**CMUG Deliverable**
**Number:** D8.3
**Submission date:** 13 December 2022
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# Climate Modelling User Group

# CCI+ Phase 1 (Oct 2018 – Dec 2022)

## Deliverable 8.3

## Final Report

CMUG centres providing input: Met Office, MPI-M, ECMWF, MétéoFrance, IPSL, SMHI, DLR, BSC, STFC-UKRI

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# 1 Introduction

The Climate Modelling User Group (CMUG) is a European Space Agency (ESA) Climate Change Initiative (CCI) project that works to ensure the relevance of the ESA CCI Essential Climate Variables (ECVs) for the climate research community and climate services and their uptake within those areas. Phase 1 of CMUG CCI+ began in October 2018 and was due to end September 2021. Due to several challenges, including the COVID-19 pandemic and significant staff changes, a no cost extension was issued in May 2021 with a new end date of June 2022.

CCI+ CMUG phase 1 comprises the following work packages

- WP1: Meeting the evolving needs of the climate community
- WP2: Providing an integrated view and feedback to ESA and the CCI teams
- WP3: Quality assessment of CCI products
- WP4: Exploiting CCI products in Model Intercomparison Project (MIP) experiments
- WP5: Adaptation of community climate evaluation tools for CCI needs
- WP6: Coordination and outreach
- WP7: Interface of CCI data to climate services
- WP8: Project management

# 2 Project objectives

CCI+ CMUG phase 1 objectives were:

- Support integration within the CCI programme through:
    - Gathering user requirements from the Climate Modelling Community
    - Feedback on the usability of the CCI ECVs from a ‘climate system’ perspective
    - Encouraging communication between the CCI ECV projects and undertaking cross-ECV scientific studies which complement the work done by the CCI ECV Climate Research Groups (CRGs)

- Using the uncertainty information provided by the CCI ECV projects and feeding back on its usefulness to the ECV projects

- Foster the exploitation of Global Satellite Data Products within the Climate Modelling Community by:
  - Promoting the use of CCI data sets to climate modellers
  - Building partnership and links with existing research organisations, networks and scientific bodies of the Climate Modelling Community
- Assess quality and impact of individual/combined Global Satellite Data Products in a Climate Model and Data Assimilation context by:
  - Assessing the suitability of products for climate applications (e.g. climate modelling, decadal prediction, reanalysis, etc.)
  - Quantifying their incremental value to model performance in an objective manner
  - Assessing the consistency between different CCI ECV products

# 3 Consortium partners

The CCI+ CMUG phase 1 consortium consisted of the UK Met Office, Météo-France, The European Centre for Medium Range Weather Forecasting (ECMWF), the Swedish Meteorological and Hydrological Institute (SMHI), Deutsches Zentrum für Luft (DLR), the Max Plank Institute – Meteorology (MPI-M), the Barcelona Supercomputer Center (BSC), Institut Pierre-Simon Laplace (IPSL) and the Science and Technology Facilities Council-UK Research Institute (STFC-UKRI) also known as the Centre for Environmental Data Analysis (CEDA). The Met Office Hadley Centre leads and coordinates the project. Figure 1 illustrates the structure of CMUG. The roles of each of the partners and the individuals involved from each institute are summarised in Table 1.

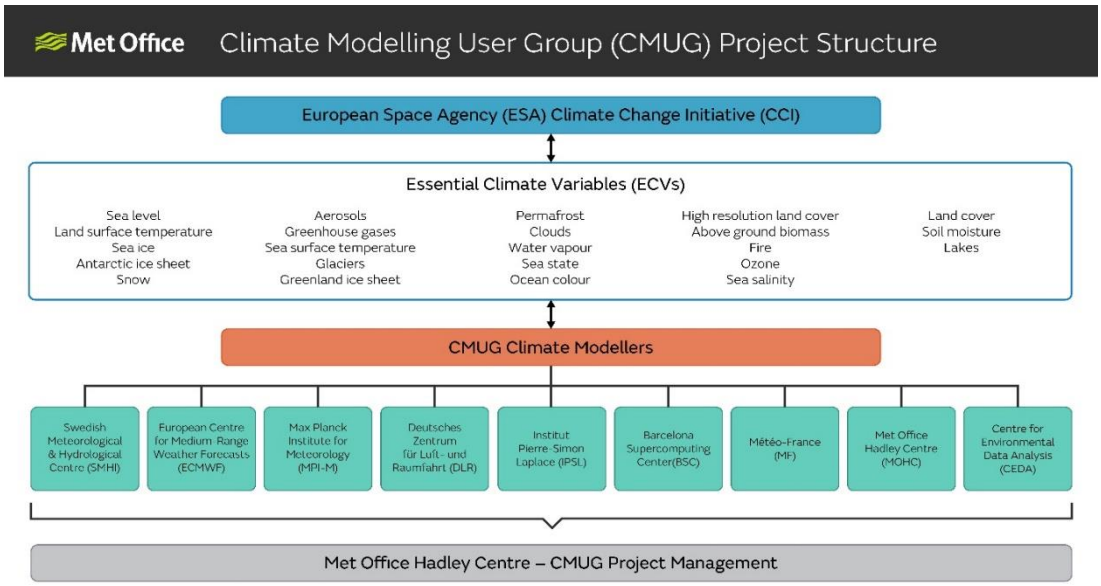


*Figure 1: A flowchart illustrating the structure of the CMUG project.*

*Table 1: The institutions, individuals, roles and work package contributions for CCI+ CMUG Phase 1.*

