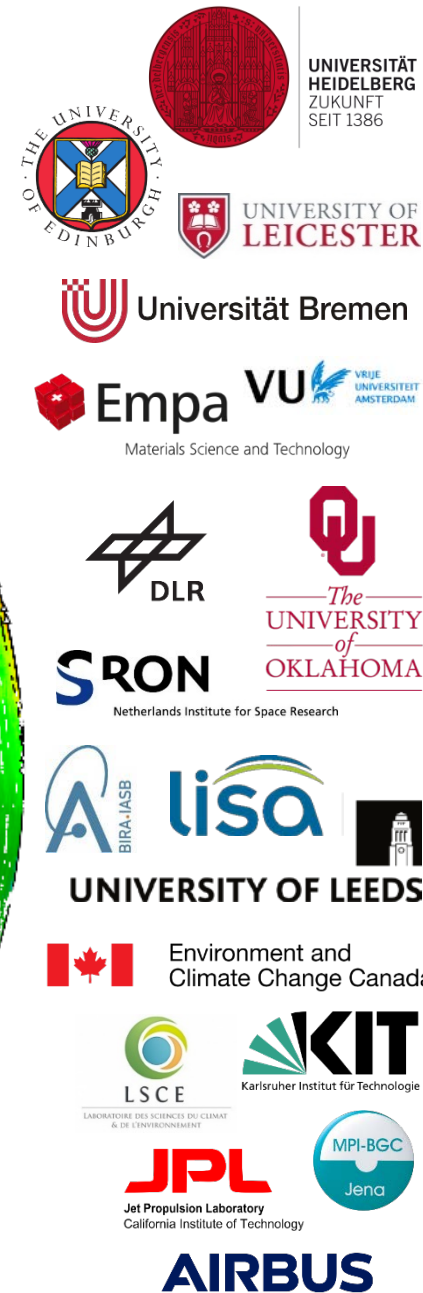
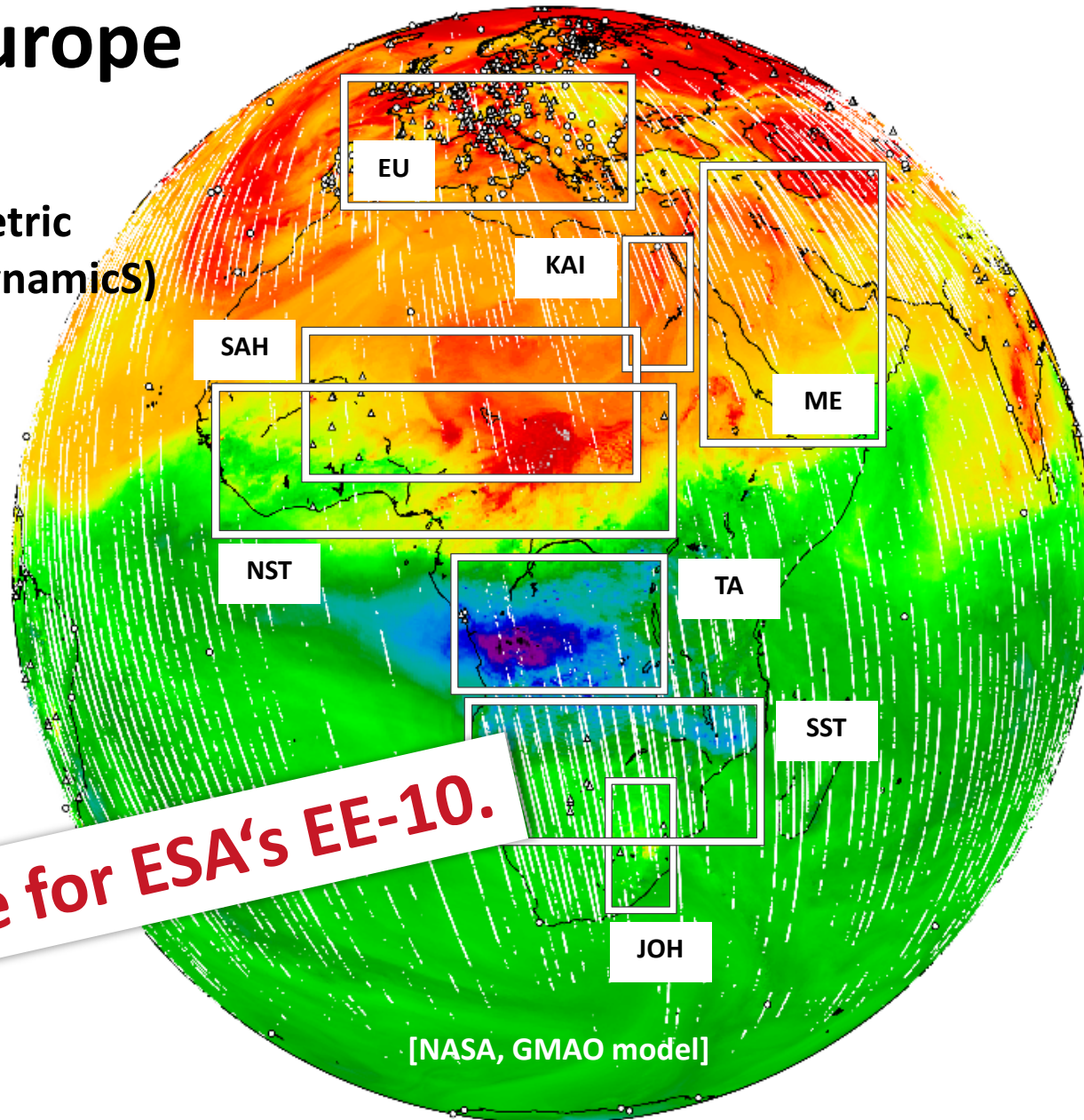


ARRHENIUS: a Geostationary Carbon Process Explorer for Africa, Europe and the Middle-East

(ARRHENIUS = Absorption spectrometric pathfinder for carbon regional flux dynamics)

- André Butz (PI, U Heidelberg, D)
- Paul Palmer (co-PI, U Edinburgh, UK)
- Hartmut Bösch (U Leicester, UK)
- Philippe Bousquet (LSCE, F)
- Heinrich Bovensmann (U Bremen, D)
- Dominik Brunner (EMPA, CH)
- Luca Bugliaro (DLR, D)
- David Crisp (JPL, USA)
- Sean Crowell (U Oklahoma, USA)
- Juan Cuesta (LISA, F)
- Bart Dils (BIRA-IASB, B)
- Emanuel Gloor (U Leeds, UK)
- Sander Houweling (U Amsterdam, SRON, NL)
- Jochen Landgraf (SRON, NL)
- Julia Marshall (MPI BGC, D)
- Charles Miller (JPL, USA)
- Ray Nassar (ECCC, CA)
- Johannes Orphal (KIT, D)
- Guido van der Werf (U Amsterdam, NL).

