→ 10th COASTAL ALTIMETRY WORKSHOP

SAR Altimetry Training Course

SAR Altimetry Processing for Open Ocean Sea Level Monitoring/SLCCI Multi Mission Datasets

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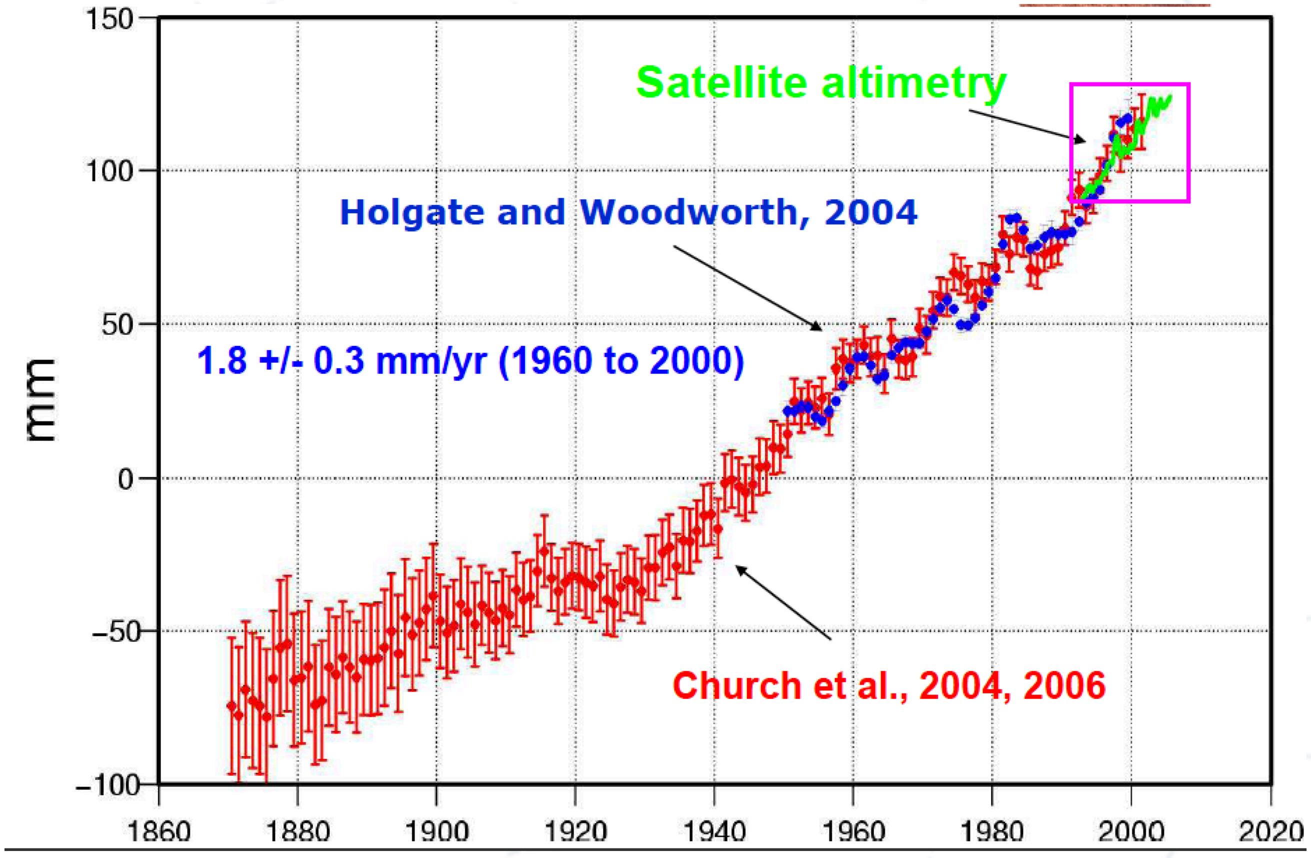
21–24 February 2017 | Florence, Italy

Outline

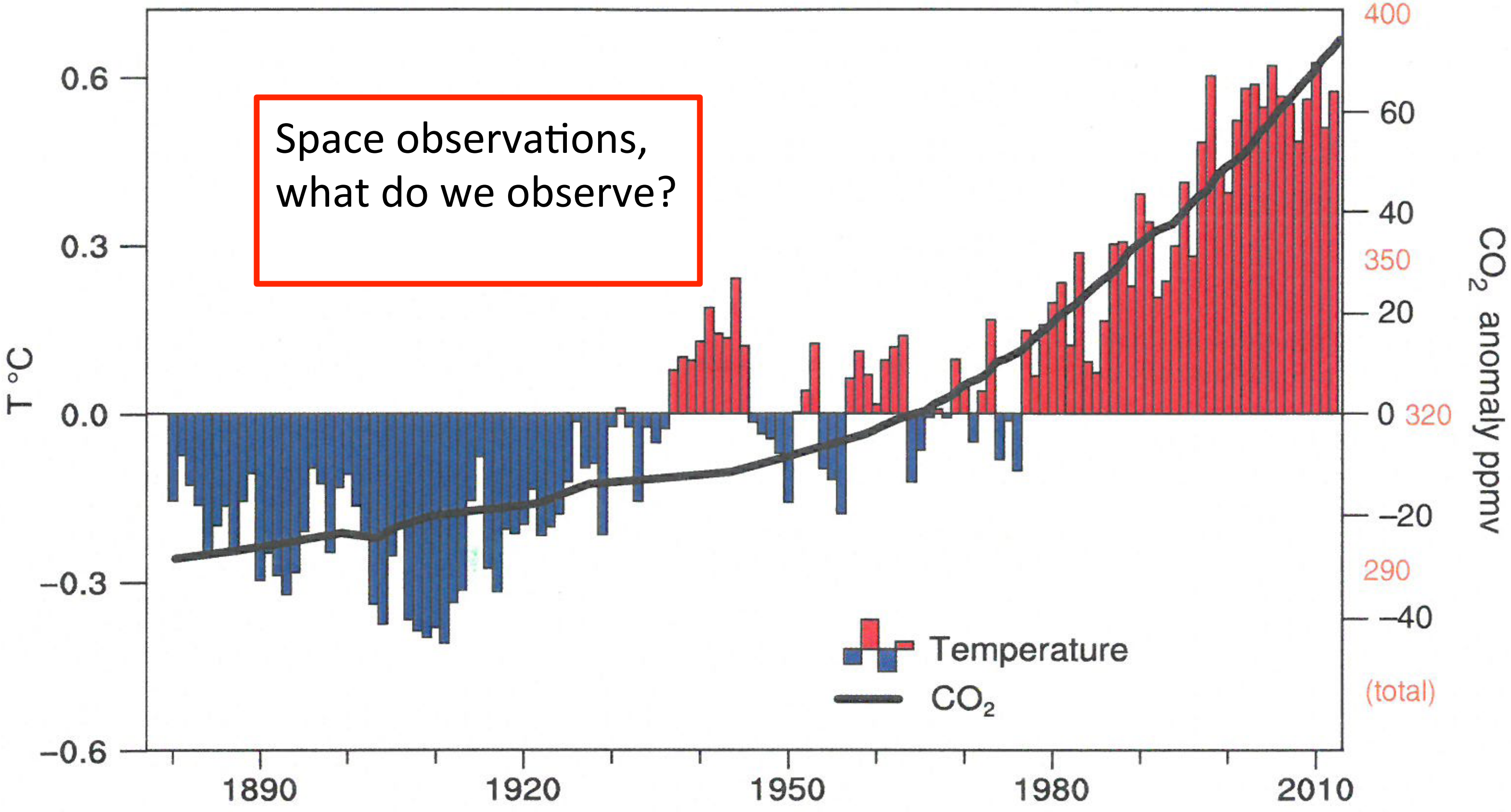
- Sea Level Monitoring / SLCCI Multimission Dataset
  - Space observations, what do we observe?
  - ESA Sea Level Climate Change Initiative (SLCCI)
  - Application of SLCCI datasets for sea level monitoring
- SAR Altimetry Processing for Open Sea
  - Novelty in SAR for sea level monitoring
  - Improvement assessment / validation
  - Applications of SAR data to open sea

OCEAN is the largest storage of **energy** & largest **water** reservoir

SEA LEVEL MONITORING: S**ea level** change is of primary importance for understanding **climate and water cycle changes**



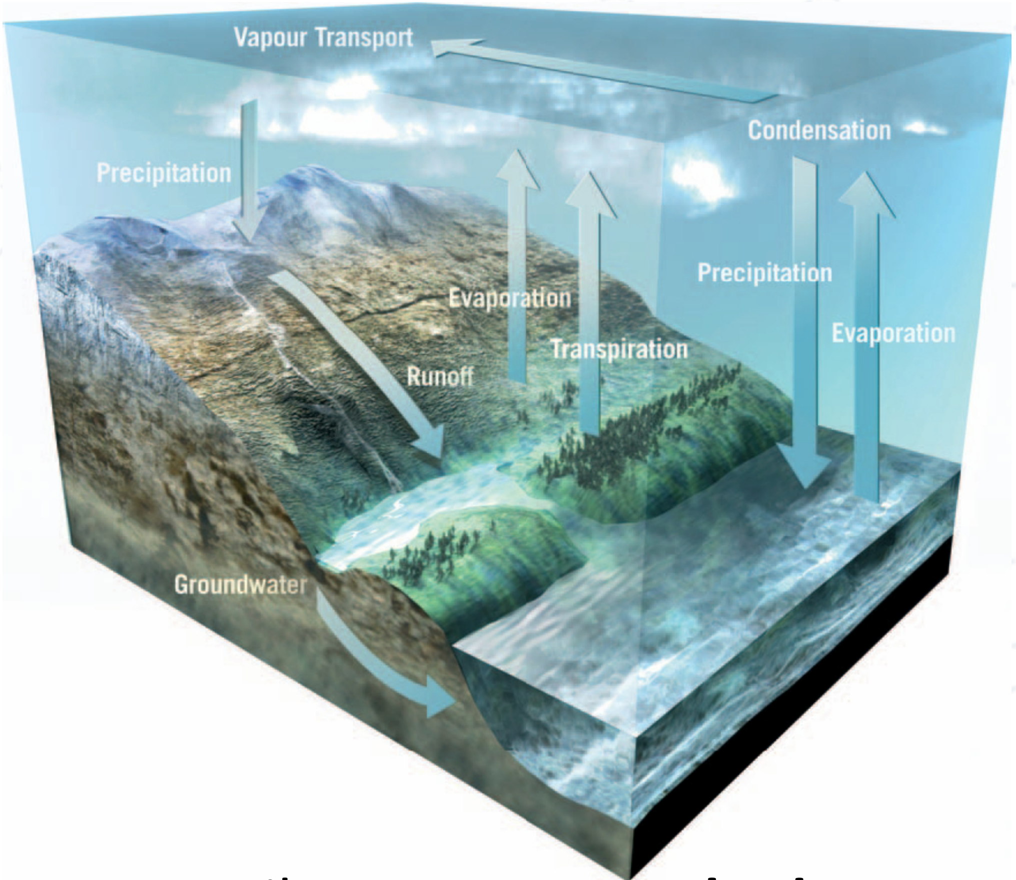
Sea level from observations (TG and altimetry)



Changes in annual global mean surface temperatures (color bars) and CO_2 concentrations (thick black line) given as anomalies from the 1901-2000 average values.

