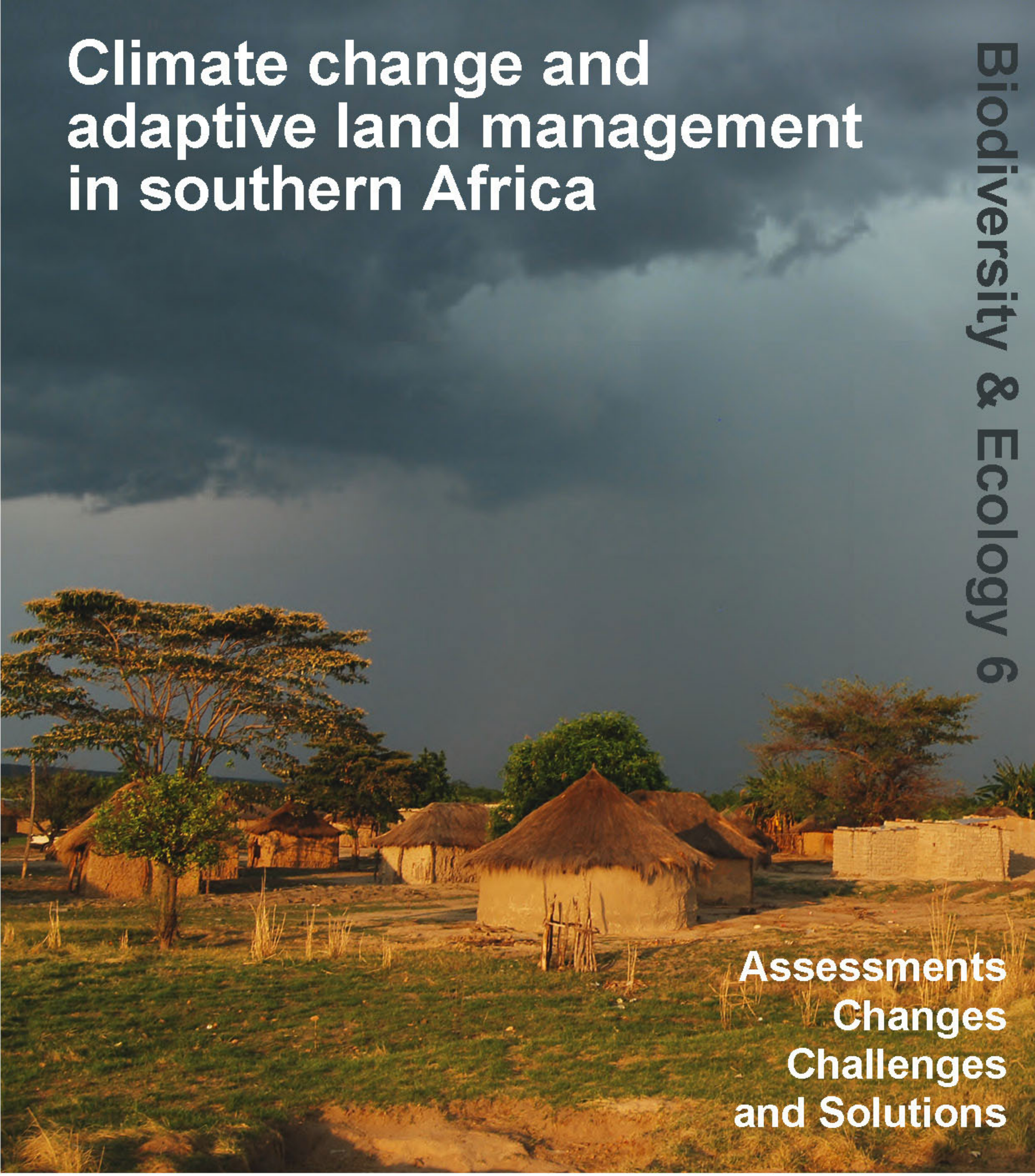
Climate change and adaptive land management in southern Africa

Biodiversity & Ecology 6



Assessments
Changes
Challenges
and Solutions

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Climate change and adaptive land management in southern Africa

Assessments, changes, challenges, and solutions

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Climate

SASSCAL WeatherNet: present state, challenges, and achievements of the regional climatic observation network and database

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Abstract: Automatic weather stations (AWSs) serve a number of goals in the SASSCAL context and beyond. A sufficient cover and density in geographical space is needed to record spatial climatic variability and to feed climate models and forecast services. In addition, research projects using an ecosystem approach require robust information on local weather. In response to these goals and under consideration of the low density of climate stations in the SASSCAL region (Angola, Botswana, Namibia, South Africa, and Zambia), the establishment of a network of weather stations was initiated in 2009–2010. The SASSCAL network, meanwhile, includes 154 AWSs and has achieved a reputation for providing unprecedented progress in terms of coverage and access to climatic data for the SASSCAL region. This paper presents the most important strategic and technical steps, from setting up the station network for data transmission and data quality controls to the Internet publication of the SASSCAL WeatherNet climatic data.

Resumo: As estações meteorológicas automáticas (AWSs) servem uma série de fins no contexto do SASSCAL e mais além. São necessárias uma cobertura e densidade suficientes no espaço geográfico para registar a variabilidade espacial climática e alimentar os modelos climáticos e serviços de previsão. Além disso, projectos de investigação que usam uma abordagem ecossistémica requerem informação robusta sobre as condições meteorológicas locais. Em resposta a estes objectivos, e considerando a baixa densidade de estações climáticas na região do SASSCAL (Angola, Botswana, Namíbia, África do Sul e Zâmbia), foi iniciado o estabelecimento de uma rede de estações meteorológicas em 2009-2010. Entretanto, a rede do SASSCAL inclui 154 AWSs e alcançou uma reputação de proporcionar progresso sem precedentes em termos de cobertura e acesso a dados climáticos para a região do SASSCAL. Este artigo apresenta as etapas estratégicas e técnicas mais importantes, desde a criação da rede de estações para a transmissão e controlo da qualidade dos dados até à publicação online dos dados climáticos da SASSCAL WeatherNet.

Introduction

The Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL) is a joint initiative of Angola, Botswana, Namibia, South Africa, Zambia, and Germany in response to the challenges of global change. SASSCAL research activities aim at improving our knowledge on the complex interactions and feedbacks between terrestrial and atmospheric systems. To better understand and assess processes, fluxes, and linkages in and between the systems, reliable data of high quality are needed. This is especially important considering climate variability and its projected change as well as socio-economic development in sub-Saharan Africa. However, a major challenge faced by most countries of southern Africa is the lack of adequate monitoring networks to provide reliable data, specifically for the development of efficient management strategies for sustainable water and land resources management, drought and flood risk analyses and forecasts, and climate change impact assessments. For example, in Angola, Botswana, and Zambia there is a demand for improving existing national weather-monitoring networks to provide up-to-date information for decision-makers and the public. By implementing and operating the SASSCAL WeatherNet, SASSCAL addresses this deficiency and has extended the national monitoring networks to provide a consistent and freely accessible dataset for the SASSCAL region.

The SASSCAL WeatherNet, with its currently 154 automatic weather stations (AWSs), and the necessary IT infrastructure for data transfer and open-access presentation on the Internet have been established only within the past seven years (2010–2017). This could be achieved only by a direct SASSCAL investment of approximately 1.3 Million € and the work of a team of six to ten staff members involved on a permanent or temporary basis.

History

The SASSCAL AWSs have been installed at different stages during the SASSCAL initiative. The first installations date back to 2010, replacing earlier devices (Jürgens et al., 2010). In 2013, a workshop was held in Windhoek, Namibia, to systematically expand the network with the participation of national meteorological services, ministries, World Meteorological Organization (WMO) representatives, scientists, and representatives of the funding agency to assess the current situation and identify the most pressing needs. A basic set of sensors, according to WMO standards, was decided upon for each station. One result of the workshop was the implementation of ten stations each in Angola, Botswana, and Zambia. The locations were suggested by the respective national meteorological services. Basics were decided upon for the open-access availability of data.

