RESEARCH PROGRAMME FOR EARTH OBSERVATION
STEREO III

TEAM

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THEME

Global warming is expected to increase the frequency and severity of droughts, extreme precipitation events and heatwaves. Yet, the recent Intergovernmental Panel of Climate Change (IPCC) AR5 report remains inconclusive on this matter and reveals surprisingly large discrepancies among the different studies of past trends. These discrepancies partly result from the limited availability of global-scale observations to evaluate the skill of climate models at representing these climatic extremes. Additionally, recent studies have underlined the critical impacts that these extremes have on the terrestrial carbon cycle, particularly on the dynamics of vegetation. A poor model representation of climate extremes and their impacts on vegetation will undoubtedly lead to uncertainties in our climate predictions for the future. This hinders society capabilities for long-term management and adaptation. However, recent advances in satellite Earth observation – with the development of consistent global historical records of crucial environmental and climatic variables – now start to provide the means to unravel the processes driving climate extremes, uncover the spatiotemporal scales at which they operate, and understand their impact on terrestrial biomass.

The SAT-EX project uses recent satellite-based datasets to study the global spatiotemporal variability of wet, dry and warm spells over the past three decades, and their associated impacts on the global vegetation dynamics. Results will reveal how droughts, heatwaves and extreme rain events have changed in frequency and intensity, and uncover the causes behind these changes and their consequences for vegetation dynamics. Moreover, the ability of our current IPCC climate models to estimate these processes will be evaluated. In the long run, our findings will advance towards the timely forecasting of climate extremes, provide valuable insights about the management of water resources during these extreme events, help improve global terrestrial carbon budgets, and reduce the uncertainty in long-term climate model predictions of climate extremes global vegetation dynamics.

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CONTEXT

Meteorological droughts, rainfall extremes and heatwaves are major natural disasters with diverse socio-economical and environmental consequences. There is a perception that these climatic events are becoming unusually abundant after recent droughts in Western United States (2011) or North-Eastern China (2009), unprecedented wet periods accompanied by floods in U.K. (2007) or Pakistan (2010), and unparalleled mega-heatwaves in Europe (2003, 2010). These events caused the failure of the agricultural and food production systems, natural biomass loss, the spread wild fires, air pollution, water scarcity, and multiple other consequences that raised the mortality tolls by tens of thousands[1,2]. As we progress into the future, our climate models predict that the exacerbation and proliferation of such events will continue, following the expected rise in greenhouse gases[3].

There are several reasons why climate extremes are affected by the global rise in temperatures. Heatwaves will unavoidably exacerbate as average and variability of global temperatures continues increasing. Yet, higher temperatures also mean more intense terrestrial evaporation, which is expected to aggravate dry conditions in regions that are already dry, and increase the volume and rates of precipitation in regions that are wet. This 'wet-gets-wetter, dry-gets-drier' hypothesis is currently intensively investigated within the fields of climate and hydrology[4]. In addition, climate models also predict other, more indirect, effects of global warming on climate extremes. For instance, the rise in temperatures may lead to a global reorganization of the hydrological cycle with a polewards migration of current climatic regions; this widening of the tropical belt implies an overall reduction in the input of rainfall to mid latitudes[5] and a subsequent intensification of regional land-atmosphere feedbacks that may further intensify droughts and heatwaves[6]. Moreover, a series of biotic feedbacks on climate can also be expected, as the intensification of climate extremes can severely impact vegetation biomass, reducing the efficiency of land as a sink of CO_2[7].

Up to date, the expectations of a future aggravation of climatic extremes, and the impact that this aggravation may have on Earth's vegetation, remain to a large extent speculative. This limits the societal capabilities for long-term adaptation. Observational evidence of trends in magnitude and variability of extreme precipitation and temperature spells is still scarce, and without observational evidence, climate model representation of extremes is condemned to remain uncertain. Just recently, the AR5 report of the Intergovernmental Panel of Climate Change (IPCC) has underlined the current disagreements in studies of past changes in these climate extremes, particularly for the case of droughts[8]. These discrepancies raise due to **(a)** the limited availability of observational datasets that can be used to evaluate past changes in these extremes at the global scale and over multidecadal periods, **(b)** the shortcomings of statistical and physically-based methods typically used to detect these changes, **(c)** the confronting scales at which these processes operate and the importance of disentangling the effects of multi-year ocean-atmospheric oscillations from longer-term trends. These inconsistencies among existing studies were already noted in the IPCC AR4 report (2007)[9] and could not be solved before the new AR5 (2013); therefore, the understanding of recent changes in climate extremes and the effects they had on biomass is considered as a major milestone for the AR6 report, scheduled to be released by the end of 2018[10].

