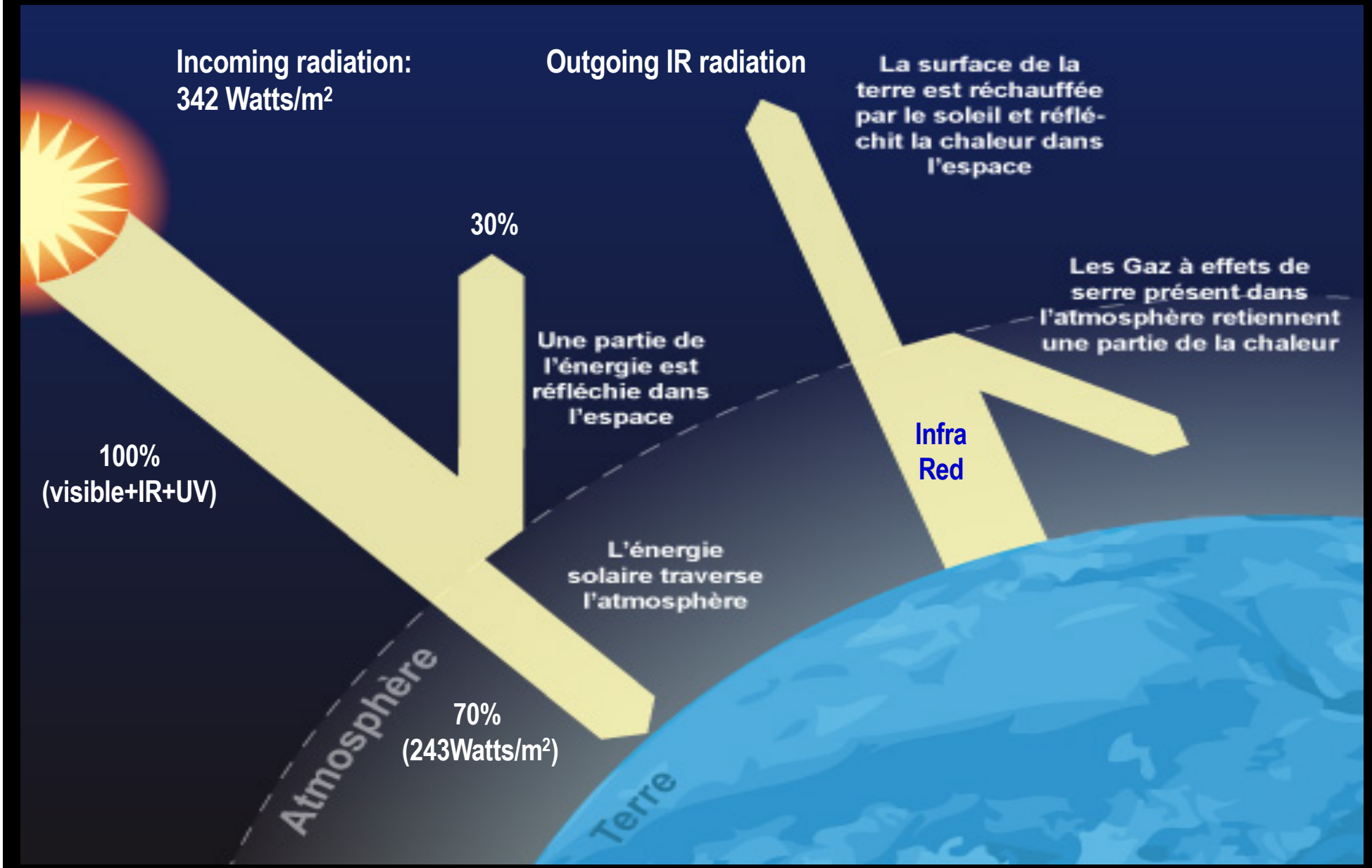
Measuring Global Ocean Heat Content to estimate the Earth Energy Imbalance

Meyssignac B., Boyer T., Zhao Z., Hakuba M.Z., Landerer F., Stammer D., Köhl A., Kato S., L'Ecuyer T., Ablain M., Abraham J.P., Blazquez A., Cazenave A., Church J., Cowley R., Cheng L.J., Domingues C.M., Giglio D., Gouretski V., Ishii M., Johnson G.C., Killick R.E., Legler D., Llovel W., Lyman J., Palmer M., Piotrowicz S., Purkey S.G., Roemmich D., Roca R., Savita A., von Schuckmann k., Speich S., Stephens G., Wang G.J., Wijffels S., Zilberman N.

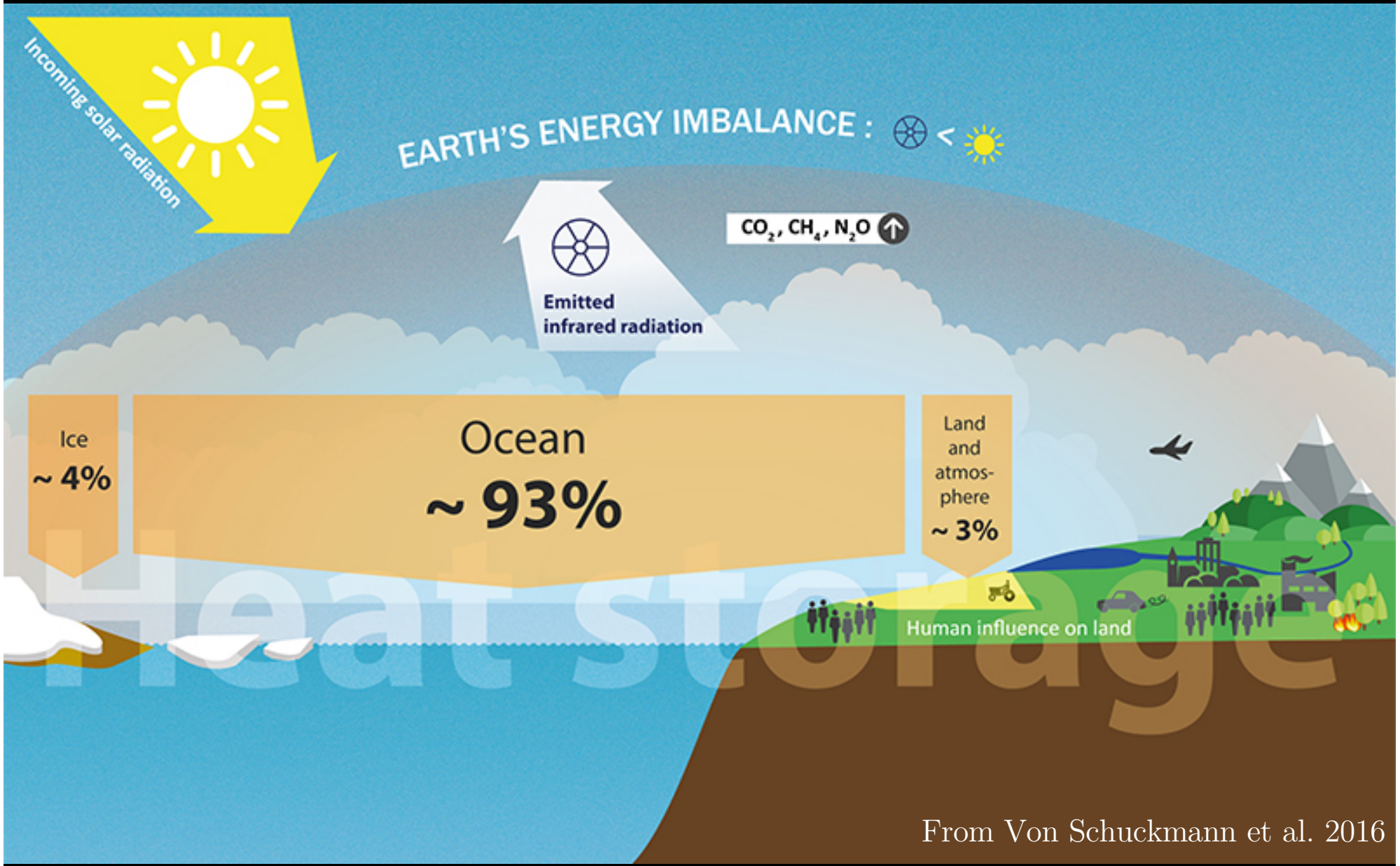
(benoit.meyssignac@legos.obs-mip.fr)