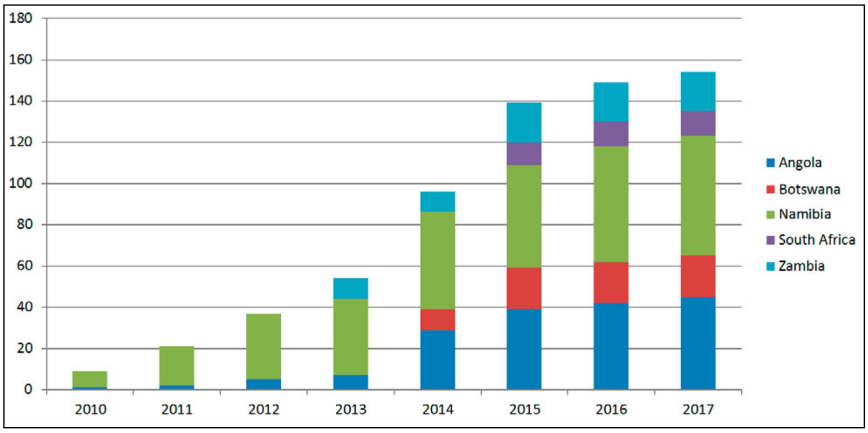

Figure 1: Implementation of automatic weather stations within SASSCAL WeatherNet. Row: cumulative number of AWSs per country; column: first data

Over the years, the network has been expanded in stages (Fig. 1). Many of these stations were financed from funds earmarked for SASSCAL, some of them directly for the purchase of equipment, and others through efforts in individual projects such as SASSCAL Task 001, Task 054, and Task 337.

Other donors have also participated, convinced by the possibilities of SASSCAL WeatherNet (BIOTA AFRICA; Ministry of Agriculture, Water and Forestry (MAWF), Namibia; Local Institutions in Globalized Societies [LINGS], Germany; Instituto Nacional de Meteorologia de Angola [INAMET], Angola; Instituto de Desenvolvimento Florestal [IDF], Angola; Instituto de Desenvolvimento Agrário [IDA], Angola; Universidade José Eduardo dos Santos [UJES], Angola; Gestão de Terras Aráveis [Gesterra], Angola; Gabinete para a Administração da Bacia Hidrográfica do rio Cunene [GABHIC], Angola; University of Basel, Switzerland).

The implementation of the AWSs has been done in several campaigns with a team of technicians from providers as well as from SASSCAL participants. All the IT components (data transmission pathways, algorithms for quality control, SASSCAL WeatherNet website design) have been set up by three staff members at the University of Hamburg. Maintenance of the stations in the field was carried out by only three staff members in Namibia, three staff members in South Africa, two staff members each in Angola, and the national weather services in Botswana and Zambia. In 2017, a second workshop with the participants of the SASSCAL WeatherNet was organised to gather the experiences had so far and to plan necessary steps for the future. For a sustainable future SASSCAL WeatherNet, it will be necessary to either integrate the stations into the maintenance networks of the national meteorological services or to increase the available trained maintenance staff within SASSCAL structures.

Technical implementation

Stations

At the end of 2017, the SASSCAL WeatherNet AWSs are distributed in the five countries of the SASSCAL region (see Tab. 1 and 2, Fig. 2). Currently, 88 stations have been purchased with SASSCAL funding and 66 stations were contributed