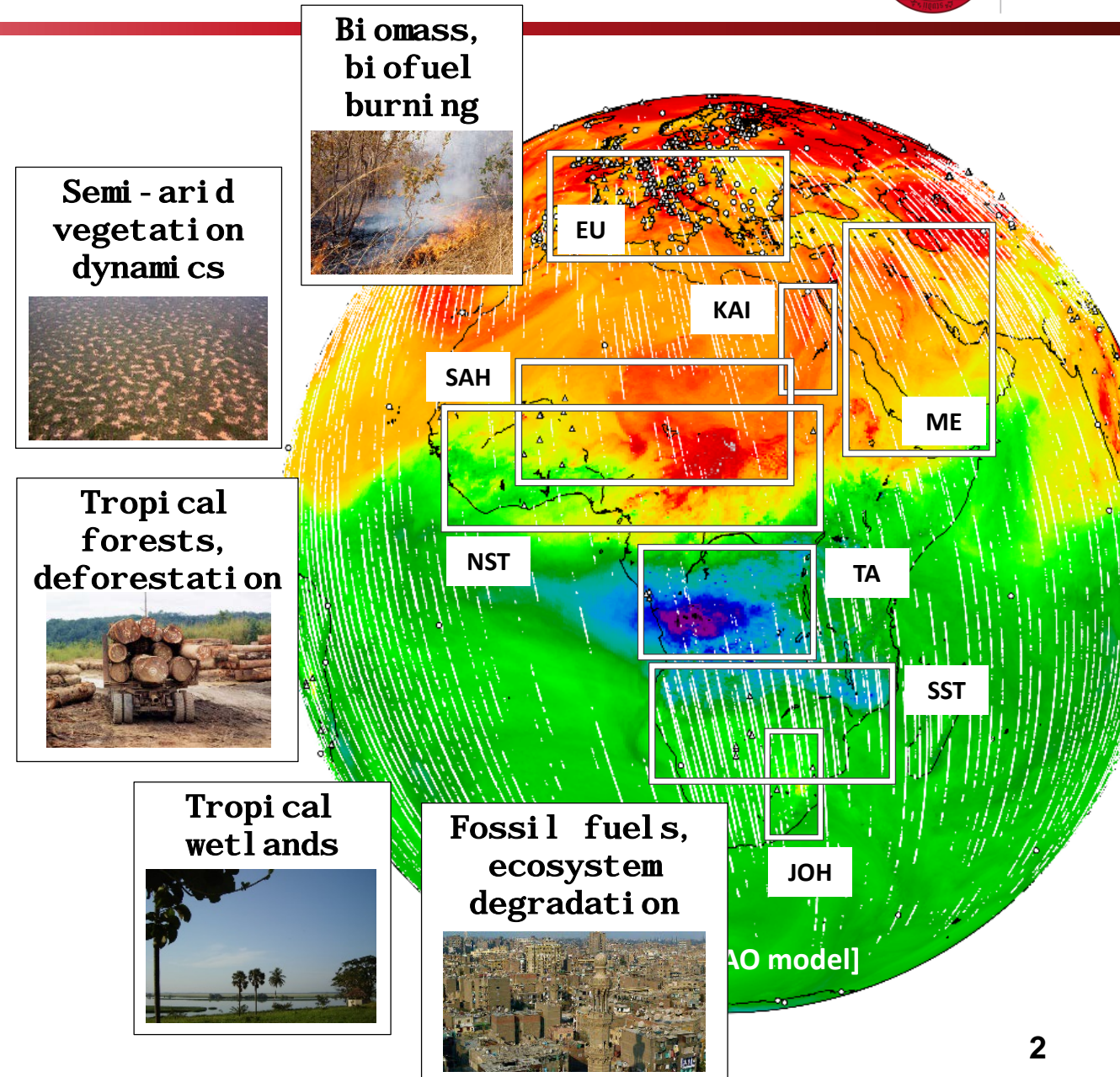


ARRHENIUS: a Geostationary Carbon Process Explorer



WHAT FOR?

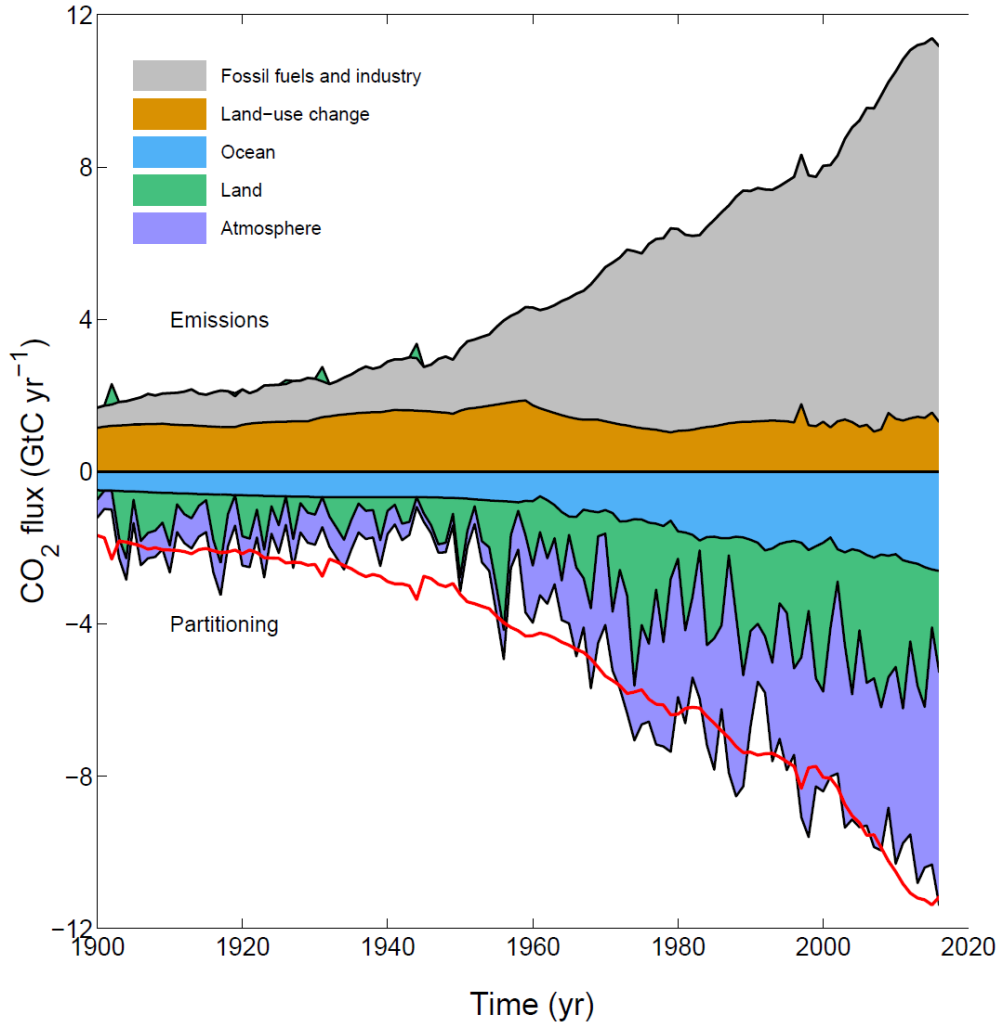
- Understand **terrestrial carbon cycle processes** that determine the **global carbon sink**.
- **Quantify carbon-feedbacks** in response to **climatic, meteorological, and human forcing**.
- Ultimately, improve the **carbon cycle representation** in Earth System Models to estimate **climate sensitivity**.



ARRHENIUS: a Geostationary Carbon Process Explorer



Sources and sinks of anthropogenic CO₂.



