June 21, 2024

Systematic Observations Financing Facility

GBON National Gap Analysis

Democratic Republic of Congo

Systematic Observations Financing Facility

Weather and climate data for resilience

WEATHER CLIMATE WATER

Systematic Observations Financing Facility

Screening of the National Gap Analysis (NGA) of the Democratic Republic of Congo

WMO Technical Authority screens the GBON National Gap Analysis to ensure consistency with the GBON regulations and provides feedback for revisions as needed. *The screening of the NGA is conducted according to the SOFF Operational Guidance Handbook, version: 04.07.2023 and the provisions in Decision 5.7 of the SOFF Steering Committee.*

Following iterations with peer advisor and beneficiary country, WMO Technical Authority confirms that the National Gap Analysis is consistent with GBON regulations. While the WMO GBON Global Gap Analysis identified the need for 59 surface stations and 10 upper air station over land to meet the GBON horizontal requirement, the **WMO Technical Authority confirms the NGA results which indicate the need for 68 surface land stations and 12 upper station based on specific national circumstances.**

Date: 18 November 2024

Signature:

Albert Fischer

Director, WIGOS Branch, Infrastructure Department, WMO

GBON National Gap Analysis
Democratic Republic of Congo

ISO 3166-1 Alpha-3: COD

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Disclaimer

All information in this document is valid as of June 21, 2024, unless otherwise specified. In particular, statements related to the information content of OSCAR/Surface are prone to become obsolete as updates/corrections are implemented.

Several regions of the Democratic Republic of Congo, namely the ones in the East (North-Kivu and Ituri), are subject to severe security threats and active, long-lasting armed conflicts. The GBON target and associated station list discussed in this report should therefore be considered a long-term goal. The deployment/exploitation of any given GBON station is subject to METTELSAT and its personnel gaining stable, safe, long-term access to the station site.

This file was compiled using the 2024/10/22 - v1.0 soffreport LaTeX class.

1 Country information from the baseline GBON Global Gap Analysis

The country-specific results of the WMO baseline global GBON gap analysis for the Democratic Republic of Congo, assembled in June 2023 as part of the SOFF "first batch" evaluations and communicated to MeteoSwiss by the SOFF Secretariat on January 4, 2024, is presented in Table 1.

Table 1: GBON Global Gap Analysis for the Democratic Republic of Congo.

GBON Requirements	Target	Reporting to req.	Gap to improve	Gap new	Gap total
Surface land stations Horizontal res.: 200 km	59	0	35	24	59
Upper-air stations on land Horizontal res.: 500 km	10	0	0	10	10

2 Analysis of existing GBON stations and their status against GBON requirements

As of January 2024, 59 COD stations were formally assigned to GBON in OSCAR/Surface. The information associated to these entries should however be treated with caution, as a non-negligible part of it is outdated and/or erroneous. Two types of problems affect the reliability of the data. On the one hand, several sets of coordinates have a wrong latitude sign. This also seems to have caused one station (KASONGO) to be registered twice, with two homonymous sites located symmetrically above and below the equator (WIGOS-IDs 0-180-0-64264 vs 0-20000-64264). Station coordinates in general are specified with an accuracy of $\sim$10 km on OSCAR/Surface, which hinders the ability to understand the immediate surrounding of stations from satellite images. On the other hand, and perhaps more importantly, 27 of these stations are formally no longer in activity[1] according to the following definition:

Definition 1. A station is deemed to be **in activity** if it is visited on a very regular basis by METTELSAT personnel as part of their operational duties.

For these 27 stations, the status of the equipment on the ground, the continued meteorological suitability of the station site, and limitations in terms of physical access are all uncertain (METTELSAT, 2023).

As of March 2024, METTELSAT reported that 33 COD stations were in activity throughout the country (see Fig. 1 and Tables 2 & 3). Among these, 32 are assigned to GBON on OSCAR/Surface[2]. The 33 stations in activity all host manual systems that are used for assembling synoptic reports. Automatic weather stations from (at least) two different manufacturers have been deployed on (at least) 20 of these stations in recent years, as part of several development programs and collaborations (including CREWS). Out of these 20 automatic weather stations, at least 6 are no longer operational as of November 7, 2024.

The only COD GBON data to reach the GTS and contribute to the station statistics reported on WDQMS are acquired using the manual systems. Over the month of December 2023, the WDQMS indicates partial data availability of less than 30% for 15 stations[3] (see Table 3). No data was received from any other GBON station over that month, which is representative of the state of the network in 2023 as a whole.

Several organisations have deployed parallel networks of meteorological stations in the Democratic Republic of Congo over the years. These organizations include, for example, the National Agronomical Research Institute (INERA - *Institut*

[1]COD stations that are assigned to GBON on OSCAR/Surface but no longer in activity as of November 7, 2024 are: BAFWASENDE 0-20000-0-64056, BASANKUSU 0-20000-0-64008, BASOKO 0-20000-0-64018, BONDO 0-20000-0-64021, BUMBA 0-20000-0-64016, DILOLO 0-20000-0-64301, KABINDA 0-180-0-64005, KAHEMBA 0-180-0-64223, KALIMA 0-20000-0-64156, KAMINABASE 0-20000-0-64315, KASONGO 0-20000-0-64264, KASONGO 0-180-0-64264, KENGE 0-20000-0-64217, KITONA 0-20000-0-64203, LIBENGE 0-20000-0-64015, LUOZI 0-20000-0-64209, LUPUTA 0-20000-0-64248, LUSAMBO 0-20000-0-64246, MAMBASA 0-20000-0-64071, MITWABA 0-20000-0-64348, RUTSHURU 0-20000-0-64157, SANDOA 0-20000-0-64303, SHABUNDA 0-180-0-64165, UBUNDU 0-20000-0-64159, WALIKALE 0-20000-0-64170, WAMBA 0-180-0-64068, and WATSA 0-20000-0-64074

[2]The station of Beni in Nord-Kivu is the only METTELSAT operational station that had not yet been associated to GBON in OSCAR/Surface as of November 7, 2024. This station was set up as part of the so-called "Hydromet" project (World Bank, 2023).

[3]13 stations transmit pressure measurements; 14 stations transmit temperature and relative humidity measurements; 15 stations transmit wind measurements

National pour l'Étude et la Recherche Agronomiques), and the MONUSCO[4]. None of these networks are sharing data internationally, and in fact never were intended to do so. They serve very specific purposes for the organizations that set them up, that are under no obligation to abide by GBON regulations (be it in terms of data quality or availability). These organizations will all strongly benefit from the outcome of SOFF investments in improving the METTELSAT network of meteorological stations. However, these alternate networks (whose current states are very comparable to the METTELSAT network, if not worse) cannot be taken into consideration when assessing the GBON compliance of the Democratic Republic of Congo at a national level.

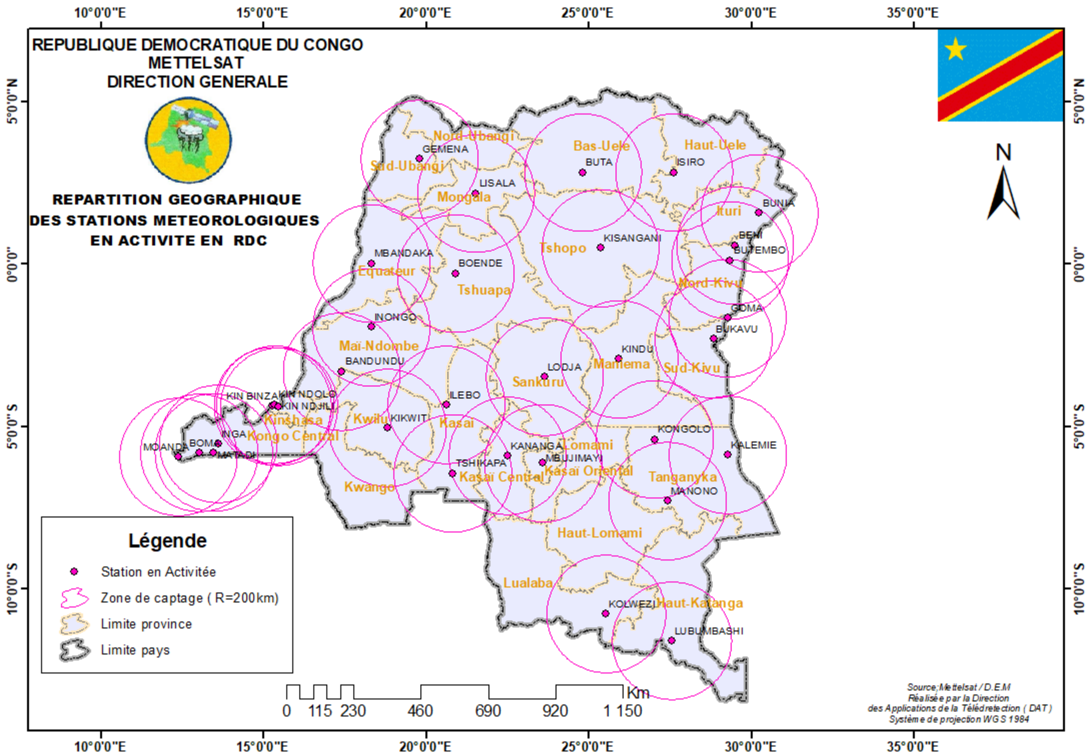

Figure 1: Map of the 33 METTELSAT surface (land) stations in activity (according to Definition 1) as of March 2024. Source: METTELSAT