(Trenberth and Fasullo, 2013)

Water Cycle = Exchange of water



- SL change =
- Thermal expansion
  +
- mass addition from the others **reservoirs of water cycle**

Exchange among the reservoirs

- atmosphere (l,s,g)
- ocean (l,s)
- cryosphere (s)
- land surface (l,s)

Water contributes to **energy budget**

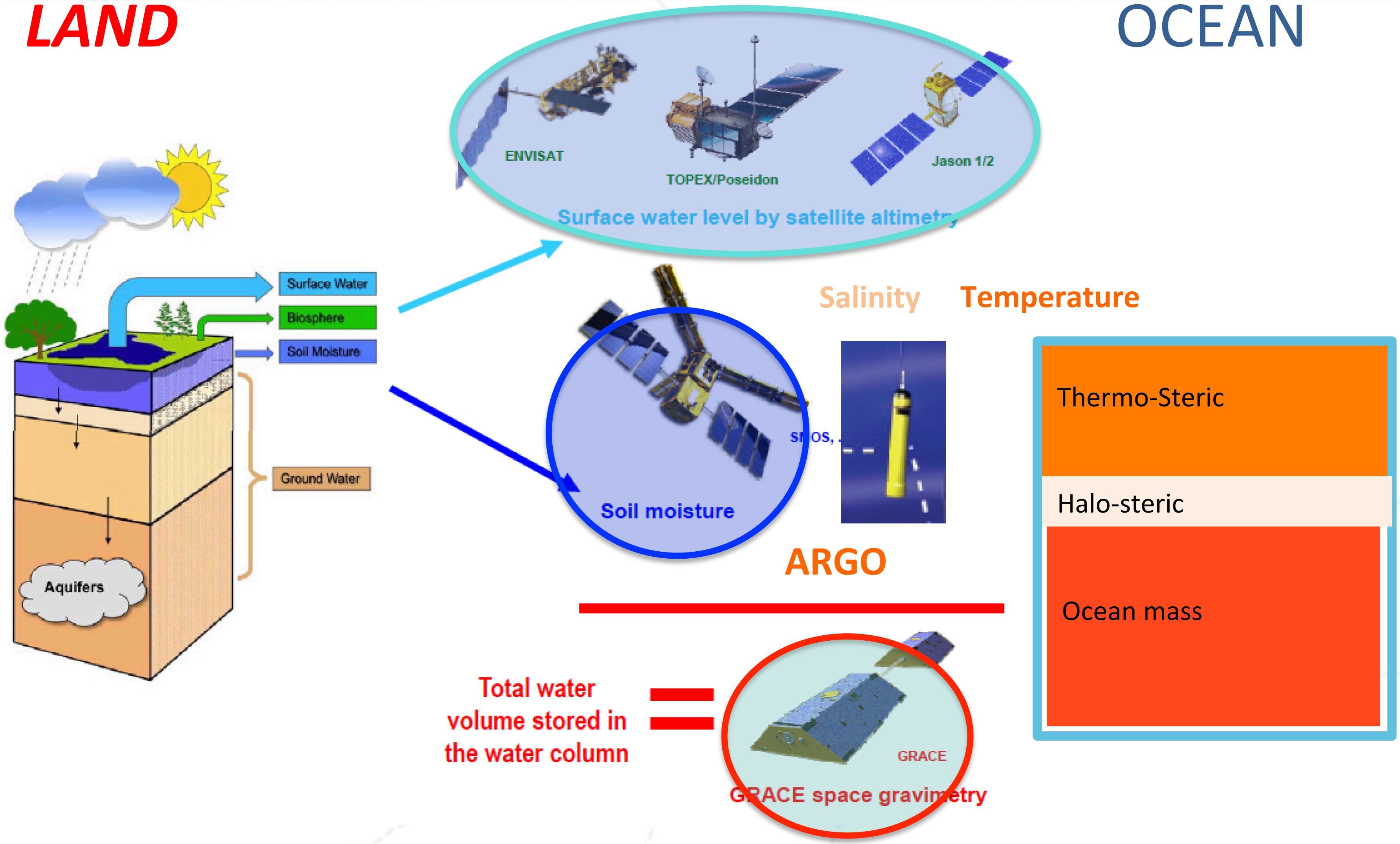
(greenhouse gas, albedo, change state, water transport=energy transport)

- Satellite altimeter SEA LEVEL MONITORING provide one of the observations (SEA LEVEL) relevant for climate change

- Altimetry is a measurement of Geometry

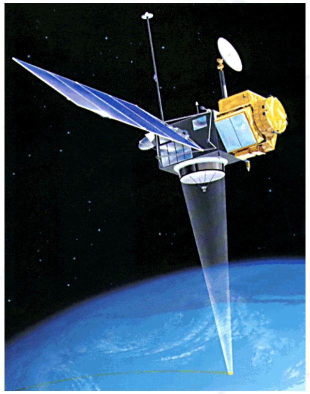
Geometry	Gravity
Sea level	Ocean Mass
In-land Water Level	Mass transport in ocean
Ice height	Ice mass

Which is one of the 3 geodetic observables in Geodesy: Geometry, Earth orientation, Gravity and geoid

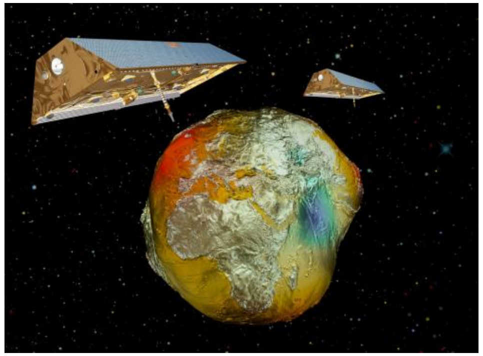


LAND
OCEAN
ENVISAT
TOPEX/Poseidon
Jason 1/2
Surface water level by satellite altimetry
Surface Water
Biosphere
Soil Moisture
Ground Water
Aquifers
Soil moisture
Salinity
Temperature
ARGO
Thermo-Steric
Halo-steric
Ocean mass
Total water volume stored in the water column
=
GRACE
GRACE space gravimetry

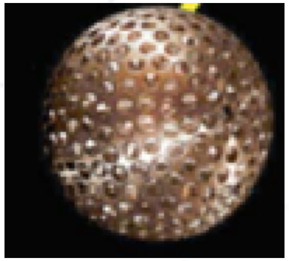
Satellite Altimetry
1992-



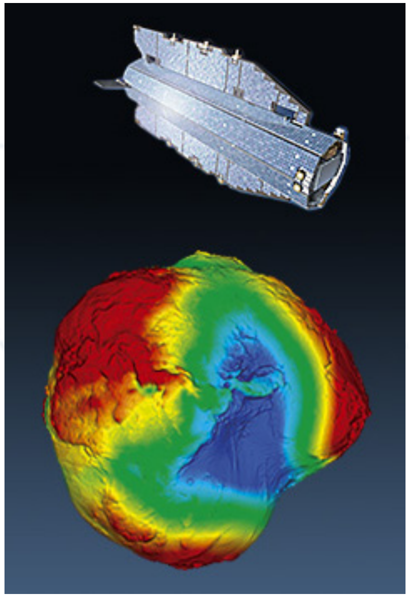
GRACE
2002-



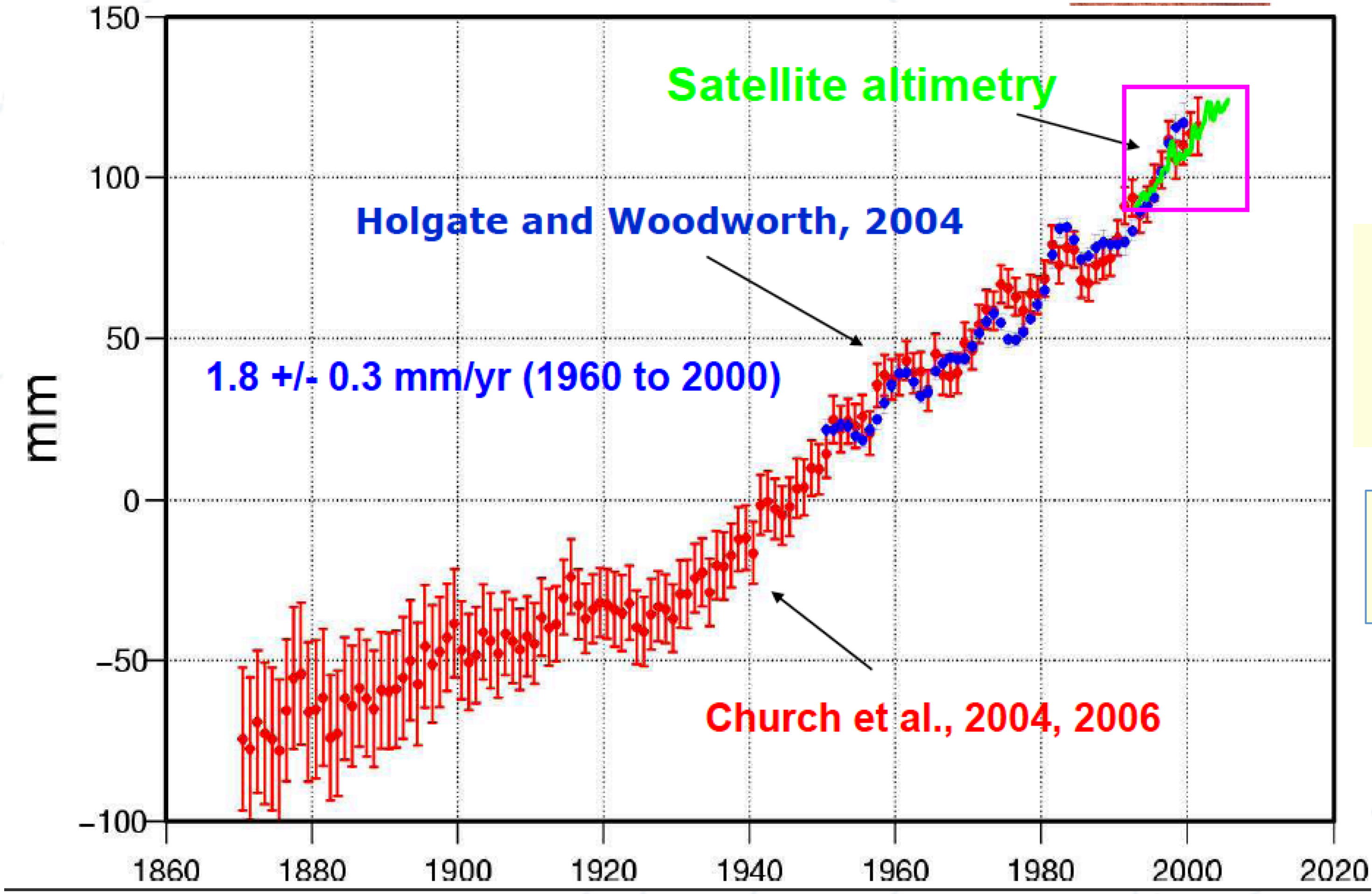
Satellite Laser Ranging
1980-



GOCE
2010-2013



Global Navigation Satellite Systems (GNSS)
1988-



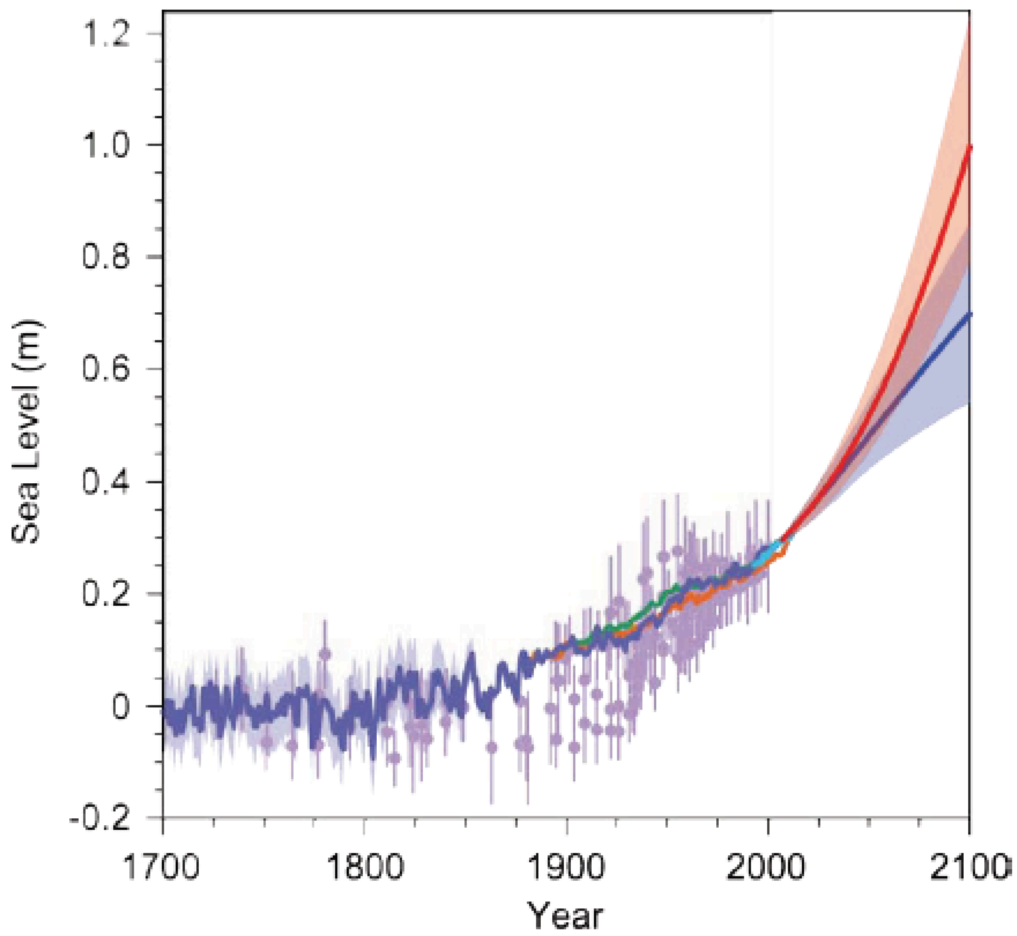
1. Thermal expansion of the water column
T, S

2. Lost of volume of ice: Ocean mass **O**

Satellite observations allow estimation of the present situation

accelerating?