LeQuéré et al., ESSD, 2018

Semi-arid
vegetation
dynamics



Tropical
forests,
deforestation



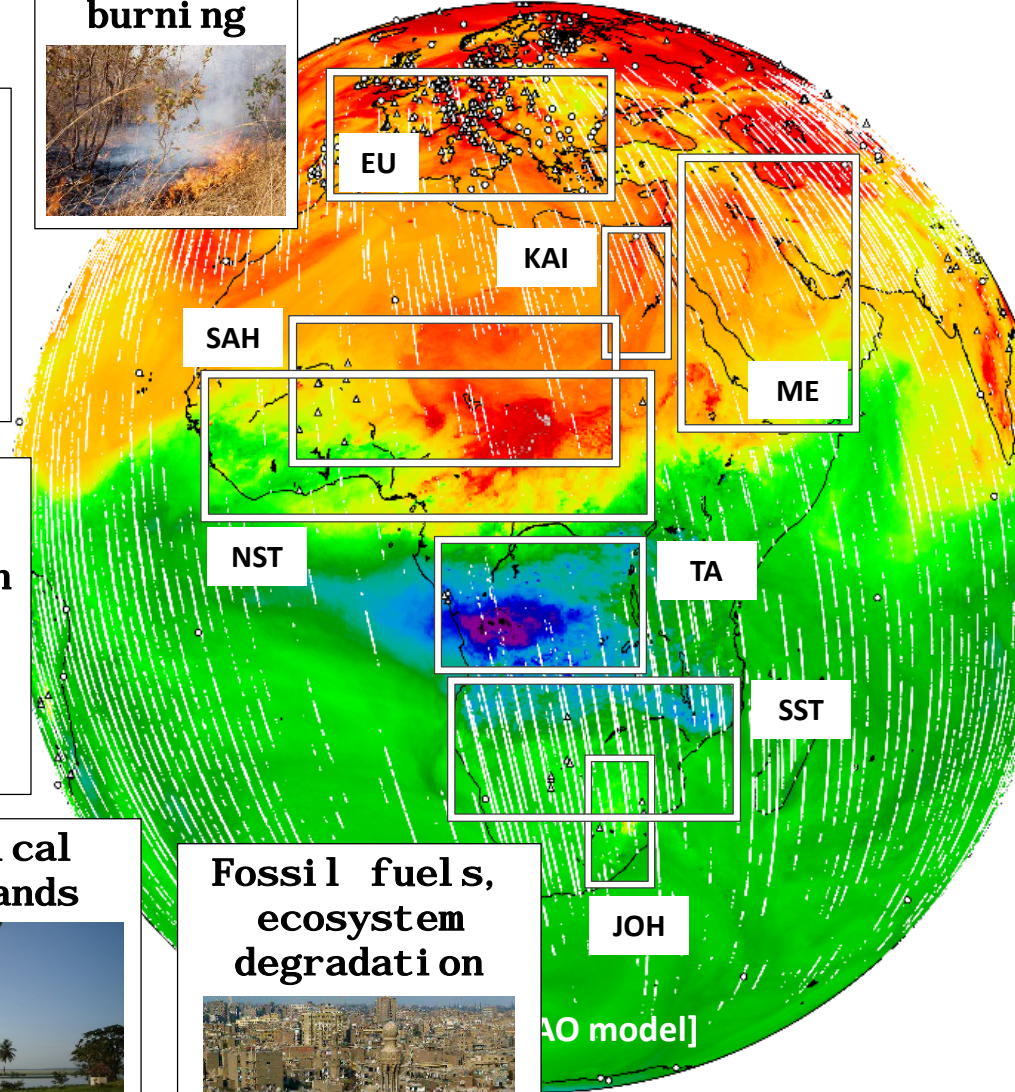
Tropical
wetlands



Biomass,
biofuel
burning



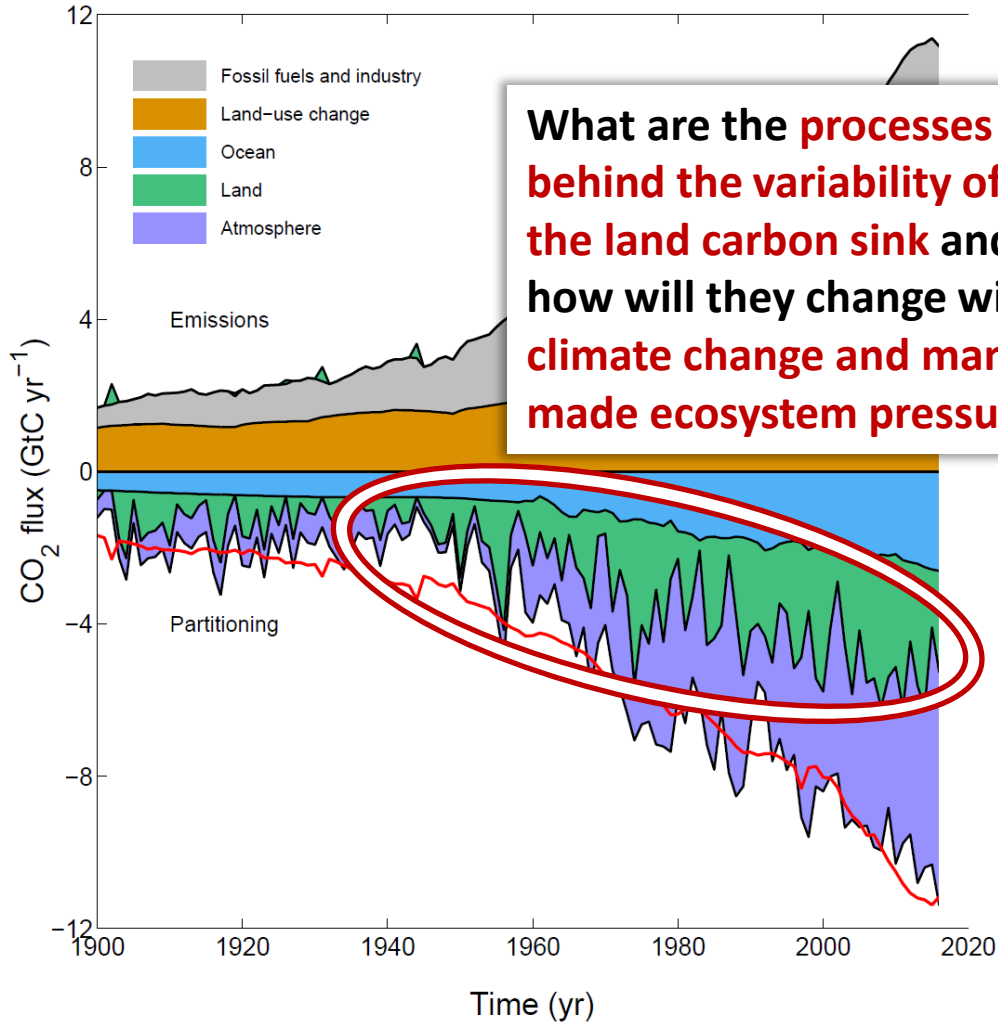
Fossil fuels,
ecosystem
degradation



ARRHENIUS: a Geostationary Carbon Process Explorer



Sources and sinks of anthropogenic CO₂.



What are the **processes behind the variability of the land carbon sink and how will they change with climate change and man-made ecosystem pressure.**

LeQuéré et al., ESSD, 2018

Bi omass, bi ofuel burni ng
 [Image of a forest fire]

Semi - ari d vegetati on dynami cs
 [Image of a semi-arid landscape]

Tropi cal forests, deforestati on
 [Image of a logging truck with logs]

Tropi cal wetl ands
 [Image of a tropical wetland]

Fossil fuels, ecosyst em degradati on
 [Image of an industrial site]

EU, KAI, SAH, ME, NST, TA, SST, JOH

[AO model]

WHY THERE? WHY THEN?

- The African continent is **heavily undersampled**.
- By 2030, **highest population growth** rates on the planet will be in Africa (growing **emissions and ecosystem degradation**).
- By 2030, Europe will **transition to a low-carbon** economy.
- Middle-East **fossil fuel industry will adapt** to changes in consumer patterns.

