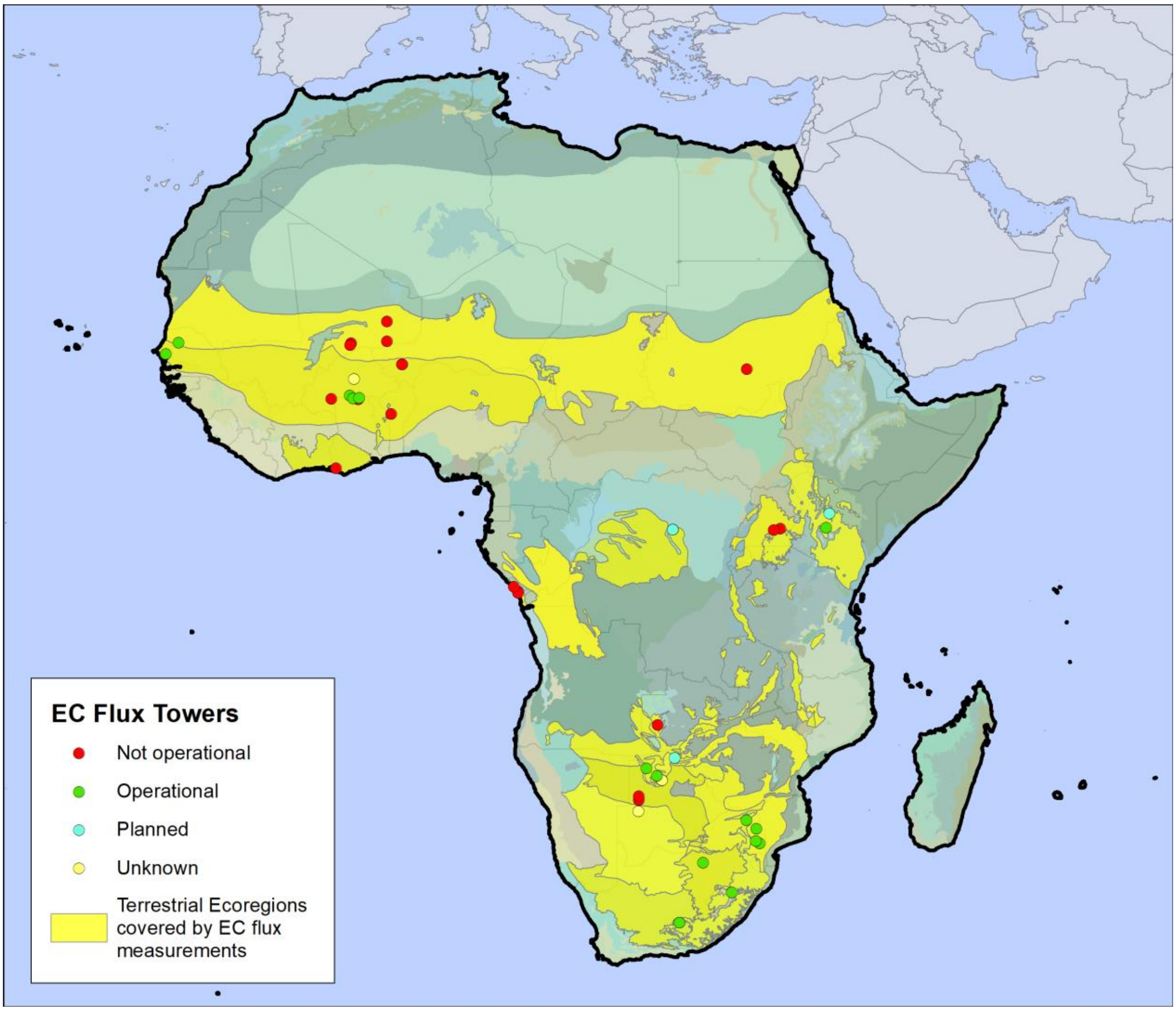

Figure 1. Map indicating EC flux towers in Africa and their status. Terrestrial ecoregions (Olson et al., Bioscience 2001) covered by these observations (and for which some flux data should therefore be available) are highlighted in yellow. Based on SEACRIFOG EC Flux inventory, May 2019 (Beck et al., Data Science Journal 2019).

2.1.3.3. Automated weather stations

The reliable functioning of meteorological and hydrological models, as well as the various GHG-estimation models in agriculture and forestry, depend on the existence of an accurate and sufficiently-dense network of weather stations. In addition, such a network is important for the detection and attribution of climate change, and for many other national purposes. The contemporary trend is for such stations to be automated and web-enabled, to ensure consistency and continuity in observation, at the lowest total cost.

The variables directly provided to the essential variables list by this mechanism include the following: rainfall, surface temperature, humidity, wind speed, direction, net radiation, shortwave radiation (or PAR), air pressure. They can with minor modifications also provide soil moisture and temperature. The WMO standard for an adequate weather station network is approximately one per 1,000 km^2 in flat country, and up to 1 per 250 km^2 in complex terrain. This translates to around 20,000 stations for the whole of Africa; about two orders of magnitude more than the current network that reports regularly to international databases, and one order of magnitude more than the currently installed network which includes all stations, i.e. stations which do not meet WMO requirements or do not report to WMO.

The relatively sparse weather station network specified below serves to continuously calibrate hybrid remotely-sensed/modelled products, which then act as the interpolators in space and time, for the redundancy mechanism.

The topic of weather station networks has been extensively investigated elsewhere, and the patchiness and apparent deterioration of the African network has been commented on. Since such a network is important to both individual countries and the global community, we will not allocate full costs for its establishment and maintenance here. WASCAL, a partner to the SEACRIFOG project, provides regional data collection services from automated weather stations from member countries. This happens through wireless interlinkages to the observation networks of automatic weather and hydro stations. The Trans-African Hydro Meteorological Observatory (TAHMO) network is aiming to develop a vast network of weather stations across Africa. SASSCAL, another SEACRIFOG partner, has extensive experience in establishing, operating and processing the data from automated weather stations in Africa. The cost per station is indicated in table 6.

Table 6. Costs to establish, operate and serve the information from a single automated weather station in Africa. The cost is given per additional station, assuming that the network already exists. Each station needs to be serviced once a year, and visiting the station is assumed to require a 600 km round trip at 0.6 €/km. The equipment costs are based on ICOS specifications and prices. Technician time is costed at 30 k€ per year but not included in the costs below. The initial acquisition costs are included under the levelised costs, along with operation, and averaged over the operating period. The initial and installation costs have been considered for 100 stations while the operational and data-related costs as well as maintenance have been considered for the 300 existing stations.

Initial cost per station (k€)	**Installation (k€)**	**Annual operating cost per station (k€.y^{-1})**	**Incremental cost for data services (k€.y^{-1})**	**Maintenance cost per station (k€.y^{-1})**	**Levelised cost over 30-year period (k€.y^{-1})**
25	2	0.5	1	1	3.4

For purposes of costing a comprehensive climate forcing observation system for Africa, we estimate that a further 100 automatic weather stations are needed, and at least 300 existing stations maintained. This is far below the estimate of stations required for a comprehensive weather monitoring network in every country (see above), but is about the same order of magnitude as the system implemented in Southern Africa by SASSCAL, and the one implemented in West Africa by WASSCAL. The idea would be to fill in critical gaps, in Central Africa in particular, and have sufficient stations, with the existing reporting stations, to adequately constrain the remotely-sensed/modelled climate surfaces. The maintenance costs are those for periodic sensor replacement and upgrade which would be at least every 10 years.

Occasional accidents are also budgeted for in this category. The operational cost in the table is mostly travel costs. In addition to flux towers and weather stations, further in situ observations may be required for river discharge to reduce uncertainty of lateral C transport estimates.