Sea level change **future (model scenarios)**



Projections of global MSL rise for **RCP2.6** and **RCP8.5** scenarios

geodetic observations help in critical evaluation of models

closure of the observational budget

(IPCC AR5, Chapter 13)

Which are the most important questions?

1. Is sea level change **accelerating**?
2. Is ice melting **accelerating**?
3. Is runoff **increasing**?
4. Can we evaluate the **changes** in each hydrological reservoirs?
5. Can we identify the **causes** of sea level change, e.g. distinguish between mass & steric, natural & anthropogenic changes?
6. Can we close the budget of water cycle using **geodetic observations** ?

SLCCI V2.0

- **FCDR**: Fundamental Climate Data Record, along-track data resolution of 1Hz (distance 6km)
- **ECV** : Essential Variable Climate (ECV), gridded data ¼ x ¼ degree
  - Monthly averaged Sea Level Anomalies (SLA)
  - Mean Sea Level changes indicators
    - Global trend
    - Grid of trends
    - Grids of Amplitude, Semi-annual periodic signals
- **Missions**: all
- **Format:** Netcdf

SLCCI

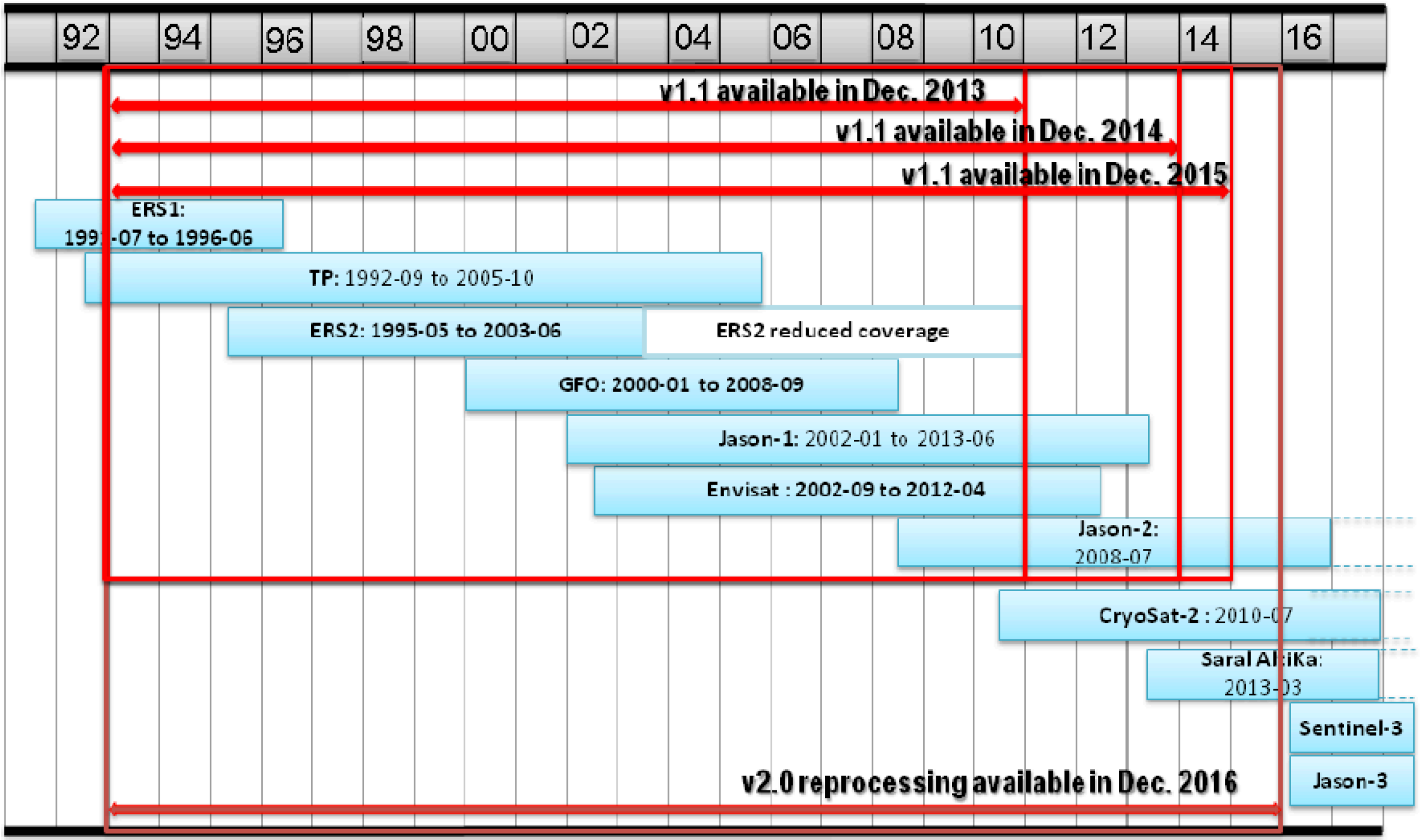


Figure 1: Level 2 GDR altimeter data, used as input data to generate the FCDR and ECV products, are included in the red squares according to the version of the product.

SLCCI

VariableProject	SLCCI	Sea Level Climate Change Initiative
Data	ALTDB	Altimeter Database
Mission	E1	ERS-1
	E2	ERS-2
	EN	Envisat
	TP	Topex/Poseidon
	J1	Jason-1
	J2	Jason-2
	G2	Geosat Follow On
	AL	SARAL/AltiKa
	C2	Cryosat-2
Cycle	xxx	Cycle number of the given altimeter mission
Version	Vx	version number

Figure 2:Nomenclature of the FCDR product

SLCCI

- FCDR analysis

corssh = alt – range - dyn_atmosph_corr - sea_state_bias - ocean_tide - loading_tide - pole_tide - solid_earth_tide - dry_tropo_corr - gpd_wet_tropo_corr - iono_corr

Ablain et al., Surv Geophys (2017) 38:7–31

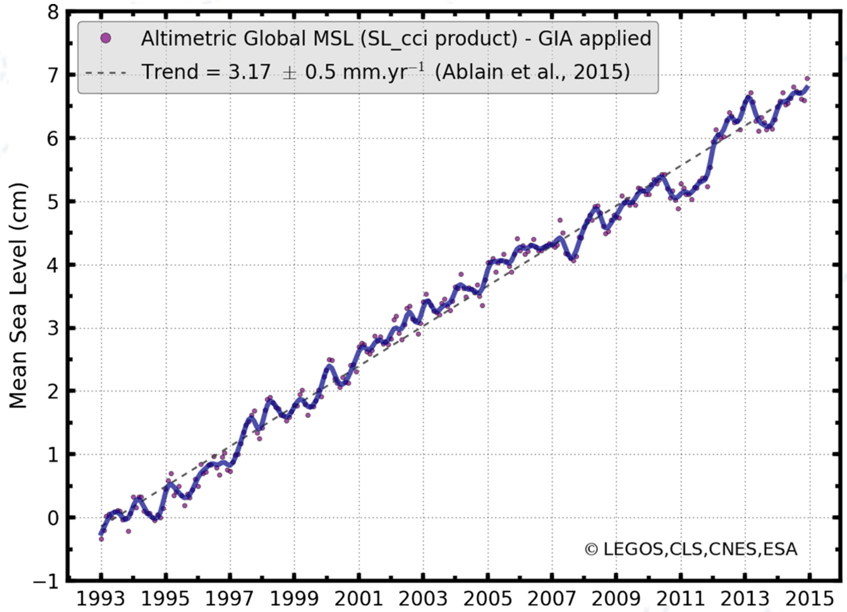


Fig. 2 Global mean sea level over 1993–2014 from SL_cci project. Annual and semi-annual Signals removed from the monthly estimates (red dots) and a 6-month filter applied

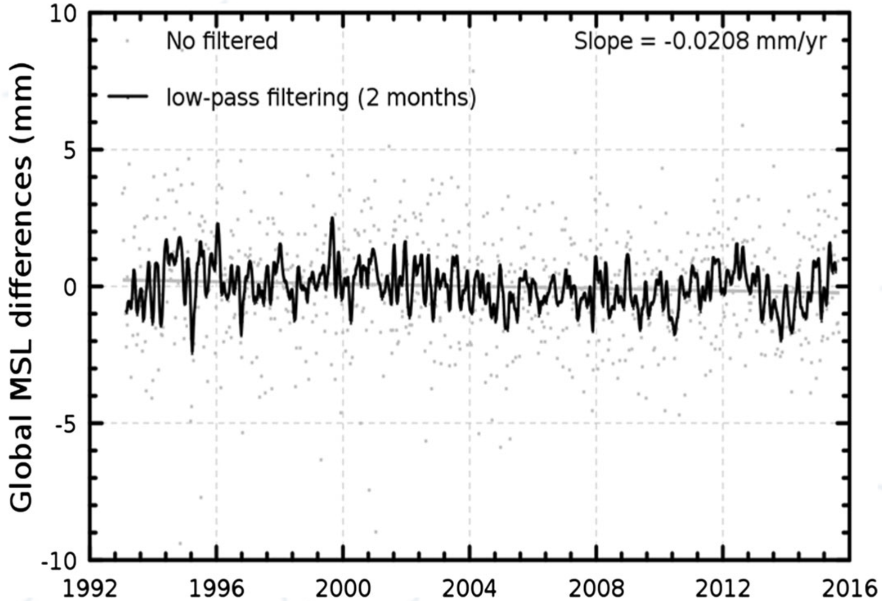
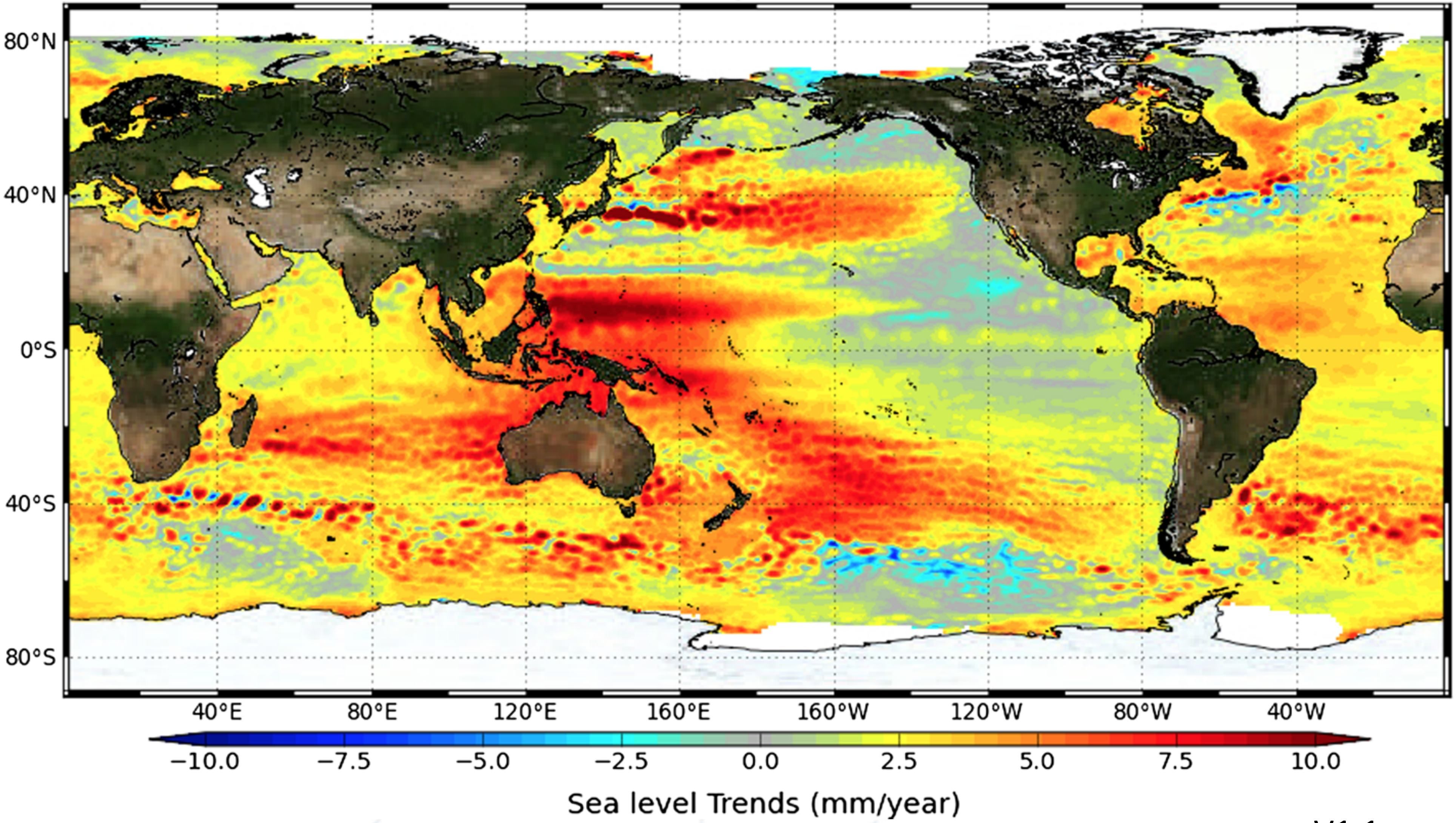


