Remote Sensing of Environment 203 (2017) 2–8

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

The ESA Climate Change Initiative (CCI): A European contribution to the generation of the Global Climate Observing System

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ARTICLE INFO

Article history:
Received 27 January 2017
Received in revised form 30 June 2017
Accepted 16 July 2017
Available online 4 August 2017

Keywords:
Climate Change Initiative
Essential Climate Variables
GCOS
European Space Agency

ABSTRACT

The Earth System behaves as a highly coupled system comprising physical, chemical, biological, and anthropogenic components and processes with complex interactions and feedbacks between them. Climate change is arguably the greatest challenge to balance in the Earth system. The Paris Agreement (UNFCCC, 2016) recognised the need to reduce the risks from and impacts of climate change and called for the increase in the global average temperature to be held well below 2 °C above pre-industrial levels, with the ideal aim being to limit it to 1.5 °C. The UN Framework Convention on Climate Change (UNFCCC) agreement is based on the evidence for, and likely causes of, climate change synthesised by the Intergovernmental Panel on Climate Change (IPCC) and is supported, for climate, by the Global Climate Observing System (GCOS). GCOS has defined a set of Essential Climate Variables (ECV), established the requirements for their systematic observation, and the development of data archives, needed to support the study the climate system. The Climate Change Initiative (CCI), represents the contribution by the European Space Agency (ESA) to GCOS. CCI is a programme designed to bring together European expertise in Earth Observation with that from the climate research community to address those ECV that can be generated using satellite observations. Specifically the objective is 'to realise the full potential of the long-term global Earth Observation archives that ESA together with its Member States have established over the last thirty years, as a significant and timely contribution to the ECV databases required by the United Nations Framework Convention on Climate Change (UNFCCC)'. In doing so the intended legacy of the programme is to put in place mechanisms capable of providing long term, fully traceable, and transparent access to its records. This paper provides an overview of the CCI Programme and highlights a few of its achievements to date.

1. Introduction

The Earth System behaves as a highly coupled system comprising physical, chemical, biological components and processes with complex interactions and feedbacks between them. The Intergovernmental Panel on Climate Change (IPCC) has produced a series of Assessment Reports, for example, IPCC (2013), which summarise the level of understanding of the Earth System, the state of the climate and the likely impacts of climate change. The UN Framework Convention on Climate Change (UNFCCC) responds to these reports through its Convention of the Parties (COP), with the latest resulting in the Paris Agreement (UNFCCC, 2016). A key component of the implementation of the Paris Agreement is the identified requirement for systematic observation and development of data archives related to the climate system. This comprises an integrated observing system involving numerical models complemented by long-term, carefully calibrated and documented data sets of the Earth system from both satellite and in situ sources. Such a system should be designed to enable variations and trends in both space and time and allow climate impacts to be distinguished from short-term natural variability.

The Global Climate Observing System (GCOS) has become the de facto recognised mechanism for facilitating this commitment on behalf of the UNFCCC (see for example, UNFCCC, 2010). In its second report in 2003 GCOS established a list of Essential Climate Variables (ECV) needed to address UNFCCC needs. Since 2003 the list of ECVs, and their associated requirements, have evolved in response to conclusions of IPCC and assessments of the adequacy of data by GCOS. While products from satellites can contribute to realising many of these ECV there remains an issue of how to provide a set of cross-consistent products, covering a long time period, which closely match the target requirements set by GCOS. To achieve this it is essential to recognise that no single data set from any single satellite or space agency is sufficient, and combining observations from different sensors and sources is a critical step in the generation of a complete ECV.

In 2009, the European Space Agency (ESA) initiated the Climate Change Initiative (CCI), in response to the UNFCCC and GCOS needs for ECV databases. CCI was designed to coordinate European Earth

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http://dx.doi.org/10.1016/j.rse.2017.07.014
0034-4257/© 2017 Published by Elsevier Inc.

Observation expertise across all aspects of satellite product generation, while encouraging international collaboration within and without Europe.

The objective of this exercise is to establish lasting and transparent access to consistent, multi-sensor products generated from the global Earth Observation archives. The framework behind the CCI is identified through a series of cardinal requirements, which are applicable across all ECV projects (Table 1).

