Climate Modelling User Group

Deliverable 7.1

Interface of CCI data to climate services

Centres providing input: Met Office, ECMWF

Version nr.	Date	Status
0.1	20 Aug 2015	First draft for ESA comment
0.2	10 Nov 2015	ECMWF input in Chapters 1, 2 and 3
0.3	11 Nov 2015	ECMWF input to Chapter 4, sec 2.3, Annex
0.4	04 Dec 2015	ECMWF draft for Met Office comment
1.0	11 Jan 2016	First version
1.9	19 Dec 2016	ECMWF modifications (all) for v2
2.0	04 Jan 2017	Second version

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1. Introduction

The purpose of this document is to demonstrate how CCI climate datasets and CMUG validation work of those datasets can support the aims and objectives of Copernicus Climate Change Services (C3S). The points made in this report are also applicable to climate services in general. This report covers aspects of the wider Copernicus programme where relevant. It is conceived as an incremental update from the first CMUG D7.1 document (version 1.0).

1.1 CCI Climate Modelling User Group (CMUG)

CMUG is the Climate Modelling User Group of the Climate Change Initiative (CCI) of the European Space Agency (ESA), to which it brings a climate system perspective. CMUG does this by applying CCI datasets in climate models and reanalyses using a range of applications and techniques, by examining climate consistency between CCI datasets, and by developing tools for evaluating both models and data. CMUG has recently conducted an extensive survey of user requirements (CMUG URD, 2015), and maintains a dialogue with key international coordinating bodies and research centres with a specific interest or stakeholder role in climate services (ECMWF, EEA, JRC). All these CMUG activities were used to inform this report.

1.2 Copernicus Climate Change Service (C3S)

The Copernicus Climate Change Service (C3S) forms part of the larger Copernicus programme, the European Union (EU) Earth observation programme for operational, independent and accurate data and information on environmental and security matters for Europe which started in April 2014. Copernicus consists of the six main components (Figure 1) that are in different development stages (Figure 2). Copernicus is structured as a user driven programme, building on existing national and European capacities, providing continuity with past and current activities. C3S, which is currently under development, will provide Essential Climate Variables (ECV), climate analyses, projections and indicators at temporal and spatial scales relevant to adaptation and mitigation strategies for the different sectoral and societal areas of the EU. Information on how the CCI can support the C3S comprises the largest part of this report although other Copernicus services (e.g. Land, Atmosphere, Marine) are also included when relevant.

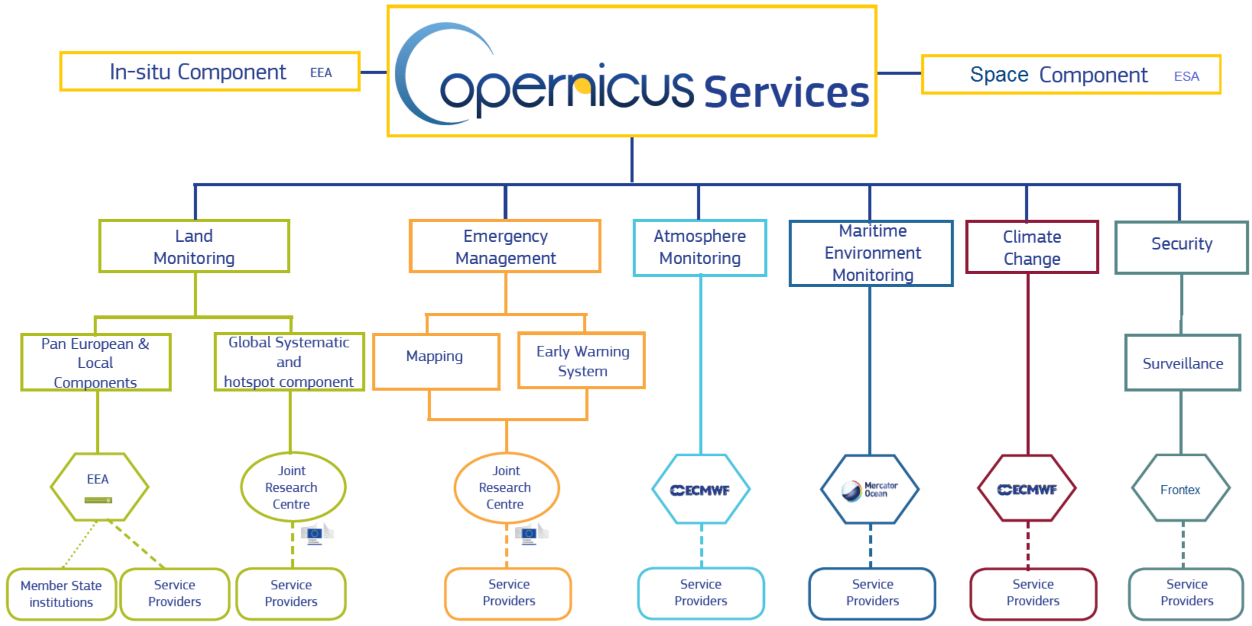

Figure 1: Organisation of the Copernicus Services. C3S is highlighted with a red box.

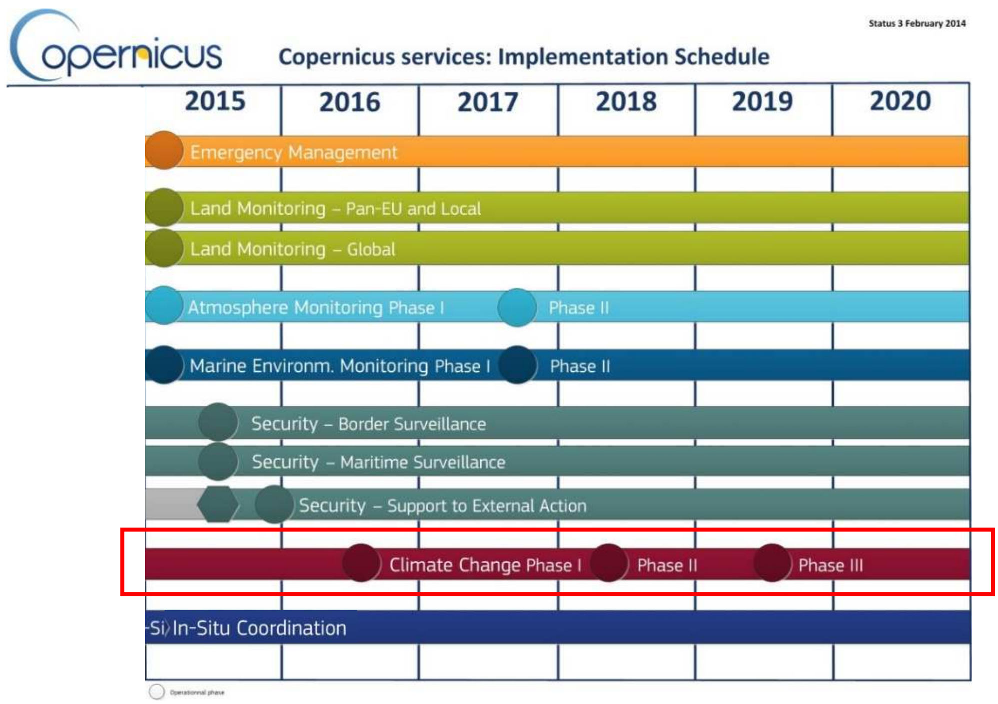

Figure 2: Implementation schedule for the Copernicus Services (2015-2020). C3S is highlighted with a red box.

Two aspects of the C3S relevant to the ESA CCI should be kept in mind:

- The C3S is an operational service thus no research activity as such can be funded as part of its work;
- The ECV selection will result from an open and competitive tender process that all interested parties, including CCI, will need to go through.

The C3S requirements for the ECV datasets are specified in the C3S ITT call C3S_312a published on 24 February 2016.

At the time of writing, C3S had issued nine ITTs (one per ECV) and selected the nine consortia to deliver operational ECVs of SI, SSH, SST, O3, Aerosol properties, GHG, SM, Glaciers, and Albedo/FaPAR/LAI. Eight CCI consortia successfully responded to C3S ITT calls to transfer their operational activities to the C3S. Additional C3S ITTs covering new ECVs are expected to be issued in the coming months.

1.3 Role of CMUG

The CMUG was established in 2009 to provide among other things independent feedback on the CCI ECV data quality and documentation. This followed a recommendation of the CCI Climate Scientific Advisory Body and ESA's Earth Science Advisory Committee to "Bring an integrated climate system perspective within the CCI programme and to provide a forum for the Climate Modelling Community (CMC) and Re-analysis community to work closely together with the data providers". This motivation is just as relevant to C3S as a user of climate data.

With the establishment of the C3S, it is important to recognize that the role of CMUG could be adapted to provide the CCI with and interface to the C3S operational service. Although this document focuses on the CCI ECVs and on how their scientific and technical features meet the potential requirements of an operational service like the C3S, here a mention is made to an area of possible adaptation/extension of the CMUG role to account for the changing international scenario.

