WCRP workshop

"The Earth's Energy Imbalance and its implications"

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Sponsors:

ABSTRACT BOOK - PRESENTATIONS

SESSION 1: Global estimates of Earth's Energy Imbalance

Can we derive Earth's energy imbalance from Sun and Earth's radiation pressure acting on spherical LEO satellites? (*Maria Hakuba, Graeme L. Stephens, Felix W. Landerer, Frank H. Webb, Srinivas V. Bettadpur, Byron D. Tapley, Bruno Christoph, Bernard Foulon)*: The direct measurement of Earth's energy imbalance (EEI) is one of the greatest challenges in current climate research. The global mean EEI represents the integrated value of global warming and is tightly linked to changes in hydrological cycle and the habitability of our planet. Current space-born radiometers measure the longwave and shortwave radiative components of the energy balance with unprecedented stability, but with calibration errors too large to determine the absolute magnitude of global mean EEI as the components' residual. Best estimates of long-term EEI are currently derived indirectly from temporal changes in ocean heat content at about 0.7 Wm-2. Known sampling caveats of Argo's ocean profiling system may not induce large uncertainty in the long-term estimate of EEI, but aggravate the estimation of EEI on sub-decadal time scales and require additional knowledge on deep-ocean heat uptake. To monitor EEI directly from space, we propose an independent approach based on accelerometry that measures non-gravitational forces, such as radiation pressure, acting on Earth orbiting spacecrafts. The concept of deriving EEI from radiation pressure has been considered in the past, and we provide evidence that today's capabilities are sufficiently accurate to answer the question: At what rate is our planet warming? To measure global mean EEI to within at least +-0.3 Wm-2 may require multiple spacecrafts of near-spherical shape and well-characterized surface properties to reduce confounding effects and to measure radiation pressure simultaneously across the solar and terrestrial radiation spectra. While the instrument accuracy is more than sufficient (<<0.1 Wm-2), uncertainties due to space craft design, perturbing forces, and space-time sampling, are still to be explored. With this concept, we aim to provide the basis for a data record of global and zonal mean EEI on annual and potentially monthly time scales. While this concept aims at providing the first and only direct measurement of EEI, it is not meant to replace existing concepts designed to measure energy balance components or ocean heat storage, but to complement these by providing an independent estimate of EEI for inter-comparison and to anchor data products and climate models that lack energy balance closure.

Towards monitoring trends and variability in the atmospheric heat content (AHC) primarily based on radio occultation (*Gottfried Kirchengast, Florian Ladstädter, Barbara Angerer, Andrea K. Steiner, Maximilian Gorfer, Florian Lippl):* Since the pioneering Global Positioning Satellite (GPS) radio occultation (RO) mission GPS/Met in the mid-1990s, and in particular since the start of the continuous RO dataflow by 2001, an RO data record of almost two decades has been accrued that is clearly set to continue also over the next decades to come. RO probes the fundamental state of the atmosphere, the thermodynamic state of the gas as expressed by air density, pressure, temperature, and tropospheric water vapor. These are the fundamental thermodynamic variables for tracking climate variability and change, including in terms of atmospheric heat content (AHC), both for sensible heat content (SHC) and latent heat content (LHC). RO provides exceptional utility for the purpose due to its unique combination of high accuracy, high vertical resolution, long-term stability, and nearly all-weather global coverage in its monitoring of the troposphere and stratosphere. A data record from select high-quality (Vaisalä) radio sondes (RS) complements these data since the mid-1990s as do re-analyses (RA) of increasing quality and long-term stability such as the recent European Reanalysis ERA5. We use the RO data record 2001-2018, complemented by and cross-evaluated with RS and RA data records, to compute and analyze latitude-resolved monthly-mean AHC and its SHC and LHC components over the last 25 years. Based on understanding the level of long-term stability and homogeneity in the record, and related limitations, we investigate contributions to SHC, LHC, and total AHC changes along different domain separations. These include land and ocean areas, the main atmospheric layers as delineated by the altitude-resolved RO data (boundary layer, free troposphere, stratosphere), and AHC trends and variability as compared to upper ocean heat content (OHC) changes. We show initial results from this on-going work based on our Wegener Center Occultation Processing System OPSv5.6 RO data record and related Vaisalä RS and ERA-Interim RA records. In addition, we discuss the status of the AHC record based on our new Reference Occultation Processing System (rOPS), which provides SI-traceable RO data complemented by ERA5 RA data and includes integrated propagation of estimated systematic and random uncertainties from the raw RO observations down to the final AHC data.

