Challenges of remote sensing for hydrology : the SMOS and SWOT missions

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OUTLINE

- **Introduction**
  - The new challenges
  - Space context
- **The SWOT mission**
- **The SMOS mission**

Introduction

The new challenges

- What climate shall we have tomorrow ?
  - Increases in global sea and air temperatures
  - Widespread melting of snow and ice
  - Rising global sea level

- Global changes - Climate change & increased demand on water resources - are shaping the challenges associated to hydrology that humanity needs to tackle in the next century:

  food security / flood mitigation / water quality

- How to improve our models at global scale to quantify the changes ?
  - » What are **the observation and accuracy needs** for global water cycle & energy budget research ?

    From continental to global scales to augment climate networks

- How to predict at a finer scale to mitigate the impacts (IPCC Report 4) ?
  - » What are **the accuracy needs for water management** for flood prediction, reservoir operation, agriculture and drought assessment ?

    Solve regional problems and acquire real-time data to augment operational networks

➔ **There is need to spatialize and to refine the curent scale of perception**

- » Observations at high spatial and temporal scales

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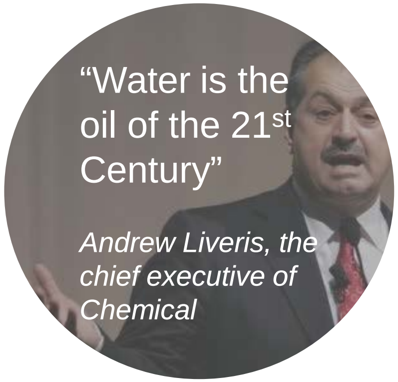
Introduction

The new challenges

Water is a major stake in the 21th century



There is still need to understand the processes that govern the production and distribution of water in the compartments of the Earth surface and to evaluating the impact of human activities on them.

What are the data needs and with which distribution scheme ?

» programs addressing hydrology and water (GEOS, HYMEX, H2020…) are expecting space-based observations to provide needed observations **of sufficient accuracy for water resource applications (Essential Climate Variables, Climate Change Initiative) .**

How to address the socio-economic benefits?

» Consider end-users requirements
» Benefits of Earth observations applications to decision making
» Develop services

Water balance components

Soil moisture

Surface water

Ground water

$$\frac{dS_{SM}}{dt} + \frac{dS_{SW}}{dt} + \frac{dS_{GW}}{dt} = P - E - Q$$

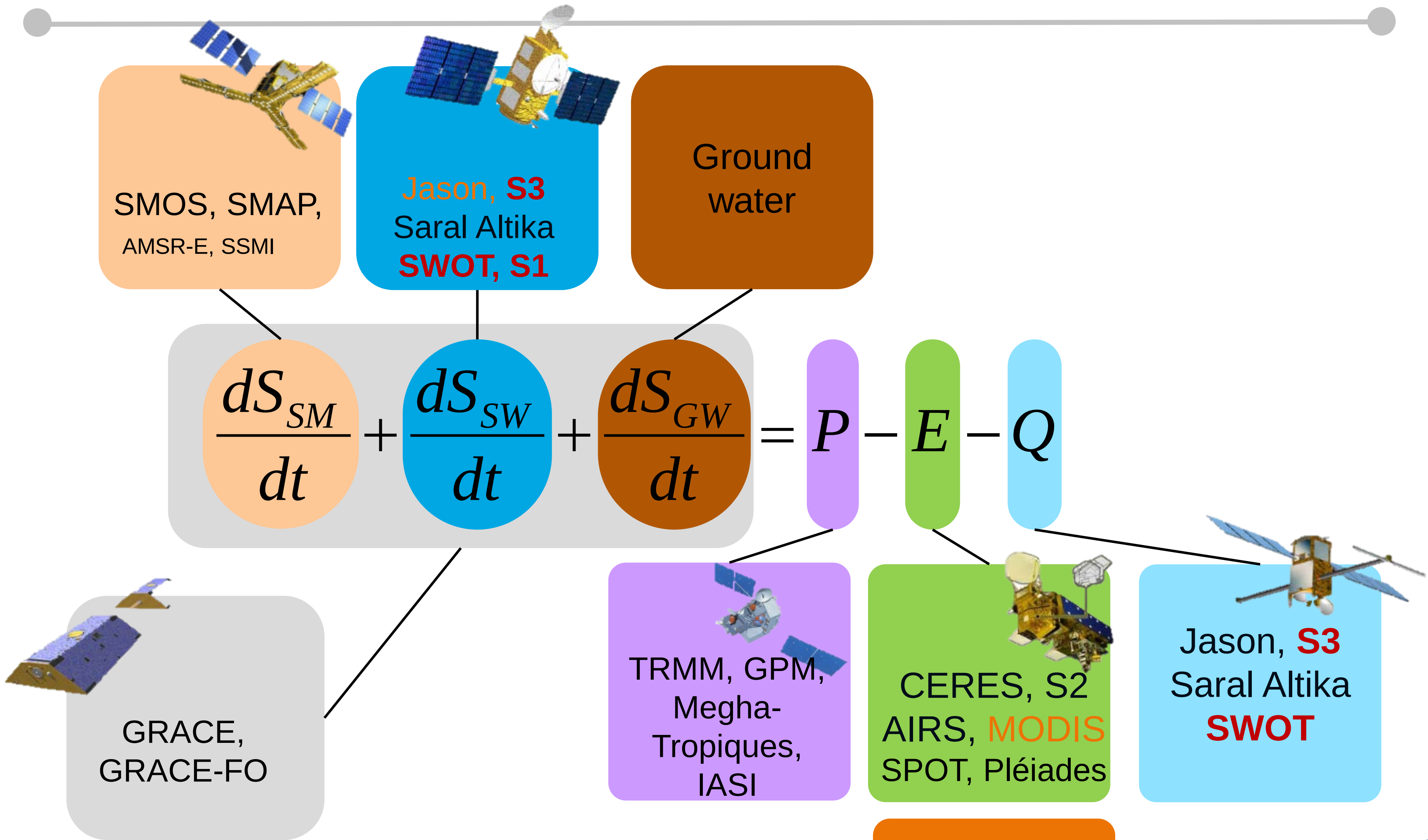
Precipitation

Evapo-transpiration

Discharge

Energy budget

Space measurements for water cycle



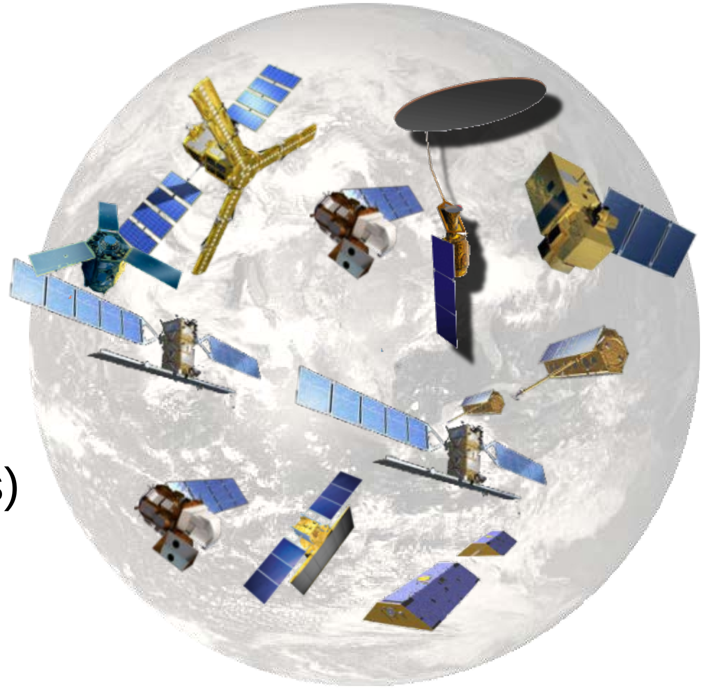
Not all components are observed at the desired resolution and accuracy

The « revolution » in space missions for hydrology

Increase in accuracy (more adapted spectral bands)

example of soil moisture:

from AMSR-E (C-Band) *to* SMOS (L-Band)



Increase in spatial resolution

example of altimetry:

from Jason (kilometric) *to* SWOT (100m)

Increase in temporal resolution

example of visible:

from SPOT5-6 (local) *to* Sentinel 2 (5 days)

Increase in accessibility of data

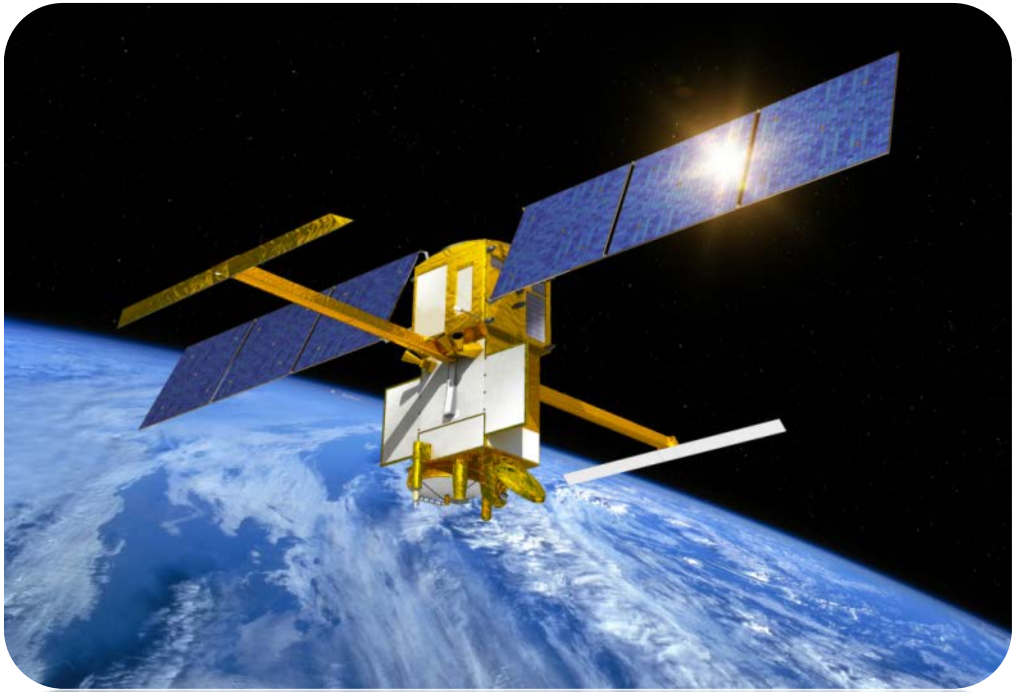
Vast majority (S2,3, SMOS, LandSat)

are freelly accessible

The SWOT and SMOS missions that we present here pertain to the newest generation of sensors.

