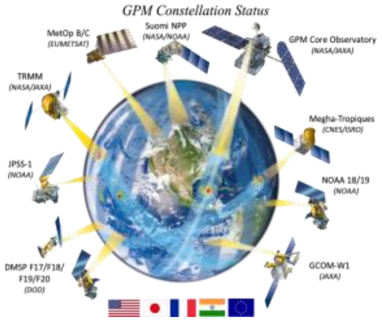
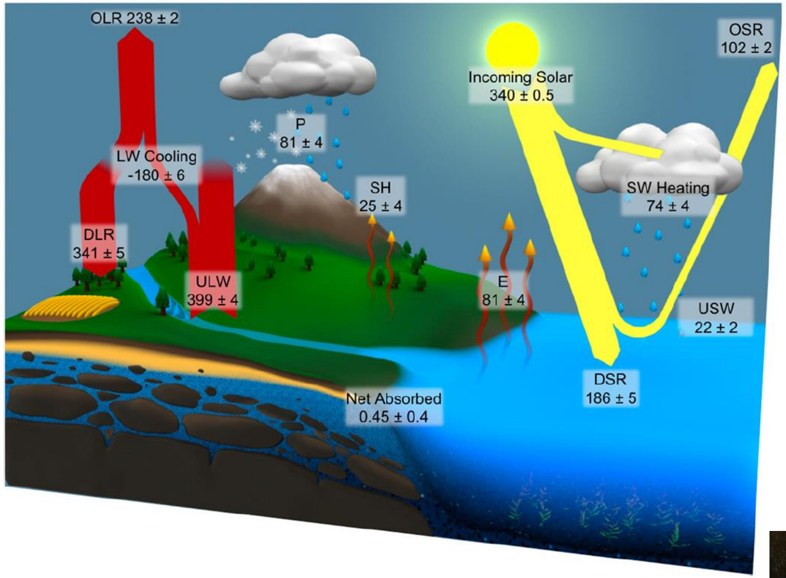
What satellite observations do we need to close the global water and energy cycle ?

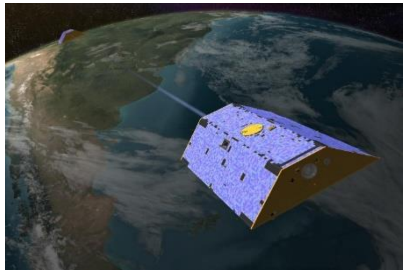




Sea level

TOA Radiation

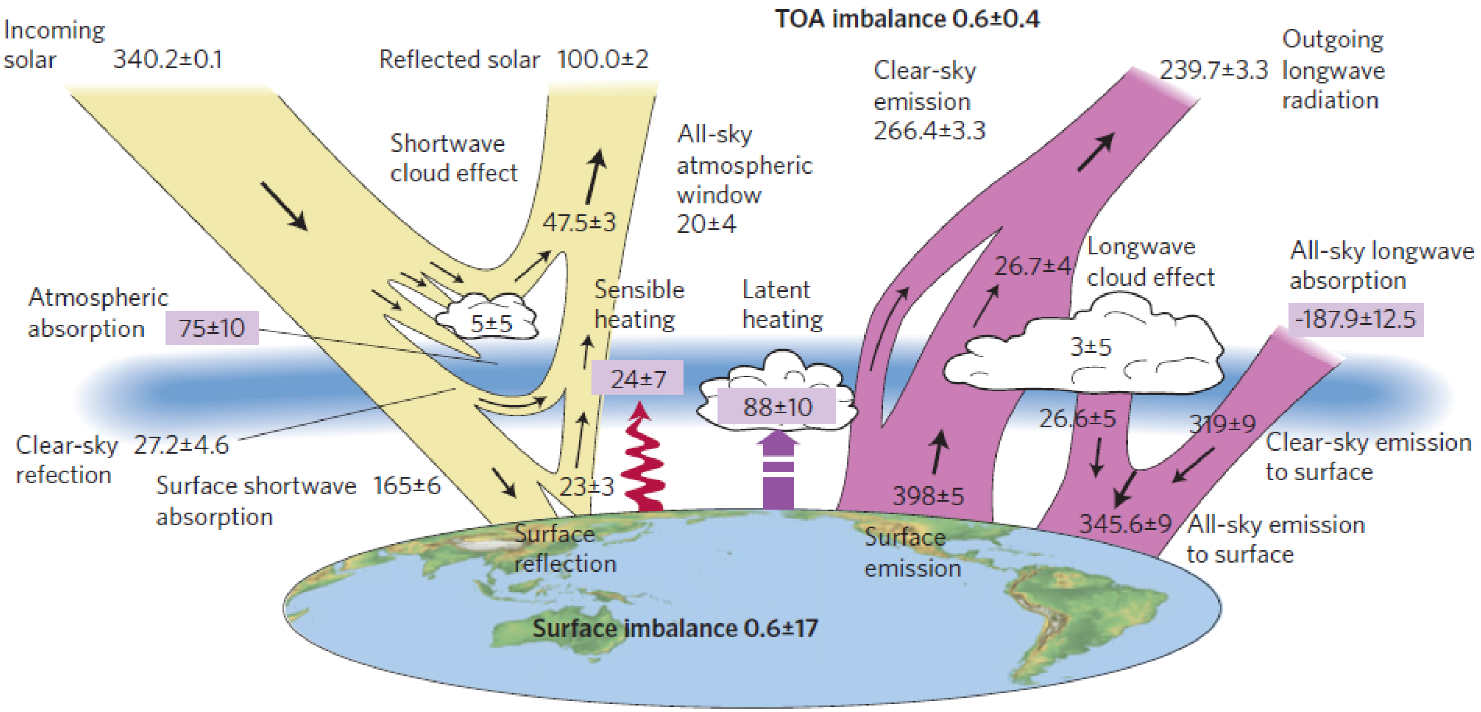
Gravimetry



Surface Flux

Rémy Roca and Benoît Meyssignac

Why observing the global energy cycle ?



Stephens et al 2012

Various different inter plays between the energy flux and the components of the Earth system
Same EEI for different reasons: need to understand the changes in all the fluxes and their physical causes

Need to elaborate a observational constraint on these fluxes

- **Assess theory** (the trends in precip and the Clausius Clapeyron)
- **Evaluate climate models** (both CMIP-6 like models as well as new generation storm-resolving models)
- **Detection & Attribution of climate change**

Outline of the presentation

1) Introduction

2) Why do we need both water & energy cycle ?

3) Closing or not closing the budget ?