Earth Energy Imbalance



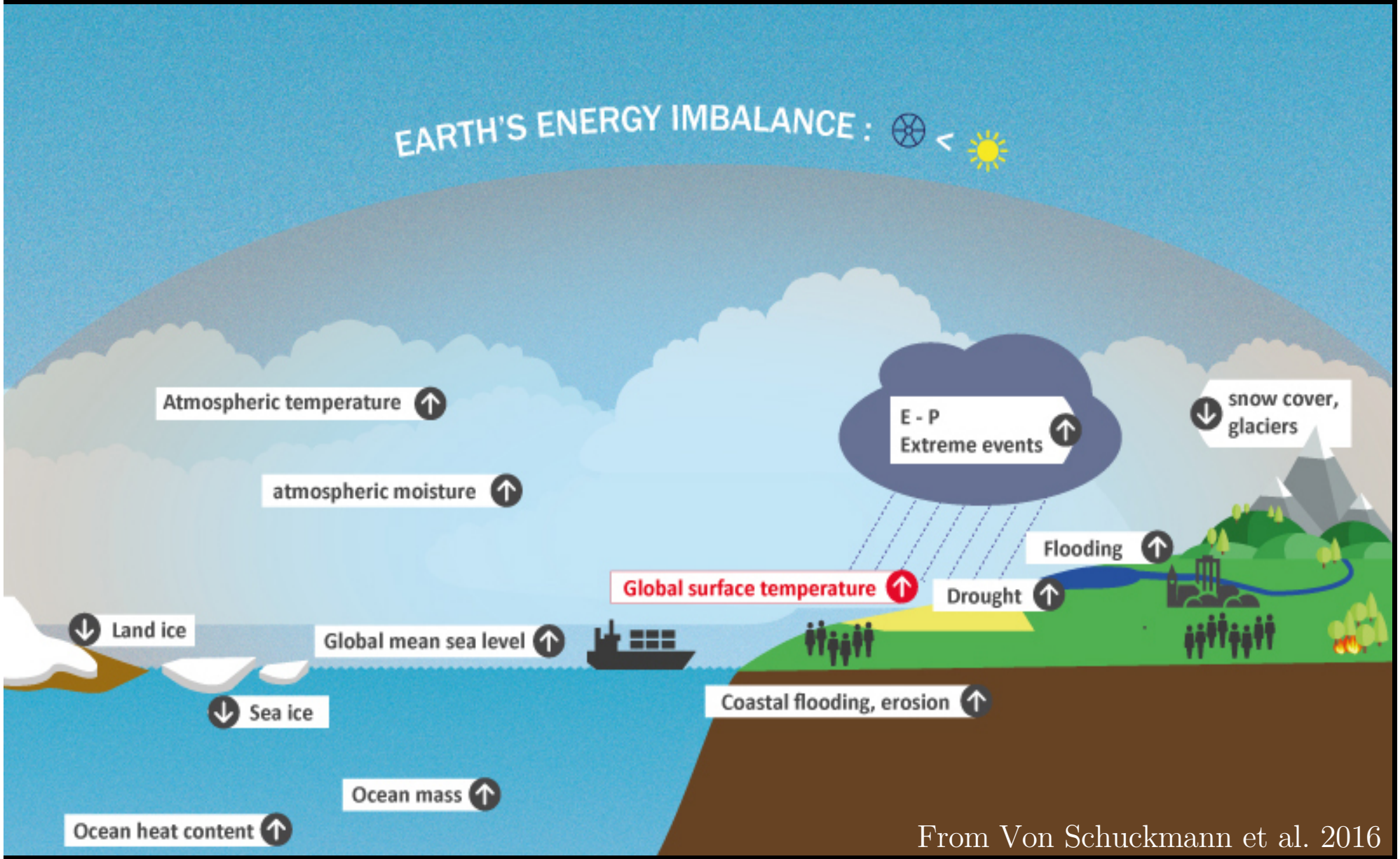
Under climate change
Net =Energy in - Energy out