An important area of C3S is represented by the Evaluation and Quality Control (EQC) of all operational products that will be included in the C3S data store and the sectoral information system products. A comparison of the C3S EQC ITT (2015) and the CCI CMUG Statement of Work (2014) highlights a number of common elements between these two activities. An account is presented in table 1.

Although in two different contexts, this clear overlap between the CMUG and C3S EQC will need to be exploited to the benefits of both activities, for instance in the definition and application of evaluation and quality control best practices. From the CCI perspective, the use of a standardized, common methodology could facilitate the future uptake of new research products or of product upgrades by the operational service. From the C3S perspective, selection of new products would be eased if these were assessed using among others the same metrics and methods used by the EQC on the operational data.

At the time of writing, the consortium to deliver the C3S EQC function for ECV products from satellite and in situ observations has been created anticipating to 1) clarify user requirements for observations, 2) establish a climate data inventory, 3) assess a selected number of ECVs, and 4) make recommendations on CDS development during 2017.

1.4 Road map for this report

The consideration of CCI data and CMUG validation of relevance to C3S is covered in four chapters in this report.

Chapter 2 covers scientific features of CCI data and CMUG analysis which makes them suitable for use in C3S (either directly or in combination with other data) and applications of CCI data for users (excluding research).

Chapter 3 covers architecture and technical of CCI data that need consideration by both C3S and CCI.

Chapter 4 covers tools for serving, processing and analysing ECV data. Potential synergies with the C3S climate data store, currently being developed, should be explored. C3S will also provide users with state-of-the-art tools and software for data manipulation (see chapter 3). However, it is important to recognize that other climate services and users willing to exploit the CCI data might not have a readily-available toolbox and therefore may wish to take advantage of the CCI data portal.

Chapter 5 covers the main institutional interactions and linkages between the CCI, the institutional and structural components of Copernicus, and other actors in this field.

EQC mandate (C3S_51 ITT)	CMUG mandate (SoW CCI-PRGM-EOPS-SW-13-0043)
EQC will conduct activities to monitor the technical service performance using standard key performance indicators (e.g., timeliness, data access and availability, etc.) as well as the scientific quality of the delivered products.	In Phase 1 (P1), ***CMUG has provided CCI teams with independent feedback on their documentation and the quality and suitability of the CCI products*** [CCI Statement of Work (SoW) 2009; 2012]. **In Phase 2 (P2), CMUG shall *Provide independent feedback on CCI products and documents to ESA and the CCI teams.***
The EQC function will design routine reporting procedures to inform ECMWF and the Commission about the outcome of its investigations and propose appropriate ways to improve the service.	*Within P1,* ***CMUG has developed methodologies for assessment of pre-cursor data sets … to prepare for the assessment of CCI products.*** *CMUG, through ECMWF, has also developed* ***a Climate Monitoring Facility (CMF) tool to … rapidly investigate the homogeneity and consistency of climate data* sets** …[CMUG SoW 2002]
This [EQC function] includes identifications of priorities for updates, upgrades and modifications *of the operational production chain.*	In P1, ***CMUG provided feedback to the teams, recommending some potential improvement and tailoring of products*** **and will be continued in P2.**
This [EQC function] also includes a proactive engagement with users (via surveys, reports, structured/unstructured interviews and workshops) to ensure that user requirements are appropriately reflected in the design and content of the CDS.	In P1 and P2, ***CMUG has also been pro-active in building links with European and international climate research activities****….* In P2, **CMUG *shall update the [user] requirements captured in P1, and extend them to new climate applications. It shall inventory and review … the community, their … needs / priorities (going beyond CCI selected ECVs), and their particular needs for CCI-related variables.***
The EQC will also provide recommendations to the European Commission about needs for additional R&D efforts.	CMUG **shall** *also assess the fitness-for-purpose of CCI products for the climate modelling and service communities and* ***provide recommendations for future developments****.*
The EQC will provide *the appropriate link between research and operations.*	**CMUG shall** *explore ways towards sustained processing of CCI products, in particular within the framework of the operational Climate Service* thus **act as a link between research and operations.**

Table 1: Side-by-side comparison of the C3S EQC and CMUG mandates as defined in the C3S_51 ITT and in the CMUG Statement of Work *(SoW) 2014, respectively. Text in italic is taken from the referred documents; text in bold highlights the commonalities between C3S EQC and CMUG.*

2. Scientific features of CCI data relevant to C3S

2.1 General scientific features of CCI data

The current set of thirteen CCI ECVs have achieved, or are close to achieving the following specifications:

- are decadal or longer time scale datasets
- have good global and regional coverage
- have high temporal resolution (sub-daily to monthly).
- have good uncertainty characterisation and good estimates of random errors
- show accurate and realistic climate variability
- show realistic estimates of long term climate trends
- are validated (often against *in situ* data) homogenous, high quality climate data
- have excellent provenance to source
- are already well linked to user communities (mostly research but includes others)

A summary of these features for each ECV is given in Table 2, but see Annex 1 for the full scientific and technical specifications and potential for application in C3S.

ECV	timescale	coverage	resolution	Uncertainty description	Shows trends	Meets GCOS requirements
Atmospheric						
Clouds	2007-2009	Global	50 km	yes		partly
Ozone	1996-2015	Global	100-500 km	yes		partly
GHG	2003-2014	Global	10-60 km	Yes#	yes	partly
Aerosols	2001-2013	Global	13-24 km	yes		partly
Oceanic						
SST	1991-2010	Global	4-25 km	yes	yes	yes
Sea level	1992-2010	Global	0.25 degree	yes	yes	
Sea ice	1978-2008	Global	25-100 km	yes	yes	partly
Ocean colour	1997-2012	Global	4 km	yes		yes
Terrestrial						
Glaciers	1984-2011	Global	30-170 m	yes	yes	
Ice sheets	1991-2012	Greenland	0.25-5 km	yes		
Land cover	2000, 05, 10	Global	0.3-1 km	no		
Fire	1995-2010	Global	0.3-1 km	yes		partly
Soil Moisture	1978-2010	Global	50 km	yes		

Table 2. Summary of key scientific properties of the current CCI ECVs (see Annex 1 for full details). #Description is included in other GHG-CCI documents and not available as a standalone report.

2.2 Specific features of CCI data

A number of specific features characterize the CCI ECVs desirable in any dataset that could be contemplated by an operational, user-driven service like C3S, in addition to the general features summarized in section 2.1. These include:

- **User requirement-based datasets:** The user requirements set by GCOS (acronyms not defined in the text are defined in section 6, GCOS, 2006; 2011) were considered as starting goal requirements for the CCI ECVs. In addition, potential CCI ECV users are periodically engaged to provide application-specific user requirements for each ECV. These requirements are independently collected by CMUG and each CCI team to reach as many users and sectors as possible, they are documented and periodically revised. All the collected requirements constitute the goal towards which the CCI ECVs have been derived. Many of these user requirements have now been met. See Table 6 in Annex 1.
- **Algorithm Maturity:** Most CCI teams have reached a good algorithm maturity resulting from i) objective algorithm selection through Round-Robin inter-comparisons of available European models, ii) identification in the selected algorithm(s) of areas in need of improvements to meet the user requirements, iii) fully documented ATBDs, iv) fast turn-around with typically one-year cycle required to go from updating the algorithm to releasing validated datasets to users for most CCI ECVs.
- **Data Maturity:** Each dataset is fully characterized. Metadata is included with each product. Fully documented uncertainty characterization with quantitative estimates at pixel level for L2 data in most cases. User-friendly flags are routinely included in the ECV product format and specification. Fully validated datasets by each ECV Climate Research Group and independently by CMUG. Details on data format, data compliancy, levels of processing, and data access are given in chapter 3. Many CCI ECVs were both self-assessed and assessed by the Core-CLIMAX consortium using the Core-CLIMAX Data Maturity Matrix before and during the 2014 Core-CLIMAX Workshop.
- **Temporal coverage:** An important element of CCI was to create long, consistent time series of ECVs exploiting a number of available satellite instruments. This was achieved by applying the ECV state-of-the-art algorithm selected through the round-robin exercise to different sensors. Whenever applicable, the single-sensor datasets were merged together to produce longer time series. Attention was paid to inter-instrumental biases to avoid sudden, unphysical jumps in the obtained records.
- **Consistency:** This aspect is considered at many levels. In Phase 1, all CCI teams were encouraged to use the same source of a priori information, namely the ERA-Interim reanalysis. This aspect was achieved throughout the CCI. A Land-Sea Mask (LSM)

and a Freshwater Mask have been produced by the Land Cover project and other CCI teams and independent researchers are encouraged to use these masks for consistency. (see also section 3.5). Consistency between different CCI ECVs is the main topic of the CMUG Phase 2 work (see section 2.3) and a deeper understanding will become available throughout and by the end of the project. Nonetheless, examples of improved internal consistency with other model variables and/or not-CCI observations used in the user models has been already documented (e.g. the assimilation of the CCI GOME-2 ozone profiles improved the fit to the assimilated AIRS ozone-sensitive radiances, CMUG QAR 2015). Activities are also on-going to improve the across-ECVs consistency. For instance, Aerosol-CCI and Cloud-CCI collaborate to ensure a consistent interpretation in their own algorithms of the same measurements when they are found to be either cloud-affected or aerosol-affected pixels.

