Scoping document for the GCOS Joint Panels Meeting:
The Global Energy Budget.

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The GCOS-IP 2016 produced targets based on closing the cycles of water, carbon and energy with associated uncertainty targets on annual time scales. According to the current status of science, and international collaborations on this topic, it is proposed to approach the observational targets for Earth's energy budget through two topics, i.e. Earth's Energy Imbalance and the surface energy budget. The aim of this proposal is to review the accuracy requirements for Earth energy budget based on different elements of the global climate observing system. It is important to emphasize that the uncertainties and proposed targets presented here are related only to the global budget. At regional and local scales, larger uncertainties would apply and are more difficult to quantify.

Comment [1]: I wonder if there
should be some flexibility here on the
timescales?

Comment [2]: this is what had bee
given from GCOS-IP, not from us, ar
strongly agree that this should go fro
seasonal to longer - and is already
reflected in my "other proposed targe
at least for the EEi', see table 1

1. Global observations for Earth's Energy Imbalance

Comment [3]: if you think it is more
appropriate, you could also change
order, start with the surface budget, a
then the imbalance (i.e. the budget
closure).

All energy entering or leaving the climate system does so in the form of radiation at the top of Earth's atmosphere. The difference between incoming solar radiation and outgoing radiation, which is the sum of the reflected shortwave radiation and emitted longwave radiation, determines the net radiative flux at the top-of-atmosphere (TOA). Radiative forcing of the climate system from increased greenhouse gas emissions has brought about a persistent imbalance in these radiative fluxes, leading to a net accumulation of energy in the Earth System; and is referred to as Earth's Energy Imbalance (EEI).. Observing net radiative flux at TOA is thus fundamental in determining the status of climate change at a global scale. At annual and longer time scales, the EEI can be reliably estimated through changes in ocean heat content, since the ocean dominates the planetary energy inventory at these timescales (Loeb et al., 2012; Palmer and McNeall, 2014; Johnson et al., 2016). However, a more comprehensive view and improved closure of Earth's energy budget requires estimates of changes in the other inventory components: land surface; atmosphere and cryosphere (e.g. Rhein et al, 2013)

1.1 Background

Additional targets are proposed for the EEI and are drawn from joint international scientific efforts. The EEI at TOA, and the inventory of EEI illustrated in Fig. 1. Proposed GCOS target observing EEI is given in Box 1. The CLIVAR research focus CONCEPT-HEAT (Consistency between planetary heat balance and ocean heat storage, http://www.clivar.org/research-foci/heat-budget, not active anymore) has worked with the wider international research community to provided recommendations for uncertainty targets based on monitoring of EEI l(ox 1; von Schuckmann et al., 2016). The rationale for this recommendation of additional targets is given in Appendix 1. The different approaches to estimate the EEI, current estimate accuracy and limitations are summarized in Table 1.

Box 1: The Earth Energy Imbalance

Target from GCOS IP	**Balance energy budget to within 0.1 Wm^{-2} on annual timescales**
Other proposed targets (see appendix 1)	**Quantify changes in the Earth Energy Imbalance with an accuracy of < 0.1 Wm^{-2} on multiannual-to-decadal time scales, and with an accuracy of < 0.5 Wm^{-2} on subannual-to-interannual timescales** **Quantify changes in heat stored in the Earth system on multiannual-to-decadal time scales with an accuracy of < 0.1 Wm^{-2} for ocean, land, cryosphere and atmosphere (expressed relative to Earth's surface area)**
Who	**Operators of GCOS-related systems, including data centres**
Time frame	**Ongoing**
Performance indicator	**Regular assessment of uncertainties in estimated changes and inventories**

Comment [4]: I think this is an apsirational target?

