Abstract book

Records of Essential Climate Variables from Space: Lessons Learned and Half-Learned

Christopher Merchant

The variety and ambition of climate data records from space-based observations has increased markedly over recent decades. This is in part driven by the expanding range of quantities classed as Essential Climate Variables, in part by advances in observation technology, and in part by programmatic innovations such as the ESA Climate Change Initiative. Many lessons have been learned along the way, and can be carried forward into new endeavours as the 'ECV community' continues its welcome growth. Key aspects for any climate data record include: clarity of definition of the quantity measured and the scales data represent; stability, and the technical means to achieve and demonstrate it; the structure of errors and the implications for how uncertainty propagates across scale; the need to distinguish quality and uncertainty; and how to maximise the accessibility of data records to users.

ESA's new climate change initiative (CLIMATE-SPACE)

Susanne Mecklenburg

The Climate Change Initiative (CCI) is ESA's flagship programme for providing climate relevant and actionable information to assess the state of the climate. From 2023 to 2029, up to and beyond the 2nd UNFCCC Global Stocktake, CCI will support ESA Member States by expanding its Essential Climate Variable portfolio, support progression towards UNFCCC Paris Agreement goals; provide pre-operational R&D for operational climate services, enhance the link between the climate observation and modelling community, and conduct cross-ECV and Tipping Points studies. For further information: www.climate.esa.int

The Copernicus Climate Change Service and the ECV programme

Joaquin Munoz-Sabater

The Copernicus Climate Change Service (C3S) is one of the six thematic services of the EU funded Earth Observation programme Copernicus, overseen by the European Commission (EU). C3S is implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF), and it has as objective providing authoritative climate information in support of the EU's climate adaptation and mitigation policies. C3S aligns with the objectives of the United Nations Framework Convention on Climate Change (UNFCCC) by supporting the implementation needs of the Global Climate Observing System (GCOS). This support is facilitated by ensuring timely access to a substantial number of quality-assured Climate Data Records (CDRs) of Essential Climate Variables (ECVs). C3S has already successfully implemented 22 thematic ECVs, spanning land, ocean, and atmosphere, derived from space based Earth observations. Target requirements for most ECV products, including specifications related to uncertainty, stability, temporal and spatial resolution, are predominantly rooted in the GCOS Implementation Plans. Access to data and associated information products is provided through the C3S Climate Data Store (CDS). Other associated services include extensive user documentation, user support and user-oriented resources, including training materials. This presentation will offer an insightful overview of the ECV program within C3S.

CM SAF Land ECVs

Anke Tetzlaff

The EUMETSAT Satellite Application Facility on Climate Monitoring provides satellite-derived ECVs for climate monitoring. The CM SAF ECVs describe important components of the Earth`s Energy budget and its water cycle, i.e. water vapour, could properties, precipitation and all components of the surface radiation budget. In the last project phase the CM SAF has extended its existing components on the ECV-bye-ECV retrieval to a simultaneous (joint) retrieval of the full surface radiation balance, land surface temperature, evapotranspiration and sensible heat fluxes for all Meteosat sensots covering the entire WMO 1991-2020 climate reference period. Those data have a high temporal stability, in particular over Europe. CM SAF Land Surface Temperatures show excellent agreement with ESA CCIs MODIS Climate Data Records.

Uncertainties in ECVs: A metrological viewpoint

Emma Woolliams

It is a principle of both GCOS and QA4EO that observational data of ECVs are provided with detailed metadata and an associated indicator of quality traceable to reference standards. However, satellite uncertainty analysis poses challenges due to the multi-dimensional nature of the data and its complex error covariance structures. This presentation will discuss collaborative projects on different ECVs that apply metrological principles both to satellite data products and to the in situ observations that are used in the calibration and validation of satellite products. It will introduce the 'five steps to a metrological uncertainty assessment' and present the CoMet software toolkit that supports the rigorous propagation of uncertainties in satellite data.

ECVs terrestrial water storage and groundwater (G3P)

Andreas Güntner, Adrian Jäggi

Satellite gravimetry missions such as the on-going GRACE Follow-On (FO) mission, the planned GRACE-FO continuation mission as well as a Next Generation Gravity Mission (NGGM) that will form together with the GRACE-FO continuation mission the Mass-change and Geosciences International Constellation (MAGIC), are unique observing systems to measure the tiny variations of the Earth's gravity field. Time-variable gravity derived by satellite gravimetry provides integrative measures of Terrestrial Water Storage (TWS) variations on a regional to global scale. In this presentation first an overview of the underlying principles of the challenging satellite gravimetry data analysis will be given and selected key scientific results and products will be highlighted, e.g. from the Combination Service of Time-variable Gravity Fields (COST-G), to exploit the unique ECV TWS in order to eventually derive the ECV groundwater. Groundwater is a most fundamental resource, but there is no service available yet to deliver data nor is there any other data source worldwide that operationally provides information on changing groundwater resources in a consistent, observation-based way with global coverage. By capitalizing from TWS derived from satellite gravimetry and from other satellite-based water storage compartments the H2020 project G3P established a prototype to provide groundwater storage change for large areas with global coverage that is planned to be included as a cross-cutting extension of the existing service portfolio of the European Union's Earth Observation program Copernicus.