An integrated weather system cost for the 400 stations over 30 years would be around 40 M€ plus 5 FTE.

2.1.4. Campaign-based calibration products

There are three essential variables which require focused campaigns in order to establish the values and drivers allowing more reliable models to be constructed: species traits, crop yields and land use. The equipment costs are relatively small, at about 5 k€ per campaign. Each campaign would cost about 200 k€, for a levelised cost of around 450 k€ per year for all campaign-based approaches.

The following agricultural and forestry land use emission factors for the GHG-related emissions are Africa-specific. They are all known to some degree, but most require further elaboration. Once well established, the exercise does not need to be repeated unless something significant occurs to cause them to change – for instance, if the diet of animals changes dramatically.

Table 7. Emission factors which require Africa-specific investment if accuracy is to be improved to target levels.

Factor	**Elaboration**	**How many campaigns a year**	**Campaigns per system over 30 years**	**Cost per campaign (k€)**	**30-year cost of campaigns (k€)**	**Levelised cost over 30 years (k€.yr^{-1})**
Livestock CH_4 emission factors	Includes African cattle breeds under African management, and indigenous wildlife, and manure management practices	NA	3[2]	60	4,500 (25 systems)	150
		1[3]	NA	200	6,000	200

[2] The campaigns are carried out per system, there are roughly 25 livestock and agricultural systems considered, with a campaign every 10 years. The same applies to emission factors from agricultural fields.

[3] For livestock, this annual campaign corresponds to one animal trial with gold standard respiration chamber

Factor	Elaboration	How many campaigns a year	Campaigns per system over 30 years	Cost per campaign (k€)	30-year cost of campaigns (k€)	Levelised cost over 30 years (k€.yr^{-1})
Emission factors from agricultural fields, by management practice and crop	C dynamics under African crop management systems, on African soils and climates. May include low-till and biochar options. Includes CH_4 emissions in relation to flooding and N_2O in relation to N-use	NA	1[4]	100	2,500 (25 systems)	83
Tree allometry and below-ground biomass expansion factors	Several thousand forest and savanna species exist in Africa, for which allometry exists for several hundred. Rare species can be put in classes	NA	1	300	300	10
Emission factors for wild and domestic fires	EFs are generally adequate for vegetation fires, charcoal making and open burning of wood, but may need verification in some cases	NA	1	200	200	7
Total		**NA**	**6**	**860**	**13,500**	**450**

An integrated system budget includes a 14 M€ cost for campaigns over 30 years.

[4] This is based either on continuous observations or on trials (using chambers and gas chromatography)

2.1.5. TCCON sites

Five TCCON (Total Column Carbon Observing Network) sites situated close to atmospheric sites and at locations relevant to calibrate satellite observations have been estimated as necessary to add to the designed GHG observation system. TCCON provides a weighted column of integral GHGs to complement atmospheric in situ measurements. TCCON provides additionally the link between ICOS and GHG satellite data and provides a reference network for the calibration and validation which are vital for the GHG satellite retrievals. The data from these sites is requested by atmospheric modelers in order to validate their models. Initial cost estimates come to 600 k€ and the levelized cost is estimated at 320 k€ a year.

TCCON data is also used for the detection and evaluation of long-term trends. The TCCON instrument is composed of a high spectral resolution FTIR spectrometer of the type Bruker IFS 125HR operating in the near-infrared spectral region (4,000–9,000 cm^{-1}), and coupled to a sun tracker operated automatically or remotely. For automatic observations, a weather station coupled to the TCCON instrument is needed to detect atmospheric measurement conditions, that need to be cloud free and no rain. The automation software detects when measurement conditions exists, opens the cover of the solar tracker and starts the measurements. The data is stored locally or transferred via the internet to the institution of the PI of the instrument.

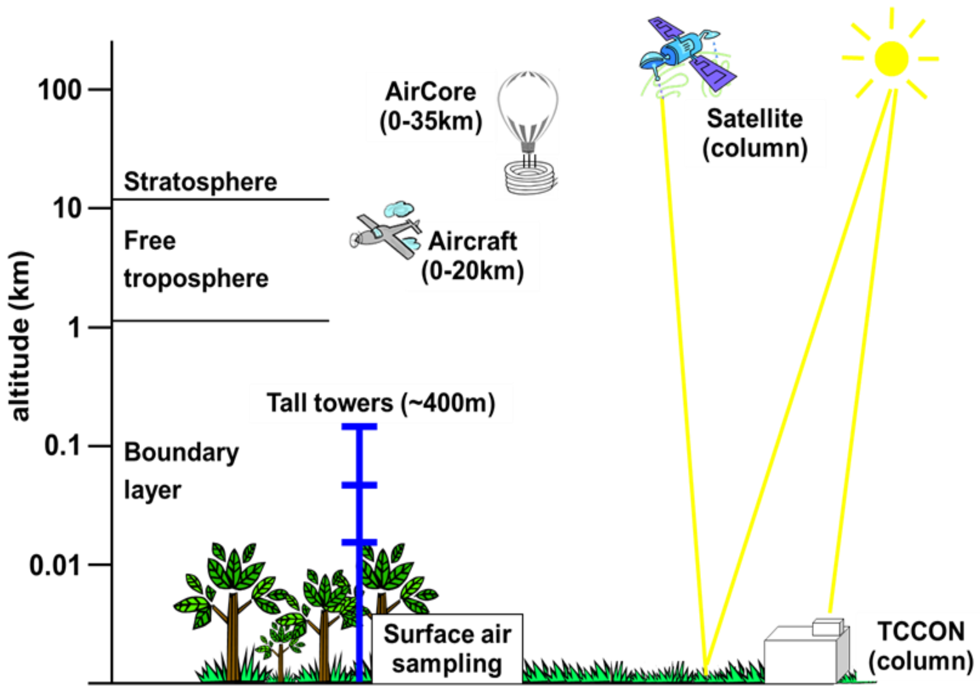

Figure 2. Integral observations of atmospheric greenhouse gases.

Table 8. TCCON sites cost estimation.

Initial cost (k€)	Sites (N)	Annual operating cost ($k€.y^{-1}$)	Related data services ($k€.y^{-1}$)	Levelised cost over 30-year period ($k€.y^{-1}$)
600	5	200	100	320

The cost estimate for the 5 sites added to 5 weather stations is 10 M€ for 30 years.

2.1.6. National GHG inventories

All UNFCCC countries must submit a GHG inventory, so in principle using this information to constrain an Africa-wide GHG inventory does not constitute any 'additional cost'. However, if the inventory is to meet a consistent and acceptable standard, external funding and technical support may continue to be needed for several iterations of the reporting cycle, before the skills, data systems and institutions have been built to the point that they become self-sustaining. The Global Environmental Fund finances capacity-building for greenhouse gas inventories associated with National Communications, ranging from 90 k€ to 3.2 M€ per country[5].

Several Official Development Assistance agencies have also supported greenhouse gas inventory development in Africa. The experience in several African countries over the past two decades suggests that the unit cost depends on several factors: the complexity/heterogeneity of the emission sources (for instance if there are many different AFOLU sources); the physical size, population and economic activity of a country (the GHG emission total is a rough proxy for the combined effect of these factors); the degree to which existing, reliable systems exist for recording energy statistics, transport and land use; and the target accuracy (IPCC Tier 1, 2 or 3). The communications of non-Annex 1 countries (all African countries are in this category) are performed every five years, and take around 3 years to prepare; therefore, there is a good argument to making the institution which performs them permanent, working on a rolling basis. The IPCC approach of relaxing the rigour (and therefore cost) of the inventory process in proportion to the size of the likely emission (and its contribution to uncertainty) is a good one, both from a practical and scientific point of view. Countries with large emissions overall should expect to spend more on quantifying their emissions than countries with small emissions, and the same applies to emission-generating sectors within countries. Such a differentiated approach leads to the greatest overall reduction in uncertainty for a given expenditure (figure 1).