ARRHENIUS: a Geostationary Carbon Process Explorer

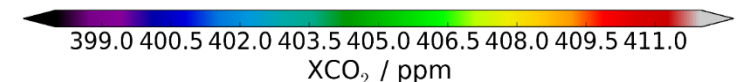
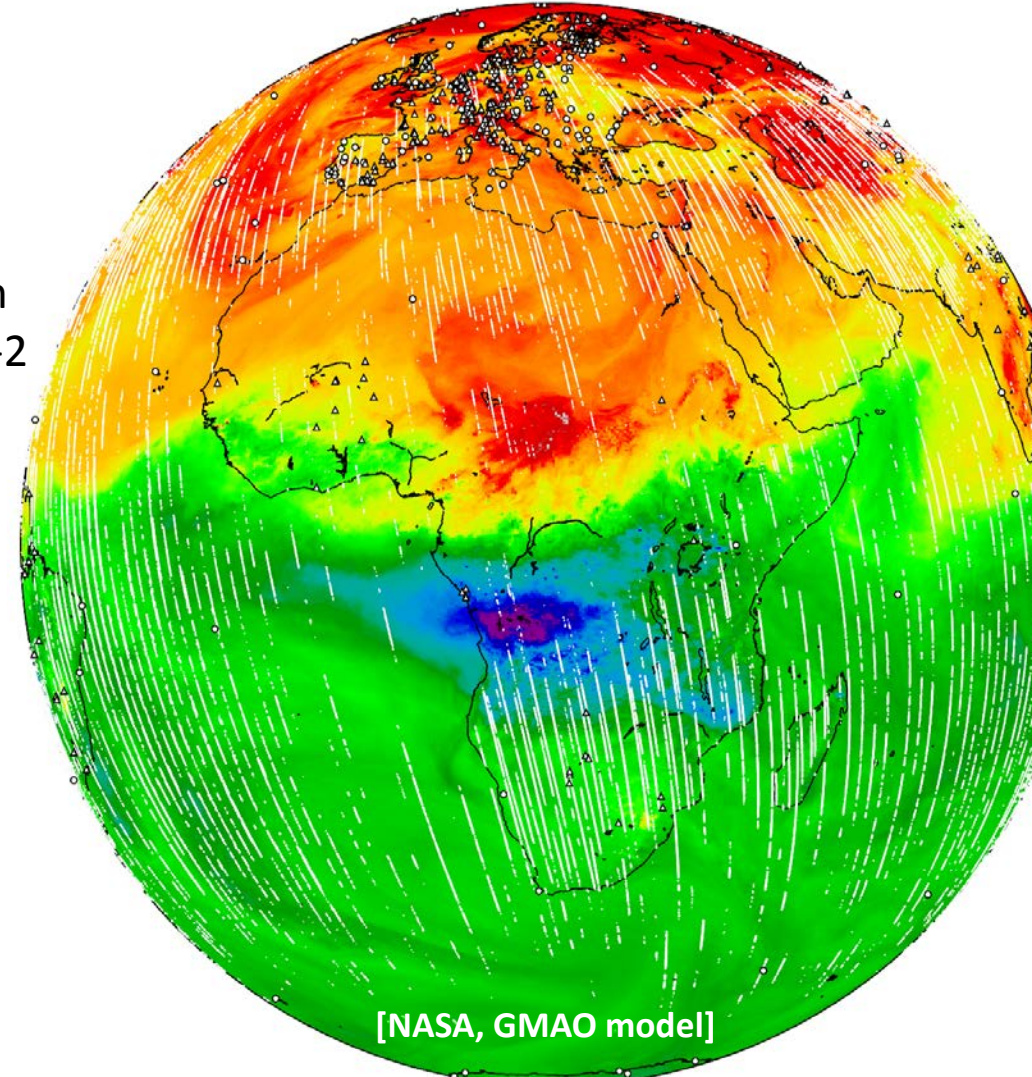


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We need denser sampling in space and time!

White stripes: 1 month of decent quality OCO-2 soundings; white dots and triangles: in-situ GAW stations and FLUXNET stations.



ARRHENIUS: a Geostationary Carbon Process Explorer

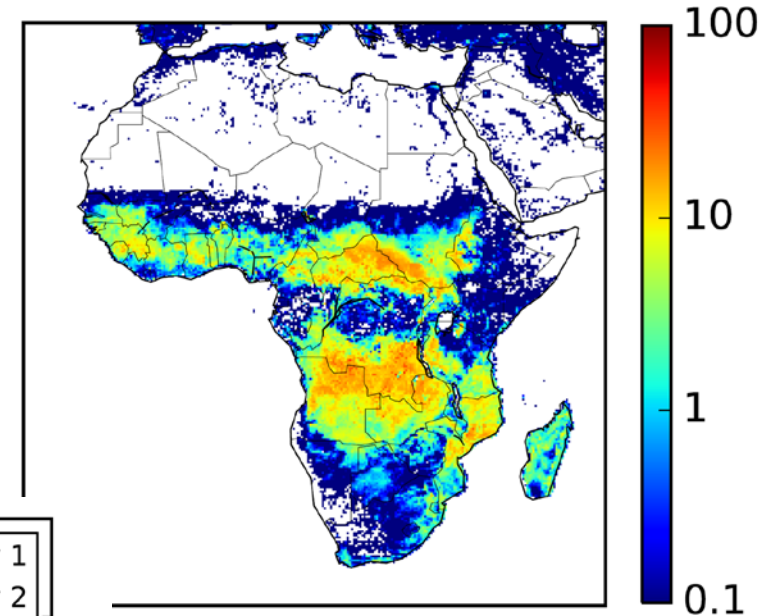


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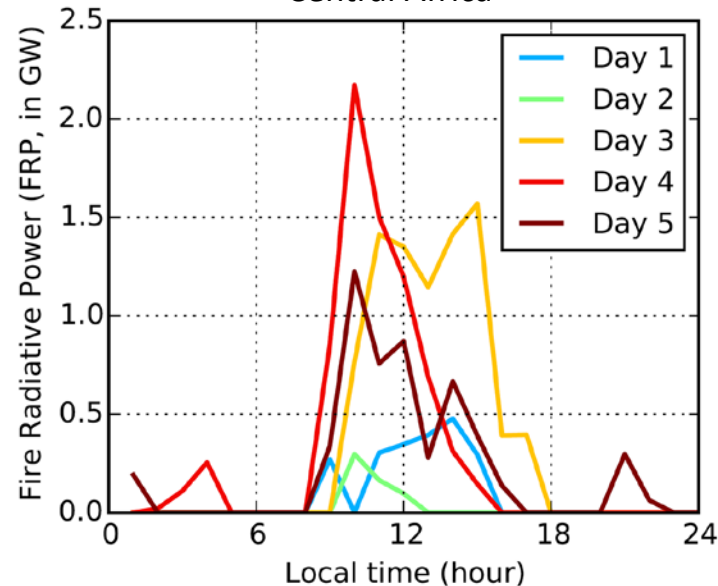
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CO emissions from fires
(average 1997-2016) [gCO/m²/a]



Diurnal cycle of fire emission for 5 illustrative consecutive days in Central Africa



ARRHENIUS: a Geostationary Carbon Process Explorer



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We need think in terms of 2030s and later!

Africa will dominate the worlds population dynamics (consequences: urbanization, ecosystem degradation).

Countries accounting for 75% of the worlds population change [UN-WPP, 2017]

Country or area	Annual population increase 2010-2015 (millions)	Cumulated percentage	Rank	Country or area	Annual population increase 2045-2050 (millions)	Cumulated percentage
India	15.615	18.4		1. Nigeria	7.904	14.8
China	7.455	27.2		2. India	4.496	23.2
Nigeria	4.521	32.5		3. Dem. Republic of the Congo	4.089	30.8
Pakistan	3.764	36.9		4. United Republic of Tanzania	2.982	36.4
Indonesia	3.128	40.6		5. Pakistan	2.787	41.6
Ethiopia	2.434	43.4		6. Ethiopia	2.410	46.1
Dem. Republic of the Congo	2.335	46.2		7. Uganda	2.258	50.3
United States of America	2.258	48.9		8. Niger	1.965	54.0
Egypt	1.934	51.1		9. Angola	1.729	57.2
Brazil	1.833	53.3		10. Egypt	1.572	60.1
Bangladesh	1.810	55.4		11. United States of America	1.507	63.0
Mexico	1.714	57.4		12. Iraq	1.497	65.8
Philippines	1.598	59.3		13. Kenya	1.407	68.4
United Republic of Tanzania	1.556	61.1		14. Mozambique	1.360	70.9
Uganda	1.246	62.6		15. Sudan	1.310	73.4
Turkey	1.189	64.0		16. Philippines	1.126	75.5
Kenya	1.177	65.4				
Iraq	1.071	66.7				
Viet Nam	1.020	67.9				
Afghanistan	0.987	69.0				
Iran (Islamic Republic of)	0.959	70.1				
Angola	0.898	71.2				
Sudan	0.852	72.2				
Saudi Arabia	0.826	73.2				
Mozambique	0.758	74.1				
Algeria	0.751	75.0				
South Africa	0.741	75.8				
WORLD	84.968	100.0		WORLD	53.523	100.0

