WCRP workshop
"The Earth's Energy Imbalance and its implications"
13 – 16 November 2018, Toulouse, France

Sponsors:

ABSTRACT BOOK - POSTER

SESSION 1: Global estimates of Earth's Energy Imbalance

Larger than expected ground heat flux storage *(Pierre Gentine, Edouard Davin, Sonia I. Seneviratne)*: We here show using direct observation of ground heat flux that the estimates of heat storage over land regions might have been underestimated. To do so we use globally available ground heat flux plate observations, which given an estimated 0.2 W/m2 long-term heat flux, much higher than typical estimates based on too shallow models or long-term boreholes. Those estimates are complemented by new boreholes estimates, which seem to agree fairly well. We conclude that continental heat storage might have been underestimated but more data observations are needed to give a better estimate of the magnitude.

Preliminary global energy budget calculations with ERA5 data *(Johannes Mayer, Michael Mayer)*: Long-term trends, the interannual and decadal variability of sea level in the Tropical Atlantic and along the Cameroonian coast, have been studied over the period 1993–2016. This region has a sparse and few dense networks of tide gauges, and non-frequent hydrographic measurements in the surrounding area. We have focused on the few documented coastal areas east of 8° E and 5°N including Bioko Island and Inter Cameroon-Bioko corridor (ICBC). Sea level rise variability in this region has been few evaluated. Monthly data of Sea Surface Height Anomaly (SSHA) at 0.25˚X0.25˚ computed from merged data by Archiving, Validation, and Interpretation of Satellite Oceanographic data (AVISO) is available at https://www.aviso.altimetry.fr/en/my-aviso.html. This data is derived using up-to-date datasets with up to four satellites at a given time, from Jason-2/Jason- 1/Envisat/Topex/Poseidon/GFO. We have used AVISO monthly SSHA data for the period 1993 to 2016 in this study. In the open ocean surface, geostrophic currents are caused by the variability of sea surface elevation. We have extensively studied the decadal and interannual variability and find out that the Sea Level Pressure and winds stress are tightly correlated to the Sea Level Anomaly with a predominant peak from JJA during the predominance of the Equatorial upwelling and the onset of the West

African Monsoon. A strong coastal upwelling has been identified along the northern part of the Gulf of Guinea with a delay of 15 days after the Equatorial upwelling onset accompanying with a deep slope of the SLA. This fits with the theory of longshore wind forcing along the eastern boundary of the Tropical Atlantic specifically along the Cameroonian coastline causing coastally trapped waves to propagate over thousands of kilometers along the continental slope. According to these findings, we have found out that the removal of known variability helps us to characterize more accurately the estimation of the linear trends and have highlighted possible fluctuations due to some possible anthropogenic climate change in the Gulf of Guinea. Local authorities need to know as early as possible how much Sea Level Rise is likely to be expected over the next decades in order to prevent coastal flooding and establish coastal planning and safety management.

Towards essential climate variables (ECVs) assessment in the frame work of Copernicus climate service *(Chunxue Yang, Rosalia Santoleri, Salvatore Marullo, Vincenzo Artale, Bruno Buongiorno Nardelli)*: Integrated and systematic evaluation and cross-comparison of multiple climate dataset is a crucial task in order to foster the routinely use of Earth's system reanalyses for climate monitoring, from one hand, and be able to combine remotely sensed and in-situ observing networks, from the other. Among the most important metrics to evaluate the signature of the recent global warming, the study of the Earth's energy imbalance requires the integrated assessment of several model- and observation- based datasets. In the framework of the Copernicus Climate Change Service (C3S), the dedicated project "Quality assessment of Essential Climate Variables (ECVs)" (C3S_511) aims to assess ECVs derived from observations and reanalyses. Individual variables such as, SST, SSS, and wind will be assessed based on the Global Climate Observing System (GCOS) target requirements. Furthermore, taking the global earth system as a whole, we will assess the global energy fluxes and associated uncertainties by using multiple ECVs. This strategy will provide us an overall assessment of the earth system as seen by multiple and merged climate datasets in terms of the earth energy budget. Further to presenting the project, preliminary results for the energy imbalance based on reanalyses and observations will be shown in the workshop.

Global Warming, New Energy Balance, New Atmospheric Circulation and Extreme Meteorological Phenomena *(Mohammed Said Karrouk)*: Cumulating ocean-atmospheric thermal energy caused by global warming has resulted in the reversal of the energy balance towards the poles. This situation is characterized by a new ocean-continental thermal distribution: over the ocean, the balance is more in excess than in the mainland, if not the opposite when the balance is negative inland. Thanks to satellite observation and daily monitoring of meteorological conditions for more than ten years, we have observed that the positive balance has shifted more towards the poles, mainly in the northern hemisphere. Subtropical anticyclones are strengthened and have extended to high latitudes, especially over the Atlantic and Pacific oceans. This situation creates global peaks strengthened in winter periods, and imposes on cosmic cold the deep advection toward the south under the form of planetary valleys "Polar Vortex". This situation imposes on the jet stream a pronounced ripple and installs a meridional atmospheric circulation in winter, which brings the warm tropical air masses to reach the Arctic Circle, and cold polar air masses to reach North Africa and Florida. This situation creates unusual atmospheric events, characterized by hydrothermal "extreme" conditions: excessive heat at high latitudes, accompanied by heavy rains and floods, as well as cold at low latitudes and the appearance of snow in the Sahara! The populations are profoundly influenced by the new phenomena. The socioeconomic infrastructures can no longer assume their basic functions and man when unprotected is weak and hence the advanced vulnerability of all the regions especially those belonging to poor and developing countries This is why climate sciences must deal nowadays with short term prediction of phenomena: weekly, monthly, or seasonly a bit more advanced than meteorology (72 hours) but less advanced than climate models (50-100 years) to allow the policy makers enough time to intervene efficiently in order to protect the populations from extreme meteorological phenomena and to benefit from the opportunities of the new meteorological conditions These are the characteristics of "New Meteorological Events" resulting from the "New Atmospheric Circulation", caused by the "New planetary Climate" consequence of "Global Warming". It is the new global challenge.