[5] www.globalenvironmentfund.com

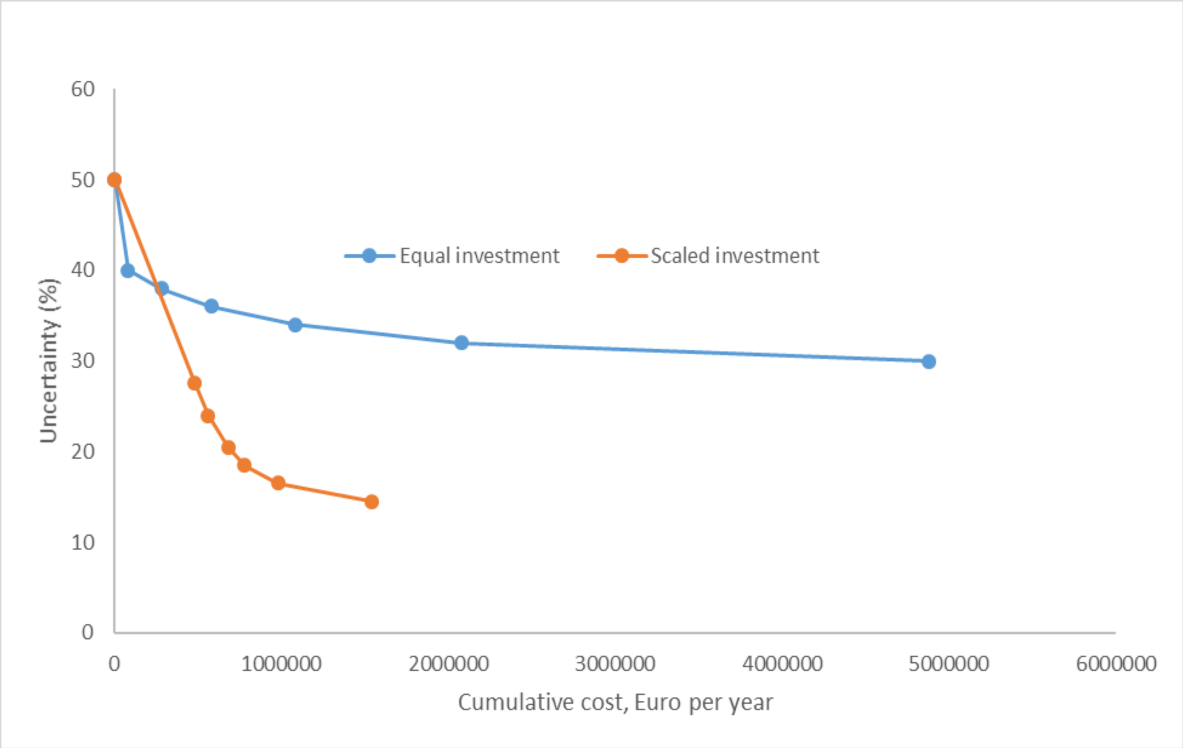

Figure 3. If every African country spends 100 k€ every 5 years to generate its GHG inventory to Tier 3 accuracy (+30%), the 'equal investment' uncertainty-reduction curve is followed, assuming that the uncertainty in the absence of any inventory is around 50%. If instead countries with annual emissions > 180 MtCO_2e invest at Tier 3 level (estimated to cost 600 k€, and achieve +5% accuracy), countries with 130–180 MtCO_2e emissions invest at Tier 2 (estimated to cost 200 k€, and achieve +15% accuracy) and countries with annual emissions <130 MtCO_2e invest at Tier 1 level, then the scaled investment curve is followed. The scaled investment approach achieves greater uncertainty reduction per unit investment nearly across the board, and achieves the target of overall 15% uncertainty for an annual Africa-wide investment of 1.5 M€ per year.

Table 9. The cumulative emission uncertainty for African countries in deciles from 50% upwards. Based on estimated national emissions from African countries in the year 2014. It is assumed that uncertainty scales linearly with emission magnitude.

Category	**Number of countries**
First 50% of uncertainty	4: South Africa, Nigeria, Egypt, Algeria
Next 10% uncertainty (i.e. to 60%)	2: Angola, Libya
Next 10% (i.e. to 70%)	3: Ethiopia, Cameroon, Morocco
Next 10% (i.e. to 80%)	5: Tanzania, Kenya, Zambia, Central African Republic, Democratic Republic of Congo
Next 10% (i.e. to 90%)	10: Tunisia, Uganda, Côte d'Ivoire, Ghana, Mali, Chad, Mozambique, Zimbabwe, Niger, Madagascar
Remaining uncertainty to 100%	28: Trinidad and Tobago, Senegal, Burkina Faso, Equatorial Guinea, Guinea, Botswana, Benin, Namibia, Mauritania, Malawi, Gambia, Gabon, Republic of the Congo, Sierra Leone, Eritrea, Rwanda, Togo, Mauritius, Lesotho, Burundi, Eswatini, Liberia, Guinea-Bissau, Djibouti, Seychelles, Cape Verde, Comoros, São Tomé and Príncipe

2.1.7. Ancillary socioeconomic and environmental data

There is a complementary set of information needed to calculate the bottom-up emission estimates. Most of these so-called ancillary data involve information which is collected for government planning, development and management purposes, and so in principle does not constitute an additional cost. However, they can be very patchy in quality and availability across the countries of Africa, especially those distracted by conflict or other socioeconomic development challenges. Therefore, accessing a default set of ancillary data at Africa scale from one of the international providers is a good redundancy strategy. The variables include human population (preferably by gender, age class and wealth category, rural and urban); national (and in some cases sub-national) GDP; number, type and distance driven by motor vehicles; livestock by breed and management system; and trade data, especially fossil fuel imports and exports, but also the embodied carbon in traded products such as food and timber.

A further category of information needed for many of the above estimates relates to the extent and properties of various soil types. The indispensable variables are soil depth, and by major horizon, coarse fraction content, percent clay and sand, SOC, water holding capacity at -0.001 MPa and at -1.5 MPa. These data are increasingly available[6], at suitable accuracy and resolution, for Africa, but may not be known or readily accessible in many African countries.

In addition, a fine-resolution (~20 m) Digital Elevation Model is needed, for several purposes, particularly relating to drainage. Such DEM and derived drainage products are available for Africa.

[6] Africa soil grids https://data.isric.org/geonetwork/srv/eng/catalog.search#/search?resultType=details&sortBy=relevance&any=Africa%20SoilGrids&from=1&to=20

2.2. Cost integration

2.2.1. Initial and maintenance costs for an in situ network

It would cost an estimate 163 M€ to build and maintain an in situ network over 30 years. Personnel cost of about 38 M€ are included in this estimation and details are provided in table 11 in the following section. Since a large part of the 30-year cost consists of investments in instruments, more than half of this sum should be available during the first developmental phase. Over the 30-year period, an annual levelized cost of 5 M€ is estimated, but for the first three years, a slightly higher annual cost of 10 M€ is considered instead, to allow for the kickoff of operations. After a lump sum initial investment of 30 M€ in the first three years, 10-year development phases can be envisaged with an incremental 2 M€ for upgrade and maintenance after every phase, depending on the type of site.