The consistency approach

4) What satellite data do we need for the global water & energy cycle

To describe the fluxes

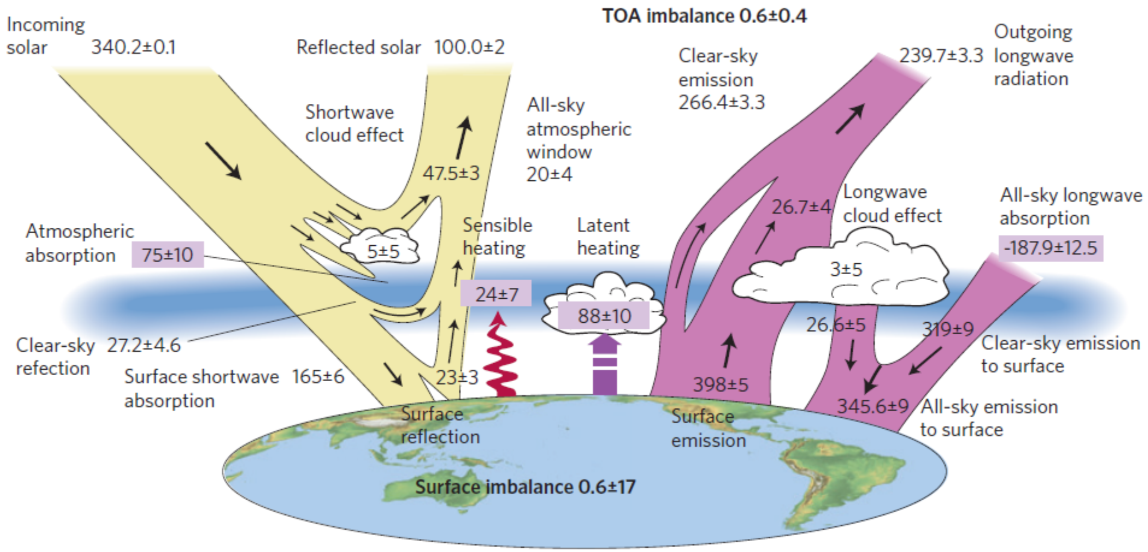
To describe the components ECV

4) Conclusions

With what accuracy do we need the product to close the budget consistenly ?

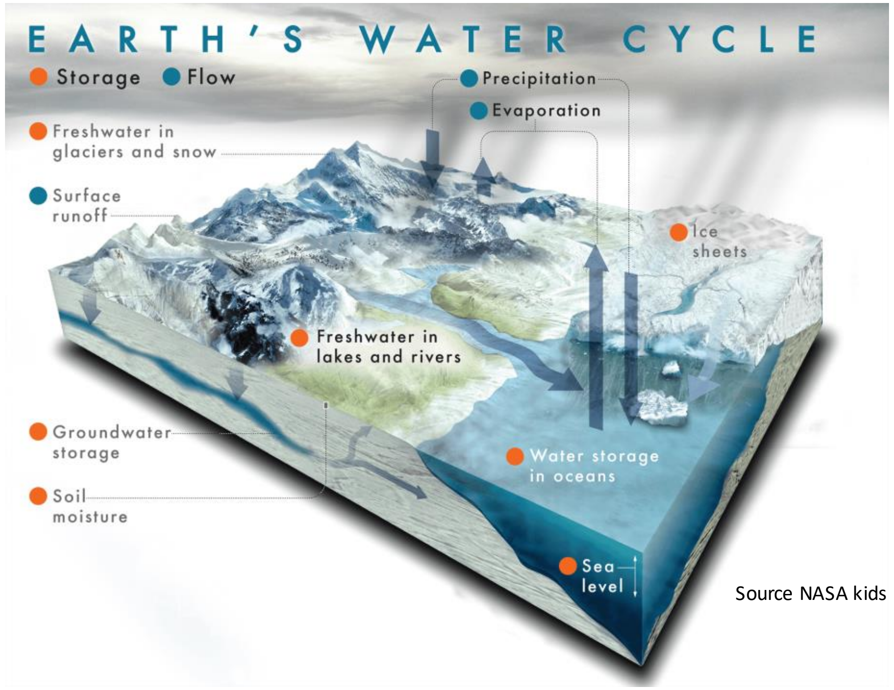
The global water and energy cycle: why both ?

The energy cycle



Stephens et al 2012

The water cycle



Source NASA kids

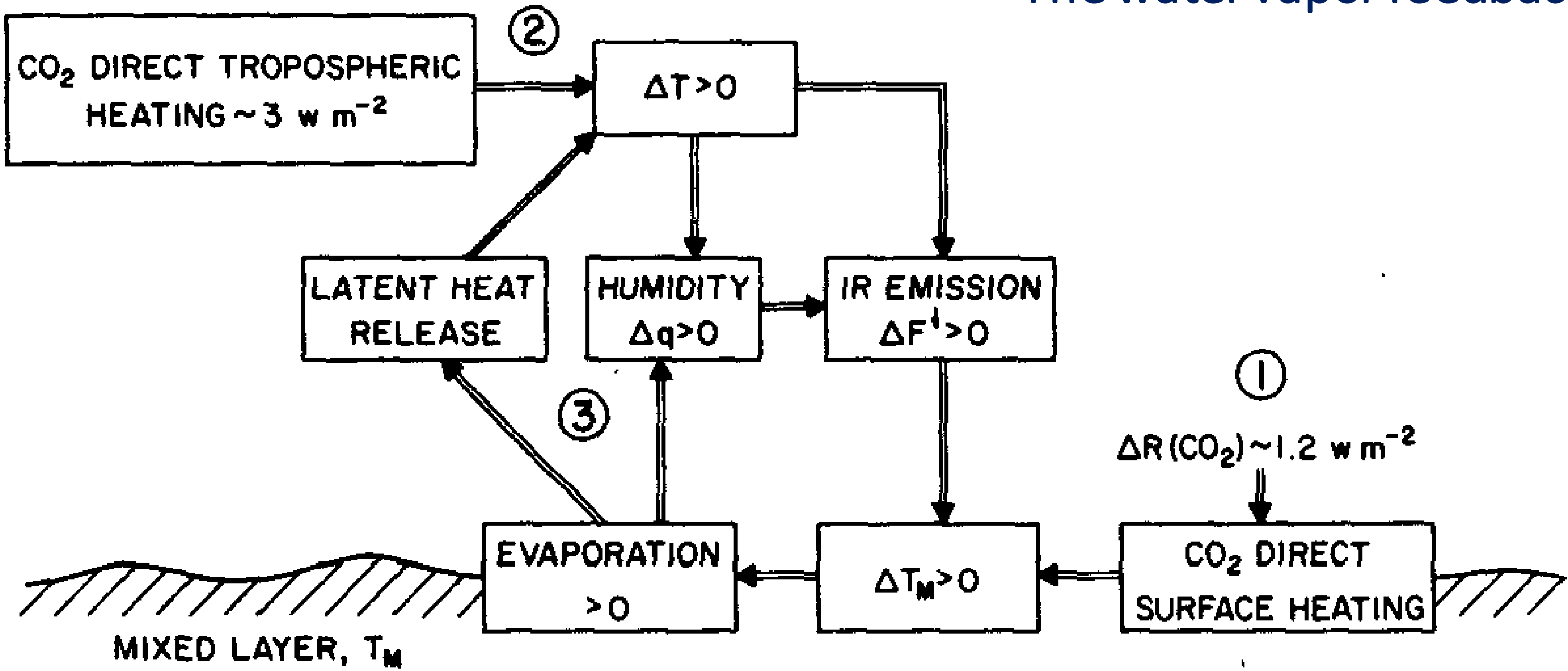
Strongly coupled cycles

evaporation/precipitation and surface-atmosphere radiation budget
ocean mass/ ocean heat content and TOA radiation
….