Updated global surface energy flux estimation and evaluation *(Chun Lei Liu, Richard Allan)*: Based on the procedures of Liu et al. (2015, 2017) and considering the enthalpy fluxes associated with precipitation and evaporation (Mayer et al. 2017), the global net surface energy flux is updated using a combination of satellite-derived radiative fluxes at the top of atmosphere (Allan et al. 2014) adjusted using the latest estimation of the net heat uptake of the Earth system, and the atmospheric energy tendencies and transports from the ERA-Interim (Berrisford et al. 2011) and ERA5 reanalyses. Comparisons of the estimations show that the derived turbulent flux is basically consistent with that of OAFLUX, but the agreement with buoy observations is better. The inferred global and Atlantic meridional heat transports show good consistency with observations, particularly the inferred mean transport of 1.24PW at 26oN of North Atlantic over 2004~2013 is much close to the RAPID observation of 1.23PW, due to the treatment of the excess land surface flux redistribution to the oceans (Liu et al. 2015, 2017). Allan et al. (2014), Geophys. Res. Lett., 41, 5588–5597, doi:10.1002/2014GL060962. Berrisford et al. (2011), Q. J. R. Meteorol. Soc., 137, 1381–1399. Liu et al. (2015), J. Geophys. Res., Atmospheres. ISSN 2169-8996 doi: 10.1002/2015JD023264. Liu et al. (2017), J. Geophys. Res. Atmos., 122, doi:10.1002/2017JD026616. Mayer et al. (2017), J. Climate, Vol 30, 9225-9246, doi: 10.1175/JCLI-D-17-0137.1

Determine the Daytime Earth Radiation Budget from DSCOVR *(Wenying Su, L. Liang, D. P. Duda, K. Khlopenkov, M. K. Thiemann, P. Minnis)*: The Deep Space Climate Observatory (DSCOVR) platform provides a unique perspective for remote sensing of the Earth. With the National Institute of Standards and Technology Advanced Radiometer (NISTAR) and the Earth Polychromatic Imaging Camera (EPIC) onboard, it provides full-disk measurements of the broadband shortwave and total radiances reaching the Earth-Sun Lagrange-1 (L-1) position. Because the satellite orbits around the L1 spot, it continuously observes a nearly full Earth, providing the potential to determine the daytime radiation budget of the globe at the top of the atmosphere. The NISTAR is a single-pixel instrument that measures the broadband radiance from the entire sunlit side of the Earth, while EPIC is a spectral imager with channels in the ultraviolet and visible ranges. The Level 1 NISTAR shortwave radiances are filtered radiances. To determine the daytime TOA shortwave and longwave radiative fluxes, the NISTAR measured shortwave radiances must be unfiltered first. We will describe the algorithm used to un-filter the shortwave radiances. These unfiltered NISTAR radiances are then converted to the full disk shortwave and daytime longwave fluxes, by accounting for the anisotropic characteristics of the Earth-reflected and emitted radiances. These anisotropy factors are determined by using the scene identifications determined from multiple low Earth orbit and geostationary satellites matched into the EPIC field of view. Comparison of the fluxes from NISTAR with those from CERES synoptic product indicates that the NISTAR SW fluxes are about 12% larger than those from CERES, and the NISTAR LW fluxes are about 6% larger than those from CERES. The narrowband EPIC radiances are converted to broadband radiances using the narrowband-to-broadband regression relationships developed from collocated MODIS and CERES data. These EPIC broadband radiances are then used to derive EPIC SW fluxes using the same methodology as for NISTAR. The agreement between the EPIC SW fluxes and the CERES SW fluxes are within 2%.

Observational ocean heat content changes: progresses and limitations *(Lijing Cheng, Gongjie Wang)*: Ocean heat content (OHC) is the key measure of planetary energy imbalance (EEI), for example, ocean stores >90% of the extra-heat related to global warming. Here I will review the major progress in estimating ocean heat content change based on in situ observations since IPCC-AR5, and then analyze the capabilities of current ocean observation system in estimating EEI on different scales based on synthetic ocean observations. Since AR5, efforts were devolved to understand the instrumental error in ocean observations. Now we have better accounted for systemic errors in measurements from XBTs. At the same time, it was identified that many traditional gap-filling strategies may introduce a conservative bias toward low magnitude changes. Some methods suffer less by this error, using those OHC estimates show highly consistent changes since the late 1950s. And the new/updated estimates show more rapid warming than the estimates featured in the IPCC-AR5. Moreover, recent OHC estimates show warming quite similar to the average of CMIP5 models over the past 50 years. To understand and quantify the error in OHC estimate related to irregular/incomplete data coverage, which is the major source of error in observational OHC estimate, we used an ocean reanalysis as one "truth" of the past ocean, constructed a synthetic observation dataset by re-sampling the ocean from the reanalysis according to spatial-temporal locations of in situ ocean observations. Based on this synthetic data, we calculated OHC based on available gap-filling method and compared the reconstruction with the reanalysis (as "truth"), by which we could quantify the capabilities of the current observation system in estimating OHC and its rate. I will show that on global scale, the error in the reconstruction on the rate of OHC reduces from ~0.7 W/m2 to ~0.4 W/m2 after 2005, revealing the improvement by Argo. Locally, larger uncertainty persists in the west boundary currents and Antarctic Circumpolar Current (ACC) regions (~100 W/m2) on quasi-annual scales.