Global to regional manifestation of Earth's energy imbalance *(Richard Allan, Chunlei Liu, Pat Hyder, Matt Palmer, Chris Roberts, Michael Mayer)*: Decadal changes in surface temperature, water vapour, precipitation and the Earth's energy budget display the imprint of climate variability and change while the upper ocean mixed layer energy budget provides an interface between ongoing heating of climate due to rising greenhouse gas concentrations and the changes in global surface temperature. A reconstruction of the energy balance at the top of Earth's atmosphere based on ERBS and CERES satellite data and ERA Interim reanalysis mass-corrected energy transports documents regional manifestation of Earth's energy imbalance. Corrections to unrealistic surface land fluxes are redistributed across the ocean and some further updates relating to enthalpy calculations are under development. Results will also focus on regional aspects of the climate system including hemispheric energy imbalance and precipitation asymmetry including co-variability, north Atlantic ocean heat transport changes and systematic southern ocean biases and feedbacks in coupled climate simulations.

Poleward energy transport: is the standard definition physically relevant at all time scales? *(Minyi Liang)*: Poleward energy transport in the atmosphere and oceans constitutes an important branch of the global energy budget, and its role in the climate system has been the subject of many studies. In the atmosphere, the transport is affected by “eddies” and large scale meridional cells, both with zero net mass transport across latitude circles, but also partly by processes associated with a net transport of mass across latitude circles. The latter must cease to operate in steady state, but they may be significant when time variability of the heat budget is considered. Indeed, examination of reanalysis data on short (daily to monthly) timescales shows that mass variations on these timescales result in surprisingly large fluctuations (in excess of 10^15 W = 1 PW) in the poleward heat transport. These fluctuations are referred to as “extensive”, for they primarily alter the mass integrated energy of the region considered, but not its averaged value. It is suggested that extensive fluctuations mask more meaningful climate signals present in the heat transport variability on monthly and interannual timescales, and a new formulation is proposed to isolate the latter. The new heat transport definition was shown to lead to stronger correlations with heat content than the standard one, and was also shown to display a more robust statistical link with modes of climate variability. For example, a clearer relationship between the AO and heat transport emerges in our analysis, the atmosphere carrying less heat poleward in a positive phase than in a negative phase of the AO. El Niño variability was also found to be linked more robustly to changes in poleward heat transport with more poleward heat transport at low southern latitudes in El Niño years. New and standard definitions of heat transport also display pronounced differences in autocovariance functions and produce different time sequence of events with large/weak poleward heat transport. Finally, the variability of the heat budget in the new formulation is also different, with a larger role for diabatic effects, even on short (less than seasonal) timescales. It is hoped that the new definition of heat transport may shed further light on the intuitive link between energy transport and climate variability.

Determine Earth Radiation Imbalance (ERI) Using GEO-MEO Constellations *(Dong Wu)*: Earth radiation imbalance (ERI) at the top of atmosphere (TOA) is a fundamental variable to diagnose the state of Earth's climate system. It requires sensors with high radiometric accuracy (<0.3 W/m2) as well as high spatiotemporal resolution (~100 km and hourly) around the globe. While highly accurate instruments for the total TOA flux measurements remain technologically challenging, it is feasible to achieve the requirements of spatiotemporal sampling through cost-effective smallsat constellations. In this paper we present an innovative concept to measure the ERI from space with the number of satellite as fewer as 6. In this simulated constellation study, The Earth, treated as an exoplanet, is viewed from satellite radiometers at geosynchronous equatorial orbit (GEO) and medium Earth orbit (MEO) distances using wide-view total-flux radiometers. Because Earth's outgoing radiation is largely fluctuated due to cloud and surface processes, the number of satellites in a constellation becomes a key issue of affordability and capability of monitoring the total TOA flux at various time scales. Using the MERRA-2 hourly radiation outputs, we performed an observing system simulation experiment (OSSE) simulation to evaluate how many satellites are needed from GEO and MEO in order to monitor the ERI accurately. These wide-view radiometers ignore details of individual radiative flux sources (e.g., clouds and surfaces) and rely on a network of sensors for coincident observations to determine ERI collectively from space. The simulation study shows that a 6-member MEO-GEO constellation could yield the temporal sampling needed for the ERI accuracy (0.1 W/m2) on a daily basis. Residuals due to cloud/surface inhomogeneity can be further reduced by increasing the number of sensors in space.