These cardinal requirements have evolved over the 6 years of the programme with improvements in algorithm quality and, in the capability to generate products consistently, and changes in GCOS requirements and the funding and collaborative landscape. In addition to these cardinal requirements each individual project is guided by a set of technical requirements aimed at tackling issues with particular data streams, uncertainty characterisation, sensor combination to ensure extension of the data record and development of a potentially sustainable system of production.

The CCI programme has focused on 13 GCOS ECVs where the potential contribution from ESA and/or European satellite sensors was considered unique and/or significant. Each of these ECVs has been tackled through a dedicated project (Table 2) involving assessment of algorithm quality, cycles of algorithm improvement, large-scale EO data processing, uncertainty characterisation (see Merchant et al., 2017), validation, product inter-comparison and assessment by the climate research community.

The CCI has enabled the European Earth Observation and climate research communities to work together to realise the scientific benefits from satellite observations. This has been expressed through almost 400 peer-reviewed publications (as of December 2016) contributing new insights in climate research, responding to needs raised by IPCC and addressing requirements from GCOS. The resulting products, which are available through the CCI Data Portal (http://cci.esa.int), have been generated with an emphasis on traceability and consistency both within and across projects, include quantitative estimates of uncertainty, have been fully validated and have been evaluated by leading members of the climate research community.

Table 1
Cardinal requirements established for each project in the CCI over the 6 years and 2 phases of the programme.

Phase I	
[CR-1]	Develop and validate algorithms to meet GCOS ECV requirements for (consistent, stable, error-characterised) global satellite data products from multi-sensor data archives
[CR-2]	Produce and validate, within an R&D context, the most complete and consistent possible time series of multi-sensor global satellite data products for climate research and modelling
[CR-3]	Optimize the impact of ESA EO missions data on climate data records
[CR-4]	Generate complete specifications for an operational production system
[CR-5]	Strengthen inter-disciplinary cooperation between international earth observation, climate research and modelling communities, in pursuit of scientific excellence
Phase II	
[CR-1]	Develop and validate algorithms to approach the GCOS ECV and meet the wider requirements identified in Phase I for (consistent, stable, error-characterised) global satellite data products from multi-sensor data archives
[CR-2]	Produce and validate the most complete and consistent possible time series of multi-sensor global satellite data products for climate research and modelling, for the period where data are available including up to the present day. This will include at least one full ECV reprocessing
[CR-3]	Optimize the impact of ESA EO missions data on climate data records
[CR-4]	Generate and fully document an ‘operational’ production system using as a basis the prototype processors developed in Phase I, following the CCI System Requirements, capable of processing and reprocessing at least once the data in CR-2.
[CR-5]	Develop the system to be able to cope with extension to major new data sources e.g. Sentinels, Earth Explorers, Third Party and other non-ESA Missions as they become available.
[CR-6]	Strengthen inter-disciplinary cooperation between international earth observation, climate research and modelling communities, through involvement in major intercomparison or assessment initiatives using the collective resources from the CCI projects in terms of consistent, error characterised data products across the 13 ECVs.
[CR-7]	Publish the results of the CCI projects in world class peer-reviewed scientific journals in time to contribute in particular to the 6th IPCC Assessment Report and the WMO Ozone Assessment Report and to actively pursue collaborations in preparation to ensure these papers are known to these communities.

In addition to the generation of products a concerted effort has taken place to strengthen the interface between EO product developers and climate research scientists. This interface has been targeted throughout the programme by including climate research groups within each project. The objectives of this exercise were:

- to achieve common understanding of what individual products are and how they can be used.
- given the multidisciplinary approach of the programme, encourage the establishment of improved cross-domain links spanning the land, ocean, atmosphere and cryosphere science communities.

This has been reinforced through efforts to tailor products for major intercomparison exercises e.g. the Coupled Model Intercomparison Project (CMIP), coordinated through the CCI Climate Model User Group (CMUG), including provision of access to CCI products under Obs4MIPs (https://www.earthsystemcog.org/projects/obs4mips/). The projects funded under the CCI are now coming to end but, as identified early in the programme, the intention is that product generation will continue through the transfer of approaches, production systems and experience to operational programmes, such as Europe's Copernicus Climate Change Service (C3S) and the EUMETSAT Satellite Applications Facilities (SAFs). Such a transition fits with the overall concept of the Copernicus Programme (www.copernicus.eu) while permitting ESA to focus on research and development aspects for the existing and potential future projects. This latter is one of the foci of the extension to CCI, which is currently being implemented, after its acceptance at the ESA Ministerial Council in December 2016.

