WCRP-GCOS workshop on Earth's energy, water and carbon cycles and budgets

22-23 June 2023, Paris, France

November 2023
WCRP Publication No.: 11/2023
GCOS Publication No.: 258

Bibliographic information

This report should be cited as:

World Climate Research Programme (WCRP)/Global Climate Observing System (GCOS). *WCRP-GCOS Workshop on Earth's Energy, Water and Carbon Cycles and Budgets (WCRP Publication No. 11/2023/GCOS-258); World Meteorological Organization (WMO): Geneva, 2023*.

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Executive Summary

The Global Climate Observing System (GCOS) and the World Climate Research Programme (WCRP) convened a joint workshop in Paris on 22 - 23 June 2023 to assess the current state of knowledge of the Earth system cycles of energy, water, and carbon, and our capability to assess emerging changes related to these cycles.

The aims were to i) identify challenges for research (knowledge of processes), modelling and observing system capabilities; ii) identify key indicators for measuring (observational needs), monitoring and modelling the cycles and indicate how they can be used in global assessment frameworks; and iii) identify key processes that need to be better understood to improve the monitoring of the cycles and to infer if and how the cycles are coupled.

The following sections describe the outcomes of the workshop and the recommendations proposed to achieve the objectives identified during the workshop.

Objectives

The Earth's climate system is governed by three crucial global cycles: energy, water, and carbon. Although they involve inherently different forms of energy and matter, they share several characteristics and interact at various levels. The processes that drive their interactions are complex and highly variable in time and space.

All cycles are characterized by various time scales when considering their global budget. However, the water and carbon cycles are exchanged and stored only within the Earth system, so they can be considered as closed cycles and some assumptions can be made (depending on the time scales) to consider them as obeying the conservation laws. In contrast, there may be an imbalance between incoming and outgoing radiation at the top of the atmosphere that affects the energy cycle within the Earth system. Therefore, in the following, we will use the term "energy cycle" to refer to the exchanges and transformations of the internal energy of the Earth system.

Since the beginning of the last century, the scientific community involved in assessing these three cycles has been striving to close the energy, water, and carbon budgets based on estimates of the terms in the continuity equation. This reveals potential imbalances or unexplained residuals. In the water and carbon cycles, the residual is an indication of the uncertainty involved in quantifying the terms, or a lack of knowledge about key processes. For the energy cycle, it is manifested in the Earth's energy imbalance, which is the difference between incoming and outgoing radiative fluxes at the top of Earth's atmosphere and which reflects the interplay of external and internal forcing and the response of the Earth system to perturbations of natural and anthropogenic origin.

Different approaches are used to monitor and estimate the budgets of the three cycles and their changes. The global integrals are the accumulation of the fluxes or stocks of the conservative quantities over the entire Earth system, including the ocean, atmosphere, cryosphere, and land. It is also assumed that the different terms of the budgets have been well-quantified but often without precise error characterization.

However, substantial improvements in the observing system over the last 30 years, both for satellite and in-situ observations, now allow scientists to move from expert judgments about the magnitude of the global fluxes to observation-based estimates with an error characterization, thus closing the continuity equation. This offers the possibility of establishing a global budget for these quantities.

A series of talks on each of the cycles gave a diversity of perspectives on the key challenges for their closure.

The key outcome of the workshop was to propose to GCOS and WCRP Steering Committees setting up a joint project, that would focus on i) quantifying the uncertainties involved in determining the terms of the conservation equation in the three cycles, ii) providing a common framework for analyzing and periodically reporting updated values of these terms, iii) identifying further areas where increased process understanding is needed to make progress in understanding the cycles and iv) providing a tool where interaction between cycles and future changes can be studied.

Proposed recommendations

To bring together the communities working on the energy, water and carbon cycles and accelerate the exchange of expertise in closing the budget, we, the participants of the workshop, propose a common recommendation plan. This activity would allow to quantify the various terms of the continuity equations for the three conservative quantities and the associated errors on a regular basis.