Ocean Reference Stations - Sustained in situ observing of air-sea fluxes *(Robert Weller, Albert J. Plueddemann, J. Thomas Farrar, Sebastien P. Bigorre, Michael Schlundt)*: Long-term deployments of well-instrumented surface moorings are part of the strategy to observe and map the air-sea fluxes of heat, freshwater, and momentum across the global ocean. Three sites, called Ocean Reference Stations (ORS), have been collecting data since 2000, 2001, and 2004, respectively. Two redundant Air-Sea Interaction Meteorological (ASIMET) packages are mounted on the surface buoys and have been very successful at returning a complete record of surface meteorology sampled once per minute over the year-long deployments. The deployments are overlapped and the deployment ship carries an independent meteorological sensor set to support quality control of data from each deployment and also the merging of successive deployments into longest possible continuous records. Work is ongoing to quantify the accuracies of the observations and to improve those accuracies. Present work underway includes: 1) upgrades to the shortwave radiation sensors and to our process for calibrating those sensors; 2) upgrades to the relative humidity and air temperature sensors and assessment of their accuracy and drift; and 3) examination of the impacts of flow distortion around the buoy superstructure on wind speed and direction sensing. Observations from the buoys also include near surface currents as well as high resolution GPS location, which allow for improved measurement of wind relative to sea surface. Further work planned on assessing errors will look at the impacts of mean buoy tilts due to current and/or wind drag on the buoy and mooring and of wave-induced motion. Paths toward future improvements to sensor performance include addition of ventilation to reduce errors associated with radiative heating and using computational fluid dynamic studies of the flow around the surface buoy to improve the buoy superstructure and sensor placement. Meteorological data are telemetered but not placed on the Global Telecommunication System (GTS) in order to keep the data from being assimilated into numerical weather prediction models. As a result, the ORS time series can be used as independent data to evaluate models. The ORS data have also been used to ground-truth and validate remote sensing fields of surface fluxes and to tune and assess hybrid air-sea flux products. The time series from the Ocean Reference Stations are freely available on our website (http://uop.whoi.edu) and also through OceanSITES (http://www.oceansites.org). We summarize the utility of the ORS time series by stating the accuracies we associate with net heat flux, latent heat flux, sensible heat flux, net shortwave radiation, net longwave radiation, and wind stress at the sea surface and showing comparisons between the ORS-based air-sea fluxes and those from models, remote sensing, and hybrid products.

Progress in measuring planetary energy imbalance from space *(Benoit Meyssignac, A. Blazquez, R. Roca, M. Ablain, B. Picard)*: It is essential to measure Earth Energy Imbalance (EEI) in order to monitor and understand the perturbation of the water and energy flows in the climate system in response to external forcing and in particular to anthropogenic forcing. Because of the EEI the climate system stores energy (essentially in the form of heat) in the ocean (93% of the excess of energy due to EEI), in the cryosphere (~3%) , in the atmosphere (~1%) and on land (~3%). An efficient method to estimate EEI consists in making the inventory of energy in the different climate system reservoirs. This is now possible from space by combining satellite altimetry and space gravimetry observations. Gravimetry observations from the GRACE mission provides global estimates of land ice melt and the associated cryosphere heat uptake. In addition, when these observations are combined with satellite altimetry through the sea level budget approach they provide an estimate of the ocean heat uptake. The current published best estimate of the EEI using this approach from space is 0.77 ±0.52 wm-2 (at 1.65 sigma) over 2005-2013 (Llovel et al. 2014, Dieng et al. 2015). Since these estimates, significant progresses have been made on the uncertainty by refining the uncertainty estimate of both altimetry and gravimetry data and by changing the terrestrial reference frame in which altimetry and gravimetry data are combined. In this presentation we propose to recall the principles of this approach to estimate EEI and to show the progresses achieved in the uncertainty estimate. We will propose a uptodate estimate of the EEI over 2005-2017 with improved uncertainty estimate.

Towards quantifying uncertainty in ocean heat content changes using synthetic profiles *(Matt Palmer, Lesley Allison, Chris Roberts, Rachel Killick, Leon Hermanson, Nick Rayber, Doug Smith)*: Estimates of global ocean heat content (OHC) change are the primary means of assessing the magnitude of Earth's energy imbalance over the 20th Century. However, intercomparison studies show that results vary greatly among the different estimates, with the mapping method used to interpolate the sparse ocean temperature profile data a key source of uncertainty. We present a new approach to assessing OHC mapping methods using "synthetic profiles" generated from a state-of-the-art global climate model simulation. Synthetic profiles have essentially the same sampling characteristics as the observed historical ocean temperature profile data but are based on model simulation data. Mapping methods ingest these data in exactly the same way as the real observations, but in this case the resultant mapped fields can be compared to a model simulation "truth". We use this approach to assess two mapping methods that have been developed at the Met Office and are used routinely for climate monitoring and initialisation of decadal forecasts. The results show a systematic underestimation of total OHC change, particularly for the Southern Hemisphere and the deep ocean below 2000m. In addition, the sampling characteristics of the historical data introduces spurious variability in the estimates of global OHC on sub-annual to multi-annual timescales. The results of this "proof-of-concept" study are encouraging for gaining further insights into the capabilities and limitations of different mapping methods using synthetic profiles.