Sea level change since 2005: importance of salinity *(William Llovel, Sarah Purkey, Benoit Meyssignac, Nicolas Kolodziejczyk, A. Blazquez and J. Bamber)*: Sea level rise is one of the most important consequences of the actual global warming. Since 1993 (over the satellite altimetry era) global mean sea level has been rising at rate faster than previous decades. This rise is expected to accelerate over the coming decades and century. At global scale, sea level rise is caused by a combination of freshwater increase from land ice melting and land water changes (mass component) and ocean warming (thermal expansion). Estimating the causes is of great interest not only to understand past sea level changes but also to validate projections based on climate models. In this study, we investigate the global mass contribution to recent sea level changes with an alternative approach based on the freshwater budget of the ocean. We estimate the global ocean freshening from unprecedented amount of salinity measurements from Argo floats for the past decade (2005-2015) and correct it for the freshwater input from sea ice melt estimated. From this, we deduce the freshwater input into the ocean from land. We compare our results to the ocean mass inferred by GRACE data and based on a sea level budget approach. Our results bring new constrains on the global water cycle (ocean freshening) as well as on the global ocean mass directly inferred from GRACE data.

An alternative view on Earth Energy Imbalance *(Miklos Zagoni)*: Analyzing annual global mean energy budget estimates from different sources, a peculiar feature can be realized: all the internal flux components (shortwave, longwave and non-radiative) can be expressed as integer multiples of a unit flux, both for clear-sky and all-sky conditions: F = N x UNIT. The deviation of the observed values from their prescribed 'lattice' (integer multiple) position is less than the acknowledged top-of-atmosphere (TOA) flux uncertainty (4.2 Wm-2). We recognize this structure in several independent sources such as: the 18-year long CERES EBAF data sets [1]; a modeling approach based on direct surface observations [2]; an estimate utilizing global energy and water cycle assessments [3]; and an earlier update on Earth's energy balance [4]. These studies exhibit distributions where the unit flux is connected to the accepted value of outgoing longwave radiation as UNIT = OLR(all-sky)/9 and, in turn, equals to the value of longwave cloud radiative effect (UNIT = LWCRE). A clear-sky radiative transfer computation [5] extends the small integer ratios to the non-observable flux elements such as atmospheric upward LW emission and window radiation. — The consistency between the observed flux values and their integer multiple position is the best in some of the clear-sky solar fluxes (within 0.3 Wm-2); this gives confidence to the magnitude of the unit flux (defining the difference of the clear-sky and all-sky OLR); which, in turn, leads to an excellent accuracy in the absolute value of the essential flux component of atmospheric LW cooling (its CERES value and the integer position differ only 0.2 Wm-2). Deviation is the largest in the clear-sky surface downward longwave radiation (6 Wm-2), still within the one-sigma range. — This poster displays the integer ratios projected at the above-listed data sets; the numbers in the found integer systems are not arbitrary but show reasonable structure: they describe meaningful energetic relationships between the TOA and surface fluxes. Confidence in the revealed system is enhanced further by deducing the structure from a simple geometric model (shown elsewhere [6]), which might serve as a possible theoretical explanation of the physical basis [7]. — If the 'atomic' structure that expresses itself in the 18-year long global mean data set is not a (very unlikely) characteristic of these two decades only but represents a permanent feature of Earth's physical reality, energy imbalance at the surface should be understood as a natural or forced long-term fluctuation (vibration) around the system's ground state rather than a systematic deviation from the integer position. This would make possible to hindcasting and forecasting the magnitudes of the fluxes in the energy budget as a function of the available energy.

SESSION 2: Regional Energy Budgets and Energy Transports

Towards consistent diagnostics of the coupled atmosphere and ocean energy budgets *(Michael Mayer, Leopold Haimberger, John M. Edwards, Patrick Hyder)*: The widely used diagnostic vertically integrated total energy budget equations of atmosphere and ocean contain inconsistencies that should no longer be disregarded. The neglect of enthalpy fluxes associated with precipitation and evaporation leads to a spurious dependence on reference temperature. This seemingly small inconsistency is amplified because enthalpy of water vapor implicitly included in lateral atmospheric energy transports usually is computed on Kelvin scale, leading to inconsistencies which, though zero when globally averaged, attain values on the order of 20Wm-2 in the tropics. A more consistent energy budget framework is presented, which is independent of reference temperature and takes full account of enthalpy fluxes associated with mass transfer through the surface. The latter include effects of snowfall and additional non-latent contributions, which have a net cooling effect on the Earth's surface (-1.3Wm-2). Using the energy budget formulation presented here, instead of that commonly used, yields enhanced self-consistency of diagnosed atmospheric energy budgets. It is also shown that fields of net surface energy flux inferred as a residual from satellite-based radiative fluxes and the divergence of lateral atmospheric energy transports are structurally biased when using the commonly used budget formulation. Using the improved budget formulation removes this bias and brings fields of inferred net surface energy fluxes into much better agreement with those from independent surface flux products. Results imply that previous estimates of radiative plus turbulent surface fluxes over the ocean, balancing the observed ocean warming, are biased low by ~1.3Wm-2. Moreover, previous studies seriously underestimated cross-equatorial atmospheric and oceanic energy transports. Overall, the presented framework allows for unambiguous coupled energy budget diagnostics and yields more reliable benchmark values for validation purposes.