Comment [5]: this is coming from gcos, and not from us. the point as i understand this here is to discuss th targets given from gcos, and to see how and if they should be revised. th you have the next column where I propose other targets, those we hav published in the EEI paper

Observational approach	Related ECV	Climate observing system type	Challenge	Current achieved accuracy
Net radiative flux ~~radiation~~ at the top of the atmosphere	Earth radiation budget	Remote sensing	Achieve required accuracy for the absolute value; Need of inventory approach to "anchor" flux measurement (mitigate against sensor drifts)	Estimated random errors on CERES on annual means are reported to be +/- 0.1 Wm-2 (one standard error~~deviation~~;. Loeb et al, 2012; Johnson et al, 2016; Palmer, 2017). Uncertainties on monthly estimates estimated as : 0.3 Wm–2 with a sensor stability

				of better than 0.5 W m-2 per decade (Loeb et al., 2009; Palmer, 2017)
Inventory (ocean, atmosphere, land and cryosphere) of heat stored in the Earth system	Ocean: Subsurface temperature Atmosphere: air temperature Land: soil moisture / continental heating Cryosphere: sea ice volume, ice sheet mass; glacier mass changes	In situ Remote sensing (Reanalyses)	Achieve required accuracy; In situ data sampling gaps for monitoring, validation and assimilation	Ocean: > 0.3 W/m2 prior 2005 (0-700m); < 0.3 W/m2 after 2005 (0-2000m, During the Argo era uncertainties on annual 0-2000m OHC values estimated as 0.5 Wm-2 and 0.1 Wm-2 at decadal timescales (one standard error; Johnson et al, 2016; Palmer, 207). Abraham et al., 2013) Atmosphere: ? Land: ? Land + Cryosphere: 0.01 Wm-2 (Rhein et al. 2013)

Comment [6]: This is my understanding. I think we need input from Seiji or Norm to make sure we have our interpretation of the CERES uncertainties correct.

Comment [7]: I'm not sure what va to assign prior to Argo. Since GCOS foward-looking it may be fine to start from the Argo/CERES era anyway?

Comment [8]: we need an expert t add numbers - i will also go and have go in AR5

Table 1: *Overview on approaches, challenges and current achieved accuracy to estimate the absolute value and changes over time of the EEI. Although the ocean heat storage is used in literature as an approximate for the EEI inventory approach, the full inventory is proposed to be discussed here.*

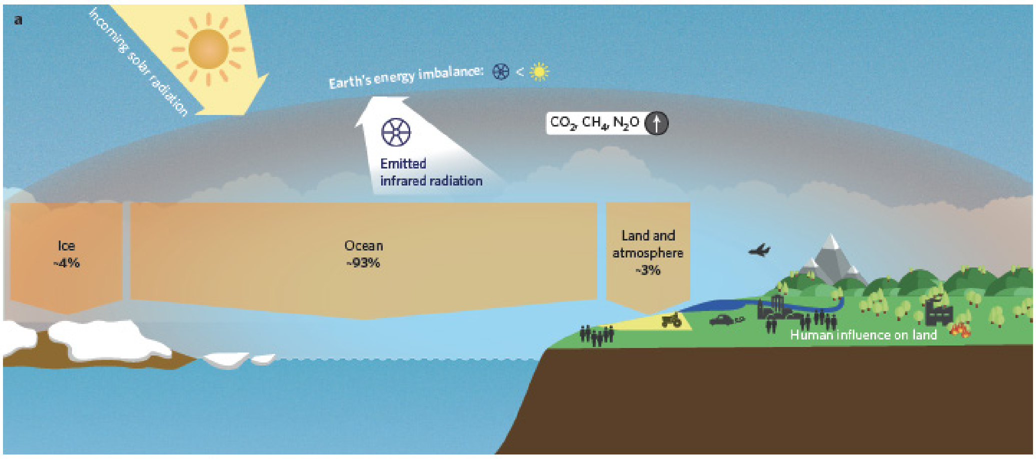

Figure 1: *Schematic representations of the flow and storage of energy in the Earth's climate system for the Earth energy imbalance as a result of human activities. The global ocean is the major heat reservoir, with about 90% of EEI stored there on decadal and longer. The rest goes into warming the land and atmosphere, as well as melting ice (as indicated). After von Schuckmann et al., 2016.*