- **Added value:** Many of the assessments performed to date confirm the quality of most CCI ECVs and their potential added value to several applications. This is corroborated by the wide use of many CCI datasets in international assessments like the IPCC AR5 and the 2014 WMO Ozone Assessment, as well as by the foreseen usage in forthcoming activities, for instance the use of many O3-CCI products in the ERA5 reanalysis.
- **Documentation:** For each CCI ECV, the following documents are publicly available and periodically updated: i) Algorithm Theoretical Basis Document; ii) Uncertainty Characterization Report; iii) Product User Guide**;** iv) Product Validation Plan; v) Product Validation Inter-comparison Report; vi) Climate Assessment Report (CAR); vii) System Specification Document. Results are also documented in peer reviewed papers (an excess of 188 papers have already been published by the CCI). All the above documents are reviewed by CMUG. In addition to the ECV CAR, periodic assessments are independently carried out by CMUG (CMUG QAR 2015, see also section 2.3).

In addition to the value of each single ECV, it is worth mentioning and should not be underestimated that the CCI programme has brought together scientists from a very diverse background and originally dedicated to tackle specific scientific questions, creating a closely-linked community. This community has blossomed with time and has promoted a number of cross-ECV studies to improve their products (as discussed above between Aerosol and Cloud-CCI), and to address and explain some of today's climate change signatures. An example of the latter is represented for instance by the global Sea-Level rise. A project is currently on-going to achieve the Sea-Level budget closure. This project involves all CCI teams that work with ECVs relevant to or that could have a bearing on SL changes, for instance Glacier-CCI and Sea Ice-CCI, and might also provide information relevant to climate change services and their users.

2.3 Potential applications for CCI data in C3S

Detailed C3S ECV data requirements have not yet been published. An ITT is currently in preparation and expected to be published by the beginning of 2016. Thus, at the time of writing one can only make an educated guess on what will be the ECV data requirements included in the C3S ITT call based on the likely needs of the service users.

The C3S will be concerned with a variety of users and sectors, including:

- Climate monitoring and attribution
- Reanalyses
- Seasonal forecasts
- non-modelling climate applications
- Adaptation community (including EEA)
- Mitigation community (including national governments and the EC)
- System users (for instance town planner, governments, Climate services at a national level, (for example the Climate Change Risk Assessment defines user requirements in the UK with respect to addressing climate change on different systems and sectors)
- Sectoral users in the following sectors: water, agriculture, forestry, fisheries, energy, health, insurance, tourism, transport, infrastructure, natural environment, and others

Arguably, all CCI ECVs have a bearing and could be useful in one or more of these applications and sectors.

It is recognized that each category of data users and sector listed above have very specific data requirements. The CCI has put user-requirements at the centre of its activity since its start. Detailed user-requirements have been collected independently by CMUG and by each CCI team through surveys and one-to-one interviews with expert users, documented and periodically reviewed. Documents can be find at the CMUG and each CCI ECV web site accessible through the CCI portal. These together with the GCOS ECV data requirements have been considered the goal each ECV strove to achieve.

Here, we want to link the applications and validation work performed by CMUG on the CCI ECVs to the above list so as to demonstrate how the CCI climate datasets can support the aims and objectives of C3S.

In its Phase 2 the CMUG work deals with many ECVs at once, in most cases, assimilation or model evaluation, including boundary conditions, using both global and regional climate models. Different levels of data processing are also considered. The overall work is summarised in table 3 where the final column gives an indication of potential climate users and applications these assessments could be relevant to.

CMUG Model	Ocean				Atmosphere				Land				Level of process	CMUG assessment	Climate data users, applications, sectors and International Studies
	SST	SSH	Sea Ice	OC	Cloud	Ozone	Aerosol	GHG	LC	SM	Fire	Glacier			
FOAM	X	X	X	X									L2	Assimilation	Reanalysis, Seasonal forecasts climate monitoring, CC detection, IPCC, fisheries
ORA	X	X	X	X									L2/L3	Assimilation and detection	Reanalysis, Seasonal forecasts climate monitoring, CC detection, IPCC, fisheries
ERA						X							L2	Assimilation	Reanalysis, Stratospheric trends, WMO assessments, IPCC
CAMS						X	X	X					L2	Assimilation	Reanalysis, Stratospheric trends, WMO assessments, IPCC, climate monitoring, health, tourism, transport,
JSBACH, TM3								X	X	X	X		L2	Assimilation	Reanalysis, Seasonal forecasts, Climate monitoring, CC detection, IPCC, CCIAV, agriculture, ecosystems
EC-Earth, CMIP5	X				X	X	X	X		X			L3	Assessment, evaluation	Reanalysis, Seasonal forecasts climate monitoring, IPCC
LMDz, ORCHIDEE								X	X	X	X		L3	Boundary Conditions	Climate monitoring, CC detection, IPCC, CCIAV, agriculture, ecosystems
MPI-OM, MPI-ESM	X		X	X	X								L2	Assimilation, Polar regions	Reanalysis, Seasonal forecasts climate monitoring, CC detection, IPCC, CCIAV, polar ecosystems, fisheries
EMAC-MADE					X		X						L3	Comparisons	Climate monitoring, CC detection
RCA HARMONIE	X				X					X			L3	Evaluation (CORDEX Africa)	Climate monitoring, CC detection
Artic HYPE		X							X			X	L3	Assessment	Climate monitoring, CC detection, IPCC, CCIAV, ecosystems, fisheries
CNRM-RCM	X	X			X		X			X			L3	Comparison (Med CORDEX)	Climate monitoring, CC detection, IPCC, CCIAV, marine ecosystems, fisheries

Table 3. Overview of the CMUG Phase 2 assessments in relation to potential C3S users and applications, as well as international assessments. (CCIAV = Climate Change Impacts, Adaptation and Vulnerability.)

In addition, two tools are under development by CMUG that are also relevant for these assessments in particular and for those of climate products in general: the **ESMValTool** and the **CMF**. The former will be used to evaluate climate models through the definition of a number of matrices; the latter will enable users to rapidly investigate the homogeneity and consistency of climate data sets by comparing pre-defined diagnostics.

A Quality Assessment Report will be published every year providing updates on the table 3 assessments. The first two reports were published in September 2015 and July 2016, respectively. Here a few selected highlights from these reports are presented, grouped in four main themes: Comparison with other observations, Model evaluation, Assimilation, Consistency in climate products. For more detailed information, the reader should refer to the published documents (CMUG QAR 2015, 2016). It should also be noted that many of these assessments still need to produce and/or consolidate their results, which will be discussed in the next two QARs. So far, the following can be said:

1. **Comparison with other, non CCI observations and precursors:**
    a. A good agreement was found between ESA-CCI Aerosol Optical Depth (AOD) and AERONET with a ratio between the CCI AOD and AERONET collocated data of 0.98.
    b. The OC-CCI products were found to be of equal quality to the GlobColour product. The global mean and spatial standard deviation of the OC-CCI chlorophyll products are also more stable with time than GlobColour.
    c. A comparison of the CCI and NSIDC Sea Ice concentrations shows that the Arctic sea ice area computed from SICCI data lies between NASA-Team (Cavalieri et al., 1984) and Bootstrap (Comiso, 1995) datasets from NSIDC. A major advantage of the SICCI product with respect to other datasets is its error characteristics. The different types of uncertainties provided with the dataset allow for more accurate studies, e.g., on the evaluation of model physics.
    d. The SICCI ice thickness product with other data products derived from observational time series reveals a substantial positive bias in SICCI data.
    e. CCI land cover was compared to the precursor data GlobCover 2004-2006 with regards to differences in land cover distribution and showed more surface water in CCI Land cover compared to its pre-cursor GlobCover. The difference between the CCI glacier area and the area with “permanent snow and ice” from CCI LC is smaller than that the GlobCover dataset.
    f. Comparisons of the OC-CCI dataset with GlobColour products show that the latter has greater spatial coverage prior to 2002 thanks to a less strict data filtering processing while the former has greater coverage afterwards thanks to

the use of MERIS data. The global mean and spatial standard deviation of the OC-CCI chlorophyll products are also more stable with time than for GlobColour. A reduction in variability is noted when MERIS is introduced in 2002.

g. Comparisons of the CCI SST, SSH and SIC with precursor data (namely the HadISST2, AVISO, OSI-SAF, and ORAS4 datasets) show good level of consistency and similarity in the major climate modes of variability and change.
h. A comparison of SI CCI and NSIDC sea ice concentration products shows that the Arctic sea ice area computed from SICCI data lies between NASA-Team and Bootstrap datasets from NSIDC.
i. The observed variabilities of CCI cloud cover, CCI soil moisture (SM) and EOBS precipitation are consistent over Europe and Africa, and suitable for climate model evaluations. The regional model anomalies are of similar magnitude as the observed anomalies.
j.