Exploring the Atlantic/Pacific heat uptake contrast using a GCM with idealised geometry *(Peter Shatwell, David Ferreira, Arnaud Czaja)*: As the world continues to warm, the vast majority of the excess heat energy is taken up by the oceans (Stocker et al., 2013). Across models and observations, heat is taken up more rapidly in the Atlantic than in the Pacific, and is stored to greater depths (Chen and Tung, 2014; Durack et al., 2014; Frölicher et al., 2015). It is thought that this contrast in heat uptake is largely due to differences in the mean circulations of the two basins, and, notably, to the presence of a meridional overturning circulation in the Atlantic (AMOC) (e.g. Kostov et al. 2014). This study aims to better understand this Atlantic/Pacific asymmetry in heat uptake. To this end, we employ a coupled atmosphere-ocean-ice model in a CO2-doubling experiment. The model set-up has an idealised geometry that splits the northern hemisphere ocean up into a small basin and a large basin. The small and large basins exhibit distinctive Atlantic and Pacific-like characteristics, with the small basin being warmer and saltier, and supporting a deep overturning circulation akin to the AMOC. In this idealised model, the small basin is much more efficient at taking up heat than the large basin, a behaviour similar to that found between the Atlantic and Pacific in more complex models and in observations. Over a period of 150 years, while the two basins' upper ocean warming responses are similar, the anomalous temperature signal penetrates almost the full depth of the small basin, but only reaches mid-depth in the large basin. The temperature signal structures are also very different, with heat being taken up much more rapidly in the small basin once the signal reaches ~1/4 depth. The change in heat content (J/m^2) at depth (below ~500 m) in the small basin is almost double that in the large basin. To explain these different basin heat uptakes (rate, vertical structure, etc.), we attempt to decouple the wind-driven circulation (present in both basins) from the meridional overturning circulation (present only in the small basin). We will use the theory of Rhines and Young (1982b) to predict a depth of the wind-driven circulation, and thus a depth at which the two basin heat uptake vertical structures diverge. References: Stocker, T. ed., 2014. Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press. Chen, X. and Tung, K.K., 2014. Varying planetary heat sink led to global-warming slowdown and acceleration. Science, 345(6199), pp.897-903. Durack, P.J., Gleckler, P.J., Landerer, F.W. and Taylor, K.E., 2014. Quantifying underestimates of long-term upper-ocean warming. Nature Climate Change, 4(11), p.999. Frölicher, T.L., Sarmiento, J.L., Paynter, D.J., Dunne, J.P., Krasting, J.P. and Winton, M., 2015. Dominance of the Southern Ocean in anthropogenic carbon and heat uptake in CMIP5 models. Journal of Climate, 28(2), pp.862-886. Kostov, Y., Armour, K.C. and Marshall, J., 2014. Impact of the Atlantic meridional overturning circulation on ocean heat storage and transient climate change. Geophysical Research Letters, 41(6), pp.2108-2116. Ferreira, D., Marshall, J. and Campin, J.M., 2010. Localization of deep water formation: Role of atmospheric moisture transport and geometrical constraints on ocean circulation. Journal of Climate, 23(6), pp.1456-1476. Rhines, P.B. and Young, W.R., 1982. A theory of the wind-driven circulation. I. Mid-ocean gyres. J. Mar. Res, 40(3), pp.559-596.

Global ocean heat content redistribution during the 1998-2012 Interdecadal Pacific Oscillation negative phase *(Guillaume Gastineau, Andrew R. Friedman, Myriam Khodri, Jérôme Vialard)*: Previous studies have linked the slowdown in global surface temperature warming since 2000 to a negative Interdecadal Pacific Oscillation (IPO) phase. Here, we investigate the changes in ocean heat content (OHC) during this period. We compare two ensembles of coupled model experiments with either zero or observed prescribed tropical Pacific wind stress interannual anomalies. This successfully constrains the global surface temperature, sea level pressure and OHC patterns associated with the IPO phase transition around 1998. The negative IPO phase (1998 to 2012) is associated with a global ocean heat redistribution. The anomalously cold tropical Pacific Ocean leads to an increased oceanic uptake in this region, and a global OHC increase of 4x1022 J. The cold equatorial Pacific also forces mid-latitude wind changes through atmospheric teleconnections, leading to an enhanced wind-driven heat transport convergence at 40°N and 40°S. Enhanced Pacific easterlies also yield an enhanced heat transport to the Indian Ocean via the Indonesian throughflow. As a result, the anomalous Pacific heat uptake is entirely exported towards the North Pacific (~50%), Indian (~30%) and Southern (~20%) Oceans. A significant fraction of this heat is released back to the atmosphere in the North Pacific and Indian basins, and transported across 31°S in the Indian Ocean. Overall, OHC increases most in the Southern Ocean (~60% of global changes) and northern Pacific (~40%), with negligible changes in the Indian and Atlantic basins. These results point to the major importance of oceanic circulation in re-distributing the Pacific heat uptake globally during negative IPO phases.