Table 10. In situ network cost estimates

Element	**Initial cost**	**Operational cost**	**Data processing costs**	**FTE**	**Levelised cost over 30 years**	%
	(M€)	**(M€ · yr^{-1})**	**(M€ · yr^{-1})**	**(M€ · yr^{-1})**	**(M€ · yr^{-1})**	
Remote sensing products	See integrated data and modelling centre.					
Modelled products						
Atmospheric component measurement stations	5.50	0.80	0.11	0.33	1.42	28 %
Ecosystem fluxes	6.35	0.50	0.20	0.63	1.54	30 %
Automated weather stations	2.70	0.60	0.40	0.15	1.24	24 %
Campaigns	0.00	0.45	0.00	0.00	0.45	9 %
National inventories	0.00	0.05	0.00	0.00	0.05	1 %
TCCON sites	0.60	0.20	0.10	0.15	0.47	9 %
Total	**15.15**	**2.60**	**0.81**	**1.26**	**5.18**	**100 %**

2.2.2. Personnel costs for the in situ maintenance

Personnel costs are difficult to estimate since salaries differ substantially between countries and qualifications needed. Nevertheless, a first estimate is provided in Table 10 above assuming average annual costs for 1 full-time equivalent (FTE) being 30 k€.y^{-1}. A detailed account of personnel estimations for the in situ component is available in table 11. For the campaigns, however, personnel have not been budgeted for, as these are not continuous activities and services are planned to be bought from providers when necessary. National inventories are also considered governmental services, which means that activities will simply be coordinated with the relevant government offices. The total estimate for in situ maintenance over 30 years is therefore rounded to 38 M€.

Table 11. This table presents a full-time equivalent estimation budget for the maintenance of the observations listed above. The FTE costs will vary largely depending on the model of the system. In the beginning, there may have to be higher costs considering experienced employees while, the costs will probably reduce as skills are transferred for local ownership.

Personnel costs for elements	**FTE**	**Cost**	**Total cost over 30 years**
	(y^{-1})	**(M€ · yr^{-1})**	**(M€)**
Remote sensing	See integrated data and modelling centre.		
Modelled products			
Atmospheric sites	11	0.33	9,90
Ecosystem fluxes	21	0.63	18,90
Automated weather stations	5	0.15	4,50
Campaigns	0	0.00	0,00
National inventories	0	0.00	0,00
TCCON sites	5	0.15	4,50
Total	**42**	**1.26**	**37,80**

2.2.3. Costs for an integrated data and modelling centre

Exact and precise cost estimations including required servers, computers and cost of data transfer networks cannot be carried out without more detailed plans related to the implementation. However, it is a fair assumption that in the beginning of its lifetime, an EU-African Research Infrastructure can either decide to build its own data and modelling center if the required long-term funding is available, or it can start to build its data center and portal functions using commercially available services. In the beginning, the data storage and processing requirements are smaller for the operational measurement infrastructure, but they increase nearly linearly with operation time. The more modelling products and remote sensing based elaborated data products will be produced, the more computational capacity will be needed. In Europe, Copernicus has arranged several different platforms that can provide data access and processing capacity in the same services platform following IaaS (Infrastructure as a Service) principles. A solution containing large storage and processing capacity in WEkEO[7] service can be used either on a monthly or an annual service plan and would cost around 300,000 € per year). An integrated data and modelling centre including remote sensing data for hosting and for processing is estimated at a total cost of 284 Me. The blue bars in figure 4 below illustrate a steady rise according to estimated needs and data use, from the initial cost above to 9.5 M€ by the 30th year. The personnel cost estimates for this data centre, i.e. the red bars, is projected to increase at double the instrument cost to

[7] www.wekeo.eu/offer

allow for capacity building and African ownership of this development process through the participation of the African partners in the system.

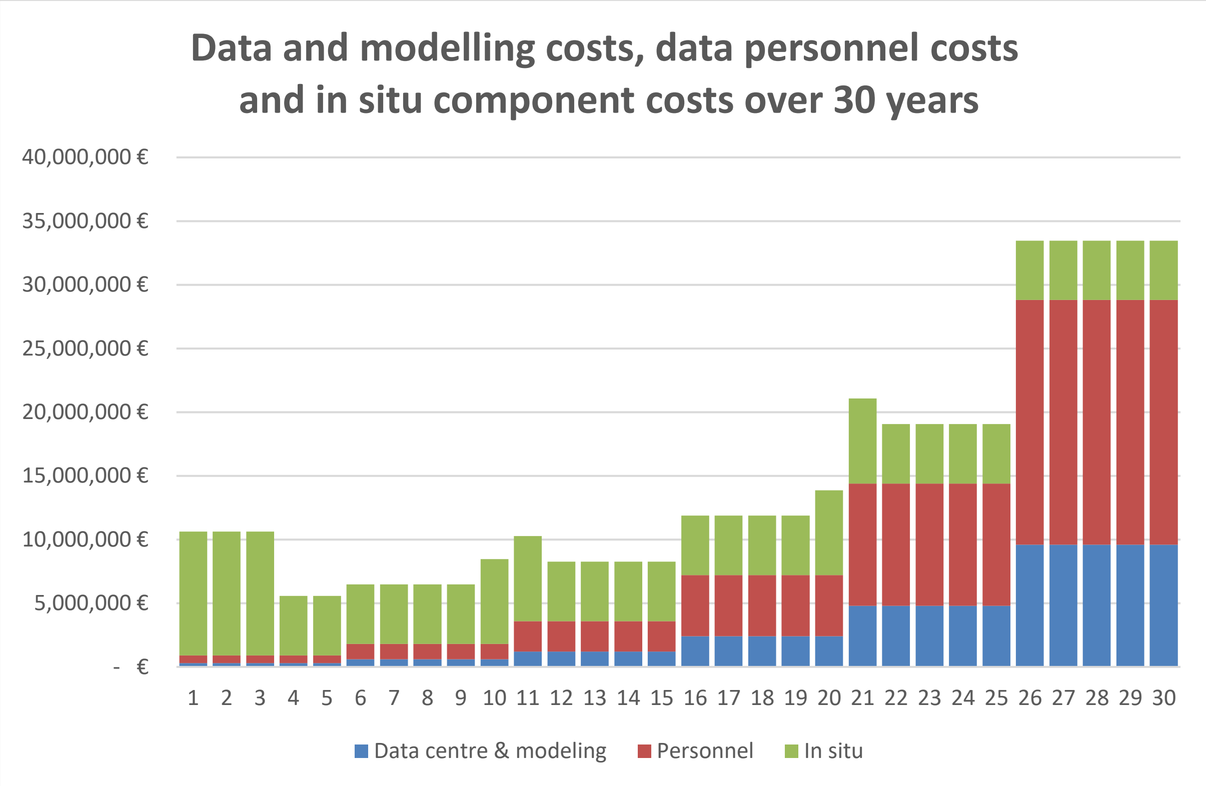

Figure 4. The blue bars are the data centre and modelling costs that are projected to increase over 30 years. The red bars are the personnel costs that would provide for capacity building for the data centre, an essential element to accompany investments in the instruments. The green bars represents the in situ component cost detailed in section 2.2.1. It is initially high but then decreases, unlike the data component. It is assumed that once the investment to build the in situ sites is done, no essential increment in costs is expected. Overall cost estimations are detailed below.

2.2.4. Total costs for an African GHG observation system

The initial expenditure for all the elements of the system for the first three years, considering all components can be estimated at 30 M€. The sum of levelized costs (equipment, operations and data processing costs) comes to 10 M€ a year. Over 30 years, an investment of about 450 M€ is needed for initial, operational and data processing costs. An overall budget of 500 M€ is therefore fit to estimate for a greenhouse observation system, considering the future need of extended modular developments, that would accommodate aerosol measurements for example as well as cater for concurrent human resources. In figure 5 below, the operational costs for the remote sensing data and modelling component of the infrastructure are included in the data processing estimations, as details of these costs for the data component will depend on future technology. In situ operational costs on the other hand have been broken down as specifics of these are better known at this stage. Overall personnel costs are about 50 % of the infrastructure budget to enable the infrastructure to focus on capacity-building as one of its main agendas in line with the expected socio-economic impact. This is planned in linear increase of investment in the academia to support researchers from an early stage of their learning especially for the data component of the system.