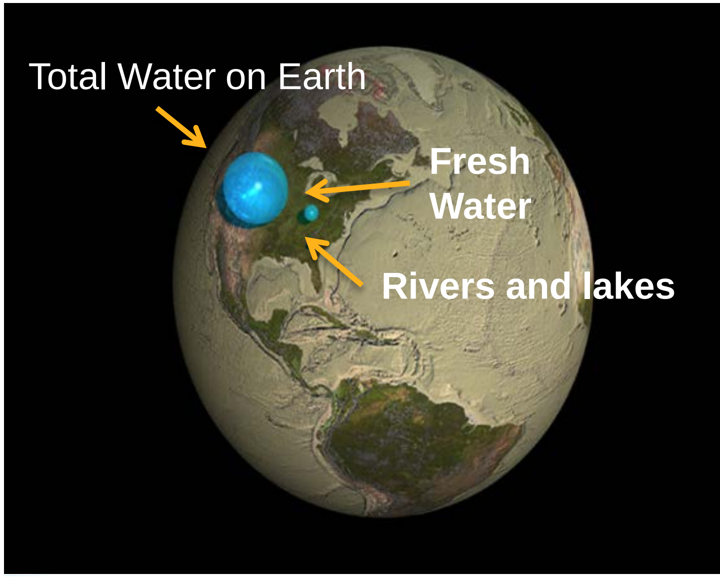
The SWOT mission

A wide swath altimeter for observing **S**urface **W**ater and **O**cean **T**opography



SWOT - MISSION GOALS

- **Science Goals**
  - study hydrological processes by determining the storage and discharge rate of water on land.
  - study the oceanic mesoscale and submesoscale processes that determine the kinetic energy of ocean circulation and its transport of water properties.



- **Societal Benefits**

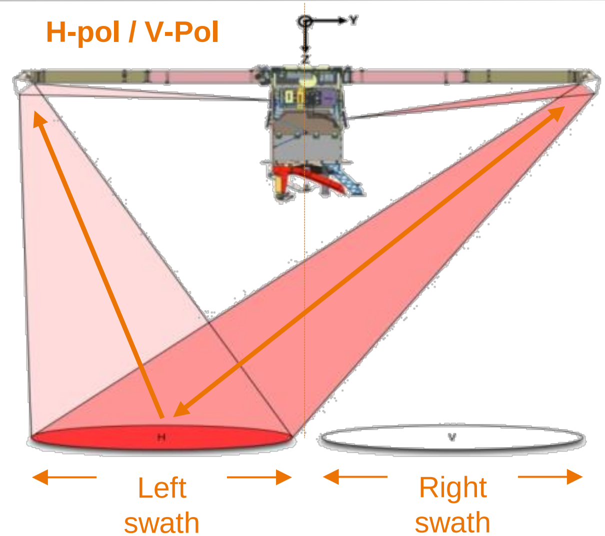
Address two key issues facing a warming planet:
  - the variability of fresh water resources.
  - the capacity of ocean circulation in regulating the rate of warming.

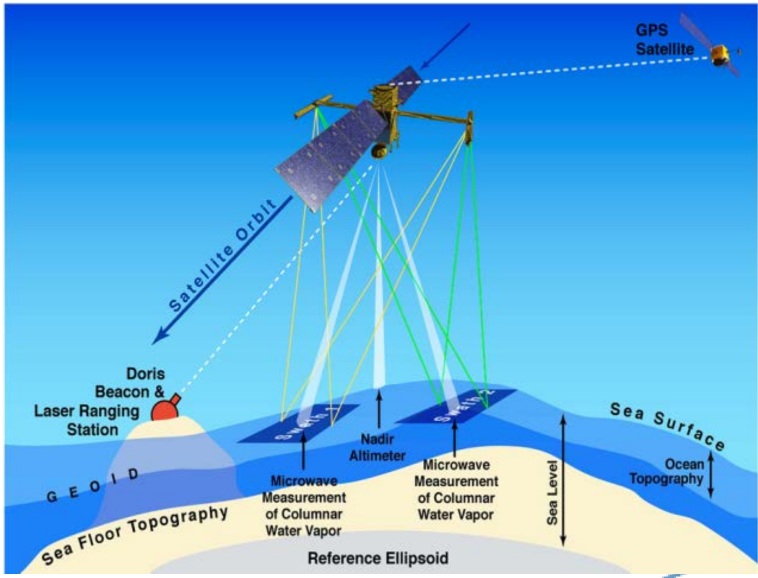
- **Technology Goal**

Set the standard for future operational altimetry missions.

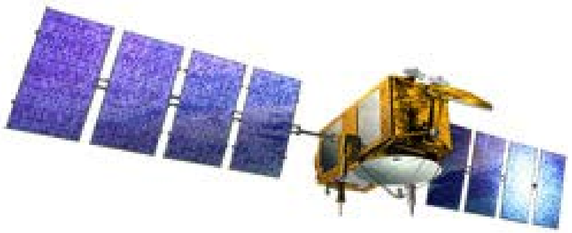
SWOT Mission FACT SHEET

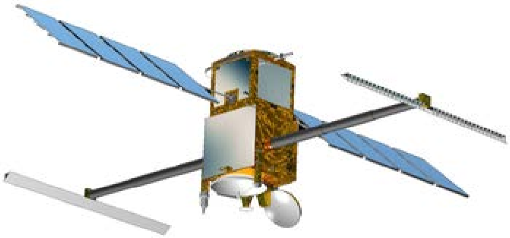
- The SWOT mission is a partnership between the **hydrology** and **oceanography** scientific communities
- Partnered mission : **NASA / CNES / CSA / UKSA**
- **Ka-band SAR interferometric (KaRIn)** system with 2 swaths, 50 km each
- Jason-class **altimeter for nadir** coverage,
- **Radiometer** for wet-tropospheric delay
- **GPS/DORIS/LRA** for POD
- Science mission duration of **3 years**
- Calibration orbit: 857 km, 77.6º Incl., **1 day repeat**
- Science orbit: 891 km, 77.6º Incl., **21 day repeat**
- Target Launch Readiness: **Apr. 2021**





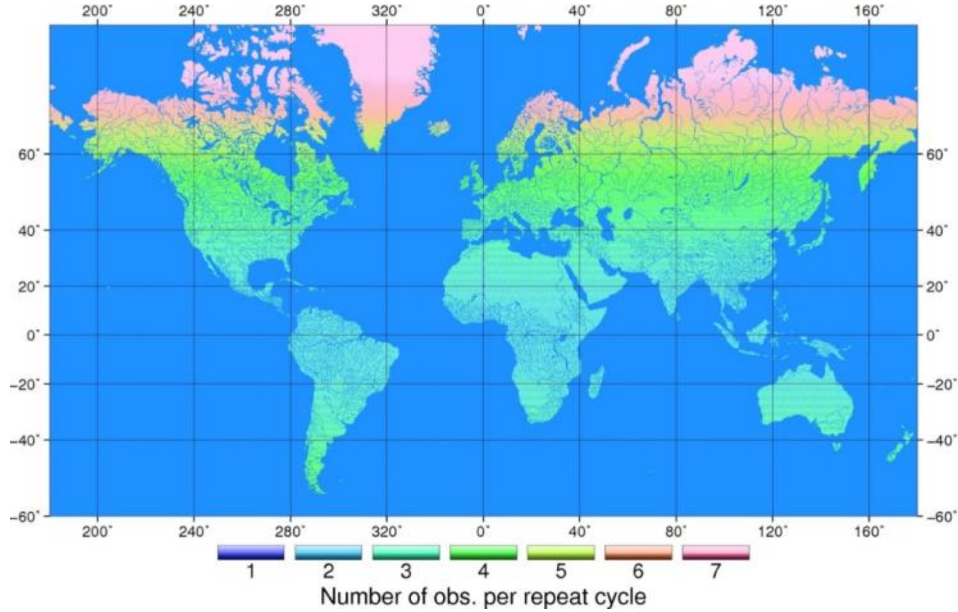
SWOT Coverage Leap - *from local altimetry to topography*