Coupling between energy and water (1/2)

Radiation and precipitation

The water vapor feedback loop

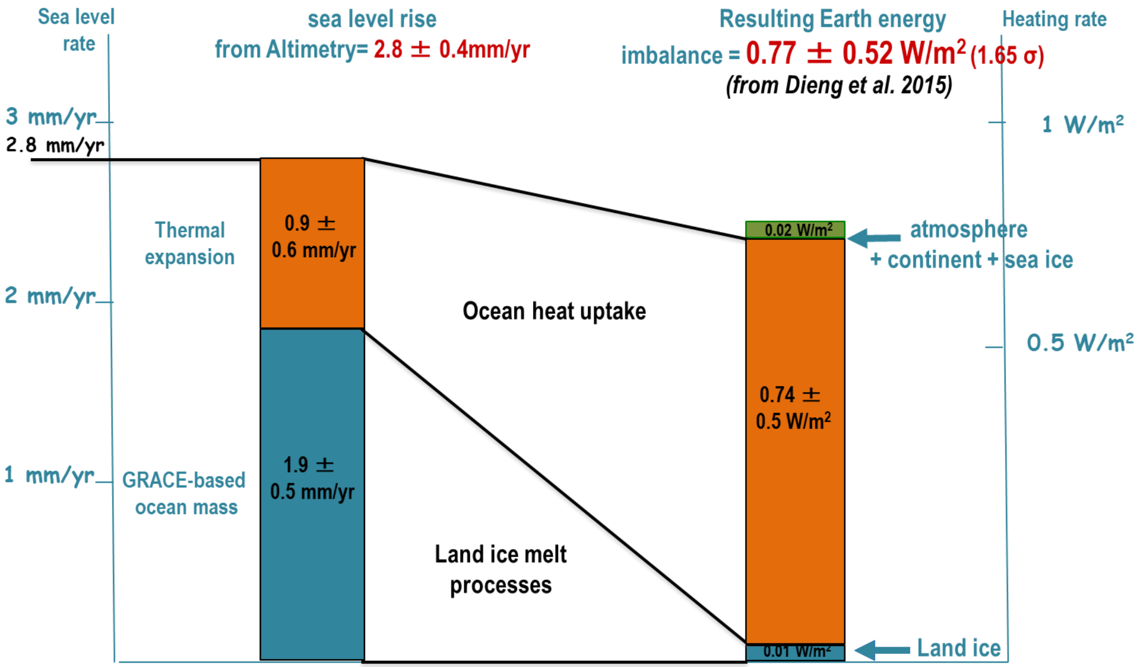


From Ramanathan, 1981

Global « warming » = verified
Global « moistening » = ~ verified
Global « raining » = verified?

Coupling between energy and water (2/2)

Earth energy imbalance, Ocean heat uptake and ocean mass



Most of the energy imbalance is in the ocean
Mass of ocean changes due to glaciers melting -> sea level increases
Volume of ocean changes due to warming (thermal expansion)-> sea level increases
sea level rise rate -> energy

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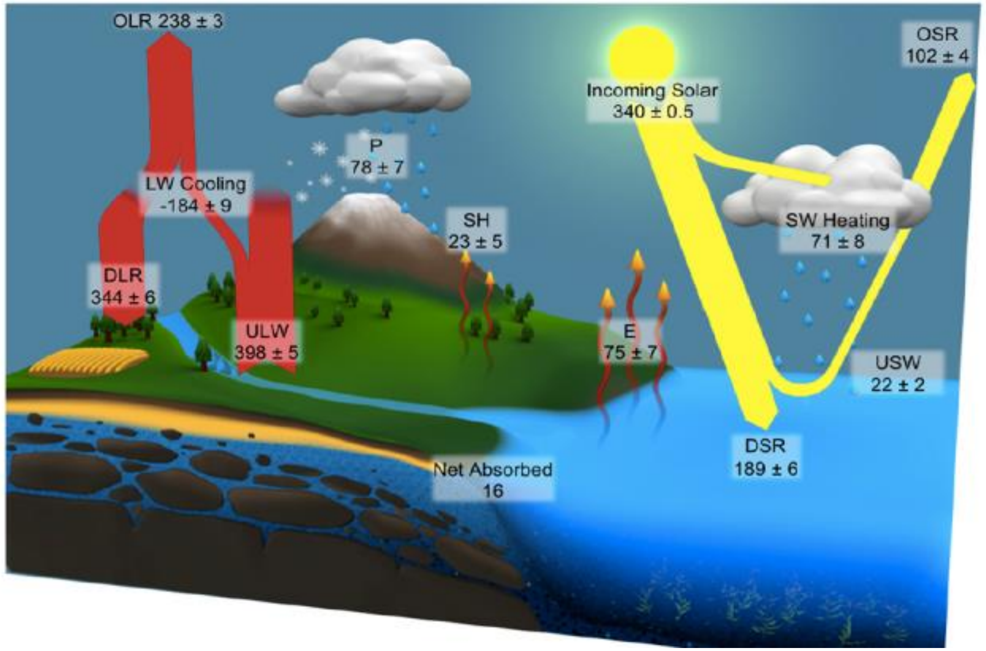
Assessing the global water and energy cycle closure

Long term research goal of WCRP/GEWEX (Stephens et al. , 2012; Trenberth)

- Remote sensing developments
- Need to adjust some fluxes to tend towards closure
- Objective techniques to do the adjustement : Optimization



Work from L'Ecuyer and Rodell under the NASA NEWS program

- Not so many studies using both energy & water closure
- Not many studies at global scales (Wood et al)
- Regional water budget optimization over mediterannean basins
- (Aires et al., Munier et al.)
- Haynes focused on the energy transport in the ocean

Exploring closure is interesting because the various ECV of the budget are usually developed independantly although they should be consistent altogether