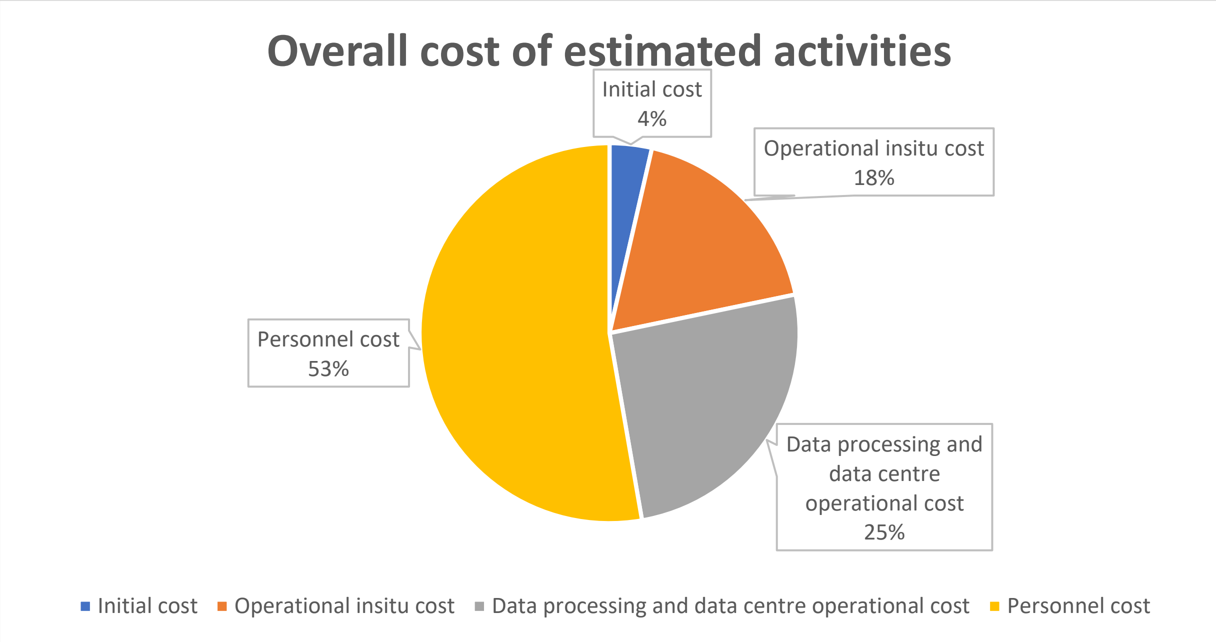

Figure 5. An overview of the overall cost for the operational activities of the infrastructure.

Overall estimates of the whole system are shown in table 12 below and later represented in figure 6 by annual levelized costs.

Table 12. Estimates of the initial and annual costs of an Africa-wide climate forcing observation network sufficient to bring the uncertainty over the African continent within the same range as that for other similar-sized regions of the world.

Element	**Initial cost**	**Operational cost**	**Data processin g costs**	**FTE**	**Levelised cost over 30 years**	%
	(M€)	**(M€ · yr^{-1})**	**(M€ · yr^{-1})**	**(M€ · yr^{-1})**	**(M€ · yr^{-1})**	
Remote sensing	0.15	0.00	1.43	3.15	4.58	32 %
Modelled products	0.15	0.00	1.43	3.15	4.58	32 %
Atmospheric measurement site	5.50	0.80	0.11	0.33	1.42	10 %
Ecosystem fluxes	6.35	0.50	0.20	0.63	1.54	11 %
Automated weather stations	2.70	0.60	0.40	0.15	1.24	9 %
Campaigns	0.00	0.45	0.00	0.00	0.45	3 %
National inventories	0.00	0.05	0.00	0.00	0.05	0 %
TCCON sites	0.60	0.20	0.10	0.15	0.32	2 %
Totals	**15.45**	**2.60**	**3.66**	**7.56**	**14.19**	**100 %**

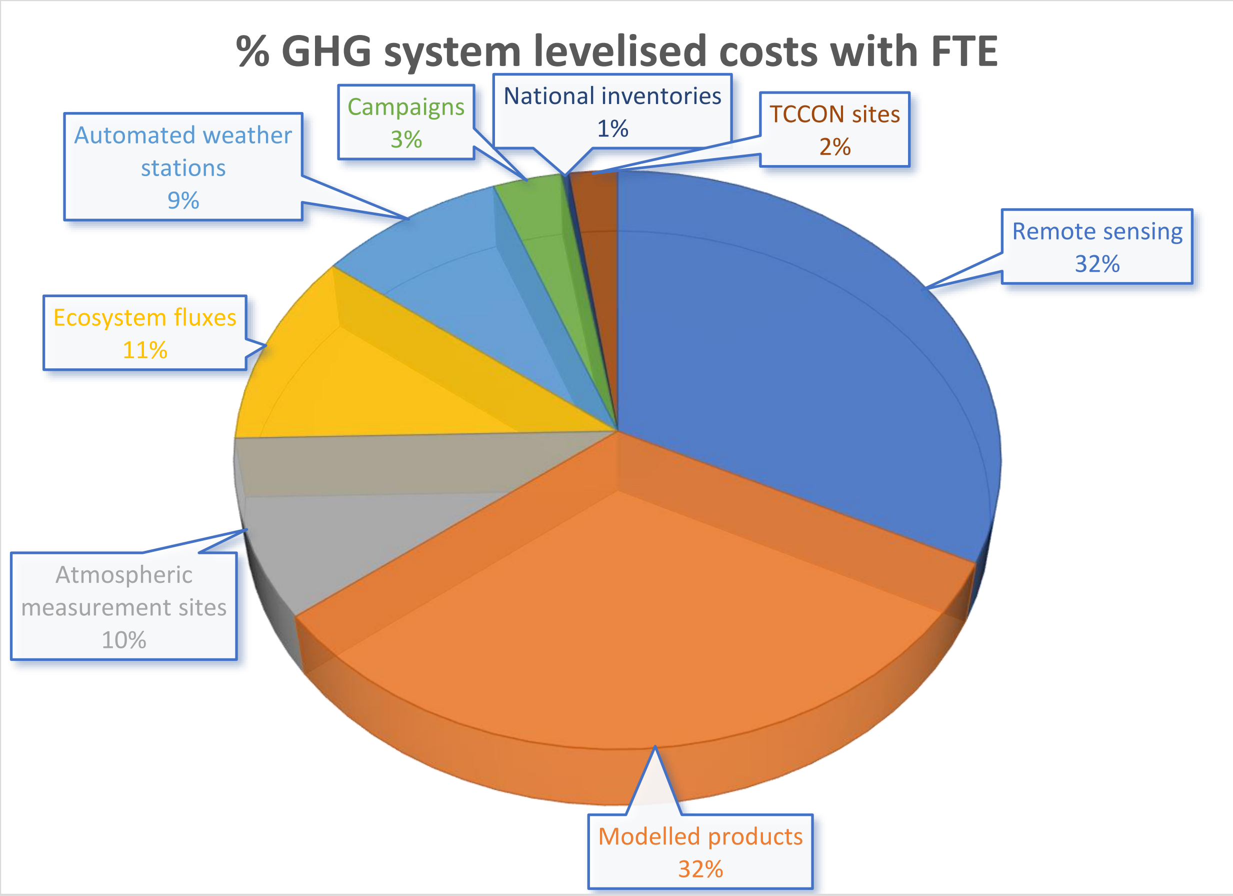

Figure 6. Total levelized costs of a pan-African GHG observational system are presented in the figure with an estimation of human resources included per year. A larger initial investment would go towards the atmospheric measurement and ecosystem flux sites as well as the establishment of automated weather stations coupled with the TCCON sites. The modelled products and remote sensing products are the highest in percentage in the pie chart representation due to their significant personnel costs. The main objective through the conception of this system, and through the budgeting process, is to build on existing resources for optimization.