SESSION 2: Regional Energy Budgets and Energy Transports

North Atlantic Ocean heat budget on different time scales from VOS data and reanalyses *(Sergey Gulev, Konstantin Belyaev, Alexander Gavrikov, Marina Aleksandrova)*: Accurate space-time integration of surface heat fluxes is critical for estimating regional heat budgets. This problem is especially sensitive to the use of inhomogeneously distributed Voluntary Observing Ship (VOS) observations. VOS provide the longest coverage of the World Ocean by in-situ meteorological observations in time going back to the mid 19th century. However, being collected primarily along the major ship-routes, VOS observations have poor sampling density, especially for the period prior WW2. We consider the potential of VOS for estimating ocean surface heat budget at different time scales. In order to minimize sampling impact on the flux estimates computed from VOS, we propose a concept suggesting integration of the turbulent heat fluxes in the coordinates of steering parameters (vertical surface temperature and humidity gradients on one hand and wind speed on the other). For these variables we consider two-dimensional distribution of surface fluxes in the space of parameters and approximate them by Weibull distribution for the wind speed and Modified Fisher-Tippet distribution for surface temperature and humidity gradients. Replacing the integration of fluxes over the geographical domain by the integration in the parameter space allows for obtaining less biased and more robust large-scale estimates. Analysis was performed for the North Atlantic latitudinal band from 25 N to 60 N, for which also estimates of the meridional heat transport are available from the ocean cross-sections. Over the last 35 years turbulent fluxes within the region analysed increase by about 6 W/m2 with the major growth during the 1990s and early 2000s. Further these estimates were enriched by the computations of radiative fluxes for which we used an advanced parameterization for short wave radiation accounting for cloud types. In order to apply this parameterization we used new algorithms to exclude biases associated with astronomical factors, and used probability density functions for the cloud cover occurrence distributions to minimize sampling uncertainties in cloud cover. Decreasing incoming short wave radiation during the same time (over the last 35 years) about 1 W/m2 and very small changes in long-wave radiation imply upward change of the ocean surface net flux of about 7-8 W/m2. These estimates as well as characteristics of interannual variability are further compared to the similar estimates derived from different reanalyses and satellite data for the last decades and with meridional transports in the ocean from the North Atlantic oceanic cross-sections at 25N and 60N.

Evolution of ocean heat change related to ENSO *(Lijing Cheng, Kevin E. Trenberth, John Fasullo, Michael Mayer, Magdalena Balmaseda, Jiang Zhu)*: As the strongest inter-annual perturbation to the climate system, the El Niño-Southern Oscillation (ENSO) dominates the inter-annual variability of the ocean energy budget. Here we combine ocean analysis, re-analysis, Earth system model simulations and surface flux datasets to better understand the regional and global evolution of ocean heat related to

ENSO. A robust cooling of the climate system and global ocean is identified during and after El Niño, as seen from multiple datasets. This negative ocean heat content tendency (OHCT) is dominated by the net cooling of the tropical Pacific Ocean through enhanced air-sea heat fluxes driven by high sea surface temperatures. The adiabatic redistribution of heat, both laterally and vertically, in the tropical Pacific and Indian Ocean dominates their local OHCT: for example, heat content increases in the West Indian and East Pacific Ocean before El Niño, reflecting the effects of weakened Pacific trade winds and related walker circulation changes. Heat also discharges into off-equatorial regions within 5-20oN during and after El Niño. The tropical Atlantic and Indian oceans are found to experience a net warming during El Niño, and the North Atlantic is slightly warming after El Niño. Consistency between OHCT and the net surface flux in these regions indicates that atmospheric teleconnections play a main role in observed changes. However, in the North Pacific, OHCT is positive during El Niño but the surface flux contributes to a net cooling effect, implying the regulation of meridional ocean heat transport by ENSO in Pacific. OHCT in the Indian Ocean is found to be out of phase with surface flux, indicating a strong modulation of ocean transport: i.e. Indonesian Throughflow.

Magnitude and changes in surface radiation budget inferred from surface observations and climate models *(Martin Wild)*: The radiative energy exchanges at the Top of Atmosphere between Sun, Earth and space can be fairly accurately quantified from satellite missions such as CERES or SORCE. However, the magnitudes of the radiative fluxes at the Earth surface, which cannot be directly measured by satellites, are afflicted with larger uncertainties. Accordingly, also state of the art climate models show substantial discrepancies particularly in their surface energy budgets already on a global mean scale, which further accentuate on regional and seasonal scales. In addition to satellite observations, the worldwide distributed surface station observations can be used to better constrain the radiative fluxes not only from space, but also from the surface. Such observations become increasingly available for example through the Baseline Surface Radiation Network (BSRN) and the Global Energy Balance Archive (GEBA, Wild et al. 2017 ESSD). I will give an overview over recent research aiming at constraining surface radiative fluxes and their representation in climate models, both in terms of their absolute magnitudes as well as their decadal changes, based on the information contained in the surface observations. Advances have been achieved with the establishment of clear-sky flux climatologies from surface radiation records with sufficiently high temporal resolution (minutes up to daily) to allow for the differentiation between cloudy and cloud-free periods. The clear-sky flux climatologies are shown to be of use to constrain the surface fluxes under cloud-free conditions, which may serve as a base state to infer the magnitude of cloud radiative effects not only at the Top of Atmosphere, but also within the atmosphere and at the Earth's surface. The clear-sky fluxes further allow the differentiation between trends in radiative fluxes under cloudy and cloud-free conditions. A prerequisite is thereby that the underlying records are homogeneous, as shown for long-term solar radiation records from China and Italy. Assessments of trends in surface radiation under both all-sky and clear-sky conditions may be able to provide a better understanding of the underlying causes of the substantial decadal variations and thereby a better estimation of its future evolution.