Optimization approach further provides a framework **to enforce closure to assess the consistency** and rely on both the data and the associated uncertainty

Assessing the water and energy cycle consistency

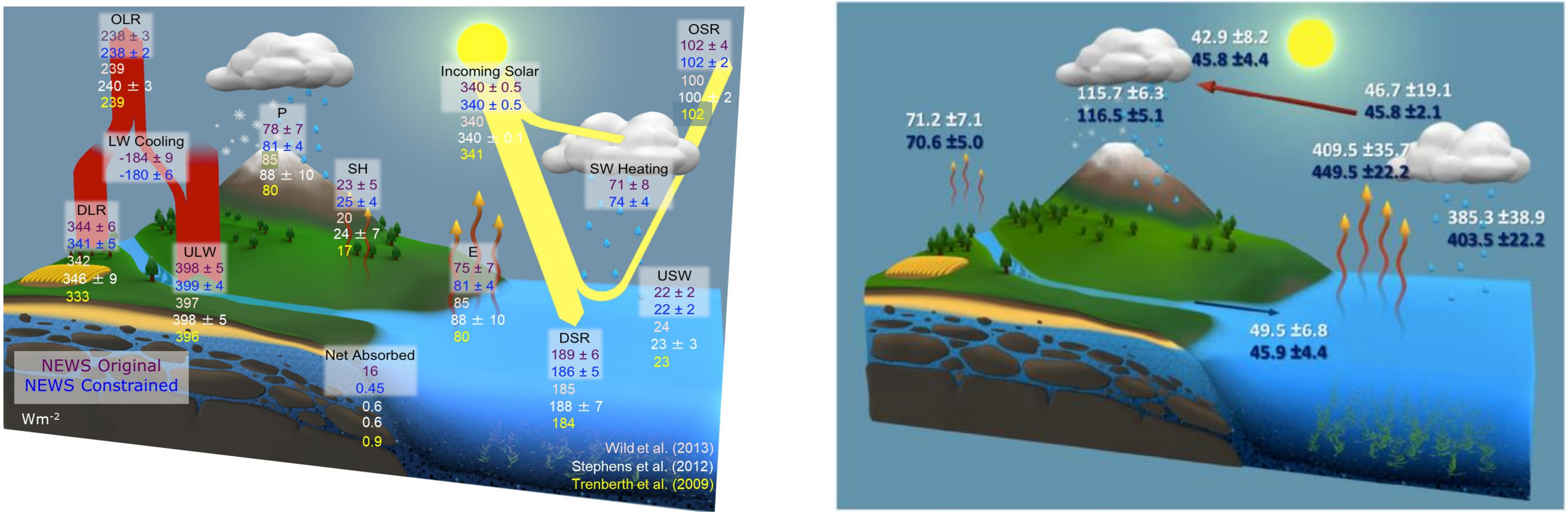


Figure 1: Annual mean global energy-water budget of Earth and associated uncertainties during the first decade of the millennium (energy fluxes in W.m^{-2} and water fluxes in 10^{3} km^{3}.yr^{-1}). White numbers are based on observational products and data integrating models. Blue numbers are estimates that have been optimized by forcing water and energy budget closure, taking into account uncertainty in the original estimates (from L'Ecuyer et al, 2015 and Rodell et al.,2015)

Variational Optimization and uncertainties

General budget equation:

$$R = \sum_{i=1}^{M} F_i - \sum_{o=1}^{N} F_o$$

R = residual; F =flux
i=in ; o=out

The goal is to find the most likely vector of fluxes F (Fi, Fo) given the vector of independent observational flux datasets Fobs (Fi,obs, Fo,obs) and the observed value of the residual Robs.

If errors are assumed to be Gaussian and random, the optimal flux can be objectively imposed by minimizing the cost function:

$$J = (\mathbf{F} - \mathbf{F}_{\mathrm{obs}})^{\mathrm{T}} \mathbf{S}_{\mathrm{obs}}^{-1} (\mathbf{F} - \mathbf{F}_{\mathrm{obs}}) + \frac{(R - R_{\mathrm{obs}})^2}{\sigma_R^2}$$

Where Sobs is the error covariance from uncertainty
σR is the error variance in the residual (e;g. heat storage)

Minimum occurs when:

$$\mathbf{F} = \mathbf{F}_{\mathrm{obs}} + \mathbf{S}_F \mathbf{K}^{\mathrm{T}} \mathbf{S}_{\mathrm{obs}}^{-1} (R_{\mathrm{obs}} - \mathbf{K}\mathbf{F}_{\mathrm{obs}})$$

SF is the error covariance after optimization

“Goodness of Fit” (χ^2) helps answer ‘can balance be achieved within current uncertainties?’

$$\chi^2 = (\mathbf{F} - \mathbf{F}_{\mathrm{obs}})^{\mathrm{T}} \mathbf{S}_{\mathrm{obs}}^{-1} (\mathbf{F} - \mathbf{F}_{\mathrm{obs}}) + \frac{(R - R_{\mathrm{obs}})^2}{\sigma_R^2}$$

L’Ecuyer et al 2015

Examples using ERA-interim 1979-2015

Namr	Before	After
TSI	343.8 (0.2)	343.8(0.2)
OSR	100.32(7.0)	99.5(6)
OLR	**245.2(18)**	**243.6(6)**
DSR	187.3(13)	186.7 (13)
USW	23.8(2)	23.8(2)
DLR	340.9(24)	339(19)
ULW	397.1(28)	399.8(20)
SH	17.4 (1)	17.4(1)
E	82.8(15)	84.0(6)
P	84.5(6)	84.0(6)

Preliminary results !

Value of dV in Global Equation: dV=E-P+C
Init, dV = -1.78 +- 16.43
Optim, dV = -2.00e-14 +- -NaN

Value of NETS in Oceans
Equation: NETS=DSR-USW+DLR-ULW-SH-E
Init, NETS = 8.90 +- 60.42
Optim, NETS = 0.85 +- 0.57

Value of NETA in Global
Equation: NETA=TSI-DSR-OSR+USW+ULW-DLR-OLR+SH+P+CS
Init, NETA = -7.32= +- 44.97
Optim, NETA = 7.63e-14 +- -NaN

Value of NETTOA in Global
Equation: NETTOA=TSI-OLR-OSR
Init, NETTOA = -1.82 +- 18.98
Optim, NETTOA = 0.60 +- 0.39

Value of NETS in Global
Equation: NETS=DSR-USW+DLR-ULW-SH-E
Init, NETS = 7.01 +- 43.05
Optim, NETS = 0.60 +- 0.39