These costs include those of existing observational elements, notably weather stations maintenance costs as well as data collected already for other purposes. How they are to be apportioned between individual African countries, UNFCCC-related (Paris Accord) funding streams administered by the GEF, development aid, and interested African regional bodies such as the AU and the African Development Bank, is an issue for negotiation, both initially and in the future. The funding concept will be further elaborated in Deliverable D7.2.

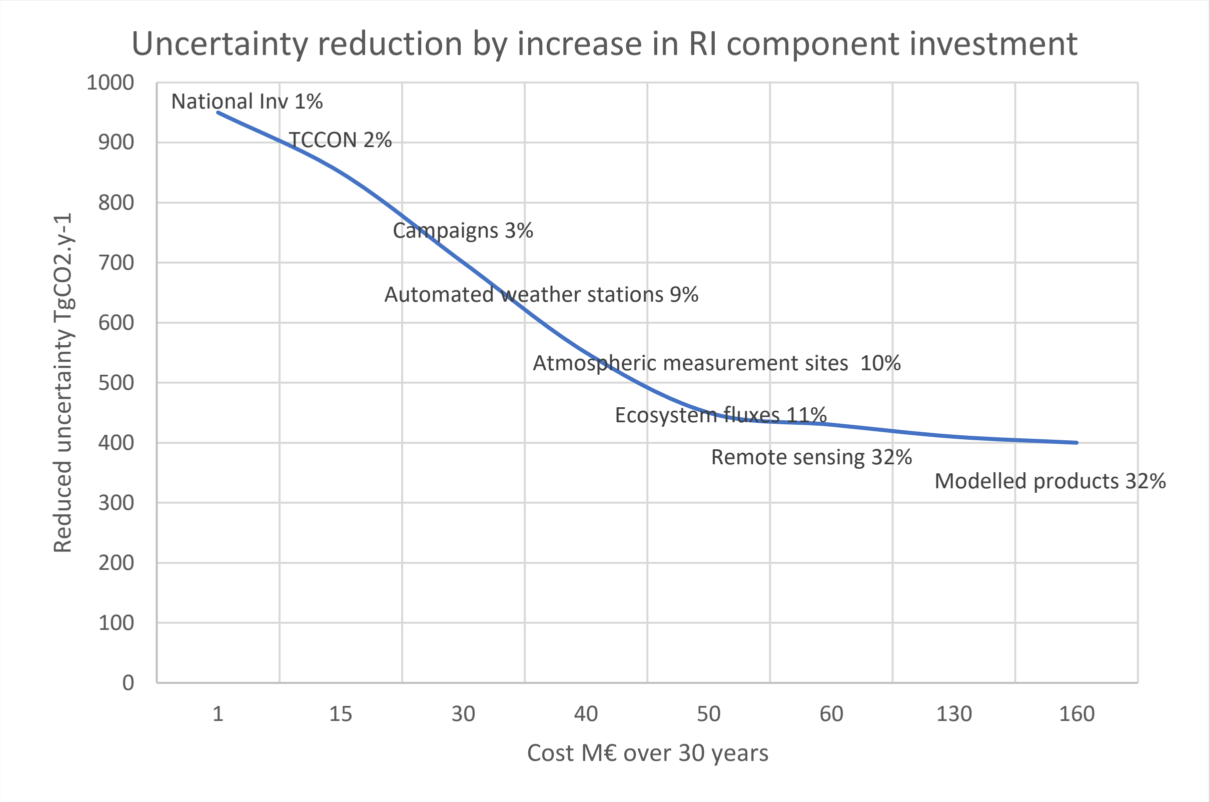

Figure 7. This is an indicative curve of reduced uncertainty of greenhouse gas emission measurements with each cumulative investment. It is assumed that the lowest uncertainty will be achieved over the African continent with an integral investment to the observational and data system, impacting positively the research, innovation and capacity building agendas. The next section explores in detail where site locations would impact uncertainty reduction the most.

3. SEACRIFOG Task 3.2.2: Site locations for uncertainty reduction

This subtask investigates where new atmospheric GHG measurements should be located in and around Africa, in order to reduce the uncertainty in the overall system by the largest amount. It 'inverts' (i.e. runs in reverse) models of GHG fluxes and transport, constrained by existing observations and their locations and prior estimates of the emission fields from both anthropogenic and natural sources, to determine the best location for the next sensor, in order that it reduces the overall uncertainty the most. The site selection procedure continues this process until a given level of accuracy is reached. Locations can be excluded as being impractical or otherwise unsuitable, and the effects of moving them a small distance to a more practical location can be explored. The initial model SEACRIFOG explored was for CO_2, and was subsequently expanded to CH_4 and N_2O as well. The full technical details of how the analysis was performed can be found in Nickless et al. (2019).

There are currently around 6 operational atmospheric gas composition monitoring stations at the GAW standard on the African continent or on islands surrounding it (Table 11).

Table 13. The 59 candidate sites considered in the optimisation approach. Of these, a small subset are already active tall towers for atmospheric measurements (category "GAW, active"). Others are existing meteorological observation sites and 2 were imaginary sites, to fill large gaps in case they were important in the optimised selection.

Station Number	Station Name / Location	Latitude (°N)	Longitude (°E)	Network
1	Cabauw 200m, The Netherlands	51.97	4.93	ICOS, active
2	Cabauw 20m, The Netherlands	51.97	4.93	ICOS, active
3	OPE, France	48.56	5.50	ICOS, active
4	Macehead, Ireland	53.33	-9.90	GAW, active
5	Hegyhatsal, Hungary	46.95	16.65	ICOS, active
6	Springbok, South Africa	-29.67	17.90	GAW, inactive
7	Amersfoort, South Africa	-27.07	29.87	GAW, inactive
8	Gobabeb, Namibia	-23.57	15.03	GAW, inactive
9	Maun, Botswana	-19.98	23.43	GAW, inactive
10	Irene, South Africa	-25.91	28.22	GAW, inactive
11	Taolagnaro, Madagascar	-25.03	46.95	GCOS, active
12	La Reunion, France	-21.08	55.38	GAW, active
13	Point Canon, Mauritius	-19.68	63.42	GCOS, active
14	Lubango, Angola	-14.93	13.57	GCOS, active
15	Mwinilunga, Zambia	-11.75	24.43	GCOS, active
16	Lilongwe, Malawi	-13.78	33.78	GAW, inactive
17	Nampula, Mozambique	-15.10	39.28	GAW, inactive