ARRHENIUS: a Geostationary Carbon Process Explorer



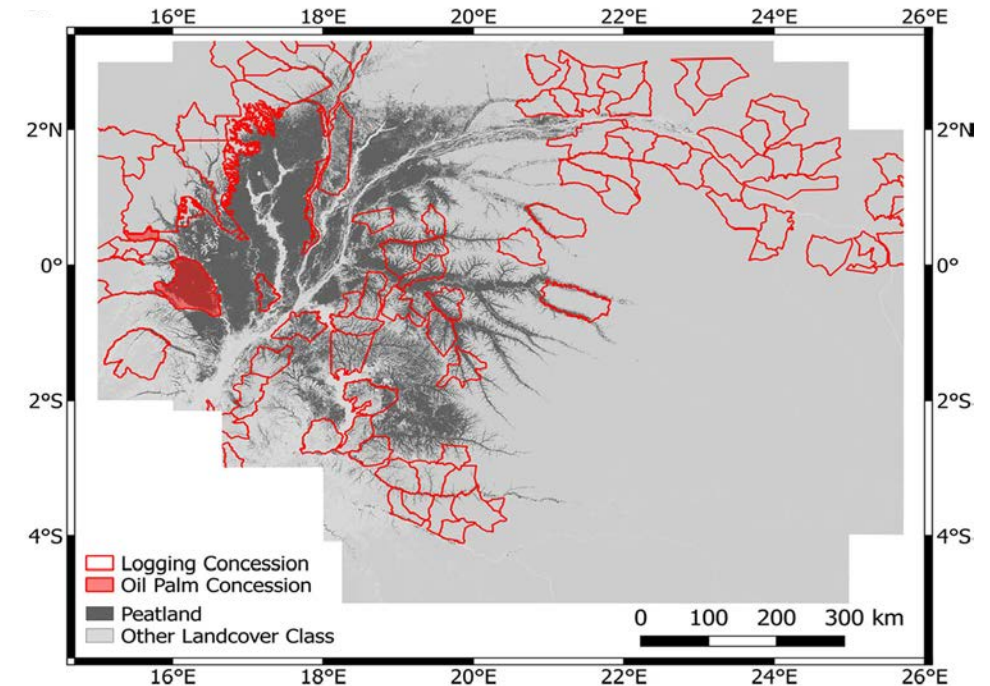
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Presumably world's largest tropical peatland area in Congo (Cuvette depression) – only discovered recently [Dargie et al., 2017]



Peatland within the Cuvette central depression threatened by logging and oil palm concessions [Figure 2a of Dargie et al., 2018, distributed under Creative Commons Attribution 4.0 International License.

ARRHENIUS: a Geostationary Carbon Process Explorer

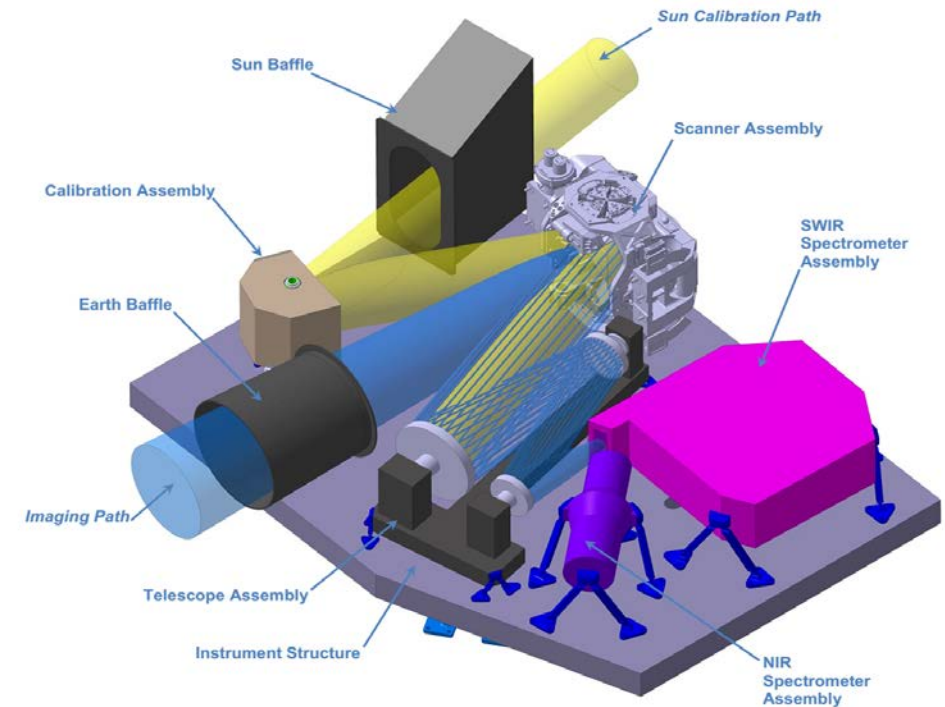


HOW?

- **Quasi-contiguous mapping** of atmospheric CO₂, CH₄, CO and SIF.
- **Freely selectable** scientific focus regions.
- **Flexible process-oriented sampling** approach.
- **Several region revisits per day** to study process dynamics.
- **Active and intelligent cloud avoidance** to overcome data scarcity.
- Lessen **sampling biases**, avoid **missing events** (e.g. fires), and reduce **data gaps**.

State-of-the-art imaging spectroscopy in solar backscatter configuration
(heritage: GOSAT, OCO-2, Sentinel-5, Sentinel-7)

Sketch of ARRHENIUS spectrometer assembly (aperture 12-15 cm)



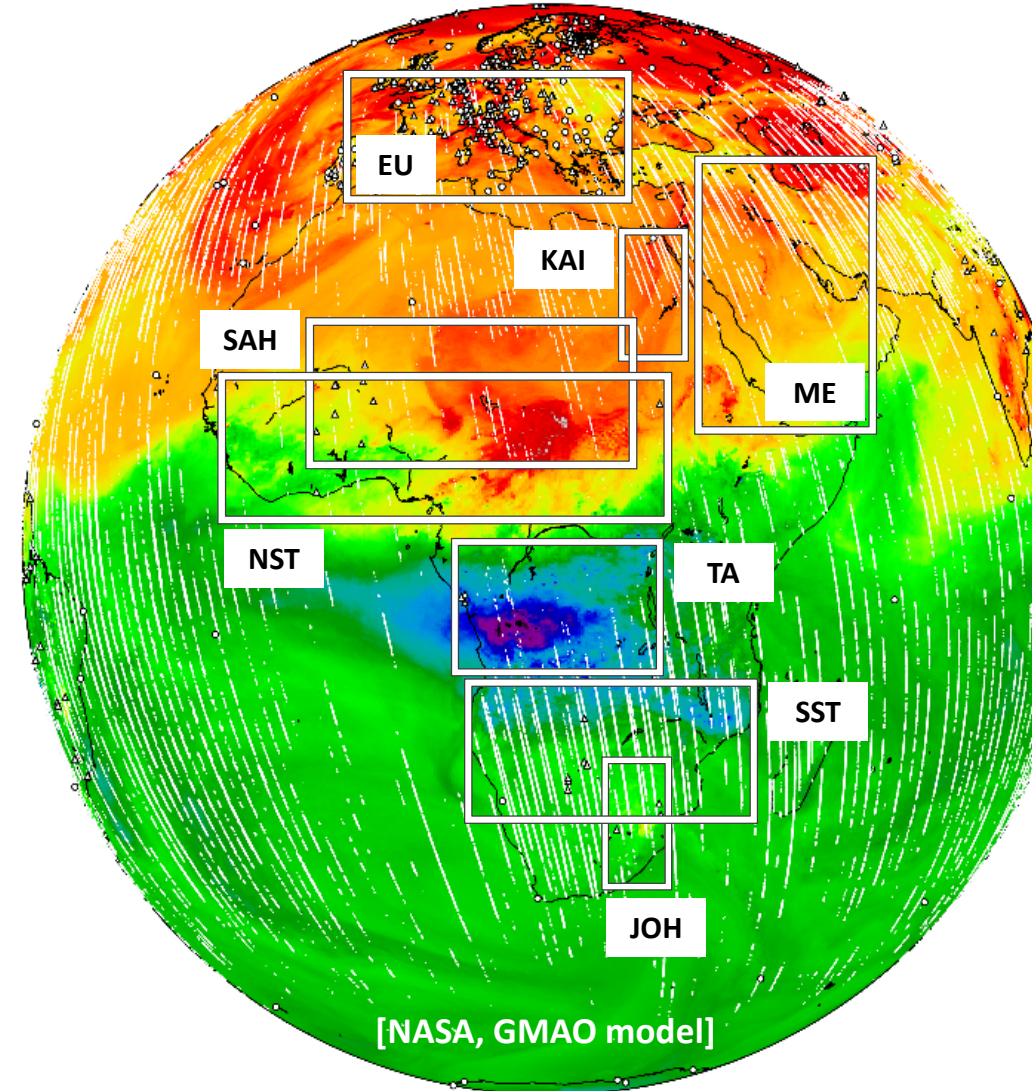
For details of instrument and performance see Butz et al., AMT, 2015.