Large, systematic, and often overlooked: Uncertainties in aerosol and cloud ECVs

Adam Povey

The interactions between aerosol and cloud have been repeatedly identified as the greatest source of uncertainty in anthropogenic climate feedbacks. Models return a wide range of responses to aerosol forcing that are consistent with historic observations. To help constrain these, several ECVs has been defined including cloud cover, optical depth, the vertical profile of aerosol extinction, and various measures of particle size or number. This talk will summarise the range of challenges in determining the uncertainty of those products, outlining current and prospective solutions. Aerosol-cloud observations require the use of numerous techniques (including visible/infrared imagery, light/radio ranging, and particle counting) which have highly distinct sources of error that can be non-Gaussian. Hence, existing uncertainty estimates are often diagnostic (i.e. derived from comparison to an external truth). As most aerosol-cloud measurements are underconstrained, the nature of particles being observed must be assumed. Errors in that classification are highly non-linear, systematic, and rarely verifiable but have been assessed through the use of ensembles. Some cloud products are derived from instruments with less rigorous calibration/characterisation procedures, requiring vicarious calibrations which propagate through later retrievals. However, the ongoing utility of aerosol-cloud products demonstrates that these challenges are not insurmountable and much progress has been made in recent years towards providing prognostic uncertainty estimates for each pixel.

Characterising uncertainties in multi-satellite soil moisture climate data records

Wouter Dorigo

ESA's Climate Change Initiative and the Copernicus Climate Change Service produce climate data records of soil moisture covering the period 1978-present. These datasets blend soil moisture retrievals from more than 20 different satellites and sensors. Various statistical methods are used to optimally merge these datasets and characterise the uncertainties and systematic errors of the resulting climate data records. The presentation will give an overview of the input data, the statistical methods and the reference data used for merging and evaluation, and the error characteristics of the merged multi-satellite climate data records.

Defining an uncertainty budget for surface temperature retrievals

Claire Bulgin

Sea, land, and lake surface temperature climate data records developed within the European Space Agency (ESA) Climate Change Initiative (CCI) provide uncertainties for every measurement, at all processing levels. A common approach to uncertainty estimation is followed, using protocols developed within the Fidelity and Uncertainty in Climate data records from Earth Observation (FIDUCEO) project. An uncertainty budget is built using the measurement equation at each stage of the CDR generation process (e.g. retrieval, gridding, merging data) and identifying all the possible sources of error. Uncertainties are then estimated for each error source, either by direct measurement of the error distribution or through use of model to represent the error distribution. Users are provided with both the total uncertainty for each measurement and a breakdown of the uncertainty components according to their correlation properties.

About Uncertainties of the sea ice Essential Climate Variable

Stefan Kern, Thomas Lavergne

Sea ice comprises a substantial part of the Earth’s cryosphere. It forms and melts in both polar regions. It is redistributed by winds and currents. Thanks to its high surface albedo and low winter-time surface temperature – particularly when snow covered, it has profound influence on the net short- and longwave radiation balance of the polar regions with implications for the Earth’s climate. The reduction of the Arctic sea ice cover has been seen as a herald of amplified global climate change. The sea ice essential climate variable (sea ice ECV) used to characterize the polar sea ice cover comprises seven sea ice ECV products: sea ice concentration – the fraction of an ocean area covered with sea ice, sea ice thickness – the vertical extent of the sea ice from its bottom to its surface, snow thickness on sea ice – the vertical extent of any snow on sea ice, sea ice motion, sea ice surface temperature, sea ice surface albedo, and sea ice age – aka the time a piece of sea ice has existed since its formation. Due to the remoteness and weather conditions of the polar regions, observations of the sea ice ECV are a logistical challenge. Therefore, the majority of today’s sea ice ECV monitoring is realized with satellite remote sensing. This implies that we need to address a number of uncertainty sources for each sea ice ECV product. This number is particularly large because of the different methodologies that are used to derive sea ice ECV products, and because of the different satellite sensors required for the monitoring. In this presentation, we will introduce the different types of satellite remote sensing techniques used to derive sea ice ECV products. We will discuss uncertainties related to the methodologies and algorithms, uncertainties related to the input satellite data, and uncertainties related to the gridding of the data. In addition, we will comment on uncertainty issues related to sea ice ECV product evaluation and, in particular, to the representativity error. We aim to primarily focus on sea ice concentration, sea ice thickness and snow thickness on sea ice but will also briefly touch upon uncertainties of the other four sea ice ECV products.

Roles of uncertainty in the retrieval of biophysical ECVs

Simon Blessing

The retrieval of biophysical parameters from remotely sensed data is an indirect measurement. Using the example of the retrieval system OptiSAIL used in the current esa CCI+ vegetation parameters project, we demonstrate the role and treatment of uncertainties in the process.