Regional Surface Energy Budget Derived from Satellite Observations *(Seiji Kato, Fred G. Rose, David A. Rutan, Norman G. Loeb, and John T. Fasullo)*: The regional surface energy budget consists of net downward shortwave and longwave radiative fluxes, surface turbulent heat fluxes (latent and sensible heat), and internal energy flux associated with water mass transfer. The sum of these components provides the energy input to the oceans. However, when these flux components are inferred from satellite observations, there is an imbalance of 10 to 15 Wm-2 in the global annual mean net surface energy flux (downward positive), which is more than an order-of-magnitude larger than the Earth energy imbalance. As a result, satellite-derived regional surface energy balance has significant uncertainty. The aim of this analysis is to identify the causes of the surface energy budget residual by examining the regional distribution of the surface energy balance and by using surface observations to quantify the uncertainty in the radiative components. We use satellite products produced by the Clouds and the Earth's Radiant Energy System (CERES) for surface radiation, Global Precipitation Climatology Project (GPCP) for precipitation, SeaFlux for turbulent fluxes, and ERA-Interim for energy divergence in the atmosphere. We show that the annual global mean ocean surface energy balance residual computed with these data sets is substantially larger than the annual mean water mass balance residual at the global ocean surface. While surface net radiative flux is used to calculate the surface energy balance, it is not used in the computation of the mass balance. The regional surface energy balance residual indicates that the largest contribution to the global energy balance residual occurs over the tropical oceans. The bias in monthly mean downward shortwave and longwave radiative flux over ocean is, respectively, 4.7 Wm-2 and 1.0 Wm-2 compared with radiative flux measured at 46 buoys that are predominately located in tropics. We estimate the uncertainty in the annual global mean surface net radiative flux over ocean to be 8.6 Wm-2 with an assumption that errors in shortwave and longwave upward and downward radiative fluxes are uncorrelated, which gives an upper bound of the 1-sigma uncertainty. These results suggest that the surface energy balance residual over ocean cannot entirely be explained by a bias in surface radiative flux. Uncertainties in the surface turbulent fluxes likely contribute substantially to the excessive surface energy budget residual.

Synthesis and evaluation of historical meridional heat transport from midlatitudes towards the Arctic *(Yang Liu, Jisk Attema, Wilco Hazeleger)*: Meridional Energy Transport (MET), both in the atmosphere (AMET) and ocean (OMET), has significant impact on the sea ice in the Arctic. We quantify the AMET & OMET from six reanalysis datasets and investigate their relations with sea ice variation at annual to interannual scales. The results indicate that, although the mean transports in all datasets agree well, the spatial distribution and temporal variation of AMET & OMET deviate substantially. This leads to a large difference in the low frequency variability of AMET

& OMET in subpolar regions. Only after 2010, the low frequency signals from ocean reanalysis products agree well. A comparison with the observation from RAPID ARRAY and a high resolution NEMO ORCA hindcast suggests the overall trend captured by all the ocean reanalysis products converge well. For the atmosphere, the deviations between datasets mainly originate from temperature transport. Presumably, the assimilated observations are not sufficient to constrain the MET. A more detailed analysis of the linkages between the Arctic sea ice concentration (SIC) and AMET & OMET identifies a strong anticorrelation between AMET/OMET and SIC at the Greenland Sea and the Barents Sea. However, with respect to AMET-SIC relationships, there are large differences among the datasets. Only ERA-Interim data corroborates physical explanations hypothesized from climate models. With respect to the ocean data, ORAS4 and SODA3 agree well on the relation between OMET and SIC, while GLORYS2V3 differs from them. All the reanalysis products find strong links between AMET/OMET at subpolar latitudes and ENSO, which hints towards teleconnections between MET at high latitudes and climate variability at lower latitudes. As a result, our study suggests, since the reanalysis products are not designed for the quantification of energy transport, the AMET & OMET estimated from reanalysis should be used with great carefulness, especially when studying low frequency variability.