Energy storage in the climate system



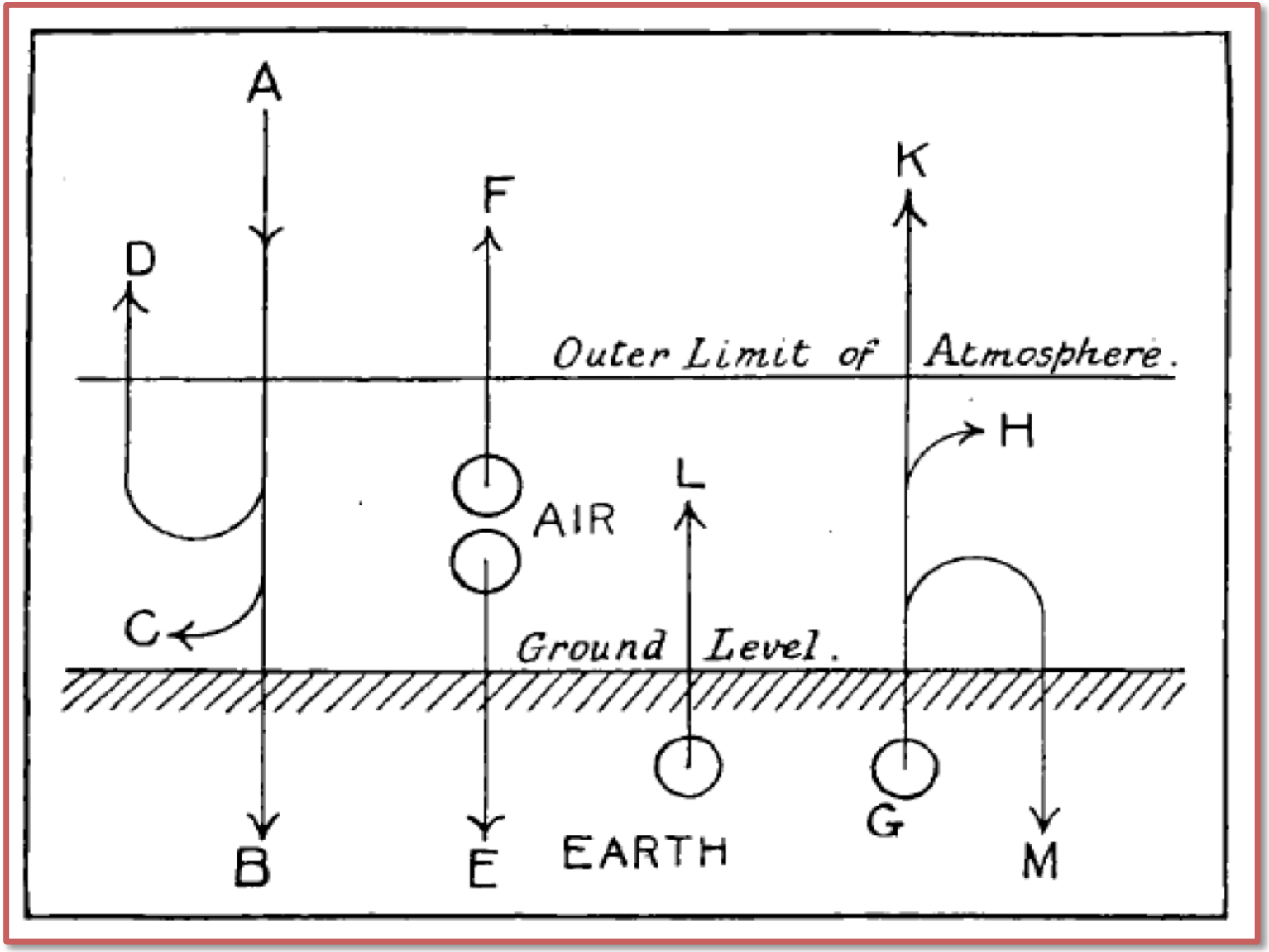
From Von Schuckmann et al. 2016

Earth Energy Imbalance and Climate changes



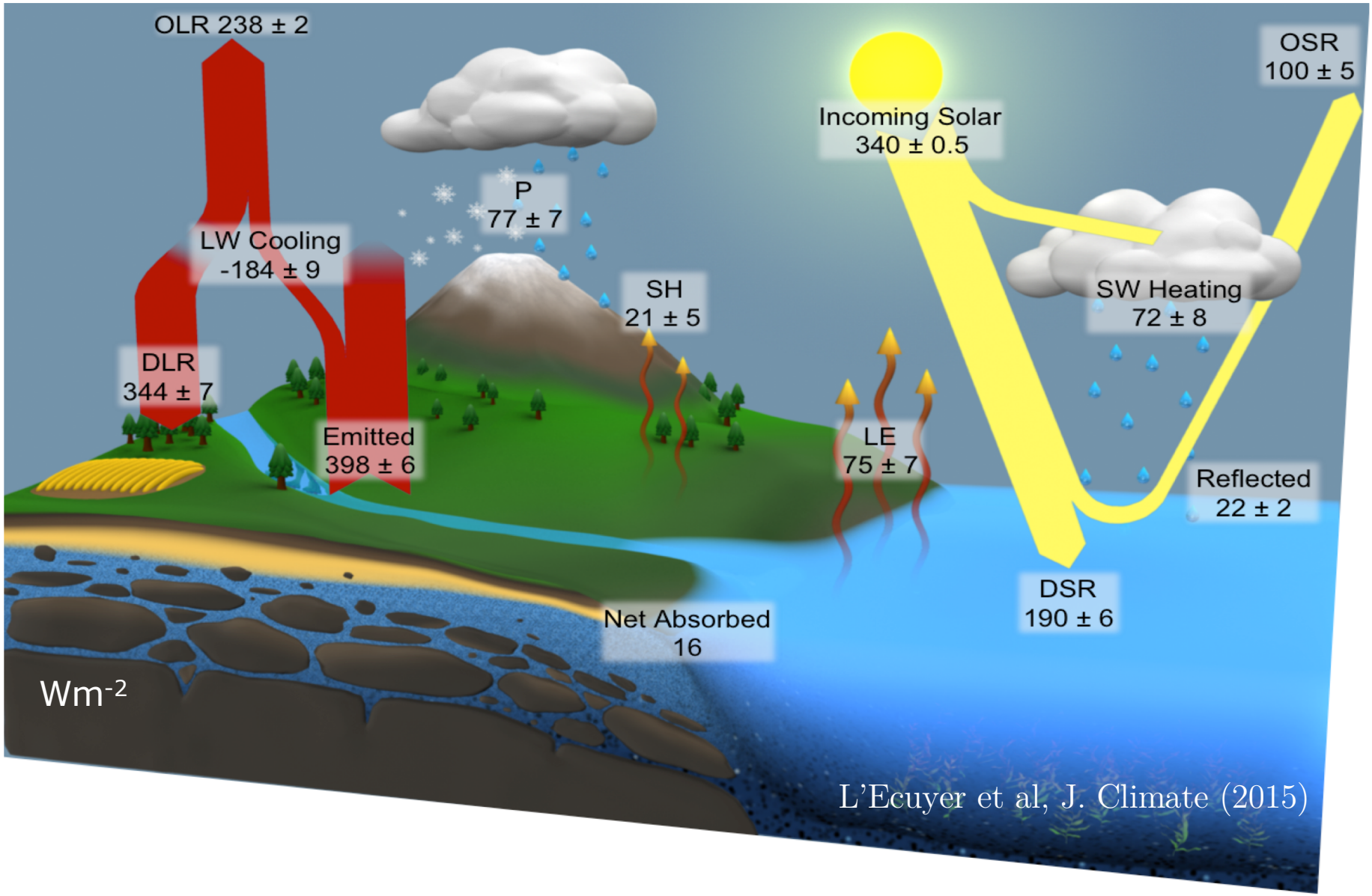
From Von Schuckmann et al. 2016

EEI estimation from surface energy budgets



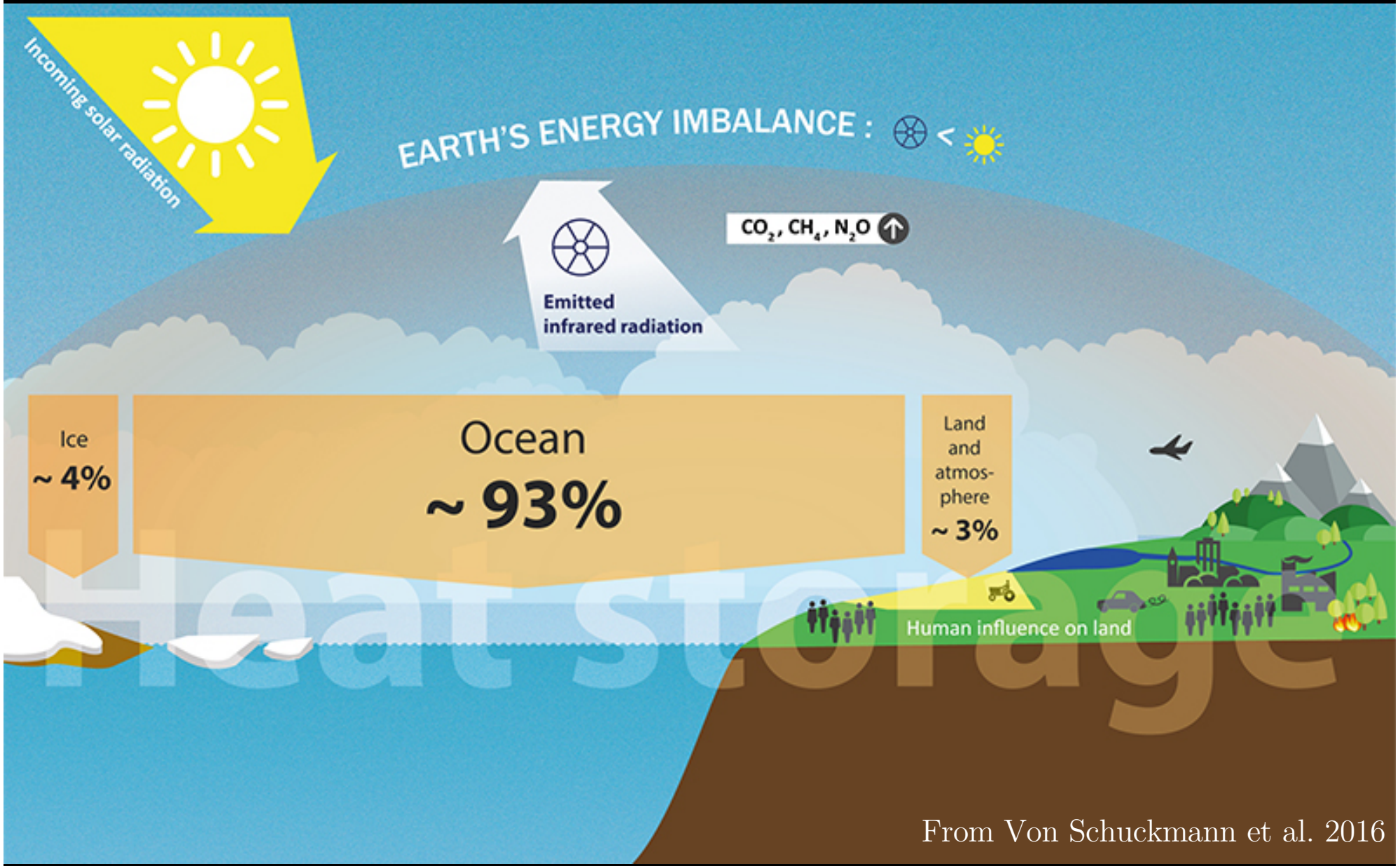
From Dines (1917)

OHC/EEI estimation from surface energy budgets



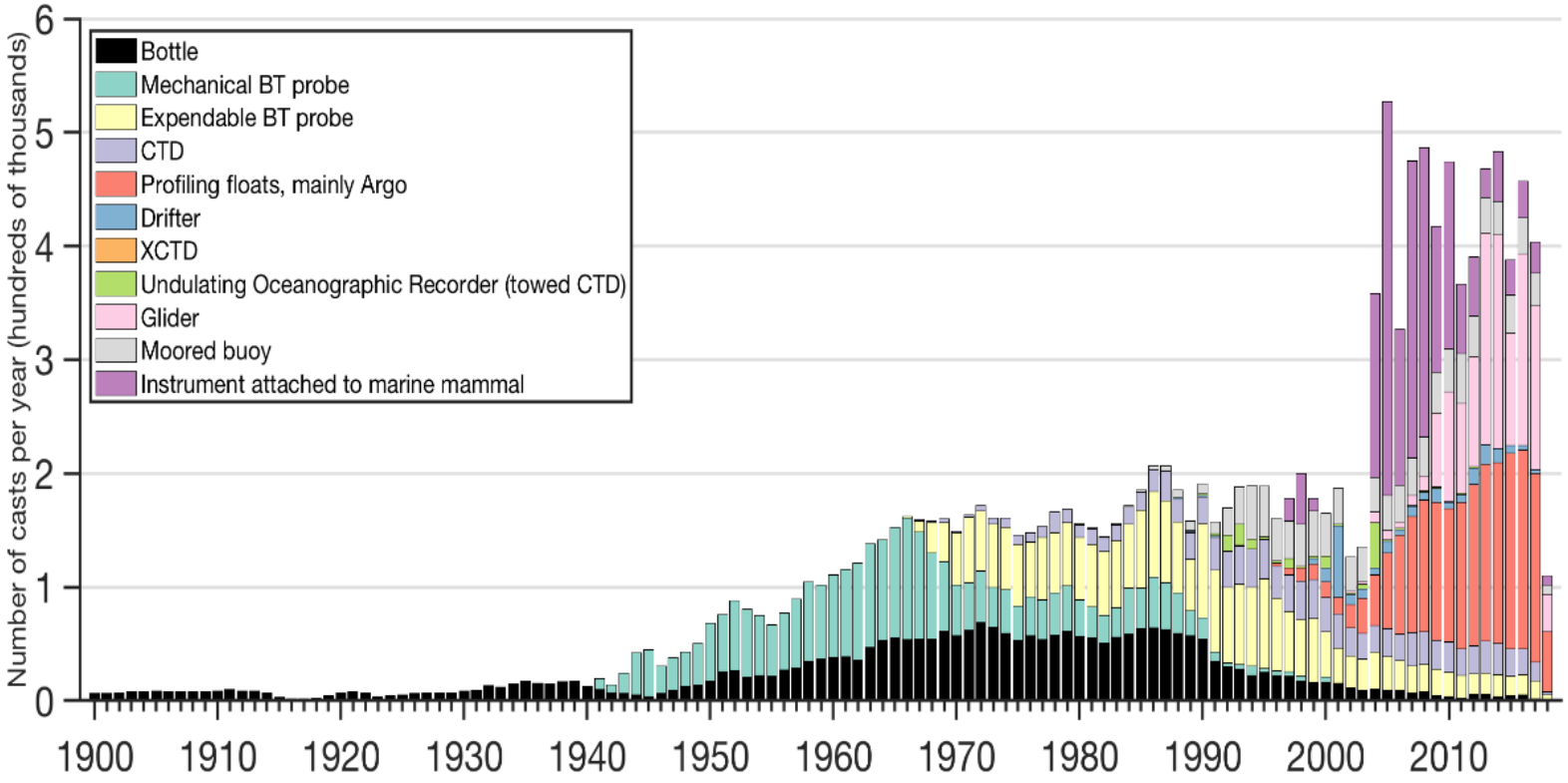
global EEI from surface budgets 16 ± 20W.m^{-2} (1.65 σ, i.e. 90% CL)