2. CCI achievements in the context of IPCC and GCOS

The role of the IPCC is to produce an assessment of the current state of knowledge on climate change, the potential impact and mechanisms for mitigation and adaptation. This is addressed through review of published evidence, backed by specific efforts to obtain key information. Each specific issue includes a statement on the confidence associated to it. While CCI was very early in product development when the IPCC AR5 was produced in 2013, it nevertheless had an impact on some of the conclusions in specific areas through the availability of improved ECV products and greater community consensus.

For GCOS, CCI has contributed significantly to updating and improving GCOS specifications in the last satellite supplement (GCOS, 2011) and in the recent assessment of the adequacy of climate observations and, in particular, the Implementation Needs (GCOS, 2016). Throughout, CCI has adhered to the GCOS Climate Monitoring Principles and focused, as far as practical, in achieving the target requirements set by GCOS. The following examples demonstrate the impact.

2.1. Cryosphere

2.1.1. The Randolph Glacier Inventory

The IPCC (2013) concluded, with high confidence, that, for the cryosphere, both the Greenland and Antarctic ice sheets have been losing mass over the last two decades and that globally, glaciers have continued to retreat. In addition, Arctic sea ice and Northern Hemisphere spring snow cover have continued to decrease in extent.

Table 2
ECVs addressed by the ESA Climate Change Initiative.

Domain	GCOS ECV	Project	Lead organisation
Atmosphere	Cloud properties	Cloud_cci	Deutsche Wetter Dienst (DWD)
	Aerosol properties	Aerosol_cci	Finnish Meteorological Institute (FMI) and German Space Centre (DLR)
	Carbon dioxide, methane and other GHGs	GHG_cci	Univ. Bremen
	Ozone	Ozone_cci	Royal Belgian Institute for Space Aeronomy (BIRA)
Ocean	Sea surface temperature	SST_cci	University of Reading
	Sea level	SL_cci	Collecte Localisation Satellites (CLS)
	Sea ice	SI_cci	Nansen Environmental and Remote Sensing Centre (NERSC)
	Ocean colour	OC_cci	Plymouth Marine Laboratory (PML)
Terrestrial	Glaciers & ice caps	Glaciers_cci	Univ. Zurich
	Land cover	LC_cci	Catholic Univ. Louvain
	Fire disturbance	Fire_cci	Univ. Alcala
	Ice sheets	Greenland_cci	Danish Technical Univ. (Greenland)
		Antarctica_cci	Univ. Leeds (Antarctic)
	Soil moisture	SM_cci	Technical Univ. Vienna

In the case of glaciers this conclusion was based on the international effort to produce the Randolph Glacier Inventory (RGI), the first globally complete inventory of glaciers (Pfeffer et al., 2014). The RGI was coordinated by an ad hoc group, under the auspices of the International Association of Cryospheric Sciences (IACS) to bring together a large number of individual records of glacier outlines. Consortium members from Glacier_cci were instrumental in the successful creation of RGI and the project itself contributed approximately 1/3 of all glacier outlines (Fig. 1). The inventory is available through the Global Land Ice Measurements from Space (GLIMS) website (http://glims.org). RGI is under continuous evolution, under IACS and Glacier_cci has been dedicated to its improvement by addressing specific issues with data quality (Paul et al., 2013, 2015, 2017).

The development of the RGI was a critical first step in addressing the uncertainty in sea-level budget calculations associated with the global contribution from glacier retreat (Marzeion et al., 2017). In tandem with the RGI, Glacier_cci has worked closely with the World Glacier Monitoring Service (WGMS) to improve the spatial distribution of records of glacier mass change by incorporating satellite observations. Part of this process is greater coordination between individual databases such as GLIMS, RGI, the Glacier Photography Collection and the World Glacier Inventory (WGI) (http://gtn-g.org/data_browser.html).