Station Number	Station Name / Location	Latitude (°N)	Longitude (°E)	Network
18	Antananarivo, Madagascar	-18.80	47.48	GCOS, active
19	Antalaha, Madagascar	-14.88	50.25	GCOS, active
20	Ascension Island	-7.97	-14.40	GAW, active
21	Kinshasa, DRC	-4.30	15.55	GAW, inactive
22	Dundo, Angola	-7.40	20.82	GCOS, active
23	Kasama, Zambia	-10.22	31.13	GCOS, active
24	Dodoma, Tanzania	-6.17	35.77	GCOS, active
25	Sassandra, Côte d'Ivoire	4.95	-6.08	GCOS, active
26	Douala, Cameroon	4.02	9.70	GCOS, active
27	Zoetele, Cameroon	3.25	11.88	GAW, inactive
28	Kisangani, DRC	0.52	25.18	GCOS, active
29	Bunia, DRC	1.50	30.22	GAW, inactive
30	Mt. Kenya, Kenya	-0.06	37.30	GAW, active
31	Lungi, Sierra Leone	8.62	-13.20	GCOS, active
32	Lamto, Côte d'Ivoire	6.22	-5.03	ICOS, active
33	Ilorin, Nigeria	8.53	4.57	GAW, inactive
34	Ngaoundere, Cameroon	7.35	13.57	GCOS, active
35	Am-Timan, Chad	11.03	20.28	GCOS, active
36	En Nahud, Sudan	12.70	28.43	GCOS, active
37	Neghelle, Ethiopia	5.33	39.57	GCOS, active
38	Imaginary1, Somalia	9.00	46.00	Imaginary, inactive
39	Bambey, Senegal	14.70	-16.47	GAW, inactive
40	Tidjikja, Mauritania	18.57	-11.43	GCOS, active
41	Tessalit, Mali	20.20	0.98	GCOS, active
42	Banizoumbou, Niger	13.52	2.63	GAW, inactive
43	Bilma, Niger	18.68	12.92	GCOS, active
44	Genina, Sudan	13.48	22.45	GCOS, active
45	Sennar, Sudan	13.55	33.62	GCOS, active
46	Kassala, Sudan	15.47	36.40	GCOS, active
47	Bir Moghrein, Mauritania	25.23	-11.62	GCOS, active
48	Imaginary2, Algeria	25.00	-2.00	Imaginary, inactive
49	Assekrem, Algeria	23.27	5.63	GAW, active

Station Number	Station Name / Location	Latitude (°N)	Longitude (°E)	Network
50	Sebha, Libya	27.02	14.45	GCOS, active
51	Kufra, Libya	24.20	23.30	GCOS, active
52	Aswan, Egypt,	23.97	32.78	GAW, active
53	Casablanca, Morocco	33.57	-7.20	GAW, active
54	Ifrane, Morocco	33.50	-5.17	ICOS, active
55	Thala, Tunisia	36.55	8.68	GAW, inactive
56	Hon, Libya	29.13	15.94	GCOS, active
57	Sidi-Barrani, Egypt	31.45	25.15	GAW, active
58	Cairo, Egypt	30.08	31.28	GAW, active
59	Cape Point, South Africa	-34.35	18.49	GAW, active

The network optimal expansion procedure considered adding up to another twelve potential locations. The candidates were selected from the above list of African locations where some environmental observations are currently taking place, and where some institutional support and infrastructure exist. A coarse grid was laid over Africa, and one potential site was selected from each grid to be used in the further evaluation through Bayesian Inverse Modelling.

What the analysis revealed is that the ranking of the optimal set of sites, in terms of the amount by which they individually reduced Africa-scale emission uncertainty, changed from season to season (Table 12), as the location of maximum net primary production shifted north or south. For large fixed investments such as tall towers, it would not be feasible to switch them on or off or move them, so some compromises need to be accepted. The top-ranked sites were always within tropical Africa, rather than in North Africa or Southern Africa. This is an important finding, which we attribute to two factors: first, the overall African carbon cycle is dominated by the high primary production in the tropical belt; and secondly, the existing stations are concentrated in the north and south of Africa, so the variance is already somewhat constrained there. The finding is not completely intuitive, because the centres of anthropogenic (especially fossil fuel) emissions are in South Africa and the Northern African countries.

Table 14. The uncertainty reduction in the total Africa CO_2 flux made by new stations added to the existing station network, ranked from greatest reduction (rank 1) to smallest reduction, separately for the four seasons of the year (Jan-Mar, Apr-Jun, Jul-Sep, Oct-Dec) for the year 2012. The first value in the table is the station identity number in the 59 candidates, while the second (bracketed) number is the cumulative variance reduction, as a percentage of total variance.

Rank	Jan-Mar 2012	Apr-Jun 2012	Jul-Sep 2012	Oct-Dec 2012
1	9 (18.7%)	36 (12.8%)	46 (17.2%)	22 (16.3%)
2	23 (32.3%)	27 (19.8%)	42 (26.7%)	28 (21.0%)
3	21 (37.2%)	45 (23.9%)	35 (33.5%)	21 (25.4%)
4	17 (41.1%)	34 (27.5%)	40 (38.3%)	9 (29.1%)
5	28 (44.7%)	29 (30.6%)	29 (42.4%)	27 (32.5%)
6	14 47.3%)	26 (32.8%)	28 (45.1%)	14 (34.8%)
7	24 (49.5%)	28 (34.9%)	36 (47.5%)	31 (37.1%)
8	22 (51.4%)	42 (36.5%)	38 (49.4%)	26 (38.8%)
9	18 (53.0%)	37 (38.0%)	45 (50.8%)	15 (40.5%)
10	15 (54.4%)	14 (39.4%)	39 (51.8%)	29 (42.0%)

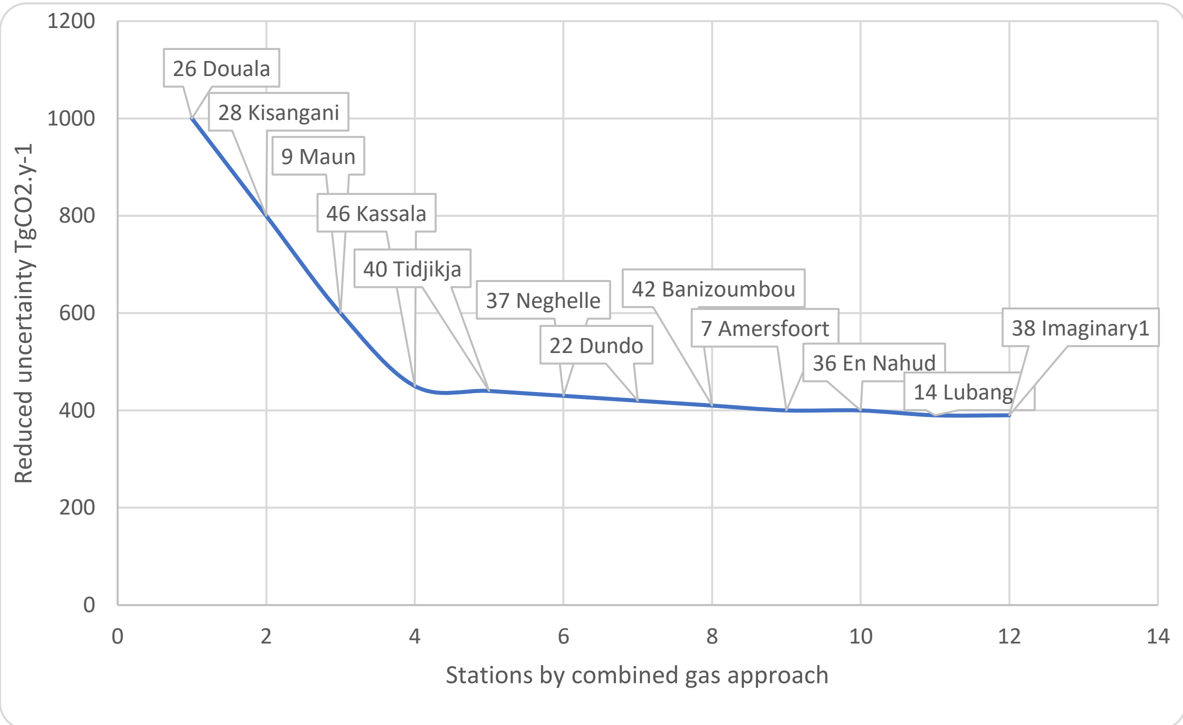

Figure 8. The reduction in top-down African GHG uncertainty as a function of site location from the combined approach considering all gases, up to 12 stations. Site locations in tropical Africa would influence a greater reduction in top-down GHG uncertainty.