| Institution | Names of individuals | Role | Work packages (deliverables) | |
|---|---|---|---|---|
| | | | **Lead** | **Contributor** |
| Met Office | Richard Jones | Science Lead | WP1 (D1.2) | All |
| | Amy Doherty | Project manager (science) | WP1 (D1.1)<br>WP2 (D2.1, D2.3)<br>WP8 (D8.1) | All |
| | Hannah Griffith | Communication and outreach | WP6 (D6.1, D6.2) | WP2<br>WP8 |
| | | | | |
| | David Ford | Scientist | | WP3 |
| | Debbie Hemming | Scientist | | WP3, WP4 |
| | Rob King | Scientist | | WP3, WP4 |
| | Erasmo Buonomo | Scientist | | WP3 |
| | Grace Redmond | Scientist | | WP3 |
| | Dom Lethem | Admin/Finance | | |
| | Richard Ozanne | Admin/Finance | | |
| DLR | Veronika Eyring | Institution lead | | |
| | Axel Lauer | Institution co-lead | WP5 (D5.3) | WP1, WP2, WP6 |
| | Björn Brötz | Scientist | WP5 (D5.7) | |
| | Rolf Thiess | Admin/finance | | |
| BSC | Pablo Ortega | Institution lead | | WP1-WP7 |
| | Enza Di Tomaso | Scientist | | |
| | Mar Rodriguez | Admin/Finance | | |
| ECMWF | Angela Benedetti | Institution Lead | WP7 (D7.1) | WP1-WP3, WP6 |
| | Iryna Rozum | Scientist | WP5 (D5.2) | |
| MPI-M | Dirk Notz | Institution Lead | | |
| | Andreas Wernecke | Scientist | WP4 (D4.1) | WP1<br>WP2<br>WP6 |
| | Martina Boether | Admin/finance | | |
| Meteo France | Jean-Christophe Calvet | Institution Lead | WP3 (D3.1) | WP1, WP2, WP6, WP7 |
| SMHI | Ulrika Willén | Institution Lead | | WP1, WP2, WP5-WP7 |
| | Madeleine Benderyd | Admin/finance | | |
| IPSL | Frédérique Cheruy | Institution Lead | | WP1-WP4, WP6, WP7 |
| | Agnès Ducharne | Scientist | | |
| | Yanfeng Zhao | Scientist | | |
| STFC-UKRI | Alison Waterfall | Institution Lead | Obs4MIPs CCN (D5.7) (see below) | |

# 4 Tasks and Deliverables

CCI+ CMUG Phase 1 tasks:

Task 1: Meeting the evolving needs of the climate community

Task 2: Providing integrated view of CCI and feedback to ESA and CCI teams

Task 3: Assessing consistency and quality of CCI products across ECVs

Task 4: Exploiting CCI products in MIP experiments

Task 5: Adaptation of community climate evaluation tools for CCI needs

Task 6: Coordination and Outreach

Task 7: Interface to the European Climate Service

Task 8: Management

In addition to these main tasks a Contract Change Notice (CCN) was put in place in February 2022 for continuation of the WP5 activities working to include CCI ECV datasets in the obs4MIPs (Observations for Model Intercomparison Projects) database. This runs until February 2023 so not all deliverables are complete at time of writing.

A breakdown of the individual deliverables for each task is shown in Table 2 with a description of the deliverable, the lead institute and a link to the final version of the deliverable, where that has been made publicly available on the CMUG web pages.

*Table 2: CCI+ CMUG Phase 1 Tasks and Deliverables*

| **Deliverable** | **Description** | **Main author** | **Type** | **Link to final version** |
|---|---|---|---|---|
| **Task 1** | | | | |
| **D1.1 User Requirements Document** | List of requirements for the CCI ECV datasets from a broad cross-section of the climate modelling community. One section for each of the 23 ECV projects current at the time of writing. | MOHC | Doc | Not publicly available |
| **D1.2 Earth Observation for Climate Foresight report** | Overview of Earth Observation contribution to climate research and services and recommendations for the future. | MOHC | Doc | https://climate.esa.int/documents/1188/CMUG_D1.2-Foresight-Report-V4.1_8EMjc8o.pdf |

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| **Task 2** | | | | |
| **D2.1 CCI Scientific Impact Report** | This deliverable is fulfilled by the 'Information hub' tab on the CMUG website. Examples of news articles that have been produced include descriptions of the CMUG developments to ESMValTool and Obs4MIPs, and results from CMUG experiments using ESA CCI ECV datasets such as "Assimilating ESA CCI marine datasets for reanalysis" and "Assimilating ESA CCI Aerosol dataset improves model output". Each page includes an 'about the author' section to showcase the expertise involved. | MOHC | Web page | Case Studies (esa.int) https://climate.esa.int/en/projects/cmug/information_hub/ |
| **D2.2 Climate Data Forum** | For each key result produced during the CMUG studies in WP 3, 4 and 5 a briefing note and PowerPoint slide was produced for use by CMUG and the ESA project office in science comms. | MOHC | Set of brief-ing notes plus slides | Not publicly available |
| **D2.3 Product Documentation Assessment** | A review by CMUG expert data users of the main documents produced by each of the CCI ECV projects related to the latest datasets. | MOHC | Doc | Not publicly available |
| **Task 3** | | | | |
| **D3.1 Quality Assessment Report** | Report on experiments carried out by the CMUG partners to assess the quality and consistency of the CCI datasets through comparison between CCI products and model output, or use of the CCI products within models or reanalysis. | Météo France | Doc | Not publicly available |
| **Task 4** | | | | |
| **D4.1 Report on exploiting CCI products in MIP experiments** | Report on CMIP6 model intercomparison experiments carried out using the CCI datasets providing feedback on the suitability and application of CCI climate data products in climate models. | MPI-M | Doc | Not publicly available |
| **Task 5** | | | | |