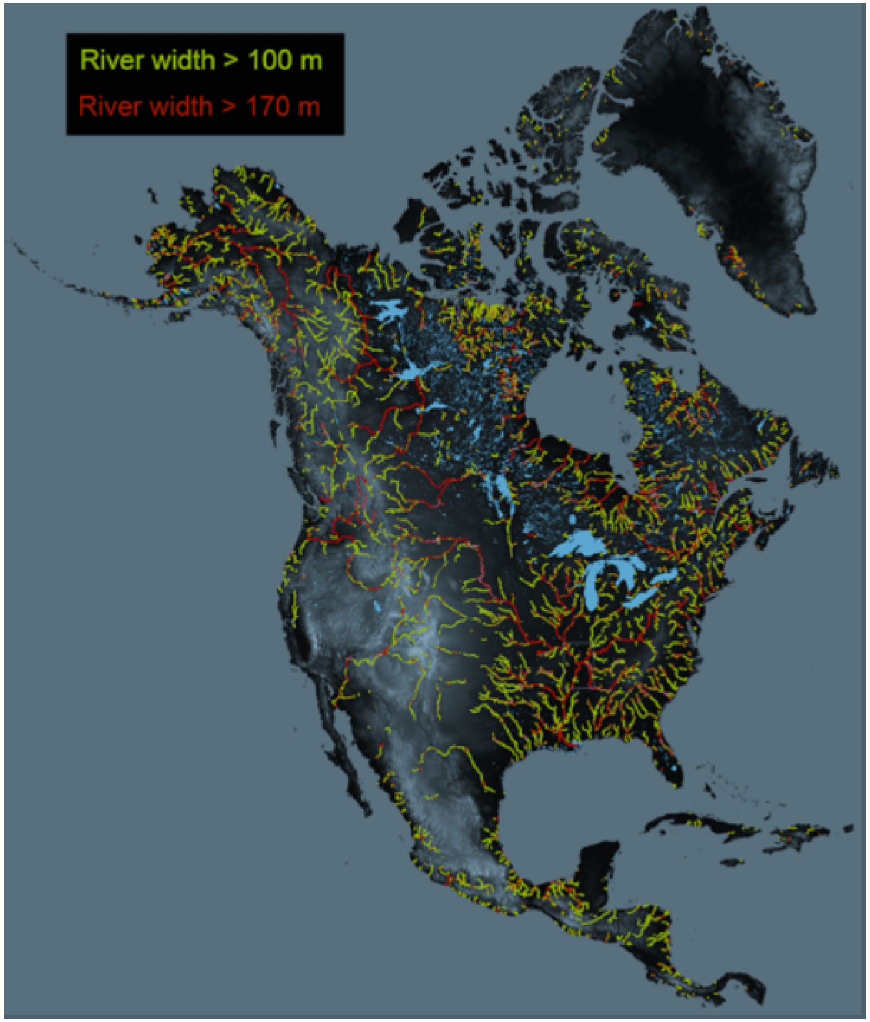
Conventional Nadir Altimeter

SWATH Altimeter : SWOT



SWOT mission will address challenges and shortcomings of conventional altimetry (e.g., spatial coverage and resolution) in both oceanographic and hydrologic applications and will enable a wide range of research opportunities in oceanography and land hydrology.

SWOT – Requirements rivers



From Allen et al., in press, GRL

- Inundated Area/River Width:
  - 15% error for 100 m wide rivers over 10 km reach (baseline)
  - 15% error for 170 m wide rivers over 10 km reach (threshold)
- Water surface elevation/height:
  - 10 cm error for 1 km^2 area and 25 cm error for between $(250\ m)^2$ and 1 km^2 (baseline)
  - 11 cm error for 1 km^2 area (threshold)
- Water surface slope:
  - 10 μrad error for 100 m wide river over 10 km (baseline)*
  - 20 μrad error for 100 m wide river over 10 km (threshold)*

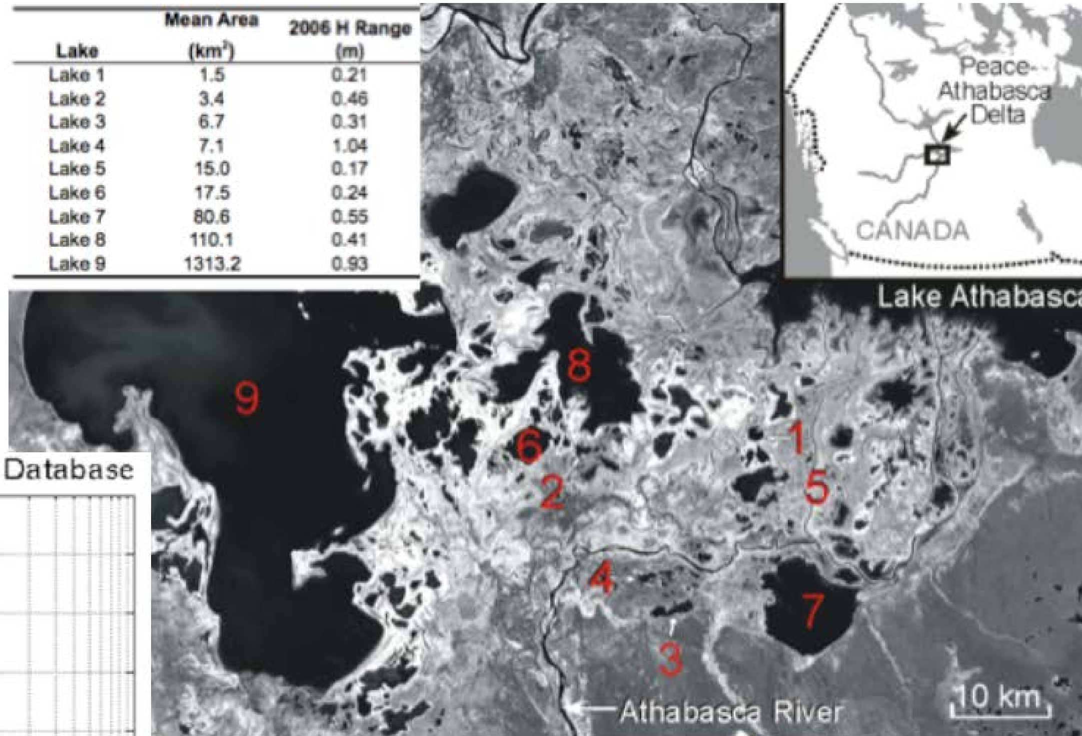
*Nominal

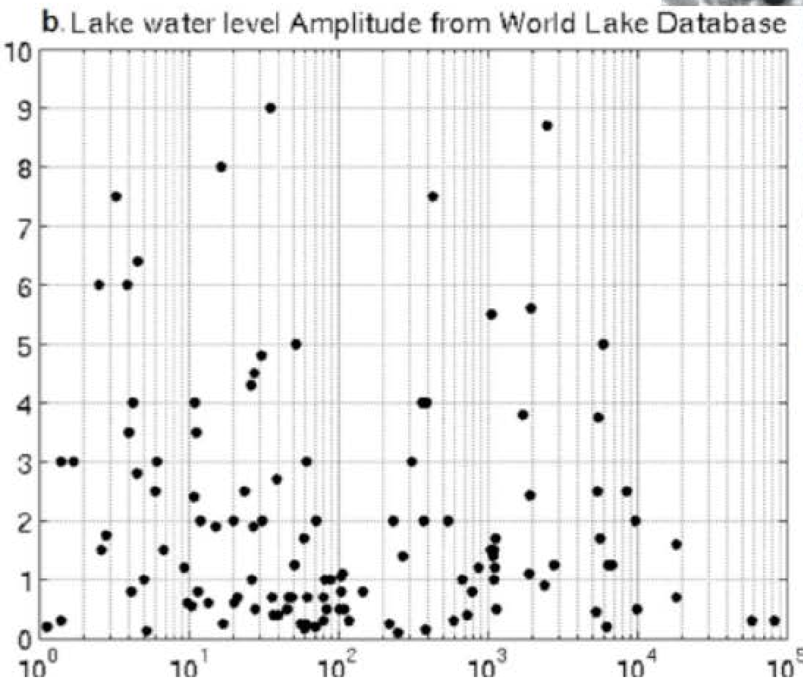
SWOT Mission Requirements lakes

Inundated Area:

- 15% accuracy for lakes larger than $(250\ m)^2$ (baseline)
- 15% accuracy for lakes larger than 1 km^2 (threshold)

Lake	Mean Area (km^2)	2006 H Range (m)
Lake 1	1.5	0.21
Lake 2	3.4	0.46
Lake 3	6.7	0.31
Lake 4	7.1	1.04
Lake 5	15.0	0.17
Lake 6	17.5	0.24
Lake 7	80.6	0.55
Lake 8	110.1	0.41
Lake 9	1313.2	0.93





- Lake Water Surface Height:
  - 10 cm accuracy for lakes larger than 1 km^2 and 25 cm accuracy for lakes between 1 km^2 and $(250m)^2$ (baseline)
  - 11 cm accuracy for lakes larger than 1 km^2 (threshold)

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KARIN DATA PRODUCTS

KaRIn will generate about 7Tb of data per day, which will be processed on ground to generate the following products :

- Level 0: Instrument Telemetry
- Level 1: Sensor data.
  - SWOT Low Resolution (Ocean Data) – OBP partial interferograms.
  - SWOT High Resolution (Land data) – full resolution complex interferograms in radar coordinates, phase flattened. (Images are internal product)
- Level 2 : Users level.
  - SWOT Low Resolution (Ocean Data) : Swath of sea surface height, slope, height uncertainty and backscatter
  - **SWOT High Resolution (Land data) : Geolocated water mask with Surface Water height, slopes with uncertainties,**
  - **SWOT High Resolution Enhanced: Discharge on river database, flood plain on long-term data collection**

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SWOT application program support

- **Outreach :** Inform the stakeholders about the SWOT capabilities (website, workshop), develop communication strategies to target and support requirements of the user community etc…

- **The improvement of the existing applications**
  - Sea transport shipping, fisheries, prediction of ENSO, forecast of extreme events (cyclones, storms) and the monitoring of climatic parameters