[4]United Nations Organization Stabilization Mission in the Democratic Republic of the Congo
→ `https://peacekeeping.un.org/en/mission/monusco`

Table 2: Assessment of COD stations in activity per their operational status and network ownership. This list includes all the stations reported to be in activity (according to Definition 1) by METTELSAT as of November 7, 2024. It is not to be confused with the list of stations assigned to GBON on OSCAR/Surface.

GBON Requirements	Observation stations in activity (# of stations)			
	NMHS network		Third party network	
	Reporting to req.	To improve	Reporting to req.	To improve
Surface land stations Horizontal res.: 200 km Variables: SLP, T, H, W, P, SD	0	33	0	0
Upper-air stations on land Horizontal res.: 500 km Vertical res.: 100 m, $\geq$30 hPa Variables: T, H, W	0	0	0	0
Surface marine stations in EEZs Horizontal res.: 500 km Variables: SLP, SST	0	0	0	0
Upper-air stations in EEZs Horizontal res.: 1000 km Variables: T, H, W	0	0	0	0

Table 3: Assessment of characteristics for stations currently in activity. The reporting cycle is measured using WDQMS for the wind variables, and accounts for data transmission issues towards the GTS. These values are taken for weekdays, as the amount of observations drops on weekends. Various technical issues prevent COD automated weather stations from contributing data to the GTS.

Station name	Type	Owner	Funding source	GBON variable measured							Reporting cycle [obs/day]	GBON compliant ?
				SLP	T	H	W	P	SD	SST		
BANDUNDU	surface	METTELSAT	METTELSAT	×	×	×	×	×			0	No
BENI	surface	METTELSAT	METTELSAT	×	×	×	×	×			0	No
BOENDE	surface	METTELSAT	METTELSAT	×	×	×	×	×			∼4	No
BOMA	surface	METTELSAT	METTELSAT	×	×	×	×	×			∼2	No
BUKAVU	surface	METTELSAT	METTELSAT	×	×	×	×	×			0	No
BUNIA	surface	METTELSAT	METTELSAT	×	×	×	×	×			0	No
BUTA	surface	METTELSAT	METTELSAT	×	×	×	×	×			∼2	No
BUTEMBO	surface	METTELSAT	METTELSAT	×	×	×	×	×			0	No
GEMENA	surface	METTELSAT	METTELSAT	×	×	×	×	×			∼1	No
GOMA	surface	METTELSAT	METTELSAT	×	×	×	×	×			∼2	No
ILEBO	surface	METTELSAT	METTELSAT	×	×	×	×	×			∼2	No
INGA	surface	METTELSAT	METTELSAT	×	×	×	×	×			0	No
INONGO	surface	METTELSAT	METTELSAT	×	×	×	×	×			0	No
ISIRO	surface	METTELSAT	METTELSAT	×	×	×	×	×			0	No
KALEMIE	surface	METTELSAT	METTELSAT	×	×	×	×	×			∼2	No
KANANGA	surface	METTELSAT	METTELSAT	×	×	×	×	×			∼1	No
KIKWIT	surface	METTELSAT	METTELSAT	×	×	×	×	×			∼2	No
KINDU	surface	METTELSAT	METTELSAT	×	×	×	×	×			0	No
KINSHASA/BINZA	surface	METTELSAT	METTELSAT	×	×	×	×	×			∼3	No
KINSHASA/N'DJILI	surface	METTELSAT	METTELSAT	×	×	×	×	×			∼5	No
KINSHASA/N'DOLO	surface	METTELSAT	METTELSAT	×	×	×	×	×			∼1	No
KISANGANI	surface	METTELSAT	METTELSAT	×	×	×	×	×			∼2	No
KOLWEZI	surface	METTELSAT	METTELSAT	×	×	×	×	×			0	No
KONGOLO	surface	METTELSAT	METTELSAT	×	×	×	×	×			0	No
LISALA	surface	METTELSAT	METTELSAT	×	×	×	×	×			0	No
LODJA	surface	METTELSAT	METTELSAT	×	×	×	×	×			0	No
LUBUMBASHI	surface	METTELSAT	METTELSAT	×	×	×	×	×			∼1	No
MANONO	surface	METTELSAT	METTELSAT	×	×	×	×	×			0	No
MATADI	surface	METTELSAT	METTELSAT	×	×	×	×	×			0	No
MBANDAKA	surface	METTELSAT	METTELSAT	×	×	×	×	×			0	No
MBUJI-MAYI	surface	METTELSAT	METTELSAT	×	×	×	×	×			∼3	No
MOANDA	surface	METTELSAT	METTELSAT	×	×	×	×	×			0	No
TSHIKAPA	surface	METTELSAT	METTELSAT	×	×	×	×	×			0	No

3 Results of the GBON National Gap Analysis

We summarize in Table 4 the outcome of the GBON National Gap Analysis for the Democratic Republic of Congo. Each category will be discussed separately in Secs. 3.1 to 3.4. Given their geographical distribution, 5 (out of 33) stations that are in activity today are not recommended to be considered for GBON.

Table 4: Results of the GBON National Gap Analysis

GBON Requirements	Global GBON target	Approved national target	Reporting	Gap	
				To improve	New
Surface land stations Horizontal res.: 200 km Variables: SLP, T, H, W, P, SD Observing cycle: 1/1 h	59	68	0	28	40
Upper-air stations on land Horizontal res.: 500 km Vertical res.: 100 m, $\geq$30 hPa Variables: T, H, W Observing cycle: 2/24 h	10	12	0	0	12
Surface marine stations in EEZs Horizontal res.: 500 km Variables: SLP, SST Observing cycle: 1/1 h	1	1	0	0	1
Upper-air stations in EEZs Horizontal res.: 1000 km Variables: T, H, W Observing cycle: 2/24 h	0	0	0	0	0

3.1 Surface stations (land)

We present in Fig. 2 a network map of 68 COD surface (land) station sites that we find are sufficient to achieve GBON compliance at the country level (see Table 6 for details). Station sites are primarily selected from a list of 128 historical sites for meteorological observations in the Democratic Republic of Congo (see Appendix B for details), with the following exception:

- Yangambi, the inclusion of which is warranted on the basis of the strong synergy potential with the research activities of the National Agronomical Research Institute (INERA - *Institut National pour l'Étude et la Recherche Agronomique*) at that location (see e.g. Sibret et al., 2022; Kasongo Yakusu et al., 2023).

When selecting sites, preference is given to locations that are either in activity today, or are considered by METTELSAT to be best suited for rehabilitation (as of November 2023, based on site access, security and long-term viability; METTELSAT, 2023), with one exception:

- Monkoto, a very remote site where the headquarters of the Salonga National Park are located. Salonga National Park is a UNESCO World Heritage site, and the largest tropical rainforest reserve in Africa: a status which would very much warrant the inclusion of this area within the GBON network, given its importance for climate on a global scale.

The 20 sites hosting automated weather stations installed recently (be they still operational or not) are selected in priority. Additional sites are chosen to 1) decrease the network horizontal resolution ρ below the GBON threshold of 200 km (see Appendix A.2), and 2) maximize the network baseline influence area $A^*_{\rm inf}$ (see Definition 3 in Appendix A.1). The local population density, topography, and lightning frequency are also used to guide the selection of sites of interest for the GBON network (see Appendix C for the corresponding maps).