The target is to reach around 400 $TgCO_2.y^{-1}$ uncertainty for the entire African CO_2 budget. Adding more than 6 new stations delivers very little further uncertainty reduction by itself, and decreasing uncertainty further and far below around 400 $TgCO_2$ requires either a much higher number of sites for the current point-sample based inversion technologies or a more integrated system with remote sensing. The 10 sites suggested in Chapter 2 would result in an uncertainty about the same size as the current uncertainty in the bottom-up inventories, but about twice the uncertainty that could be achieved with a more optimal spend on inventories. The key constraint on the accuracy of the inversion techniques is the uncertainty in the biospheric flux 'priors'. Thus, by improving the estimates of ecosystem fluxes through a network of eddy covariance towers and improved remote-sensing-driven models from around 40% down to 15% as proposed, this 'floor' level of achievable uncertainty will decrease, hopefully to within the same range as the improved uncertainty on the inventories.

The analysis also showed that when it was performed for CH_4 and N_2O in addition to CO_2, the selected sites were different in order of selection, but overall rather similar, focusing on the tropics and inland areas. The CH_4 sites showed less seasonal dependency, and achieved a 38 % variance reduction for 10 sites. The N_2O sites had high seasonality since the dominant source is the soil. The uncertainty reduction was 38% in January-March, but only 10% in April-June. As a result, a combined network design involves some compromises, and for the same number of stations achieves slightly less variance reduction (1–5% less, depending on the season) than when the network is optimized for a given gas. We explored two approaches of combining information on the uncertainty reduction of all three gases to provide an optimal selection of sites. The first approach selected the top two sites in the Northern and Southern Hemisphere summers for all three gases. This resulted in a solution consisting of 12 stations. The second approach used an average of the uncertainty reduction across all three gases and both summer periods as the quantity to optimize. Both approaches selected sites which covered most of tropical and sub-tropical Africa.

Table 15. Uncertainty reductions achieved by optimal network design aiming to maximize uncertainty reduction across all three gases (CO_2, NH_4 and N_2O) and across both northern and southern hemisphere summers. Results are presented for the approach using the solutions from the separate network designs, and for the combined optimization of uncertainty reduction across all three gases.

	Separate approach			Combined approach			Combined approach		
	12 stations			10 stations			12 stations		
Period	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O
January to March	47.8%	28.1%	32.5%	35.6%	23.5%	6.1%	39.1%	25.0%	7.1%
April to June	33.3%	27.5%	7.1%	30.0%	27.8%	5.3%	31.6%	29.3%	5.6%
July to September	40.4%	30.0%	27.9%	44.2%	30.9%	24.6%	45.9%	34.3%	24.6%
October to December	30.6%	22.6%	4.9%	30.0%	22.1%	8.1%	32.2%	23.7%	8.2%

Table 16. List of stations in each of optimal network design for both the separate and combined approaches. Stations listed under the separate approach are put in order of the placement from the separate solutions, which began with the best stations from the CO_2 solutions, followed by CH_4, and then NO_2 stations.

Rank (Combined approach only)	Separate approach		Combined approach	
1	9	Maun, Botswana	26	Douala, Cameroon
2	23	Kasama, Zambia	28	Kisangani, DRC
3	46	Kassala, Sudan	9	Maun, Botswana
4	42	Banizoumbou, Niger	46	Kassala, Sudan
5	15	Mwinilunga, Zambia	40	Tidjikja, Mauritania
6	28	Kisangani, DRC	37	Neghelle, Ethiopia
7	22	Dundo, Angola	22	Dundo, Angola
8	45	Sennar, Sudan	42	Banizoumbou, Niger
9	18	Antananarivo, Madagascar	7	Amersfoort, South Africa
10	16	Lilongwe, Malawi	36	En Nahud, Sudan
11	36	En Nahud, Sudan	14	Lubango, Angola
12	34	Ngaoundere, Cameroon	38	Imaginary1, Somalia

Full technical details of this analysis are available as a scientific manuscript under preparation for submission to a peer-reviewed journal (Nickless et al., in prep)[8].

4. Conclusion

To have an observation system for the observation of greenhouse gases over the African continent in order to reduce uncertainty of GHG emissions is a next step in worldwide initiatives to mitigate and adapt to climate change. The budget for different components of the system have been estimated, considering domain specific needs for an infrastructure that would reduce uncertainty in observational data. The components of the RI will need to be distributed over the continent, ideally in the locations that would reduce uncertainty the most. An issue of sustainability remains key to the establishment of such a system, hence the 30-year timeframe consideration of all cost estimates as well as a conclusive regard of a data component to the infrastructure in a separate deliverable. Strategic coordination will be key given the distributed nature of such a system, through the lifetime of the infrastructure. This ideally should be done through roadmapping and funding solicitation for the different research and innovation agendas, through setting knowledge frameworks by which results are communicated as knowledge to societal players, and finally through monitoring and evaluation for system improvement. The next development phase after the SEACRIFOG project will involve setting up and building the technical infrastructure in order to start operation.

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List of abbreviations

APAR	Absorbed photosynthetically-active radiation
BNF	Biological Nitrogen Fixation
CCAM	Conformal-Cubic Atmospheric Model
CLIVAR	Climate and Ocean - Variability, Predictability and Change
CMIP	Coupled Model Intercomparison Project
CSIR	Council for Scientific and Industrial Research
DEM	Digital Elevation Model
DMS	Dimethyl Sulfide
EBV	Essential Biodiversity Variable
EC	Eddy Covariance
ECV	Essential Climate Variable
EOV	Essential Ocean Variable
FAPAR	(Fraction of Absorbed) Photosynthetically Active Radiation
FRE	Fire Radiative Energy
FTE	Full-time Equivalent
FTIR	Fourier-Transform Infrared Spectroscopy
GAW	Global Atmosphere Watch
GCM	General Circulation Model
GCOS	Global Climate Observing System
GEOBON	Group on Earth Observations Biodiversity Observation Network
GHG	Greenhouse Gas
GPP	Gross Primary Production
ICOS	Integrated Carbon Observation System
IOC	Intergovernmental Oceanographic Commission
IPCC	Intergovernmental Panel on Climate Change
IRGA	Infrared Gas Analyzer
LAI	Leaf Area Index
LC	Land Cover
LCCS	Land Cover Classification Scheme
LULUCF	Land Use, Land Use Change and Forestry
LW	Longwave

MISR	Multi-angular Imaging Spectral Radiometer
NEE	Net Ecosystem Exchange
NIR	Near Infrared
NMVOC	Non-Methane Volatile Organic Carbons
NPP	Net Primary Production
PET	Potential Evapotranspiration
Ppb	parts per billion
ppt	parts per trillion
Re	Ecosystem respiration
RH	Relative Humidity
SASSCAL	Southern African Science Service Centre for Climate Change and Adaptive Land Management
SEACRIFOG	Supporting EU-African Cooperation on Research Infrastructures for Food Security and GHG Observations
SLA	Specific Leaf Area
SOC	Soil Organic Carbon
SST	Sea Surface Temperature
SW	Shortwave
TCCON	Total Carbon Column Observing Network
ToA	Top of Atmosphere
ToC	Top of Canopy
UNFCCC	United Nations Framework Convention on Climate Change
WHC	Water Holding Capacity
WP	Work Package