A Preliminary Comparison of Air-Sea Fluxes From Coupled Earth-System Reanalysis Against OceanSITES Mooring Data *(Maria Valdivieso, Magdalena Balmaseda, Michael Mayer, Steffen Tietsche, Hao Zuo)*: Surface meteorology and air-sea fluxes from recent ECMWF reanalyses are described and compared to high-quality flux measurements from OceanSITES moorings deployed by WHOI and NOAA PMEL. The ECMWF data used in the comparisons with the buoy data come from both coupled (CERA-SAT) and atmospheric-only (ERA5) ECMWF reanalysis models. None of these reanalysis products assimilates in situ flux measurements from the OceanSITES network, so this is an independent comparison. We have recently begun a preliminary comparison of the reanalysis fluxes with existing long-term flux observations from WHOI Ocean Reference Stations spanning 2000 to 2015 and present initial findings here. Flux differences are expected to arise from biases in surface meteorological variables and deficiencies in flux parameterizations or model physics, especially in regions poorly constrained by data assimilation in reanalyses. We will look to summarize what we can learn from these direct pointwise comparisons with OceanSITES and comment on the importance of evaluating global assimilation flux products to understand near-surface ocean and atmospheric processes and their representation in reanalysis models.

Coupled heat budget diagnostics using ECMWF's new reanalyses *(Michael Mayer, Steffen Tietsche, Magdalena A. Balmaseda, Hao Zuo, Leo Haimberger)*: The degree of consistency between the variability of energy storage (most notably ocean heat content) and energy fluxes through the climate system on both global and regional scales are an important quality indicator for reanalyses and other climate data sets. This contribution presents various aspects of the Earth's energy budget as evaluated from ECMWF's most recent reanalysis efforts, Ocean Re-Analysis System 5 (ORAS5) and ERA5, and will also touch upon recent advances in diagnostic methods. On a global scale, agreement of ocean heat content from ORAS5 with satellite-based net radiation at top-of-the atmosphere is much improved over its predecessor ORAS4 after 2005, when Argo coverage became quasi-global. Besides the improved observational coverage, the higher ocean model resolution (1/4 degree compared to 1 degree) is shown to be essential for this improvement. The good agreement on the global scale motivates "cage-studies" exploring regional energy budgets, as advocated by CONCEPT-HEAT. The Arctic Ocean is one of the few regions globally that are enclosed by moorings providing in-situ-based oceanic transport estimates. It thus lends itself for investigation of its regional heat budget, including ocean, atmosphere, and sea ice. Exploration of the annual cycle and residual of the Arctic heat budget using various independent data sets highlights the advances made in data consistency when compared to previous studies. However, remaining uncertainties in ocean heat content and sea ice volume data indicate the need for further improvements of the observing system and assimilation capabilities. The tropical Pacific is another focus region. The residual of its large-scale coupled atmosphere-ocean budget is sufficiently small to explore the energy cycle of single El Nino events, e.g. how much heat is released from the ocean and where it is transported subsequently. These diagnostics reveal the markedly different heat re-distribution during the 1997/98 and 2015/16 El Nino events and how this affected these events' evolution.

Sensitivity of the Energy Budget and Water Cycle to Global Climate Models' Resolution *(Benoît Vanniere, Marie-Estelle Demory, Reinhard Schiemann, Pier Luigi Vidale)*: Demory et al (2014) have demonstrated that the global water cycle is sensitive to global climate model (GCM)'s horizontal resolution, up to about 60 km, where the results converge. While ocean precipitation decreases with higher resolution, land precipitation increases due to higher moisture convergence over land. The contribution of moisture transport to land precipitation also increases, whereas moisture recycling, a quantity that is known to be overestimated by state-of-the-art GCMs, tends to decrease. One question that came out of this study is whether such mechanisms are model dependent. The seven GCMs involved in the EU Horizon 2020 project PRIMAVERA, spanning a range of atmospheric resolutions from 200 km to 20 km, offers an unprecedented opportunity to look at the systematic sensitivity of the global energy budget and hydrological cycle to resolution. Our results show that: (1) there is no asymptotic convergence of the components of the energy budget and water cycle with increasing resolution; (2) models simulate an increase of global precipitation and evaporation with increasing resolution (up to 5% over the range of resolutions investigated); (3) in all models, there is an increase of moisture transport to land when resolution increases, but the increase in grid-point models (>10%) is more than twice that of spectral models; (4) at the global scale, the increase of moisture transport is balanced by an increase of orographic precipitation (which amount is larger in grid-point models with better resolved orography); (5) at the regional scale, several systematic improvements are found which can be linked to a better simulated seasonal mean circulation. Those results might bring valuable information for future estimation of the the global energy budget and water cycle. In particular, they support the recent values of surface evaporation estimated by Stephens et al. (2012) and land precipitation and moisture transport to land estimated by Rodell et al. (2015), which are all larger than previously thought.