ARRHENIUS: a Geostationary Carbon Process Explorer



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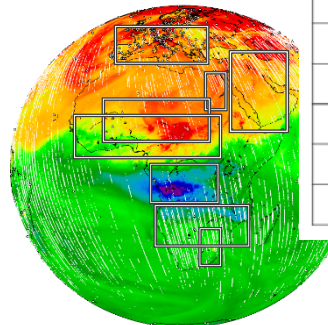


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Illustrative process-oriented observation schedule: to be consolidated.

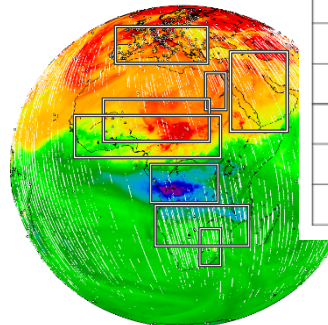
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Over-ruling priority	<div style="border: 1px solid green; padding: 2px; display: inline-block;">TA</div> whenever cloudless at most twice per day											
Priority chain	NST JOH ME VAL EU SST KAI SAH	NST JOH ME VAL EU SST KAI SAH	NST JOH ME VAL EU SST KAI SAH	EU ME SAH KAI JOH VAL SST NST	EU ME SAH KAI JOH VAL SST NST	SST EU ME SAH KAI VAL JOH NST	SST EU ME SAH KAI VAL JOH NST	SST EU ME SAH KAI VAL JOH NST	SAH SST EU KAI JOH VAL ME NST	SAH SST EU KAI JOH VAL ME NST	NST JOH ME VAL EU SST KAI SAH	NST JOH ME VAL EU SST KAI SAH
<5UT					ME	ME	ME	ME	VAL	VAL	VAL	VAL
5UT	VAL	VAL	VAL	VAL	VAL	VAL	VAL	VAL	ME	ME	ME	ME
6UT	ME	ME	ME	ME	VAL	VAL	VAL	VAL				
7UT	JOH	JOH	JOH	KAI	KAI	SST	SST	SST	KAI	KAI	JOH	JOH
8UT	NST	NST	NST	EU	EU	EU	EU	EU	SAH	SAH	NST	NST
9UT				EU	EU	SST	SST	SST	SST	SST		
10UT	JOH	JOH	JOH	KAI	KAI	VAL	VAL	VAL	KAI	KAI	JOH	JOH
11UT	NST	NST	NST	SAH	SAH	EU	EU	EU	SAH	SAH	NST	NST
12UT	VAL	VAL	VAL	VAL	VAL	SST	SST	SST	VAL	VAL	VAL	VAL
13UT	JOH	JOH	JOH	EU	EU	EU	EU	EU	SST	SST	JOH	JOH
14UT	NST	NST	NST	EU	EU	EU	EU	EU	SAH	SAH	NST	NST
15UT				KAI	KAI	SST	SST	SST				
16UT	JOH	JOH	JOH	SAH	SAH	VAL	VAL	VAL	KAI	KAI	JOH	JOH
>16UT	VAL	VAL	VAL	VAL	VAL				VAL	VAL	VAL	VAL

ARRHENIUS: a Geostationary Carbon Process Explorer



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<5UT			VAL								VAL	VAL
5UT	VAL	VAL	VAL								ME	ME
6UT	ME	ME	ME								KAI	JOH
7UT	JOH	JOH	JOH								SAH	NST
8UT	NST	NST	NST								SST	JOH
9UT				EU		SST	SST	SST	SST	SST	JOH	JOH
10UT	JOH	JOH	JOH	KAI	KAI	VAL	VAL	VAL	KAI	KAI	NST	NST
11UT	NST	NST	NST	SAH	SAH	EU	EU	EU	SAH	SAH	VAL	VAL
12UT	VAL	VAL	VAL	VAL	VAL	SST	SST	SST	VAL	VAL	VAL	VAL
13UT	JOH	JOH	JOH	EU	EU	EU	EU	EU	SST	SST	JOH	JOH
14UT	NST	NST	NST	EU	EU	EU	EU	EU	SAH	SAH	NST	NST
15UT				KAI	KAI	SST	SST	SST				
16UT	JOH	JOH	JOH	SAH	SAH	VAL	VAL	VAL	KAI	KAI	JOH	JOH
>16UT	VAL	VAL	VAL	VAL	VAL				VAL	VAL	VAL	VAL

We suggest to explore an **on-demand scheduling system** driven by scientific user needs?

ARRHENIUS: a Geostationary Carbon Process Explorer

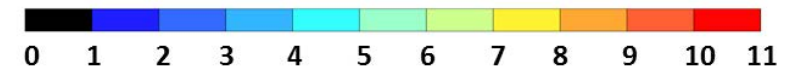
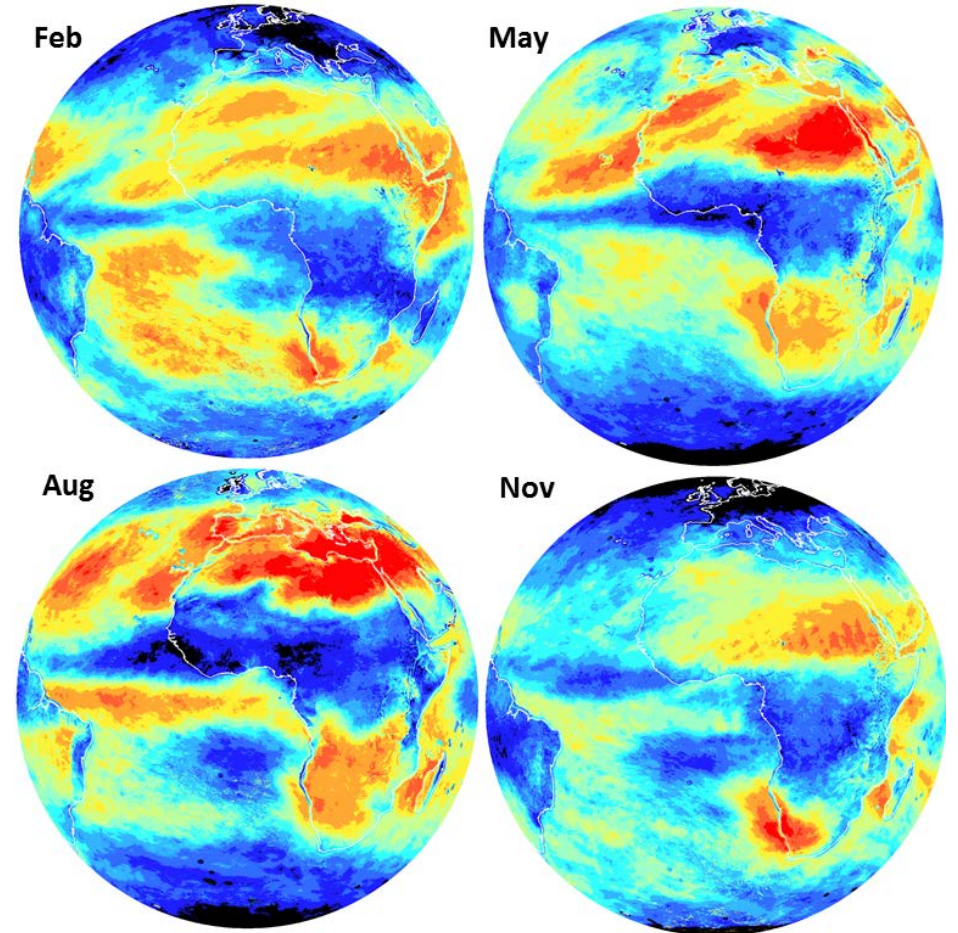


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Active cloud-avoidance through near-real-time cloud information from MTG-FCI, i.e. **point to the focus regions at the right time.**

SEVIRI-based clear-sky (opt. thickness <0.1) hours for 2013



Monthly mean clear-sky daily hours

HOW DOES IT FIT INTO GLOBAL GHG OBSERVATIONS?