Built around the widespread PROSAIL canopy reflectance simulation, OptiSAIL is a physically-based retrieval system. It uses a gradient-based inversion, which is made efficient enough for global coverage by adjoint code, obtained from Automatic Differentiation (AD) of the simulation source code. AD-generated code also makes the computation of Hessian and Jacobian viable, which are used for the computation of posterior uncertainties of the parameters of the simulation and for uncertainty propagation. This includes covariance information, which further characterises uncertainty. Its importance is highlighted. Going through the uncertainty budget from end to end, uncertainties accounted for and not accounted for are discussed.

ECV snow cover fraction

Stefan Wunderle, Colleen Mortimer

Snow cover is a key climate indicator – accurate assessment of its state, variability, and trends is critical to understanding the earth's energy budget, freshwater supply, terrestrial and freshwater ecosystems. There are numerous publicly available Snow Cover Fraction (SCF) products derived from satellite data, but few are accompanied by detailed uncertainty information. Of the dozen products included in the European Space Agency's (ESA) Satellite Snow Intercomparison Project, only one had an accompanying pixel-wise uncertainty estimate beyond the traditional semi-qualitative quality flags.

Here we outline the measurement of snow cover fraction from satellite data and discuss sources of uncertainty. We present two methods that have been applied to calculate pixel-wise uncertainty in the ESA Snow CCI SCF products – one that uses a traditional error propagation approach and the other which describes the error using a generalized linear model. We seek input on an appropriate method to quantify the uncertainty in satellite derived SCF estimates and their time series, and of the sources of uncertainty to include in these estimates.

Ozone as an ECV: cause and effect, trend and uncertainty

Tijl Verhoelst

In this contribution, we describe the role of ozone as a vertically (non-)stratified climate change driver and tracer. We introduce the various remote sensing techniques used to monitor ozone, with an emphasis on the uncertainty quantification of these level-2 data, which is performed both prognostic (ex ante) and through ground-based validation (ex post). Building climate data records (CDR, at level 3 or 4) from these measurements requires spatio-temporal gridding and averaging, merging of multiple data records from different sounders, and a thorough assessment of both the propagated uncertainties and the new representativeness uncertainties introduced in this process. Finally, the analysis of these CDR to detect climate change features, either directly from the observations or through assimilation by a model, requires further focus on the appropriate use of the underlying uncertainties. We review the various methods and corresponding results, and we highlight the gaps still present in this chain from level-1 data to trends with uncertainties.

Uncertainty aspects of Surface Radiation Budget (SRB)

Anna Christina Mikalsen

In this presentation, different approaches for quantification of uncertainties are discussed.

A Fiduceo-like analysis of the uncertainty budged for the CLARA-A3 satellite data record, recently released by CM SAF, has been carried out at DWD. Starting from the measurement equations of irradiation observed by the Advanced Very High Resolution Radiometer (AVHRR) and following basic metrological concepts, the observing errors have been propagated. This allowed an overview of all sources of errors and quantifying their contribution to the overall error budget.

A full calculation of errors for each grid point of the long-term global dataset, however, was considered too costly in terms of computing time and resources. In case of another satellite Climate Data Record (CDR), the UK Met Office recently produced full L3-error-propagation for their new UTH product.

In contrast to the error-propagation approach from the FIDUCEO[1] project, the GAIA-CLIM[2] project chose a more pragmatic approach based on so-called traceability model diagrams. The instrument model diagram consists in a visual sketch of the processing steps leading to a product and its traceability chain.

Global ocean heat content and Earth Energy imbalance from space geodetic observations

Alejandro Blazquez

The increase of atmospheric greenhouse gas concentrations caused by human activities is causing an imbalance at top of the atmosphere between the amount of energy the Earth receives from the sun and the amount of energy it radiates back into space. This imbalance is called Earth energy imbalance (EEI). The ocean acts as a huge heat reservoir absorbing in form of heat around 90% of the excess energy that is stored by the climate system because of the EEI. It makes the global ocean heat content (GOHC) a precise proxy for the EEI. An accurate knowledge of the GOHC change allows us to assess the EEI and helps in understanding actual anthropogenic climate change. The space geodetic approach derives GOHC and EEI from satellite altimetry and gravimetry measurements by estimating the ocean thermal expansion.

[1] https://cordis.europa.eu/project/id/638822
[2] http://www.gaia-clim.eu/

This approach leverages the maturity of satellite altimetry C3S sea-level product and satellite gravimetry GRACE L3 CNES manometric sea-level product to provide an estimate of the GOHC, the EEI with their uncertainty .In this presentation we will present the geodetic approach and the associated estimate of the EEI time series since 2002. The geodetic estimate of the EEI shows a EEI mean of 0.95 +-0.19W.m^{-2} (the 5-95% confidence interval is [0.76-1.27] W.m^{-2}) and a positive trend over the period 2002-2022 of 0.4 W/m^{-2} per decade (the 5-95% confidence interval is [0.1-0.7] W.m^{-2}) . This trend in EEI that is significant at the 90% confidence level indicates an accelerated warming of the ocean and increasing EEI, in agreement with CERES observations and some in-situ observation based estimates.

Quantification and presentation of uncertainties in global (sea) surface temperature analyses, 1850 onwards.