Methodology

Substantial efforts have been made by the international and multidisciplinary community to provide state-of-the-art assessments and foster discussions on the three major cycles (l'Ecuyer et al., 2015; Rodell et al., 2015; Stephens et al., 2023; Friedlingstein et al., 2022; Crispet al. 2022; Dorigo et al., 2021; von Schuckmann et al. 2023). These efforts have provided a unique view of the Earth system cycles, identified current uncertainties and knowledge gaps, and provided recommendations for the observing system. However, limitations remain in the scope of each assessment. These include consistency of methodology, knowledge of the coupling between cycles, and decomposition of errors into systematic and random contributions. There is therefore an opportunity for further development on and strengthening of these considerable international efforts.

We propose that these assessments of the closure of the three cycles should be a community effort. This will allow to pool the best estimates of the global integrals of the fluxes and reservoirs that make up the continuity equations. By achieving a common description of the system, we can ensure that the state of the three cycles as well as the fluxes coupling the three cycles, and the budgets over the three surfaces (land, ocean, and cryosphere) are treated in a consistent way. The added value of this proposal is that all the integrals are put into one set of continuity equations and the global consistency of the three cycles can be evaluated.

The radiation balance at the top of the atmosphere is the starting point for any budget study of the Earth system. It has only been directly observed since 2000, providing good estimates of its variability. However, its absolute value has large uncertainties. More precise estimates of the absolute value have been derived from the Earth heat inventory. This available energy drives the continuity equations for the three cycles over the three major surface types of the Earth - ocean, land and the cryosphere. These equations must be written as completely as possible (including the internal energy of water fluxes) for global integrals over each climate subsystem (ocean, atmosphere, continents). This will highlight any couplings that need to be investigated. The atmosphere is the link between the surface continuity equations and the radiative balance of Earth. It is also a reservoir with very short time constants in contrast to the ocean and land reservoirs. By monitoring the integrals in the continuity equation averaged over a year, changes in the reservoir of the atmosphere can be neglected and a stationary assumption can be applied.

GCOS has identified all Essential Climate Variables (ECVs) to estimate the global integrals to be considered. Observations are therefore available for most of the variables. Where a variable is not yet observed or cannot be estimated indirectly, or where observations or estimates lack coverage or precision, it can always be set to zero or another value based on expert judgement while the WCRP community works towards a more accurate solution. For the carbon integrals, the work is part of the Global Carbon project and therefore does not need to be repeated in this project.

Activities such as the Global Precipitation EXperiment (GPEX) could provide some elements to improve estimates of the global integral of precipitation and to understand the errors and their sources. For the refinement of the global closure proposed here, all efforts aimed at the improvement of any of the ECVs within the continuity equation can be capitalized on.

Procedures

What follows is the broad roadmap for GCOS-WCRP joint work that we agreed upon during the meeting. This will be further developed over the coming year, coordinated by a joint GCOS-WCRP working group that will liaise with their respective expert groups (including the Global Carbon Project) and scientific communities. The first task of the working group would be to develop a more detailed blueprint for the recommendations outlined below (possibly in a joint paper), including timelines and milestones.

Recommendation 1:
Formulate the global integrals corresponding to the 12 continuity equations, encompassing four systems (land, ocean, cryosphere, atmosphere) and the three distinct cycles (carbon, energy and water). The selection of whether to express these integrals in terms of extensive or intensive variables, as well as the adoption of appropriate units, requires consideration. This necessitates a rigorous quantification of the uncertainties inherent in the determination of the equation terms within the three distinct cycles. Moreover, the provided data should be accompanied by estimations of errors, which must be categorized into systematic and random errors. To achieve this, it is advisable to draw from established methodologies and best practices for uncertainty assessment as documented in pertinent literature, such as Bialek et al. (2020).

The scientific community and Earth observation agencies will be encouraged to provide the global integrals of ECVs and other pertinent variables essential for closing the Earth's climate cycles. These data sets are to be published with DOI and FAIR policies.
In terms of temporal averaging, flexibility is required, as some data products may necessitate evaluation over extended time periods rather than just annual averages. For some cycles (the energy cycle is a good candidate), the annual cycle may provide a test bed for evaluating the closure, while for others it may not offer sufficient precision for error estimation.