Fig. 3 Global mean sea level differences of SL_cci products and AVISO global mean sea level time series. Same altimeter standards used in both cases


80°N
40°N
0°S
40°S
80°S
40°E
80°E
120°E
160°E
160°W
120°W
80°W
40°W
−10.0
−7.5
−5.0
−2.5
0.0
2.5
5.0
7.5
10.0
Sea level Trends (mm/year)

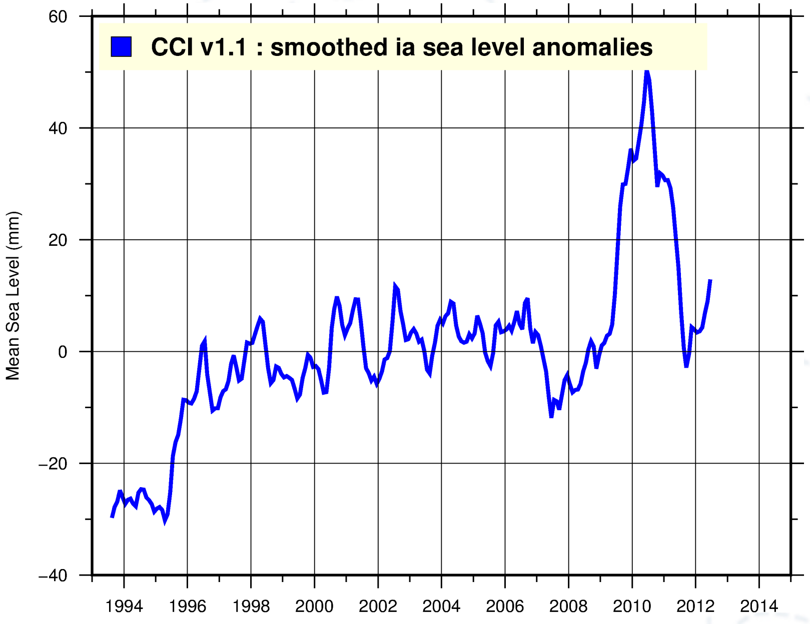
V1.1

Applications

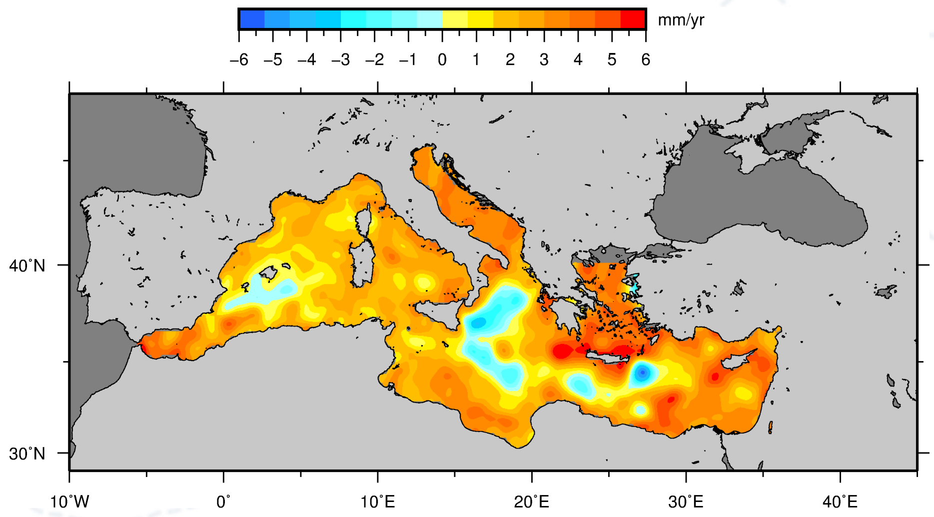
- To assess regionally the quality of the CCI product with a Water Mass Budget estimation

- To assess regionally the quality of SLCCI data in an in-situ validation against geodetic data

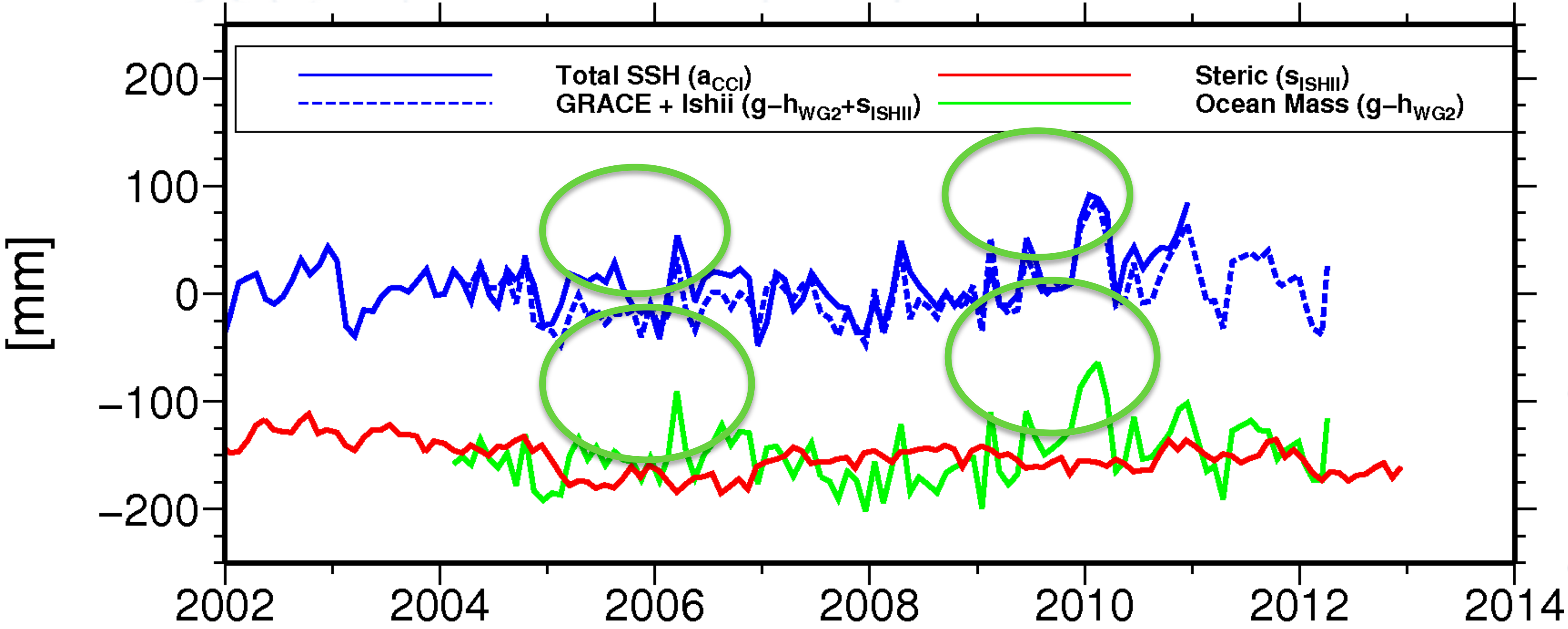
Example 1: Mediterranean Sea



From ECV



Example 1: Mediterranean Sea *de-seasonalized time-series*
SL(altimetry) = mass(GRACE) + steric