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|---|---|---|---|---|
| **D5.1 Release of Version 2.5 of the ESMValTool and User Guide** | Version 2.5 of ESMValTool includes new recipes and diagnostics using CCI datasets: LST, GHG (CH4), WV, SSS and OC | DLR | Community Tool | ESMValTool [https://www.esmvaltool.org/] |
| **D5.2 CMF for CCI products and model evaluation** | The Climate Monitoring Facility (CMF) is a tool for comparing model and observation CDRs which has now been incorporated into the Copernicus Climate Change Service (C3S) Climate Data Store (CDS) Toolbox. The following CCI datasets have now been added and can be visualised alongside model timeseries: SST, SSH, SIC, SM, O3, CH4, CO2, AER | ECMWF | Data Evaluation and visualisation Tool | Climate monitoring facility: comparing model and observations datasets (copernicus.eu) https://cds.climate.copernicus.eu/cdsapp#!/software/app-climate-monitoring-cci?tab=app |
| **D5.3 ESMValTool GitHub repository and Namelist** | Update to ESMValTool components | DLR | Community Tool | ESMValTool [https://www.esmvaltool.org/] https://climate.esa.int/documents/1616/CMUG_D5.3_ESMValTool_Namelist_v2.0.pdf |
| **D5.4 Report on CMIP6 Global Model Evaluation from ESA CCI/CCI+ Data from Task 5.3 and Improvements Compared to CMIP5 in Support of IPCC AR6** | The purpose of this document is to summarise and document the CMIP6 evaluation work done by CMUG partners within task 5.4 *Evaluating the CMIP6 ensemble with ESA CCI and CCI+ data using the ESMValTool*. | DLR | Doc | Not publicly available |
| **D5.7** | CCI Contribution to Obs4MIPs<br>a) Training material<br>b) Roll out schedule<br>c) Annual report<br>d) CCI data added to Obs4MIPs | DLR/ STFC-UKRI | Community Tool | Training materials: Preparation of ESA/CCI data for obs4MIPs CCIDataPreparation documentation https://ccidatapreparation.readthedocs.io/en/latest/ Other output not publicly available |

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| **Task 6** | | | | |
| **D6.1 Scientific Exploitation Report** | Describes the scientific engagement and outreach activities of CMUG CCI+ phase 1 | MOHC | Doc | https://climate.esa.int/documents/1699/CMUG_D6.1_V3_Scientific_Exploitation_Report.pdf |
| **D6.2 Promotion Package** | Documents how CMUG has promoted CCI datasets and CMUG results to the climate modelling and reanalysis community, international bodies and climate researchers. | MOHC | Doc | https://climate.esa.int/documents/1700/CMUG_D6.2_V3_Promotion_Package_Report.pdf |
| **Task 7** | | | | |
| **D7.1 Climate Service Interface Requirements & Roadmap** | Explores the use of ESA CCI ECV products by climate services and identifies how this can be improved and extended. | ECMWF | Doc | https://climate.esa.int/documents/1640/CMUG_D7.1_Climate_Service_Interface_v2.0.pdf |
| **Task 8** | | | | |
| **D8.1 Quarterly Progress Reports** | Quarterly Progress Reports | MOHC | Doc | Not publicly available |
| **D8.2 CMUG web pages** | Maintenance of CMUG web pages | MOHC | Web | Climate Modelling User Group (CMUG) (esa.int) https://climate.esa.int/en/projects/cmug/ |
| **D8.3 Final report** | Final Report, providing overview of phase | MOHC | Doc | This current document |
| **Obs4MIPs CCN** | | | | |
| **D5.7b v1** | Roll out schedule and delivery plan for CCI datasets to be published on obs4MIPs | STFC-UKRI | Spread sheet | Not publicly available |
| **D5.7b v2** | Updated roll out schedule and 6 monthly meetings attended | STFC-UKRI | Spread sheet | Not publicly available |
| **D5.7d** | Datasets published on obs4MIPs | STFC-UKRI | Data | obs4MIPs - Home \| ESGF-CoG (llnl.gov) |

# 5 Activities and achievements

CMUG has three main aims:

1) To improve communication between the climate observation and the modelling communities through:
    a. Ensuring climate modellers are aware of CCI datasets and how to access them
    b. Feeding back to the observation community the needs of the modellers
    c. Identifying opportunities for extending the user base of the CCI datasets
2) To assess the CCI ECV datasets for quality, consistency and useability, including the ease of access, the uncertainty information supplied and the documentation.
3) To encourage and contribute to the development of common data formats and accessible tools which will facilitate the use of the CCI data by a broad range of users.

To meet the first aim, CMUG carried out a range of activities including: organising meetings, publishing papers, attending conferences and reaching out to climate modellers to discuss use of ECV datasets. A user requirements document was compiled based on results of a survey of a cross-section of the climate modelling community and circulated to all CCI+ ECV projects.