Table 1: List of weather stations and time series properties as at end of 2017

Name	Country	Latitude	Longitude	Altitude [m]	Type	WMO	Transmission	Air temperature	Soil temperature	Wind	Rain	Relative humidity	Barometric pressure	Solar irradiance	Leaf wetness	Fog precipitation	Soil moisture	Sunshine duration	Dew point	Wet bulb	First data	Status/Last data
Açucareira	Angola	-8.59100	13.60400	14	Adcon/OTT		GPRS	x		x	x	x		x							01.11.2017	active
Alto Dondo	Angola	-9.68333	14.46667	185	INOVA		GPRS	x	x	x	x	x	x	x	x				x		14.04.2014	undetermined
Barragem das Neves	Angola	-14.95200	13.36300	2074	Adcon/OTT		GPRS	x		x	x	x	x	x							19.10.2014	active
Benfica	Angola	-9.00000	13.09100	70	Adcon/OTT		GPRS	x		x	x	x		x							10.10.2009	active
Bentiaba	Angola	-14.25700	12.38700	11	Adcon/OTT		GPRS	x		x	x	x	x	x							27.10.2014	active
Bibala	Angola	-14.80800	13.34100	1061	Adcon/OTT		GPRS	x		x	x	x	x	x							21.10.2014	active
Cacuso	Angola	-9.42808	15.74621	1064	INOVA		GPRS	x		x	x	x	x	x							15.04.2014	09.03.2016 (1)
Caiundo	Angola	-16.41440	17.82000	1204	Adcon/OTT		GPRS														-	(1)
Campus ISPT	Angola	-14.95800	13.44500	2047	Adcon/OTT		GPRS	x		x	x	x	x	x							17.10.2014	active
Caope	Angola	-8.75500	13.42300	21	Adcon/OTT		GPRS	x	x	x	x	x		x							01.01.2016	active
Capangombe	Angola	-15.09600	13.13800	535	Adcon/OTT		GPRS	x		x	x	x	x	x							22.10.2014	active
Caraculo	Angola	-15.01900	12.65800	470	Adcon/OTT		GPRS	x		x	x	x	x	x							24.10.2014	active
Chianga (Huambo)	Angola	-12.74349	15.82923	1695	INOVA		GPRS	x	x	x	x	x	x	x	x				x		13.04.2014	undetermined
Cuito Cuanavale	Angola	-15.18150	19.17833	1214	INOVA		GPRS	x	x	x	x	x	x	x	x				x		15.08.2014	undetermined
Cusseque	Angola	-13.71000	17.10000	1529	Adcon/OTT		GPRS	x	x	x	x	x	x	x							27.03.2015	inactive
Damba	Angola	-6.68333	14.13333	602	INOVA		GPRS	x	x	x	x	x	x	x	x				x		28.04.2014	inactive
Espinheira	Angola	-16.77577	12.34777	448	Adcon/OTT		SAT	x	x	x	x	x	x	x		x	x				20.10.2015	active
Fazenda Pongo-Andongo 2	Angola	-9.64400	15.49100	1072	Adcon/OTT		GPRS	x	x	x	x	x		x							20.06.2011	inactive
Flamingos Bay	Angola	-15.56784	12.02124	13	Adcon/OTT		MAN	x			x	x				x					13.10.2017	active
Gambos	Angola	-15.65000	14.06667	1318	INOVA		GPRS	x	x	x	x	x	x	x	x				x		11.04.2014	undetermined
Ganda	Angola	-12.95000	14.63333	1412	INOVA		GPRS	x	x	x	x	x	x	x	x				x		08.04.2014	undetermined
Gove	Angola	-13.45500	15.85900	1741	Adcon/OTT		GPRS	x		x	x	x		x							18.06.2012	active
Great Welwitschia	Angola	-15.56800	12.14000	98	Adcon/OTT		GPRS	x			x	x				x					26.10.2015	active
Humpata	Angola	-15.06900	13.35100	1880	Adcon/OTT		GPRS	x		x	x	x	x	x							17.10.2014	active
IMA - Huambo	Angola	-12.81500	15.64100	1736	Adcon/OTT		GPRS	x		x	x	x	x	x							01.01.2014	inactive
Iona Coastal	Angola	-16.80562	11.88445	187	Adcon/OTT		MAN	x		x	x	x									15.01.2017	active
ISPKS - Sumbe	Angola	-11.28500	13.89600	275	Adcon/OTT		GPRS	x		x	x	x	x	x							02.02.2016	active
Kessua	Angola	-9.46400	16.28500	1115	Adcon/OTT		GPRS	x		x	x	x	x	x							24.11.2014	active
Kibala (Catofe)	Angola	-10.73597	14.98446	1272	INOVA		GPRS	x	x	x	x	x	x	x	x				x		14.04.2014	undetermined
Matala	Angola	-14.88700	15.08300	1204	Adcon/OTT		GPRS	x		x	x	x	x	x							08.10.2013	active
Muconda	Angola	-10.58769	21.31772	1096	INOVA		GPRS	x	x	x	x	x	x	x	x				x		05.07.2014	undetermined
Mukongo	Angola	-14.74900	12.50500	390	Adcon/OTT		GPRS	x		x	x	x	x	x							26.10.2014	active
Munhino	Angola	-14.95655	12.97733	402	Adcon/OTT		MAN	x		x	x	x	x	x							23.04.2016	active
Namacunde	Angola	-17.31200	15.85300	1112	Adcon/OTT		GPRS	x		x	x	x		x							01.04.2015	inactive
Namibe	Angola	-15.15900	12.17800	11	Adcon/OTT		GPRS	x		x	x	x	x	x		x					30.10.2014	active
Onjiva	Angola	-16.97600	15.61500	1119	Adcon/OTT		GPRS	x		x	x	x		x							01.04.2015	active
PN Bicuar	Angola	-15.10000	14.83330	1243	Adcon/OTT		SAT	x	x	x	x	x	x	x			x				21.03.2015	active
Projecto Terra do Futuro (PTF)	Angola	-10.46700	15.71100	1602	Adcon/OTT		GPRS	x		x	x	x	x	x							03.04.2015	inactive
Quibaxi	Angola	-8.51300	14.59000	872	Adcon/OTT		GPRS	x		x	x	x		x							11.05.2012	active
Tchivinguiro	Angola	-15.16900	13.29900	1662	Adcon/OTT		GPRS	x		x	x	x	x	x							02.04.2015	active
Tundavala	Angola	-14.84500	13.40700	2060	Adcon/OTT		GPRS	x		x	x	x	x	x							18.10.2014	17.04.2016 (2)
Tundavala Observatory	Angola	-14.79990	13.40750	2300	Adcon/OTT		GPRS	x	x	x	x	x	x	x							18.03.2015	active
UJES-Huambo	Angola	-12.86300	15.73100	1664	Adcon/OTT		GPRS	x	x	x	x	x	x	x							02.10.2013	inactive
Wako-Kungo	Angola	-11.41100	15.12900	1331	Adcon/OTT		GPRS	x		x	x	x	x	x							02.06.2012	active
Xangongo	Angola	-16.71900	14.98200	1123	Adcon/OTT		GPRS	x		x	x	x		x							20.05.2015	active
Baines Drift	Botswana	-22.48983	28.69675	709	CTS	68088	SAT	x	x	x	x	x	x	x	x				x	x	17.03.2015	active
Ghanzi	Botswana	-21.71508	21.65317	1137	CTS	68024	GPRS	x	x	x	x	x	x	x	x			x	x	x	13.02.2014	active
Goodhope	Botswana	-25.46025	25.42678	1275	CTS	68325	GPRS	x	x	x	x	x	x	x	x			x	x	x	01.02.2014	active
Lephepe	Botswana	-23.36564	25.84719	1024	CTS	68151	GPRS	x	x	x	x	x	x	x	x			x	x	x	06.02.2014	active
Lotlhakane East	Botswana	-25.08000	25.43000	1216	Cimel		GPRS	x	x	x	x	x	x	x					x		25.08.2015	active
Mababe	Botswana	-19.01800	23.96669	931	CTS	68028	SAT	x	x	x	x	x	x	x	x						30.03.2015	active
Mahalapye	Botswana	-23.11253	26.85922	1015	CTS	68148	GPRS	x	x	x	x	x	x	x	x			x	x	x	07.02.2014	active
Malopowabojang	Botswana	-25.20000	25.57000	1224	Cimel		GPRS	x	x	x	x	x	x	x					x		27.08.2015	active
Mogobane	Botswana	-24.98000	25.70000	1076	Cimel		GPRS	x	x	x	x	x	x	x					x		25.08.2015	active
Ngwatle	Botswana	-23.71239	21.07972	1176	CTS	68218	SAT	x	x	x	x	x	x	x	x				x	x	25.08.2015	active
Pandamatenga	Botswana	-18.54463	25.63583	1074	CTS	68030	GPRS	x	x	x	x	x	x	x	x			x	x	x	21.02.2014	active
Ramotswa	Botswana	-24.88000	25.88000	1040	Cimel		GPRS	x	x	x	x	x	x	x					x		25.08.2015	active
Ranaka	Botswana	-24.90000	25.45000	1224	Cimel		GPRS	x	x	x	x	x	x	x					x		25.08.2015	active
Shakawe	Botswana	-18.36856	21.83931	1002	CTS	68026	GPRS	x	x	x	x	x	x	x	x			x	x	x	12.02.2014	active
Sowa	Botswana	-20.54742	26.07842	911	CTS	68038	GPRS	x	x	x	x	x	x	x	x			x	x	x	22.02.2014	active
Tsabong	Botswana	-26.03136	22.40086	960	CTS	68328	GPRS	x	x	x	x	x	x	x	x			x	x	x	14.02.2014	active
Tshane	Botswana	-24.01928	21.86856	1125	CTS	68226	GPRS	x	x	x	x	x	x	x	x			x	x	x	14.02.2014	active
Tubu (Okavango Delta)	Botswana	-19.35786	22.28400	967	CTS	68027	SAT	x	x	x	x	x	x	x					x	x	26.03.2015	active
Werda	Botswana	-25.26800	23.25919	1030	CTS	68320	GPRS	x	x	x	x	x	x	x	x			x	x	x	07.02.2014	active
Xade	Botswana	-22.34072	23.02983	1004	CTS	68084	SAT	x	x	x	x	x	x	x	x				x	x	22.08.2015	active
Alex Muranda Livestock Devel	Namibia	-18.36430	19.25620	1166	CTS		GPRS	x	x	x	x	x	x	x	x						07.10.2010	active
Aussinanis	Namibia	-23.44354	15.04594	405	Gobabeb		GPRS	x	x	x	x	x		x	x						07.08.2014	active
Bagani	Namibia	-18.09464	21.55997	1008	CTS		GPRS	x	x	x	x	x	x	x	x						19.02.2013	active
Claratal	Namibia	-22.78760	16.81440	1950	CTS		GPRS	x	x	x	x	x	x	x	x						24.11.2010	active
Coastal Met	Namibia	-23.05631	14.62595	94	Gobabeb		GPRS	x	x	x	x	x	x	x	x						07.09.2014	active
Conception Water	Namibia	-24.01533	14.55038	9	Gobabeb		SAT	x	x	x	x	x		x	x						01.01.2017	active
Dieprivier (Namib Desert Lodg	Namibia	-24.12960	15.89470	1056	CTS		GPRS	x	x	x	x	x	x	x	x						07.06.2011	active
Erichsfelde	Namibia	-21.59860	16.90120	1499	CTS		GPRS	x	x	x	x	x	x	x	x						26.11.2010	inactive
Ganab	Namibia	-23.12180	15.53830	1002	CTS		GPRS	x	x	x	x	x	x	x	x	x					09.06.2011	active
Garnet Koppie	Namibia	-23.11539	15.30504	733	Gobabeb		GPRS	x	x	x	x	x	x	x	x						14.08.2014	active
Gellap Ost	Namibia	-26.40110	18.00720	1080	CTS		GPRS	x	x	x	x	x	x	x	x						24.02.2011	active
Giribisvlakte	Namibia	-19.09570	13.32611	630	CTS		SAT	x	x	x	x	x	x	x	x						27.06.2015	active
Gobabeb Met	Namibia	-23.56044	15.04100	406	Gobabeb		GPRS	x	x	x	x	x			x						04.10.2014	active
Hamoye	Namibia	-18.23475	19.73231	1122	MCS		GPRS	x	x	x	x	x	x	x	x			x			18.02.2013	active