Nick A Rayner

Quantification of uncertainties in climate data records over the full instrumental period presents extra challenges associated with a lack of metadata on how measurements were actually made in many cases. In this presentation, I will discuss the challenges and approaches used to estimate uncertainties in global gridded (sea) surface temperature observations and how production of an ensemble can help us to represent them. This will include uncertainties arising from inadequate sampling, uncertainties in bias corrections applied and uncertainties in methods used to create globally-complete fields.

Laboratory measurements of spectral emissivity: can we trust the 'truth'

Mary Langsdale

Spectral emissivity is a key input for remotely sensed retrievals of land surface temperature (LST), an Essential Climate Variable (ECV). However emissivity is non-trivial to estimate from a longwave infrared sensor as there is an undetermined problem such that for N bands, there are N+1 unknowns. Instead emissivity measurements often come from either spectral libraries based upon laboratory spectroscopic measurements or spectroscopic measurements of samples from the field. In each case, known dynamical drivers of emissivity such as soil moisture and canopy structure may be neglected, which can introduce errors into the derived emissivity and consequently LST. Furthermore, due to lack of research into characterization of such setups, uncertainties on these measurements are either typically either derived from repeated measurements or not presented at all. In this talk, I first present results from two published inter-comparison exercises using different laboratory measurements. The results from these exercises suggest that differences between measurements of emissivity derived via laboratory setups may be larger than anticipated and highlight the need for the infrared spectroscopy community to work towards standardized and interlaboratory comparable results. In addition to this, I present a recent study comparing different methods of sample preparation to demonstrate the impact that this can have on emissivity and highlight the potential differences between field and laboratory measurements. In each case, the potential impact on retrieved LST is considered.

Standardised validation of satellite-based terrestrial ECVs

Fernando Camacho

Terrestrial Essential Climate Variables, terrestrial ECVs, are key sources of information for climate research. Many global terrestrial ECV products have been derived from remote sensing. End-users need to know their uncertainties and error magnitudes. However, due to the lack of standardization among validation strategies, a wide range of validation approaches have been employed to assess their uncertainties, which have resulted in reduced comparability and even different impressions of accuracy. Addressing this challenge in validation requires the use of standard, traceable and objective validation procedure for all terrestrial EVCs climate data records. This is one of the main goals of the Land Product Validation subgroup of the CEOS Working Group on Calibration and Validation, where a number of terrestrial variables like surface albedo, leaf area index, land surface temperature, soil moisture, fraction of absorbed PAR, or above ground biomass among other are considered. This talk will present the efforts of the validation community to achieve an operational standardized validation framework which allow to assess the uncertainties of terrestrial ECVs until stage 4 in the CEOS WGCV LPV hierarchy. This presentation will introduce the standardized validation framework for terrestrial ECVs which is composed of four main components: i) the good practices validation protocols, ii) fiducial reference measurements, iii) the sampling or sub-setting of satellite-based ECVs and their uncertainties, iv) online validation platform, which allow the users to perform comparative analysis and conformity testing in a transparent way. The readiness level for a standardized validation approach for the above-mentioned terrestrial ECVs will be presented with focus on remaining gaps and challenges.

Climate data record stability for trend analysis: the importance of uncertainties

Claire Bulgin, Jonathan Mittaz

Climate data records (CDR) of essential climate variables are generated with the intent of evaluating climate signals, but the process of analysing trends must be approached with care. Temporal variability in the uncertainties on the geophysical variable can result in non-geophysical trends observed in the data. Examples of this include changes in instrument calibration over time or changes in the performance of pre-processing steps such as cloud detection. Natural variability is also important to consider when evaluating trends: does the model that you are fitting to your data account for the external factors that might affect the trend? i.e. the impact of rainfall on sea-level rise or the impact of changes in cloud fraction or type on the retrieval of surface variables? Considering differences between the CDR data and the associated uncertainties, the details of the trend model and its complexity, and the error covariance matrix of the fit can provide useful information as to the quality of the fit and what to consider in producing a trend estimate with uncertainties that are as meaningful as possible.

Uncertainties in calibration and uncertainty propagation

Jonathan Mittaz

The foundation for generating satellite-based Essential Climate Variables (ECVs) lies in the Level 1 data collected by relevant sensors. To provide estimates of uncertainties at subsequent processing stages, it is imperative to understand the uncertainties at Levels 0 and 1. While basic Level 1 uncertainties, such as noise (e.g., NeDT), are often readily available, the true Level 1 uncertainty can be considerably more intricate as numerous factors contribute spanning from sources of noise to pre-launch issues to the structure and application of the measurement equation and even unaccounted sources of error. In the following discussion, I will illustrate various types of error and uncertainty within the Infrared (IR) and Microwave (MW) domains. These encompass challenges related to pre-launch data, issues associated with the formulation of the measurement equation as well as other forms of error pattern which can be present in passive Earth Observation (EO) sensors, both historical and modern. Additionally, I will delve into the identification of error correlations evident in EO data. Finally, I will address the necessity of reprocessing Level 1 data for the purpose of generating ECVs.