2.1.2. Ice Sheet Mass Balance Intercomparison Exercise (IMBIE)

The Ice Sheet Mass Balance Intercomparison Exercise (IMBIE), initiated via the Greenland Ice_Sheet_cci, was a joint ESA-NASA effort to reconcile the 20-year disagreement between different methods for calculating ice sheet mass balance from satellite observations. The output from IMBIE was an agreed estimate of ice sheet mass balance changes in both Antarctica and Greenland, and their contribution to sea level change from satellite altimetry, gravimetry and the input-output method (Fig. 2) (Shepherd et al., 2012). A second extended IMBIE (http://imbie.org/imbie-2016/), started in 2016, builds on this effort with the intention to establish a capacity to annually update estimates of ice sheet contributions to sea level rise, to improve understanding of differences between estimates and the processes driving ice sheet imbalance.

2.2. Oceans

2.2.1. Sea level

Long term in situ observations of sea level since the mid-19th century indicate that the rate of increase in sea level rise has been larger than in the previous two millennia with global mean sea level increasing by 0.19 [0.17 to 0.21] m between 1901 and 2010 (IPCC, 2013). Satellite

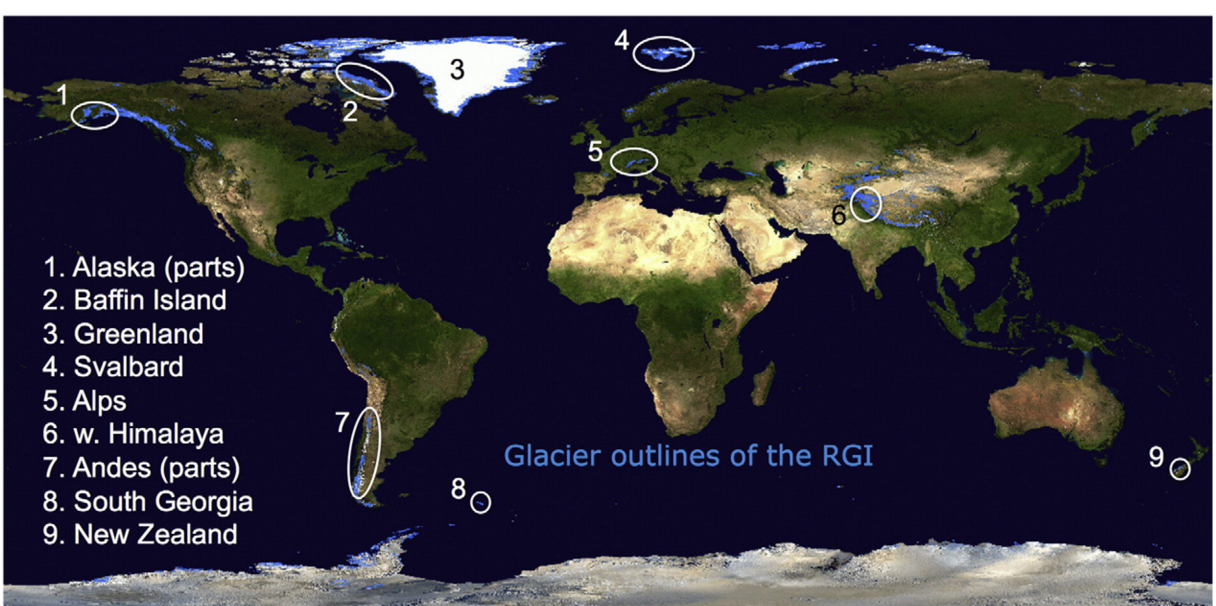

Fig. 1. Glacier_cci contributed outlines listed to the left and circled in white to the RGI (blue). Background image copyright NASA.

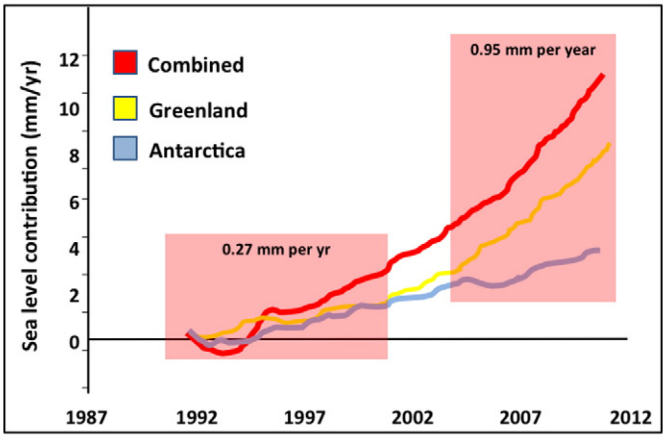

Fig. 2. Sea level contributions due to mass loss from the Greenland and Antarctic Ice Sheets from reconciled satellite methods (after Shepherd et al., 2012).

observations, which exist since the early 1990′s, provide not just the mean sea level but also its spatial and temporal dynamics.