Name	Country	Latitude	Longitude	Altitude [m]	Type	WMO	Transmission	Air temperature	Soil temperature	Wind	Rain	Relative humidity	Barometric pressu	Solar irradiance	Leaf wetness	Fog precipitation	Soil moisture	Sunshine duration	Dew point	Wet bulb	First data	Status/Last data
John Pandeni	Namibia	-19.70778	18.03528	1434	MCS		GPRS	x	x	x	x	x	x	x	x			x			24.11.2012	active
Kalahari	Namibia	-24.16283	18.47672	1229	MCS		GPRS	x	x	x	x	x	x	x	x			x			12.10.2012	inactive
Kalimbeza	Namibia	-17.54472	24.52669	939	CTS		GPRS	x	x	x	x	x	x	x	x						17.07.2013	active
Kanovlei	Namibia	-19.33269	19.48108	1217	CTS		SAT	x	x	x	x	x	x	x	x						12.02.2016	active
Kaoko Otavi	Namibia	-18.30023	13.65983	1427	CTS		SAT	x	x	x	x	x	x	x	x						17.04.2016	active
Karios (Gondwana Canyon Lod	Namibia	-27.67450	17.81950	893	CTS		GPRS	x	x	x	x	x	x	x	x						23.02.2011	active
Khorixas	Namibia	-20.37892	14.96952	967	CTS		SAT	x	x	x	x	x	x	x	x						27.02.2016	active
Kleinberg	Namibia	-22.98950	14.72817	185	MCS		GPRS	x	x	x	x	x	x	x	x			x			24.03.2011	active
Kleinberg-FN	Namibia	-22.98928	14.72793	184	Gobabeb		GPRS	x	x	x	x	x		x	x						07.08.2014	active
Koichab Pan	Namibia	-26.20761	15.86300	525	CTS		SAT	x	x	x	x	x	x	x	x						19.10.2015	active
Konop Pos	Namibia	-20.16800	14.96456	1073	CTS		SAT	x	x	x	x	x	x	x	x						29.11.2016	active
Mahenene	Namibia	-17.44433	14.78481	1114	MCS		GPRS	x	x	x	x	x	x	x	x			x			24.02.2012	active
Mannheim	Namibia	-19.16861	17.76336	1222	MCS		GPRS	x	x	x	x	x	x	x	x			x			06.12.2012	active
Marble Koppie	Namibia	-22.96948	14.98968	421	Gobabeb		GPRS	x	x	x	x	x		x	x						07.08.2014	active
Marienflusstal	Namibia	-17.60886	12.60181	572	CTS		SAT	x	x	x	x	x	x	x	x						30.06.2015	07.05.2017 (1)
Mashare	Namibia	-17.89460	20.20850	1066	CTS		GPRS	x	x	x	x	x	x	x	x						17.02.2012	inactive
Mopanie Pos 6	Namibia	-20.25674	15.06718	1097	CTS		SAT	x	x	x	x	x	x	x	x						26.11.2016	active
Narais - Duruchaus	Namibia	-23.12125	16.90061	1627	CTS		GPRS	x	x	x	x	x	x	x	x						25.11.2010	active
Ngoma	Namibia	-17.89950	24.70794	938	CTS		GPRS	x	x	x	x	x	x	x	x						16.07.2013	inactive
Nico	Namibia	-25.31275	17.83458	1058	MCS		GPRS	x	x	x	x	x	x	x	x			x			02.04.2010	active
Ogongo	Namibia	-17.67853	15.29481	1111	CTS		GPRS	x	x	x	x	x	x	x	x						25.02.2012	active
Okahandja (NRFC)	Namibia	-22.00564	16.91797	1321	CTS		GPRS	x	x	x	x	x	x	x	x						23.08.2012	active
Okamboro	Namibia	-22.00949	17.04139	1461	MCS		GPRS	x	x	x	x	x	x	x	x			x			24.03.2011	active
Okangwati	Namibia	-17.43025	13.27810	1081	CTS		SAT	x	x	x	x	x	x	x	x						15.04.2016	active
Okapya	Namibia	-18.47250	17.33908	1138	CTS		GPRS	x	x	x	x	x	x	x	x						24.02.2012	active
Okashana	Namibia	-18.41111	16.63853	1106	MCS		GPRS	x	x	x	x	x	x	x	x			x			25.02.2012	active
Okomumbonde	Namibia	-20.48327	17.34317	1389	MCS		GPRS	x	x	x	x	x	x	x	x			x			21.11.2012	active
Omatako Ranch	Namibia	-21.50940	16.72910	1496	CTS		GPRS	x	x	x	x	x	x	x	x						08.12.2010	active
Omatjenne	Namibia	-20.44278	16.49333	1376	MCS		GPRS	x	x	x	x	x	x	x	x			x			03.02.2012	active
Oshaambelo	Namibia	-17.84286	14.77008	1114	MCS		GPRS	x	x	x	x	x	x	x	x			x			24.02.2012	active
Rooisand	Namibia	-23.29453	16.11467	1176	MCS		GPRS	x	x	x	x	x	x	x	x			x			24.03.2011	active
Sachinga	Namibia	-17.67367	24.03189	982	CTS		GPRS	x	x	x	x	x	x	x	x						17.07.2013	active
Salt Works	Namibia	-23.02352	14.46317	5	Gobabeb		GPRS	x	x	x	x	x		x	x						20.11.2017	active
Sandveld	Namibia	-22.04450	19.13210	1527	CTS		GPRS	x	x	x	x	x	x	x	x						11.01.2011	active
Sonop Research Station	Namibia	-19.01010	18.90390	1218	CTS		GPRS	x	x	x	x	x	x	x	x						09.10.2010	inactive
Sophies Hoogte	Namibia	-23.00681	14.89087	334	Gobabeb		GPRS	x	x	x	x	x		x	x						07.08.2014	active
Station 8	Namibia	-23.26530	15.05627	487	Gobabeb		GPRS	x	x	x	x	x		x	x						07.08.2014	active
Tsumis	Namibia	-23.72978	17.19386	1376	MCS		GPRS	x	x	x	x	x	x	x	x			x			25.05.2012	active
Tsumkwe Breeding Station	Namibia	-19.61560	20.44200	1153	CTS		GPRS	x	x	x	x	x	x	x	x						05.08.2011	active
Vogelfederberg	Namibia	-23.09797	15.02903	501	Gobabeb		GPRS	x	x	x	x	x	x	x	x						11.08.2014	active
Waterberg	Namibia	-20.39710	17.35290	1575	CTS		GPRS	x	x	x	x	x	x	x	x						09.09.2011	active
Windhoek (NBRI)	Namibia	-22.57070	17.09570	1700	CTS		GPRS	x	x	x	x	x	x	x	x						01.10.2010	active
Windhoek (Satellite)	Namibia	-22.57238	17.09481	1737	CTS		SAT	x	x	x	x	x	x	x	x						09.07.2014	active
Wlotzkasbaken	Namibia	-22.31490	14.46210	55	CTS		GPRS	x	x	x	x	x	x	x	x	x					10.06.2011	active
Alexanderbay Lichen Field	South Africa	-28.62496	16.50674	80	Adcon/OTT		GPRS	x		x	x	x				x					01.10.2015	active
Alpha	South Africa	-26.76178	20.62504	872	Adcon/OTT		GPRS	x	x	x	x	x	x	x							03.10.2015	active
Eksteenfontein	South Africa	-28.83653	17.29039	606	Adcon/OTT		GPRS	x	x	x	x	x	x	x							05.10.2015	active
Koeroegabvlakte	South Africa	-28.23590	17.02557	641	Adcon/OTT		SAT	x	x	x	x	x	x	x			x				08.03.2015	active
Moedverloor	South Africa	-31.47273	18.44542	147	Adcon/OTT		GPRS	x	x	x	x	x	x	x		x					06.10.2016	active
Numees	South Africa	-28.31426	16.96585	391	Adcon/OTT		SAT	x	x	x	x	x	x	x		x	x				06.03.2015	active
Paulshoek	South Africa	-30.39500	18.28118	996	Adcon/OTT		SAT	x	x	x	x	x	x	x			x				11.10.2015	active
Ratelgat	South Africa	-31.28616	18.60281	209	Adcon/OTT		GPRS	x	x	x	x	x	x	x		x					10.10.2015	inactive
Soebatsfontein	South Africa	-30.18294	17.55062	244	Adcon/OTT		SAT	x	x	x	x	x	x	x			x				11.10.2015	active
Vandersterrberg	South Africa	-28.47126	17.11159	1063	Adcon/OTT		GPRS	x	x	x	x	x	x	x		x					07.03.2015	active
Verlorenvlei	South Africa	-32.59810	18.68285	53	Adcon/OTT		GPRS	x	x	x	x	x	x	x							24.09.2015	active
Yellow Dune - Grootderm	South Africa	-28.61105	16.65436	161	Adcon/OTT		GPRS	x	x	x	x	x	x	x		x					09.03.2015	active
Chadiza	Zambia	-14.06000	32.43200	1056	Adcon/OTT		GPRS	x	x	x	x	x	x	x							29.06.2015	active
Copperbelt University	Zambia	-12.80610	28.23740	1220	Adcon/OTT		GPRS	x	x	x	x	x	x	x							10.04.2015	active
Dongwe	Zambia	-14.01259	24.02188	1071	Adcon/OTT		SAT	x	x	x	x	x	x	x			x				14.05.2015	inactive
Kabwe Mulungushi	Zambia	-14.29257	28.56632	1142	Adcon/OTT		GPRS	x	x	x	x	x	x	x							08.10.2013	active
Kafue National Park-Tatayoyo	Zambia	-14.90153	24.43200	1231	Adcon/OTT		GPRS	x	x	x	x	x	x	x							06.04.2015	inactive
Kalabo	Zambia	-14.98895	22.68175	1018	Adcon/OTT	67625	GPRS	x	x	x	x	x	x	x							02.12.2013	active
Kalomo	Zambia	-16.96000	26.47500	1274	Adcon/OTT		GPRS	x	x	x	x	x	x	x							24.02.2015	inactive
Kasempa	Zambia	-13.45696	25.83370	1227	Adcon/OTT	67541	GPRS	x	x	x	x	x	x	x							26.11.2013	active
Luampa	Zambia	-15.14233	24.49237	1130	Adcon/OTT		GPRS	x	x	x	x	x	x	x							05.04.2015	inactive
Lusaka Int. Airport	Zambia	-15.31929	28.44050	1149	Adcon/OTT	67665	GPRS	x	x	x	x	x	x	x							08.10.2013	active
Lusaka University of Zambia	Zambia	-15.39117	28.33204	1260	Adcon/OTT		GPRS	x	x	x	x	x	x	x							10.10.2013	active
Mpulungu	Zambia	-8.77300	31.11700	801	Adcon/OTT		GPRS	x	x	x	x	x	x	x							20.05.2015	active
Mwinilunga	Zambia	-11.73998	24.43100	1360	Adcon/OTT	67441	GPRS	x	x	x	x	x	x	x							04.12.2013	active
Namwala	Zambia	-15.75000	26.43300	998	Adcon/OTT		GPRS	x	x	x	x	x	x	x							22.02.2015	active
Nangweshi	Zambia	-16.24592	23.23711	1014	Adcon/OTT		GPRS	x	x	x	x	x	x	x							23.02.2015	inactive
Samfya	Zambia	-11.37119	29.56057	1194	Adcon/OTT	67469	GPRS	x	x	x	x	x	x	x							06.10.2013	active
Serenje	Zambia	-13.22670	30.21508	1395	Adcon/OTT	67571	GPRS	x	x	x	x	x	x	x							07.10.2013	active
Sesheke	Zambia	-17.47110	24.30130	944	Adcon/OTT	67741	GPRS	x	x	x	x	x	x	x							22.11.2013	active
Zambezi	Zambia	-13.53365	23.10790	1066	Adcon/OTT	67531	GPRS	x	x	x	x	x	x	x							27.11.2013	active