Uncertainty Assessment of Terrestrial Water Storage Data

Ulrich Meyer, Eva Boergens, Henryk Dobslaw

With the GRACE (2002-2017) and GRACE-FO (since 2018) satellite missions, we can quantify the ECV terrestrial water storage (TWS). GRACE and GRACE-FO observe the spatial and temporal variations of the Earth's gravity field. Over the continents, water mass redistributions mainly cause these changes. TWS describes such variations and encompasses the whole water column from surface water, soil moisture, snow and ice to groundwater.

The GRACE and GRACE-FO satellite missions' main product is monthly Earth gravity fields. Here, the basic Level-2 representation is in a series of global spherical harmonic coefficients determined by least squares, together with satellite orbit and instrument parameters. From these Level-2 gravity fields, gridded monthly TWS fields are derived for the usage of a broader user community. The least squares process relies on realistic signal and noise models, where the formal error estimates co-estimated with the gravity field coefficients heavily depend on the noise model. However, the noise characteristics of the main observables, i.e. the K-Band ranges, the non-gravitational accelerations, and the satellites' attitude and position, are poorly known. Generally, the analysis centres apply their own over-simplistic noise models. Consequently, the formal errors of the Level-2 products are very diverse and cannot be used in the combination process. The error estimates currently provided with the combined Level-2 products are determined empirically from the spread of the individual contributions.

The uncertainty assessment of the combination of Level-2 data leads to a set of formal errors, which could be variance propagated to the TWS grids. However, this variance propagation is usually only feasible for some expert data users besides the described shortcomings of these formal errors. Thus, we developed a spatial covariance model for the TWS data provided by GravIS (Gravity Information Service, gravis.gfz-potsdam.de). This covariance model is non-stationary (time-depending), non-homogeneous (location-depending), and anisotropic (direction-depending). The model allows to compute covariances between two given grid points at a given time and the uncertainty of regional mean TWS time series.

We will present both the uncertainty assessment of the Level-2 data combination and the Level-3 TWS covariance model. Our presentation will close with a look into the future: Error source separation between random and systematic errors, leakage effect handling, or consideration of temporal correlations.

Assessing Uncertainties in Geophysical Time Series: Advancing from Temporal to Spatio-Temporal Stochastic Modelling

Kevin Gobron, Roland Hohensinn

The statistical analysis of geophysical and geodetic time series is a preliminary step to understanding many geophysical processes, including the water cycle and sea-level change. Unfortunately, in addition to deterministic variations, most sets of geophysical time series tend to exhibit spatially and temporally correlated stochastic variations - sometimes called "noise" – which induce uncertainties on the parameters of interest (e.g., long-term trend or periodic signal parameters). The realism of these parameter uncertainties is contingent on the realism of the stochastic noise model used to obtain them. While temporal correlations are frequently modelled and accounted for to get realistic uncertainties on time-dependent parameters, there is no agreed-upon strategy for including spatial correlations in the uncertainty assessment. In this presentation, by taking the example of the Global Navigation Satellite Systems (GNSS) position time series analysis, we will present a strategy for the joint modelling of spatially and temporally correlated stochastic variations in a global geophysical dataset. We will then discuss the benefits of such a spatio-temporal approach for uncertainty assessment and the possible implications for subsequent geophysical studies.

Strengths and Weaknesses of the use of GNSS in determining ECVs

Janusz Bogusz, Anna Klos

We present an overview of the use of GNSS (Global Navigation Satellite System) observables, namely position time series, also known as station displacements, and zenith tropospheric delays, in using them to determine Essential Climate Variables. We present how the time series should be processed, as well as how to assess whether a time series is suitable for climate interpretation. We also show the compatibility of GNSS time series with other geodetic observations or ways to determine ECVs, such as groundwater. Finally, we focus on combining GNSS observables with other observations, with the goal of minimizing the shortcomings of each technique and obtaining results that are as climatically reliable as possible.

Uncertainty quantification in deep learning applied to geodetic problems

Benedikt Soja, Junyang Gou

The increasing utilization of machine learning, particularly deep learning (DL), has demonstrated remarkable efficacy in addressing diverse challenges within Earth and climate sciences. Despite achieving unprecedented accuracy in prediction and classification tasks, assessing the reliability of results obtained using these methods remains a significant challenge. This contribution focuses on bolstering confidence in DL-based outcomes by exploring various strategies for comprehensive uncertainty quantification and confidence interval estimation . The discussion encompasses both aleatoric and epistemic uncertainties by featuring techniques such as deep ensembles and Bayesian deep learning. We focus on practical examples from the field of geodesy, highlighting the application of these methods in forecasting Earth orientation parameters and ionospheric electron content variations as well as spatially modeling terrestrial water storage anomalies.

Uncertainty in deep neural networks

Arnt B. Salberg

Over the last decade, deep neural networks have been extensively applied in a number of applications in Earth Observation. However, even though the out of the deep neural networks often provide score values that are scaled between zero and one, the score values do not deliver certainty estimates since they often suffer from over- or under-confidence, and are, hence, badly calibrated. There has therefore been research activities on understanding and quantifying uncertainty in a neural network's prediction. This presentation gives an broad overview of uncertainty estimation in deep neural networks, reviews some of the most common methods and the recent advances, and highlight current challenges and limitations.