Working within the framework of multi-agency Ocean Surface Topography Science Team (OSTST) and the Intergovernmental Oceanographic Commission (IOC) Global Sea Level Observing System (GLOSS), the SeaLevel_cci has produced improved Global Mean Sea Level estimates through reprocessing of satellite data from multiple satellites and evolution of algorithms to reduce estimate uncertainty and improve inter-satellite consistency (Fig. 3) (Ablain et al., 2017; Quartly et al., 2017). The constant cross-domain exchange within the CCI Programme has encouraged collaboration with other CCI teams (Meyssignac et al., 2016), and this has allowed the calculation of improved sea level budgets both regionally and globally (Cazenave et al., 2017; Forsberg et al., 2017). Improved sea level observations allied with better information on mass change from glaciers and ice sheets has allowed estimates of less well known contributions (e.g., the land water storage change due to human activities) to be constrained better. This is being pursued further by bringing the CCI teams together to focus on sea level budget closure.

2.2.2. Sea surface temperature

The ocean is the dominant component of the Earth System in the regulation of heat energy given its heat storage capacity. Since 1971 it has stored more than 90% of the excess energy accumulated between 1971 and 2010 (IPCC, 2013) with most of that being stored in the upper ocean. This ocean warming has, by expansion, resulted in global and regional sea-level rise, has energised the transport of water both vertically and horizontally and affected the ability of the ocean to absorb carbon dioxide. To help understand these impacts, the SST_cci has focused on improved long term observations of sea surface temperature focusing on their homogeneity, stability and determination of quantified uncertainties (Merchant et al., 2014; Robert-Jones et al., 2016). This has established a 35-year record (1981–2015) of skin SST and SST at standard depth (20 cm), based primarily on the ATSR and AVHRR sensor series with SEVIRI for diurnal modelling of infrared temperatures, that are independent from in situ observations (http://www.esa-sst-cci.org/). The generation of spatially complete fields from this record has allowed departures from the mean to be calculated (Fig. 4).

2.3. Atmosphere

2.3.1. Aerosol properties

The role of aerosols in contributing to radiative forcing represents one of the least well known areas in climate science. While total radiative forcing is dominated by increases in the concentration of CO_2 in the atmosphere, aerosols and their interaction with clouds may offset the radiative impact. Better understanding of this radiative forcing role requires improved observations but also critically a better interaction between in situ, satellite and model communities. For aerosols, the CCI has reconciled a very disparate satellite community and streamlined the range of aerosol algorithms (de Leeuw et al., 2015) and has generated datasets from multiple satellites and improved global aerosol ECV estimates covering 17 years (1995–2012) with a focus on provision of quantitative error information (validation of annual datasets and pixel-wise uncertainty) (Popp et al., 2016). In addition, it was fundamental in establishing the AeroSAT initiative (http://www.aero-sat.org) as a complement to the established Aeronet in situ and AeroCom modelling communities. AeroSAT brings together the global satellite aerosol science community with the aim to improve the interface between in situ, satellite and particularly modelling communities to ensure the increasing complexity on cloud and aerosols introduced into climate models can be effectively tested.

2.3.2. Greenhouse gas concentrations

Much of the discussion around climate change centres on the greenhouse effect/global warming, which relates to the increases in the atmospheric concentrations of the greenhouse gases (carbon dioxide, methane, and nitrous oxide in particular). The current levels of these gases have not been seen in the temporal record going back over the