Surface Energy Budget and Monsoon Precipitation over North East India(NEI) *(Pramod Kumar, A.P.Dimri)*: The recent years of climate change and its absolute impact over North East India (NEI) is an effect of surface and atmospheric energy budget imbalance. As the sun is a source of whole energy mechanism. In the present scenario, the precipitation over the NEI decreased possibly due to continuous temperature rise. That keeps the surface sensible and latent heat imbalance distribution and vice~versa. As the latent heat and sensible heat is controlled by soil water content (e.g. evaporation, evapotranspiration and convection). The present study shows a small increasing near surface temperature trend in the interval of 1951-1985, but a strong increase in the interval of 1986-2015. That influences the precipitation trend. However, the precipitation trend during the first interval is significant increased, while in the second interval is decreased with 95% significant over most of the region. IMD, CRU and ERAIN gridded data sets are used for the current experiment. As the surface net solar and thermal radiation change is an equilibrium of the surface sensible and latent heat to sustain the energy budget. And a small change in surface net radiation causes an imbalance of surface energetics.

Evaluation of estimated incoming solar radiation in central parts of Iran using RegCM4 *(Yazdanpanah Hojjatollah, Mehran Heidary Benni)*: The amount of energy received from the sun on the ground needed to estimate crop water use, use of clean energy and issues related to climatic factors. In this study, the ability of two estimation methods based on statistical and dynamic methods were evaluated. Angstrom equation, as a widely accepted statistical model, and Regional Climate Model (RegCM version 4.0) were chosen to obtain radiation estimations. To perform this study, meteorological data of 6 IRIMO's automatic weather stations located in Chaharmahal and Bakhtiari province, west of Iran, were used. RegCM4 model was run considering initial values and boundary conditions of NNRP1 ,at 18 sigmoid levels, with spatial resolution of 30 km and temporal resolution of 150 minutes, in the period of 2010 to 2014. Results showed the RegCM4 model output has the minimum Root mean square error (RMSE) of 10 W m -2 in warm months (June to September) and highest RMSE of 408 W m -2 in February. The lowest RMSE was obtained in September in Borujen station and the highest value was recorded in month of February in Ardal. The average value of overall RMSE in the region was 175 W m -2 . Monthly values of Angstrom model was calibrated for study stations. The highest correlation coefficient and lowest RMSE and MBE were obtained for September. The maximum value of RMS was 321 W m -2 in April. Angstrom model showed an underestimation in 73% of the cases while RegCM showed an overestimation 93 % of the cases. These results tend to confirm the need for post-processing of the climate model outputs. Keywords: Solar radiat

Seasonal Changes in Outgoing Longwave Radiation over Arctic as Depicted by AIRS, CERES, MERRA-2, and TOVS *(Jae N. Lee)*: We compare the temporal and spatial characteristics of monthly mean level-3 anomaly time series of Outgoing Longwave Radiation (OLR) contained in the AIRS Version-6 with those in the CERES Edition 4 and MERRA-2 data sets over the 15 year period 2002-2017. Fifteen year global mean OLR trends of AIRS and CERES data sets show slightly positive trends. However, the increases of Arctic OLR and clear sky OLR over Barents-Kara Seas and Canadian Archipelago during last decade are noteworthy. The trends over Barents-Kara Seas are larger than 0.4W/m2/yr. The clear sky OLR changes more rapidly with surface warming up to 0.8 W/m2/yr, since it is more sensitive to surface skin temperature than the OLR. AIRS and CERES OLR time series agree extremely well in this aspect. Analogous results are shown with regard to the MERRA-2 OLR data set. Some aspects of the MERRA-2 OLR data set perform reasonably well. The recent arctic OLR changes from AIRS and CERES are compared with those from TOVS observation over the 25 year period 1978-2002. Recent increase of OLR is more than twice of those shown with TOVS. In both AIRS and TOVS periods, OLR shows significant increase during winter and fall seasons. There exists a big difference between two periods in spring OLR trends. The positive spring season OLR trend is not appeared in TOVS period, while the increase of OLR is significant during last decade.

Interannual Oscillations and Meridional Progression of Arctic Summertime TOA Fluxes *(Wu Dong, Jae N. Lee)*: Arctic albedo in the summer months (June-August) is subject to large year-to-year variability from the regional warming, as perennial sea ice and snow cover continue to decrease. In this paper we report coherent oscillatory features of the summer Arctic and subarctic top-of-atmosphere (TOA) fluxes, at interannual scales, as observed by Clouds and the Earth's Radiant Energy System (CERES) since 2000. The monthly CERES TOA flux data are analysed by simply removing the multi-year means, to highlight their fluctuations as a function of time and latitude. The summer fluxes oscillate strongly with a period of ~4 years since 2009 with clear equatorward progression at 60°N-85°N latitudes. The interannual oscillations in the summer total TOA flux are dominated by the shortwave (SW) flux, consistent independent albedo observations from the Multiangle Imaging SprectroRadiometer (MISR) instrument. The SW and total TOA flux time series are further decomposed into poleward and equatorward components, in which the equatorward component contributes approximately two third of the variance. A further empirical orthogonal function (EOF) analysis helps to identify two Arctic regions, Beaufort Sea and Queen Elizabeth Islands (BS-QEI) and the Barents-Kara Sea (BKS), which are strongly associated with the observed interannual oscillations due to vulnerability in spring snow cover and summer sea ice extent. The excessive and deficient Arctic TOA energy fluctuations have profound impacts on mid-latitude weather and climate at intra-seasonal and interannual scales.