With a mean distance between (neighboring) stations $\rho = 213.1$ km (see Appendix A.2 for details), a 59-sites network (which corresponds to the baseline GBON target estimate, see Sec. 1) does not meet the GBON low-density horizontal resolution requirement of 200 km. One should note that this measurement does account for existing and proposed GBON sites in neighboring countries, including South Sudan, Uganda, Rwanda, Tanzania, and Zambia which are all SOFF beneficiary countries, as well as Angola, the Republic of Congo, and the Central African Republic. The addition of 9 stations (for a total of 68 surface stations) is sufficient to bring the network horizontal resolution down to $\rho = 199.2$ km.

We list in Table 5 these additional stations in the order they are added to the network, alongside the scientific motivation for their inclusion.

Table 5: List of 9 surface (land) stations required for COD to meet the low-density GBON requirements, in addition to the baseline set of 59 stations chosen to maximize the network baseline area of influence. Stations were chosen and added sequentially until the network horizontal resolution ρ decreased below 200 km.

Station name	Justification
LUPUTA	high population density
OPIENGE	complex topography, baseline area of influence
LUBAO	baseline area of influence
PANGA	baseline area of influence
FESHI	baseline area of influence
MONKOTO	baseline area of influence
KWAMOUTH	baseline area of influence, fluvial navigation
LUKOLEA	baseline area of influence, fluvial navigation
MUTSHATSHA	baseline area of influence

3.2 Upper-air stations (land)

A total of 7 sites used to host upper-air (land) stations (see Table 7 in Appendix B for details), but none remain in activity today. We present in Fig. 3 a network map of 12 upper-air (land) stations sufficient to meet the GBON horizontal resolution of $\rho_{\rm GBON} = 500$ km. Specifically, given the disposition of the country and the existing/planned GBON upper-air (land) stations in its immediate vicinity, we find that an additional 2 stations in addition to the baseline estimate (for a total of 12 stations) are sufficient to meet the low-density GBON requirements.

3.3 Surface stations (marine)

The size of the COD Exclusive Economic Zone (EEZ) in the South Atlantic Ocean could eventually warrant the installation of 1 GBON surface (marine) station for compliance purposes. There is, however, a strong potential for international synergies given the thickness of the EEZ (~35 km). GBON compliance over the COD EEZ area could certainly be achieved by means of surface (marine) stations located in neighboring EEZs.

3.4 Upper-air stations (marine)

The size of the COD EEZ does not warrant the existence of an upper-air marine station for GBON compliance purposes.

3.5 Recommended surface, upper-air and marine stations to be designated to GBON

We present in Table 6 the list of stations recommended to become operational before being designated to GBON, in order for the Democratic Republic of Congo to meet the low-density GBON requirements. **We note that several of these stations are located in regions subject to severe security threats and active armed conflicts. This list should therefore be considered a long-term goal, with the actual deployment of a given station requiring that METTELSAT and its personnel gain stable, safe, long-term access to the station site.** This list is assembled based on the data available at the time of writing. The need to alter the suggestion of a specific site (in favor of a neighboring one) may arise over time, as the local geo-political, security, economical, and connectivity situation evolves.

Table 6: Recommended surface, upper-air and marine stations to become operational before being designated to GBON, in order for the Democratic Republic of Congo to meet the low-density GBON requirements. Station coordinates are approximate, with an accuracy of ~10 km for the sites that are no longer in activity today.

	Province	Station name	Type	Latitude	Longitude	In activity ?
1	KINSHASA	KINSHASA/N'DJILI	Surface/Upper-air	-4.3868	+15.4482	yes
2	KONGO CENTRAL	MATADI	Surface	-5.7945	+13.4403	yes
3	KWILU	BANDUNDU	Surface	-3.3089	+17.3752	yes

Table 6: continued.

	Province	Station name	Type	Latitude	Longitude	In activity ?
4	KWILU	KIKWIT	Surface/Upper-air	-5.0394	+18.7840	yes
5	KWANGO	KENGE	Surface	-4.8376	+17.0294	no
6	KWANGO	FESHI	Surface	-6.1170	+18.1330	no
7	KWANGO	KASONGOLUNDA	Surface	-6.4830	+16.8170	no
8	KWANGO	KAHEMBA	Surface	-7.3330	+19.0000	no
9	MAINDOMBE	INONGO	Surface	-1.9456	+18.2856	yes
10	MAINDOMBE	OSHWE	Surface	-3.4170	+19.7500	no
11	MAINDOMBE	KWAMOUTH	Surface	-3.1830	+16.2330	no
12	EQUATEUR	MBANDAKA	Surface/Upper-air	+0.0214	+18.2911	yes
13	EQUATEUR	BASANKUSU	Surface	+1.2247	+19.7907	no
14	EQUATEUR	LUKOLELA	Surface	-1.0500	+17.2000	no
15	MONGALA	LISALA	Surface/Upper-air	+2.1761	+21.5037	yes
16	MONGALA	BUMBA	Surface	+2.1830	+22.5500	no
17	TSHUAPA	MONKOTO	Surface	-1.7437	+20.6848	no
18	TSHUAPA	DJOLU	Surface	+0.5500	+22.4500	no
19	TSHUAPA	BOENDE	Surface	-0.2865	+20.8796	yes
20	TSHUAPA	BOKUNGU	Surface	-0.6000	+22.3330	no
21	NORD UBANGI	GBADOLITE	Surface	+4.3000	+21.2000	no
22	SUD UBANGI	GEMENA	Surface	+3.2373	+19.7697	yes
23	BAS-UELE	BONDO	Surface	+3.8000	+23.0820	no
24	BAS-UELE	ANGO	Surface	+4.0170	+25.8670	no
25	BAS-UELE	BUTA	Surface/Upper-air	+2.8217	+24.7965	yes
26	HAUT-UELE	ISIRO	Surface	+2.8226	+27.5982	yes
27	HAUT-UELE	WATSA	Surface	+3.0670	+29.5000	no
28	TSHOPO	KISANGANI	Surface/Upper-air	+0.4904	+25.3327	yes
29	TSHOPO	YANGAMBI	Surface	+0.8198	+24.4562	no
30	TSHOPO	BAFWASENDE	Surface	+1.0830	+27.0130	no
31	TSHOPO	OPALA	Surface	-0.5830	+24.3500	no
32	TSHOPO	OPIENGE	Surface	+0.1670	+27.5000	no
33	TSHOPO	PANGA	Surface	+1.8330	+26.4170	no
34	ITURI	BUNIA	Surface/Upper-air	+1.5686	+30.2210	yes
35	NORD-KIVU	GOMA	Surface	-1.6604	+29.2395	yes
36	NORD-KIVU	BUTEMBO	Surface	+0.1157	+29.3135	yes
37	NORD-KIVU	BENI	Surface	+0.5758	+29.4713	yes
38	NORD-KIVU	WALIKALE	Surface	-1.4170	+28.0330	no
39	SUD-KIVU	BUKAVU	Surface/Upper-air	-2.3119	+28.8089	yes
40	SUD-KIVU	SHABUNDA	Surface	-2.6830	+27.3800	no
41	SUD-KIVU	FIZI	Surface	-4.3000	+28.9500	no
42	MANIEMA	KINDU	Surface	-2.9271	+25.9140	yes
43	MANIEMA	LUBUTU	Surface	-0.7500	+26.5670	no
44	MANIEMA	KIBOMBO	Surface	-3.9170	+25.9330	no
45	MANIEMA	LUBAO	Surface	-5.3000	+25.7500	no
46	SANKURU	LODJA	Surface	-3.4660	+23.6180	yes
47	SANKURU	LOMELA	Surface	-2.3000	+23.2830	no
48	SANKURU	LUSAMBO	Surface	-4.9649	+23.3825	no

Table 6: continued.