2. Climate Model and Climate Reanalysis Evaluation:

a. The good agreement between the CCI AOD with AERONET justified its use for the evaluation of AOD in the CMIP5 models with the diagnostic routines implemented in the ESMValTool that currently also includes data from MISR and MODIS.
b. The OC-CCI products were found to be of sufficient quality for data assimilation purposes, and of at least equal quality to the GlobColour. Assimilating OC-CCI chlorophyll data improved the model's representation of sea surface chlorophyll compared with both satellite data sets, and also a range of independent in situ observations.
c. The CCI-SSH was used to assess the seasonal cycle of the mean sea level anomaly over the buffer zone and the Mediterranean Sea generated by the ORAS4 ocean reanalysis, the coupled regional climate system model RCSM4 and the Nemomed12 Mediterranean sea model. Poorer agreement is found with models where the thermosteric term contribution is missing and SSH observations are not assimilated.
d. Inconsistencies between CCI Sea Ice concentrations and the ORA-S4 reanalysis product were deduced from problems in the assimilation of the CCI product in regional model nudged to the ORA-S4 ocean temperature. The inconsistencies are likely due to the fact that the ORA-S4 system did not contain a dynamical sea-ice model.
e. The RCA regional model shows higher SM values over the Sahel than the CCI SM would indicate. The differences are most likely related to the thickness of

the layer the two SM products refer to. Over the Southern Africa region the absolute RCA SM is closer to the corresponding CCI SM although the model and the observations seem to be out of phase.

f. A dry bias was found in the HARMONIE Regional Climate Model compared against the CCI SM product over the Mediterranean.
g. The CCI Glacier data (Randolph Glacier Inventory, RGI v4.0) was found to be very useful for evaluating and improving the setup of the glacier sub-model in the Arctic-HYPE model:

3. **Assimilation for Reanalysis:**
   a. A number of ozone products from O3-CCI were individually assimilated within the ECMWF IFS system (using a configuration similar to the one that will likely be used for ERA5). The O3-CCI showed i) negligible bias; ii) uncertainties that well-compared in structure with estimates obtained with the Desroziers et al (2005) method; iii) added value in terms of improved ozone analyses compared to independent observations; iv) negligible to positive impact on the fit to other used observations. These observations will be assimilated in the forthcoming ERA5.
   b. The impact of the OC assimilation on the model carbon cycle was assessed against surface fugacity of carbon dioxide (fCO2) observations from the SOCAT V2 database (Bakker et al., 2014). Overall, the effect of the chlorophyll assimilation was small compared with the magnitude of model biases. In regions of strong biological activity, the chlorophyll assimilation was found to have a beneficial impact on carbon variables.
   c. Reanalyses assimilating ocean colour products produce realistic variability in response to climatic events, allowing their use as a tool for climate studies.
   d. Assimilation run performed with the CCI Sea Ice concentrations shows that in the Antarctic the SICCI product resembles the NSIDC Bootstrap product, while the NASA-Team product shows about 10% less sea ice area.
   e. The regional investigation of the assimilation of CCI-SI concentrations showed that a notable amount of sea ice in the marginal ice zone melts directly after assimilation into the model due to the inconsistencies noted at point 2.d.
   f. The assimilation of either the SU or the ADV AATSR AOD produces AOD forecasts that show similar level of agreement with independent observations from the AERONET network, providing a high level of confidence we have in the data.
   g. Over the Antarctic region, the SIC analysis departures obtained by nudging the MPI-EMS to the CCI SI data is comparable to the departures obtained from the NASA NSIDC data.

4. **Consistency in climate products:**
    a. CMUG, through ECMWF, has also developed the prototype of a Climate Monitoring Facility (CMF) tool to enable users to rapidly investigate the homogeneity and consistency of climate data sets by comparing pre-defined diagnostics. Comparisons of selected CCI data with a wealth of reanalysis, such as ERA, the MACC reanalysis, the Japanese reanalysis Project (JRA), the NCEP Reanalysis (NRA2), and in some cases the Modern-Era Retrospective Analysis for Research and Applications (MERRA) were performed and documented in CMUG D3.1v_1d (2013). It showed good consistency and agreement in ozone and aerosol products, some issues with the SM L3 product due to sampling issues and later addressed.
    b. A distinct relationship between the CCI fire product of burned area and the CCI soil moisture with low burned area for low soil moistures (fuel limitation) and low burned areas for high soil moistures (moisture limitation).
    c. Disagreement between CCI Glacier and CCI Land cover (snow and ice cover in CCI LC can be as 30% larger than that reported by CCI Glacier in some regions).
    d. Assimilation of the CCI AATSR Aerosol products together with MODIS data leads to the best fit to AERONET globally compared to the assimilation of either MODIS or AATSR data.
    e. The assimilation of SMR O_3 on top of a fix baseline of O_3, AOD and GHG datasets impacts the quality of the AOD forecasts leading to an improved agreement with AERONET data (+0.17%).
    f. Assimilation of the CCI SST product in a ORA S5-like experiment produces SIC analyses that show a higher level of consistency with the CCI SIC than the ORA S4 SIC field.
    g. The CCI SST, Cloud cover, sea level and ocean colour all capture the ENSO variability consistently. They ECV's are suitable for evaluating processes and climate models.
    h. The integrated assessment of the consistency between the ECVs related to regional moisture processes (clouds, soil moisture, precipitation and water vapour) in the context of the African monsoons and European rainfall shows that the CCI cloud and soil moisture products are consistent on a regional scale.

3. Technical aspects of CCI data versus Copernicus requirements

3.1 Data formats and conventions

All CCI ECVs are produced in NetCDF format, and attention has been paid to make them CF-complaint. Metadata is provided with each product. To meet different users and application requirements, the CCI ECVs are provided at different levels of processing (see section 3.3). Fully documented uncertainty characterization with quantitative estimates at data level (i.e. at pixel level for the L2 datasets) are provided in many cases.

A **PSD** (Product Specification Document) and a **PUG** (Product User Guide) are available for all products to guide users on how to best use the CCI ECVs. These are in addition to the **CRDP** (Climate Record Data Package) which contains information for users about the data.

Data versioning is used with all CCI ECV datasets, with agreement on the need for using DOI identifiers for each ECV release to ensure data traceability and how these identifiers can be obtained.

For some CCI ECVs, gridded products from the latest release are also produced in the Obs4MIPs format, and are available through the Obs4MIPs web-site.

The C3S ITT on Software Infrastructure for the Climate Data Store provided some indications on format, standards and ingestion methods that data provider will need to adhere to include their selected datasets in the C3S CDS. These are as follows (source C3S_23a):
"Data suppliers will make the output available to the CDS users via the CDS. They can do so by either of the following methods:

- *(a) uploading their data and products to a designated server ("push") within the C3S (e.g. when volumes are small and no infrastructure in place, at their site);*
- *(b) providing them via web services (e.g. when volumes are large or infrastructure is in place).*

In the case of (a), suppliers will only use data formats agreed by ECMWF. ECMWF will only accept data in formats that follow internationally recognised standards. Such standards must be open (e.g. non-proprietary), managed by a recognised international standardisation body (e.g. ISO, WMO, OGC, etc.), or any de-facto standard Open Source software should also exist that can read and write files of these standards. Serialisation formats (e.g. NetCDF, XML, JSON) should be supported by standard schemas and conventions. All text based formats should be encoded in UTF-8. ECMWF will implement tools to check the compliance of the provided data and products to the agreed standards before they are added to the CDS.

Examples of case (a) are data uploaded to the CDS in WMO GRIB edition 1 and 2, NetCDF files conforming to CF-1.6, or greater.

In the case of (b), suppliers will only use protocols agreed by ECMWF to invoke the web services. ECMWF will only accept protocols that follow internationally recognised standards. Such standards must be open (e.g. non-proprietary), managed by a recognised international standardisation process (e.g. ISO, WMO, OGC, etc.), or be a de-facto standard such as OpenDAP. ECMWF will consider using bespoke web based APIs to access the data and products if they implement very simple protocols (e.g. REST), and the results returned by these APIs are compatible with (a). It should be noted that requests for these web services will mostly originate from the Climate Data Store itself, as part of a workflow run on behalf of an end-user; ECMWF will therefore need to have the necessary credentials to invoke these services. ECMWF will not provide information on the end user's identity when invoking the web services. ECMWF will nevertheless collect usage statistics for all aspects of the C3S.

Examples of case (b) are OGC standards (WMS, WCF, WFS, etc.), OpenDAP, etc. Other protocols could be considered as the system evolves."

3.2 Metadata

There are various metadata required to be made available with the satellite CDRs which need to be clearly documented. Examples include a timeline of both satellite and instrument related anomalies, documentation on version of level 1 processing, what ancillary datasets have been used in the level 2 processing, and processing algorithm versions at all levels.

Every dataset and/or service provided by C3S will have to be documented using the appropriate metadata standards (ISO19115, source C3S_23a). All CCI ECVs have been enriched with detailed metadata, but whether this adhere to the required standards will need to be ascertained.