SESSION 3: Earth energy imbalance evaluation and budget closure for climate models and reanalyses

Earth's Energy Imbalance, SST Patterns, and Natural Variability *(Cristian Proistosescu, Kyle Armour, Robert Jnglin Wills, David S. Battisti, Yue Dong, Malte Stuecker)*: Earth's Energy Imbalance, SST Patterns and Natural Variability Joint observations of surface temperature and the Earth's energy imbalance allow for a unique opportunity to empirically constrain Earth's net radiative feedback. This net feedback quantifies how much more energy is radiated to space for a given change in near-surface air temperature, thus controlling how much the Earth needs to warms in order to balance an external radiative forcing. Present day observations of the Earth's net radiative imbalance yield a strongly negative radiative feedback, or, equivalently, a very low climate sensitivity, particularly due to a strong negative short-wave cloud feedback. Here we show that this negative radiative feedback can be linked to the peculiar pattern of recent sea-surface temperature (SST) anomalies. Indeed, we find that an atmospheric model (CAM5) forced with observed SSTs yields a net feedback up to three times more negative than that from the same period (2000-2016) in freely-evolving coupled ocean—atmosphere model simulations that employ the same atmospheric physics (CESM1). Consequentially, the model's true equilibrium climate sensitivity is up to three times larger than would be inferred under given recent SST anomalies. We also compare radiative feedbacks generated by the observed pattern of SSTs to those within the CESM1 large ensemble over the same period. The large ensemble produces a wide range of feedbacks due to internal variability alone. Yet, global radiative feedbacks (cloud feedbacks in particular) generated by observed warming patterns are far outside this range of CESM1 natural variability. We identify the West Pacific as the region where the discrepancy between observed and modeled historical SST anomalies is most important for the discrepancy in the global net radiative feedback. Finally, we discuss whether the recent pattern of SSTs and cloud feedbacks is due to a particularly extreme phase of natural variability, or whether the coupled model is simply unable to reproduce the transient response to greenhouse gases.

Inverse modelling of the Earth's energy and water budgets using EO and reanalysis data *(Chris Thomas, Bo Dong, Keith Haines, Chunlei Liu, Davi Mignac, Richard Allan)*: We present an inverse analysis of the global energy and water budgets, extending the range of solutions based on the NASA NEWS studies of L'Ecuyer et al. (2015) and Rodell et al. (2015). We have introduced two innovations in our study. The original NEWS analysis does not account for energy exchanges between the ocean basins. We use both atmospheric and oceanic reanalyses to introduce weak constraints on the inter-basin exchange fluxes for heat (and freshwater) into the inverse analysis.

The results remain consistent with the EO flux products but show considerably more realistic ocean surface flux distributions. We contrast the surface fluxes in these combined solutions with those obtained using atmospheric reanalyses and Top of Atmosphere energy fluxes alone. We also look at the impact of accounting for enthalpy transports (Mayer et al 2017) in atmospheric energy transports. We show that, despite being less well assessed, ocean reanalyses sometimes provide better constraints on regional energy and freshwater budgets than atmospheric reanalyses, especially in confined regions such as the Arctic. We also discuss the NEWS inverse model under non-diagonal spatial error covariances for individual flux components of the EO data products. These may produce inverse analyses quite similar to those obtained when using reanalysis convergences. We develop some fingerprinting diagnostics to show the impact of different constraints on the regional and seasonal flux adjustments. This suggests that more work is needed, particularly to assess different components of error in EO derived flux products.

Constraining the Global Ocean Heat Content Through Assimilation of CERES-Derived TOA Energy Imbalance Estimates *(Chunxue Yang, Andrea Storto and Simona Masina)*: The Earth's energy imbalance (EEI) is stored in the oceans for the most part. Thus, estimates of its variability can be ingested in ocean retrospective analyses to constrain the global ocean heat budget. Here, we propose a scheme to assimilate top of the atmosphere global radiation imbalance estimates from Clouds and the Earth's Radiant Energy System (CERES) in a coarse-resolution variational ocean reanalysis system (2000–2014). Data are ingested through introducing an additional term in the variational cost function that penalizes against the global EEI estimates. The methodology proves able to shape the heat content tendencies according to the EEI estimates, without compromising the reanalysis accuracy. Spurious variability and underestimation (overestimation) present in experiments with in situ (no) data assimilation disappear when EEI data are assimilated. The warming hiatus present without the assimilation of EEI data is mitigated, inducing ocean warming at depths below 1,500 m and slightly larger in the Southern Hemisphere, in accordance with recent studies. Furthermore, the methodology will be discussed as a promising tool for future applications in the context of Earth's System reanalyses and climate simulations to realistically constrain the global energy budget.

The Impact of Uncertainties in Radiative Forcing on the Earth's Energy Imbalance *(Brian Soden, Ryan Kramer, Daniel Feldman, Bill Collins)*: Radiative forcing is a fundamental quantity for understanding both anthropogenic and natural changes in climate. It measures the extent that human activities and natural events perturb the flow of energy into and out of the climate system. This perturbation initiates all other changes of the climate in response to external forcings. While several methods exist to estimate the effective radiative forcing (ERF) from idealized climate model simulations, the calculation of the instantaneous radiative forcing (IRF) is rarely computed explicitly. The intermodel spread in effective radiative forcing is widely documented and accepted to be a substantial contributor to intermodel differences in their projections of historical and future climate change. Here we argue that much of the intermodel spread in ERF arises from differences in IRF. This applies for both well mixed greenhouses gases (WMGG) as well as aerosols. In particular, inconsistencies in the calculation of radiative forcing by CO2 introduce unnecessary uncertainties in model projections of climate change. This problem has persisted for more than two decades despite well publicized studies documenting this issue. For WMGG, the spread in model calculations of radiative forcing does not represent an uncertainty in radiative transfer theory, but rather the failure to implement that theory consistently in radiative transfer parameterizations. This introduces unnecessary noise into the model experiments that is difficult to remove, and while the users of these models are largely unaware of this ongoing problem, the unsatisfactory implementation of forcing propagates needlessly onto efforts to reduce uncertainty in projections of future climate change. The explicit calculation of radiative forcing and a careful vetting of radiative transfer parameterizations provide a straightforward means of significantly improving these projections.