1.2 Core ECVs

Earth radiation budget	Ocean: Subsurface temperature	Atmosphere:	Land:	Cryosphere:

- Earth radiation budget: The most direct approach in monitoring variations in EEI is through satellite instruments orbiting Earth that observe the incoming and reflected solar and emitted thermal radiation in broad spectral regions spanning the ultraviolet to the far-infrared parts of the electromagnetic spectrum (Loeb et al., 2012a, Wielicki et al.,1996). The EEI is a small residual of the TOA radiative flux components that are two orders of magnitude greater. As a result, it is extremely challenging to achieve the required 0.1Wm–2 absolute accuracy in EEI from satellite observations. Absolute calibration uncertainty (given as 1σ) alone is 0.13 W m–2 for incident solar radiation (Kopp and Lean, 2011), 1 W m–2 for reflected solar radiation and 1.5 Wm–2 for emitted thermal radiation (Loeb et al., 2009). In addition, there are other sources of error associated with the conversion of measured radiances to fluxes (0.2 W m–2) (Loeb et al., 2007), time sampling uncertainties (0.2 Wm–2) (Loeb et al., 2009, Doelling et al., 2013) and uncertainty in assuming a 20 km reference level (0.1 W m–2) (Loeb et al., 2002). Nevertheless, satellite observations are the most useful means to track variations in EEI over a range of space- and timescales. This is because most uncertainties are systematic, so although the absolute value is uncertain, its variations can be determined to within 0.3 W m–2 per decade (Loeb et al., 2009). TOA radiative fluxes derived from a combination of geostationary and sun-synchronous satellite instruments (Doelling et al., 2013) can be tracked from hourly to decadal timescales, and from to within 1° on regional to global spatial scales. Currently, the longest running continuous global TOA record is from the NASA Clouds and the Earth's Radiant Energy System (CERES, Loeb et al., 2009), which started providing usable data in March 2000.

Comment [9]: I believe our main focus here should be discussing the interannual (and potentially sub-annu accuracies? We can use OHC chang on decadal timescales to "anchor" th time series? Johnson et al (2016) qu 0.1 Wm-2 at decadal timescales from OHC estimates (this may be optimist guess?)

Comment [10]: I do not understand your point in this context. that is what said: the absolute value is uncertain, but the change over time is quite wel described

Table 2: ECV related Earth Radiation Budget product requirements

ECV	Components	Spatial resolution (km)	Temporal resolution		Accuracy (Wm^{-2})	Stability (Wm^{-2} $decade^{-1}$)		
			Averaging time	Sampling time		SW	LW	net
Earth radiation budget (TOA irradiance)	Solar irradiance	-	1 Month	daily	1.5 (0.8)	0.3 (0.1)	-	-
	Global means		1 Month	3 (1) hours	1.0 (0.5)	0.1*	0.07*	0.12*
	Zonal means		1 Month	3 (1) hours	2.0 (1.0)	0.5 (0.2)	0.3 (0.1)	-

	Regional mean	250 (100)	1 Month (plus daily variance)	3 (1) hours	5.0 (2.0)	0.5 (0.3)	0.5 (0.3)	-
			1 day		10.0 (5.0)			
	Mean diurnal cycle	250 (100)		3 (1) hours	5.0 (2.0)	-	-	-
	Synoptic scale	250 (100)	No averaging	At or interpolated to synoptic hours	10.0 (3.0)	-	-	-

Values are extracted from NOAA Technical Report NESDIS 134(available from *ftp://ftp.library.noaa.gov/noaa_documents.lib/NESDIS/TR.../TR_NESDIS_134.pdf)*

- Subsurface ocean temperature: To obtain estimates of the ocean heat sink, the volume integral of subsurface temperature multiplied by seawater density and the specific heat capacity is evaluated at each given depth layer (units: Joules). The traditional approach to estimating OHC from ocean temperature profiles based on uneven spatio-temporal coverage involves gridding the available observations and interpolating across data gaps using a statistical mapping method (Abraham et al, 2013). The choice of climatology, the type and resolution of the grid, vertical interpolation, bias corrections, and the mapping method all contribute to the uncertainty in OHC estimate (Boyer et al., 2016). This is in particular the case for the historical in situ ocean observing system, and the uncertainty is considerable reduced during the Argo era from 2005 onwards (Riser et al., 2016; Wjiffels et al., 2016). Estimates of OHC from space can be also obtained from the sea level budget approach (Chambers et al., 2016), but still suffer from large uncertainties (Lowell et al., 2014).