Narrowing Ocean Latent Heat Flux Uncertainties: Perspectives from Reanalysis and Satellite Estimates *(Franklin Robertson, Jason B. Roberts, Michael G. Bosilovich)*: Latent heat flux (LHF) is a major component of the net surface energy exchange governing ocean heat content and storage rate. The broad contours of LHF distributions with energy loss to the atmosphere over subtropical bands and western boundary currents are well known but accuracies of regional patterns, global means, and modes of variability sufficient to aid in quantifying ocean heat storage remain elusive. In this work we bring together a range of reanalysis products and latest retrievals from satellites to quantify current best estimates of climatological values, weather regime dependent biases and variability on interannual to decadal scales. Atmospheric reanalysis estimates suffer from assimilating model physics uncertainties along with changes in constraining observations. The latter interact with model biases to induce spurious regional to global trends and are prevalent in ERA-Interim, MERRA-2 and JRA-55 reanalyses. Experiments with reduced observational input avoid this by assimilating either surface pressure (NOAA 20th Century Reanalysis), additional marine wind data (CERA-20C), or all conventional data except satellites (JRA-55C). The question remains, then, how much realism in water and energy cycle processes is retained in these data sets. We critically evaluate the differences across this spectrum of products at monthly, 1.0 degree lat / lon resolution. Depending on availability of pre-2008 data, some comparison to ERA-5 will also be provided. Satellite retrievals relying predominantly on passive and active microwave retrievals of near surface meteorology to drive bulk aerodynamic calculations offer key insights via their comparisons to corresponding estimates from ocean buoy and ship data. However satellite inter-calibration, lack of direct sensitivity to near-surface moisture, and ambiguities in surface wind stress / wind speed relationships have hampered accuracy. Here we examine products from the latest J-

OFURO3, SeaFlux, HOAPS4, and IFREMER algorithm revisions. Our analysis of all these estimates considers both climatological and interannual to decadal variations. By stratifying near surface moisture (qa) according to various parameters (SST, column water vapor, and mean atmospheric temperature) weather regime dependencies in satellite retrievals are identified. The various LHF estimates are also partitioned according to ascending and descending regions over the tropical band to clarify the different trends in these regimes. A first order Taylor Series expansion of the bulk aerodynamic quantities around monthly climatological values is used to understand the role of wind speed, humidity and SST constraints on both reanalysis and satellite data. Together, these metrics help explain differences in behavior among the data sets and the impact on trends and variability associated with recent swings in Pacific Decadal Variability. Results are summarized as current best estimates of LHF and uncertainty over the 1988-near present period.

Sensitivity of the arctic sea ice to and its impact on the regional energy budget *(Wieslaw Maslowski)*: Oceanic heat content (OHC) is the primary contributor to the Earth Energy Imbalance, which is considered one of the most fundamental metrics defining the status of global climate change. Some of the largest sources of uncertainty in OHC estimates are associated with polar and shelf regions and marginal seas. The Arctic Ocean, while it occupies a relatively small area of the Earth's surface, it's a polar region consisting of a large fraction of shelves (~40%) and marginal seas, which control its exchanges with the lower latitude oceans, including northward oceanic heat convergence. In addition, the Arctic sea ice cover modulates the surface radiation budgets and it is an important factor in a number of feedback loops affecting the evolution of Arctic climate and its OHC. Thus, the combined changes in Arctic-wide energy imbalance are exemplified through polar amplification and are of relative importance to the global energy imbalance and climate change. We use the Regional Arctic System Model (RASM) to investigate and quantify some of the key uncertainties of the Arctic surface energy budget, including the oceanic forcing of the Arctic sea ice and the potential role of its ongoing decline in the regional and global energy imbalance. RASM is a fully coupled limited-domain ice-ocean-atmosphere-land model developed to better understand the linkages and coupling channels within the Arctic System at a process scale and to improve prediction of its change at a spectrum of timescales. Its domain is pan-Arctic, with the atmosphere and land components configured on a 50-km grid. The ocean and sea ice components are configured on rotated sphere meshes with four configuration options: 1/12o (~9.3km) or 1/48o (~2.4km) in the horizontal space and with 45 or 60 vertical layers. The main objective of this study is to quantify the oceanic fluxes in and out from the Arctic Ocean in order to understand their sensitivity to model spatial configurations and varying parameter space as well as their impacts on the sea ice cover and regional surface energy budget. Our results imply significant variability of the total oceanic heat convergence into the central Arctic Ocean subject to different model configurations. We find that the range of
uncertainty in the net oceanic heat transport is comparable to the amount of extra energy required to melt almost all the Arctic sea ice in summer. We argue that basin-wide changes in the sea ice cover contribute substantially to the regional energy imbalance, via the dramatic reduction of surface albedo and accumulation of heat in the upper ocean due to insolation.