Energy storage in the climate system



From Von Schuckmann et al. 2016

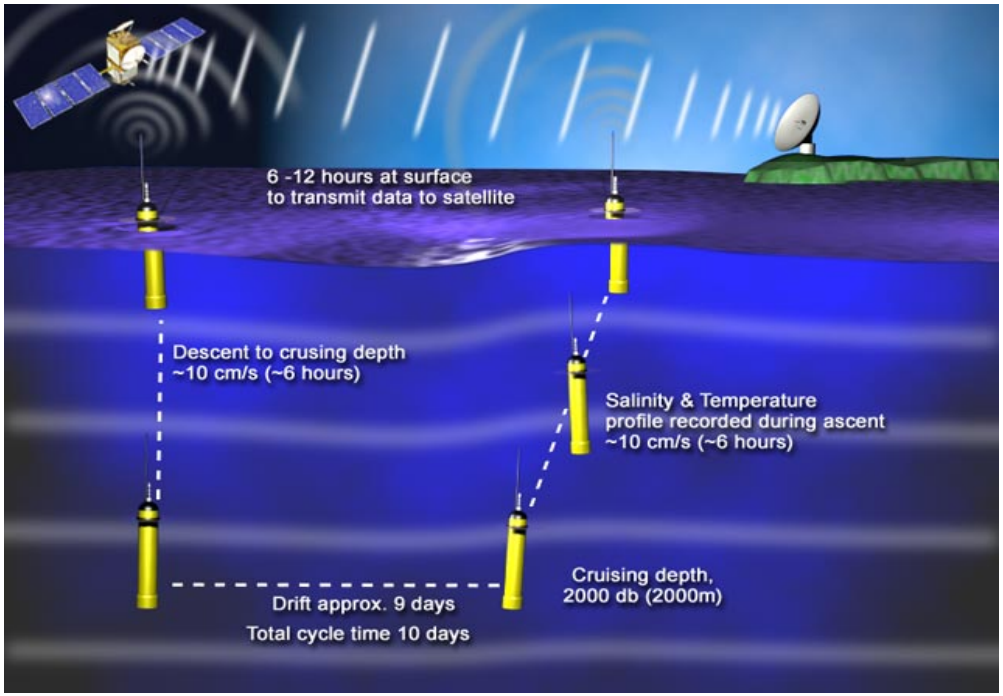
OHC estimation from Ocean in situ temperature



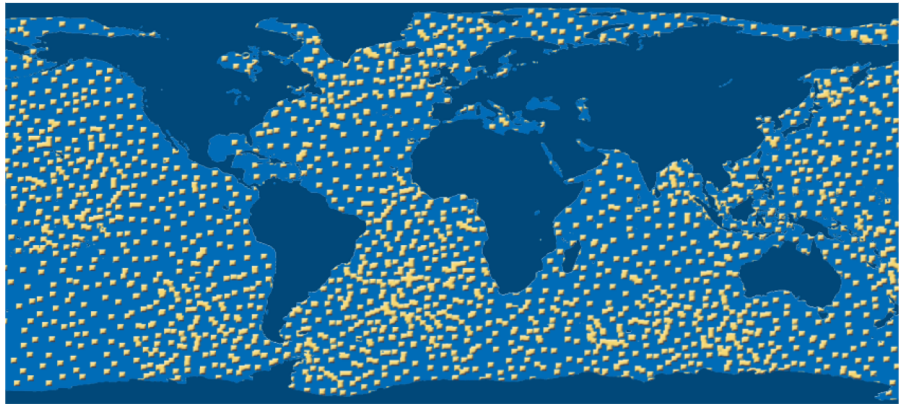
From Meyssignac et al. in press

global OHC since 1993 (0-700m) $0.4 \pm 0.18 W.m^{-2}$ (1.65 σ, i.e. 90% CL)

OHC estimation from Argo since the 2000s



Global coverage on the 4th of May 2018



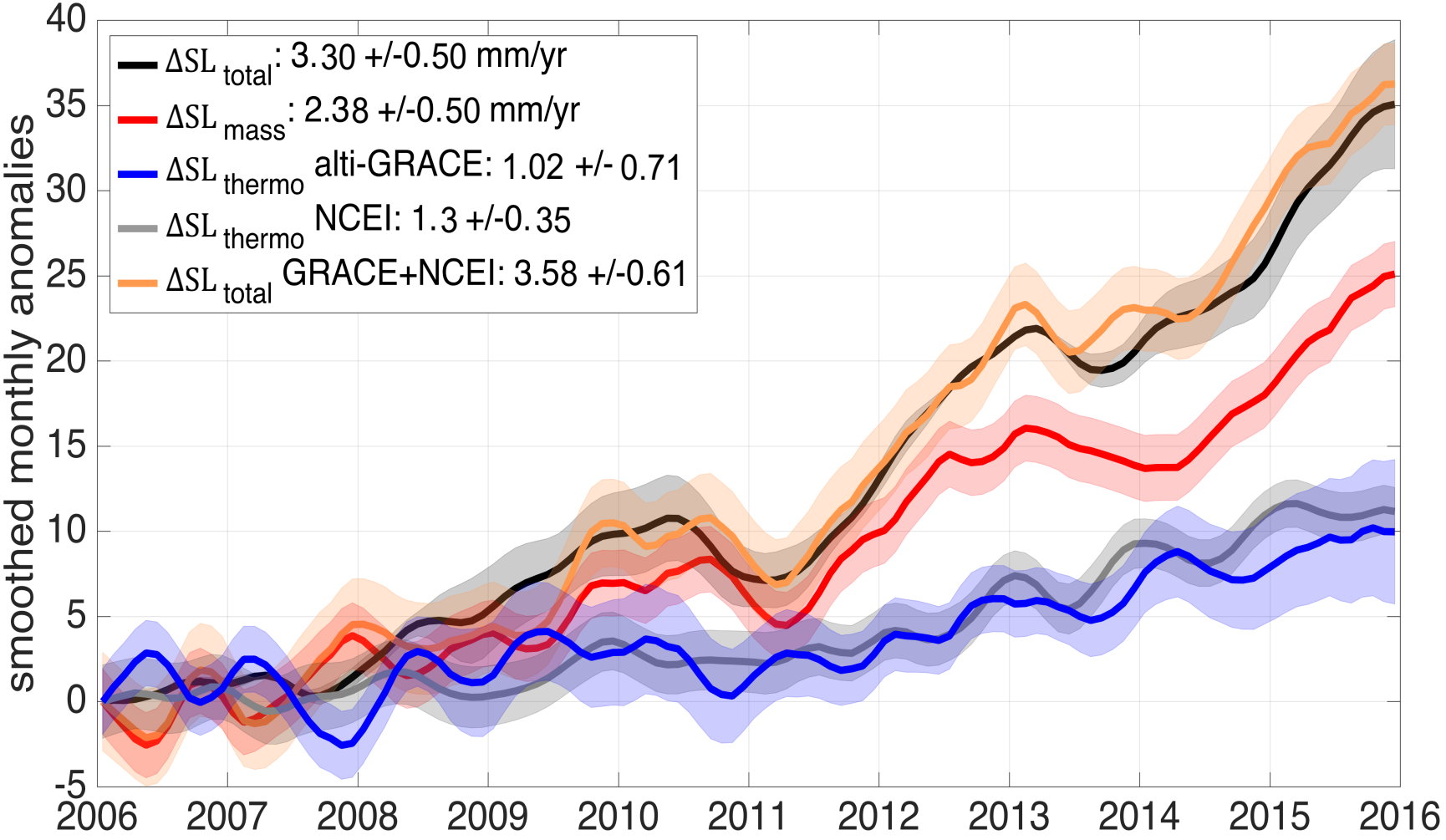
global OHC from Argo since 2005 (0-2000m) 0.66 ± 0.26W.m^{-2} (1.65 σ)