(1) lost by vandalism
(2) shifted to Munhino

GPRS	Transmission via GPRS
SAT	Transmission via satellite
MAN	Manual download
active	station measures data
-	Time series terminated
inactive	Data flow stopped, maintenance is needed
undetermined	Status about the station is undetermined

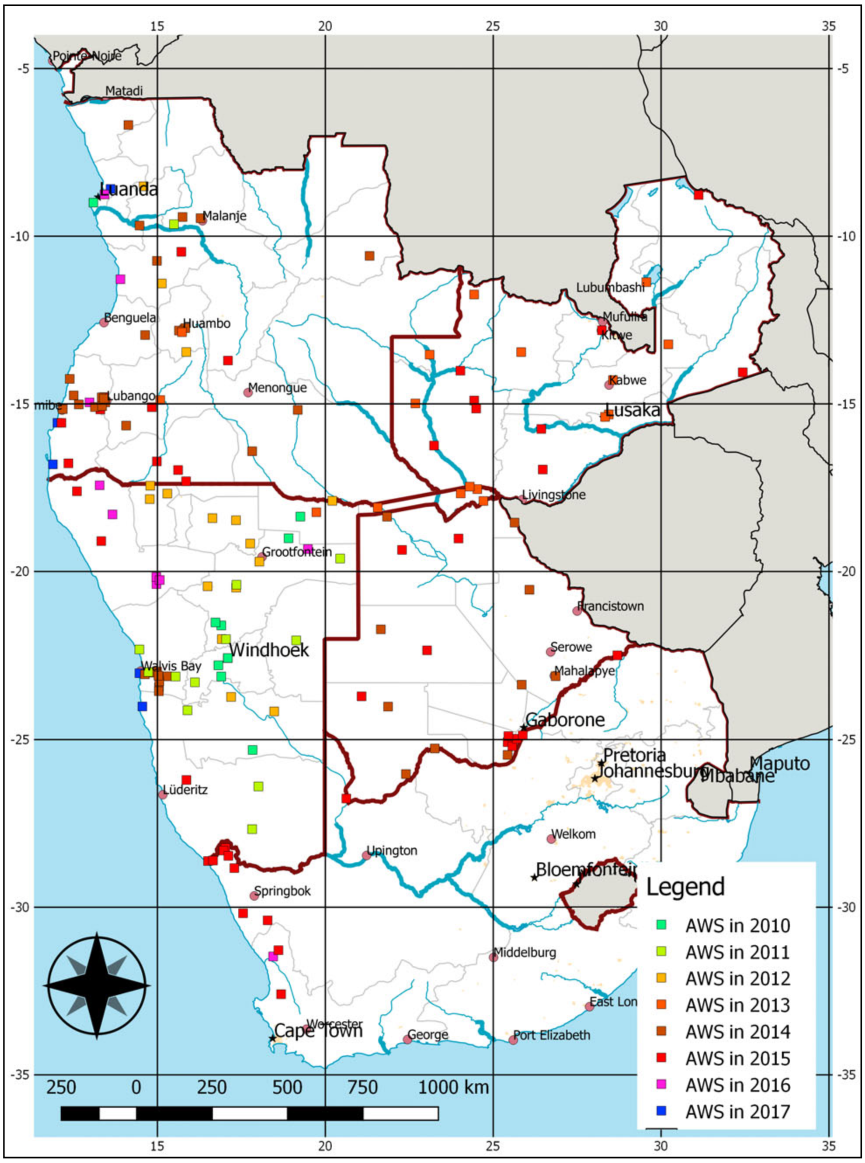

Figure 2: Locations of automatic weather stations within the SASSCAL WeatherNet.

by other sources (see the section 'History'). Each AWS is equipped with several sensors measuring more than ten climatic elements (see Fig. 3, Tab. 3).