Conveniently, advances in satellite Earth observation in recent years have culminated with the development of consistent global historical records of environmental and climatic variables that are critical for the study of these extreme events. Novel continuous datasets of soil moisture, vegetation water content and land evaporation have been derived by merging multi-satellite information since the late '70s[11,12]. These remote sensing datasets share the large-scale advantage of climate models with the observational nature of meteorological measurements. This confers them great potential as a mean to study global changes in past extreme events, but also as an observational benchmark to evaluate climate models[13]. These new datasets can be combined with *in-situ* measurements and more conventional satellite-based global products of precipitation, temperature or vegetation properties, in order to: **(a)** unravel past global changes in frequency and severity of extreme precipitation and temperature spells, **(b)** uncover the spatiotemporal scales at which the processes driving these changes operate, **(c)** give evidence of the global impact of droughts, heatwaves and extreme rainfall events on terrestrial vegetation, **(d)** allow climate model selection and improvement on the basis of the model's skill to represent changes in climate extremes and their impacts on biomass.

Some recent studies have already used these datasets on their own with the focus of studying past climate extremes[14,15]. Others have applied them with the explicit goal of evaluating climate model representation of general average hydrological patterns[13,16,17], and more recently to evaluate the representation of heatwaves in Europe[18]. Conversely, the Global Climate Model (GCM) representation of climate extremes has also been evaluated by comparison to reanalysis and *in-situ* measurements[19,20]. However, to our knowledge, long-term remote sensing datasets have not yet been applied to evaluate the global-scale variability of precipitation and temperature extremes in climate models, neither to identify the drivers responsible for the ongoing changes in these extremes nor their impacts on global vegetation dynamics. The objectives of SAT-EX strive in that direction. Two statistical techniques – that have gained popularity in recent years in other fields of research – appear optimal for our analysis: the *random forest* machine-learning technique and the *fingerprint* analysis[16,17]. These techniques are applied to analyse *climate extreme indices*[21] and vegetation fields derived from our multi-decadal satellite records and from IPCC CMIP5 Earth System Models (ESMs).

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OBJECTIVES

1. To provide new **observational evidence of how droughts, heatwaves and extreme high rainfall events have changed** in frequency and intensity during the past three decades and at the global scale.
2. To **attribute the causes of these changes** (e.g., intensification of the hydrological cycle, the widening of the tropical belt, ocean-atmospheric oscillations, etc.) and **gain understanding about their sensitivity** to specific climatic and environmental variables.
3. To provide new insights into **past global changes in vegetation distribution and dynamics**, and uncover the **impact of extreme hydrological and climatic events** on these vegetation changes.
4. To show if the spatiotemporal variability of **past hydrological and climatic extremes from the IPCC climate models agrees with that revealed by the remote sensing data**.
5. To test the **skill of IPCC climate models at representing the vegetation response to changes in extremes**.
6. To **rank IPCC climate models on the basis of their skill** at representing the evolution of past climate extremes and the subsequent impacts on vegetation.

METHODS

The term 'extreme' is applied to those climatic events that are significantly larger than expected, considering a non-changing (stationary) climate as reference. While this concept still depends on the definition of stationary conditions and the setting of extreme thresholds, a wide range of statistical indices have been used in recent years aiming to minimize the subjectivity on the characterization of extreme events. Yet, analysing these events is challenging given that, by definition, their frequency of occurrence is low. This is especially problematical when using remote sensing data due to the characteristic short lifespan of satellite platforms and sensors. However, recent scientific efforts have yielded global records of climatic and environmental variables through the combination of data from multiple satellite sensors. In this blending of multi-sensor data, several cross-calibration techniques have been applied, validation exercises against *in situ* measurements performed, and error estimates calculated. Now, records of 30–35 years are available for some variables (e.g., temperature, soil moisture, vegetation greenness, evaporation). This timespan is still short, but appears long enough to assess some of the critical aspects of the changes in frequency and severity of climate extremes in recent decades.

Assuming a sufficiently long, high-quality time series of a given climatic variable (e.g. precipitation, temperature), the number of extremes should remain constant over time for a stationary climate. Therefore, if a trend in the number or intensity of these extremes were detected, this would be indicative of climate change, i.e. a long-term change in the mean and/or the shape of the probability density function of that climatic variable. In our context, this climatic change may reflect: **(a)** the direct impact of greenhouse gases, aerosols or land-use change on the radiation budget, **(b)** the subsequent intensification of the hydrological cycle, **(c)** a reorganization of the large-scale preferential climatic and hydrological patterns (e.g. the widening of the tropical belt), **(d)** the 'confounding effects' from multi-year and decadal ocean-atmosphere oscillations. Needless to say that these drivers of long-term changes in climate extremes are not mutually exclusive. In SAT-EX we propose the use of traditional *climate extreme indices* derived based on remote sensing datasets, and the analyses of these indices with a combination of two rather novel statistical methodologies: the *fingerprint* analysis and the *random forest* machine-learning method. These techniques will be applied to both satellite based datasets and IPCC climate model outputs within the course of seven work packages and four years.

WORKFLOW

Work package	**YEAR 1**												**YEAR 2**												**YEAR 3**												**YEAR 4**											
WP1: Coordination, management and dissemination	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
WP2: Exploration of user requirements	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
WP3: Database and pre-analyses	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																																				
WP4: Variability analysis										▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																								
WP5: Impact quantification																			▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																		
WP6: Earth System Models evaluation																												▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨									
WP7: Project synopsis																																						▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