Over time we should be able to document our ability to better quantify the global integrals and close the cycles. It will help identify poorly understood processes and gaps in observations (geographical and quality) and focus the attention of the research and the observational communities on these issues.

As the errors are reduced or better understood, significant variability and trends in the various integrals will emerge, serving as topic of research. This will allow the scientific community to document where in the cycle the imbalance is increasing most rapidly and to understand how the cycle adjusts in response to anthropogenic forcing.

It will be the role of GCOS and WCRP to evaluate and publish the global integrals defined above and their error quantifications. Once a year, the annual closure of the continuity equations over the longest possible time period can be calculated and published. Monitoring of the errors in the global integrals and balance should also be the responsibility of GCOS and WCRP.

Recommendation 2:
Describe in detail the procedures for submitting estimates and the minimum requirements. These could be the first elements of a good practice guide.

It will also be crucial to determine how regular updates can be published for each of the time series corresponding to the variables (e.g., the DKRZ data centre, IPCC data centre; and/or a dedicated dashboard, etc.).

Recommendation 3:
To reduce systematic errors GCOS/WCRP will provide a reference ocean/land/cryosphere mask. All integrals will need to be calculated using a reference ocean/land/cryosphere mask and averaged over the annual cycle. The first step will be to get the community to agree (or get community agreement) on the mask to be used. As the system changes, the mask will evolve and updates to the mask will be required.

Also, a common practice needs to be agreed on the method of global averaging (e.g., simple weighting or geodetic weighting). Simple monthly averaging (rather than accounting correctly for days per month) can also sometimes be ignored and both these factors can impact calculations of key quantities such as the interhemispheric energy budget differences which are important in coupling the energy and water cycles (e.g., Loeb et al., 2015). Further common practice needs to be agreed such as for example method for derivatives, or trend evaluations.

Recommendation 4:
Write a technical guide to define a common framework for how best to calculate the integral quantities and document the various types of errors. Document known pitfalls. This should be part of a best practices guide.

Recommendation 5:
Building on existing community activities, establish a scientific community (including early career scientists and experts from the Global South) to evaluate the global integrals needed for closing the continuity equations. This community should focus on identifying further areas where observational gaps exist and where improved process understanding is needed to make progress in understanding the cycles. Emphasis should also be placed on estimating the errors resulting from the observations and the various processes used to obtain the desired geophysical variable.

Recommendation 6:
Seek funding opportunities: In order to bring together the strong scientific community and work on the recommendations, both GCOS and WCRP will need sufficient funding. This can come from existing initiatives and from funding sought by the community.

Expected outcomes:

- Provide a multidisciplinary meeting place for the climate research community
- Provide an independent assessment of our ability to monitor and understand the global Earth system through the coupled energy, water and carbon cycles

- The closure assessment will trigger process studies and identify critical knowledge that needs to be developed.
- It will also identify weaknesses in our observing systems and initiate recommendations for new variables to be observed or networks to be strengthened.
- As our understanding of the global cycles and errors improves, the decomposition of the Earth system can be refined: geographical regions or process-oriented regions, wherever possible.
- Improved methods will be developed to estimate geophysical variables and their error characteristics.
- With a strong commitment from the community, annual updates of the global integrals for the different fluxes and stocks can be achieved, making a continuous assessment (at annual frequency) close to real time feasible.

Contents

1. Introduction

Global Climate Observing System (GCOS) and World Climate Research Programme (WCRP) convened a joint workshop in Paris on 22 and 23 June 2023 to assess the current state of knowledge of the cycles as well as our capability to assess emerging changes in the cycles.

The aims were to i) identify challenges from research (knowledge of processes) to modelling and observing system capabilities; ii) identify key indicators for monitoring, measuring (observational needs) and modelling the cycle and indicate how they can be used in global assessment frameworks; and iii) identify key processes which require a better understanding to improve cycle monitoring or coupling with other cycles.

The following sections provide a summary of the two-day workshop.