Table 2: Number of weather stations within the SASSCAL region and their methods of data transmission

	#	GPRS	SAT	MAN	a	-	i	x
Angola	45	40	2	3	28	3	6	8
Botswana	20	15	5	0	20	0	0	0
Namibia	58	47	11	0	52	1	5	0
South Africa	12	8	4	0	11	0	1	0
Zambia	19	18	1	0	14	0	5	0
Total	154	128	23	3	125	4	17	8

#	Number of weather stations/time series
GPRS	Transmission via GPRS
SAT	Transmission via satellite (Meteosat)
MAN	Manual download
a	Active: data available
-	Time series terminated
i	Inactive: data flow stopped
x	Undetermined

In Table 1, details about the availability of time series for each station are presented, including the first date and, in the case of termination, the last date. Not all stations produced continuous data; causes of data flow interruption include vandalism, communication interruptions, and in some cases the necessity to change the location of certain stations.

The AWSs have been purchased from different providers, coming with a variety of data loggers and sensors (Tab. 4). The variety of types is one of the reasons for the need for careful data management, which has to harmonize the many variants of incoming data.

Table 1 also provides information about locations of AWSs registered by the WMO, and Table 5 compares SASSCAL AWSs with WMO-registered AWSs in the SASSCAL region.

Data transfer

Starting from the respective climate station, the data is transferred over different transmission channels to the FTP server (see Fig. 4 for a simplified representation). From here the raw data are picked up, processed, and written into the database. Several data quality examinations take place during the processing phase (see 'Data processing and quality control'). With the diversity of AWSs, the variety of transfer methods has increased. The providers Adcon/OTT, MCS, and Cimel collect the data first and forward these to the SASSCAL FTP server. The data from most of the Gobabeb AWSs are downloaded remotely from the data logger with the assistance of the Campbell LoggerNet tool. For the AWSs with transmission via Meteosat satellite, an Eumetsat download portal is in use. From there, the current data are retrieved, processed, and forwarded to the SASSCAL FTP server every hour.

The volume of data increases every day: 95 AWSs have a resolution of one record per hour and 69 AWSs have a resolution of four records per hour, which results in 8,904 expected records per day. Despite data loss caused by malfunctions, especially as a result of transmission problems either at the AWS or on the side of the GPRS service provider, on average 7,500 records per day are recorded.

Table 3: Number of stations measuring respective weather variables

	Air temperature	Soil temperature	Wind	Rain	Relative humidity	Barometric pressure	Solar irradiation	Leaf wetness	Fog precipitation	Soil moisture	Sunshine duration	Dew point	Wet bulb
Angola	44	15	42	44	44	32	41	8	4	2	0	8	0
Botswana	20	20	20	20	20	20	20	14	0	0	10	19	14
Namibia	58	58	58	58	58	50	57	58	2	0	14	0	0
South Africa	12	11	12	12	12	11	11	0	6	4	0	0	0
Zambia	19	19	19	19	19	19	19	0	0	1	0	0	0
Total	153	123	151	153	153	132	148	80	12	7	24	27	14

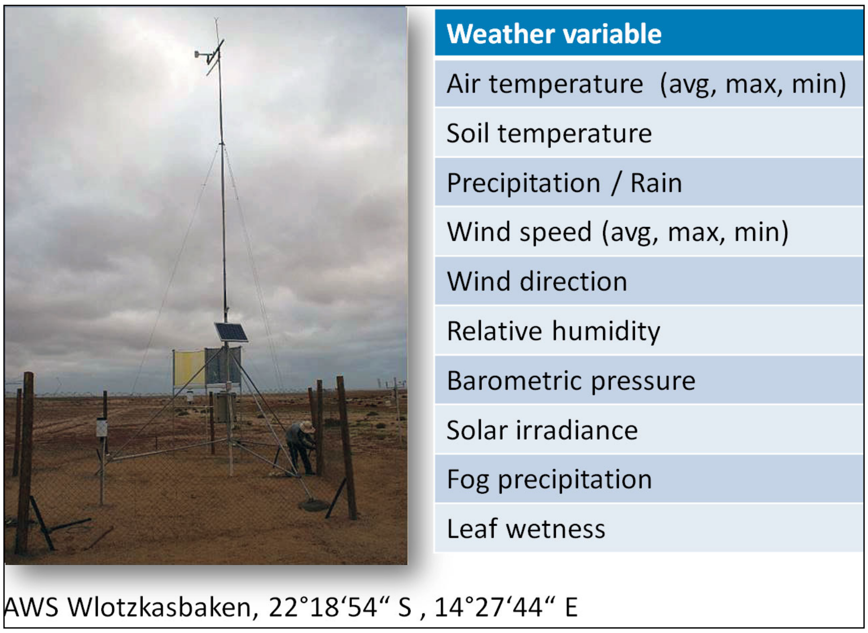

Figure 3: Typical weather variables recorded by the SASSCAL weather stations.

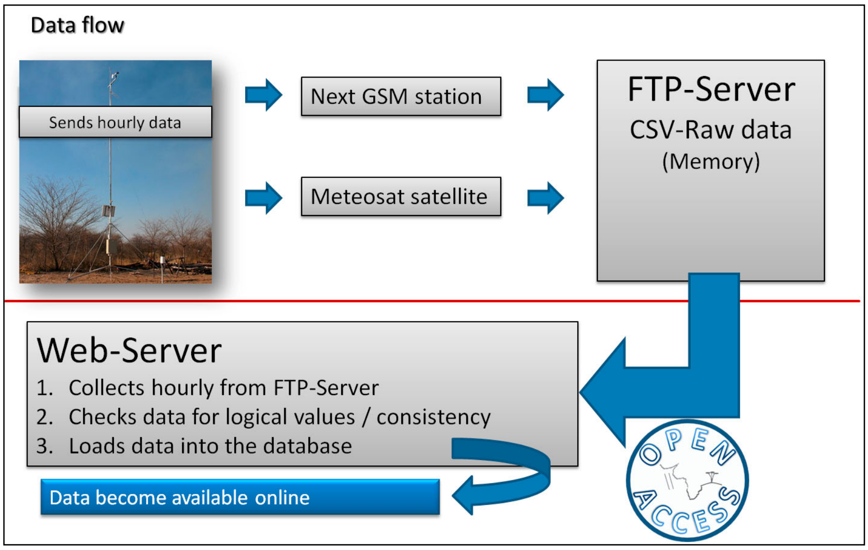

Figure 4: Data flow from the automatic weather station to online presentation.