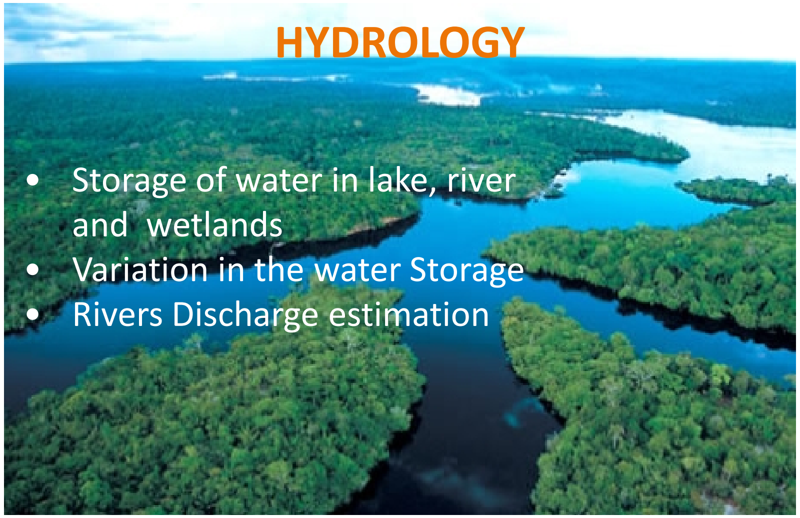
- **Innovative applications for coastal areas**
  - In particular for coastal management and off shore resource exploitation mining, oil continental shelves

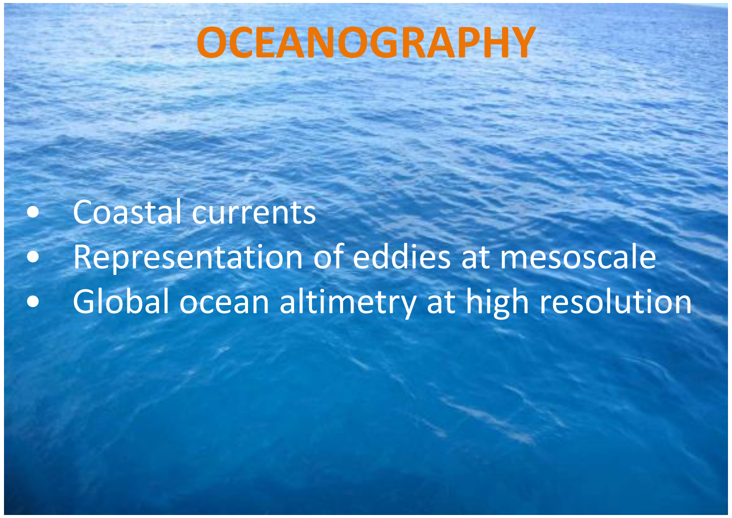
- **The creation of new environmental services**
  - For inland waters (lakes, reservoirs, major rivers) at global scale to leverage opportunities for water resources management, estuaries, the risk prevention of flood, the prevention of the propagation of epidemics

- **An open data policy**
  - This will strengthen the existing services for oceanography and create new services in for water resources

The “French” SWOT application program support

Data products





…which allows

which allows

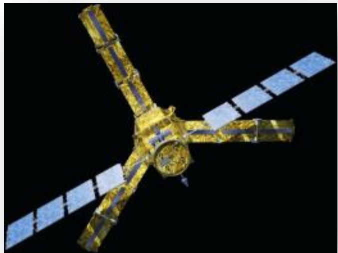
Potential applications

1. Transboundary rivers management (international & interregional)
2. A better modelling of flood
3. Clear water management for urban, industrial and agricultural sectors
4. Hydroelectricity production management
5. Prevention of the propagation of epidemics
6. Fluvial navigation support

7. Climate and weather forecast with better accuracy
8. Marine operations
9. Fisheries
10. Aide aux plateformes pétrolières

SWOT-Aval – *pushing forward the SWOT applications*

A multi-sensor approach to support high-end applications from SWOT

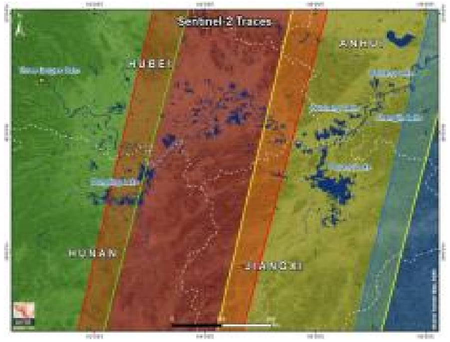


SMOS/SMAP

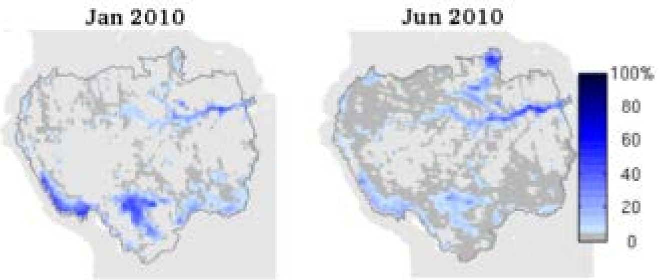
GPM/ MGT

JS3/S3/S6

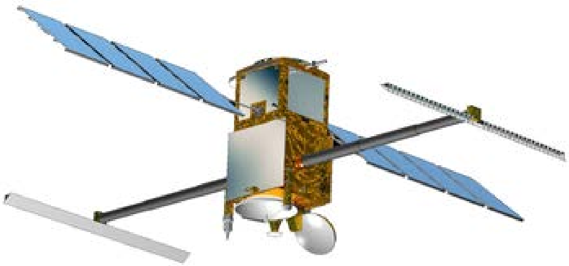
S2/LDCM/S1…



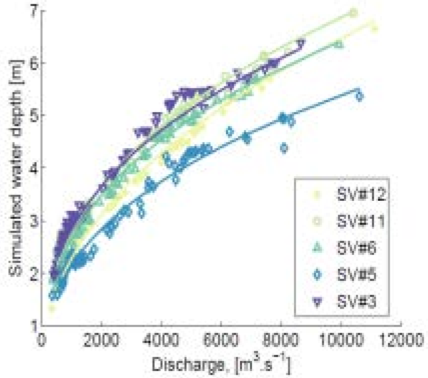
Lac Poyang water balance (credits: **Sertit**)



Dynamic wetlands surfaces and volumes (credits **Cesbio / Legos)**



A multi-sensor flood prediction system for the Niger Basin
(credits: **GET**)



A priori-discharge db based on SWOT simulator
(credits: **Legos/UFRGS**)

The SMOS mission

A 2D interferometric L-Band radiometer for Soil Moisture and Ocean Salinity

SMOS mission fact sheet

- An **ESA earth explorer** mission with the contributions of **CNES** and **CDTI**
- Main products are **Soil Moisture (0-5cm)** and Sea Surface Salinity
- An **L-band (1.4Ghz)** passive instrument
- **2D Interferometric** radiometer (std: 2.4 k)
- **Full polarimetric** acquisitions
- **Multi-angular** acquisitions (0° - 60°+)
- **3 days global coverage** at 6 am and 6 pm
- Spatial resolution (**27 -55 km**)
- RFI mitigation at ground segment
- Operational since **Nov. 2009**

- Similar missions SMAP (NASA) operational since 2015

The CATDS SMOS center

CATDS

Centre Aval de Traitement des Données SMOS

A data production center & two scientific centers for SMOS high-end Level 3 & 4 products from CNES.

CATDS data over land :

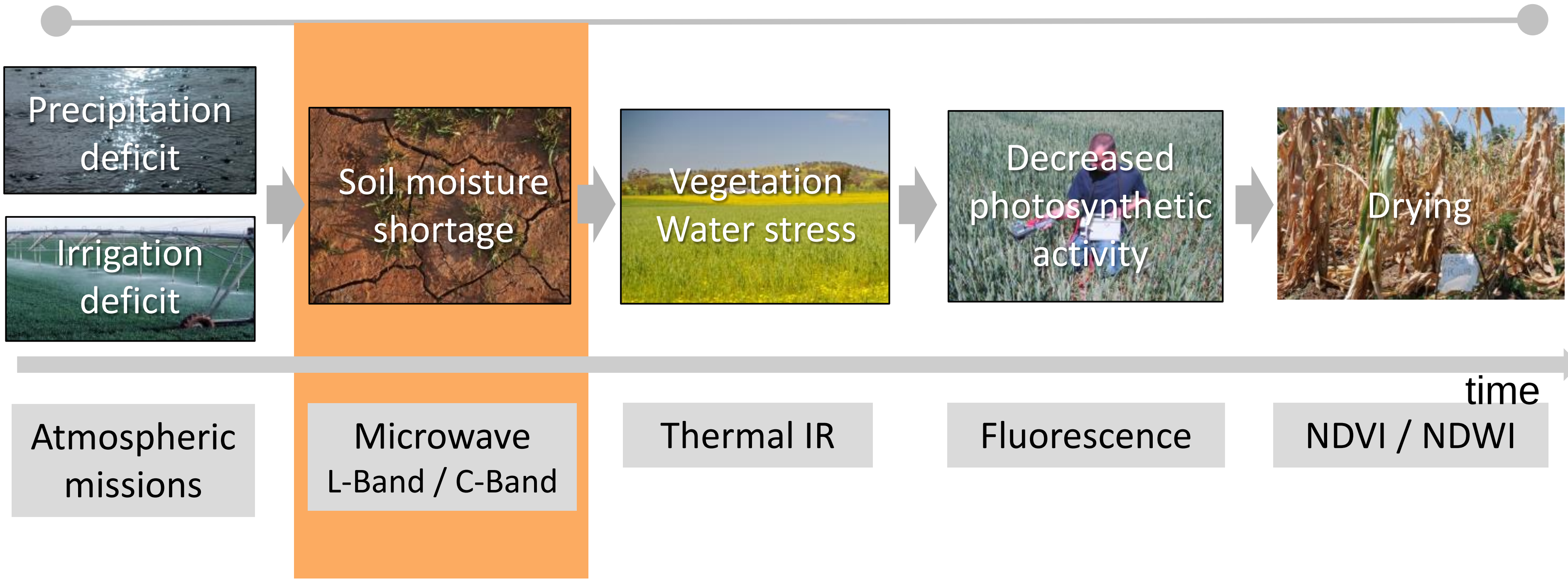
- Multi-temporal retrievals of surface soil moiture (0-5cm)
- Root zone soil moisture and Drought monitoring
- Dynamic Wetlands maps
- High resolution products using optical and radar sensors