Assessing the water and energy cycle consistency

In Summary

- Though precipitation and evaporation, both the energy AND the water cycle are tightly coupled and as a direct consequence, any constraint of a water flux can influence the estimation of any energy flux and vice-versa.
- The conservation laws cannot be easily enforced within the development of individual ECVs data products and as such the capability of a suite of products to actually respect these conservation laws is a genuine characteristic of their potential for climate scientific investigation.
- The relevance of the individual ECVs uncertainty information is assessed at the same time as the consistency among the corECVs

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The budget equations and the conservation laws

Over large continental catchments and over the global ocean and under long temporal average (interannual to centennial) the **budget equations** of the water and energy cycle can be written (Hartmann, 1994; Kato et al., 2016)

At the surface

$dLWS=Pc-Ec-Rc$

$dOWS=Po-Eo+Rc$

$NETc=DLMc-DSWc-ULWc-USWc-SHc-LeEc$

$dOHC=DLMo-DSWo-ULWo-USWo-SHo-LeEo$

In the atmosphere

$dVc=Pc-Ec+conv(Vc)$

$dVo=Po-Eo-conv(Vc)$

$NETAc=TSIc-OLRc-OSRc-DLWc-DSWc+ULWc+USWc+SHc+LePc+conv(MSEc)$

$NETAo=TSIo-OLRo-OSRo-DLWo-DSWo+ULWo+USWo+SHo+LePo-conv(MSEc)$

At global scales **the conservation laws** further reads

$dLWS+dOWS+dVc+dVo = 0$

$NETAc+NETc+NETAo+dOHC=0$

$NETc=0$

$dOHC=0.6$

Water and energy fluxes and stocks

Full name	Short name	Units	Type
	Top of Atmosphere		
Total Solar incoming radiation	TSI	Wm^{-2}	Flux
Out going longwave radiation	OLR	Wm^{-2}	Flux
Out going shortwave radiation	OSR	Wm^{-2}	Flux
	In-atmopshere		
Dry static energy convergence	Conv DSE	Wm^{-2}	Flux
Water vapor convergence	Conv V	Wm^{-2}	Flux
Water vapor	V	mm sea level equivalent	Stock
	Surface (land and ocean)		
Precipitation(liquid+solid)	P	mm.yr^{1} sea level equivalent	Flux
Latent heat fluxes	LH	Wm-2	Flux
Sensible heat fluxes	SH	Wm-2	Flux
upward shortwave radiation	USW	Wm-2	Flux
incoming shortwave radiation	DSW	Wm-2	Flux
the upward longwave radiation	ULW	Wm-2	Flux
downward longwave radiation	DLW	Wm-2	Flux
	Land Surface		
Runoff	R	mm.yr	Flux
Land Water storage (glaciers, ice sheets ,surface lakes, groundwater and rivers)	LWS	mm.yr	Stock
	In-Ocean		
Ocean Heat Content	OHC	J	Stock
Ocean Water Storage	OWS	mm.yr^{1} sea level equivalent	Stock

17 core-ECVs

A satellite perspective on the GWEC (1/2)

The recent advances of the satellite observing system permit to explore an (almost) satellite based depiction of the global water and energy cycle fluxes and stocks.

Full name	Short name	Units	Type
	Top of Atmosphere		
Total Solar incoming radiation	TSI	Wm^{-2}	Flux
Out going longwave radiation	OLR	Wm^{-2}	Flux
Out going shortwave radiation	OSR	Wm^{-2}	Flux
	In-atmopshere		
Dry static energy convergence	Conv DSE	Wm^{-2}	Flux
Water vapor convergence	Conv V	Wm^{-2}	Flux
Water vapor	V	mm sea level equivalent	Stock
	Surface (land and ocean)		
Precipitation(liquid+solid)	P	$mm.yr^{-1}$ sea level equivalent	Flux
Latent heat fluxes	LH	Wm-2	Flux
Sensible heat fluxes	SH	Wm-2	Flux
upward shortwave radiation	USW	Wm-2	Flux
incoming shortwave radiation	DSW	Wm-2	Flux
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downward longwave radiation	DLW	Wm-2	Flux
	Land Surface		
Runoff	R	mm.yr	Flux
Land Water storage (glaciers, ice sheets ,surface lakes, groundwater and rivers)	LWS	mm.yr	Stock
	In-Ocean		
Ocean Heat Content	OHC	J	Stock
Ocean Water Storage	OWS	$mm.yr^{-1}$ sea level equivalent	Stock

SORCE,
CERES + MODIS + GEOring

reanalysis

SSM/I
GPM constellation or SSMI/I
SSM/I, AVHRR + models

CERES+MODIS+AVHRR+GEORING…

Model residual ; altimetry
GRACE + altimetry
GRACE + altimetry
Altimetry…

A large number of ECV products from these various satellites and reanalysis with different sensitivities
Not all of the satellite products have their uncertainty well characterized

A satellite perspective on the GWEC (2/2)