For the outreach and communications work package a large variety of activities were undertaken. For example:

- Production of a master slide pack
- Social media posts including a takeover of the Met Office Twitter account
- Quarterly newsletters
- Posters
- CMUG representation at a number of events, such as the Met Office science profession fair
- Article on CCI in ECMWF newsletter (Use of ESA Climate Change Initiative data in ECMWF's Earth system model | ECMWF)[1]
- Blog posts

[1] https://www.ecmwf.int/en/newsletter/171/news/use-esa-climate-change-initiative-data-ecmwfs-earth-system-model

These outputs and the meetings and workshops organised and attended by CMUG are listed in full in the Promotion Package Report (D6.2) linked from the table above.

One major highlight of the CMUG activities is the Climate Science Working Group (CSWG) meetings. These are held every quarter and bring together a cross-section of the CCI projects. The format of these meetings has evolved as the number of ECV projects has increased, making a meeting involving the whole of the CCI+ programme difficult to organise. The current format focuses on a subset of ECVs. The meeting is open to all of CCI+ but organised around availability of CMUG partners working with these datasets and the CCI projects which produce them. The meetings carried out in CCI+ CMUG phase 1 were:

- Jan 2019: CSWG on errors and uncertainties
- May 2019: CSWG on general organisation
- Sept 2019: CSWG on URD and engagement
- Feb 2020: CSWG on LST and SM
- Oct 2020: CSWG on SST, SSS and Sea Ice
- Jan 2021: CSWG on LC, HRLC, Fire and Biomass
- May 2021: CSWG on Lakes, Snow and Permafrost
- April 2022: CSWG on CMUG next phase plans

Now that the format has been established and a list of CRG members has been compiled and is continuously updated these meetings provide an important forum for discussions between the various ECV projects as well as between ECV projects and CMUG.

Another highlight of the CMUG outreach activities is the newly collated web pages on the CMUG website which is linked from the ESA CCI project web pages. The new CMUG website and its integrated web pages are a significant improvement over the previous web pages. They provide all the information needed to understand the CMUG project, including project objectives and main activities, contact details for the project, comprehensive FAQs, deliverables and documents made available, a ‘Case Studies’ section which highlights key scientific findings within the project, and links to partner institute websites.

To meet the second aim, a range of scientific studies were carried out which are documented in D3.1, D4.1 and relevant publications. These studies used the CCI ECV data within climate models or for their evaluation. Studies include:

- A biogeochemistry reanalysis assimilating SST, Sea Ice, Sea Level and Chlorophyll (Ocean Colour) which found good consistency between the four datasets and improved the reanalysis when all four were assimilated together, identified areas for model improvement and provided insights into ocean biogeochemical process. (Ford, 2020) [D3.1]
- Assimilation of CCI Soil Moisture in the Meteo-France ISBA land surface model, improving the LST bias. The evaluation was performed by comparison with a CCI LST dataset demonstrating consistency between the products. [D3.1]
- Assessing the consistency between CCI Snow, Soil Moisture and Permafrost products through assimilation of the Snow Water Equivalent (SWE). This led to a modest improvement in Soil Moisture simulation over the Scandinavian region, compared to the CCI product, indicating limited consistency. However, for Permafrost the model output after SWE assimilation was in much better agreement with the CCI product at all depths (1 m, 2 m, 5 m and 10 m) indicating very good consistency for this variable. [D3.1]
- Assimilating Snow Water Equivalent (SWE) from CCI Snow which improved river discharge modelling in a coupled land surface-river discharge model (Gelati et al, 2018). [D3.1]
- Assimilating Arctic CCI Sea Ice Concentration (SIC) data which improved sea ice prediction and SST forecasts and led to improved modelling of large-scale atmospheric circulation and hence improved LST and precipitation forecasts over Eurasia (Acosta Navarro et al., 2022). [D3.1]
- ESA CCI Soil Moisture data used to evaluate model version upgrades from CMIP5 to CMIP6 at IPSL. Evaporation, precipitation, and radiation responses in the CMIP5 version of the IPSL land-atmosphere model (IPSL-CM6) to different soil moisture states (from very dry to very wet) were shown to be unrealistic. Model improvements deduced from these analyses were implemented and shown to improve the simulations in the CMIP6 version of the model, this method of evaluation could be applied to all CMIP models (Cheruy et al., 2020). [D3.1]

- Investigation into the propagation of CCI observational uncertainties to climate model scales using the method of Bellprat et al. (2018). Observational uncertainty in Arctic SIC is greater than a number of other sources of uncertainty including that related to the limited ensemble size and the length if the forecast. [D3.1]
- Assimilation of Lake surface water temperature and Lake ice in a reanalysis driven RCM over Europe. When these parameters were included the surface air temperature biases over land surrounding the larger lakes was reduced. Unfortunately, CCI Lakes datasets were not useable for this study due to data gaps, a finding fed back to the Lakes CCI team. [D3.1]
- Assimilating CCI AER and CCI Land Cover to constrain mineral dust and surface ozone simulations at the regional scale. The CCI LC leads to better short-term forecasts of 2 m air temperature and improved night-time surface ozone concentrations. [D3.1]
- Investigation into optimum model evaluation given various sources of uncertainty and error, including observational uncertainty, modelled system memory, internal model variability, spatial and temporal correlation and errors introduced by the abstraction level of observational products. This work focuses mainly on CCI Sea Ice and finds a more sophisticated SIC error correlation estimate is required for use in regional coupled models (Wernecke et al., in prep) [D4.1]
- Assessment of the model skill for decadal hindcasts within the Decadal Climate Prediction Project (DCPP), identifying the vital need for continuity of the longest timeseries ECV products and extending them back in time. [D4.1]
- Investigation of the use of the LST and air temperature difference (LST-Tair) for a large-scale indicator of vegetation moisture stress. There were similarities in the large-scale seasonal cycle of LST-Tair and soil moisture (SM) indicating a negative relationship between the variables on a global and a regional scale. The relationship between LST-Tair and SM was found to be stronger in autumn-winter than spring-summer, for vegetated biomes. This work also added the LST-Tair metric into ESMValTool for use with CMIP6 Earth System Models (ESMs) [D4.1]
- Assessment of the land-surface interaction related biases in AMIP simulations and identification of their origin. Several AMIP models exhibit a drier bias during a heatwave

than for non-heatwave days in summer which is consistent with an overestimation of the maximum temperature of the heat waves at the regional scale. [D4.1]