2. Day 1: Focus on the state of knowledge of each of the components

2.1. Session 1: Welcome and setting the ground for the workshop

2.1.1. Welcome and purpose of the workshop

The workshop began with a brief welcome note by Prof Sabrina Speich from the Department of Geosciences of the Ecole Normale Supérieure (ENS) in Paris. After a short outline on the purpose and plan of this workshop, Prof Dr Han Dolman mentioned that this workshop has been under discussion between both the observation side (GCOS) and the research side (WCRP) for many years as there are many overlaps that need to be addressed. He added that the aim of this workshop is to get the best possible perspective on cycles. Prof Dr Detlef Stammer reiterated that this workshop is a joint GCOS/WCRP workshop.

Dr Jan Polcher then presented the WCRP perspective on this workshop. Jan mentioned that the WCRP has a long-standing interest in cycles and briefly began with the history of cycles in WCRP-GEWEX. GEWEX was given the task to close the global energy and water budget in the early 1990s by Dr Pierre Morel, the then Director of WCRP. In the end of the 90s, a paper was published stating the available data was not good enough to close the global energy and water budget, and that there was no clear understanding of the processes. Jan further mentioned that while internal processes seemed less important on a global scale, at regional level, this was important. However, regional cycle studies better link the understanding of processes between water and energy. Jan emphasized that due to progress in better understanding the quantification of global water and energy exchanges using simpler closure assumption, it was now important to focus on the regional cycles as it matters to people. The scientific community must be able to answer the following questions - how much water do the catchments really hold? How much water do we have left? He mentioned that science was progressing but relevance to society has still not been made. Some major results from HYMEX project were also cited.

The list of participants can be found in Annex 1.

2.1.2. Overview of GCOS and WCRP activities within the realm of Earth Cycles

GCOS: Prof Sabrina Speich

Prof. Sabrina Speich started the session with an overview of GCOS and its activities related to Earth cycles. She began by describing the value chain that defines the goals of GCOS - GCOS supports users, defines Essential Climate Variables (ECVs) requirements, reviews the status of the observing system. She then briefly discussed the GCOS 2022 Implementation Plan (IP). She mentioned the themes of the actions of the GCOS IP and briefly addressed the ECVs requirements. Regarding the overview of the GCOS work on Earth cycles, she mentioned that it started in 2019, at the GCOS Joint Panel meeting in Marrakech. She also said that the new Implementation Plan explicitly directs attention to Earth cycles, with Action B10 of the GCOS 2022 Implementation Plan dedicated to identifying gaps in climate observing systems to monitor the global energy, water, and carbon cycles.

WCRP: Prof Dr Detlef Stammer
Detlef Stammer presented the primary objective of WCRP when it was established- to understand climate predictability and human impacts on climate. A few years ago, WCRP reworked its strategic plan and redefined the scientific objectives to include ensuring connection between climate science and society. He also addressed the six Core Projects of WCRP emphasizing that the energy cycle and other cycles can't be dealt with in isolation. The WCRP focuses on looking into these three cycles, their coupling, and understanding how they impact each other. Detlef mentioned the task team on cycle and budgets and stressed that the relation to carbon cycles needed reinforcement and that the carbon community needed to be integrated within the other cycles. He also mentioned that though the work on cycles and budgets could fit within GEWEX and CLIVAR, interactions with other Core Projects were crucial for cycles and budgets. He added that work on cycles within the WCRP goes on in different groups, and coordination was needed to maximize the outcomes.

Detlef explained that this meeting was for GCOS and WCRP to inform each other on what they were doing in terms of earth cycles, and to identify interfaces and workflows to collaborate. WCRP task team on cycles and budgets was created to see how the work on cycles and budgets was organized within WCRP. GCOS is more about observations, while WCRP also covers modelling and is about understanding what science is required to develop and inform the selection of new ECVs. However, there is a large overlap between the two. Detlef emphasized that we shouldn't give the stakeholders a feeling that the GCOS and the WCRP are doing the same things. The workshop would therefore address the role of both WCRP and GCOS together. Anne-Maria further mentioned that it was important to know the types of extra observations needed for cycles and budgets studies, what can be done in the future to improve observations, so that space agencies can be informed well in advance as new sensors would need a lot of time to become operational.