OHC estimation from in situ data

-	Uncertainty due to quality control	Uncertainty due to errors in the bias corrections	Uncertainty due to the choice of climatology	Uncertainty due to the mapping method	Uncertainty due to the time correlation of the measurements	Uncertainty due to data distribution	Uncertainty due to the formal error of the optimal procedure (e.g. least square)	Time Period (years)	Depth range (m)	Trend Wm^{-2}	Uncertainty Wm^{-2}
Cheng et al. (2019)	no	no	no	no	yes but the method shows problems when applied over the period 2005-2017.[a] This method is not mature yet and is subject to further adjustments.	no	yes (ordinary least square)	2005-2017	0-2000	0.54	±0.02
Cheng et al. (2017)	no	no	no	no	no	no	yes (ordinary least square)	1992-2015	0-700 700-2000 0-2000	0.38 0.23 0.61[b]	±0.03 ±0.02 ±0.036[c]
Johnson et al (2018)	no (except in range of estimates)	no (except in range of estimates)	no (except in range of estimates)	no (except in range of estimates)	yes (autocorrelation analysis)	no	yes (ordinary least square)	1993-2017	0-700 700-2000 0-2000	0.36 to 0.40 0.19 to 0.35 0.48 to 0.70[b]	±0.06 to ±0.18 ±0.01 to ±0.07 ±0.06 to ±0.16[c]
Lyman and Johnson (2008)	no	no	no	no	no	yes	no	2000-2005	0-750	n/a	±0.06 to ±0.18[d]
Lyman et al. (2010)	yes	yes	yes	yes	yes (autocorrelation analysis)	no	yes (weighted least square)	1993-2008	0-700	0.64	±0.11
Johnson et al. (2016)	no	no	no	no	yes (autocorrelation analysis)	no	yes (ordinary least squares)	2005-2015	0-bottom	0.68	±0.10
Levitus et al. (2009)	no	no	yes	yes	no	no	yes	2005-2017	0-2000	0.51	±0.15
Palmer et al. 2007; Palmer and Brohan., (2011)	no	no (except in range of estimates)	no (except in range of estimates)	yes	no	no	no	1993-2017	0-700	0.40	±0.18
Domingues et al. (2008)	yes	no	no but remove a trend to reduce biases from historical climatologies (space, time, location data)	yes	no	no	yes	1993-2018	0-700	0.64	±0.03
Ishii et al. (2017)[e]	no no	no no	yes no	yes no	yes yes	yes yes	yes no	1993-2018	0 - 700 0 - 2000 0 - 700 0 - 2000	0.36 0.61 0.36 0.53	±0.07 ±0.08 ±0.01 ±0.05

From Meyssignac et al. in press

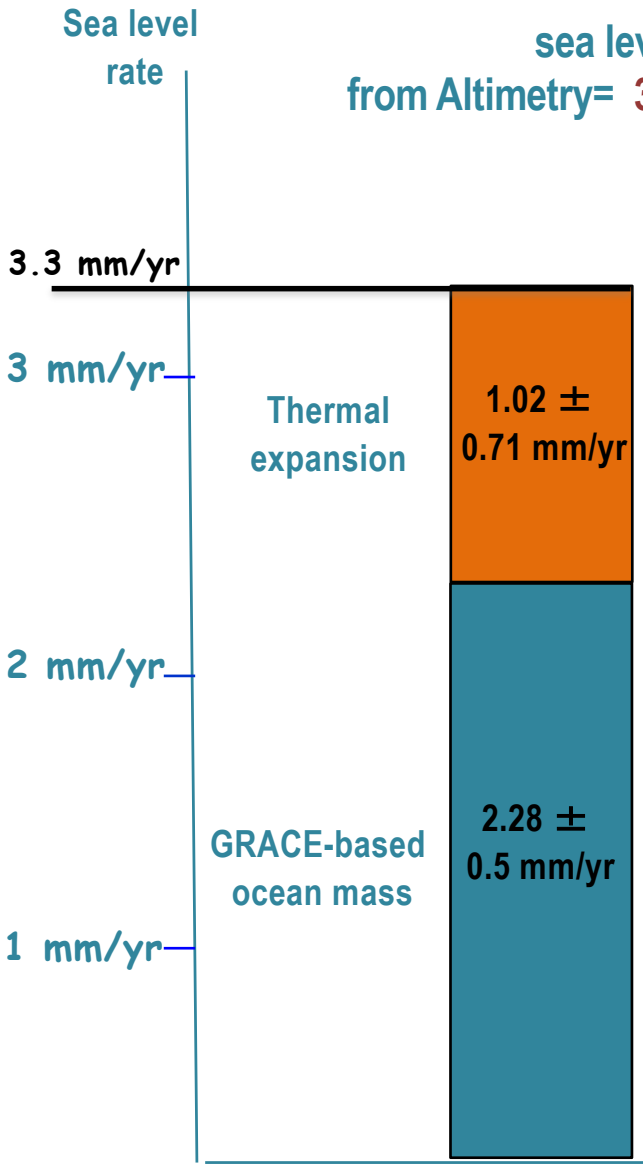
OHC estimation from the sea level budget

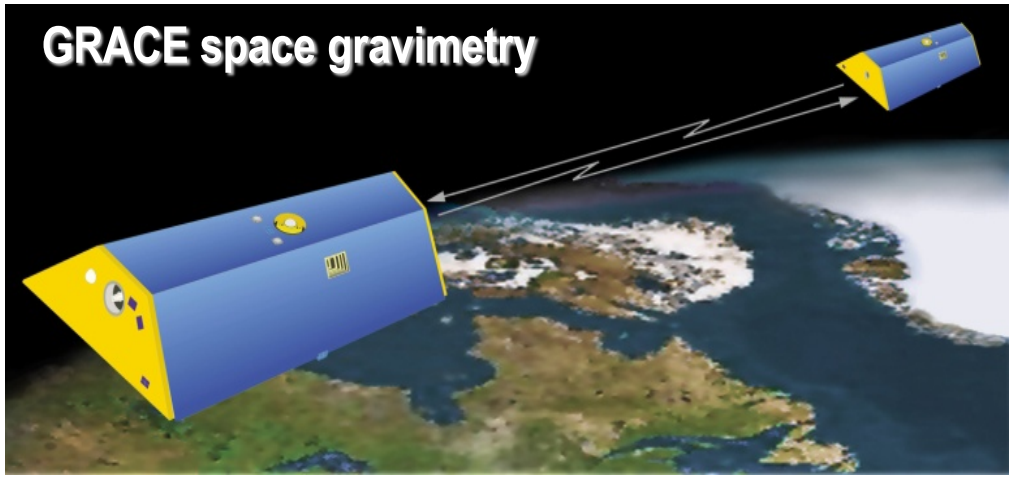


From Meyssignac et al. in press

OHC from satellite altimetry and GRACE

Example over 2006-2015

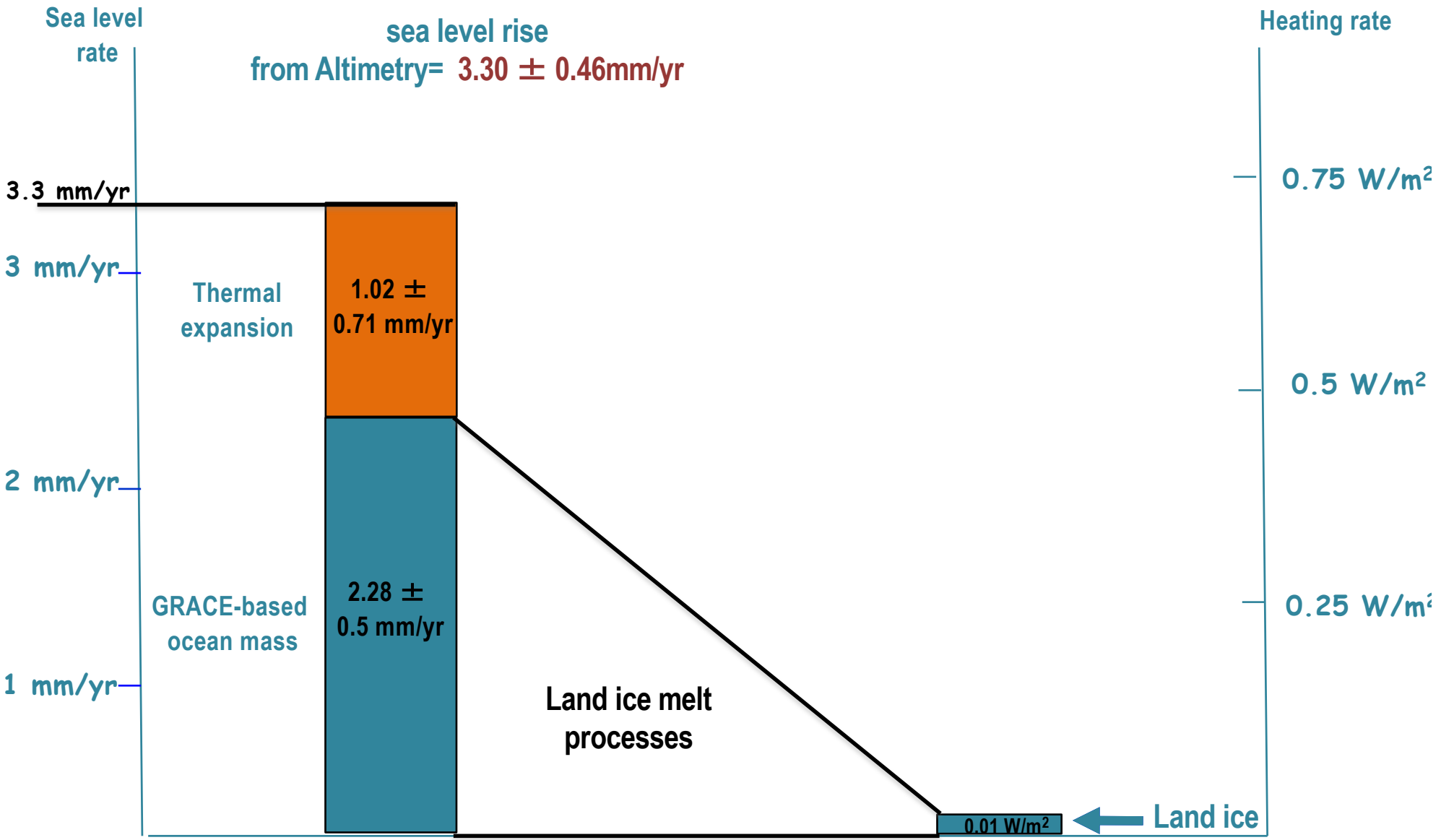




(from Dieng et al. 2015)