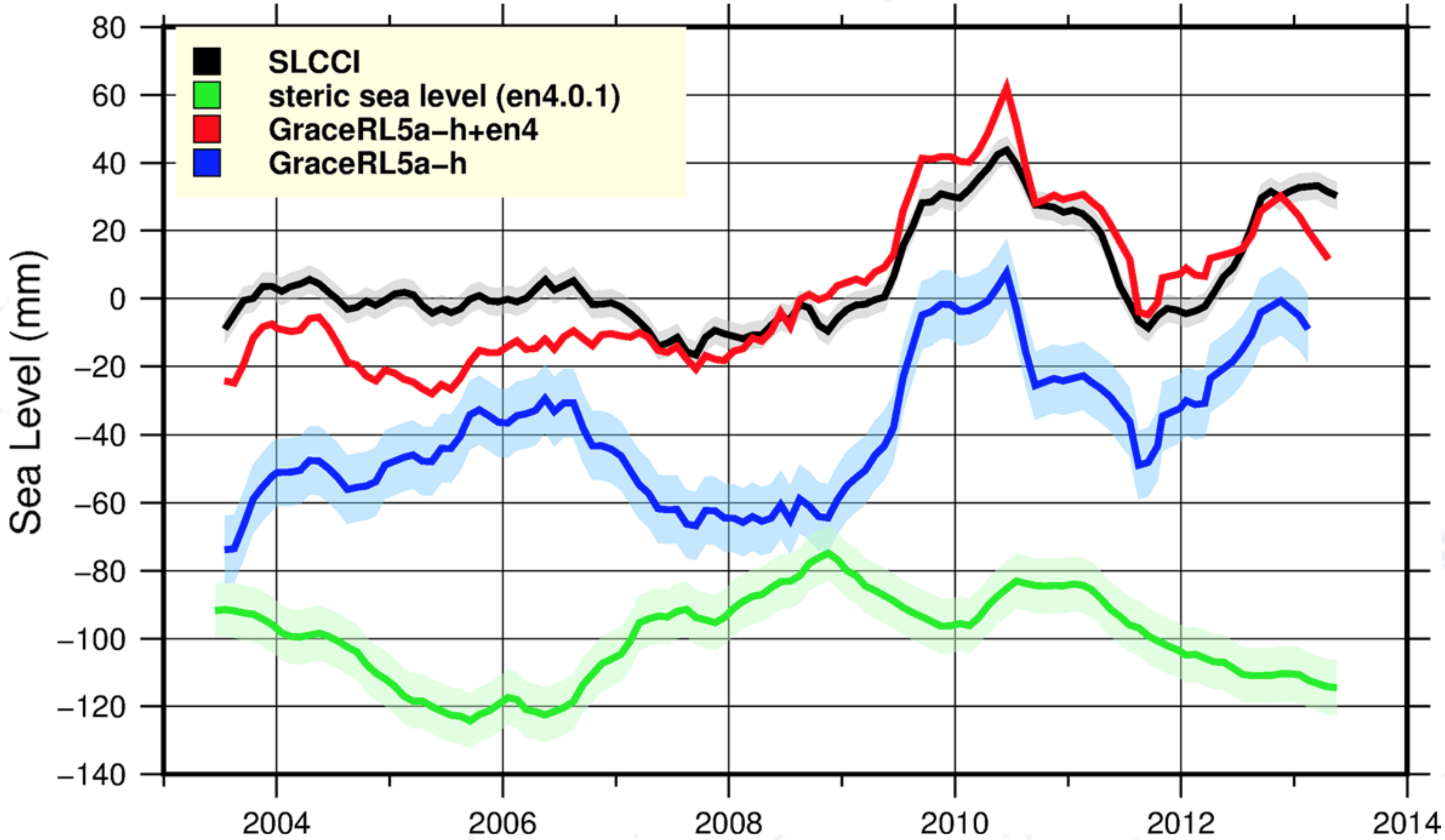
time ➔

Annual and semi-annual signals eliminated

mass change in winter 2005-2006 and 2009-2010

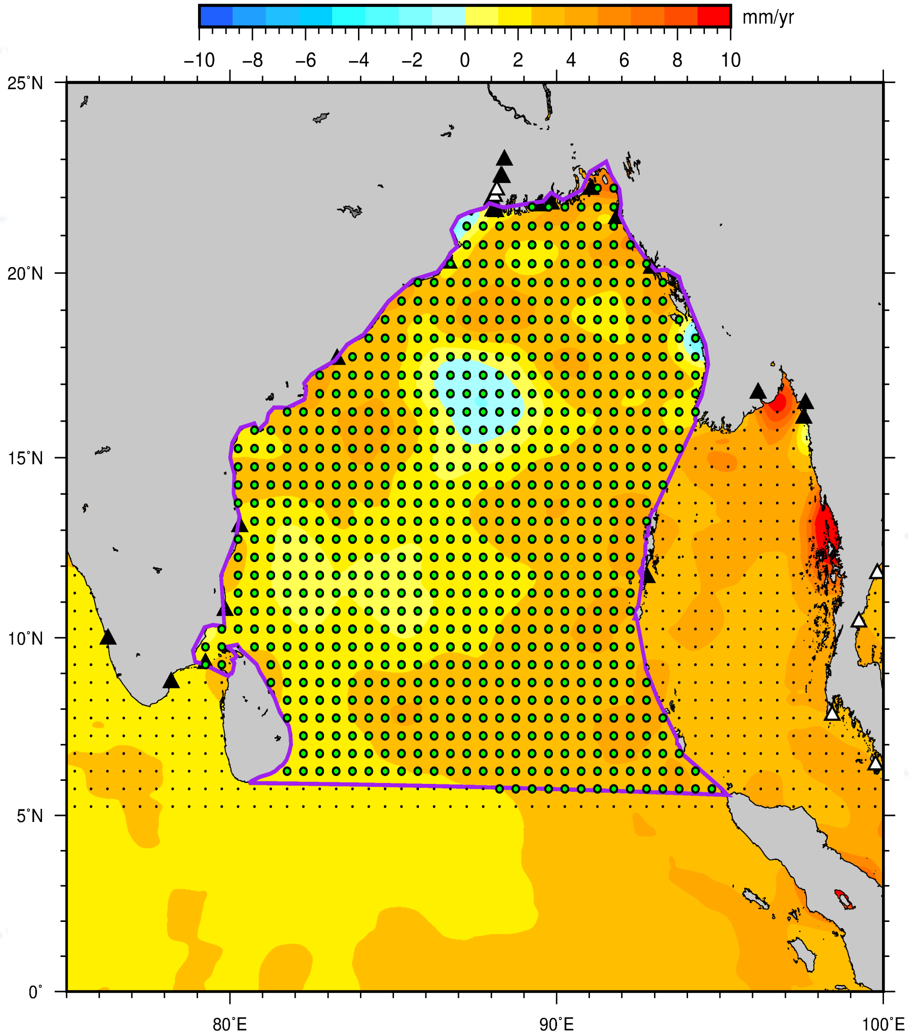
20

Example 1: Mediterranean Sea ***filtered running-average time-series***

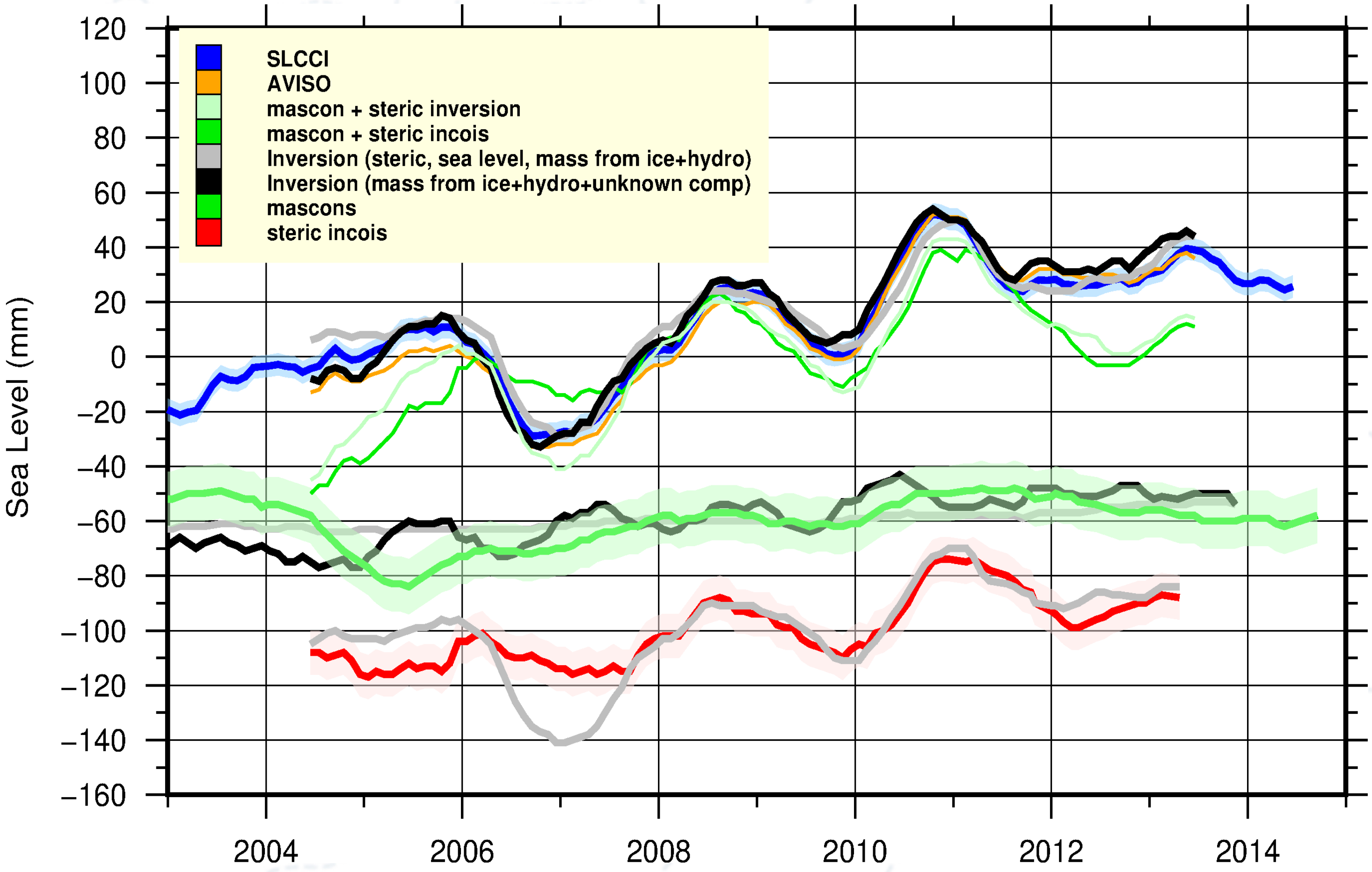


difference in trend and interannual signals of 0.8 m/year and 10.9 mm, respectively.

Example 2: Bay of Bengala region



Example 2: Bay of Bengala region

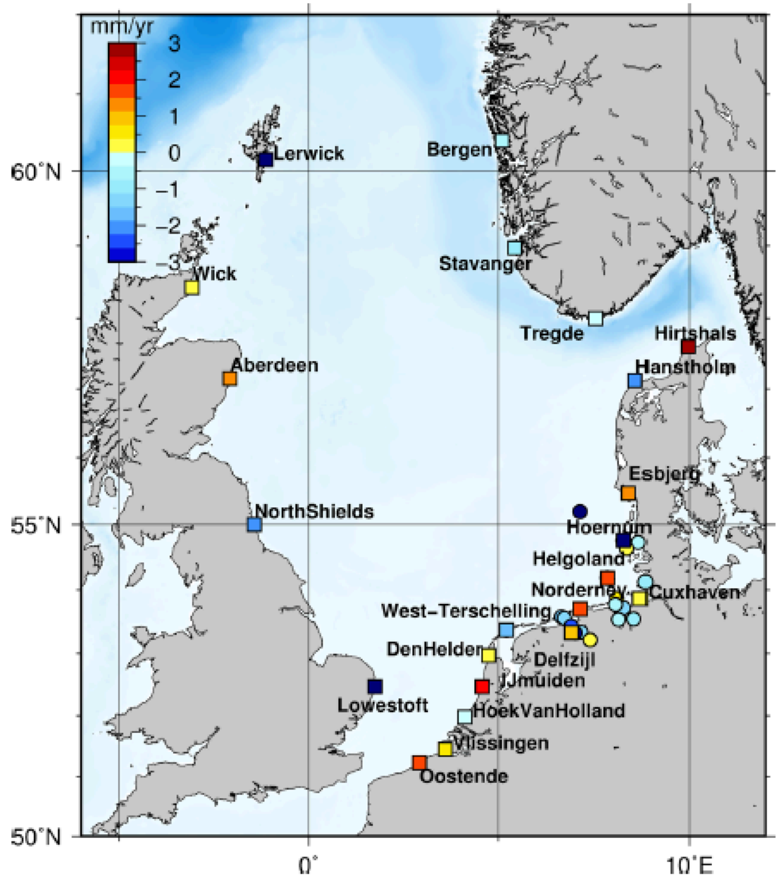


Example 2: Bay of Bengala region

1st	2nd	Corr	Std (mm)	Trend CCI (mm/yr)	Trend 2 mm/yr	type
CCI	AVISO	0.980	5.81	5.26	6.38	ia
CCI	Masc+incoi	0.445	25.3	5.26	5.45	ia
CCI	INV + INV	0.856	12.09	5.26	4.65	ia
CCI	INV+INV	0.898	10.92	5.26	6.18	ia
CCI	Aviso	0.991	3.8	5.48	6.79	mov
CCI	Masc+inc	0.406	15.8	5.48	5.21	mov
CCI	INV + INV	0.963	3.9	5.48	4.74	mov
CCI	INVTOT	0.986	2.45	5.48	6.64	mov

Table 2: Golf of Bengala: Trend and correlation of direct (trend 1) and undirect (trend 2) interannual sea level and standard deviation of their dfferences. For indirect sea level (sl) the trends of its steric (s) and mass components (m) are given. . Interval from Januar 2004 to December 2013

- To assess regionally the quality of SLCCI data in an in-situ validation against geodetic data



Vertical land motion from GPS (circle) and from SL_cci altimetry minus tide gauges (square) in the North Sea, in mm/year