2.2. Session 2: State of knowledge of each cycle - Combining observations and models to quantify the cycle from regional to global scales.

2.2.1. Energy Cycle: Dr Karina von Schuckmann

Karina began the session with a detailed overview on the current state of knowledge of the energy cycle from the top of the atmosphere to the surface energy transfer, and explained how they change over time globally at different time scales. She defined the systems required to close the energy cycle, and how the Earth's cycles were intertwined, and that their complex interactions happen across different time and space scales. She also provided an overview on the regional aspects of the energy cycle and on how the global energy budget varies at the interannual to multi-decadal and longer time scales. Impacts from anthropogenic forcing agents and internal climate variability at various time scales was also presented to address the stationary nature of cycles. With respect to processes that are currently not well understood, she highlighted our limited understanding of the exchanges/feedback between heat reservoirs and the impact of heat uptake at different scales; limited understanding of the ocean internal processes triggering changes in the Earth energy imbalance; the link of variation of changes in the Earth energy imbalance to changes in the Earth heat reservoirs and their implications; and the role of small-scale processes and variations of the thermodynamic coupling; the uncertainties in climate sensitivity; uncertainties in cloud-feedbacks, particularly with respect to the causality in aerosol–cloud relationships. She then raised several remaining challenges with respect to the uncertainty considerations, such as in the processes underlying uncertainty in the global temperature response to forcing in climate models (eg, cloud-feedbacks); large uncertainties in radiation components of the global and regional surface energy budget; uncertainties of the representation of the surface energy budget in climate models; uncertainties in the estimate of changes in Earth's heat reservoirs from observing system gaps; and uncertainties for regional budget approaches due to limited information on lateral heat/energy transports. Finally, she also highlighted the current open question of the recent increase in the Earth energy imbalance leading to increased rapidity of the accumulation of heat in the Earth system and discussed the current state of knowledge for this question.

Karina's presentation was followed by a brief discussion in which the importance of having a systematic view on analyzing different types of errors was emphasized. While sampling errors are often analyzed, there are other different errors that need to be discussed and considered. In addition to in-depth error analysis, studies should also work on reducing these errors. This could be through advances in observational systems. The importance of the connections to the water cycle was also pointed out. Surface energy processes at relatively small regional scales, such as estimation of evaporation, were also mentioned to be important. Permafrost is also an issue that is very complex in terms of energy processes and there is a lot of uncertainty in large scale models. Detlef mentioned that the processes presented need to be dealt with by the WCRP at all time and space scales. This was followed by a brief discussion on whether one must talk about closure or budget studies. Budget analysis provides knowledge of the processes and the capability to investigate what is changing and what is driving these changes. It also considers the non-linearity in the impacts and systems and is a strong tool for assessing the status of the global climate observing system. Closure is more a check on our ability to account for the terms, and to assess our knowledge. This could, however, hide the variability that exists within the system, as it covers only large-scale issues. More than the closure of the budget, one must use the budget, the uncertainty of the different terms in the budget, the trends and cycles. To a query on whether detection and attribution was emphasized enough, Karina responded that this was addressed in terms of long-term trend for ocean warming, and that the attribution has been shown to exist.

2.2.2. GEWEX-ESA EEI Assessment Workshop outcomes: Dr Benoit Meyssignac

Next in line on the agenda was Benoit's presentation on the outcomes of the Earth's Energy Imbalance workshop co-organized by ESA and GEWEX. The main objective of the workshop was to assess the different observations, estimates of the EEI mean, trend and variability, and to analyze why there was a spread by using different techniques. He mentioned that the community feels strongly about setting up a list of best practices. Additionally, having confidence in the uncertainty would also help constraining models. Good estimates of the energy imbalance with a clear understanding of uncertainty would provide information to climate services that would be interesting for global stock take.

A short discussion on the relevance of consistency checks to EEI assessments and the importance of working towards reducing uncertainties followed the presentation. A brief exchange on the suitability of reanalysis products for various cycles also followed.