3.3 Data access

Access to the CCI ECVs is free and open with just a few requiring registration before access is granted. During the CCI Phase 1, each CCI consortium stored their production in their own dedicated server, and no centralised data store was available at and through ESA. Links to these data servers are provided by each CCI team in their corresponding web-site (following the correct link from www.cci.esa.int). Subscription to ECV-specific updates/mailing list are also available from the ECV web-sites.

In May 2015, ESA started a project for the creation of a CCI data portal to provide users with an easy, one-stop shop to all CCI data and it is currently being populated with the latest CCI releases (ftp://anon-ftp.ceda.ac.uk/neodc/esacci/). Mechanisms for user subscription to ECV-specific updates/mailing list are planned for implementation and should become available with its first release scheduled for May 2016. Currently user support is provided by the ECV science leader for general matters and in the first instance, and by the ECV team members in case of more specific, technical aspects.

The C3S data and products will be available through the C3S CDS interfaced by an integrated web portal that "*will provide the single point of entry for the discovery and manipulation of data and products available in the CDS*" (C3S_23a ITT). Users will be able to seamlessly access the existing data repositories distributed over multiple data suppliers. All data and products will be provided with quality information. The integrated web portal *will also display the latest information on events, current news regarding CDS. It also provides help desk facility, FAQs, user forum*" (C3S_23a ITT). Data on existing repositories distributed over multiple data suppliers will most likely be retrieved via invocation of the corresponding web services from the Climate Data Store itself as part of a workflow run on behalf of an end-user, thus ECMWF will need to have the necessary credentials to invoke these services. A schematic of data flows around 'research', 'C3S', 'users' and 'CCI' is shown in Figure 3.

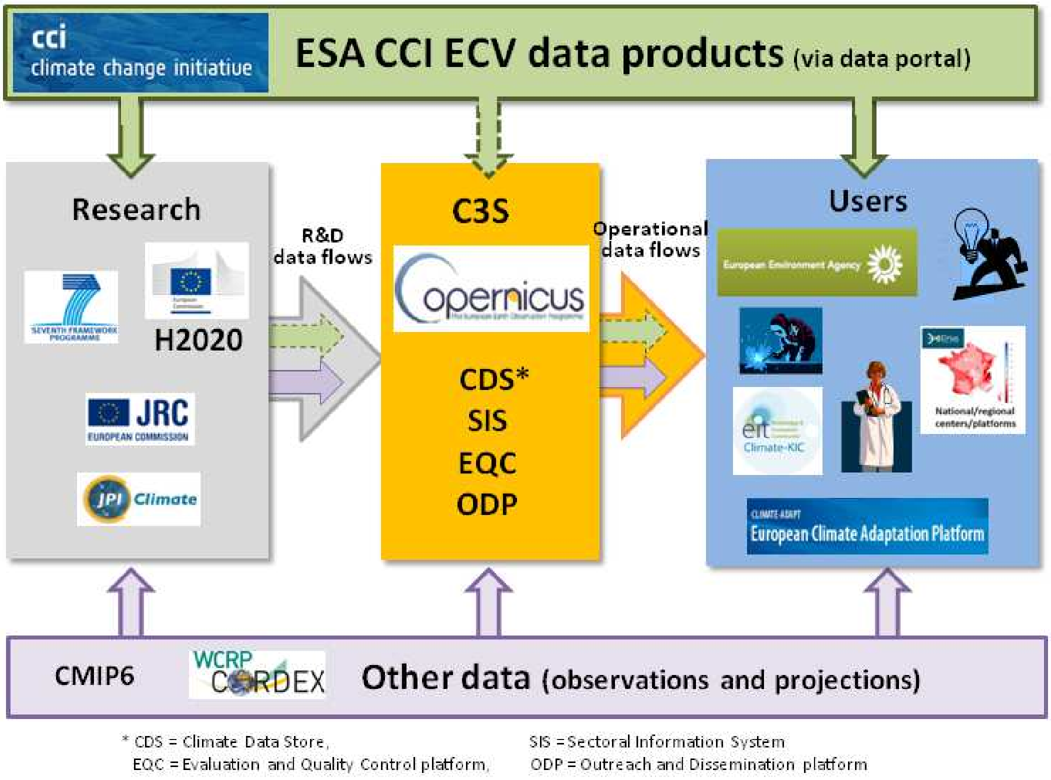

Figure 3: Schematic diagram of the existing data flows of CCI data to users and to research activities, as well as of the potential CCI data flow to C3S. It also illustrates an alternative

route for CCI to potentially reach the C3S and its users through their possible combination with data from other sources. Dashed lines indicate potential data flows.

3.4 Level of processing

To meet different users and application requirements, the CCI ECVs are provided at different levels of processing. The CMUG assessment considered different possible usage of the CCI ECV, in particular for global and regional assimilation, detection, climate model validation, and boundary conditions.

According to ESA, Level 0-1 processing and the implementation of Level 0-1 algorithm improvements is an activity that is performed outside of CCI as this activity is covered by other projects, most notably by the corresponding ESA sensor Quality Working Groups (QWGs). CCI is however expected to give feedback to Level 0-1 processing, and thus to report issues and to propose solutions. For the CCI programme, it was assumed that appropriate Level 1 (L1) data existed and could be used. In contrast, Level 1-2 and Level 2-3 processing to produce orbit-based and gridded ECVs are key priorities for CCI.

The CCI ECV data sets are derived globally whenever applicable and whenever measurements are provided globally. Vertically-resolved ECV products are also available when the instrument information content permits it.

CCI L3 daily and/or monthly mean gridded products are available whenever applicable. These averaged products also include information on their uncertainties. Discussions and workshops have been organized by CCI teams to characterize user requirements for uncertainties, and best practices.

3.5 Data issues across ECVs

Here we report on the known technical and scientific shortcomings in the CCI ECVs highlighted by either CMUG or CCI ECV team assessments.

Inter-instrumental biases due to calibration differences might still exist for some products. This is an issue when merging data from different datasets to generate longer time-series. For instance, CMUG QAR 2015 showed that

- The global mean and spatial standard deviation of the OC-CCI chlorophyll products a marked reduction in variability is noted when MERIS is introduced in 2002. This seems to suggest that the different sensors are not fully inter-calibrated.
- The comparison between burned area and CCI soil moisture shows that all products have a very similar distribution with the exception of the CCI MERGED product,

for which substantial burned areas are reported in regions with soil moistures exceeding 25%.

A land-sea mask and a freshwater mask have been produced by the Land Cover project and are available on their project website (http://www.esa-landcover-cci.org/?q=node/162). These masks were constructed from Envisat ASAR, MERIS and auxiliary datasets as pixels containing land/water content ratio at 300m resolution and temporal extent of 2005 to 2010. The full extent to which they have been taken up by the ECV teams, which would support consistency, is not known.

A number of **inconsistencies between** different sub-products of various **ECVs** are known, and cross-ECV work is ongoing to remedy to them. These include:

- A disagreement was seen between CCI Glacier and CCI Land cover. The CCI Land cover class "permanent snow and ice" is larger than the glacier area derived from the glacier outlines in CCI Glacier with >30% relative differences in places (CMUG QAR 2015).
- The Aerosol-CCI and Cloud-CCI algorithms applied to the same data showed that the same pixels were differently identified as either cloudy or aerosol-affected by the two teams. Work is on-going to converge on the data classification.
- Some inconsistencies were found between the CCI SST and SIC datasets in many regions close to the ice edge.

The data assessment has highlighted **incomplete information** in some cases. This will need to be included in forthcoming releases. For instance,

- No temporal information is available in CCI Glacier inventory (RGIv4), assumed to be the most recent snapshot of the global glaciers. At the present, such an information must be derived by users from other sources.
- The CCI Land Cover does not include the class "water bodies" in the seasonal products. From a "climate quality" perspective, it would be interesting to get information on trends and seasonal variation in the spatial distribution of surface water. Variation in small water bodies is a relevant ECV related to permafrost melting, which is of highest interest in the Arctic region.
- Limited information on hydrography is available even in rather detailed products such as land cover, for instance there is no distinction or mask to attribute water pixels to river or lakes.
- Error characteristics are not provided with the SICCI ice thickness data product.
- No Glacier thickness is provided with the Glacier inventory, although some model estimates can be obtained upon request to the CCI Glacier team.
- Spurious values were found in the CCI Sea Ice concentrations in a number of regions, especially in the Norwegian and Labrador Sea, likely due to cloudy measurements not filtered in the CCI algorithm. Spurious data values were also found in the gridded SSH product over land grid point locations. These datasets would benefit from including a

land-sea mask as an additional field that users can use to filter any spurious or suspicious data out. Alternatively, a user-friendly data quality indicator could also suffice.

3.6 System and data requirements for climate datasets in C3S

System and data requirements that climate ECVs will need to meet to be considered in an operational service like the C3S are only partly known, e.g. based on information provided in already published documentation and ITT calls, and in some cases should be expected to evolve with time. Here, we present a number of desirable aspects for climate datasets, contrast them with the current practice within CCI and whenever possible or needed provide recommendations for possible improvements that should be contemplated to make them more appealing to the C3S in particular and climate services in general.