	Province	Station name	Type	Latitude	Longitude	In activity ?
49	KASAI CENTRAL	KANANGA	Surface/Upper-air	-5.8990	+22.4778	yes
50	KASAI	TSHIKAPA	Surface	-6.4394	+20.7930	yes
51	KASAI	DEKESE	Surface	-3.4670	+21.4170	no
52	KASAI	ILEBO	Surface	-4.3287	+20.5919	yes
53	KASAI ORIENTAL	MBUJI-MAYI	Surface	-6.1245	+23.5711	yes
54	LOMAMI	LUPUTA	Surface	-7.1330	+23.7330	no
55	HAUT LOMAMI	KABONGO	Surface	-7.3330	+25.5830	no
56	HAUT LOMAMI	KAMINAVILLE	Surface	-8.7330	+25.0000	no
57	TANGANIKA	KALEMIE	Surface	-5.8721	+29.2481	yes
58	TANGANIKA	KONGOLO	Surface	-5.3948	+26.9978	yes
59	TANGANIKA	MANONO	Surface/Upper-air	-7.2901	+27.3951	yes
60	TANGANIKA	MOBA	Surface	-7.0500	+29.7120	no
61	LUALABA	KOLWEZI	Surface	-10.7653	+25.5092	yes
62	LUALABA	KAPANGA	Surface/Upper-air	-8.3500	+22.6500	no
63	LUALABA	MUTSHATSHA	Surface	-10.8170	+24.4640	no
64	LUALABA	SANDOA	Surface	-9.6330	+22.8500	no
65	LUALABA	DILOLO	Surface	-10.6830	+22.3330	no
66	HAUT KATANGA	LUBUMBASHI	Surface/Upper-air	-11.5894	+27.5298	yes
67	HAUT KATANGA	KASENGA	Surface	-10.3830	+28.6170	no
68	HAUT KATANGA	MITWABA	Surface	-8.6000	+27.3330	no

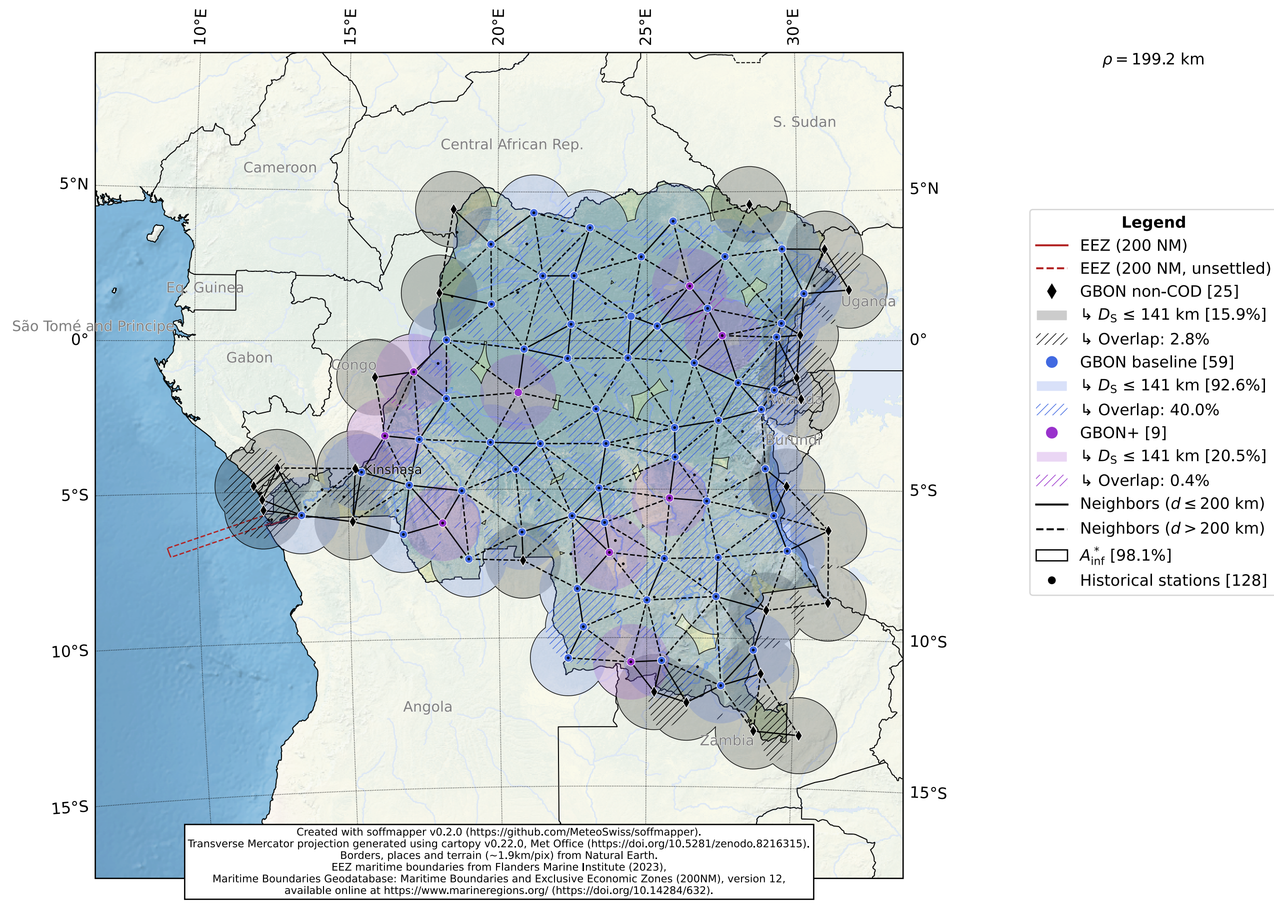

Figure 2: Network of 68 surface (land) stations (blue and purple discs) sufficient for the Democratic Republic of Congo to meet the low-density GBON horizontal resolution requirement. The corresponding network horizontal resolution is $\rho = 199.2$ km. This measurement accounts for existing/proposed GBON stations in neighboring countries (black diamonds). Purple discs mark the 9 stations added on top of the baseline 59 sites (blue discs) to have $\rho < \rho_{\text{GBON}} = 200$ km. Neighboring stations (as defined in Appendix A.2) are connected by straight black lines (continuous, if the stations are closer than 200 km from one another, dashed otherwise). A disk with a radius $R^*_{\text{inf}} = 141$ km (see Appendix A.1) is drawn around each station. The resulting network baseline area of influence is $A^*_{\text{inf}} = 98.1\%$ of the country area.

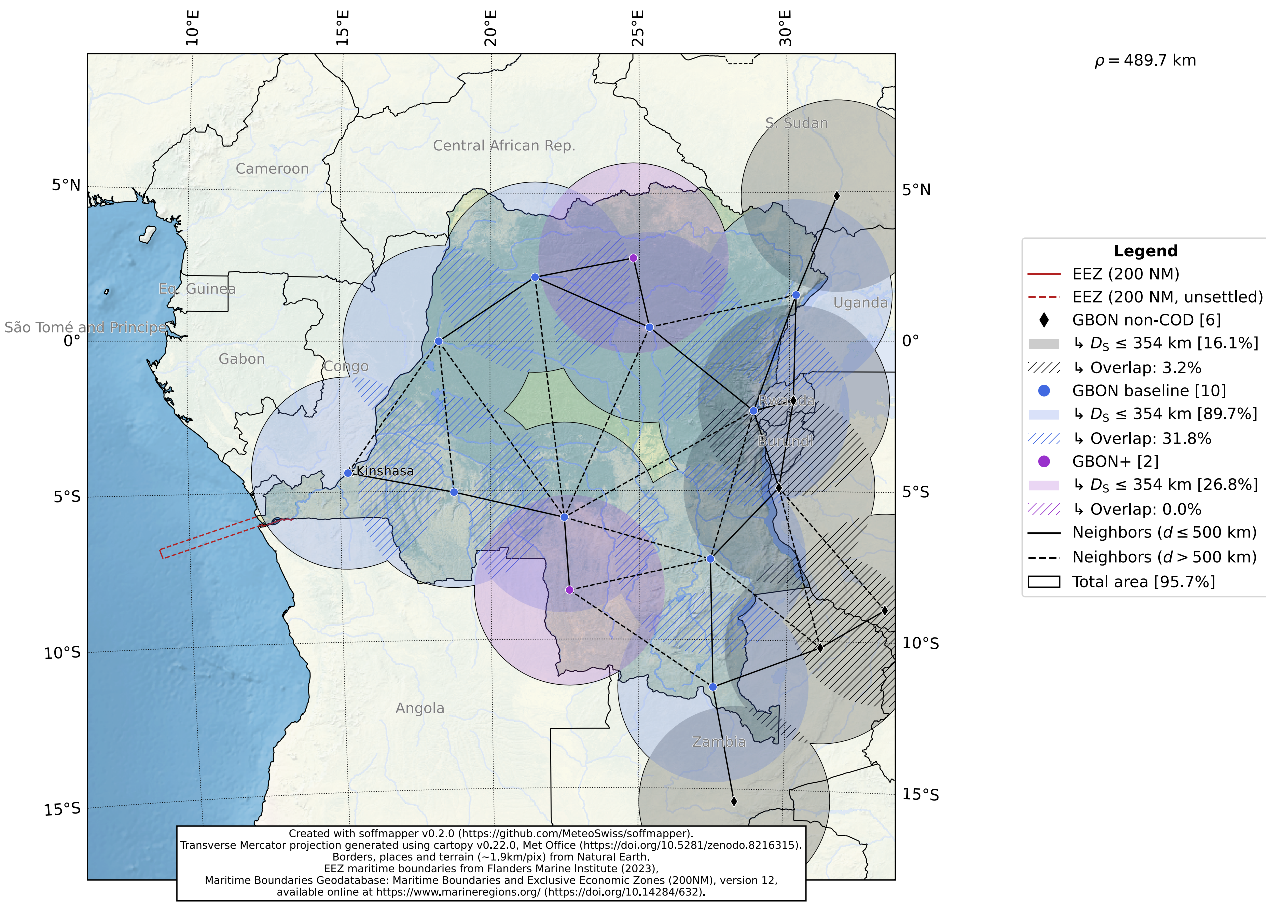

Figure 3: Same as Fig. 2, but for the 12 upper-air (land) stations (blue and purple discs) sufficient for the Democratic Republic of Congo to meet the low-density GBON horizontal resolution requirement. The corresponding network horizontal resolution is $\rho = 489.7\,\text{km}$, with a baseline area of influence of $A^*_{\text{inf}} = 95.7\%$ derived using a station radius of influence of $R^*_{\text{inf}} = 354\,\text{km}$ (see Appendix A.1).