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  – Space observations, what do we observe?
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  – Assessment / validation
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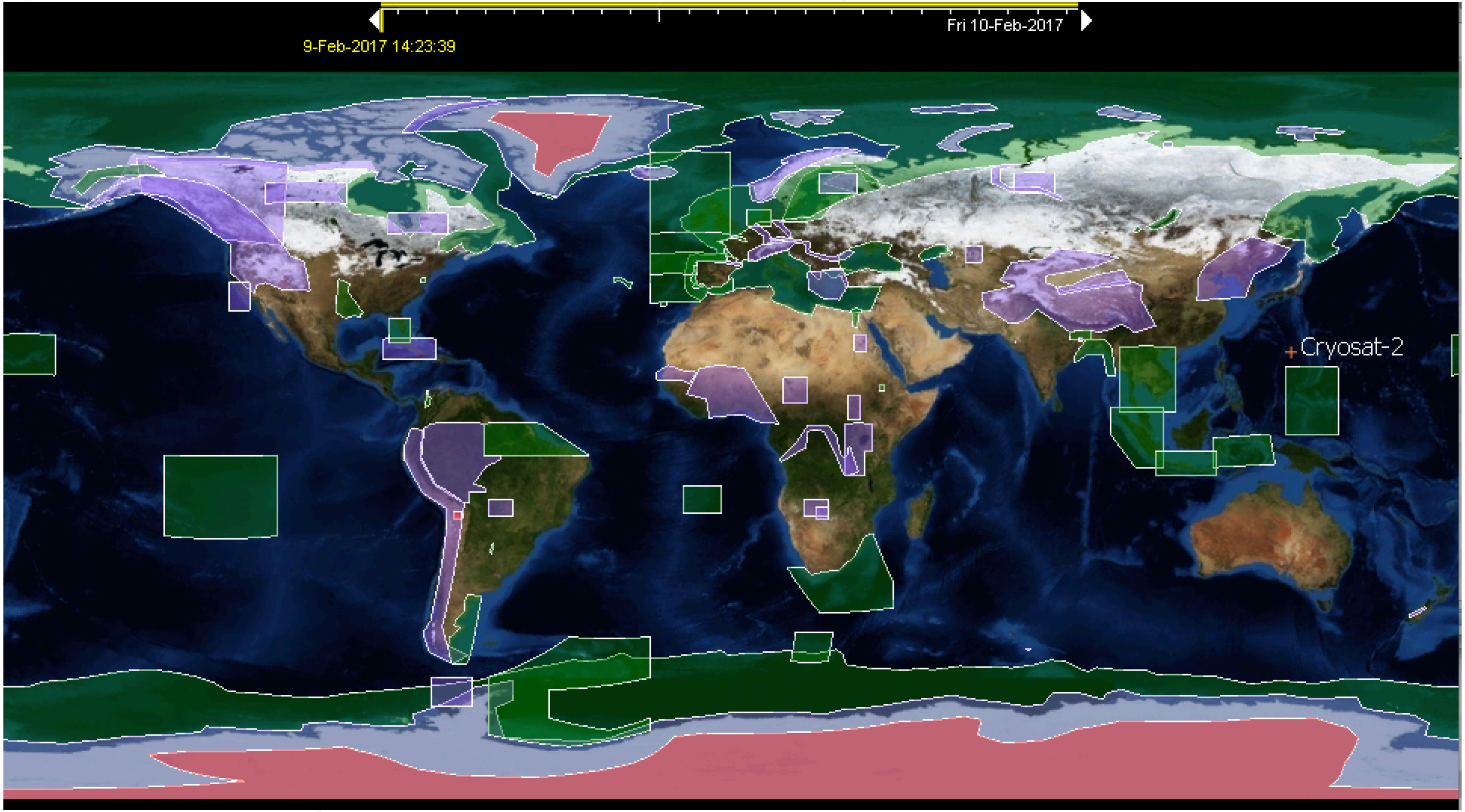
CryoSat-2 MASK 3.9

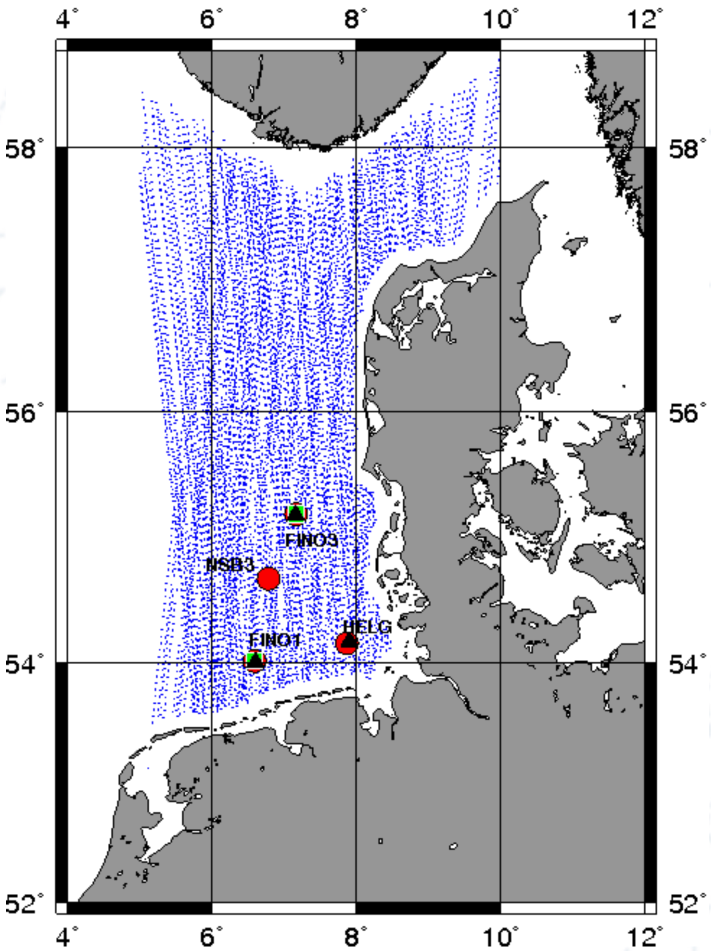


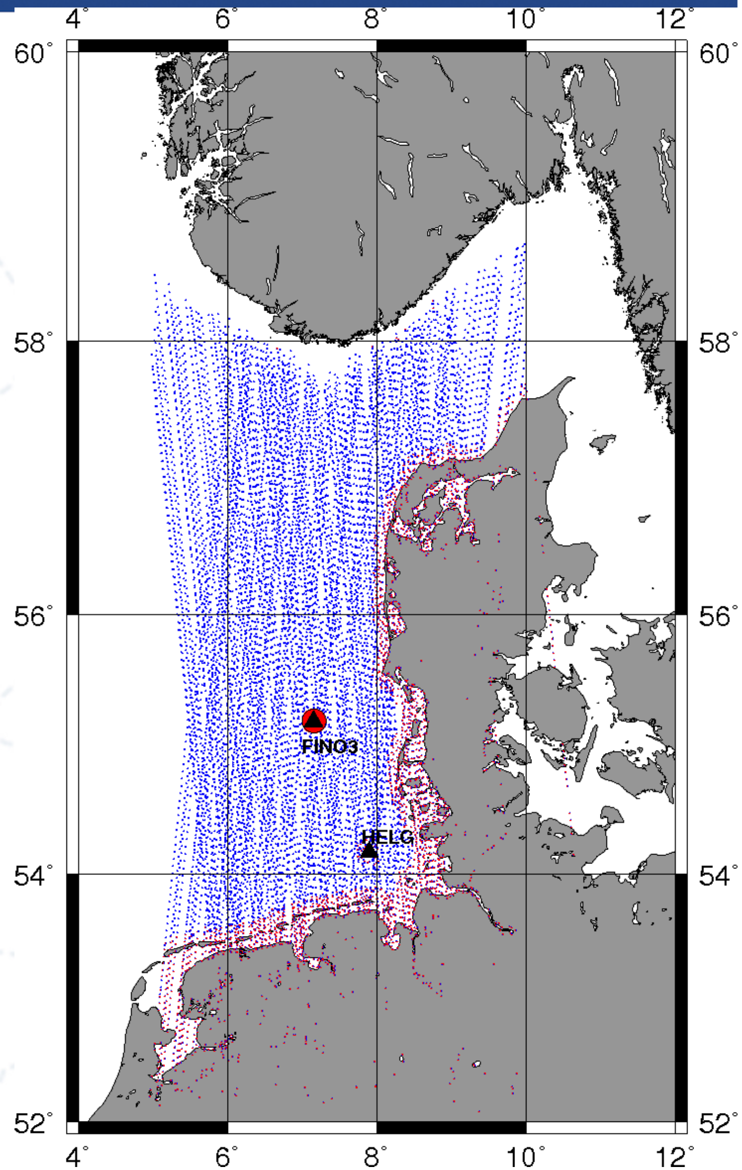
Definitions

- What is „open ocean“ ?
  - For „coastal altimetry“ is „where no disturbance in wf is caused by land
- What is „in azimuth / open ocean“ ? (Taken from Synthetic Aperture Radar Therminology)
  - Azimuth = along-track = slow time
  - in range = across-track = fast time

Open Ocean

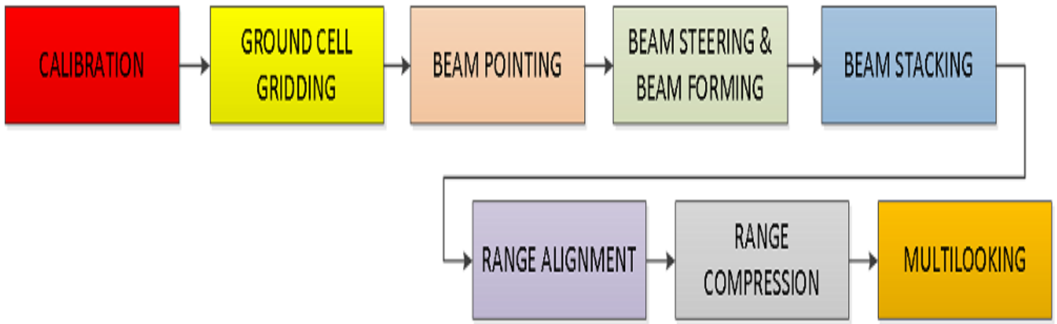
1 Hz





DELAY DOPPLER SAR L1B Processing from L1a to L1b

1. **Calibration Correction** (of SAR FBR waveforms, e.g. Path delay etc.)
2. **Ground Cell Gridding** (identify surface locations on sub-sat elevation)
3. **Beam Pointing** (vectors, angles, ranges)
4. **Beam Steering & Beam Forming: FFT** of the pulse burst **in azimuth (along track)** (synthetize a set of 64 Doppler beams per burst), weighting function, FFT→ 64 Doppler Beams equally spaced, 4.1 Approximated Beam Forming & 4.2 Exact Beam Forming
5. **Beam Stacking**
6. **Range Alignment** (correct mis-alignement between beams same stack)
   6.1 Slant Range C., 6.2 Tracker Range Correction, 6.3 Doppler Range Correction
7. **Range Compression** (compress Doppler Beam Echoes in a stack)
8. **Multi Looking** (single SAR echo in power) (summation in azimuth (along-track) to reduce noise)



How is the processing done ?