	corECV		equation	conECV		equation	conECV		equation	conECV		equation	conECV	
Energy	Incoming solar at TOA	**TSI**												
	Outgoing shortwave at TOA	**OSR**	α_TOA.F_o	Incoming solar at TOA	TSI									
				albedo at TOA	**α_TOA**									
	Outgoing longwave at TOA	**OLR**	(1-absLW_atm)ULW	Surface emitted LW	ULW									
				Atmospheric longwave absorption	**absLW_atm**									
	Atmospheric latent heat (precipitation)	**P**	P=P_l+P_s	Liquid precipitation	**P_l**									
				Solid precipitation	**P_s**									
	moist static energy convergence	**convMSE**	—U_a.?MSE	3D wind speed	**U_a**									
				Moist static energy	**MSE**	C_pT+gz+L_fq	3D air Temperature	T_a						
							3D air specifc humidity	q						
	Downwelling LW at surface	**DLW**	ε_sky σT_sky^4	sky apparent temperature	**T_sky**									
				sky apparent emissivity	**ε_sky**									
	Downwelling SW at surface	**DSW**	(1-absSW_atm)(1-α_TOA) F_o	Incoming solar at TOA	F_o									
				albedo at TOA	α_TOA									
				Atmospheric shortwave absorption	**absSW_atm**									
	Surface emitted LW	**ULW**	ε_s σT_s^4	surface temperature	**T_s**									
				surface emissivity	**ε_s**									
	Surface reflected SW	**USW**	α_s DSW	Downwelling SW at surface	DSW									
				albedo at surface	**α_s**									
	Sensible heat flux at the surface	**SH**	C_p pC_DH U_r (T_s-T_r)	Wind speed at 2m	**U_r**									
				surface temperature	**T_s**									
				air temperature at 2m	**T_r**									
	latent heat flux at the surface	**LH**	pC_DE U_r (q_s-q_r)	Wind speed at 2m	U_r									
				surface specific humidity	q_s									
				air specifc humidity at 2m	q_r									
	Ocean Heat content	**OHC**	direct: C_p T	ocean Heat capacity	**C_p**	C_p(T,S)	3D ocean temperature	T_o						
							3D ocean salinity	**S_o**						
				3D ocean temperature	**T_o**									
			residual: 1/e(SL-So/rho_o)	expansion efficiency of heat	**eeh**	e(T,s)	3D ocean temperature	T_o						
							3D ocean salinity	**S_o**						
				sea level	**SL**									
				ocean mass	**OWS**									
				density	**rho_o**	3D ocean temperature	T_o							
						3D ocean salinity	**S_o**							
	Atmospheric moisture content	**V**												
	Moisture convergence	**convV**	—U.?V	Atmospheric moisture content	V									
				3D wind speed	U_a									
Water	Surface runoff	**R**	Q_surface+Q_grounwater	surface runoff	**R_surface**	R_(surface,w)+R_mw+R_(ice calving)	surface liquid runoff	**R_(surface,w)**						
							ice calving	**R_(ice calving)**						
							surface meltwater runoff	R_mw	Q_(surface,mw)+Q_(iceshelves,mw)	surface meltwater runoff	**R_(surface,mw)**			
										ice shelves meltwater runoff	**R_(iceshelves,mw)**			
				groundwater runoff	**R_groundwater**									
	terrestrial water storage	**LWS**	S_s+S_g+S_li	surface water storage	**S_s**									
				groundwater storage	**S_g**									
				land ice	**S_li**	MB_AIS+MB_GrIS+MB_Gla+MB_IC	Ice caps Mass Balance	**MB_IC**	SMB+icedyn	Surface mass balance	**SMB**	P_s-Q_mw	solid Precipitation	P_s
													meltwater runoff	R_mw
										ice dynamics	**icedyn**			
							Glaciers Mass Balance	**MB_Gla**	SMB+icedyn	Surface mass balance	**SMB**	P_s-Q_mw	solid Precipitation	P_s
													meltwater runoff	R_mw
										ice dynamics	**icedyn**			
							Greenland ICe Sheet Mass Balance	**MB_GrIS**	SMB+icedyn	Surface mass balance	**SMB**	P_s-Q_mw	solid Precipitation	P_s
													meltwater runoff	R_mw
										ice dynamics	**icedyn**			
							Antarctic ICe Sheet Mass Balance	**MB_AIS**	SMB+icedyn	Surface mass balance	**SMB**	P_s-Q_mw	solid Precipitation	P_s
													meltwater runoff	R_mw
										ice dynamics	**icedyn**			
	ocean mass	**OWS**		Sea ice										

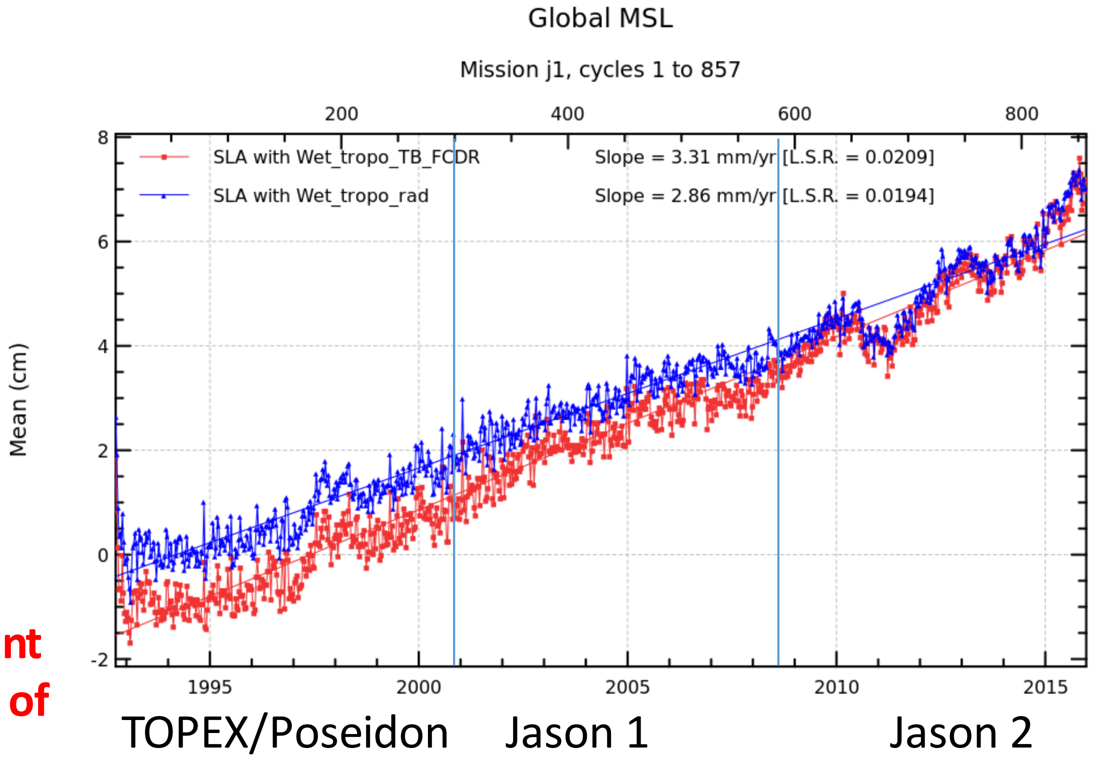
Wet tropo correction water vapor

Trends in GSML and wet tropospheric correction

Global Mean Sea level is estimated using the time series of altimetry active space observations and various processing.
The wet tropospheric correction accounts for the impact of the water vapor loading in the atmosphere in attenuating the altimetry radar signal. The water vapor is estimated using the on-board passive microwave nadir looking radiometers.
Inhomogeneties arise in the times series due to changes in the satellites, radiometers spec and the drift of the radiometers themselves.

The stated stability of the actual processing is ~0.1K/year

The CMSAF SSMI FCDR provides a climate data record of passive microwave radiometers with a stated stability of 0.01K/year.