On the definitions of 'heat' and 'work' in the atmosphere and ocean *(Remi Tailleux)*: Concepts such as poleward 'heat' transport, ocean 'heat' uptake, variability in ocean 'heat' content, etc... all require an operational definition of what one means by 'heat'. In practice, oceanographers and atmospheric scientists have resorted to quantities such as potential temperature, Conservative Temperature or moist static energy to evaluate 'heat' in the ocean and atmosphere. A conceptual problem with such quantities, however, is that they are all functions of state, that is, functions that only depend on the state of the system but not on its history. But one of the most fundamental teaching of thermodynamics is that 'heat' and 'work' must depend on the particular thermodynamic path followed, and hence that neither can be a function of state. In this talk, the problem of how one should theoretically define the concepts of 'heat' and 'work' in the ocean and atmosphere will be revisited from the viewpoint of the local theory of available potential energy. Such a theory allows one to partition a locally defined extended form of potential energy, the sum of the standard potential energy plus that of the environment, into an available component (the work) and a background component (the heat). Because such a partitioning depends on the introduction of reference states associated with notional states at rest and in thermodynamic equilibrium, the proposed definitions of 'heat' and 'work' satisfy the requirement of not being functions of state. In addition, the proposed new definition of 'heat' is showed to come in different flavors that are physically distinct, such as the dead internal energy and exergies. It is argued that current definitions of heat actually reflect the dead internal energy component of the new definition of heat, but not its exergy subcomponents. Here, the exergy components of heat are positive definite quantities that are leading order are proportional to the temperature and salinity variances in the ocean, and to the variances of temperature and humidity in the atmosphere. In general, the exergies are much smaller than the dead internal energy component. All components, however, can a priori equally contribute to the variability in ocean and atmospheric heat content.

Assessment of the Earth Energy Budget within the CMIP5 Ensemble: Preliminary Results *(Francisco José Cuesta-Valero, Almudena García-García, Hugo Beltrami, Joel Finnis)*: The energy imbalance at top-of-atmosphere over the last century has caused an accumulation of energy within the ocean, the continental subsurface, the atmosphere and the cryosphere. Although 93% of the energy gained by the climate system has been stored in the ocean, other components of the Earth's energy budget cannot be neglected because of associated climate feedback processes dependent on heat, such as soil carbon and permafrost stability. Here, we explore the ability of thirty General Circulation Models (GCMs) from the Fifth phase of the Coupled Model Intercomparison Project (CMIP5) to simulate the distribution of heat within the Earth's energy reservoirs along their Historical simulations. The CMIP5 GCM simulations show net gains of heat in all subsystems during the second half of the 20th century in agreement with observations, although with large variability among model results. Ensemble averages of the simulated energy proportion in the continental subsurface and the atmosphere agree with observations, while the ensemble averages and observations disagree on the energy proportion within the ocean and the cryosphere. The representation of land ice within these GCM simulations probably leads to this disagreement. Additionally, the land surface model depth limits the energy proportion stored in the subsurface and appears to influence the distribution of heat among the other climate subsystems, although further work is needed to confirm these results.

Ocean heat balance in ocean reanalyses from ECMWF *(Eric de Boisseson, Michael Mayer)*: The ocean heat content evolution is analyzed in a set of ocean and coupled atmosphere-ocean reanalyses produced at ECMWF. ORA-S4 and S5 are operational ocean reanalyses forced by ERA-Interim used to provide initial conditions for extended range forecasts. They are produced at a 1 degree and 1/4 degree resolution, respectively. ORA-20C is a 20th century ocean reanalysis assimilating only temperature and salinity profiles and forced by ERA-20C. CERA-20C and CERA-SAT are two coupled ocean-atmosphere reanalysis covering the whole 20th century and the satellite era, respectively. While all reanalysis products provide consistent evolution of the global ocean heat content in the recent decades, their respective ocean heat balances are noticeably different. This presentation will display results on the sensitivity of the ocean heat budgets to the coupling, atmospheric forcing, bulk formulation, resolution and observing system in the various ocean reanalyses. The reliability of ocean heat budgets and potential ways to improve them will also be discussed.