4 Report completion signatures

Peer Advisor signature
Beneficiary Country signature
WMO Technical Authority screening signature

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4 Report completion signatures

Peer Advisor signature Payerne, Switzerland, 24 June 2024
Beneficiary Country signature Prs/RDC Directeur Général de METTELSAT. 24 Juin 2024.
WMO Technical Authority screening signature

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Appendix A Assessment metrics for national networks of GBON stations

A.1 Network baseline area of influence A^*_{inf}

Let us begin by introducing the concept of a radius of influence for GBON stations:

Definition 2. The **radius of influence** R_{inf} of a given GBON station corresponds to the maximum horizontal distance between the station and any geographical location situated closer to this station than any other GBON station.

As per this definition, the radius of influence of a given GBON station is solely determined by the spatial distribution of the network stations. It evidently does not mean that the measurements of a given GBON station will be *representative* of all the locations situated up to the radius of influence. The representativity of specific measurements is dependant on the geophysical variable under consideration, and can be heavily influenced by numerous variables: for example, by the local terrain composition and topography.

We shall refer to ρ_{GBON} as the *GBON horizontal resolution*, as defined in WMO (2021) (article 3.2.2.7, note 4, p.52; see also WMO, 2023). As per these regulations, GBON-designated stations should not be located more than ρ_{GBON} apart, on average.

A so-called *baseline* GBON gap analysis has been performed by the WMO for all SOFF beneficiary countries (see Sec. 1). This analysis relies on the assumption that GBON stations are being distributed on a regular, orthogonal, two-dimensional grid[5] (see Fig. 4). Under this specific premise, all stations have the same **baseline radius of influence** of:

$$R^*_{\mathrm{inf}} = \frac{\sqrt{2}}{2}\rho_{\mathrm{GBON}} \qquad (1)$$

The standard GBON horizontal resolutions of 200 km and 500 km (for surface and upper-air stations on land, respectively) translate into baseline radii of influence of $R^*_{\mathrm{inf},200} \approx 141$ km and $R^*_{\mathrm{inf},500} \approx 354$ km.

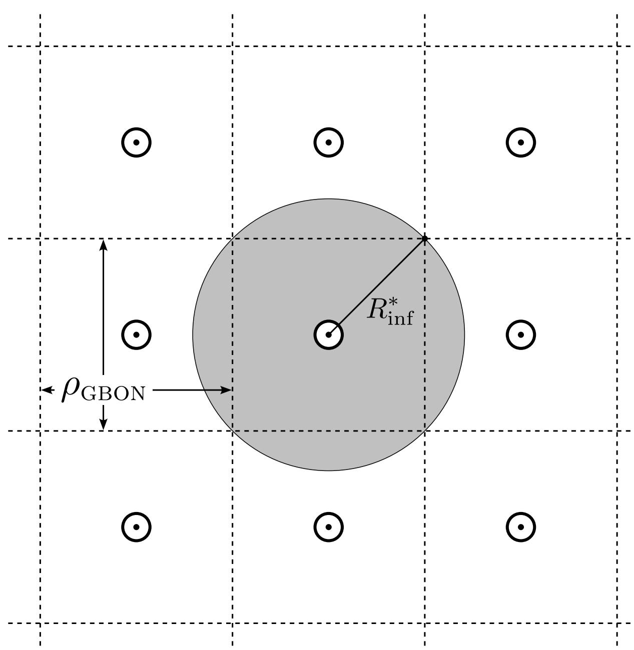

Figure 4: Schematic network of GBON stations (dot-circled symbols) distributed on a regular, orthogonal, two-dimensional grid. This theoretical setup is used to derive baseline GBON gaps by the WMO. Each grid cell has a size of $\rho_{\mathrm{GBON}} \times \rho_{\mathrm{GBON}}$. With this distribution of stations, any point in the plane is located at most R^*_{inf} away from any GBON station.

[5] The WMO Technical Authority confirmed, on 2024-01-08, that the baseline GBON gap is obtained by dividing the surface area of a given country by $(\rho_{\mathrm{GBON}} \times \rho_{\mathrm{GBON}})$.

In our analysis, we rely on this concept of baseline radius of influence R^*_{inf} to derive the network baseline area of influence:

Definition 3. The **baseline area of influence** A^*_{inf} of a network of GBON stations corresponds to all the zones situated within a distance of at most R^*_{inf} from any GBON station in the network.

We express A^*_{inf} as a percentage of the country surface area when considering national networks. Given Eq. 1, one can see that the WMO (indirectly) requires a value of $A^*_{\mathrm{inf}} = 100\,\%$ when performing a baseline GBON gap analysis.

This metric provides a useful indication of what surface area *might* be located too far from any GBON station in a given network. It must be stressed, however, that achieving $A^*_{\mathrm{inf}} = 100\,\%$ is not a formal GBON requirement per se. The meteorological importance of spatial gaps in the baseline surface coverage of a given GBON network must be evaluated against the actual measurement representativity of the nearest GBON stations (given the local population density, terrain topgraphy, regional climatology, etc . . .).

A.2 Network horizontal resolution ρ

The GBON compliance criteria are not defined in terms of the network baseline area of influence A^*_{inf}, but rather in terms of its horizontal resolution ρ:

Definition 4. The **horizontal resolution** ρ of a network of meteorological stations, in the GBON sense, is equal to the average separation between (neighbor) stations (WMO, 2021, 2023).

The main difficulty in measuring ρ for a real network of irregularly-distributed stations lies in the identification of *neighbors*. Fortunately, the Voronoï tessellation technique provides us with a natural, logical, and straightforward means to do so.

Performing a Voronoï tessellation of stations consists is subdividing the surface of the Earth into a series of cells. Each cell, one per station, contains all the locations situated closest to a given station than any other. We present in Fig. 5 an illustration of this method on the plane, but the same concept can be applied on the Earth geoid. The cell boundaries are comprised of sites located at the same distance from two near-by stations. Voronoï cells thus provide for a natural definition of stations in geometric proximity from one another:

Definition 5. Two meteorological stations within a given network are deemed to be **in geometric proximity** from one another if their respective Voronoï cells share a common vertex.

Pairs of stations in geometric proximity can be identified directly by means of a Delaunay triangulation, which corresponds to the dual graph of the Voronoï tessellation (see Fig. 5). Doing so directly on the Earth geoid is feasible, but one can also exploit the characteristics of Stereographic projections to transpose the problem in two-dimensions (see e.g. Saalfeld, 1999; Gallier, 2011), which is easier to handle from a computational perspective. The use of a Stereographic projection (to convert stations longitudes and latitudes) is paramount to ensure that the list of station pairs found to be in geometric proximity in the (projected) plane is exactly applicable to the Earth geoid.

The use of Delaunay triangulation in a geographically-limited area of the Earth (e.g. for a network of GBON stations at a national level) implies the assembly of a convex hull. Some stations might then be deemed to be in geometric proximity from one another (despite being located several hundreds of kilometers apart) on the basis that their Voronoï cells are in contact (sometimes literally) on the other side of the Earth. In practice, one would hardly consider such stations to be *neighbors*, which we define as follows instead:

Definition 6. Two meteorological stations are **neighbors** from one another if they are in geometric proximity from one another according to Definition 5 and:

1. no other station in the network is located closer than them to the mid-point location of the Great Circle arc connecting them, or
2. they are located within a polygon formed entirely by network stations that are neighbors from one another.