- Atmosphere: Still under discussions, but suggestion (M. Palmer): The energy inventory completed for IPCC AR5 Box 3.1 used the following data for computing atmospheric heat content changes: http://www.remss.com/missions/amsu/
- Land: Still under discussions, but suggestion (M. Palmer): Suggest we look up the reference quoted as part of IPCC AR5 WG1 Chapter 3 Box 3.1. My understanding is that borehole measurements are a key element?
- Cryosphere: Still under discussions, but suggestion (M. Palmer): there are a number of data streams that must be brought together to estimates different cryopshere components. For Arctic Sea Ice Volume, there is PIOMAS: http://psc.apl.uw.edu/research/projects/arctic-sea-ice-volume-anomaly/. For ice sheet mass changes, there is the IMBIE data set: http://imbie.org/about-the-project/imbie/. A number of Glacier mass change estimates are presented in Marzeion et al (2017): https://link.springer.com/article/10.1007/s10712-016-9394-y

1.3 **Key questions** to start addressing (list is non exhaustive)

1) How can we improve the absolute value of the EEI estimate, and which are the major observing system recommendations?
2) What practical steps can be undertaken to perform/update the inventory of the EEI in the Earth system, and to obtain observing system recommendations from this approach?
3) How can we improve the understanding and estimate of the implications of a positive and changing EEI?
3) Are the existing ECV requirements adequate? Do they capture the scales needed?
4) Can we formulate recommendations for improved data availability, or novel observation techniques?
5) What practical steps can be undertaken/recommended in the short term?
6) Are the existing ECV requirements adequate? Do they capture the scales needed?
4) Can we formulate recommendations for improved data availability, or novel observation techniques?
5) Next steps?

1.4 Framing discussion session

Integration, how do the disparate observations of the ECVs in the Earth system come together.

a. Discuss practical steps to be undertaken to advance on the key questions
b. Diverse variables and target scales. Are they comparable/interoperable?
c. Measurement approaches and accuracies (inc. satellite, in situ). Can we formulate recommendations for improved data availability, or novel observation techniques?
d. Make a list of priority data sets and next steps that need to be acquired to achieve the overall GCOS goal.

1.5 Next steps

a. Recommend analyses, assessments or intercomparisons (engaging WCRP, etc, see for example Fig. 5)
b. Opportunities (e.g new technologies, process studies (engaging WCRP, etc)
c. Next steps. (e.g. workshops, task team).