From Meyssignac Ablain Picard and Roca in prep

Satellite observations could be geared towards a climate consistent multi platforms estimation of EEI with enhanced characterization of the uncertainties

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Uncertainties characterization

What is uncertainty ?
Difficult to define
Difficult to quantify
Difficult to estimate (eg where no references data are found)
Hard to validate **Yet needed !**

WCRP/GEWEX/GDAP is pushing for more research on these aspects

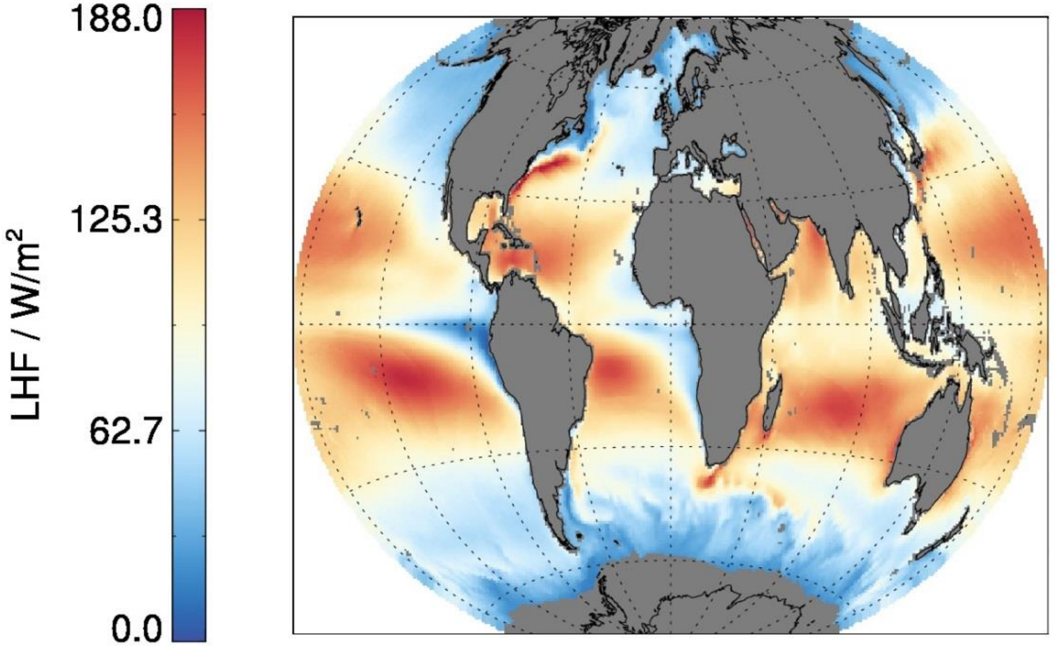
Error propagation from Level 1 to level 4
Good knowledge at the Level 0 to 1 maybe 2 (e.g. FIDUCEO effort) and some perspectives towards level 4 (example)
Still no framework for non linear issues (detection uncertainty)

Latent heat flux climatology

from HOAPS 4 data

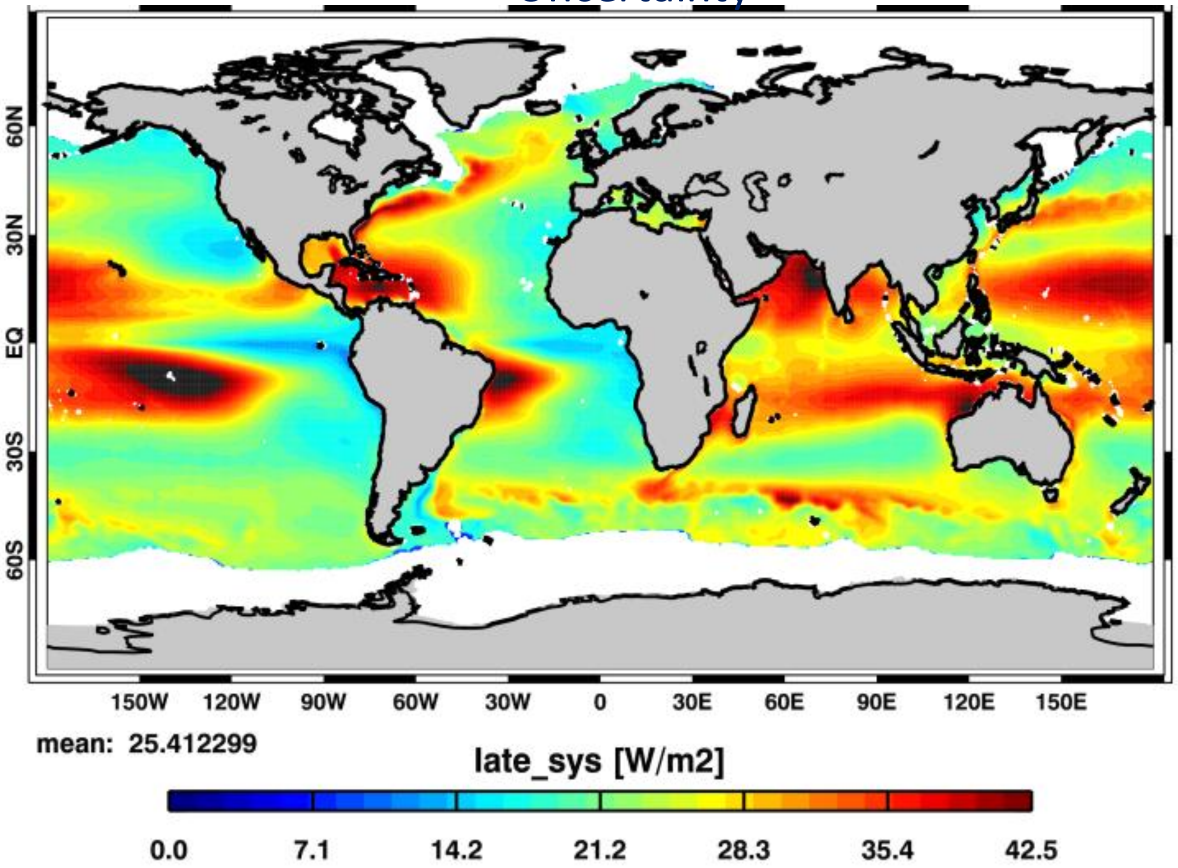
Advanced estimation based on buoy references data
Uncertainty includes : systematic, random and sampling uncertainties
does not include bulk formula induced uncertainty
Account for some of the structural error thanks to predictors