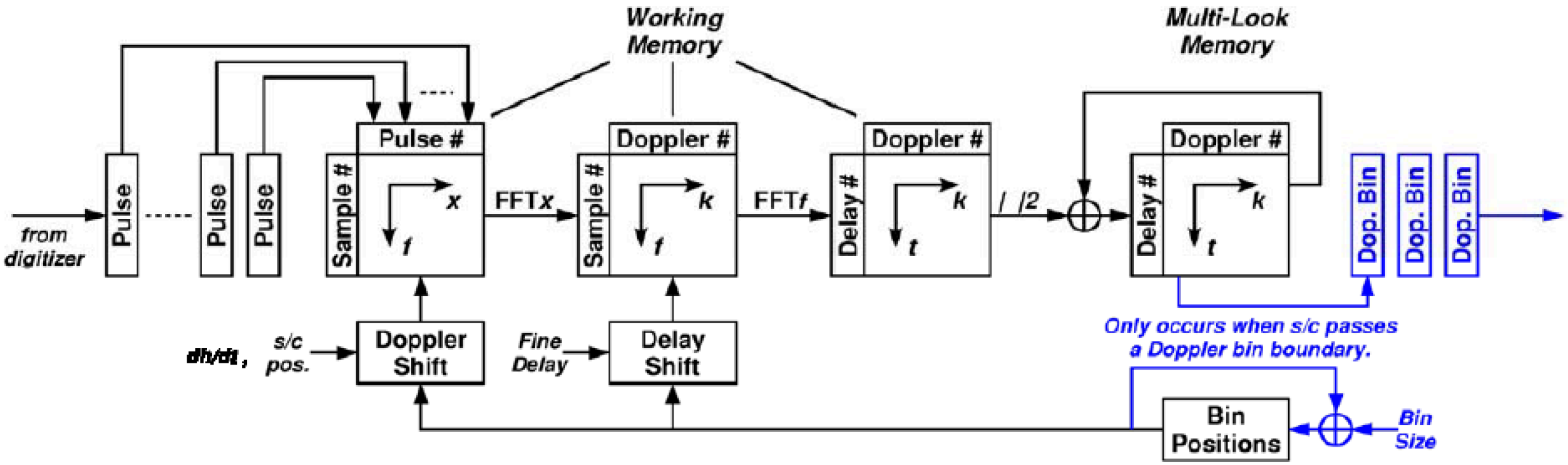


Fig. 4 Signal manipulations operated during the Delay-Doppler Processing.
The range compression and range alignment stages are performed before the stacking stage.
Image courtesy of Keith Russel Raney. From Dinardo „Guideline for SAR DD L1b Processing v2.2

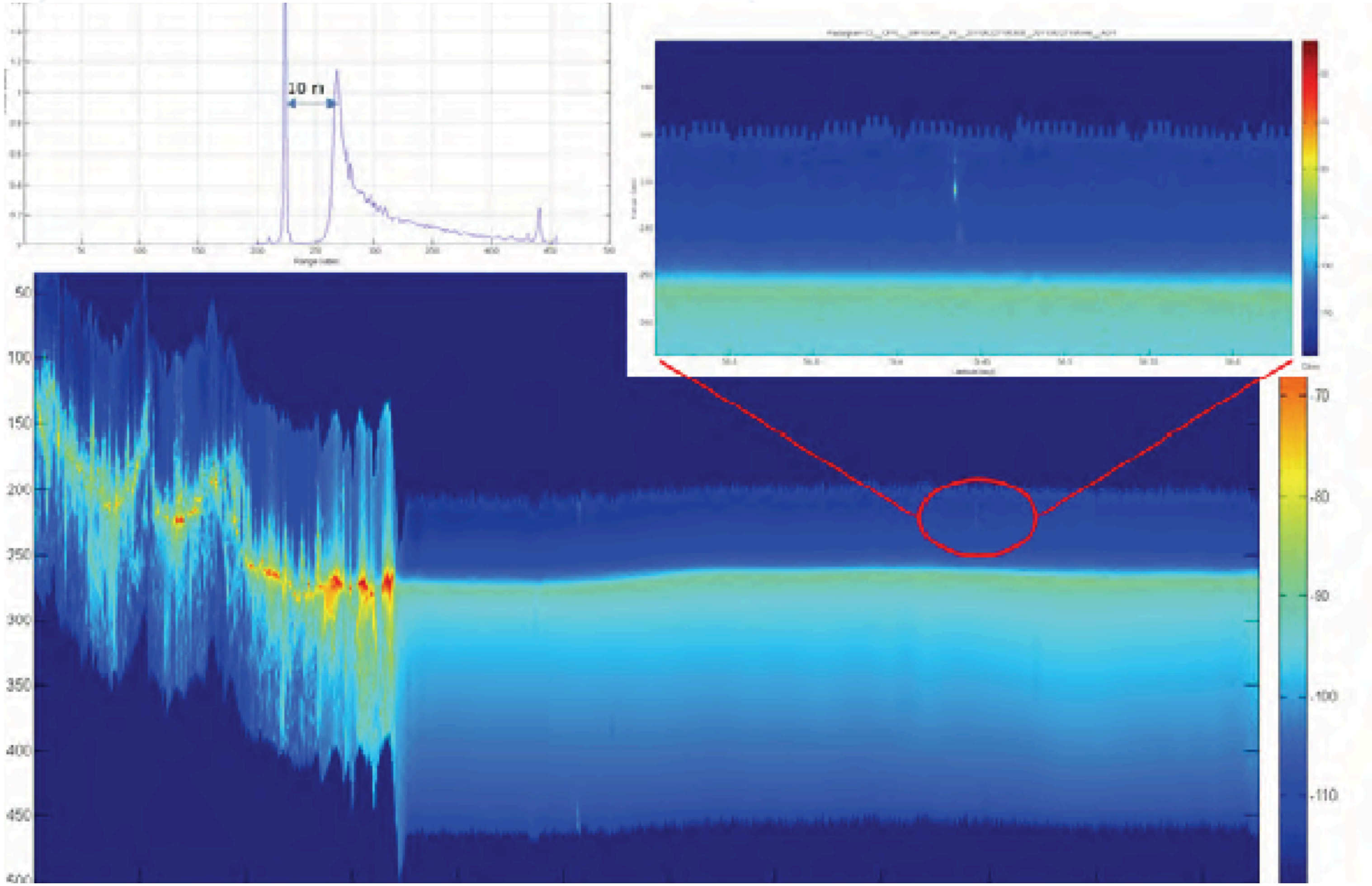


Figure F-05-11: Radargram (dBm) for the CryoSat-2 Pass in June 2011 with a zoom on the point scatterer location (around 10 meters above the sea surface), units of the range-cut waveform are in watt

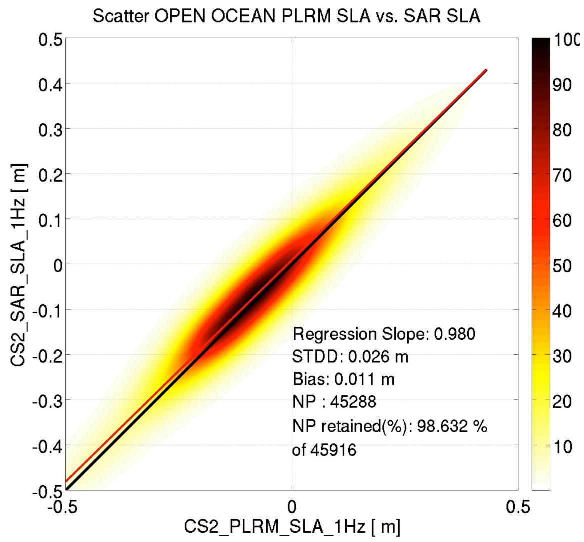
Results in open ocean 1Hz *(Fenoglio et al., AdSR 2015)*

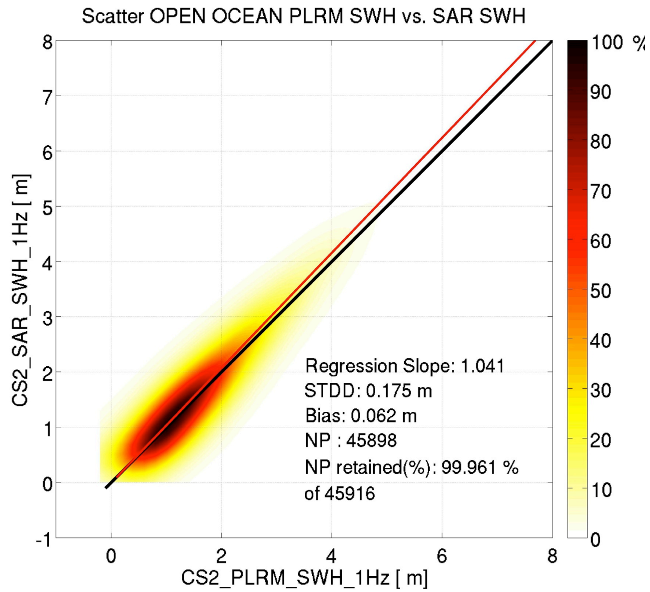
- German Bight (SAR GPOD/PLRM SINC2) for SLA, SWH, U10

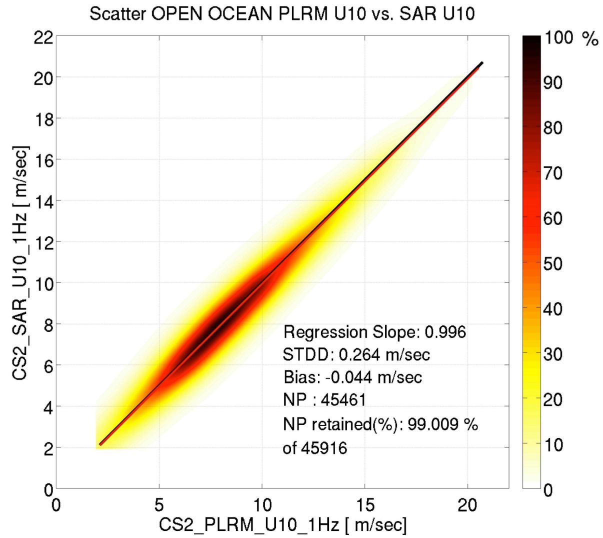
  Open ocean 1Hz

  - Precision SAR : 0.9 cm, 6.6 cm, 6 cm/s (SWH@2m)
  - Precision PLRM : **factor 2** SSH, 1.4 SWH, 0.7 U10
  - Accuracy 1Hz SAR : 7 cm, 14 cm, 1.3 m/s
  - PLRM/SAR : No bias, **STDD 3 cm, 20 cm, 0.27** m/s (SSH,SWH,U10)

Comparison with PLRM/TALES in open ocean 1Hz (SAM+)







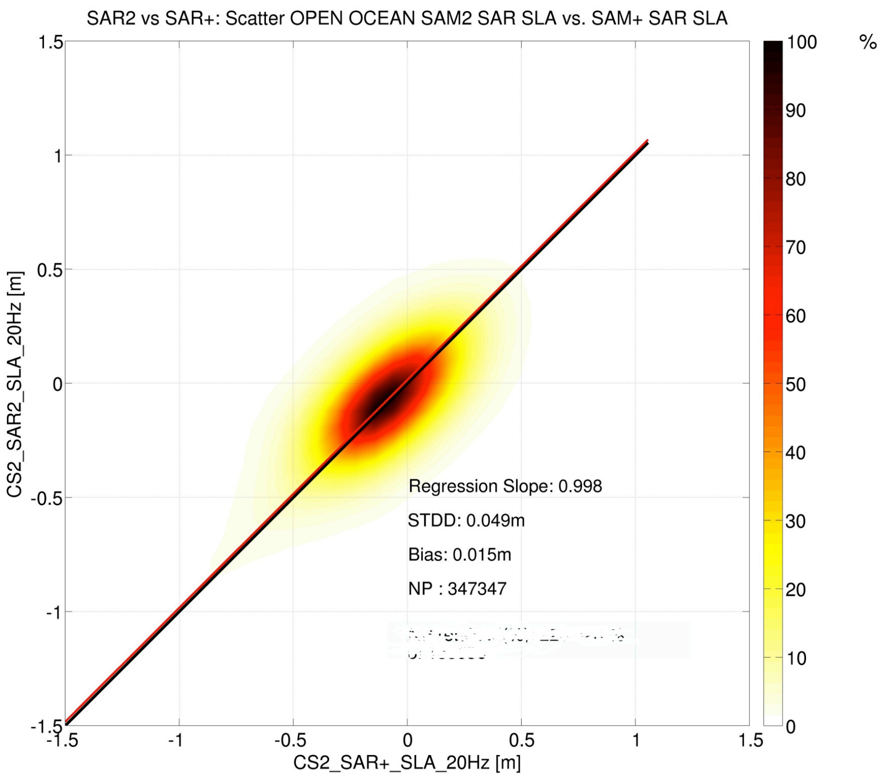
Scatterplots of PLRM agains SAM+

SLA (cm)	SWH (cm)	U10 (m/sec)	
2.6	**17.5**	**26.4**	**AdSR2017**
3.1	21.0	26.3	AdSR2015