To meet the third aim CMUG contributed to developments of three sets of software or data distribution initiatives to improve accessibility and useability of the CCI data:

- Earth System Model Validation Tool (ESMValTool) [see deliverables 5.1-5.4]
- Observations for Model Intercomparisons (obs4MIPs) [see deliverables 5.7a-c]
- Climate Monitoring Facility (CMF) [deliverable 5.2]

ESMValTool is a community diagnostics and performance metrics tool designed to improve evaluation of Earth system models (ESMs), it provides end-to-end provenance tracking ensuring reproducibility of scientific research (Eyring et al., 2020). CMUG have worked to include access to CCI ECV datasets in the tool and added diagnostics which allow all users to carry out comparisons with the data. In CCI+ CMUG Phase 1 the following CCI ECVs have been included in ESMValTool and are available in release v2.5 (adapted from D5.4):

*Table 3. CCI/CCI+ datasets implemented into the ESMValTool within CMUG WP5 (from D5.4v1).*

| CCI/CCI+ data | Dataset version | CMUG partner | Diagnostic | Recipe | Scientific documentation |
|---|---|---|---|---|---|
| Land surface temperature (LST) | ESA CCI LST based on MODIS AQUA L3 monthly data (day and night average), v1.00 | Met Office | CCI LST comparison with historical model simulations | recipe_esacci_lst.yml | https://docs.esmvaltool.org/en/v2.5.0/recipes/recipe_esacci_lst.html |
| Long-lived GHGs ($CH_4$) | C3S XCH4 v4.2 (2020), obtained from Climate Data Store (CDS) | DLR | CCI integrated atmospheric methane ($XCH_4$) comparison with historical model simulations | mpqb/recipe_mpqb_xch4.yml | https://docs.esmvaltool.org/en/v2.5.0/recipes/recipe_mpqb_xch4.html |
| Water vapour (WV) | CCI/CM SAF TCWV-global (COMBI), total column water vapour over land and ocean (CDR-2), v3.1 | DLR | Comparison of shortwave radiance absorptions in CCI water vapour with ESM historical simulations | recipe_cmug_h2o.yml | https://docs.esmvaltool.org/en/v2.5.0/recipes/recipe_cmug_h2o.html |

| | | | | | |
|---|---|---|---|---|---|
| Sea surface salinity (SSS) | ESA CCI Sea Surface Salinity ECV produced at a spatial resolution of 50 km and time resolution of 1 month and spatially resampled on 25 km EASE grid and 15-day time sampling, v1.08 and v2.31 | BSC | CCI Sea Surface Salinity comparison to historical model simulations | recipe_sea_surface_salinity.yml | https://docs.esmvaltool.org/en/v2.5.0/recipes/recipe_sea_surface_salinity.html |
| Ocean colour (OC) | ESA CCI Ocean Colour dataset, V5.0, available online at http://www.esa-oceancolour-cci.org/ | SMHI | CCI Ocean chlorophyll comparison to Earth System models' (ESMs) simulations | recipe_esacci_oc.yml | https://docs.esmvaltool.org/en/v2.5.0/recipes/recipe_esacci_oc.html |

Obs4MIPs is a database set up to store satellite observations in the standard CMIP format on a standard grid, for ease of comparison with the output from the CMIP models. Extending this to CCI ECVs encourages comparison of the CMIP models with the CCI ECV data, having them mapped to the same grid and standardised in terms of data format and temporal resolution will improve ease of use.

The CMF is an application on the Copernicus Climate Data Store (CDS) website.[2] It displays timeseries plots of comparisons between model and observation datasets, allowing users to click on a region of interest on a world map. Uncertainty information is also included. The following CCI ECV projects with data available through this app: SST, SSH, SI (sea ice concentration), Soil Moisture, Ocean colour (Chlorophyll), Ozone, GHG (Methane, CO2) and Aerosol.

[2] Climate monitoring facility: comparing model and observations datasets (copernicus.eu) [https://cds.climate.copernicus.eu/cdsapp#!/software/app-climate-monitoring-cci?tab=app]

# 6 Publications

Table 4 below lists all CMUG peer-reviewed publications from CMUG CCI+ Phase 1, covering the period October 2018 – June 2022. References are given as well as the number of citations, as sourced from Google Scholar (as of September 2022).