2.2.3. Water cycle: Prof Wouter Dorigo

Wouter provided an overview of the water cycle and its closure at global and regional scales. His overview addressed the following aspects:

- Processes that are not well represented.
- New observables (observations) that are available and those that are needed to bridge gaps.
- Future science priorities
- International programmatic landscapes

He summarized recent findings that looked at various components of the water cycle and showed evidence of large uncertainty for, among others, ground water and soil moisture.

The studies also showed that trends of the various components were not consistent in time. For fluxes, groundwater discharge, which was mostly based on models, had a very high uncertainty. The studies also showed the need for strengthening the linkage of measurements to modelling. He said that one must go beyond the usual validation of the models and can use observations to calibrate model processes. He concluded the presentation by emphasizing the following: the need for a finer spatial scale (1km) enabling to look at local processes and extremes, focus on consistency and closure in trends, focus on anthropogenic water uses, integrated assessment of data and models, coupled system approach, and the need for supersites.

During the discussion session that followed, the need for an emphasis on human-water interaction and its quantification was mentioned. Spotlight was also put on how the discussions till now have centred around water-cycle on land, and how there is a blind spot over water-cycle over oceans. It was agreed that more work needs to be done on examining how the water cycle couples with the energy cycle over oceans.

A discussion on groundwater followed where it was highlighted that studies don’t show much knowledge on groundwater. There has been progress on the knowledge of groundwater variability but not yet on where the irrigation water ends. It was also mentioned that there were no tools available to separate soil moisture and groundwater. The best way to model variables in the ground would be to assimilate space observations in land surface models. There was also a short discussion on definition of a basin and its geographical scale, which ended with a mention of the importance of disentangling the climate side and the human driven aspects of the water cycle that relate to irrigation, pumping ground water, etc. In addition to this, there was also a mention of a big uncertainty in submarine groundwater discharge and the need to assess its importance and ways to measure this variable.

2.2.4. Carbon cycle: Dr Philippe Ciais

Dr Philippe Ciais gave a presentation on the global carbon budget and risks of future destabilization of the terrestrial carbon cycle.

Atmospheric CO_2, CH_4 and N_2O concentrations have increased in the industrial era.
Looking at the timeseries, a strong seasonal cycle and a difference in the accumulation of CO_2 for different years can be observed. Yet, the observed increase is only half of what we could expect if we calculated human-produced carbon. This is due to the absorption of carbon by the Earth system. Part of the excess carbon is absorbed by vegetation and the soil (land), part is absorbed by the ocean.

The carbon cycle is perturbed by human activities. The relevant terms of this perturbation, in the order of importance, are:

- Fossil fuel emissions: The amount of CO_2 in the atmosphere due to fossil fuel emissions cannot be measured independently and is estimated from statistics from each country. The global uncertainty for the fossil emission perturbation is 5-10%.
- Expansion of agricultural land: With the increase of the population, cropland and pasture have also increased. Green revolution and technological progress have contributed to the increase in emissions.
- Land-use change emissions: Historically, this category emerged from the Northern Hemisphere, but after 1960 these emissions are high in the tropics, driven largely by deforestation. Land-use change emissions accounted for 40% of total emissions in 1960, while now they represent less than 14%.

In the global carbon budgets, all these sources are accounted for, and the goal is to balance these sources by considering the sinks (ocean, land and atmosphere). Appropriate models are used for oceans, land, and atmosphere. Roughly half (48%) of the perturbation goes to the atmosphere and creates global warming, while ocean and land take up 26% and 29% respectively. The carbon cycle is very sensitive to climate change. Thus, if the climate changes, the carbon intake by oceans and land will change leading to the potential for carbon sinks to become less efficient.

In terms of what we observe, there is an increase of ocean carbon storage, mainly in ocean gyres where vertical mixing transfers excess carbon from the surface layer to the deep sea. The storage of carbon over land is observed, even though it is difficult to assess changes in its levels. Forest inventories in the Northern and Southern Hemisphere countries show an increase in carbon storage. However, there are very few samples in the tropics. Furthermore, soil carbon changes are not measurable.