Improved compared to Fenoglio et al., AdSR2015

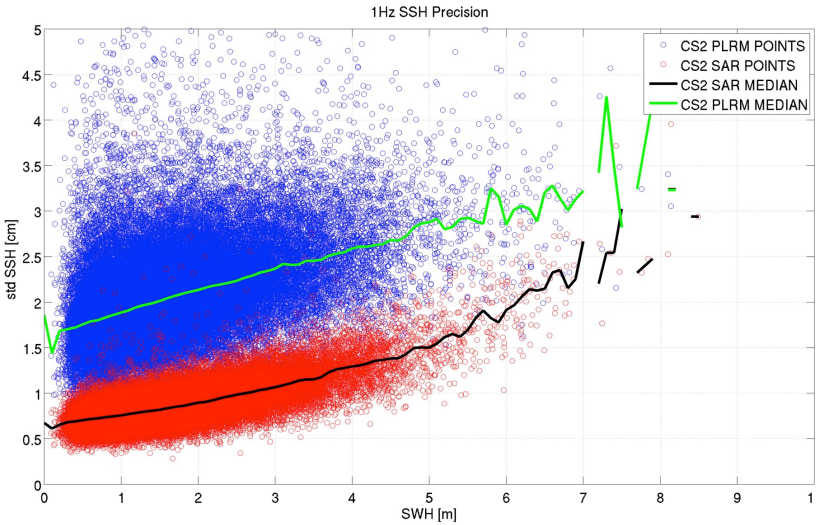
Results

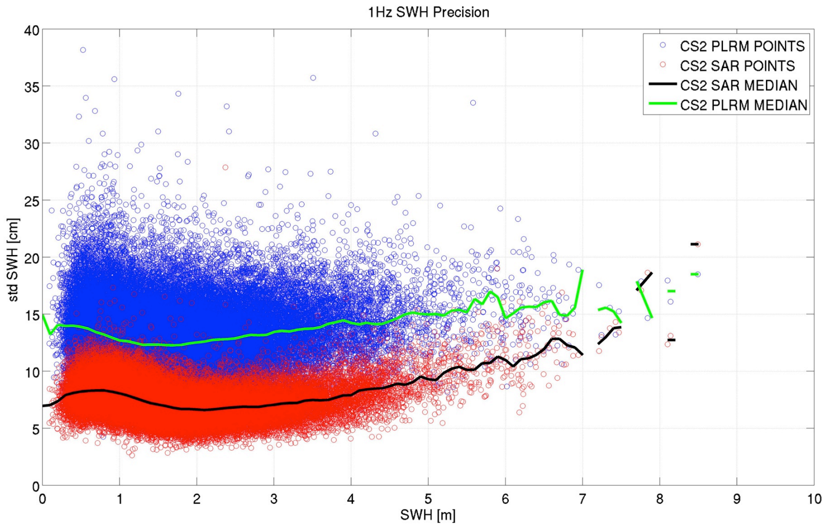
GEC 2011-2015: SLA Crossvalidation of GPODO and GPODC (SAM2 vrs SAM+)



Open Ocean (stdd = 5 cm)

Precision open ocean 1Hz

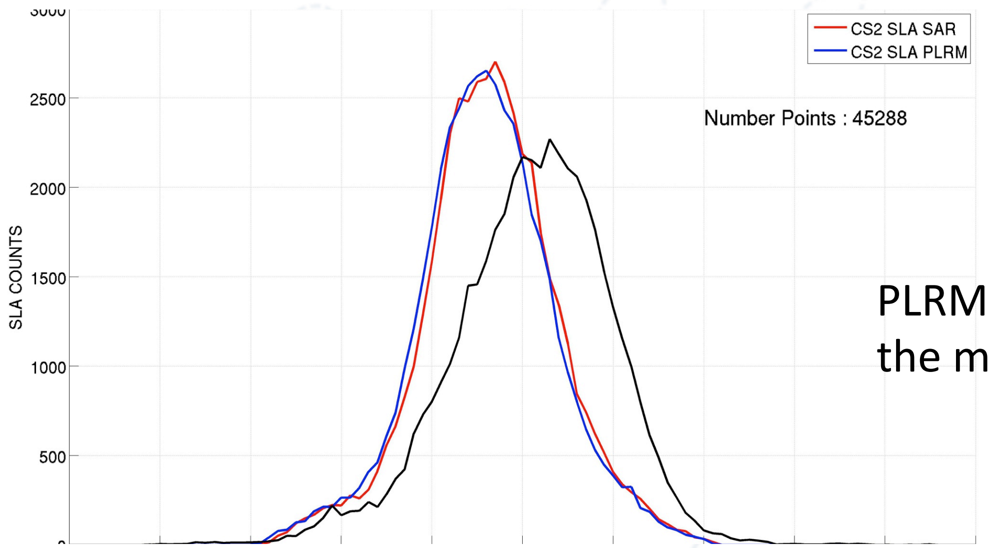




Precision SAR : 0.9 cm, 6.6 cm, 6 cm/s
(SWH@2m)

Similar to Fenoglio et al., AdSR

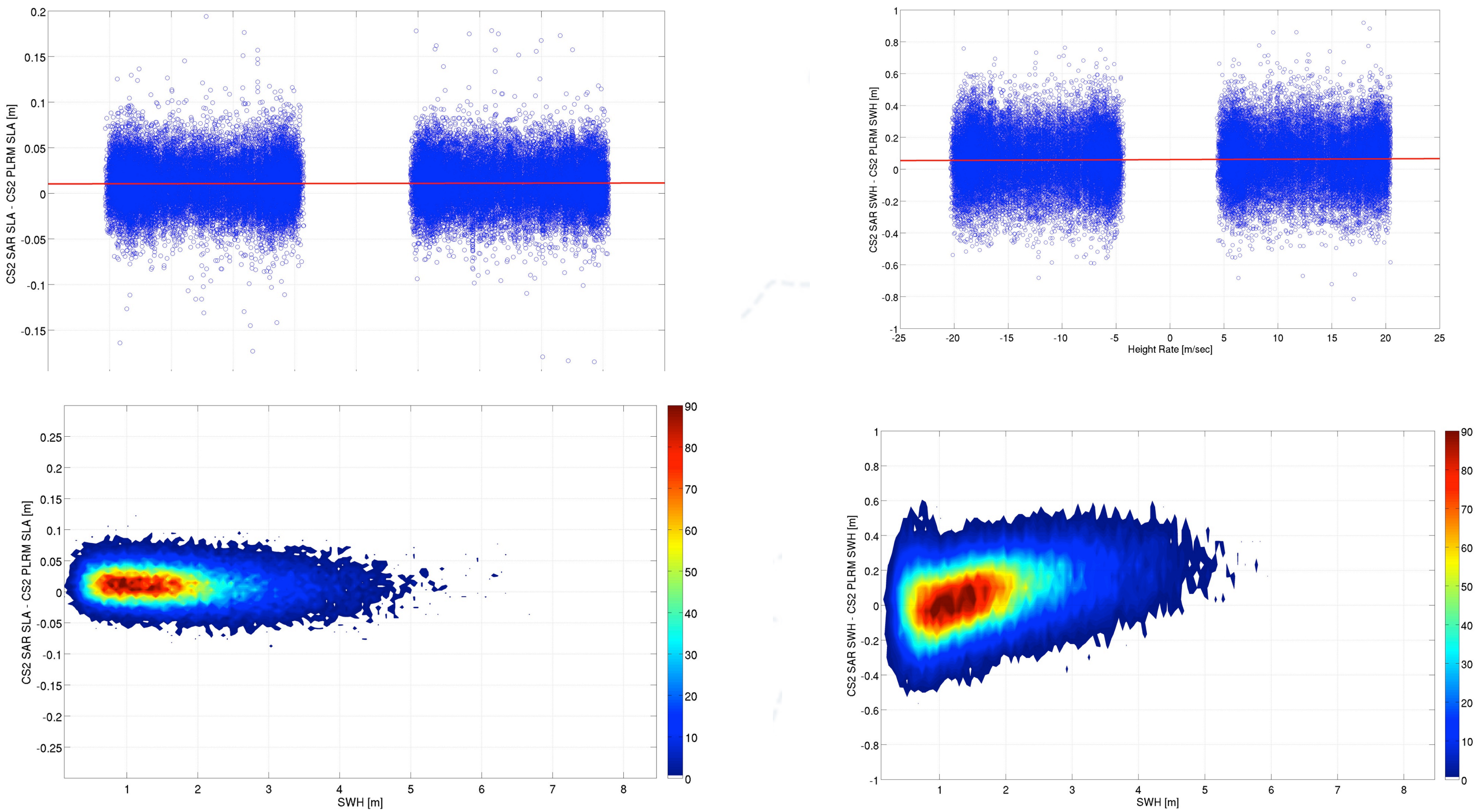
Comparison with PLRM/TALES in open ocean 1Hz



Histograms

PLRM and SAR are in very good agreement, the model is biased

Monitoring the behaviour of SAR and PLRM in open ocean 1Hz

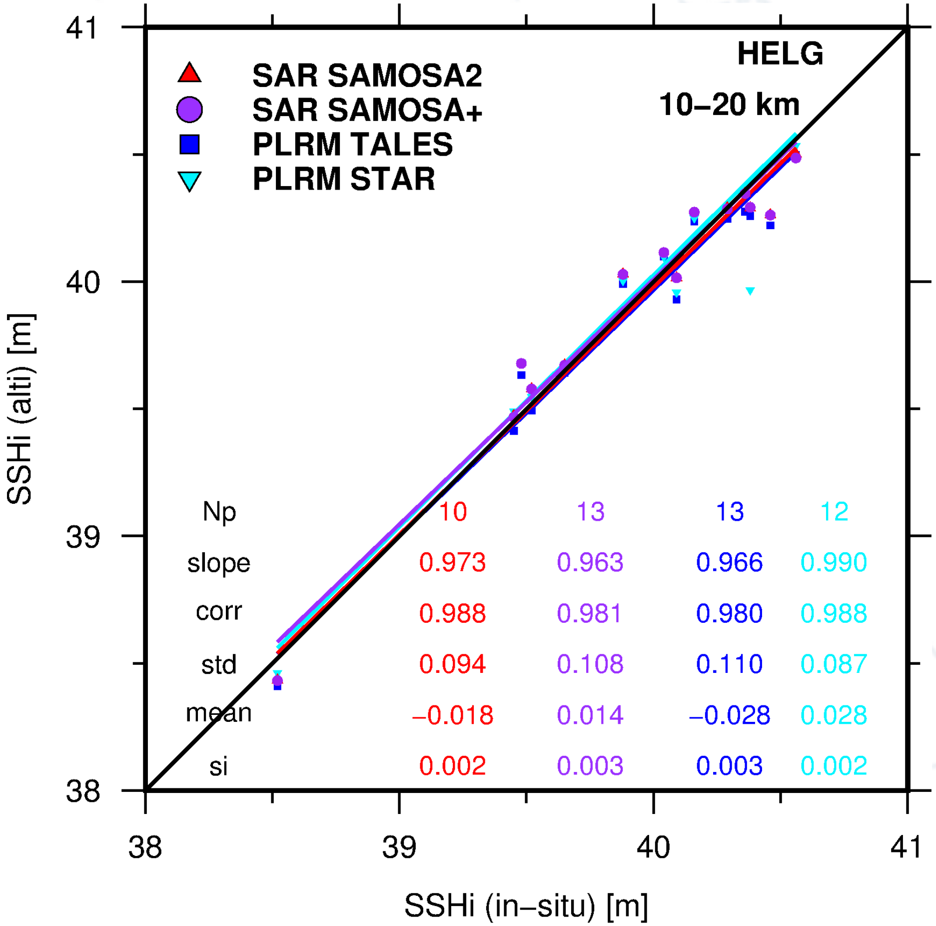


SLA SWH

Differences of SAR and PLRM SLA (left) and SWH (right) as function of orbital rate (top) and SWH (bottom)

GEC 2012: Helgoland in-situ validation

SAM2 against SAM+, PLRM TALES and STAR



	SAR SAMOSA2	SAR SAMOSA+	PLRM TALES	PLRM STAR
Np	10	13	13	12
slope	0.973	0.963	0.966	0.990
corr	0.988	0.981	0.980	0.988
std	0.094	0.108	0.110	0.087
mean	–0.018	0.014	–0.028	0.028
si	0.002	0.003	0.003	0.002

Summary

- Sea Level Monitoring provides geometric information, separation of components possible if gravity and steric data available to analyse budget closure
- SLCCI Dataset : improved consistency reached in the last release of SLCCI products
- SAR altimetry has higher precision and accuracy vs LRM
- Outlook: A large amount of data of high quality to be understood and used

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