- ARRHENIUS will be the **process-oriented complement** to the surveillance missions **Sentinel-5** and **Sentinel-7**.
- In fact, ARRHENIUS needs **LEO missions** to provide **the global carbon context and boundary conditions** for its focus region approach.
- **Meteosat Third Generation – Flexible Combined Imager** will be ARRHENIUS' companion instrument providing cloud-cover information that will **guide pointing to cloudless regions** with short lead times.
- Other synergies open with **MTG-S4** (e.g. NO₂, HCHO), **MTG-IRS** (CO, aerosols), **land surface** carbon missions (e.g. BIOMASS, FLEX).
- ARRHENIUS could be the **European contribution to a GEO-Greenhouse Gas constellation** together with a GeoCarb(-follow-on) and an Asian contribution.

ARRHENIUS: a Geostationary Carbon Process Explorer

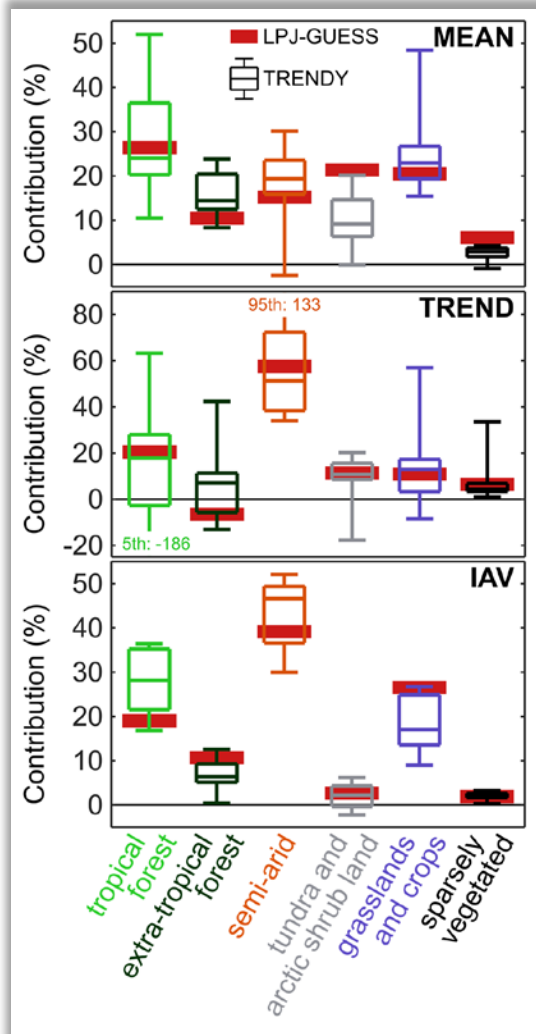


ARRHENIUS: a Geostationary Carbon Process Explorer



Semi-arid regions (vegetation dynamics, biomass burning, ...) and tropical forests control the trend and the interannual variation (IAV) of the land carbon sink.

Fractional contribution to the land carbon sink (mean, trend, IAV)



Modified from Ahlström et al., 2015.

Biomass, biomass burning



Semi-arid vegetation dynamics



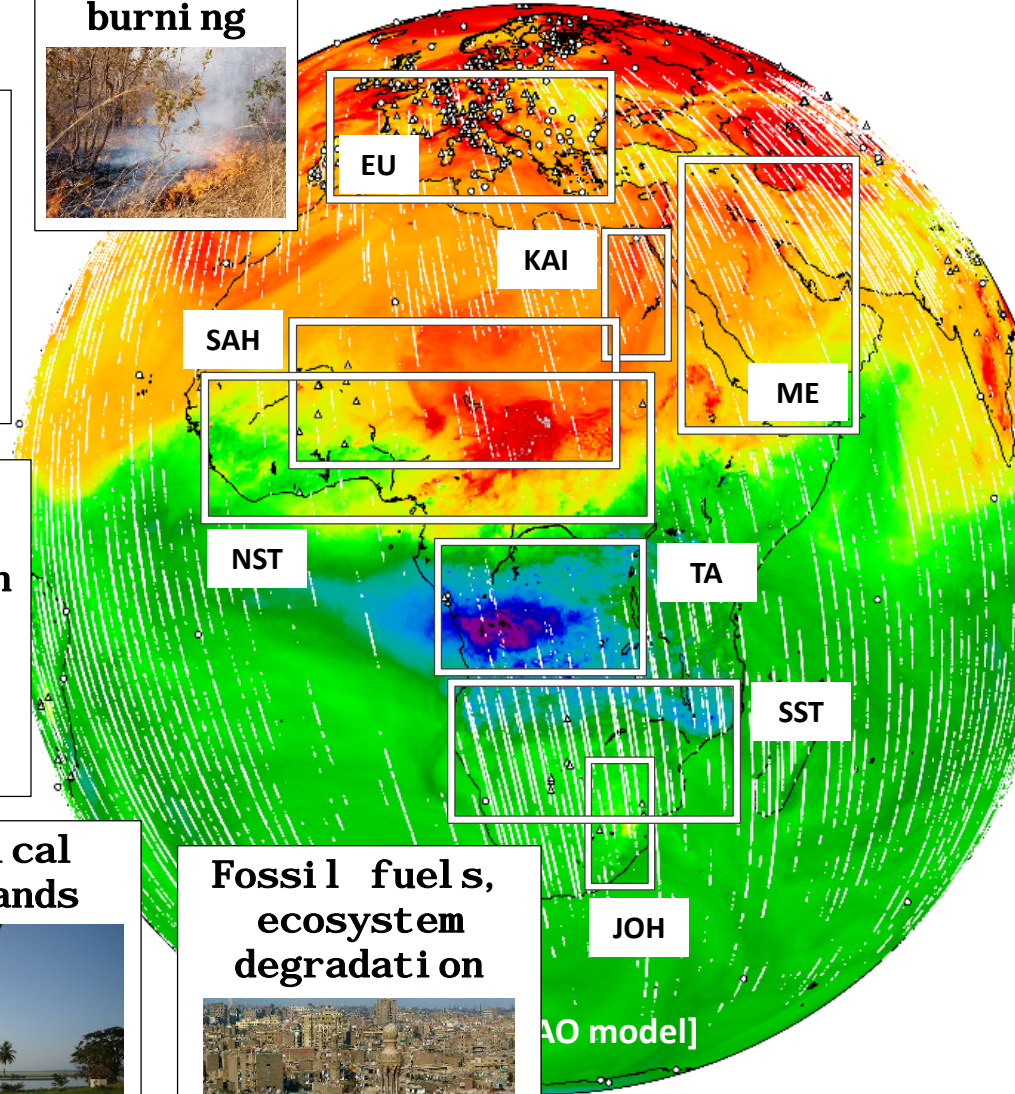
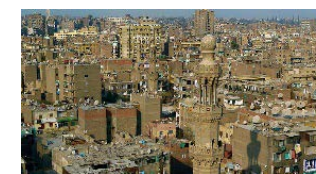
Tropical forests, deforestation