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

Separating the influence of anthropogenic aerosol and greenhouse gas forcing on the transport and storage of anomalous heat in the climate system *(Damien Irving, Susan Wijffels, John Church)*: The two major components of anthropogenic forcing are greenhouse gas (GHG) and anthropogenic aerosol (AA) emissions. While the climatic influence of these two factors tend to be in opposition (GHGs warm while AAs cool), that opposition is not uniform in space and time. The distribution of GHGs is meridionally symmetric and has experienced a monotonic and slowly accelerating rise, whereas AA concentrations are highest in the northern mid-latitudes and accelerated sharply from 1950–1980, before leveling off due to pollution regulations. In order to better understand how GHG and AA forcing has influenced the transport and storage of anomalous heat over the industrial era, we analyse an ensemble of ten CMIP5 models that archived relevant data for the historical (all natural and anthropogenic forcing), historicalGHG (GHG forcing-only) and historicalAA (AA forcing-only) experiments. On a hemispheric scale, we find that over the duration of the historical experiment (1861-2005) the accumulated heat flux anomaly at the top of the atmosphere (netTOA), accumulated heat flux anomaly at the ocean surface (ocean heat uptake; OHU) and the change in ocean heat content (OHC) are all higher in the Southern Hemisphere (SH). Northward heat transport in the atmosphere and ocean acts to reduce the netTOA interhemispheric gradient, but it is not entirely eliminated. While it would be logical to assume that the historical change in OHC is higher in the SH because the accumulated surface heat flux is higher, the single forcing experiments reveal that this is not the case. The historical interhemispheric difference in netTOA and OHU is entirely attributable to AAs, and yet in the historicalAA experiment there is little interhemispheric difference in OHC (i.e. ocean heat transport eliminates the OHU gradient). Instead, the interhemispheric gradient in OHC is attributable to GHG forcing. Data from the historicalGHG experiment shows an interhemispheric OHC gradient that is slightly larger than for the historical experiment (because warming is slightly stronger in the historicalGHG experiment), despite a negligible interhemispheric gradient in OHU. We are currently working to understand the mechanisms behind these findings, in addition to exploring intra-hemispheric changes in zonally integrated netTOA, OHU and OHC and the vertical structure of the latter.

Impact of surface spectral emissivity and longwave cloud scattering on global and regional energy budgets *(Xianglei Huang, Xiuhong Chen, Yi-Hsuan Chen, Ping Yang, Chia-Pang Kuo, Mark Flanner)*: This study examines two factors that are usually ignored in the modeling of radiation budget, namely surface spectral emissivity and longwave scattering of ice clouds. Both off-line radiative calculation and online full climate model simulations are used in the study. The surface is usually assumed to be blackbody or graybody in the calculation of upward longwave flux entering the atmosphere, while in reality its emissivity can be less than one and can vary with frequency. Surface radiative skin temperature and surface emissivity are coupled quantities. Our off-line radiative transfer calculation showed that ignoring the spectral variation of surface emissivity can lead to an overestimation of global-mean OLR by 0.9 Wm-2 for the all-sky and 1.5 Wm-2 for the clear-sky. The local overestimation can be as large as 10 Wm-2 over the desert regions. Using one year of cloud profiles from A-Train combined observations and reanalysis profiles of temperature and humidities, we also evaluated the impact caused by ignoring ice cloud scattering in the LW, which can lead to 2.6Wm-2 overestimation of global-mean OLR and a 1.2 Wm-2 underestimation for global-mean surface downward LW flux. When surface spectral emissivity and cloud LW scattering are incorporated into the CESM, the impact on simulated TOA and surface energy imbalances is negligible. When surface emissivity is included, it leads to increases of globe-mean downward and upward LW flux at the surface and, which is then largely compensated by a change of 1Wm-2 in latent heat flux. When surface emissivity and cloud LW scattering are both included, it leads to comparable changes (~1Wm-2) in the global-mean downward LW flux, downward SW flux, and upward LW flux, which is compensating by changes in both latent and sensible heat fluxes. The impact on simulated climate will be also discussed.

Detection and attribution of anthropogenic signals in the ocean heat content *(Katarzyna B. Tokarska, Gabriele C. Hegerl, Andrew P. Schurer, Aurélien Ribes, Andrew R. Friedman, John Fasullo)*: More than 90% of the energy reaching the earth's surface is stored in the oceans. While previous studies have shown that some of the observed changes in the ocean heat content are detectable, the attribution of these changes to individual forcings (e.g. greenhouse-gas forcing only, or natural forcing only) have not been quantified yet in a formal detection and attribution framework. Using comprehensive earth system models from the from the Fifth Coupled Climate Model Intercomparison Project (CMIP5), we investigate volume-averaged temperature and ocean heat content at different depths and in various basins, to study spatio-temporal signals due to different forcings in the global ocean heat storage for the historical period. This is followed by applying regularized optimal fingerprinting detection and attribution techniques, to investigate the contribution of natural and forced components of the heat stored in the ocean, and attempt to quantify how much of the ocean warming can be attributed to anthropogenic forcing alone.

Earth Outgoing Radiation Viewed from a Moon-based Platform *(Hanlin Ye, Huadong Guo, Guang Liu)*: Equipping sensors on the lunar surface have the advantages of holistic and continuous Earth observations that can meet the needs of Earth system science. The Earth radiation budget is one of the most important issues in Earth system science study. Also, it is the suitable scientific goal of the Moon-based Earth radiation due to the holistic view and global measures. In this paper, a new simulation study is established for the Earth outgoing radiation observation from the Moon-based platform and performs a one-to-one mapping method based on the geometric relationship. We use the NASA's Goddard Earth Observing System Version 5 data as the truth. Two-year periods Earth outgoing radiation data captured by the Moon-based platform are simulated. The temporal resolution of observing the outgoing longwave, shortwave, and total radiation on potential Moon-based Earth observation is assessed by sampling the simulated data. It is found that different possible starting points and temporal resolution have the uncertainty by computing means over daily, orbital periodic, and annual intervals. The criterion is measured by comparing mean values and standard derivations of the subsampled time series data. Besides, on the basis of the periodicity of the subsampled time series, four interpolation methods are introduced and compared. Results show that the higher sampling frequency has more information and less uncertainty. The suitable observation starting time in one day is 1:00 or 2:00 UTC. The temporal resolution less than 4 hours leads to significant error that can't be ignored in the Earth radiation balance study.