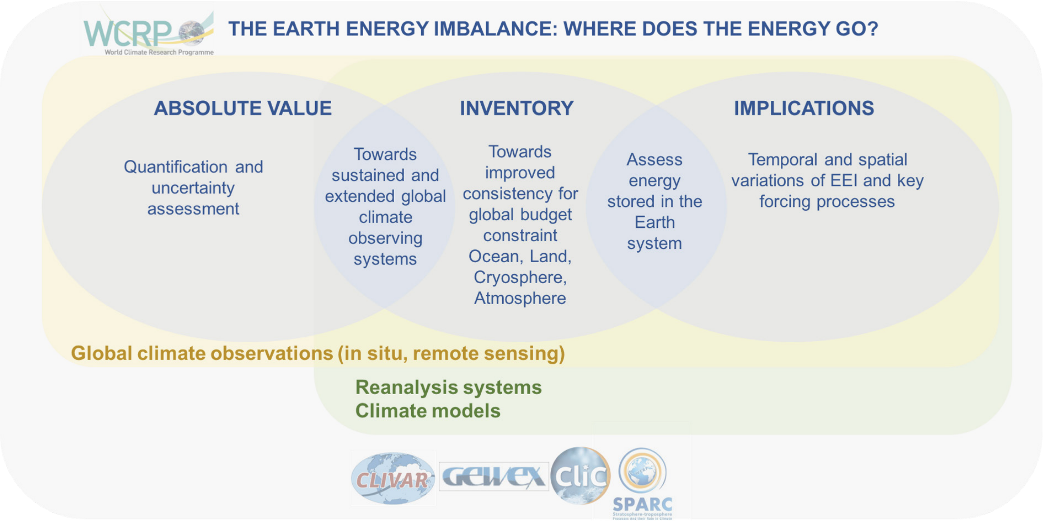

Figure 5: Synthesis of outcomes of the WCRP workshop "The Earth's Energy Imbalance and its implications", and synergy community proposal to WCRP on the topic "The Earth energy imbalance: Where does the energy go?". Three main overarching goals had been identified, i.e. 1) to improve and quantify the absolute value of the EEI; 2) to perform an inventory of the EEI in the Earth system, predominantly for the ocean, land, cryosphere and atmosphere; 3) to further understand and quantify the implications of a positive and changing EEI for societal benefit. These goals span the scientific topics of the four WCRP core-programs CLIVAR, GEWEX, CliC, SPARC and will have important implications for improvement of global climate observing systems, reanalysis systems and climate models.

2. Global observations for the Earth surface budget:

Spatial and temporal non-uniform distribution of absorbed solar radiation drives dynamics of and hydrological cycle within the climate system. Solar irradiance absorbed at the surface is converted to sensible and latent heat fluxes in addition to longwave irradiance emitted by the surface. The sum of these energy fluxes determine energy input to the surface. Estimates of these energy components are needed to understand regional surface energy budget. The sum of global annual mean net radiative flux (net shortwave plus net longwave fluxes), latent and sensible heat fluxes should match EEI. Therefore, the target accuracy of EEI by the surface budget approach is the same as the TOA budget approach discussed above. However, once these fluxes derived from observations are added, the net is about 10 to 15 Wm-2, depending on data products used for the computations. Surface budget is, therefore, primarily to understand regional surface energy budget. Although the approach does not resolve flux components, regional surface energy budget can be derived using TOA radiation budget and energy divergence and tendency in the atmosphere. Figure 2 illustrates surface energy budget residual.

Box 2: The Earth energy surface budget

Target from GCOS IP	**Balance energy budget to within 0.1 Wm-2 on annual timescales**
Other proposed targets (see appendix 2)	Upward longwave radiation: Outgoing solar radiation: Downward solar radiation: Upward solar radiation: Precipitation rate: Sensible heat flux: Latent heat flux:
Who	**Operators of GCOS-related systems, including data centres**
Time frame	**Ongoing**
Performance indicator	**Regular assessment of uncertainties in estimated changes and inventories**

Comment [11]: to fill in these information, the discussion during th workshop are needed - in particular how new/other propositions can be build up.

Comment [12]: Seiji, would it be possible to add proposed targets her for these components? @seiji.kato@nasa.gov _Assigned to Seiji Kato_