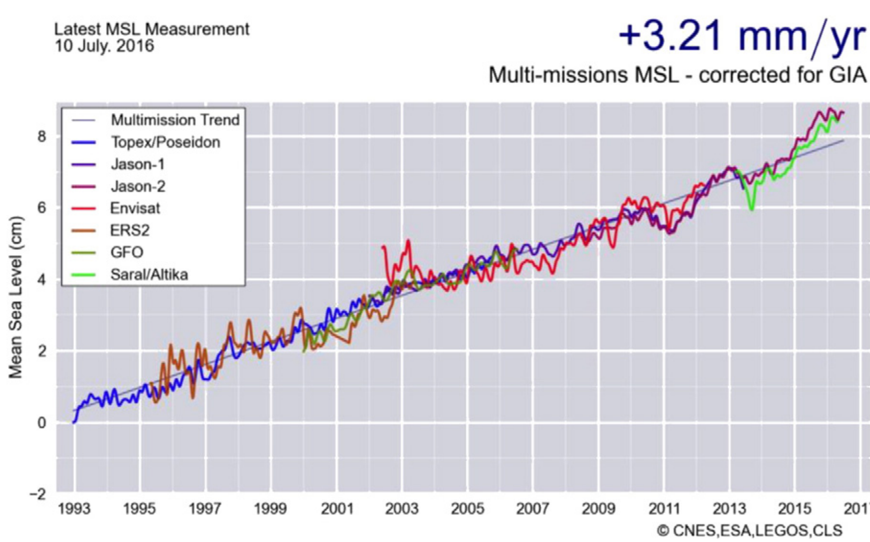

Fig. 3. Multi-mission global sea level trend from altimetry. This figure includes all the CCI satellite time series overlaid after being adjusted from biases - 1993 to 2016 (mm/yr).

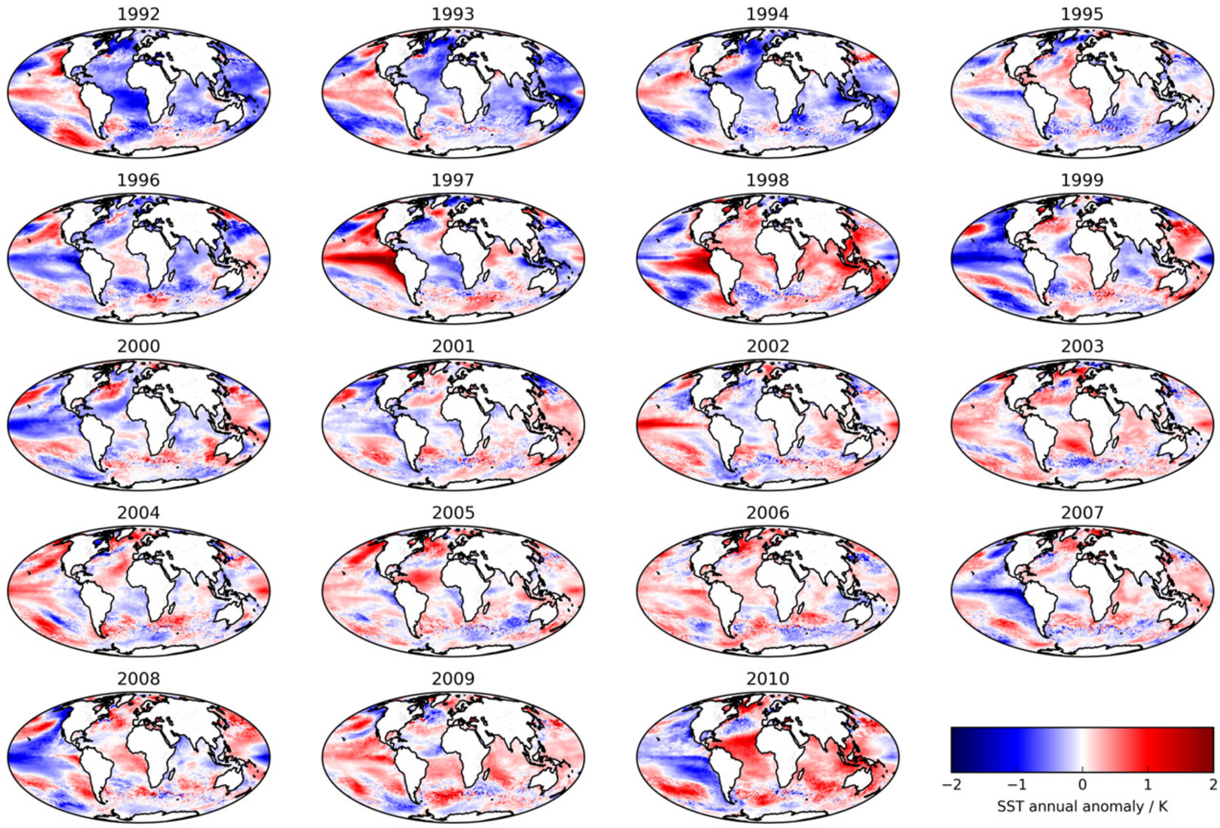

Fig. 4. CCI annual mean sea surface temperature (SST) anomaly maps for 1992–2010 (after Merchant and Embury, 2014).