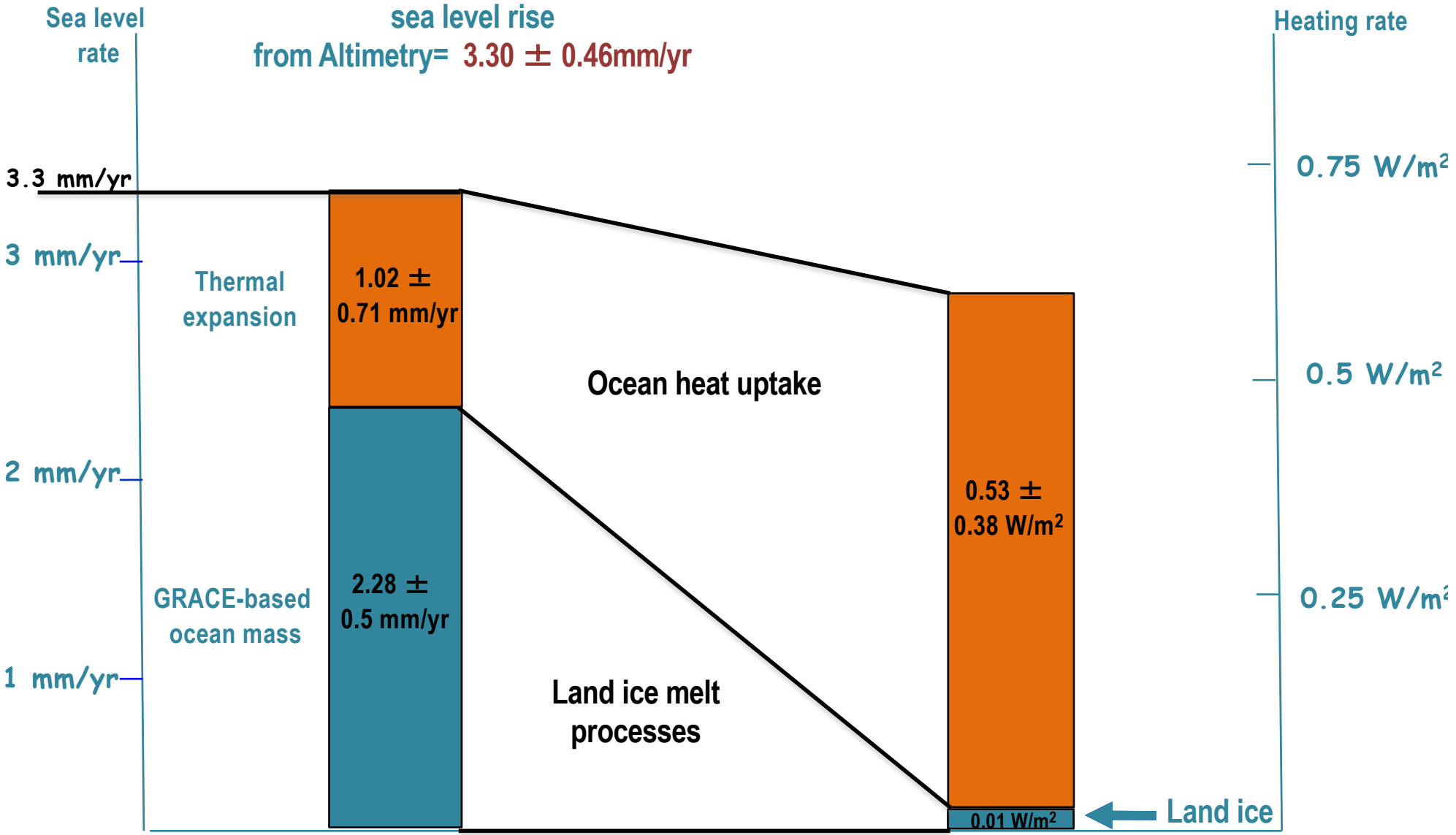
OHC from satellite altimetry and GRACE

Example over 2006-2015



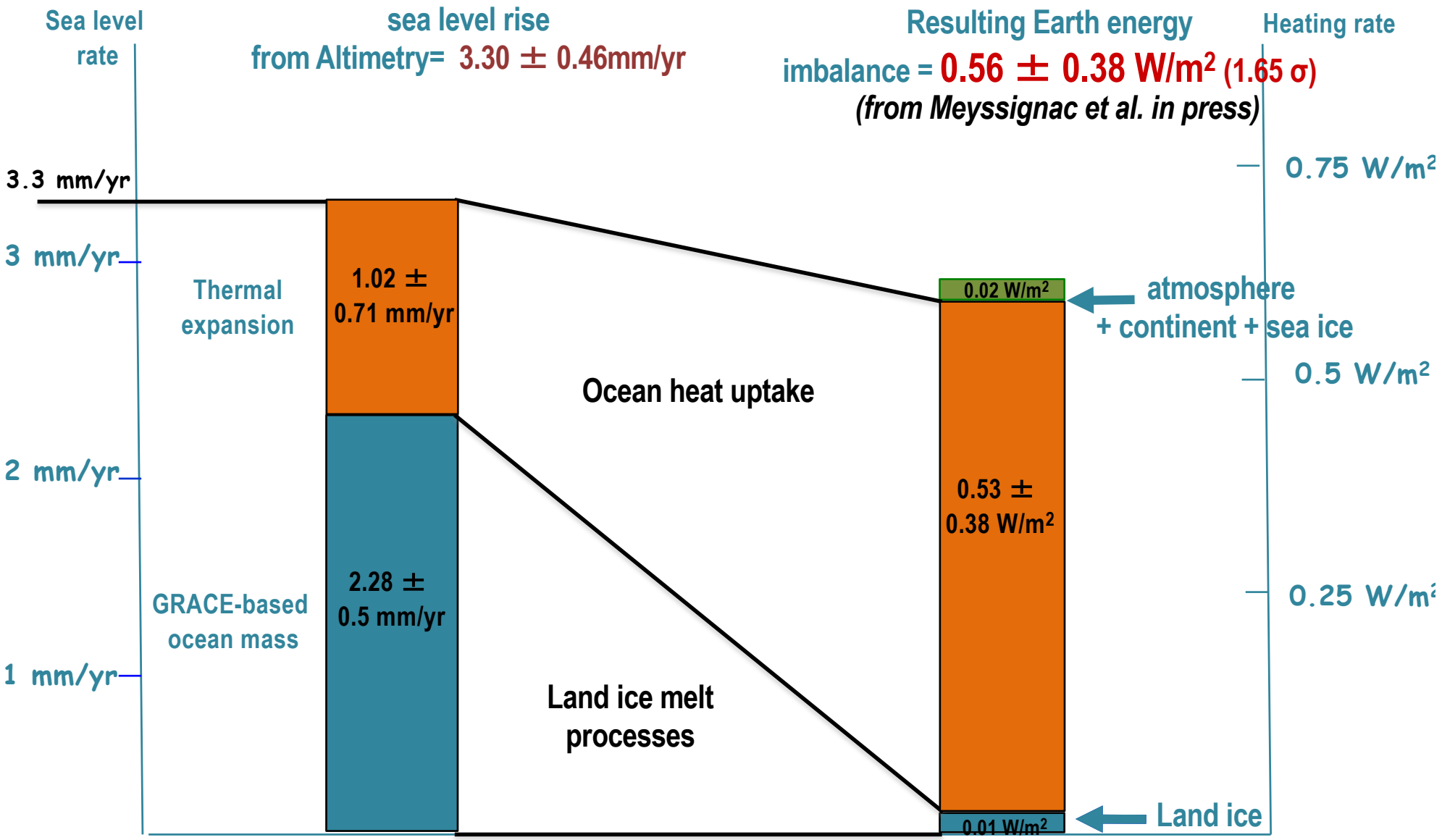
OHC from satellite altimetry and GRACE

Example over 2006-2015

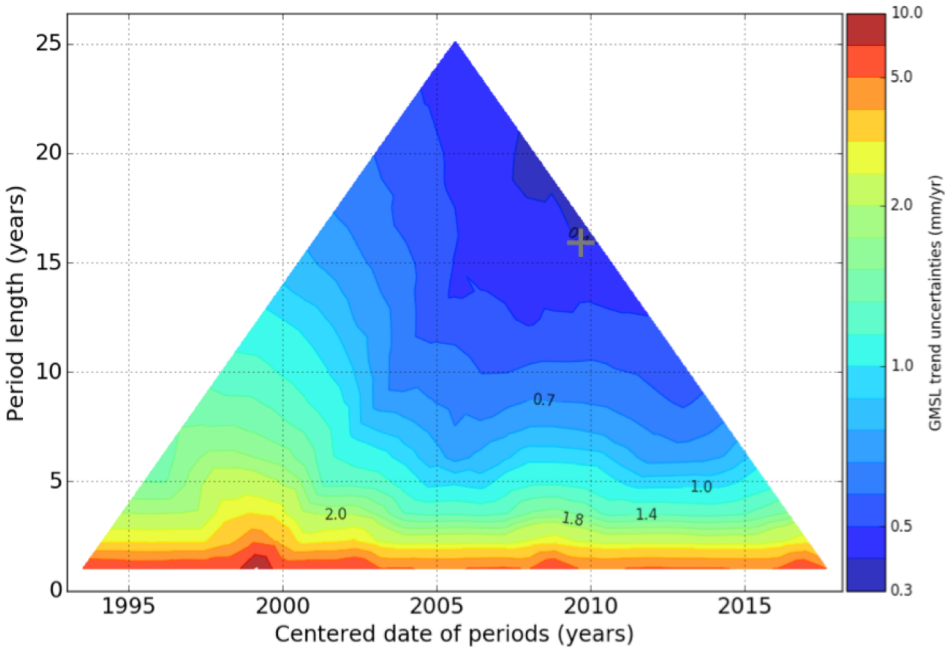


OHC from satellite altimetry and GRACE

Example over 2006-2015



OHC from satellite altimetry and GRACE



Uncertainty in sea level trend from satellite almtimetry (1.65 σ)

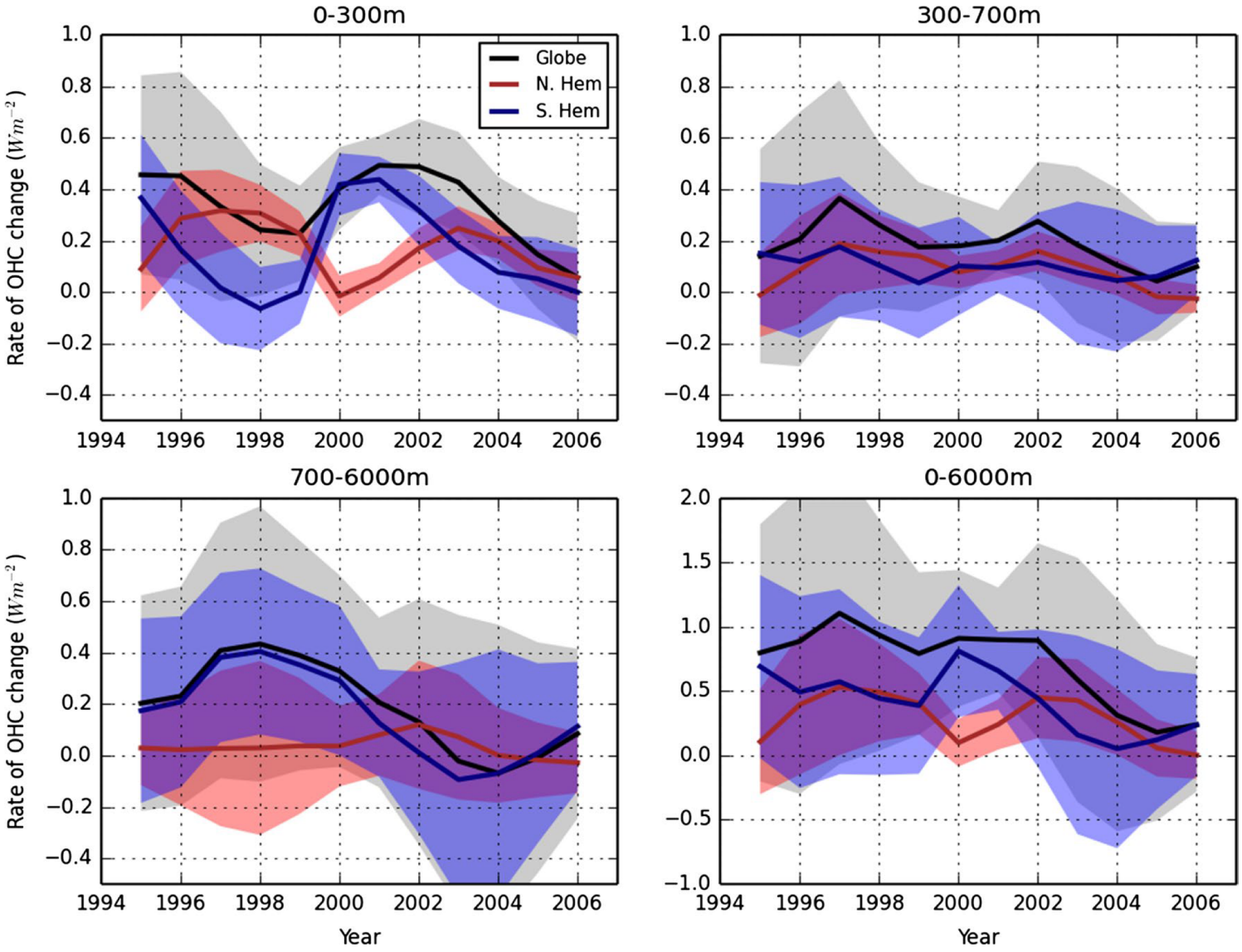
From Ablain et al. in press

(mmSLE/yr)	GOM	Greenland	Antarctica	Arctic islands	Glacier &TWS
Processing center	0.08	0.02	0.04	0.02	0.08
Geocenter motion	**0.55**	0.05	**0.17**	0.04	**0.63**
$C_{2,0}$	0.03	0.01	0.02	0.01	0.01
Filtering	0.02	0.01	0.01	0.02	<0.01
Leakage correction	0.03	<0.01	<0.01	<0.01	0.03
GIA	**0.23**	0.01	**0.13**	0.03	**0.12**
Total Uncertainty	0.52	0.06	0.18	0.06	0.56
RMS Uncertainties	0.60	0.06	0.22	0.06	0.64
Interaction	0.08	<0.01	0.03	<0.01	0.08

Uncertainty in ocean mass trend from GRACE (1.65 σ)

From Blazquez et al. 2018

OHC from ocean reanalyses



global OHC from reanalyses 0.71 ± 0.7W.m^{-2} (1.65 σ)

From Palmer et al. 2017

Earth Energy imbalance estimates

Ocean heat uptake	Time period	Spatial Coverage and/or depth range	mean in Wm^{-2}	Uncertainty in Wm^{-2} at the 5–95%CL	Correlation with CERES EBAF EEI	RMSE with CERES EBAF EEI Wm^{-2}