Table 4: Number of stations per type, **#** number of AWSs, **Adcon** Telemetry / OTT Hydromet Group (Austria/Germany) (own devices), **CTS** Central Technical Supplies (Pty.) Ltd (Namibia) (Campbell, Young, Vaisala), **MCS** Mike Cotton Systems (South Africa) (own devices, Vaisala), **INOVA** (Angola), **Gobabeb** FogNet (Namibia) (Campbell, Young, Vaisala, Setra), **Cimel** Electronique (France)

	#	Adcon	CTS	MCS	INOVA	Gobabeb	Cimel
Angola	45	36	0	0	9	0	0
Botswana	20	0	15	0	0	0	5
Namibia	58	0	33	14	0	11	0
South Africa	12	12	0	0	0	0	0
Zambia	19	19	0	0	0	0	0
Total	154	67	48	14	9	11	5

Data processing and quality control

To provide high-quality data, there are certain prerequisites that need to be met:

1. *Up-to-date, high-quality technical equipment*: sensors, data loggers, and transmitters.
2. *Protected sites*: stations are fenced in or in secure areas such as at police stations or farms.
3. *Support at the station location*: someone from the local village/station is able to undertake minor repairs and maintenance and/or provide security.
4. *Immediate checks on receipt of values for presence and plausibility*: quality checks of data should be carried out by one or two persons per country to assist the IT team in delivering high-quality data and to know in time when one of the sensors has been damaged or stops functioning.
5. *Regular maintenance measures*: regular maintenance is carried out twice annually, but for stations in exposed areas every three months to prevent the formation of rust and blockages of gauges by fine silt (dust) or other debris.
6. *Technical competence in the SASSCAL region*: the lack of manpower to assist in troubleshooting has made it necessary to compile manuals that can be used to train technicians and managers (e.g. Strohbach, 2014).
7. *Stocks with spare parts available within the countries*: spare parts at hand make it possible to effect timely repairs.
8. *Near real-time publication of the data*: not only for general use, but also for the timely detection of problems.
9. *Lean information chains to initiate repairs*: short communication paths considerably accelerate measures in case of malfunctions.

Although these prerequisites are carefully considered within the SASSCAL network, every incoming value must be checked for its reliability and suspicious measured values need to be excluded. In principle, there are several ways to check incoming values for consistency and plausibility (WMO, 2011, 2012).

1. The values must be between acceptable range limits (e.g., barometric pressure depends on altitude).

Climate

2. A value must fit within a known context (e.g., frost in the early afternoon is possible only during the winter season).
3. Logical relationships of values of different parameters must be respected (e.g., the wind speed *minimum* must be less than wind speed *average,* which in turn is to be less than wind speed *maximum*).
4. Consecutive values in a time series must be coherent (e.g., if several consecutive wind speed values are identical, this is an indication of a sensor failure; also, extraordinary rapid changes in specific values indicate sensor failures).
5. The trend of a parameter value must match the trend of other parameter values (e.g., as a rule of thumb, air humidity and leaf wetness values increase when it starts raining).
6. Long-term trends must be consistent (e.g., a rising mean humidity value over more than a year indicates a need for calibration of the humidity sensor).

Items 1, 2, and 3 relate to a single value or combination of values of the same data record and can be checked immediately after arrival of the record. In the case of items 4, 5, and 6, an examination can be carried out only at a later point in time, as data records must be compared with several, possibly even very many, other records.

It has been found to be advantageous to relate interval limits (see point 1 above) to the individual station. This makes it possible to adapt the limits to the local conditions and to detect outliers easier and more precisely. It has also proved useful to adjust the tests to the time of day or season to detect anomalies such as false positive precipitation values in a known dry period (see, e.g., Fig. 5 and Tab. 6). All abnormalities are logged in a database.

Figure 6 shows plausibility checks of the SASSCAL WeatherNet, which are automatically performed when a set of values is received.

Data presentation

For the use of the data from the SASSCAL WeatherNet, data completeness and high data quality are necessary conditions. However, data presentation is equally important. Potential data users must become aware of the network and be informed of the quality and the prerequisites for data availability. The link between on-site measurement and the use of data for scientific or other applications is data processing using the Internet, user-friendly online databases, web presence, and tools of modern data management. This is achieved with the SASSCAL WeatherNet website (www.sasscalweathernet.org), which reveals the obtained data to both the SASSCAL scientific community and any other person interested in weather data.

The website provides information about the characteristics of each AWS

Table 5: Comparison of WMO-registered stations versus stations within SASSCAL WeatherNet

Country	SASSCAL	WMO	both
Angola	45	32	0
Botswana	20	33	14
Namibia	58	20	0
South Africa	12	205	0
Zambia	19	37	8
Total	154	327	22

Sources:

Column *SASSCAL*: AWSs within SASSCAL WeatherNet
Column *WMO*: Registered weather stations at WMO; see https://oscar.wmo.int/surface//index.html#/search/station#stationSearchResults
Column *both*: Intersection of AWSs listed both in column *SASSCAL* and column *WMO, for example: 14 of the 20 Botswana SASSCAL AWSs are among the 33 Botswana WMO-registered AWSs*

Table 6: Registered causes of system failures

Causes of system failures
Vandalism, whole station got lost, or solar panels and batteries were stolen
Rain gauges indicate false precipitation, caused by, for example, small animals (wasps, baby gecko)
Insects building their nests around air temperature/humidity sensors
Formation of rust and blockages of gauges because of fine silt (dust) and debris such as leaves
Sensors get damaged by livestock and wild animals (donkeys, horses, cattle, rodents, and ants) chewing off cables and sensors
Network failures; antenna cables disconnected or damaged; cell phone modems malfunctions

Figure 5:
Wasps inside the sensor causing false rainfall values at Kalimbeza weather station.

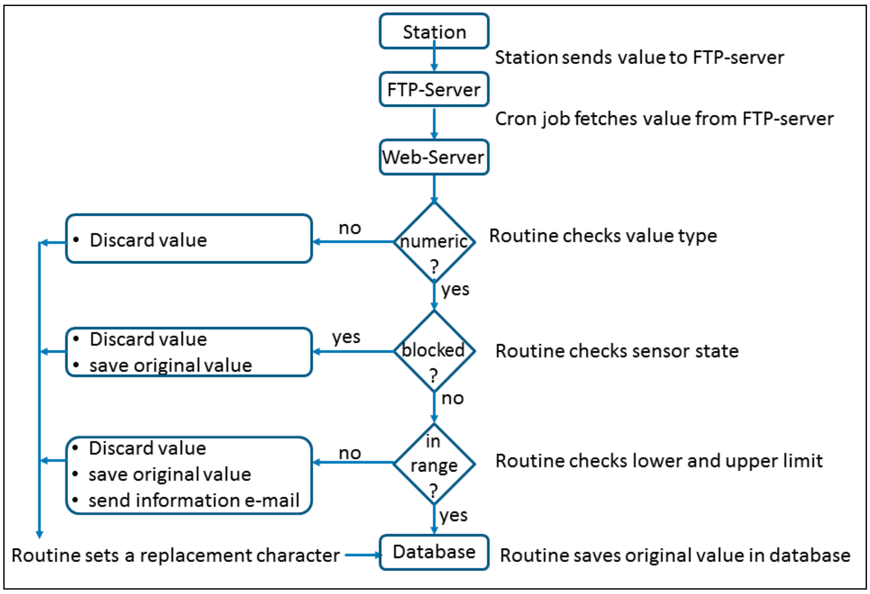

Figure 6: Flow diagram of data plausibility checks as part of data quality control procedures.