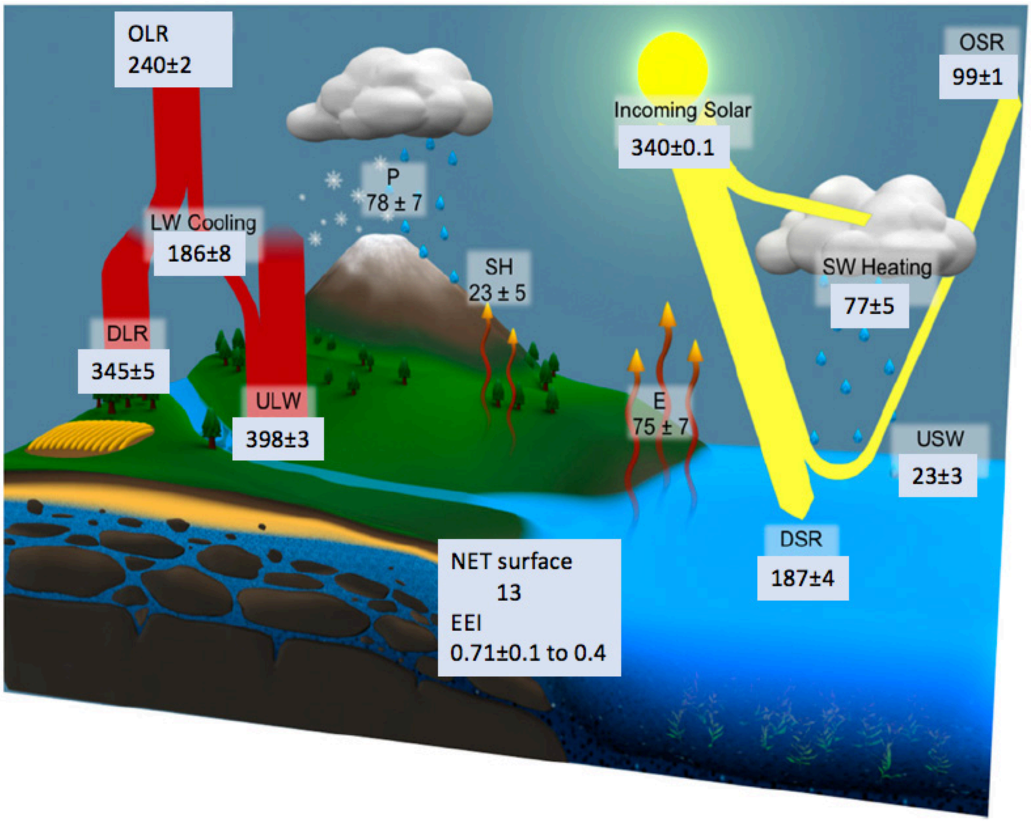

Figure 2: *Schematic diagram of the global mean energy balance of the Earth. This diagram illustrates a significant surface energy balance residual when satellite derived surface flux data products are used to estimate the budget. Flux values are in Wm-2. Note that longwave and shortwave fluxes are plotted over land and ocean regions, respectively, merely for convenience. Fluxs are, OLR: outgoing longwave radiation, DLR: downward longwave radiation, ULR: upward longwave radiation, OSR: outgoing solar radiation, DSR: downward solar radiation, USR: upward solar radiation, P: precipitation rate, SH: sensible heat flux, E: latent heat flux. (After L'Ecuyer et al. 2015, flux values are updated based on Loeb et al. 2018 and Kato et al. 2018).*

Current status of surface energy budget observations.

The annual global mean surface net shortwave and longwave irradiances estimated from satellite observations are 164 Wm^{-2}and -54 Wm^{-2}, which give the net surface irradiance of 110 Wm^{-2}(Kato et al. 2018). the uncertainty in the annual global net shortwave plus longwave irradiance is 10 Wm^{-2}(Kato et al. 2019). The annual and global sensible and latent heat fluxes and their uncertainties are, respectively, 23±5 Wm^{-2}and 75±7 Wm^{-2}(L'Ecuyer et al. 2015). The uncertainty in the sensible and latent heat fluxes appears to be smaller the uncertainty in the net surface irradiance. However, the uncertainty associated with bulk parameterization is not generally taken into account (Yu 2019). Estimating the uncertainty in sensible and latent heat fluxes over land is difficult because of their large temporal and spatial variabilities. The spread of these fluxes over land computed with 3 global data products is between 10% to 20% (L'Ecuyer et al. 2015).

2.2 Core ECVs

Table 2 lists requirements for Earth radiation budget data product requirements. Most values are extracted from NOAA technical report that is written based on outcome of the workshop on continuity of Earth radiation budget observations. Data products for different spatial scales are needed to support a wide range of climate research. Only requirements for global and regional spatial scales are listed in Table 2. This is not because surface radiation budget products with other spatial scales are not required, but because there is no documented community consensus on the product requirements for other spatial scales.