➔ Applications to Drought / flood monitoring and interdisplinary sciences

CATDS – SMOS surface soil moisture

(Al Bitar A., CESBIO)

Agricultural Drought - dynamics and monitoring



Root zone soil moisture is a very usefull information to access agricultural drought in an **early warning system**

At CESBIO **SMOS surface soil moisture** and MODIS LAI are assimilated into a double bucket model to compute **root zone soil moisture**. (Al Bitar et al. 2013, Kerr et al. 2016)

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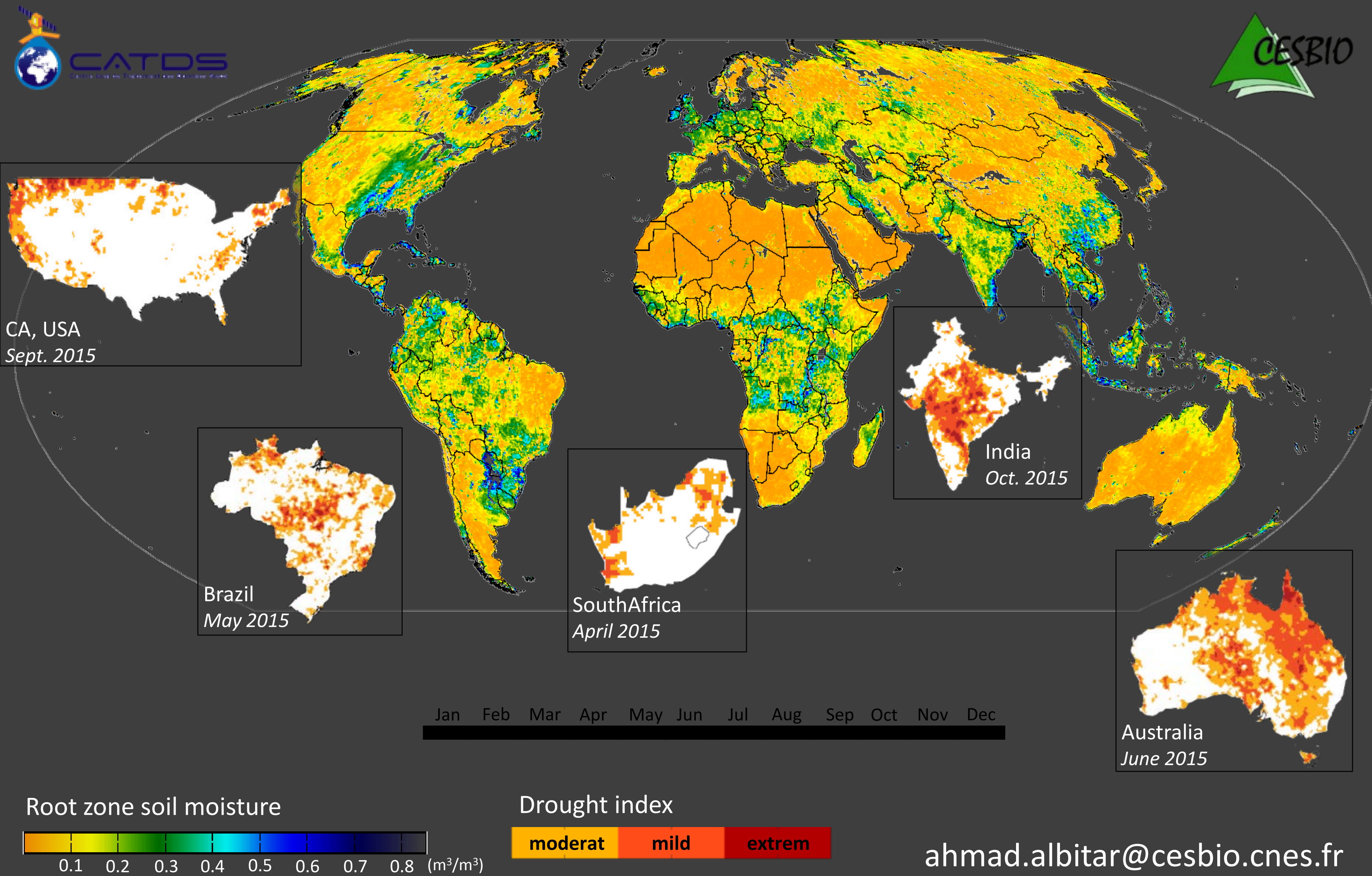
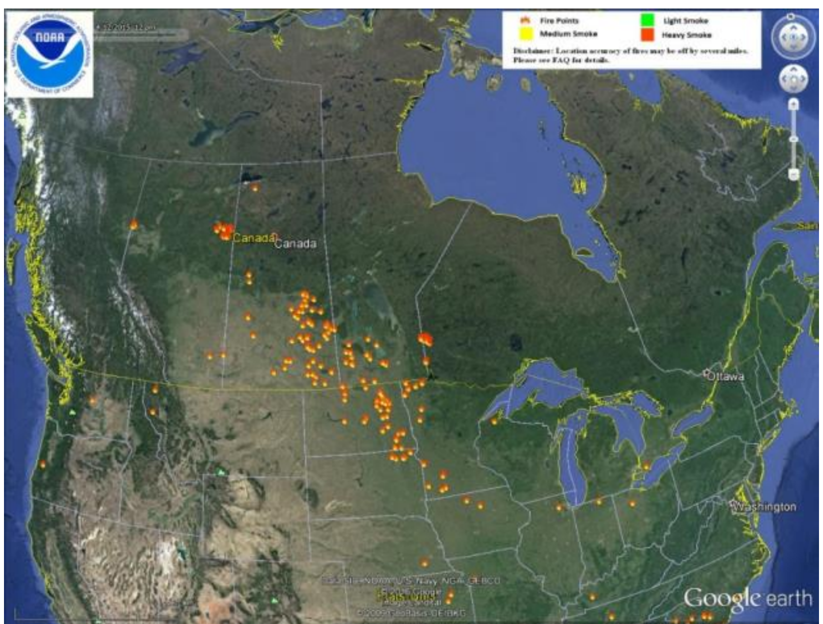
SMOS monitoring 5 major droughts in 2015