Global land models only simulate carbon sinks from rising CO_2 and sources related to climate change. While forest demography/management is the main cause of carbon sink in temperate regions, none of the models include sufficient representation of this factor.
There is a connection between the carbon and water cycles as water regulates the carbon uptake from plants while higher CO2 levels can increase water use efficiency of plants though stomatal effects. Also, there are land to ocean loops of the global carbon cycle (the river loop), as rivers bring carbon to the ocean.

Finally, Philippe presented the projection of future changes with coupled carbon climate models, which show that the more carbon we emit the more it will be absorbed by the earth system. While projected changes in ocean carbon storage have acceptable uncertainties, there is a very large uncertainty for the land carbon storage.

The key questions here are: whether this scenario can get worse, and what are the risks of destabilizing the carbon cycle?

The main problem is that the carbon models are somehow primitive and do not include fundamental processes such as extreme fires, permafrost carbon decomposition, risk of dieback of tropical moist forest, and intensive human land use.

Therefore, research should focus on reducing uncertainties using measurements and on quantifying the net effect of positive and negative feedback for a range of different scenarios.

The discussion that followed touched on many topics such as the availability of high-resolution data from private company, the involvement of biology in the role of carbon uptake from the ocean, the importance of studying the linkage of the carbon cycle with the biosphere, the declining of surface ocean partial pressure of CO_2 (pCo_2) measurements since 2017, and the need to study the cycles together.

2.3. Wrap up of the day's sessions: Dr Jan Polcher

Jan wrapped up for the day with the following crucial messages:

1. Between scientific confidence and our obligation to society, the community needs to show that we can monitor how the equilibrium (carbon-water-energy) is evolving over time.

2. Process understanding – we need to understand the processes, but we also need metrics that shows the improvement in our understanding of how water, energy and carbon are conserved on Earth.

3. The global integrals will serve as metrics that shows the improvements in our understanding (see point 2). If the components of the global integrals are clearly defined, every time there is a new estimate of one of the components, the global integrals will be updated. This will help moving progressively towards closing the equation.

4. Global integrals are good, but we can also identify regions to establish these metrics. However, we are not going to be able to solve the regional problems without solving the global problem.

3. Day 2: Focus on the coupling between energy, water and carbon cycles: as well as information drawn from other cycles presented in Day 1. What can we learn from each other?

3.1. Session 3: Focus presentation from each cycle

3.1.1. Carbon Cycle: Dr Toste Tanhua

Toste presented on the carbon cycle and showed that fossil fuel burning is the largest contributor of CO_2 with its rate continuing to increase further. Though Land Use Change (LUC) is mitigated by green revolution, carbon density remains a source of large uncertainty. He further mentioned that the Global Carbon Budget projects provides an annual comprehensive stock take of this. In terms of direct link between carbon and energy in the ocean, carbon uptake from the ocean affects ocean acidification which, in turn, impacts organisms. Around 37000 GT of carbon, mostly inorganic, is stored in the ocean (much more than in the atmosphere, land, permafrost combined). If the ocean temperature changes, there will be changes in the partial CO_2 pressure which, in turn, changes the flux. Wind changes also cause flux changes. The surface carbon will be transported from into the deep ocean with changes in density gradient, overturning circulation etc.

On land, changes in the hydrological cycle affect the carbon cycle. Water cycle, temperature, land changes, changes in respiration, fires, CO_2 fertilization effect, etc. have impact on growth and growth degradation. These changes also affect the carbon cycle. Global ecosystems are more affected by water than by temperature. It was also mentioned that there was only short-term gain in planting forests as forests, in general, lose carbon for the first 20 years after which they reach an equilibrium state. It is crucial to protect existing forests rather than re-planting trees. Ocean forests such as mangroves, salt marshes and seagrass meadows have the potential to compensate for about 1% of the carbon that is lost.