*Table 4: CMUG CCI+ Phase 1 publications*

| Paper | Citations |
|---|---|
| **Acosta Navarro, J.C.**, García-Serrano, J., **Lapin, V., Ortega, P.** (2022) *Added value of assimilating springtime Arctic sea ice concentration in summer-fall climate predictions*. Environmental Research Letters, 17 (6), https://doi.org/10.1088/1748-9326/ac6c9b | **1** |
| **Albergel, C.**, Zheng, Y., Bonan, B., Dutra, E., Rodríguez-Fernández, N., Munier, S., Draper, C., de Rosnay, P., Muñoz-Sabater, J., Balsamo, G., Fairbairn, D., Meurey, C., and **Calvet, J.-C.** (2020) *Data assimilation for continuous global assessment of severe conditions over terrestrial surfaces*. Hydrol. Earth Syst. Sci., **24**, 4291-4316 https://hess.copernicus.org/articles/24/4291/2020/, https://doi.org/10.5194/hess-24-4291-2020 | **15** |
| **Bilbao, R.**, Wild, S., Otega, B., **Acosta-Navarro, J.,** Arsouze, T., Bretonniere, P-A., Caron, L-P., Castrillo, M., Cruz-Gracia, R., Cvijanovic, I., **Doblas-Reyes, F.J.**, Donat, M., Dura, E., Echevarría, P., Ho, A-C., Loosveldt-Tomas, S., Moreno-Chamarro, E., Pérez-Zanon, N., Ramos, A., Ruprich-Robert, Y., Sicardi, V., **Tourigny, E.**, Vegas-Regidor, J. (2021) *Assessment of a full-Field initialised decadal climate prediction system with the CMIP6 version of EC-Earth*, *Earth Syst.* Dynam., **12**, 173–196, https://esd.copernicus.org/preprints/esd-2020-66/, https://doi.org/10.5194/esd-12-173-2021 | **19** |
| **Bock, L., A. Lauer,** M. Schlund, M. Barreiro, N. Bellouin, C. Jones, G. A. Meehl, V. Predoi, M. J. Roberts, **V. Eyring** (2020) *Quantifying Progress Across Different CMIP Phases With the ESMValTool*. J. Geophys. Res., **125**, https://doi.org/10.1029/2019JD032321 | **32** |
| **Cheruy, F.**, Ducharne, A., Hourdin, F., Musat, I., Vignon, E., et al. (2020) *Improved near surface continental climate in IPSL-CM6A-LR by combined evolutions of atmospheric and land surface physics*. Journal of Advances in Modelling Earth Systems, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019MS002005, https://doi.org/10.1029/2019MS002005 | **26** |
| **Eyring, V.**, **Bock, L., Lauer, A., Righi, M.,** Schlund, M., Andela, B., Arnone, E., Bellprat, O., **Brötz, B., Caron, L.-P.**, Carvalhais, N., Cionni, I., Cortesi, N., Crezee, B., Davin, E., Davini, P., Debeire, K., de Mora, L., Deser, C., Docquier, D., Earnshaw, P., Ehbrecht, C., Gier, B. K., Gonzalez-Reviriego, N., Goodman, | **28** |

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| P., Hagemann, S., Hardiman, S., Hassler, B., Hunter, A., Kadow, C., Kindermann, S., Koirala, S., Koldunov, N., Lejeune, Q., Lembo, V., Lovato, T., Lucarini, V., Massonnet, F., Müller, B., Pandde, A., Pérez-Zanón, N., Phillips, A., Predoi, V., Russell, J., Sellar, A., Serva, F., Stacke, T., Swaminathan, R., Torralba, V., Vegas-Regidor, J., von Hardenberg, J., Weigel, K., and Zimmermann, K. (2020) *Earth System Model Evaluation Tool (ESMValTool) v2.0 - an extended set of large-scale diagnostics for quasi-operational and comprehensive evaluation of Earth system models in CMIP*. Geosci. Model Dev., **13**, 3383-3438, https://doi.org/10.5194/gmd-13-3383-202 | |
| **Eyring, V.,** Cox, P. M., Flato, G. M., Gleckler, P. J., Abramowitz, G., Caldwell, P., Collins, W. D., Gier, B. K., Hall, A. D., Hoffman, F. M., Hurtt, G. C., Jahn, A., Jones, C. D., Klein, S. A., Krasting, J. P., Kwiatkowski, L., Lorenz, R., Maloney, E., Meehl, G. A., Pendergrass, A. G., Pincus, R., Ruane, A. C., Russell, J. L., Sanderson, B. M., Santer, B. D., Sherwood, S. C., Simpson, I. R., Stouffer, R. J. & Williamson, M. S. (2019) *Taking climate model evaluation to the next level.* Nature Climate Change. **9**, 102–110. doi:10.1038/s41558-018-0355-y. https://www.nature.com/articles/s41558-018-0355-y https://doi.org/10.1038/s41558-018-0355-y | **285** |
| **Ford, D. A.** (2020) *Assessing the role and consistency of satellite observation products in global physical-biogeochemical ocean reanalysis*. Ocean Sci., **16**, 875-893 https://os.copernicus.org/articles/16/875/2020/ https://doi.org/10.5194/os-16-875-2020 | **3** |
| Gier, B. K., Buchwitz, M., Reuter, M., Cox, P. M., Friedlingstein, P., and **Eyring, V**. (2020) *Spatially resolved evaluation of Earth system models with satellite column-averaged CO2*. Biogeosciences, **17**, 6115–6144, https://doi.org/10.5194/bg-17-6115-2020 | **8** |
| Klose, M., Jorba, O., Gonçalves Ageitos, M., Escribano, J., Dawson, M. L., Obiso, V., **Di Tomaso, E**., Basart, S., Montané Pinto, G., Macchia, F., Ginoux, P., Guerschman, J., Prigent, C., Huang, Y., Kok, J. F., Miller, R. L., and Pérez García-Pando, C. (2021) *Mineral dust cycle in the Multiscale Online Nonhydrostatic AtmospheRe CHemistry model (MONARCH) Version 2.0*. Geosci. Model Dev., **14**, 6403–6444, https://doi.org/10.5194/gmd-14-6403-2021 | **5** |
| **Lauer, A., Eyring, V**., Bellprat, O., **Bock, L**., Gier, B. K., Hunter, A., Lorenz, R., Pérez-Zanón, N., Righi, M., Schlund, M., Senftleben, D., Weigel, K., and Zechlau, S. (2020) *Earth System Model Evaluation Tool (ESMValTool) v2.0 - diagnostics for emergent constraints and future projections from Earth system models in CMIP*. Geosci. Model. Dev., **13**, 4205-4228, https://gmd.copernicus.org/articles/13/4205/2020/ | **16** |
| **Lauer, A., Bock, L.,** Hassler, B., Schröder, M., Stengel, M. *Cloud climatologies from global climate models – a comparison of CMIP5 and CMIP6 models with satellite data*. J. Clim. Submitted | **-** |