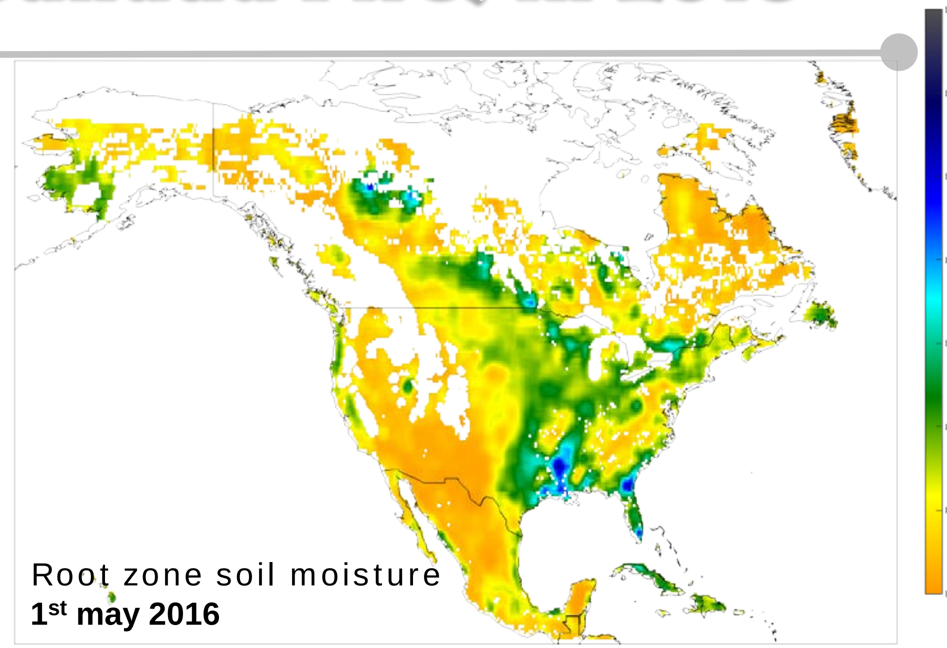


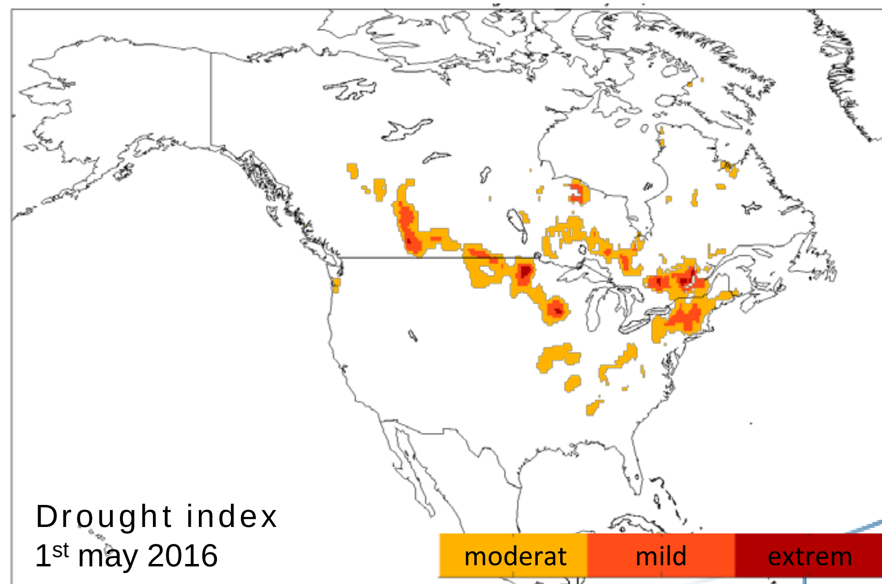
ahmad.albitar@cesbio.cnes.fr

Drought before Canada Fires in 2016

Droughts preceding the Canada fires where well depicted in SMOS drought index





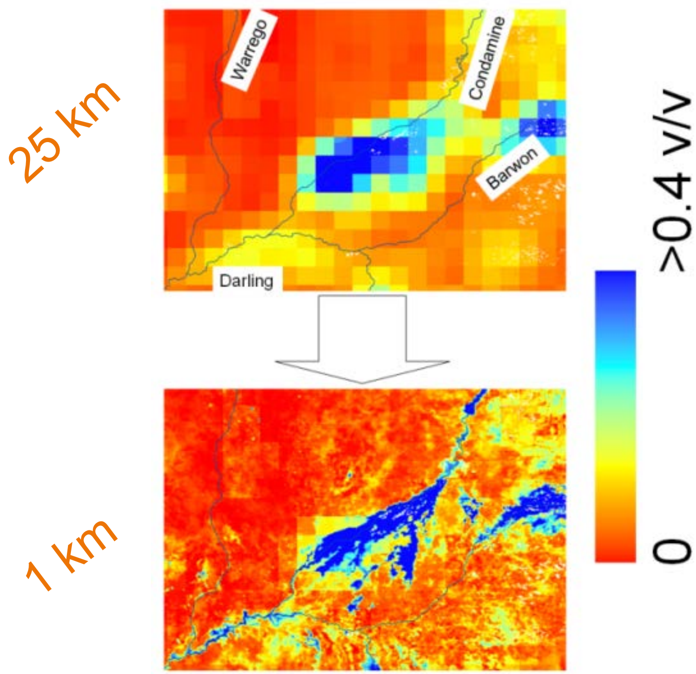


Reaching sub-kilometric Soil Moisture resolutions

A kilometric resolution is esssential for many hydrological applications.
SMOS resolution is enhanced by merging it with data from other sensors

SMOS & optical sensors

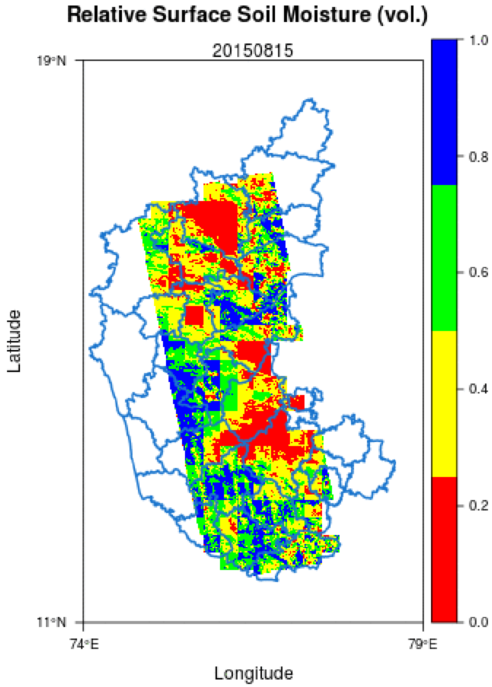
Muren Bidge basin Australia



(Merlin et al. 2012) (Molero et al., RSE, 2016)

SMOS & C-Band radar

Kabini Basin, Karnataka, India

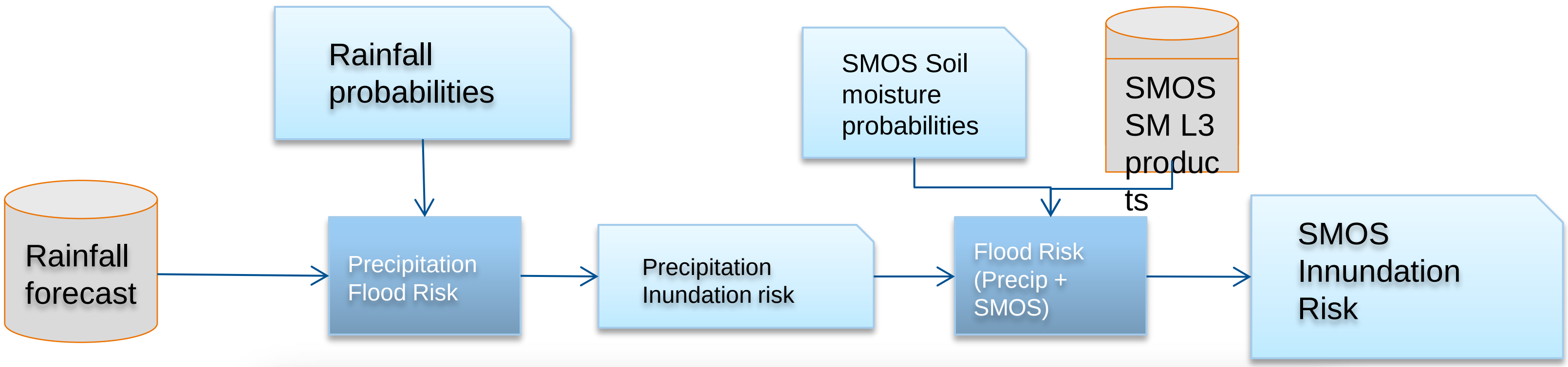


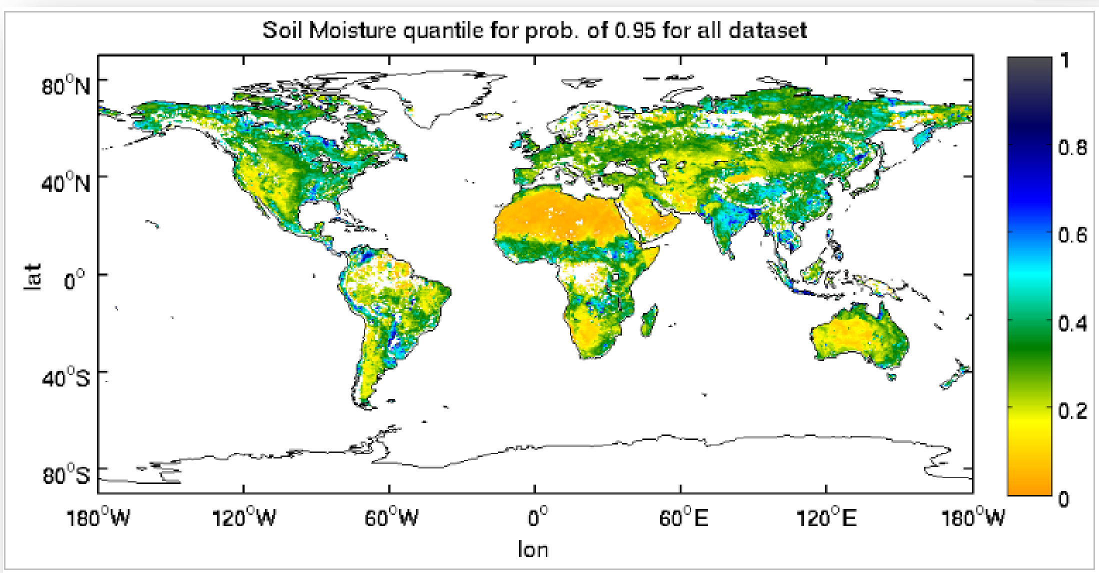
(Tomer et al., RS, 2015, 2016)
sat@aapahinnovations.com