Tropical wetlands



Fossil fuels, ecosystem degradation



ARRHENIUS: a Geostationary Carbon Process Explorer

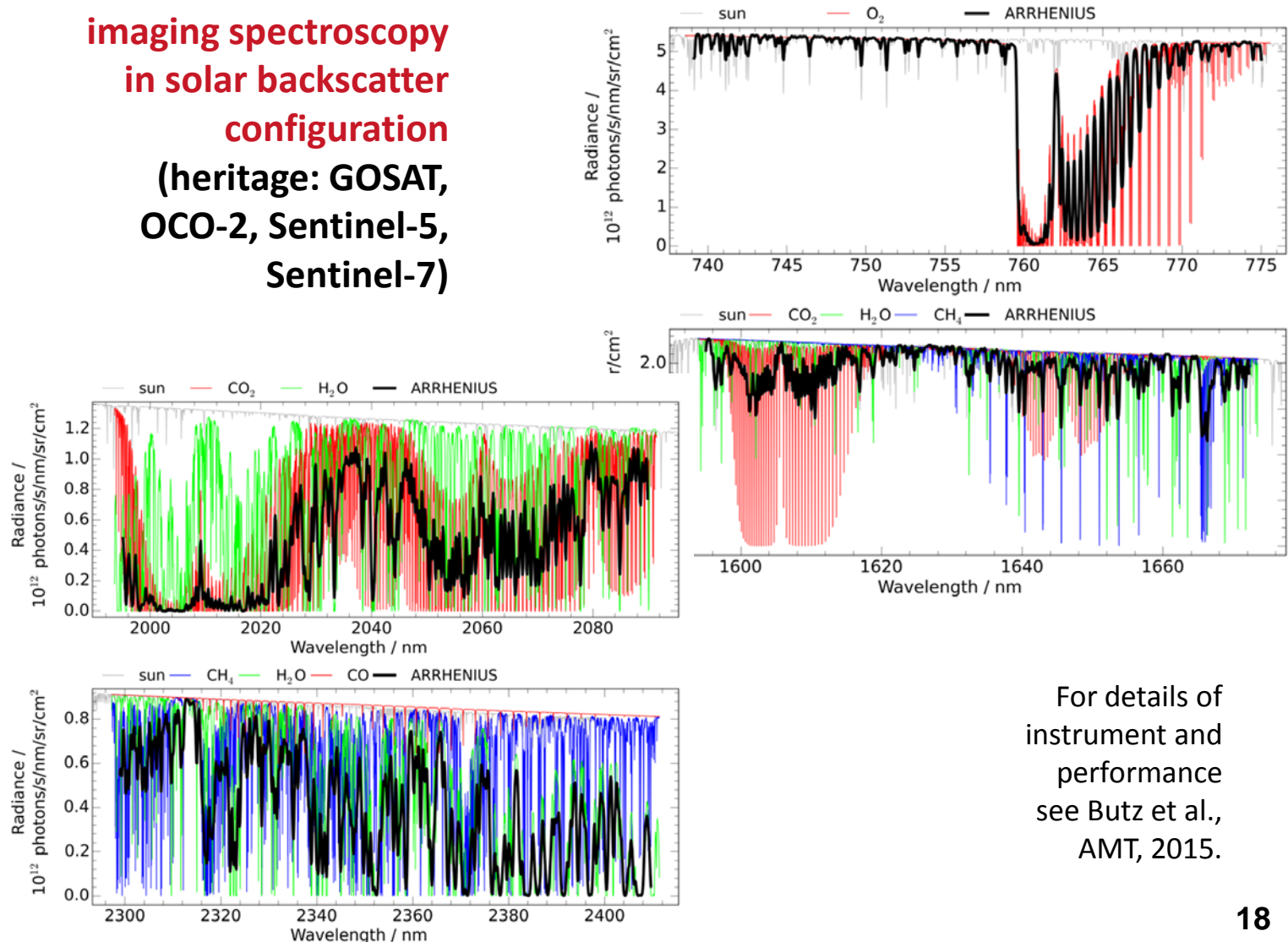


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**State-of-the-art
imaging spectroscopy
in solar backscatter
configuration**
(heritage: GOSAT,
OCO-2, Sentinel-5,
Sentinel-7)

Typical ARRHENIUS measurements
(above dark surface)



For details of
instrument and
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see Butz et al.,
AMT, 2015.

ARRHENIUS: a Geostationary Carbon Process Explorer

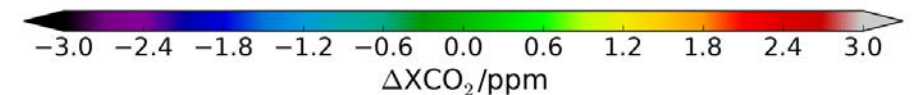
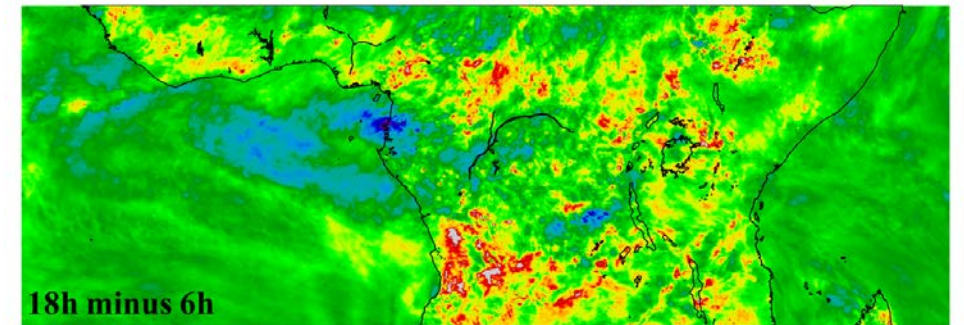
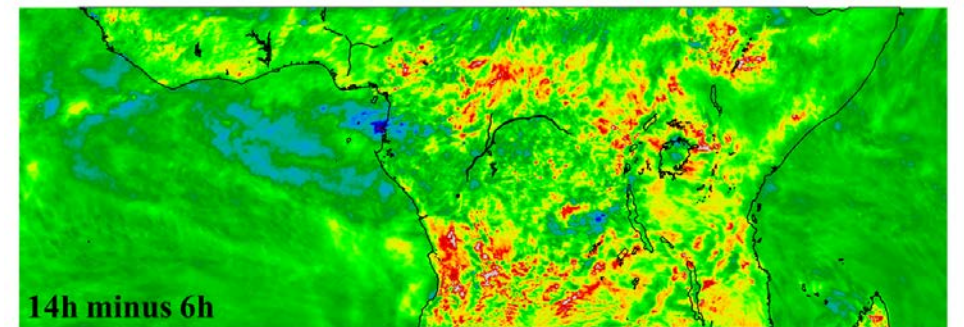
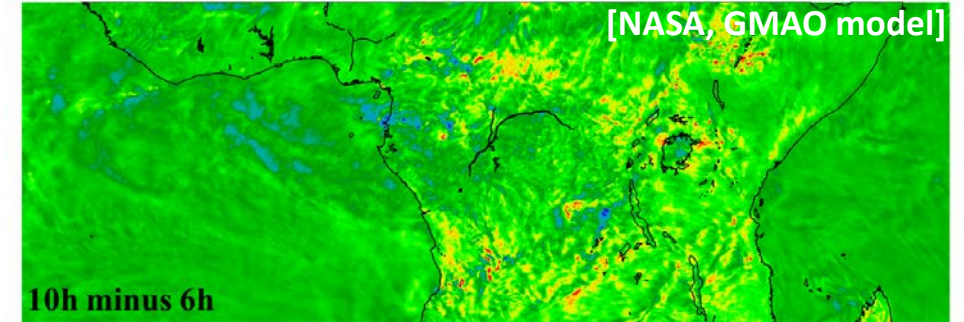


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Daytime differences in XCO₂: gain insight into **process dynamics** through **sub-daily temporal resolution**.

... and through **process marker (CO, SIF, NO₂, HCHO) fingerprinting**



ARRHENIUS: a Geostationary Carbon Process Explorer



... in a nutshell ...

- Understand **terrestrial carbon cycle processes** and **climate-carbon feedbacks** in regions that are currently **severely undersampled**.
- African carbon cycle **highly variable and uncertain**; African will lead **population dynamics by 2030**.
- **Quasi-contiguous mapping** of atmospheric CO_2 and CH_4 together with **process markers (CO, SIF)**.
- **Scientific focus regions** sampled **several times per day** to avoid missing events, sampling biases.
- Active **cloud-avoidance** through cloud-informed pointing (via **MTG-FCI**).
- ARRHENIUS needs **LEO (S5, S7, ...) carbon context**; ARRHENIUS needs **meteorological sounders** (MTG, ...).
- ARRHENIUS will be the **explorative process-oriented asset** of a global atmospheric composition constellation (e.g. together with other **GEO** missions, **HEO** missions, **land surface carbon** missions ...)