| | |
|---|---|
| Peano, D.**, Hemming, D**., Materia, S., Delire, C., Fan, Y., Joetzjer, E., Lee, H., Nabel, J.E.M.S., Park, T., **Peylin, P**., Warland, D., Wiltshire, A., Zaehle, S. (2021) *Plant phenology evaluation of CRESCENDO land surface models – Part 1: start and end of growing season.* Biogeosciences, **18** (7), 2405–2428, https://doi.org/10.5194/bg-18-2405-2021 | **9** |
| **Popp, T.**, Hegglin, M. I., Hollmann, R., Ardhuin, F., Bartsch, A., Bastos, A., Bennett, V., Boutin, J., Brockmann, C., Buchwitz, M., Chuvieco, E., Ciais, P., Dorigo, W., Ghent, D., **Jones, R.,** Lavergne, T., Merchant, C. J., Meyssignac, B., Paul, F., Quegan, S., Sathyendranath, S., Scanlon, T., Schröder, M., Simis, S. G. H., **Willén, U.** (2020) *Consistency of satellite climate data records for Earth system monitoring*. Bull. Amer. Meteor. Soc., **101**, E1948-E1971 doi: https://doi.org/10.1175/BAMS-D-19-0127.1 | **11** |
| **Zheng, Y**., Albergel, C., Munier, S., Bonan, B., and **Calvet, J.-C**. (2020) An offline framework for high-dimensional ensemble Kalman filters to reduce the time to solution, Geosci. Model Dev., **13**, 3607–3625, https://gmd.copernicus.org/articles/13/3607/2020/ | **1** |

# 7 Lessons learned

A key output from WP1 (Meeting the evolving needs of the climate community) was the CMUG Foresight Report (D1.2 https://climate.esa.int/documents/1188/CMUG_D1.2-Foresight-Report-V4.1_8EMjc8o.pdf) which synthesised experiences of CMUG scientists, and some in the wider CCI community, in applying EO data to serve the needs of the climate community. An important lesson from this was the wide range of information available from CCI datasets contributing to monitoring of, detecting and attributing trends in, and improving the understanding and modelling of the Earth System. This is seen in significant contributions of the CCI to the Intergovernmental Panel on Climate Change (IPCC) climate change assessments. Also as a consequence the report noted the broad relevance of the CCI programme to developing policy and practice for global climate-related activities including the UN Framework Convention on Climate Change (UNFCCC, and its work on mitigation, adaptation and loss and damage), the Sendai Framework for Disaster Risk Reduction and pursuing the Sustainable Development Goals (SDGs). This provided important context for the future ESA climate programme and the CCI study on EO support for the Paris Agreement (Hegglin et al., 2022).

Despite facing a number of challenges, CCI+ Phase 1 of CMUG has realised significant achievements, as outlined in Section 5. Through the course of this phase CMUG has also evolved in terms of communications and meeting formats with the lessons learned here being carried forward into plans for the next phase. Specifically:

- Improved and more frequent (continuous) communication with the ECV projects. This is particularly important when making decisions on which dataset to use in an experiment or study, attending ECV project progress meetings and user workshops is also of great value.
- Climate Science Working Group meetings focusing on a subset of ECVs
- A combination of in person and virtual attendance can be used to encourage full attendance at all meetings while keeping travel time and carbon footprint low. Experiences during the COVID-19 pandemic have shown virtual meetings can be just as productive, but in person networking is vital sometimes to build the relationships necessary for efficient working. Hybrid meetings offer a good solution when the technology is adequate for the task.

# 8 Future plans and recommendations to ESA

In CCI+ Phase 1 CMUG, in collaboration with the CCI ECV projects, has facilitated wide-spread use of CCI ECV data for climate model improvement, model and forecast evaluation and improving understanding the climate system and climate change. The CMUG and ECV teams' research and applications has enhanced provision, accessibility and usefulness of existing and new CCI ECV datasets, e.g., through the addition of CCI data and associated diagnostics to ESMValTool allowing analysis which was included in the IPCC Working Group I (WG I) contribution to its 6$^{th}$ Assessment Report (IPCC, 2021). Some interesting new avenues for research have emerged in this phase including the realisation that the treatment of uncertainty information provided with the ECV datasets needs more consideration within the tools which we use to disseminate it (namely ESMValTool and obs4MIPs). Other emerging areas of research which CMUG would recommend ESA to include a focus on are:

- the use of Machine Learning, e.g., to look for causal relationships between ECVs);
- a focus on hydrometeorology and the water cycle, a key topic assessed in the IPCC AR6 WG I report and for which observational constraints are currently lacking;
- representation of chemical and biological processes in ESMs, important for assessing the implications of different emissions scenarios and mitigation measures and related climate impacts and risks;
- an enhanced focus on high latitude regions, as they involve critical components of the climate system such as ice-sheets, sea-ice, permafrost and are experiencing some of the highest warming rates.