From *in situ* observations	2006-2015	0-2000m deep ocean contribution 0-bottom	0.61 (update of Johnson et al. 2018) [a] 0.04 (update of Purkey & Johnson, 2010). 0.65 [c]	±0.1 [b] ±0.04 (update of Purkey & Johnson, 2010); ±0.11 [d]	0.44	0.40
	1993-2017	0-2000m (no marginal seas, no ice covered areas) deep ocean contribution (below 2000m, no ice covered areas) 0-bottom	0.62 (update of Johnson et al. 2018) [a] 0.04 (update of Purkey & Johnson, 2010); 0.66 [c]	±0.22 [e] ±0.04 (update of Purkey & Johnson, 2010); ±0.22 [d]		
From surface net heat flux	2006-2015	Net ocean surface heat flux	10 to 15 [f]	±15 [g]		
From satellite altimetry and GRACE	2006-2015	0-bottom (no sea ice covered areas above 82°N)	0.53 [h]	±0.38 [i]	0.89	0.26
	2002-2016	0-bottom (no sea ice covered areas above 82°N)	0.57 [j]	±0.29 [k]		
From ocean reanalyses	2006-2015	0-2000m deep ocean contribution (below 2000m, no ice covered areas) 0-bottom	0.7 (update von Shuckmann et al. 2008) [l] 0.04 (update of Purkey & Johnson, 2010). 0.74 [c]	±0.13 (update von Shuckmann et al. 2008) [m] ±0.04 (update of Purkey & Johnson, 2010); ±0.14 [d]	0.50	0.41
	1993-2008	0-bottom	0.71 (from Palmer et al. 2017)	±0.7 (spread across 15 ocean reanalyses from Palmer et al. 2017)		
From CMIP5 climate model simulations	2000-2010	0-bottom	0.73 (from Smith et al. 2015)	±0.21 (spread across 21 CMIP5 climate model simulations, from Smith et al. 2015)		