Trend Acceleration of Global Sea-Level Changes from GGOS Observations with PCA

Jean-Phillipe Montillet, Xiaoxui He

Sea-level change is a significant consequence of climate change, primarily caused by melting of ice sheets and glaciers, and expansion of seawater. This study quantifies the global sea-level change using 200 tide gauges (TGs), co-located at 144 GNSS and satellite altimetry data from the Global Geodetic Observing System.We obtain at the TGs, linear trends between -10.00±0.46 and 9.26±0.62 mm/yr. The vertical land motion (VLM) estimated from GNSS time series at the TGs ranges from -7.42±0.24 to 9.42±0.02 mm/yr. After correcting the relative sea level for the VLM, we produce absolute sea-level (ASL) rise and obtain values from -1.59 to 6.85 mm/yr, with a mean value of -2.34±1.42 mm/yr, where the uncertainty represents the spread between the trend values. In addition, we demonstrate that the influence of different stochastic noise models on the estimated trend is small (less than 0.05 mm/yr), but that the effect on the uncertainty is larger (up to 0.16 mm/yr). Secondly, we analyze the satellite altimetry derived ASL time series covering the period 1993 to 2020 at the same 200 locations of the TGs. We obtain a mean ASL trend and acceleration of 2.76±0.97 mm/yr, 0.17±0.27 mm/yr^2. Finally, we perform a noise reduction analysis with the principal component analysis (PCA) on the TG and SSH time series. The results show that PCA preserving the trend of the original TG and SSH time series, while the trends and acceleration uncertainty's accuracy improve after PCA denoising. The uncertainty decreases about 15.0% on average after applying the PCA filter.

Towards traceable uncertainty budgets for soil moisture climate data records

Alexander Gruber

The Committee of Earth Observation Satellites (CEOS) Working Group on Calibration and Validation (WGCV) defines validation stages that describe the level of sophistication in validation activities for ECVs. Recently, soil moisture has achieved the highest validation stage 4. This achievement was driven by the establishment of community-agreed validation best practices and progress made by ESA's Fiducial Reference Measurements for Soil Moisture (FRM4SM) project, which defines protocols and procedures to establish traceable uncertainty budgets for satellite soil moisture products following metrological principles. However, community-driven best practices often deviate substantially from practices required by metrological guidelines. This talk will elaborate on the gap between metrology and established Cal/Val activities for soil moisture ECVs to spark discussions on what is needed to close it.

The use of observations and ECVs in the Coupled Model Intercomparison Project

Helene Hewitt

The Coupled Model Intercomparison Project (CMIP) is a flagship project of the World Climate Research Programme (WCRP). CMIP coordinates intercomparison of climate and Earth System models to understand past, present and future climate addressing the objectives of WCRP. Building on the successes and experiences of the previous phases, the project is moving towards its next phase, CMIP7. The CMIP Panel has set up a number of task teams to support the design and implementation of the future CMIP. The Forcings task team is working to provide the historical forcing data that is needed for models to simulate the recent past. The forcings data are closely aligned to atmospheric composition, biosphere and physical ocean ECVs. Efforts are ongoing to update the forcings and to move towards operational delivery serving not just CMIP but wider WCRP and other community activities. The Model Benchmarking task team is defining the tools available for assessing models. Obs4MIPs is important in this process as it provides earth observation data in a format suitable for model-data intercomparison. The Data Request task team defines the variables that models should output to allow analysis across models from different groups and across a number of experiments. Work is underway to define 'baseline variables' to improve consistency across model intercomparison projects. The proposed baseline variables are often either equivalent or overlapping to ECVs. Further work is planned to investigate the similarities between baseline variables and ECVs and identify gaps. There will be subsequent work to develop data request packages for the different realms (or scientific areas) which will both facilitate further model-data intercomparison but also allow understanding of physical processes that is not possible with existing observations. The data request in CMIP7 will support DECK experiments (which includes the historical simulation), a Fast Track set of experiments to support IPCC AR7, and a range of community-driven model intercomparison projects.

Climate modelling: uncertainties from a historical perspective

Gerhard Krinner

Arguably, one of the main objectives of climate modeling has been, and will be, to provide accurate and useful projections of future climate change. Reducing uncertainties on the amplitude and regional expression of future global climate change has, in this respect, been one of the major tasks of climate modelers. How successful have climate modelers then been in fulfilling this task over the last 50 years or so since the first global climate models were first used to simulate future climate change? The somewhat sobering answer is that, on face value, climate models still provide a rather large spread of estimates for the Equilibrium Climate Sensitivity (ECS: the "equilibrium" global mean temperature increase for a doubling of the atmospheric CO_2 concentration, neglecting slow feedbacks such as changes in the surface extent of global ice sheets), one of the most fundamental metrics of the climate system. Recent narrowing of the uncertainty range of this fundamental metric has been accomplished by drawing together multiple lines of evidence including paleoclimates information and process understanding instead of relying on direct estimates from climate models. I will try to show why model spread in this particular metric has not decreased over time in spite of a huge increase of computer power, theoretical knowledge and available observations, and why and how climate models nevertheless still remain central tools in climate science.