last 800,000 years, with the most rapid increases correlated with industrialisation. The Earth system partly counteracts the emissions of carbon dioxide with both the ocean and land increasing their uptake. However, the degree to which this can continue is debated given, for example, the absorption of more carbon dioxide in the ocean has the effect of increasing ocean acidity. Space based observations of greenhouse gases have proliferated over the lifetime of CCI from SCIAMACHY, through GOSAT and OCO-2, with the prospect for contributions also from China with Tansat, in Europe through national and supranational missions e.g. microCarb, Japan with GOSAT-2, and in the US with OCO-3.

CCI built on the European expertise in greenhouse gas estimation from SCIAMACHY and allied with groups efforts in the US and Japan to improve the quality and knowledge of variability in space and time of both CO_2 and CH_4 covering these multiple missions. Within GHG_cci this has resulted in significant extension in the time series with concomitant improved accuracies as algorithms become more robust (Buchwitz et al., 2017a). The products, which have been corroborated with column and profile observations and against ground-based Fourier-Transform-Spectroscopy (FTS) retrievals of the TCCON network (Buchwitz et al., 2015), have been used to improve knowledge on various natural and anthropogenic sources and sinks of both gases (Reuter et al., 2014; Buchwitz et al., 2017b; Chevallier et al., 2014).

2.4. Biosphere

2.4.1. Land cover

Land cover is defined as the physical material at the surface of the earth. Land covers include grass, asphalt, trees, bare ground, water, etc. However, despite considerable efforts the products available at the start of CCI were inconsistent and incompatible (Bontemps et al., 2012, Tsendbazar et al., 2015).

The Land_Cover_cci therefore built on previous efforts such as GlobCover, in particular focusing on universal improvements in both the pre-processing and classification methods required for the generation of a global land product. The objective to developing a system delivering global land cover information in a consistent way from various EO instruments for use by the climate change community. The focus of this work was on global surface reflectance observations at moderate spatial resolution from primarily European sensors allied with the contribution of ESA SAR sensors to delineate specific land cover types (Lamarche et al., 2017). This produced the first set of consistent global land cover state products initially on 5-year epochs, and recently converted into annual estimates at 300 m spatial resolution, supplemented by information on global water bodies and seasonality and aligned with

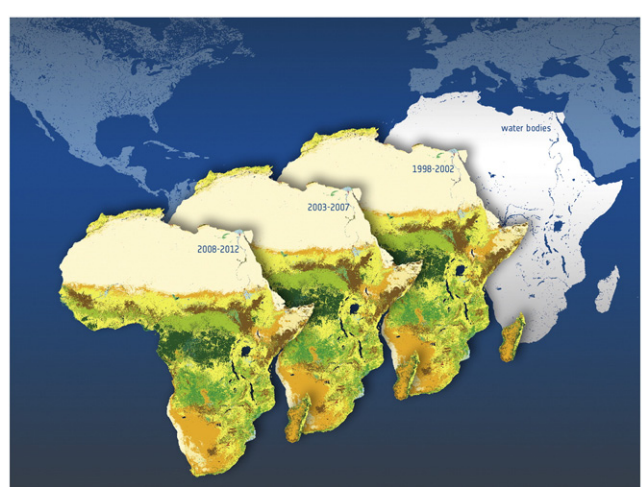

Fig. 5. Landcover_cci has delivered three global land cover state products for 2000, 2005 and 2010 epochs, supplemented by global water bodies and phenology products.

information coming from estimates of e.g. burned area generated through the Fire_cci (Fig. 5).