SMOS Flood Risk Forecast

Methodology

Leveraging inundation risk based on SMOS soil moisture prior knowledge



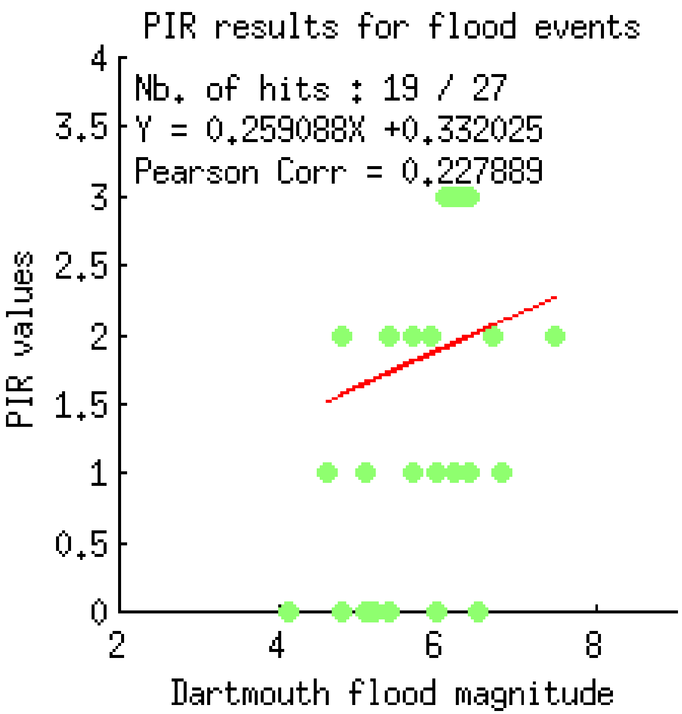


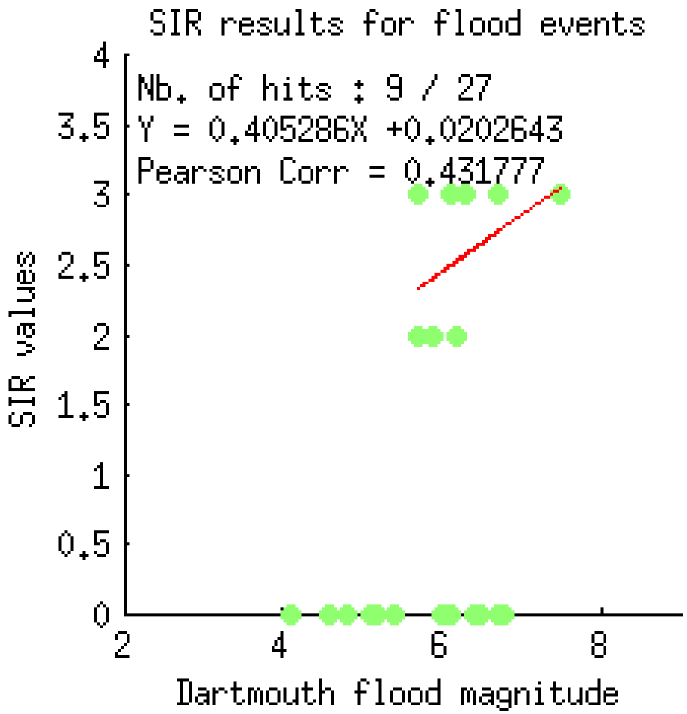
Al Bitar A., Chone A., S. K. Tomer, CESBIO

SMOS Flood Risk Forecast

Results

- Compare with the Dartmouth Flood Observatory
- Dartmouth magnitude of the flood against the Precipitation inundation risk and the SMOS inundation risk.

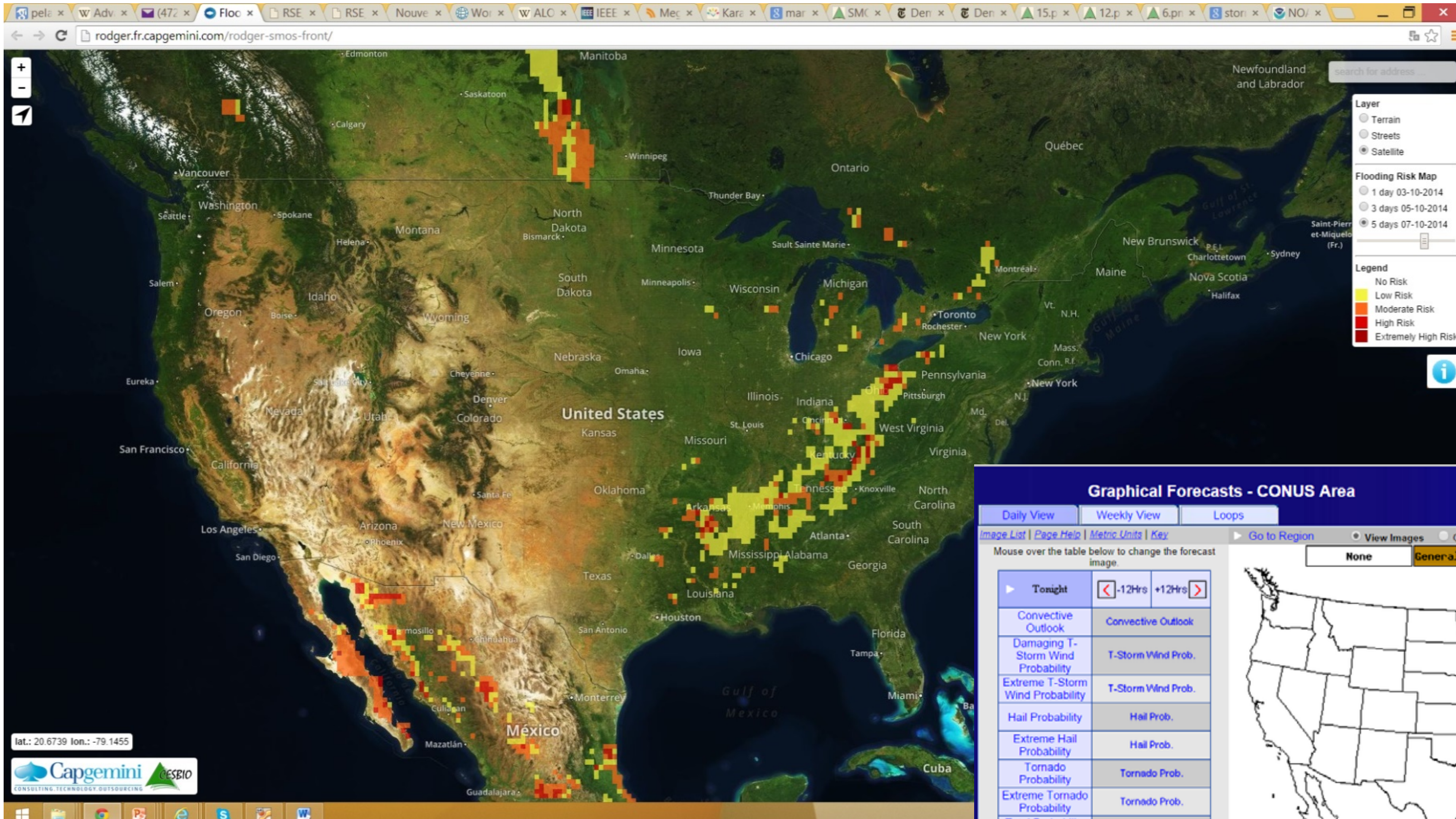




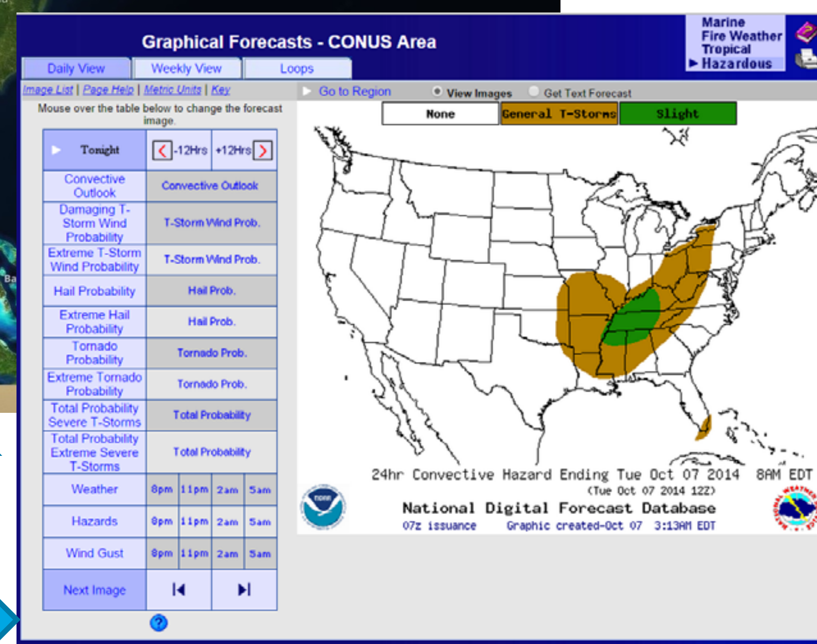
- Results show that the Precipitation Inundation risk is underperforming.
- But also that the use of SMOS globally enhances the risk product except in A