Climatology



Courtesy M Schröder

Uncertainty



Courtesy M Schröder

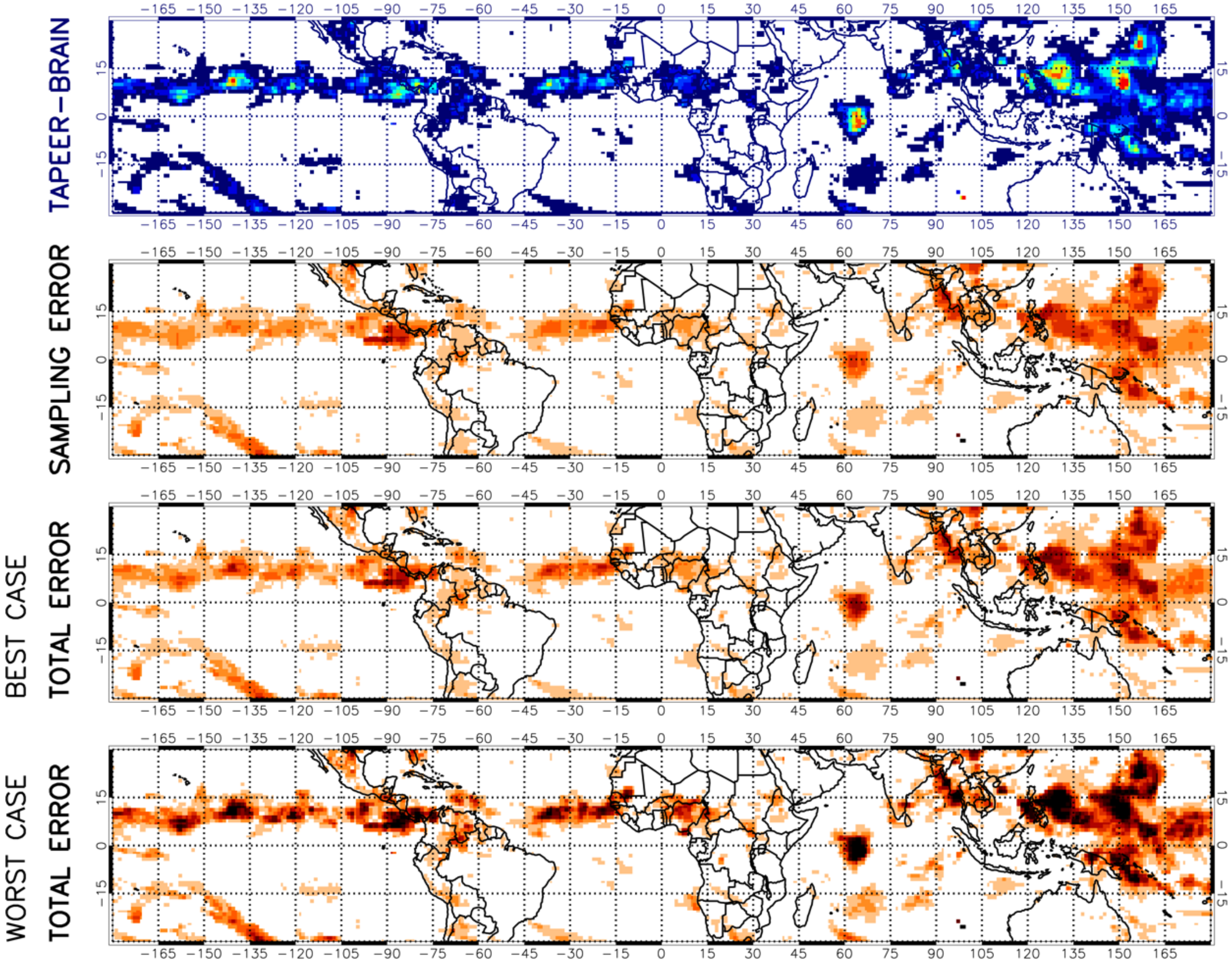
Daily 1°x1° accumulated precipitation

From L2 to L4

Monte carlo simulations

20% bias
on L2
Intermediate
instantaneous
rainrates

60%



Based on error modelling
(Roca et al. ,2010)

Chambon et al., 2012

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Difficult to estimate (eg where no references data are found)

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Still no framework for non linear issues (detection uncertainty)

From Level 4 to basin scales

How do we approach it ? Autocorrelation ? Structural errors ?

Sensitivity to the specifications of uncertainties in the consistency framework

Unlikely to have the characterzied errors for all flux and stocks

experiment with the uncertainty to span the possible range of uncertainty for the most uncertain ECV to identify the range of uncertainty for which an ECV become a constraint for the other

Elaborating the need characterization of the needed uncertainty is still on the research side

Conclusions

Observations are important to climate change (theory, models, d&a,…)

We have a framework to explore the consistency and closure of global water and energy

~17 core-ECV (fluxes) are available from space;

Much more is available and space based undertaking could promote a contribution at a much deeper level reaching the components-ECV…

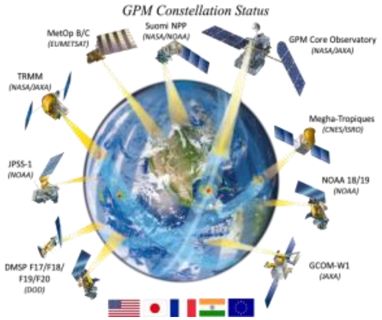
Global fluxes consistency but also multi ECV consistency in the building (same cloud mask for SST, downard LW radiation,…)

A task for WG Climate to assess ?

Uncertainty characterization is the next challenge

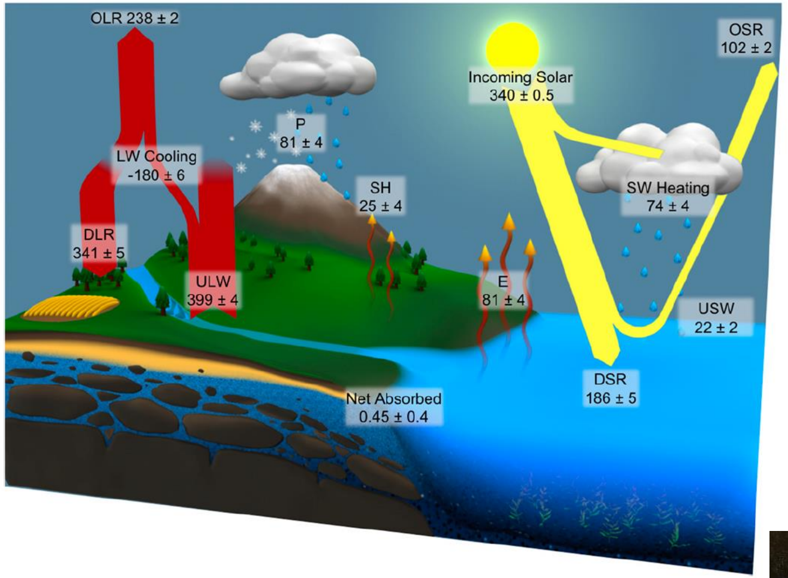
Assessing the global water and energy cycle closure

Precipitation



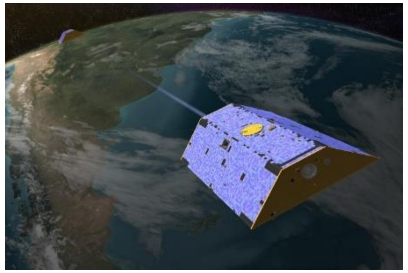
TOA Radiation

1 NOVEMBER 2015 L'ECUYER ET AL. 8335



Surface Flux

Gravimetry



Sea level

Rémy Roca and Benoît Meyssignac