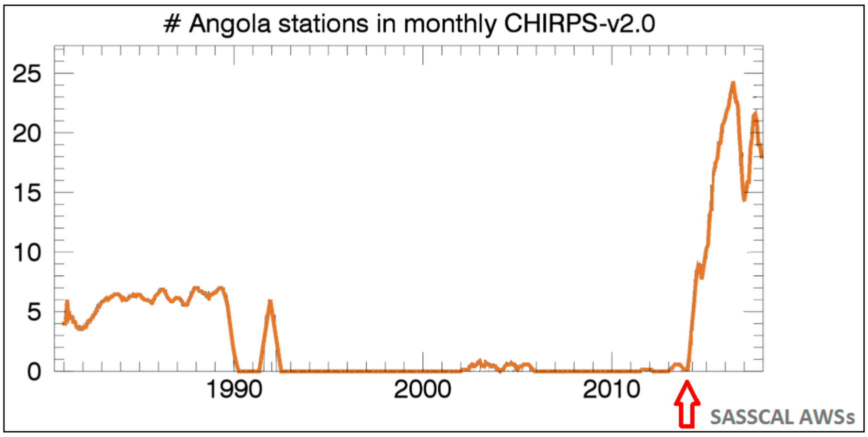

Figure 7: Number of weather stations in Angola in the monthly CHIRPS-v2.0, Climate Hazards Group Infrared Precipitation with Stations, ftp://ftp.chg.ucsb.edu/pub/org/chg/products/CHIRPS-2.0/diagnostics/stations-perMonth-byCountry/pngs/Angola.002.station.count.CHIRPS-v2.0.png (last access February 2018).

and allows users to inspect the current data in different temporal resolutions, from hourly values (or quarter-hourly, depending on the sensor) to daily and monthly averages. The data are visualized in the form of tables and intuitive diagrams. Small data packages can be downloaded by the user without restrictions. Bulk data are supplied on request.

The popularity of this data source is illustrated by the following web statistics (monthly figures for December 2017): 946,750 hits; 691,917 pages; 65,844,870 kB download; 5,230 different IP addresses ≈ visitors.

A special service is provided as a morning email: every day at 7:30 a.m. (GMT+2), an automated routine sends an email to a circle of currently 100 subscribers with the parameters of the previous day's rainfall and average, maximum, and minimum temperatures.

System architecture

The SASSCAL IT Team at the University of Hamburg uses a rented LINUX virtual server with Ubuntu OS 14.04 LTS 64bit + Plesk v12.5.30, memory 32 GB, storage 800 GB. The data are stored in a MySQL database and comprise more than 10 million rows in the tables with the finest (hourly or quarter-hourly) resolution. All the different routines and webpages are programmed with PHP.

Data applications and usage policy

The data were initially intended as a basis to understand changes in the environment resulting from the expected climate change in the following SASSCAL thematic areas: climate, water, agriculture, forestry, and biodiversity. Scientists in the SASSCAL consortium and collaborating researchers have used the time series extensively for both climatic research (e.g., Eiselt et al., 2017; Funk et al., 2015; Meyer et al., 2017; Siepker & Harms, 2017) and biological/ecological work (e.g., Strohbach & Kutuahuripa, 2014; Campbell et al., 2015; van Holsbeeck et al., 2016; Navarro et al., 2016; Scherer et al., 2016; Strohbach, 2017; Beyer et al., 2018). Another SASSCAL project supported the national meteorological services to improve the integration of data into their climate databases and internal processes (see Posada et al., 2016, 2018). In the meantime, data requests to SASSCAL are not only for the abovementioned topics but also from many other groups, which use the data for a variety of purposes such as road and infrastructure planning, wind and solar energy projects, fire management systems, and cooperation with other weather networks (e.g., Kenabatho et al., 2018; Kumwenda et al., 2017; Siepker & Harms, 2017). Additionally, data from the SASSCAL WeatherNet have been used in the creation of precipitation maps by CHIRPS since 2015 (Climate Hazards Group Infrared Precipitation with Stations; Funk et al., 2015). These are used in agroclimatology and food security monitoring systems such as FEWS-NET (Famine Early Warning Systems Network; Brown et al., 2007) and FLDAS (FEWS NET Land Data Assimilation Systems; McNally et al., 2017).

SASSCAL has a data usage policy that makes it easy for a data user to receive the data: 'Free use of the data is granted for non-commercial and educational purposes. Commercial use can be granted based on request to SASSCAL.' The most important condition is a citation of SASSCAL as data source: 'For any use SASSCAL has to be acknowledged as "SASSCAL WeatherNet (2017), www.sasscalweathernet.org"', as stated in the

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website section disclaimer. Commercial use of the data is not desired. The low inhibition threshold for sharing of the data and the discernible potential for use is a challenge for the team of the SASSCAL WeatherNet: the delivery of quality-tested data as file batches is fundamentally different from the continuous feeding of data into foreign systems and presents an additional burden to the data management team. If such commitments of data supply are made, conditions must be created for a continuous flow of data from the stations to the collecting server, quality assurance of the data close to the time of measurement, and postdelivery options for late-arriving data and updates. For these tasks, the organizational framework must be in place and the technology must be optimized. A necessary technical precondition is the establishment of data quality check routines (see 'Data processing and quality control').

Conclusions and outlook

At the end of the seven years of implementation, the question may be asked whether the abovementioned effort has been a worthwhile investment of resources. We come to an affirmative answer and regard the following points as crucial aspects:

1. There is no doubt that climate change is one of the major drivers of environmental and societal change (IPCC, 2015). Therefore, it is essential to provide robust measurements that inform on the direction and intensity of change.
2. In large areas of the SASSCAL region (more so in the northern than in the southern parts), the coverage of operating AWSs in 2010 was below one station per 100,000 km². This was a very poor overall spatial coverage compared to the geographical diversity within the SASSCAL region (Helmschrot et al., 2015; Kaspar et al., 2015). Except for in South Africa, which has a dense weather observation network, the majority of the stations in the other SASSCAL countries were located at major airports and cities while vast areas that are highly relevant for the formation of important meteorological processes were not covered. Studies in Sudan (70 stations, area ≈ 2.5 million km²) and Nigeria (28 stations, area ≈ 1 million km²) indicate station densities of 1 per 35,000 km² (Omer, 2008; Fadare 2010). Today SASSCAL operates an AWS network at a density of more than 60 stations per 1 million km² in its core areas. This figure is still low compared to industrialized countries, but it covers the spatial diversity of the SASSCAL region far better than ever before (see Fig. 7 with the number of Angolan weather stations used by CHIRPS, showing the increase in AWS numbers after a long period of civil war without data availability). The improved network is highly appreciated by climate researchers, who use the improved data for modelling, and by weather services, which integrate the new data into their forecasting.
3. With the observation network in place, allowing the capture of climate variability and supporting climate change assessments, researchers are now able to integrate field observations, environmental modelling, and measured biotic and social data with reliable and high-resolution climate data.
4. Although it was possible to apply for and obtain weather data from the national weather services in the past, the new open-access standard, jointly developed with the national weather services, allows easy and fast downloading of all data by every researcher and decision-maker. SASSCAL received a large number of letters that expressed appreciation for this improved access to urgently needed weather data in times of rapid climate change.
5. The openly accessible weather data of the SASSCAL WeatherNet allowed a wide availability of the most recent weather data and, therefore, an increased awareness of weather and climate change by the wider public. A striking example is regular rainfall reports in various print and radio media in Namibia based on SASSCAL WeatherNet data. The importance of these public-domain data has repeatedly been highlighted in statements made by many politicians.

In summary, we conclude that it was a very good investment by SASSCAL to set up the SASSCAL WeatherNet.

For the time ahead, it is particularly important to ensure that the measures taken in the years to come are sustainable and that moderate growth is achieved. The WeatherNet workshop 2017 (see 'History') emphasized the importance of AWS maintenance and capacity building with training in data management, archiving, data exchange, implementation of software, web development, satellite communication, and international data exchange.

To guarantee long-term data availability, the anchoring of knowledge in the SASSCAL region is important beyond the funding period of the SASSCAL project. The SASSCAL Open Access Data Centre (OADC) intends to take over the tasks of data management and online presentation, and the national meteorological services are ready to continue the maintenance of the AWSs handed over by SASSCAL.

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