Decadal and multi decadal climate variability in Pacific and Atlantic regions (*Rohit Srivastava*): Influence on Southwest Indian Monsoon: The southwest or Indian summer (June-September) monsoon provides about 80% of annual rainfall. Empirical studies suggested that the Pacific Decadal Oscillation (PDO), the tropical Atlantic sea-surface temperature (SST) gradient (TAG) variability, and the Atlantic Multidecadal Oscillation (AMO) are associated with southwest Indian monsoon rainfall variability. Effects of these decadal-multidecadal climate variabilities (DCV) phenomena can manifest themselves on the southwest Indian monsoon via their modulation of Walker and Hadley Circulations, and atmospheric Rossby waves. In the present study, the predictability of these phenomena and their relation with southwest Indian monsoon are investigated in different models of Coupled Model Intercomparison Project Phase 5 (CMIP5). India Meteorological Department (IMD) gridded 1-degree rainfall data are utilized in the analysis. The spatial map of temporal correlation between rainfall anomaly and DCV indices are estimated during 1961–2007. The composite rainfall anomaly for positive and negative phases of DCV are estimated. The composite rainfall anomaly over most of the Indian region for negative PDO are positive and vice-versa, suggesting that during the negative PDO phase the rainfall over most of the Indian region was increased, while during positive phase rainfall decreased. However, eastern and south-western Indian regions showed the opposite behavior. The detailed results obtained will be presented and discussed.

Surprising relationship between sensible and latent air-sea turbulent heat fluxes in CMIP5 (and other) climate model simulations *(Sergey Gulev, Ilia Serykh, Natalia Tilinina, Wonsun Park, Mojib Latif)*: Surface turbulent heat fluxes are critically important for diagnostics of the climate model experiments. However, being relatively well assessed and validated in reanalyses, surface turbulent heat fluxes always were of a lesser attention in diagnostics of climate model experiments. We analyze long-term variability of sensible and latent heat fluxes in reanalyses, buoy data and in the ensemble of CMIP5 simulations (control, historical, RCP) with a focus on the consistency of changes in sensible and latent fluxes on different time scales. Generally, sensible and latent surface turbulent heat fluxes at ocean surface computed using modern bulk parameterizations should be well correlated on most time scales. This holds in reanalyses and the other observational data sets. However, we find that many models (e.g. ECHAM, GFDL, IPSL, INM) surprisingly demonstrate large regions with significantly negative correlations between sensible and latent heat fluxes. Remarkably, this holds on both interdecadal to centennial scales and on interannual scale. Interestingly, variability in air temperature and surface humidity (which could be potentially considered as the reason for anti-correlation between sensible and latent fluxes) demonstrates consistency with each other at most scales. In search of potential reasons for the discovered phenomenon we considered frequency of coupling in climate models (for which special simulations with KCM were performed) as well as other factors.

Assessing energy and water budgets in climate models *(Paul J. Durack, Ronald J. Stouffer, Matt D. Palmer, Steve Derbyshire, John P. Krasting)*: The global ocean is the largest energy reservoir in the Earth system, and is responsible for 9/10ths of the observed heat uptake. While the bulk of additional heat is now found in the ocean, and this result can be replicated across observations and models, accurate assessment of the energy and freshwater budgets for any one climate model simulation is challenging. The issue can be highlighted by enumerating the heat and freshwater storage mechanisms captured by modern climate models. A key example is frozen soil. Melting or freezing of the soil considerably influences the heat storage estimate, and may lead to net top of the atmosphere budget imbalances. Glacier and land-ice melt is another mechanism that needs to be carefully considered, and extreme snow depth changes in single grid cells can also lead to issues for closing heat and freshwater budgets. In addition to these, heat loss through physical mechanisms such as high altitude (model top) wind damping can also confound simple budget closures. This presentation will provide case studies and highlight issues that must be considered when attempting to close heat and freshwater budgets for any one simulation. We note that in coupled models, budget closure often requires a consistent assessment of variables across model realms (e.g. atmosphere, ocean, sea-ice, land-ice and land), and this can confound the reliability and usefulness of simplistic budgets that do not consider cross-realm heat and water transports. Finally, it must be noted that some models or components do not conserve heat or water or other tracers. Most models found in the CMIP databases do a good job of closing energy budgets, however most will have small "leaks". For example, no atmospheric component to date keeps track of water temperature in the atmosphere. This can lead to small heat transport errors at some latitudes (order of ¼ of a W/m**2).

A new diagnostic tool for water, energy and entropy budgets in climate models *(Valerio Lembo, Valerio Lucarini, Frank Lunkeit)*: We here show using direct observation of ground heat flux that the estimates of heat storage over land regions might have been underestimated. To do so we use globally available ground heat flux plate observations, which given an estimated 0.2 W/m2 long-term heat flux, much higher than typical estimates based on too shallow models or long-term boreholes. Those estimates are complemented by new boreholes estimates, which seem to agree fairly well. We conclude that continental heat storage might have been underestimated but more data observations are needed to give a better estimate of the magnitude.