The potential and limitations of remote sensing for the ECV Permafrost

Annett Bartsch

The Essential Climate Variable (ECV) "Permafrost" is characterized by the variables "ground (subsurface) temperature" and "thaw depth", i.e. the maximum depth of the seasonal thaw layer. The Permafrost_CCI project by the European Space Agency (ESA) has compiled Earth Observation (EO) based products for the permafrost ECV spanning the last three decades. As ground temperature and thaw depth cannot be directly observed from space-borne sensors, different satellite and reanalysis data sets are ingested in a ground thermal model.

The Permafrost_CCI algorithm uses remotely sensed data sets of Land Surface Temperature (MODIS LST) and landcover to drive the transient permafrost model CryoGrid_CCI at 1km spatial resolution. To gap-fill LST time series and account for the influence of the seasonal snow cover, ERA-5 reanalysis data are employed. Furthermore, ERA-5 reanalysis is used to force the model for the period before 2003 when MODIS LST is not fully available, but we apply a pixel-by-pixel bias correction using the overlap period after 2003-2019 to achieve coherent times series. The correct representation of ground properties is critical for the performance of the transient algorithm, in particular for reproducing the depth of the thaw layer. Therefore, the Permafrost_CCI project has synthesized typical subsurface stratigraphies for different landcover classes, based on a large number of analyzed soil pedons from different permafrost areas. Finally, the Permafrost_CCI algorithm performs not only a single run per pixel, but simulates subpixel variability with an ensemble accounting for the typical variations in snow depth and ground stratigraphies. From the model ensemble, it is possible to infer the fraction covered by permafrost in every 1km pixel and thus reproduce the well-known zonations of sporadic, discontinuous and continuous permafrost. The quality of landcover representaion for the Arctic is thus critical and will be discussed with respect to uncertainties.

Optimisation of the snow parameterisation in the ORCHIDEE land surface model using ESA-CCI snow products

Amélie Cuynet

Snow plays a significant role in the Earth's system, affecting both the energy and water budgets, making it crucial to accurately model its behaviour. This study focuses on the snow parameterisations implemented in the ORCHIDEE land surface model (continental part of the IPSL Earth system model). We aim to improve the snow model parameters depending on the type of vegetation, by taking advantage of the new CCI Snow products which provide both Snow Water Equivalent (SWE) and snow cover fractions above and below trees (visible and ground snow cover fractions). The ORCHIDAS data assimilation tools were used for this purpose. This system facilitates the optimisation of key parameters in a Bayesian framework, by reducing the mismatch between model outputs and observations using either a genetic or a gradient-based approach. In this step, the quality and representativeness of the observations are crucial. In addition to the aforementioned CCI Snow products, the surface albedo satellite product is also used to constrain snowpack modelling, as it is key to modelling snowmelt.
The presentation will begin with an overview of the ORCHIDAS tools. Subsequently, the on-going work to optimise the snow parameters will then be described, with a prior analysis of the different CCI snow products and the impact of their uncertainties on the optimisation results.

Benefit of assimilating the ESA-CCI land surface temperatures into the ORCHIDEE land surface model

Luis Olivera

Land surface temperature (LST) plays an essential role in water and energy exchanges between Earth's surface and atmosphere. Recent advancements in high-quality satellite-derived LST data and land data assimilation systems present a unique opportunity to bridge the gap between observational data and land surface models (LSMs) to better constrain the water/energy budgets in a changing climate. In this vein, this study focuses on the assimilation of the ESA-CCI LST product into the ORCHIDEE LSM (the continental part of the IPSL Earth System Model) with the aim of optimizing key parameters and, consequently, improving simulations of LST and water-energy fluxes. To this end, we use the land data assimilation system for the ORCHIDEE model (ORCHIDAS) to conduct a series of synthetic twin data assimilation experiments accounting for real data availability and uncertainty from ESA-CCI LST in order to find the best strategy for assimilating LST. Here, we use different strategies of assimilation, notably combining: i) two methods of optimization (genetic and gradient-based), ii) varying number of the most sensitive parameters to be optimized and iii) different features of LST assimilated into the model (e.g. mean daily, daily amplitude, maximum and minimum temperatures). Upon identifying the optimal approach, we implement it to assimilate ESA-CCI LST data across 35 sites in Europe provided by the WarmWinter database (Warm Winter 2020 Team & ICOS Ecosystem Thematic Centre, 2022). Our results demonstrate the effectiveness of this assimilation process, showing a notable reduction in the uncertainty of crucial model parameters, leading to an improved accuracy of surface energy flux simulations at in situ level.

Future works will be focused on refining the utilization of uncertainties provided by the ESA-CCI LST product (e.g decomposed uncertainties and spatio-temporal variability) in ORCHIDAS.