Thinking in terms of Voronoï tessellation, the first sub-clause implies that the Great Circle arc connecting two neighbor stations must only cross their own two Voronoï cells, and none other. The second sub-clause ensures that this selection criteria is only used to cull Delaunay vertices in the outer regions of the network (see Fig. 5).

Having identified pairs of neighbor stations throughout a given network, it is then straightforward to compile the list of associated horizontal separations (measured along Great Circles on the Earth), and compute the network horizontal resolution ρ as their average. A network of GBON stations would then be formally compliant with the GBON regulations if $\rho \leq \rho_{\mathrm{GBON}}$.

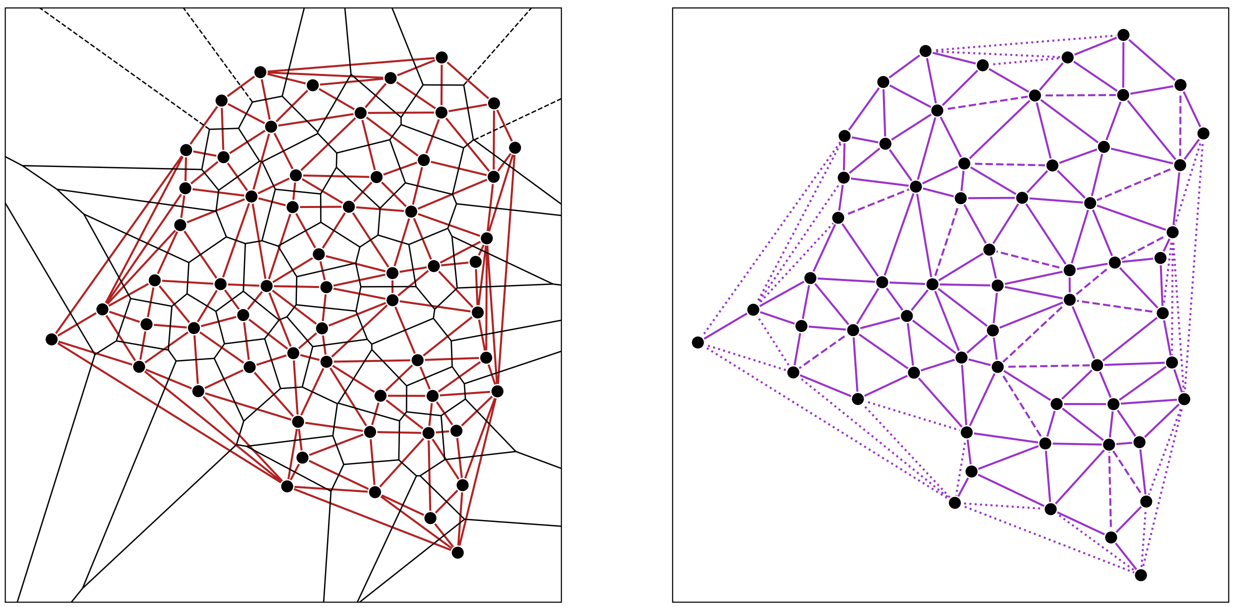

Figure 5: Left: illustration of the Voronoï tessellation (black lines) in the two-dimensional plane, for a network of 59 stations (black points). Voronoï cells provide for a natural means to identify sites in geometric proximity. All sites in geometric proximity from one another are connected by red lines, which are identified by means of Delaunay triangulation. Right: sites in geometric proximity but that are not *neighbors* according to Definition 6 are connected by dotted lines. All other connections indicate neighbor sites. Dashed connections indicate cases for which both sub-clauses 1 and 2 of Definition 6 are true.

Appendix B List of historical COD meteorological measurement sites

We present in Table 7 the list of historical meteorological measurement sites in the Democratic Republic of Congo, according to METTELSAT (2023).

Table 7: Historical COD meteorological stations and their status as of November 7, 2024. Station coordinates approximate, with an accuracy of ~10 km for the sites that are not in activity.

	Province	Station name	Type (historical)	Latitude	Longitude	In activity ?
1	KINSHASA	KINSHASA/N'DJILI	Surface	-4.3868	+15.4482	yes
2	KINSHASA	KINSHASA/N'DOLO	Surface	-4.3255	+15.3262	yes
3	KINSHASA	KINSHASA/BINZA	Surface/Upper-air	-4.3700	+15.2555	yes
4	KONGO CENTRAL	MATADI	Surface	-5.7945	+13.4403	yes
5	KONGO CENTRAL	MBANZANGUNGU	Surface	-5.2000	+14.8500	no
6	KONGO CENTRAL	INGA	Surface	-5.5285	+13.5770	yes
7	KONGO CENTRAL	KITONA	Surface	-5.9170	+12.4500	no
8	KONGO CENTRAL	BOMA	Surface	-5.8064	+12.9970	yes
9	KONGO CENTRAL	MOANDA	Surface	-5.9315	+12.3529	yes
10	KONGO CENTRAL	TSHELA	Surface	-4.9670	+12.9330	no
11	KONGO CENTRAL	LUOZI	Surface	-4.9500	+14.1330	no
12	KWILU	BANDUNDU	Surface	-3.3089	+17.3752	yes
13	KWILU	KIKWIT	Surface	-5.0394	+18.7840	yes
14	KWILU	GUNGU	Surface	-5.7500	+19.4830	no
15	KWANGO	KENGE	Surface	-4.8376	+17.0294	no
16	KWANGO	FESHI	Surface	-6.1170	+18.1330	no
17	KWANGO	KASONGOLUNDA	Surface	-6.4830	+16.8170	no
18	KWANGO	KAHEMBA	Surface	-7.3330	+19.0000	no
19	KWANGO	PANZI	Surface	-7.2670	+18.7500	no
20	KWANGO	POPOKABAKA	Surface	-5.6830	+16.6330	no
21	MAINDOMBE	INONGO	Surface	-1.9456	+18.2856	yes
22	MAINDOMBE	OSHWE	Surface	-3.4170	+19.7500	no
23	MAINDOMBE	KWAMOUTH	Surface	-3.1830	+16.2330	no
24	EQUATEUR	MBANDAKA	Surface/Upper-air	+0.0214	+18.2911	yes
25	EQUATEUR	BASANKUSU	Surface	+1.2247	+19.7907	no
26	EQUATEUR	BIKORO	Surface	-0.7670	+18.0120	no
27	EQUATEUR	LUKOLELA	Surface	-1.0500	+17.2000	no
28	EQUATEUR	BOMONGO	Surface	+1.4830	+18.4830	no
29	MONGALA	LISALA	Surface	+2.1761	+21.5037	yes
30	MONGALA	BUMBA	Surface	+2.1830	+22.5500	no
31	MONGALA	MONKOTO	Surface	+1.6170	+20.6670	no
32	TSHUAPA	DJOLU	Surface	+0.5500	+22.4500	no
33	TSHUAPA	BOENDE	Surface	-0.2865	+20.8796	yes
34	TSHUAPA	BOKUNGU	Surface	-0.6000	+22.3330	no
35	NORD UBANGI	GBADOLITE	Surface	+4.3000	+21.2000	no
36	NORD UBANGI	ABOUMOMBAZI	Surface	+3.6950	+22.1500	no
37	NORD UBANGI	BUSINGA	Surface	+3.2500	+20.9670	no
38	SUD UBANGI	LIBENGE	Surface	+3.6330	+18.6330	no
39	SUD UBANGI	GEMENA	Surface	+3.2373	+19.7697	yes
40	BAS-UELE	BONDO	Surface	+3.8000	+23.0820	no

Table 7: continued.