This work has been conducted in close collaboration with major dynamic global vegetation modelling groups to ensure there is a common understanding of the land surface description, quantification of uncertainty in land cover assignment and that these products are tested in and used to constrain model predictions of vegetation behaviour under changing climate (Li et al., 2016; Poulter et al., 2015).

3. Cross-domain and cross-discipline exchange

While GCOS identifies a set of target requirements for each the ECVs, there is a need to go beyond the narrow response in terms of improved algorithms and products. In particular for the satellite communities there is a need to ensure that these improved products are taken up and used appropriately by the climate community. Product improvements need to take place in communion with the in situ observation teams since satellite records remain short in climate terms. The CCI recognised these requirements, from its initiation, with the insistency not just on improved collaboration between groups focused on a given ECV but seeking to break down both domain and discipline barriers.

Programmatic themes emphasised transparency in production and documentation, estimation of uncertainty, and on validation. Exchange with the climate research and climate modelling communities was strongly supported in individual projects, throughout the programme, and also through the Climate Modelling User Group (CMUG) which pulls together the major climate modelling groups in Europe. These twin elements have ensured products have been evaluated in climate terms both within projects and independently (Lauer et al., 2017).

Regular meetings comprising the entire CCI community have sought to encourage and enforce cross-domain and cross-discipline exchange. While at the start this was viewed with great scepticism, after six years and with the availability of improved datasets, a clear understanding of the value of collaboration on common themes has been seen as well as a willingness to tackle larger questions e.g. how to close the sea level budget looking beyond traditional boundaries. The continuous process of exchange with the climate community has brought common understanding, and importantly, a greater openness in both product and model development. The cross-domain issues have been supported, within the programme, by a series of fellowships focused on exploitation of CCI products to answer scientific questions on climate as well as ensure consistency between the products and models.

All of these components represent signs of the success of the CCI programme, as does the impact on improved specification of ECV products exhibited in the revised GCOS Observation (GCOS, 2016). These issues need to be nurtured to ensure the value of satellite observations is recognised and effectively exploited by the climate science community.

4. Conclusions

The IPCC's Fifth Assessment Report in 2013 highlighted the importance of improvements in both observations and modelling in understanding the Earth as a system, with the increased confidence in statements when compared with the previous version. This improved confidence is partly attributable to process understanding and improved model representations but also through the developments in ECV products. This latter encompasses longer time spans, consistency and quantification of uncertainty and critically improved provision of the products themselves through the launch of more satellites and better in situ observations. The European Space Agency Climate Change Initiative (CCI) has taken a lead role in Europe providing these improved products by more effectively exploiting the data archives accrued in Europe. Similarly the most recent GCOS Implementation Needs document (GCOS, 2016) provides evidence of the improvements that have been made in satellite product provision and quality. It also implicitly recognises the value, expressed throughout this paper, of approaching the Earth System issues more holistically, encouraging shifts out of the traditional domains, specific ECV foci and individual sensor capabilities e.g. by looking at Earth System key cycles.

While the provision of improved products is vital, less tangible but equally important is the fostering of fora to exchange information internationally. This is needed within the EO community, but also across traditional domains and disciplines to improve understanding on all sides and encourage cross-domain activities focused on key aspects of the Earth system. CCI has been very successful in this regard, partly because these were in the programmatic objectives and partly because of the length and breadth of the programme. However, the nascent sense of community needs to be nurtured to help address the complex scientific challenges in understanding the Earth's climate.

While the last decade has seen as its focus the understanding the Earth as a system, the next decade for science will increasingly be focused on climate impacts, mitigation and adaptation. Europe is already gearing up for this through its investment in Copernicus and the development of operational climate services. These services require present a new challenge in terms of observation, namely that not just on the production of high quality of observational datasets (i.e. GCOS Essential Climate Variables) but ensuring they are generated tempestively and with the consistency, reliability and resolution required for climate adaptation and mitigation.

Acknowledgment

This paper provides and overview of the programmatic context for the European Space Agency Climate Change Initiative and lists some examples of achievements over the 6 years of the programme. The authors would like to thank all members of the teams who have worked on the CCI, the ESA staff responsible for managing the projects and the contributions from all those associated with the programme organisation in particular Massimo Canese, Nathalie Boisard, Cat Downy, Ed Pechorro, Anna Maria Trofaier, Anne Stefaniak, Victoria Bennett and Anne Chadwick.

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