Regional or high resolution (convective scale) modelling has emerged as an important new area of research which, with support from suitable observations, offers increased understanding of the small-scale processes. These are very important for many downstream applications of EO data, for example in cities which are an under-researched domain of climate risks despite being home to the majority of the world's population as well as growing significantly in developing countries.

A more general recommendation stems from the importance of understanding and monitoring global and regional earth systems (e.g., energy and water cycles; land, ocean, atmosphere and cryosphere components) for forming robust policy on climate change and the potential that combining ECVs and modelling has to contribute significantly to this knowledge base. A key technique here is reanalysis, which has already been exploited (within and beyond CMUG) for individual earth system components (e.g., land-surface or ocean), but generating reanalyses from models of the full earth system improves their consistency and will thus provide more robust and valuable datasets. In addition, there are opportunities to improve reanalyses for each earth system component individually as new observations as they become available. These are all important areas of research that ESA could make a significant contribution to.

Detecting and attributing trends is a key input into climate policy and the robustness of these results is improved by quantifying errors in CCI ECV data. Thus, continued work on generating traceable error estimates and understanding how to apply them in relevant contexts is essential.

The Foresight report has some key high-level recommendations for the CCI as a whole, which form the main overarching CMUG recommendations. These fall into six categories:

- New observations (generating global long-term CDRs for precipitation and other aspects of the hydrological cycle, land and sea vegetation and aerosols resulting from fires)
- Continuity in and improvement of existing observations (continuing existing good practice in maintaining continuity in satellite CDRs with suitable overlaps between new and retiring satellites, whilst enhancing the efforts to improve and further homogenise and characterise the uncertainties and inter-ECV consistency)
- Integrating ECVs, modelling and in-situ observations for applications (to provide a more complete characterisation of the state and evolution of the Earth System)
- Modelling and climate science (similar to the point above, in that improvements in modelling of all components of the Earth System provides the ability to monitor and simulate key cycles of carbon, energy and water)
- Building capability (this will naturally flow from the recommendations above generating key information on future warming levels, climate hazards, water availability etc.)

- In addition to these future EO data and research activities aimed at generating information and services for a wide range of applications, dialogue is needed between the providers of the information and services and the interested parties applying them, to establish a clear understanding of requirements, applicability and accessibility. This requires these communities to work together to integrate their knowledge and expertise, building their capability to engage effectively in the dialogue and to understand relevant details of the available knowledge, information and services. This will be key to ensuring sustainability of any services built on the outcomes of the research.

# 9 References

Acosta-Navarro, J C, García-Serrano J, Lapin, V. and Ortega, P.: Added value of assimilating springtime Arctic sea ice concentration in summer-fall climate predictions, Environ. Res. Lett. 17, 064008, https://doi.org/10.1088/1748-9326/ac6c9b, 2022.

Bellprat, O., F. Massonnet, S. Siegert, C. Prodhomme, D. Macias-Gómez, V. Guemas, F. Doblas-Reyes (2017) Uncertainty propagation in observational references to climate model scales. Remote Sensing of Environment. Volume 203, 15 December 2017, Pages 101-108. https://doi.org/10.1016/j.rse.2017.06.034.

Cheruy, F., Ducharne, A., Hourdin, F.,Musat, I., Vignon, É., Gastineau, G.,et al. (2020). Improved near-surfacecontinental climate in IPSL-CM6A-LRby combined evolutions of atmosphericand land surface physics.Journal ofAdvances in Modeling Earth Systems,12, e2019MS002005. https://doi.org/10.1029/

Hegglin MI, Bastos A, Bovensmann H, Buchwitz M, Fawcett D, Ghent D, Kulk G, Sathyendranath S, Shepherd TG, Quegan S, Röthlisberger R, Briggs S, Buontempo C, Cazenave A, Chuvieco E, Ciais P, Crisp D, Engelen R, Fadnavis S, Herold M, Horwath M, Jonsson O, Kpaka G, Merchant CJ, Mielke C, Nagler T, Paul F, Popp T, Quaife T, Rayner NA, Robert C, Schröder M, Sitch S, Venturini S, van der Schalie R, van der Vliet M, Wigneron J-P and Woolway RI (2022), Space-based Earth observation in support of the UNFCCC Paris Agreement. Front. Environ. Sci. 10:941490. doi: 10.3389/fenvs.2022.941490

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate

Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896

Ford, D. A.: Assessing the role and consistency of satellite observation products in global physical–biogeochemical ocean reanalysis, Ocean Sci., 16, 875–893, https://doi.org/10.5194/os-16-875-2020, 2020

Gelati, E., Decharme, B., Calvet, J.-C., Minvielle, M., Polcher, J., Fairbairn, D., and Weedon, G. P.: Hydrological assessment of atmospheric forcing uncertainty in the Euro-Mediterranean area using a land surface model, Hydrol. Earth Syst. Sci., 22, 2091–2115, https://doi.org/10.5194/hess-22-2091-2018, 2018.

Wernecke et al (2022) In prep.