System Specification:
The current specification of each CCI ECV System has been documented and defined according to the recommendations specified in the individual ECV **System Requirements Document** (SRD). The SRDs set also all requirements for additional external or auxiliary data required for the data processing. A schematic diagram of the CCI in general and of each ECV System Specifications as it currently stands is given in figure 4.

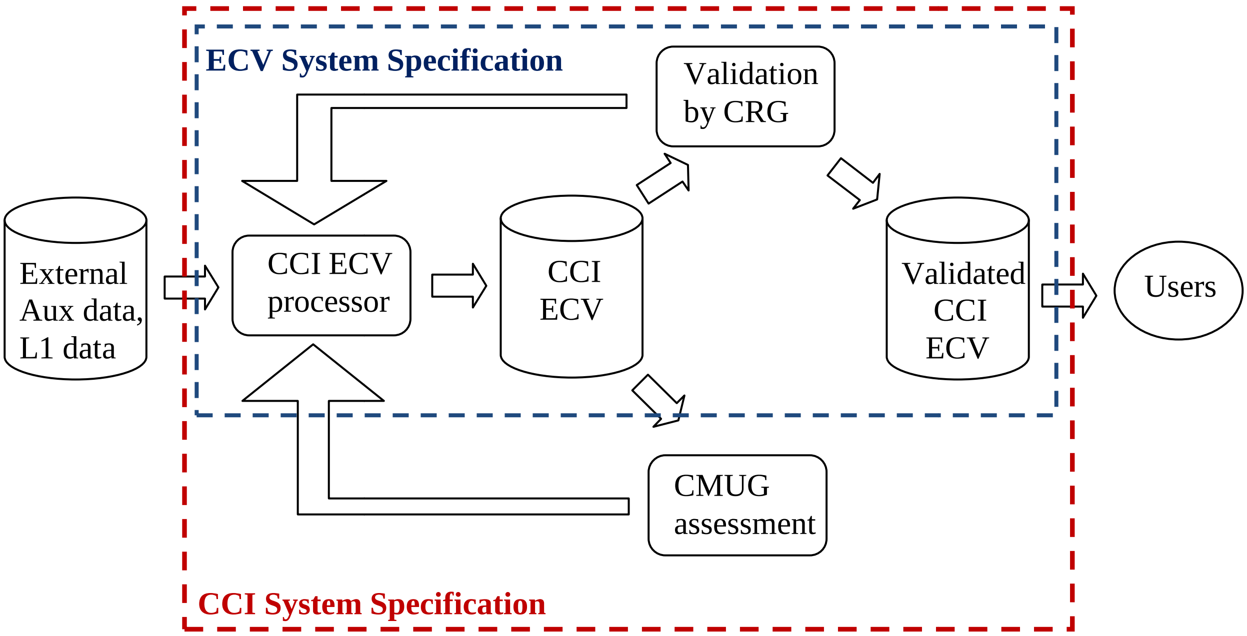

Figure 4: Schematic of any CCI ECV System Specification and its interaction with CMUG.

The system specification of many CCI ECVs were both self-assessed by the CCI team and assessed by the Core-CLIMAX consortium using the Core-CLIMAX System Performance Matrix during the 2014 Core-CLIMAX Workshop.

In the event the production aspects of a given CCI ECV was taken over by the C3S the above System Specification will require modifications. A very schematic diagram of how it could change in that case is drawn in figure 5.

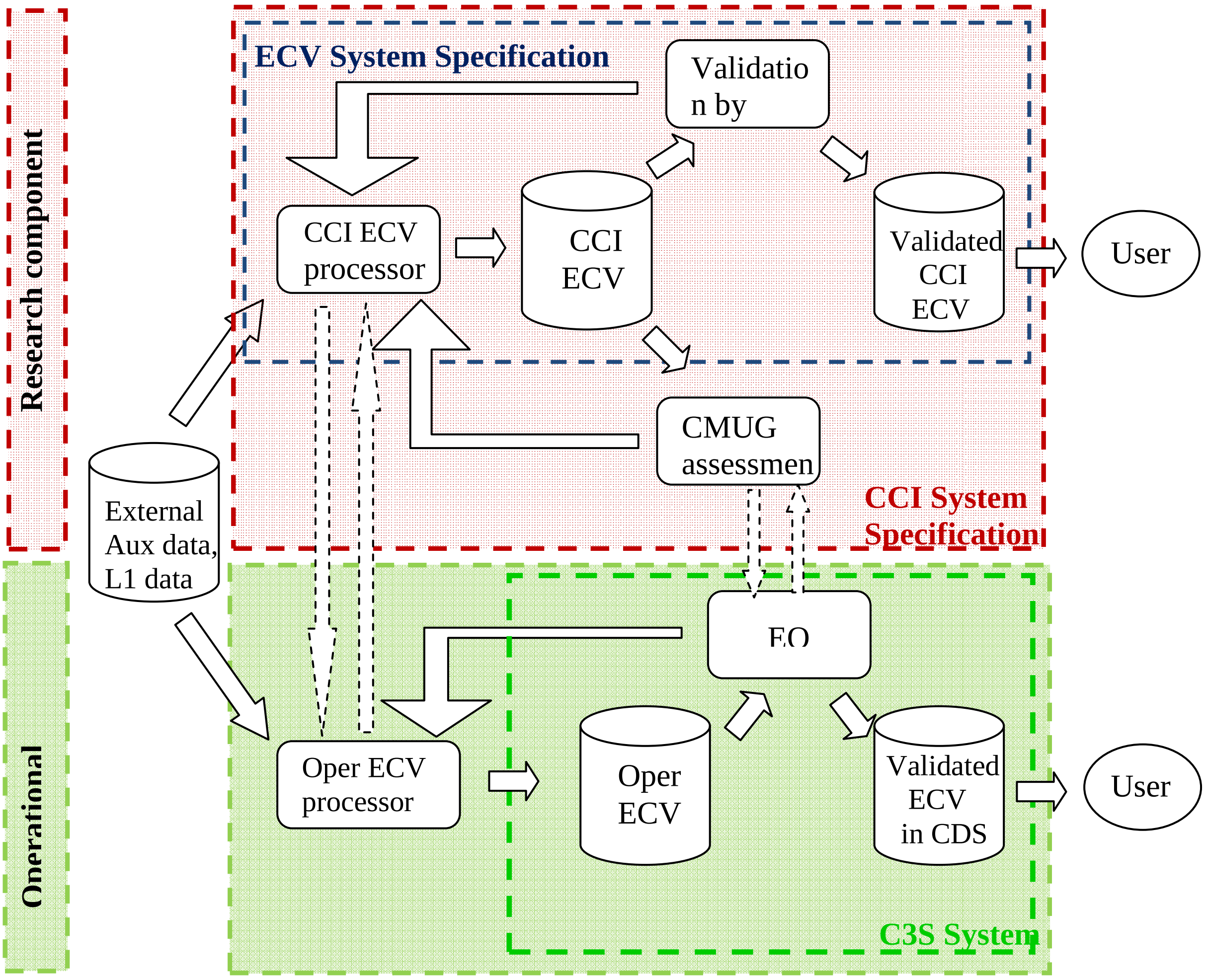

Figure 5: Schematic diagram of how the research and operational components of a generic CCI ECV might interact if that was selected for the C3S. In the diagram, the possible interaction between the C3S EQC and CMUG noted in section 1.3 is also drawn.

Data cycles:

The current CCI Phase 2 system specification foresees a fast turn-around for most (i.e. whenever applicable) CCI ECVs with typically one-year cycle required to go from updating the algorithm incrementally, i.e. according to received feedbacks, to releasing validated datasets (spanning the considered satellite missions) to users. This might be appropriate for most climate applications while it is noted that for some, like for instance reanalysis, the requirements might be different.

Reanalysis are often updated every five years or so, and a full production normally can take between two to three years for the retrospective analysis to be completed. In this respect, while a one-year reprocessing cycle might not be strictly necessary it will be important that, for the ECVs assimilated in the operational reanalysis, data production will be continued in time with the algorithm version that was operational at the time those ECV datasets were first assimilated even after that algorithm version is superseded by an upgraded one. This requirement is important to avoid jumps in the reanalysis time-series due to algorithm version and thus ensure long-term homogeneity in the resulting production. A coordination between L2 reprocessing activities and reanalysis schedule should also be considered.

If a fast turn-around and cycles are desirable, especially to include new datasets from e.g. the Copernicus Sentinels, it is important that any change should be traceable (e.g. C3S_312a Volume II ITT).

In C3S, each data provider will need to define a set of Key Performance Indicators (KPIs) to be included in a service status dashboard that will be used at the end of each year of service to review the service readiness. The KPIs shall be used to monitor the different services across Lots measuring a set of indicators and benchmarking metrics quantifying the quality, suitability, and performance of the service against the Target Requirements (C3S_312a Volume II ITT).