ECVs ice sheets / ice caps / glaciers

Isabella Velicogna

Ice sheets, Glaciers, and Ice Caps (GIC) are key Essential Climate Variables to characterize the evolution of the cryosphere. The ice mass balance of the Antarctic and Greenland Ice Sheets and GIC is of considerable importance to sea level change assessments and projections of regional and global sea level rise. Remote sensing observations are key to monitor the change in mass balance, understand the physical processes driving them, and improve the ability of models at reproducing these changes and project future changes. We use three methods for measuring ice sheet mass balance: 1) time-variable gravity, 2) mass budget (ice discharge vs surface mass balance) and 3) surface elevation from altimetry, which provide independent information about the mass changes (e.g., partitioning of surface mass balance vs ice discharge, evaluation of ESMs, etc.), with both strengths and weaknesses. We will show the most recent results from the GRACE/GRACE-FO missions which have produced monthly estimates of mass changes since 2002. In recent years, we find a pause in mass loss of Antarctica, the mass loss in Greenland is no longer accelerating, and the global GIC mass loss has reached a steady value despite strong regional variability. Other datasets of recognized importance for this ECV include glacier area, ice velocity, grounding line position, and ice thickness. Ice velocity is now produced monthly thanks to greater set of available imaging sensors, including SAR and optical. Grounding lines are produced automatically using a Machine Learning algorithm operating on EU's Sentinel-1 and other SAR data. A dataset of emerging importance, however, is ice shelf melt rates. Ice shelf melt rates have a major impact on glacier evolution but are difficult to observe. Time series of ice surface elevation (altimeter) and velocity (SAR) provide continental scale estimates assuming hydrostatic equilibrium, which is only an approximation, and only over multiple years. In-situ measurements from Automated phase-sensitive Radar Echo Sounders (ApRES) measure ice thickness changes directly, continuously (daily), but only at point locations. Finally, ocean numerical models also calculate ice shelf melt rates. At present, these three types of estimates vastly disagree. There is a need for data fusion products, using ML technology, to merge these estimates into a more cohesive dataset that can be used by ice sheet models in charge of projecting sea level rise. I will conclude with a brief inventory of planned data records available from multiple agencies to gauge what is available now, what will be available tomorrow, and the data/observational gaps that we need to think about.

Stability of climate data records - an ultimate downstream test of the uncertainty impact?

Abhay Devasthale

As the effects of anthropogenic climate change become increasingly apparent, the demands on the satellite based climate monitoring are increasing. In this context, as per the recommendations provided by the WMO's Global Climate Observing System (GCOS), the

climate data records are expected to follow certain accuracy and stability requirements to be suitable for the climate change studies.
The stability, defined here as the trend in bias against a reference, can also arguably be the ultimate test of the impact of all uncertainties propagated downstream to Level 3. Here, we present ongoing research investigating the stability of four prominent global cloud climate data records, focusing particularly on cloud fraction and cloud top properties.

The Global Climate Observing System (GCOS) Programme in support of climate research, applications, and policy

tbd

The talk will provide an overview of GCOS programme, its mission, structure, main activities and outputs, such as the regular reporting to the UNFCCC on the adequacy of the observing system for climate and on recommendations for its improvement. It will also cover the definition of ECVs and ECV requirements including uncertainty. Finally it will focus on some of the recommendations published in the last 2022 GCOS Implementation Plan related to fiducial reference measurements programs and calibration.

Next steps for ECV uncertainties: historical, current and future data

Emma Woolliams

This presentation will attempt to review the common themes of the workshop. It will identify what we as a community need to do to improve the quantification and dissemination of uncertainty information from historical and current missions, and how we use an understanding of ECV uncertainty requirements to design future observational systems and the data processing that goes alongside them. The presentation will also consider the translation of the scientific concept of 'uncertainty' into the policy concept of 'risk' and how climate data and its uncertainty can be communicated to decision makers and the public.

Uncertainties in the future - a perspective from GCOS and an operational data provider

Rainer Hollmann

The Global Climate Observing System (GCOS) is responsible to support the definition of a global climate observation system where accurate and sustained observations are being made, and access to climate data is free and open. GCOS determines observational requirements, reviews the adequacy of monitoring systems, and produces guidance for their improvements. The last GCOS Implementation Plans was published in 2022 (GCOS-244) which included a list of actions to implement an enhanced system of global climate observations. During the last GCOS cross-panel meeting in June 2023 the focus was on cross cutting GCOS activities concerning, amongst others, Earth Cycles, Adaptation, Indicators, the ECVs (Essential Climate Variables) Rationalization, and uncertainties of ECVs. Starting with an update of these latest developments within GCOS, the presentation will cover also the perspective from an operational climate data record provider in terms of an integration of uncertainty aspects. This includes also user feedback, user communication elements. In particular, for the communication with users it is of importance and useful to develop a cross-ECV uncertainty understanding.

Policy needs, inputs from ECVs, for climate change assessments.

Claire Macintosh

This talk will frame the existing policy landscape in the context of ECV uncertainties. Taking examples from recent ECV uncertainty projects in their policy relevant context, to illustrate how the policy and uncertainty landscapes intersect with a focus on emerging themes, gaps and opportunities for the ECV uncertainty community.