From Meyssignac et al. in press

Conclusion

- The most efficient method to estimate EEI is to estimate the energy storage.
- Because the ocean stores >90% of the excess of energy. The global OHC provides a strong constraint on the EEI
- There are 3 methods to estimate the global OHC: in-situ temperature from Argo, thermal expansion from altimetry minus GRACE, and OHC from ocean reanalysis
- Argo: partial coverage: 2000m depth, ocean under sea ice, marginal seas depth; high accuracy: 0.65 $\pm$0.21W.m^{-2}; low correlation with CERES: limited resolution of the interannual variability; regional distribution (vertical and horizontal)
- Altimetry minus GRACE: partial coverage: down to the bottom, until 82° N, lesser quality under sea ice ; medium accuracy: 0.53 $\pm$0.38W.m^{-2}; High correlation with CERES, horizontal distribution only
- reanalyses: global coverage; assimilate altimetry, Argo and sometimes GRACE; low accuracy: 0.74 $\pm$0.70W.m^{-2}; low correlation with CERES

- The uncertainty in global OHC is still high ~35-40%. No need to explore the energy storage in the other reservoirs that for less than 10% of the EEI until the uncertainty is reduced

Perspective/ recommendations

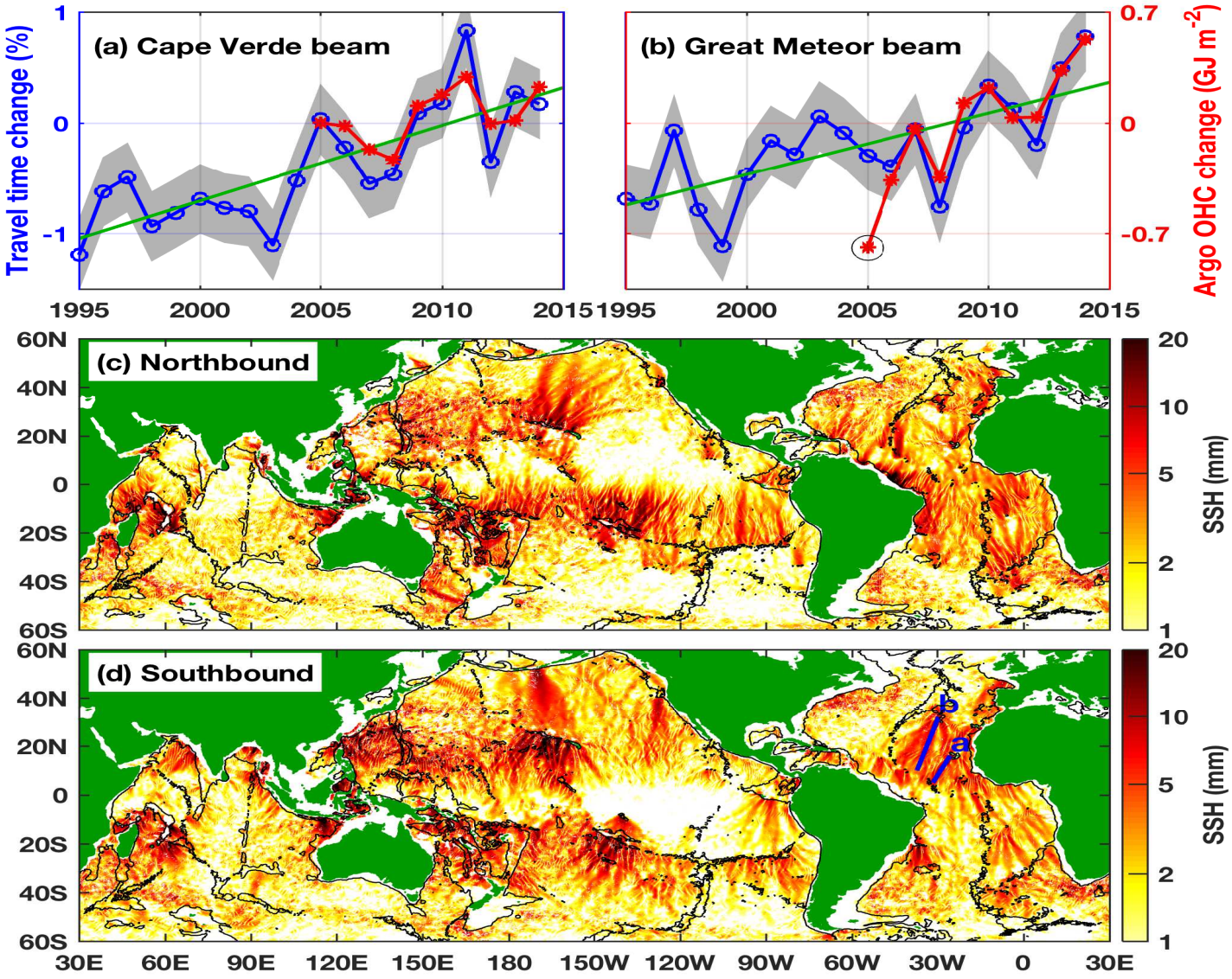
- Argo:
  Sustained observations accompanied with R&D activities to improve the climate record
  increase the coverage: down to 4000m depth, under sea ice, in marginal seas to improve the uncertainty at decadal and interannual time scales
  Intercompare,improve and validate the uncertainties by maintaining different platforms of observations and developing intercomparison studies

- Altimetry minus GRACE:
  Sustained observations accompanied with R&D activities to improve the climate record
  Improve satellite altimetry measurements in the leads, improve the resolution of GRACE and the revisit of satellite altimetry to get to monthly estimate of the EEI
  Intercompare,improve and validate the uncertainties in GRACE with the freshwater budget of the ocean using Argo salinity record

- Reanalysis:
  Intercompare the deep ocean OHC estimate and understand the reasons for the differences

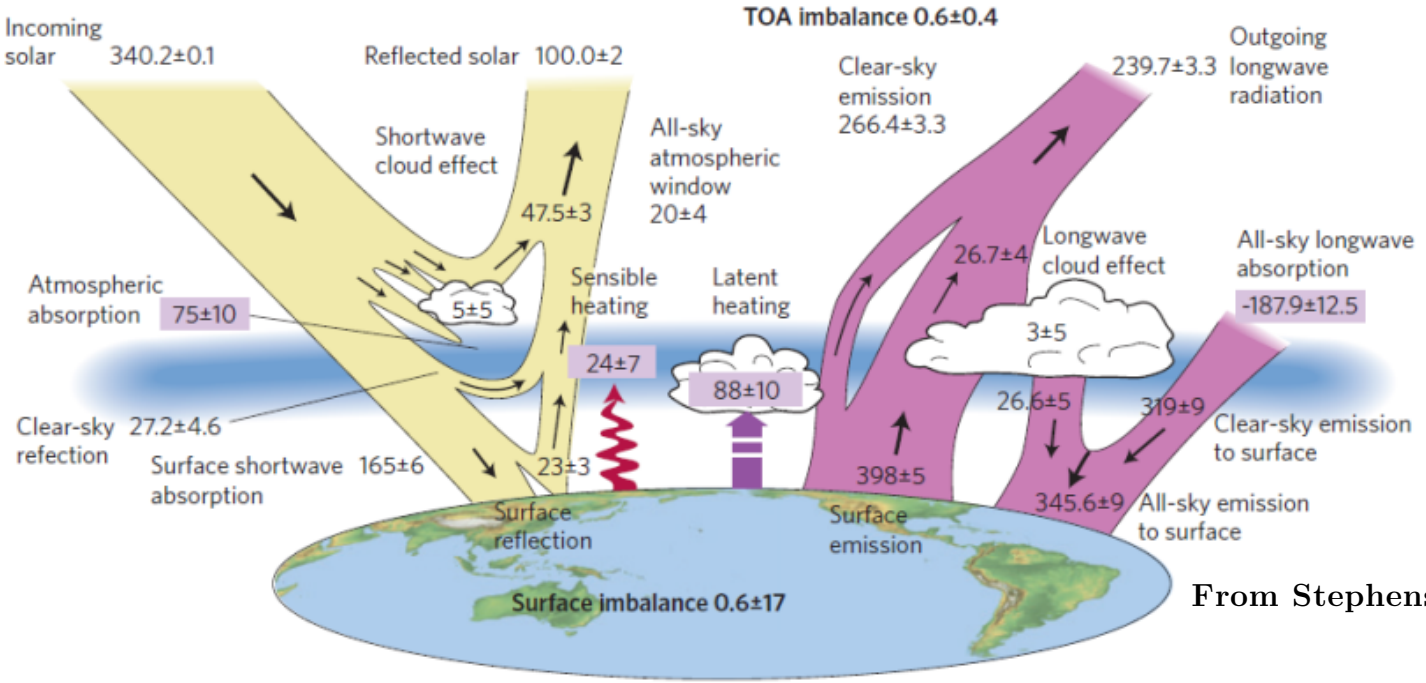
Perspective/ recommendations

- Internal tide oceanic tomography:



Extra slide

Tracking ~1W.m^{-2} in the global water/energy cycle ?



From Stephens et al 2012

Various 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

EEI observation provides an 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