Temporal coverage:

A dataset to be useful for climate studies needs to maximise the data temporal coverage to cover a sufficiently long period of several years to decades whenever possible. This is required to be able to monitor climate change and perform trend analysis. For the C3S, for instance, the target requirement consists of a minimum of ten years (C3S_312a Volume II ITT).

The formulation of the CCI System Specification and System Requirement Documents does not contemplate a Near-Real-Time (NRT) processing. It is recognized that in some areas and applications, such as monitoring of climate hazards and extreme climate events, it is essential that the climate information provided by the service is made available within a short time period to be useful. This should stimulate some changes to the CCI ECV SS that might improve their fitness to purpose.

It is important to mention that with the new satellite missions being launched, most CCI teams are considering extending their data availability forward in time applying their state-of-the-art algorithms to newly available and future measurements.

A concept similar to that applied to reanalysis productions could be useful here. New reanalysis efforts are produced typically every five years. The temporal coverage extends close to the present using whenever possible reprocessed observations. At that point in time, the reanalysis is continued forward applying the same data assimilation and forecasting system to more recent observations ensuring its availability to users typically within two to four weeks from data acquisition.

Data gaps:
Discussion on data gaps for each CCI ECV characterized part of the CCI Phase 1 project. It would be useful if this was documented for each CCI ECV if not yet available.

Here, the expression "data gap" refers to periods during which measurements of a given variable are not available at all, for instance due to a gap in EO plans. In this respect, it is noted that maximising the use of observations from as many sources as possible is encouraged and that this represents a target requirement for C3S (C3S_312a Volume II ITT).

Data format, data standards and metadata:
Indications on accepted data formats and the standards data and products are required by the C3S were provided in sections 3.1 and 3.2. Based on the known information, the CCI ECVs are already meeting or close to meet the technical requirements, it is noted that the CCI ECVs are currently produced with NetCDF version 4 in most cases and effort was put during Phase 1 to adhere to the CF standards, as well as they already include metadata information.

Nonetheless, the following will need to be ascertained:

- The CF standards used by CCI is CF-1.6 or higher.
- The metadata information meets the ISO19115 standards.

User support:
To facilitate user exploitation of the C3S data the CDS web portal will also provide state of the art tools and software "*to generate the relevant set of climate variables, indicators and indices required to analyse, monitor and predict the patterns of both the climate drivers and impacts*" (C3S_23a ITT).

While this is understood, it would be wise for data providers to engage the C3S team developing the CDS toolbox to ensure a correct interpretation of the original data is made.

This should be considered by CCI teams in the event any of their products will be selected to be included in C3S.

Another function is to help service users with any problem or issue they may encounter in a timely manner. For the C3S, a minimum of 50% of queries are expected to be answered within 5 working days (C3S_312a Volume II ITT).

System monitoring
Any data provider to the C3S is expected to *monitor routinely the performance of the system through a series of benchmarking metrics, covering both the quality of the data (e.g. validation), the performance of the system, and the quality of the service. In particular, for the C3S, the successful tenderer shall take account of the feedback of the EQC to improve iteratively its products and processing chain* (C3S_312a Volume II ITT).

4. Tools, architecture and supporting information for CDRs

4.1 Rationale

It is vital that the CCI data users are able to easily ingest the datasets into their working environment and analyse them. Within the C3S, a state-of-the-art toolbox will be made available to users to facilitate them with the C3S product handling, and manipulation. The same might not always be true for other climate services and data repositories where the CCI data might be or become available.

Also a user perspective is provided here on tools, architecture and supporting information that, while not generally required by users, might still be useful. This is especially important when the application of a particular dataset may require, for example, an in-depth knowledge of the characteristics of the used instrument(s) as they could affect the product and its interpretation. For instance, Soil Moisture product is derived from instruments that are sensitive to the soil skin layer (typically no more than 2 cm in depth) while the top layer of modelled SM often refers to a much deeper layer. Without such an understanding, conclusions drawn from simple comparisons can be misleading.

4.2 Data Ingest tools

It is vital that users of C3S data are able to easily ingest the datasets into their working environment and analyse them. The format should be familiar to users and plug in modules to ingest the data formats should be provided in commonly used software environments (e.g. Fortran, IDL, Python, Perl, ..). **All users will need the install software** unless the format is a really standard gridded dataset and so it is critical to make this part of any tool box well documented and easy to use. The final result is to populate a variable array within the users particular application.

To make reading the datasets as easy as possible a small software package consisting of source code, documentation, build scripts, and installation tests (sample input data and expected output from test programs in order to verify correct installation) is envisaged as an effective solution by climate modellers.

Note that with all the tools developed there is a maintenance cost implied as different software operating systems change and so the associated tools need to maintain compatibility with the latest version and a few of the previous versions.

4.3 Access to metadata

There are various metadata required to be made available with the satellite CDRs which need to be clearly documented. Examples that should be available with the data as it is needed by users include a timeline of both satellite and instrument related anomalies, documentation on version of level 1 processing, what ancillary datasets have been used in the level 2 processing, and processing algorithm versions at all levels.

4.4 User feedback

Among others, a potential advantage of CCI data being made available through high visibility services like the C3S would be in allowing users to comment on their experience with the data and passing these comments back to the data producers. Such user feedback can be about the strengths of the data (including links to journal papers, technical notes, validation, provenance, application, uncertainty information, and notes about external events), or maturity information. Equally, user feedback on weaknesses in the data such as gaps, previously unknown bias or errors also needs to be conveyed to the producers, usually through the service provider.

Any dataset server that is complemented by a user feedback or annotation system would be welcome by users and providers, e.g. the CHARMe system (developed to allow climate data sets to be annotated with such commentary information).

4.5 Data Analysis

Once the climate data and products have been ingested into the local software systems users will probably have the tools they need to process the datasets but nevertheless the option of tools to provide some simple data processing could be provided. There are already several software packages available such as GRADS (http://www.iges.org/grads/) developed for the modelling community, UV-CDAT (http://uvcdat.llnl.gov/) and the NASA Panoply (http://www.giss.nasa.gov/tools/panoply/) software which already perform many functions and so any tool developed could usefully add capabilities to these existing packages.

Climate Data Operators (CDO) are widely used by the climate modelling community because of their ease of processing, and a good test for a dataset is to see whether CDOs can work with it (as well as working with visualisation tools).

It might be envisaged if the tools are in an easy to develop form then the users could actually contribute to the tools themselves and make them available to the toolbox which would be maintained.

4.6 Co-location software and data

For most of the CDRs they should be accompanied by colocation software with datasets of in-situ measurements (e.g. buoys for SST, ozone sondes for ozone, fire radiative power for burnt area) to assist a wide range of users in accessing the full range of observation data for that ECV. Tools for the spatial interpolation of the data to allow for a resampling of the observational data as well as visualisation would be useful.

4.7 Climate Monitoring Facility

Although it can be expected that users might not need software and tools to display the CCI data, it is worth mentioning that a Climate Monitoring Facility (CMF) is currently under development.

The CMF is an interactive interface to visualize and facilitate model-observation confrontation for L3 products with a focus on multi-annual variability of statistical averages (monthly/regional means) based on pre-calculated mean statistics.

The CMF web-interface relies on a database (CMFDb) populated with pre-calculated statistical averages of an excess of 100 distinct variables defined over 32 different geographical regions, 12-18 layers (if applicable), and several data streams (various reanalyses and several CCI datasets).

This tool could be useful to understand the low-frequency variability of the CCI ECV, and contrast it to that of equivalent ECV products, determine the long-term homogeneity of the various datasets in terms of regional monthly means and perform a consistency analysis between different CDRs. However, caution should be used when drawing conclusions from these comparisons, as differences may occur in the data coverage of different data sets used to produce those averages.

5. Institutional links and interactions

The purpose of this section is to note the links between CCI (specifically CMUG, but also within the CCI ECV projects and the Data Portal project) that would be useful to developing the C3S, either as:

- a supporting feed-in type activity that includes several EC research projects (e.g. CLIPC, ERACLIM2, EUCLEIA, QA4ECV, UERRA, ECLISE, SPECS, EUPORIAS, CLIM-RUN, GAIACLIM, FIDUCEO), and other international activities (e.g. SPARC Reanalysis Intercomparison Project, S-RIP).
- links with groups that are developing Climate Services (e.g. JPI WG1, Climate Services Partnership, GFCS)
- links to users and user groups (EEA, Climate Support Facility)
- international perspective/coordinating organisations (GCOS, WMO, EC, IPCC)
- National coordinating bodies that would provide direction and support for climate services (e.g. research councils, adaptation bodies, CC impacts, disaster reduction, regional government and agencies)
- Business (insurance, energy, agriculture, health, water, transport)
- Relief and Emergency bodies (health, disaster response)

Links with nearly all these organisations and institutes already exist with CMUG partners such as the Met Office, ECMWF and Météo France, and can be used to the benefit of C3S.