In the discussion following the presentation, it was mentioned that given the distribution of land and ocean, carbon cycles over the ocean are driven more by temperature than water. The coupling of these cycles could be different depending whether we are in the ocean (especially more energy in the open ocean) or on land. The need to distinguish between what's going on in the land and what's going on in the ocean was emphasized. The highlight of this discussion was the exchange about how the shallow sea is currently not well-understood, and how the coupling between land and ocean can be separated easily. However, decoupling the cryosphere is difficult. Land, ocean and cryosphere need to be considered as three different regions.

3.1.2. Energy cycle: Dr Benoit Meyssignac

Benoit presented the water-energy cycle with an energy perspective and acknowledged the input from GEWEX and US CLIVAR experts to this presentation.

The study of the energy cycle is important as changes in it will drive changes in temperature, water vapor, and precipitation. The research on the energy cycle has been alive since the beginning of the 20th century and, at present, hundreds of scientists globally are involved in exploring the energy cycle in depth. However, there are still huge problems in the understanding of atmospheric and oceanic energy cycles. Small-scale processes influence the global climate, and as we don't understand these processes, they are not represented in climate models. Therefore, models have large uncertainties. To understand the energy cycle, one must resolve the competition between radiation and convection (dry and wet), and this needs to be done by climate models on a small-scale. Benoit presented a series of questions to be answered if we want to understand the energy cycle and reduce the uncertainty of climate change. He also gave details on the state-of-the-art research and progress for each of them. Those questions are:

1. What is the current global mean energy budget and how is it changing in time?
2. What is the polar energy budget and how is it changing? Uncertainty in Arctic surface imbalance is too high.
3. What is the current EEI, how is it changing with time and why?
4. How are low clouds changing with climate change? Seventy percent of the spread in climate models comes from low level clouds in the tropical pacific.
5. How does atmospheric deep convection changes with climate change? How does it affect climate change?
6. What is the coupling between Sea Surface Temperature (SST) and radiative feedback? What is the role of clouds in that coupling? How do changes in the SST affect the Earth Radiative response?
7. What is the role of aerosols in climate change, and can we quantify the indirect role of aerosols in clouds and climate change?

The main conclusions were that the water and energy cycles are deeply connected and intertwined at all time scales, and that the connection with the carbon cycle is different at different time scales. Today, closing and understanding the different aspects of the water-energy cycle is a topic that is widely covered in many specialized WCRP activities. It goes from closing the water and energy cycles consistently through understanding the role of clouds in climate change, to analyzing the global warming pattern effect and how it modulates the climate response to GHG emissions. There are several processes that need to be studied to reduce the uncertainties, together with specifically enhancing observations.

4. Conclusion of the workshop

Jan Polcher presented a proposal for an approach to monitor progress in closing cycles. The conclusion of the workshop and the way forward are presented in the executive summary of this report.

Annex 1 - List of Participants

For a meeting the annexes should include a list of participants and the meeting agenda. All reports should include a list of acronyms or abbreviations.

FirstName	LastName
Sabrina	Speich
Lijing	Cheng
Meghan	Cronin
Toste	Tanhua
Albertus Johannes Han	Dolman
Wöuter	Dorigo
Karina	Von Schuckmann
Anna Maria	Trofaier
Richard	Allan
Benoît	Meyssignac
Howard	Wheater
Thomas	Haine
Philippe	Ciais
Detlef	Stammer
Jan	Polcher
Lai-Yung (Ruby)	Leung
Caterina	Tassone
Hindumathi	Kulaiappan Palanisamy

Annex 2 - Acronyms

CLIVAR – Climate and Ocean Variability, Predictability and Change
DKRZ – Deutsche Klimarechenzentrum, German Climate Computing Center
ECV – Essential Climate Variable
EEI – Earth Energy Imbalance
ESA – European Space Agency
GCOS – Global Climate Observing System
GEWEX – Global Energy and Water Exchanges
GHG – Green House Gas
GPEX – Global Precipitation Experiment
IOC – Intergovernmental Oceanographic Commission
IPCC – Intergovernmental Panel on Climate Change
ISC – International Science Council
SST – Sea Surface Temperature
UNEP – United Nations Environment Programme
WCRP – World Climate Research Programme
WMO – World Meteorological Organization