	Province	Station name	Type (historical)	Latitude	Longitude	In activity ?
41	BAS-UELE	AKETI	Surface	+2.7330	+23.8330	no
42	BAS-UELE	ANGO	Surface	+4.0170	+25.8670	no
43	BAS-UELE	TITULE	Surface	+3.2500	+25.5300	no
44	BAS-UELE	BUTA	Surface	+2.8217	+24.7965	yes
45	BAS-UELE	POKO	Surface	+3.1500	+26.8330	no
46	HAUT-UELE	NIANGARA	Surface	+3.7000	+27.9000	no
47	HAUT-UELE	DORUMA	Surface	+4.7170	+27.6910	no
48	HAUT-UELE	DUNGU	Surface	+3.6500	+28.5500	no
49	HAUT-UELE	ABA	Surface	+3.8600	+30.2550	no
50	HAUT-UELE	ISIRO	Surface	+2.8226	+27.5982	yes
51	HAUT-UELE	WAMBA	Surface	+2.1500	+28.0000	no
52	HAUT-UELE	WATSA	Surface	+3.0670	+29.5000	no
53	TSHOPO	KISANGANI	Surface/Upper-air	+0.4904	+25.3327	yes
54	TSHOPO	IKELA	Surface	-1.1670	+23.2670	no
55	TSHOPO	BASOKO	Surface	+1.2500	+23.6000	no
56	TSHOPO	BANALIA	Surface	+1.5330	+25.0330	no
57	TSHOPO	ISANGI	Surface	+0.7500	+24.7500	no
58	TSHOPO	BAFWASENDE	Surface	+1.0830	+27.0130	no
59	TSHOPO	LOWA	Surface	-1.3670	+25.8170	no
60	TSHOPO	OPALA	Surface	-0.5830	+24.3500	no
61	TSHOPO	UBUNDU	Surface	-0.3500	+25.4500	no
62	TSHOPO	OPIENGE	Surface	+0.1670	+27.5000	no
63	TSHOPO	PANGA	Surface	+1.8330	+26.4170	no
64	ITURI	BUNIA	Surface/Upper-air	+1.5686	+30.2210	yes
65	ITURI	MAMBASA	Surface	+1.3670	+29.0670	no
66	ITURI	DJUGU	Surface	+1.8330	+30.5670	no
67	ITURI	MAHAGI	Surface	+2.3000	+30.9830	no
68	ITURI	ARU	Surface	+2.8670	+30.8330	no
69	ITURI	ALAMBI	Surface	+2.8670	+30.8330	no
70	NORD-KIVU	GOMA	Surface	-1.6604	+29.2395	yes
71	NORD-KIVU	RUTSHURU	Surface	-1.1830	+29.4500	no
72	NORD-KIVU	BUTEMBO	Surface	+0.1157	+29.3135	yes
73	NORD-KIVU	MUTWANGA	Surface	-0.3330	+29.7330	no
74	NORD-KIVU	BENI	Surface	+0.5758	+29.4713	yes
75	NORD-KIVU	WALIKALE	Surface	-1.4170	+28.0330	no
76	SUD-KIVU	BUKAVU	Surface/Upper-air	-2.3119	+28.8089	yes
77	SUD-KIVU	SHABUNDA	Surface	-2.6830	+27.3800	no
78	SUD-KIVU	KAMITUGA	Surface	-3.0500	+28.1830	no
79	SUD-KIVU	KALOLE	Surface	-3.6330	+27.3330	no
80	SUD-KIVU	FIZI	Surface	-4.3000	+28.9500	no
81	MANIEMA	KINDU	Surface	-2.9271	+25.9140	yes
82	MANIEMA	LUBUTU	Surface	-0.7500	+26.5670	no
83	MANIEMA	PUNIA	Surface	-1.4500	+26.4000	no
84	MANIEMA	KALIMA	Surface	-2.6000	+26.5500	no
85	MANIEMA	KIBOMBO	Surface	-3.9170	+25.9330	no

Table 7: continued.

	Province	Station name	Type (historical)	Latitude	Longitude	In activity ?
86	MANIEMA	KABAMBARE	Surface	-4.6830	+27.6500	no
87	MANIEMA	KASONGO	Surface	-4.5170	+26.5830	no
88	MANIEMA	LUBAO	Surface	-5.3000	+25.7500	no
89	SANKURU	LODJA	Surface	-3.4660	+23.6180	yes
90	SANKURU	LOMELA	Surface	-2.3000	+23.2830	no
91	SANKURU	LUSAMBO	Surface	-4.9649	+23.3825	no
92	SANKURU	KATAKOKOMBE	Surface	-3.4500	+24.3500	no
93	SANKURU	LUBEFU	Surface	-4.7170	+24.4330	no
94	KASAI CENTRAL	KANANGA	Surface/Upper-air	-5.8990	+22.4778	yes
95	KASAI CENTRAL	LUIZA	Surface	-7.1830	+22.4330	no
96	KASAI	TSHIKAPA	Surface	-6.4394	+20.7930	yes
97	KASAI	LWEBO	Surface	-5.3670	+21.3670	no
98	KASAI	DEKESE	Surface	-3.4670	+21.4170	no
99	KASAI	ILEBO	Surface	-4.3287	+20.5919	yes
100	KASAI ORIENTAL	MBUJI-MAYI	Surface	-6.1245	+23.5711	yes
101	LOMAMI	KABINDA	Surface	-6.1330	+24.4330	no
102	LOMAMI	NGANDAJIKA	Surface	-6.7330	+23.9330	no
103	LOMAMI	LUPUTA	Surface	-7.1330	+23.7330	no
104	HAUT LOMAMI	BUKAMA	Surface	-9.1830	+25.8500	no
105	HAUT LOMAMI	KANIAMA	Surface	-7.5170	+24.2000	no
106	HAUT LOMAMI	KABONGO	Surface	-7.3330	+25.5830	no
107	HAUT LOMAMI	KAMINAVILLE	Surface	-8.7330	+25.0000	no
108	HAUT LOMAMI	KAMINABASE	Surface	-8.6330	+25.2500	no
109	HAUT LOMAMI	MALEMBANKULU	Surface	-8.0170	+26.7830	no
110	TANGANIKA	KALEMIE	Surface	-5.8721	+29.2481	yes
111	TANGANIKA	KONGOLO	Surface	-5.3948	+26.9978	yes
112	TANGANIKA	NYUNZU	Surface	-5.2500	+28.0000	no
113	TANGANIKA	MANONO	Surface	-7.2901	+27.3951	yes
114	TANGANIKA	MOBA	Surface	-7.0500	+29.7120	no
115	TANGANIKA	KABALO	Surface	-6.0330	+26.8670	no
116	LUALABA	KOLWEZI	Surface	-10.7653	+25.5092	yes
117	LUALABA	KAPANGA	Surface	-8.3500	+22.6500	no
118	LUALABA	LUBUDI	Surface	-9.3330	+25.9330	no
119	LUALABA	MUTSHATSHA	Surface	-10.8170	+24.4640	no
120	LUALABA	SANDOA	Surface	-9.6330	+22.8500	no
121	LUALABA	TENKE	Surface	-10.7500	+26.1170	no
122	LUALABA	DILOLO	Surface	-10.6830	+22.3330	no
123	HAUT KATANGA	LUBUMBASHI	Surface/Upper-air	-11.5894	+27.5298	yes
124	HAUT KATANGA	PWETO	Surface	-8.4830	+28.3170	no
125	HAUT KATANGA	PANDA	Surface	-10.9670	+26.7330	no
126	HAUT KATANGA	KASENGA	Surface	-10.3830	+28.6170	no
127	HAUT KATANGA	SAKANIA	Surface	-12.7500	+28.5670	no
128	HAUT KATANGA	MITWABA	Surface	-8.6000	+27.3330	no

Appendix C Supplementary network maps

This Appendix contains a series of additional maps used to support the derivation of the GBON target for the Democratic Republic of Congo. These are comprised of the proposed surface (land) stations (sufficient to meet GBON compliance at a national level) overlaid on maps of:

- Fig. 6: the population density,
- Fig. 7: the terrain elevation, and
- Fig. 8: the lightning frequency.