Consideration should also be given to the usefulness of a C3S stakeholder / user group who could provide independent input and feedback on the effectiveness of C3S outputs across systems and sectors. This would include reviews of whether the C3S services are being exploited to the full benefit of users including the application of the outreach and user engagement activities of C3S.

6. Acronyms

ATBD	Algorithm Theoretical Baseline Document
CMF	Climate Monitoring Facility
CMIP	Coupled Model Inter-comparison Project
EC	European Commission
EEA	European Environment Agency
ESMValTool	Earth System Model eValuation Tool
GCOS	Global Climate Observing System
IPCC	Intergovernmental Panel on Climate Change
ORA-S4	ECMWF Ocean Reanalysis – System 4
PSD	Product Specification Document
PUG	Product User Guide
RCA	Rossby Centre Regional Climate model

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Annex 1 Details of current (January 2017) CCI ECVs

ECV	Domain	Acronym	Products	Time Span	Coverage	Resolution	Obs Cycle Sampling
Ocean Colour	Ocean	OC	Chlorophyll-a Conc.	1997-2013	Global with map	4 km	daily
			Water Leaving Radiance	1997-2013	Global with map	4 km	daily
Sea-ice	Ocean	SIE	Sea-ice Extent	1992-2011		10-15 km	weekly
		SIT	Sea-ice Thickness	1993-2012	Arctic	100 km	Monthly (Oct-Apr)
		SIC	Sea-ice Concentration	1978-2008	Arctic & Antarc	25 km	Daily
Sea-Level	Ocean	SSH	Regional Sea Level	1993-2015	Global	¼ degree	Monthly
			Global Mean Sea Level	1993-2015	Global	Scalar	10 days
Sea Surface Temperatu	Ocean	SST	Sea Surface Temperature	1991-2012	Global	~5 (0.05°)	Daily (day and night
			Sea Surface Temperature	1991-2012	Global	4-25 km	
Carbon Dioxide	Atmosphere	XCO2		2002-2014	Global	10-60 km	6 days
Methane	Atmosphere	XCH4		2002-2014	Global	10-60 km	6 days
Ozone	Atmosphere	NP	Nadir Profile	1997, 2007, 2008	Global	200 km	1-6 days
		LP	Limb Profile	2007-2008	Global	250-500 km	1-6 days
		TO(L2)	Total Column	1996-2013	Global	40-320 km (L2)	1-6 days
		TO(L3)	Total Column	1996-2013	Global	100 km (L3)	1 month
Aerosol	Atmosphere	AOD	Aerosol Optical Depth	1978-2015	Global	10, 1°	1-6 days
		AAI	Absorbing Aerosol Index	2005, 2008	Global	13 x 24 km	Near-daily
		AE	Stratospheric Extinction Profile	2008	Global	2.5° x 10°	Monthly
Cloud Properties	Atmosphere	CC	Cloud Cover	2007-2009	Global	50 km	10/day
		CTP	Cloud Top Pressure	2007-2009	Global	50 km	10/day
		CTH	Cloud Top Height	2007-2009	Global	50 km	10/day
		CTT	Cloud Top Temperature	2007-2009	Global	50 km	5/day
		COT	Cloud Optical Thickness	2007-2009	Global	50 km	5/day
		LWP	Liquid Water Path	2007-2009	Global	50 km	5/day
		IWP	Ice Water Path	2007-2009	Global	50 km	5/day
		REF	Cloud Effective Radius	2007-2009	Global	50 km	5/day
Ice Sheets	Land		Surface Elevation Change	1991-2016	Greenland	5 km	4/year
			Ice Velocity	Covering 1991-2008 pe	Greenland	500 m	Snapshot or time se
			Calving Front Location	-	Greenland	250 m	4/year
			Grounding Line Location	-	Greenland	250 m	1 year
Glaciers & Ice Caps	Land		Area	1984-2011 (data availal	Global	30 m	Multi-year composi
			Elevation Change (DEM)	1960s-2008	Global	1-100 m	1 week (SRTM), 8
			Elevation Change (Altimetry)	2001-2011	Key Regions	170 m	1 day
			Velocity	1991-2011	Key Regions	10-30 m	monthly to annual
Fire			Fire Burned Area	2005-2011	Global	0.3 -1 km	1-5 days
				1995-2010	Study sites		
Land Cover	Land		Land Cover State Map	1998-2012	Global, except p	300m or 1km	3 5-year intervals
			Global Land Cover Condition	1998-2012	Global, except p	300m, 500m, 1km	15 years
Soil Moisture	Surface		Volumetric Soil Moisture	1978-2014	Global	50 km	1 day (for some lats

Table 4: Temporal and spatial coverage of the CCI ECVs provided in terms of the actual products available.

CCI ECV	Used (core) instruments	Potential / Considered instruments
O3	GOME, GOME-2, OMI, SCIAMACHY, MIPAS, GOMOS	Sentinel-5P (S-5P), S-4, S-5
GHG	SCIAMACHY, GOSAT	OCO-2
Aerosols	ATSR-2, AATSR, OMI, MERIS, GOMOS, Modis	
Clouds	AATSR, MODIS, AVHRR, MERIS	
SST	ATSR, AVHR	
SSH	ERS-1, -2, ENVISAT, TOPEX/Poseidon, Jason-1, -2 Altimeters	Cryosat, S-3, Jason-3
OC	MERIS, MODIS, Seawifs	
S-I	SSM/I (F10, F11, F13, F14, F15), AMSR-E, ERS-1, -2, and Envisat Altimeters, AMSR2, Cryosat-2, SMOS	
Fire	MERIS	
LC	MERIS, SPOT	Landsat-8, Sentinels, ALOS-2, PROBA-V
Glaciers	Landsat, SPOT	
I-S	Ers-1, -2, Icesat, ASTER, ENVISAT Radar Altimeters	Cryosat, S-3
SM	ERS-1/2 SCAT, METOP ASCAT, SMMR, SSM/I, TMI, AMSR-E, Windsat	SMOS, SAR, RA, -2

Table 5: List of core instruments already used by the CCI teams and possible (or contemplated) sensors that could be added in the future. It is noted that in addition to the core instruments, a number of additional instruments were also already included in the CCI ECV Climate Data Packages. These are not reported here, but are described in CMUG URD 2015 and also on the CCI ECV project websites and documentation therein.

	Resolution (Days/hour; km)			Accuracy (*Unit*)			Stability (*Unit* / year)		
	GCOS	URD	Achieved	GCOS	URD	Achieved	GCOS	URD	Achieved
XCO2 (ppm)	T: 4h (*) H: 5-10	Any	Day 10 km	<1	<0.5	0.4-0.9 (+)	<0.2	<0.5	<<0.5 (#)
XCH4 (ppb)				<10	<10	3-8 (+)	<2	<10	<4 (?)
TCO3 (%)	T: 3 D H: 20-50	3 days 20-300 km	3d / better 40km	2	< 3	<2	<0.1	0.1-0.3	<0.1
SST(mK)	T: 4h (*) H: 10 km		Day 10 km	<10%		1% (L) 20% (O)	0.1		
OC	1-3day 1-5 km	1 day 4 km	Day 4 km	5-8.5-25%	30%		1%/decade	2%/decade	
SSH	1 day 25 km	2 day 25 km	10 day	1-2 cm	1 cm			2mm / decade	
SI	1-7 days 12-100 km	1 day 5 km	7 day 10-15 km	5-10%	5%	5%	5% / decade	1-5% / decade	
Clouds	3-6 h 0.1-100 km	1 h 5-30 km	5 day 50 km	10-20%	5%		1% / decade		
Aerosol	1-7 day 1-10 km	1-6h 1-25 km	1-6 days 13-24 km	0.004-0.02	0.02		0.005/decade	0.01/decade	
Glaciers	1-5 years 30-100m	3 months 30m	Day-m 30-100m	5-10% 10-100cm	5% 10cm		5%	0.01km^2/decade	
LC	1 year 0.25-1 km	2-5 years 0.3 – 1 km	5 years 0.3-1km	15%	5-10%		<15%	<10%	
Fire	1-3 days 0.25-1 km	1-3 days 0.25-1 km	1-5 days 0.3-1 km	5-10%	10-30%		5%	5%	
SM		1 day <1–25 km	1 day 50 km		0.04m^3/ m^3		1%	0.5%	
IS (elev)		<5km/yr	1-4 year 0.25-5 km		0.1m/year			<0.1m / decade	
IS (veloc)		0.5m/yr							

Table 6: Comparison between GCOS and user requirements vs. achieved ones for resolution, accuracy and stability. [Sources include GCOS 2011, 2016, CCI project documents (CRDP, PSD, CAR, UCR) and CMUG reports (URD, tech Note on Product Assessment).]

Legend for table 6:
(+) Depending on the instrument
(*) No existing or planned mission meets this requirement
(?) Trends do not account for sudden jumps, but only long term drifts
(#) Derived trends not or mostly not significant
(L) Over land
(O) Over ocean. Here there is a problem with the poor number of observations part of the validating dataset
(G) Global value
(R) Regional value
(V) Vertical resolution
(DV) Depending on the considered vertical region, some of the requirements may be actually met