Table 2: ECV related to the surface Earth Radiation Budget product requirements

ECV	Components	Spatial resolution (km)	Temporal resolution		Accuracy (Wm^{-2})	Stability (Wm^{-2} decade^{-1})		
			Averaging time	Sampling time		SW	LW	net
Surface radiation budget	Global means	-	1 Month	3 (1) hours	10.0 (5.0)	0.8* (downward)	0.8* (downward)	-

	Regional mean	250 (100)	1 Month	3 (1) hours	10.0 (5.0)			

Values are extracted from NOAA Technical Report NESDIS 134(available from *ftp://ftp.library.noaa.gov/noaa_documents.lib/NESDIS/TR.../TR_NESDIS_134.pdf)*

2.3 Key issues/questions

1) Although surface energy budget can be closed by adjusting flux components within their one sigma uncertainty, the reason for the 10 Wm-2 to 10 Wm-2 global surface energy balance residual needs to be addressed. Investigation of surface energy budget at smaller temporal and spatial scales (e.g. monthly regional) might be needed to investigate the reason for the residual to resolve specific processes that are responsible for the residual.
2) Surface energy fluxes are used in a wide range of studies, varying from climate research to solar energy applications. Accuracy and stability requirements are different, depending on the purpose of the study. Whether or not the accuracy and stability requirements of regional surface energy budget need to be established separated by the purpose needs to be considered. In addition, accuracy and stability requirements for regional surface energy budget should depends on surface type (land or ocean), regions, spatial and temporal scales.
3) Because surface energy budget is composed of radiative fluxes and turbulent fluxes, accuracy and stability requirements need to be specified by flux type.
4) Once regional energy budget is concerned, horizontal energy transport needs to be considered to achieve regional energy budget closure. Therefore, more than radiative fluxes and turbulent fluxes are needed to surface energy budget closure studies.
5) Surface observations and surface flux data products derived from satellites are complementary. How surface and satellite observations are combined to achieve the target accuracy and stability needed to be considered.

2.4 Framing discussion session

Several studies indicate that large regional surface energy budget residual exist over tropical ocean.

In determine the requirement, integration of surface observations and satellite observations and how these observations are combined to achieve the goal needs to be discussed.

2.5 Next steps

Reduce the uncertainty in surface energy fluxes by reducing uncertainties in near surface properties (e.g. temperature, water vapor, wind speed).

Assessments, intercomparisons activities are taking place under GEWEX/GDAP.

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Appendix 1: Rationale for other proposed targets for the Earth Energy Imbalance: To monitor climate change most effectively, we must resolve the timescales and magnitudes associated with the major external forcings presented in Fig. 1. In addition, we must increase our understanding of regional EEI natural variations, which can mask any climate change signal. The standard deviation in monthly EEI anomalies is approximately 0.6 W m–2 (Trenberth et al., 2015; Loeb et al., 2012), and annual average EEI can change by 1 W m–2 or more during an ENSO cycle (Trenberth et al., 2014; Loeb et al., 2012a; 2012b). EEI variability associated with solar forcing over the 11-year solar cycle is about 0.1 W m–2 (Trenberth et al., 2014) and the range in annual mean EEI during recent volcanic events was also about 0.1 W m–2 (Santer et al., 2014), but can be 20–30 times greater immediately following strong episodic volcanic eruptions, such as the Mount Pinatubo and El Chichón eruptions (Minnis et al., 1993). Underlying this variability is a mean 0.5–1 W m–2 imbalance associated with climate change (Hansen et al., 2011; Rhein et al., 2013; von Schuckmann et al., 2018), which is likely to change by only a few tenths of a W m–2 per decade. Hence, monitoring EEI requires observing systems that can reliably detect changes in EEI with an accuracy of <0.1 W m–2 on multiannual-to-decadal timescales and <0.5 W m–2 on subannual-to-interannual timescales. Advances in space-borne and in situ observations and climate modelling over the past two decades means that the ability to monitor and simulate this most vital metric of climate change is within our grasp for the first time.