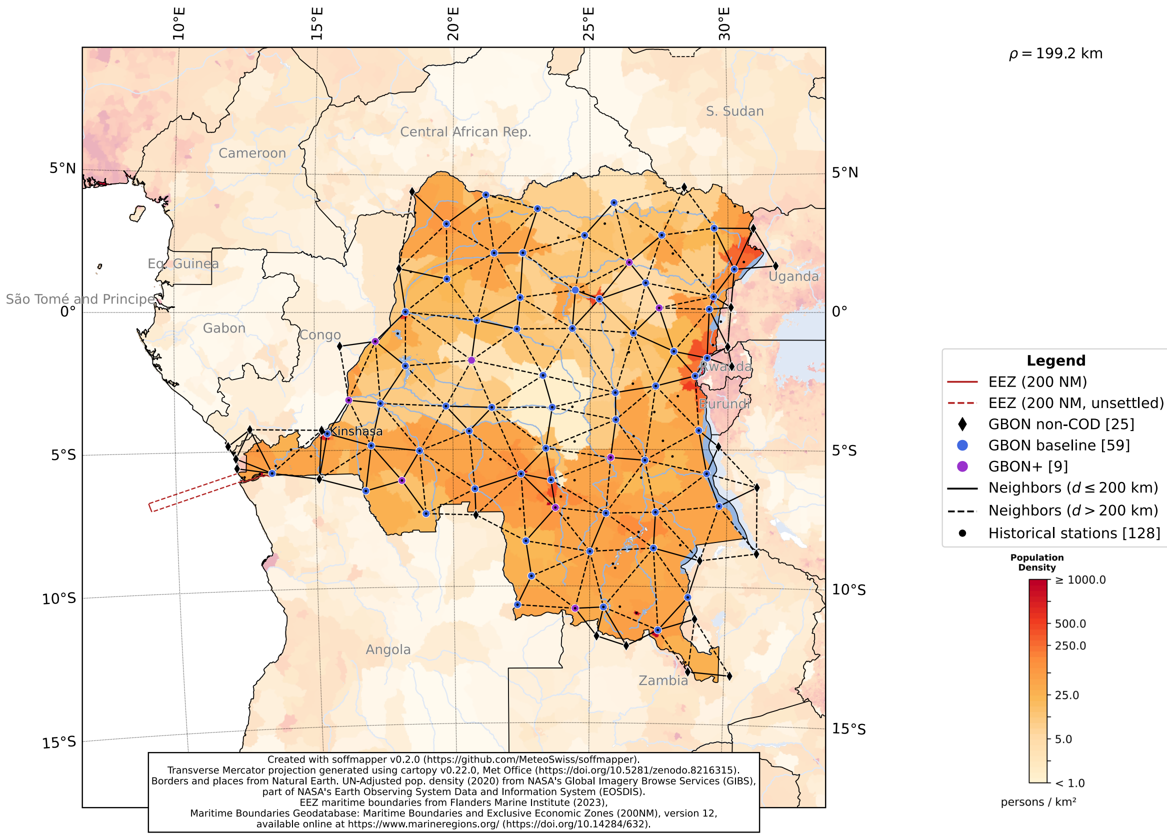

Figure 6: Same as Fig. 2, but with the proposed network overlaid over the COD population density.

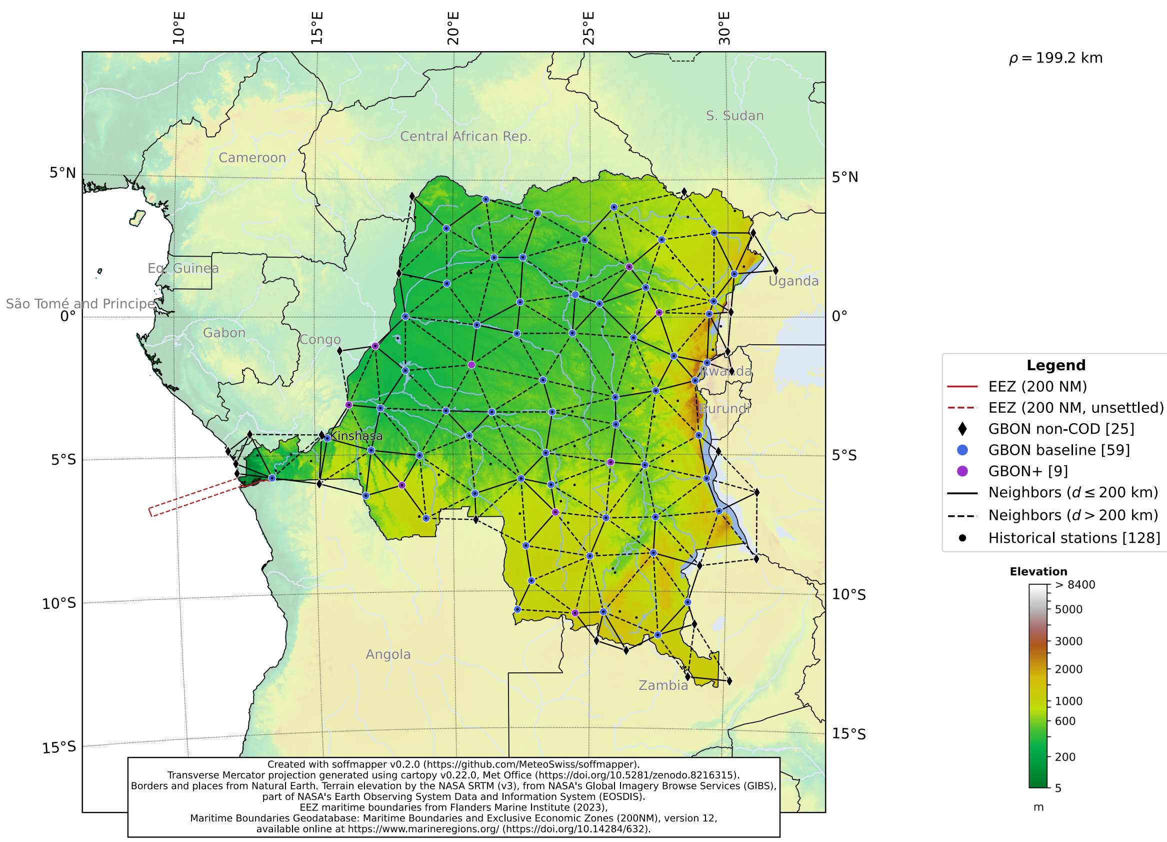

Figure 7: Same as Fig. 2, but with the proposed network overlaid over the COD elevation map.

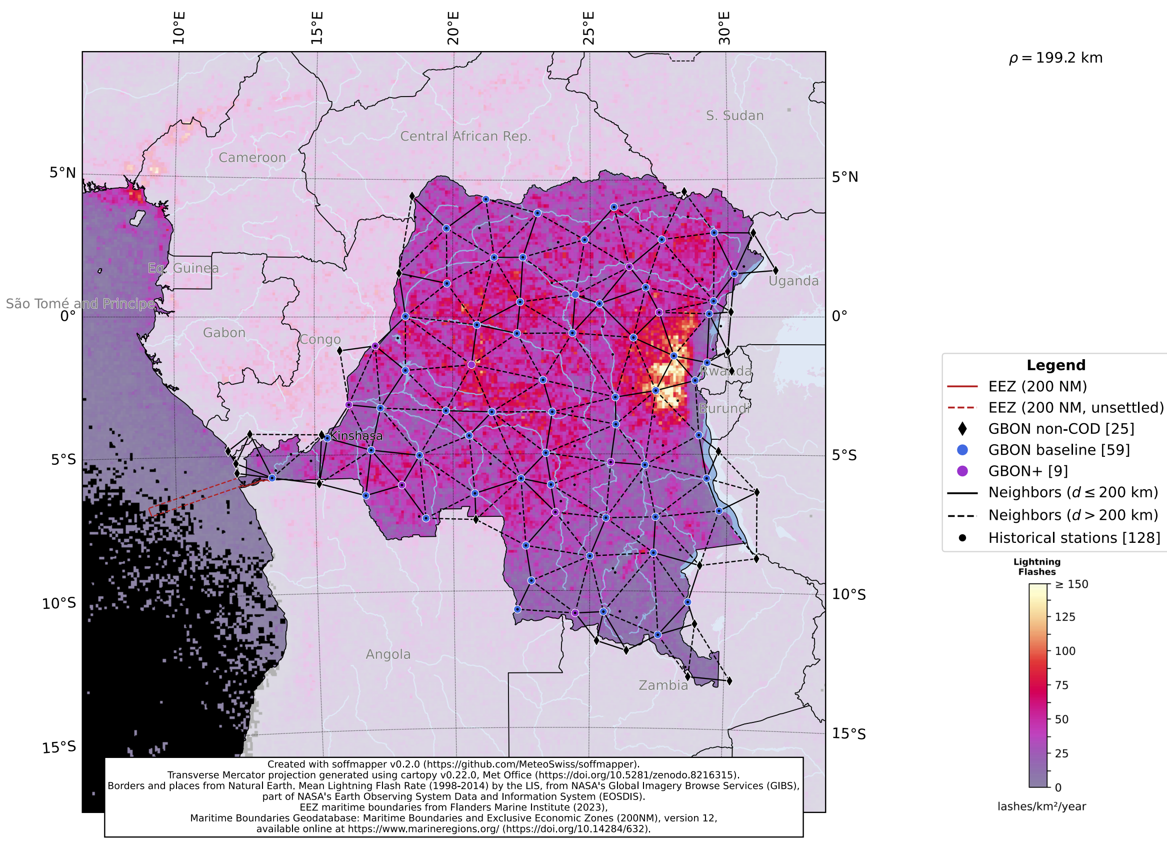

Figure 8: Same as Fig. 2, but with the proposed network overlaid over the COD lightning frequency map. The hotspot to the East of the country has the highest-recorded lightning frequency on Earth.