Al Bitar A., Chone A., CESBIO

Operational implementation by CapGemini and CESBIO

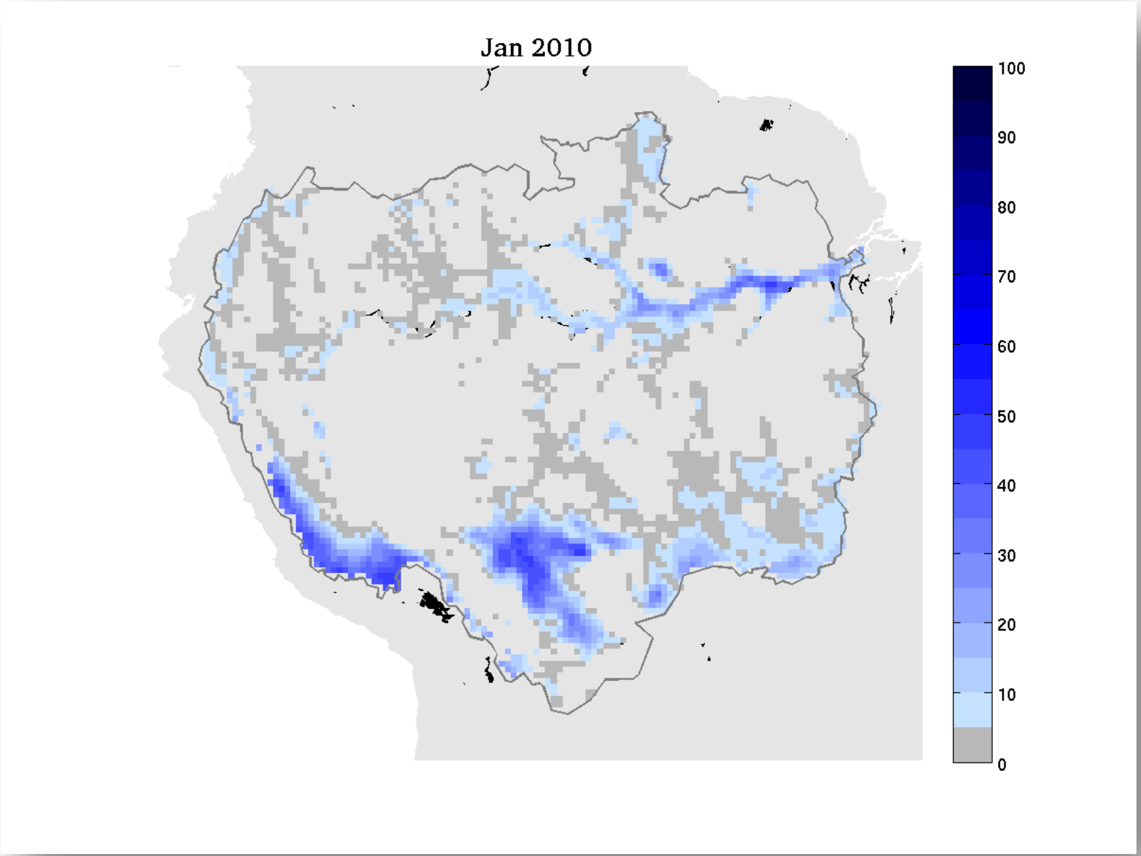


SMOS flood risk 07 Oct. 2014 at 12h45 for the next 5 days



Storm risk by NOAA 07 Oct. 2014 at 12h45

Monitoring of wetlands in Tropical basins

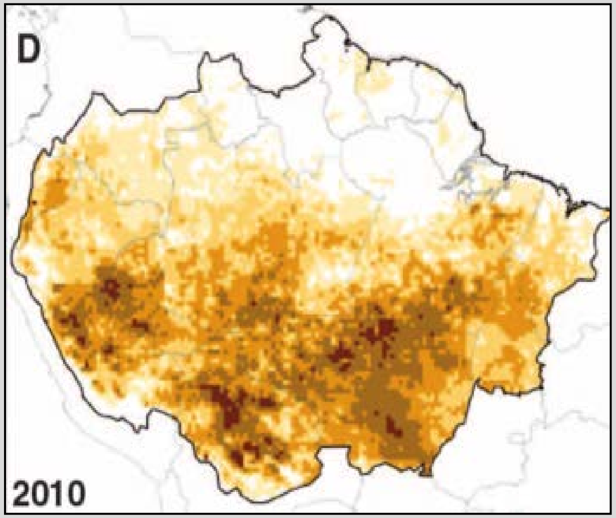


(Parrens et al. 2015, Al Bitar et al. 2015
CNES TOSCA-SOLE

SMOS - Monitoring drought in Tropical regions

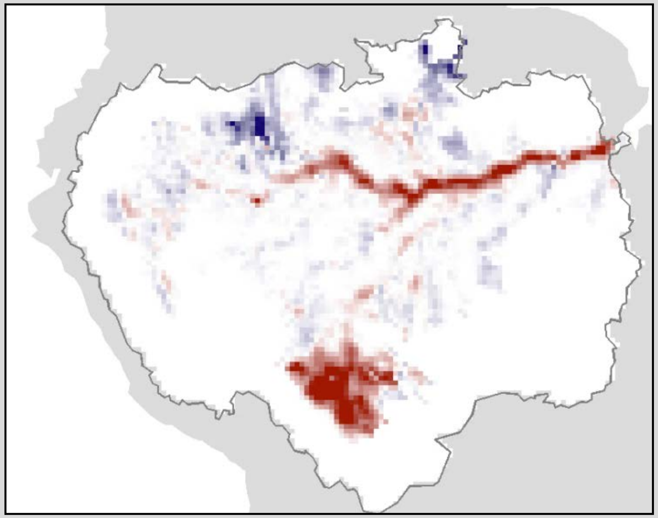
The 2010 South-Amazon drought

Clim. Water. Index



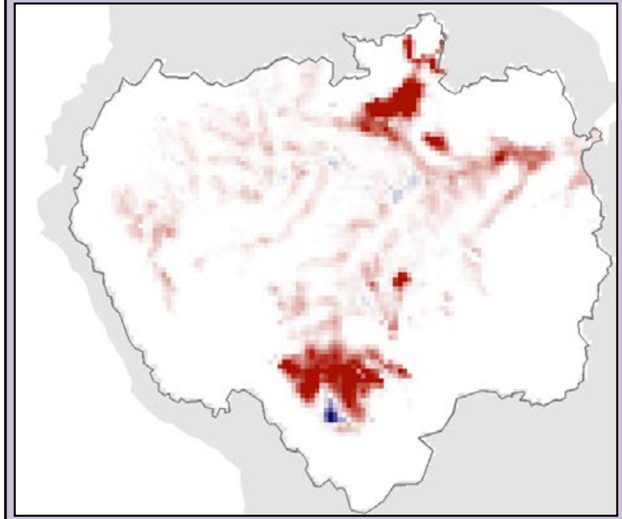
from Lewis et al. (Science 2011)

Anomaly of water fraction
Jul. – Sept. 2010



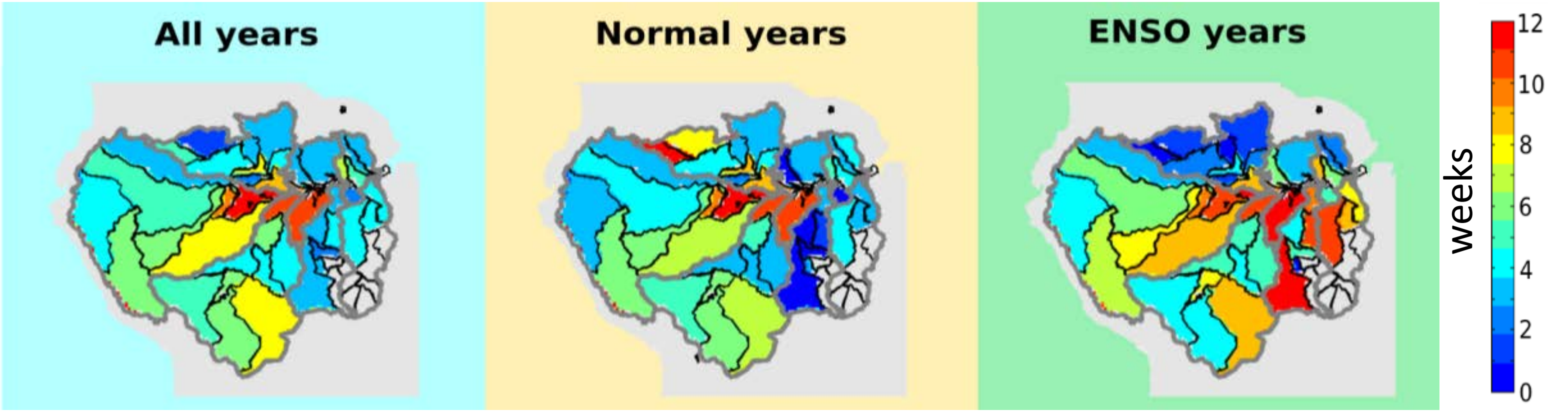
Current impact of ENSO

Anomaly of water fraction
Oct. – Dec. 2015

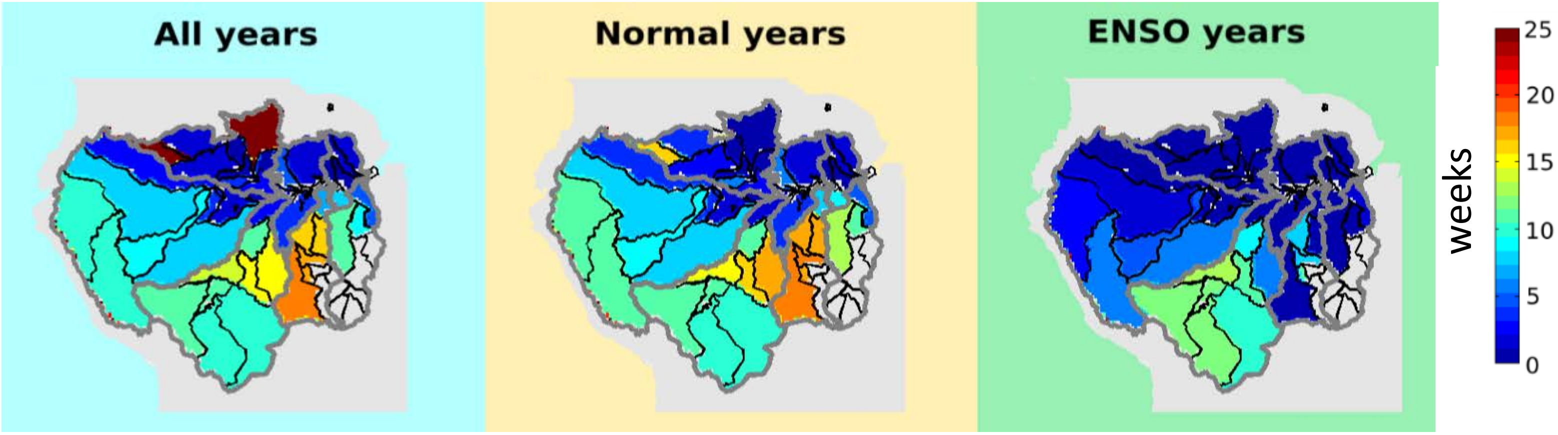


Impact of ENSO on hydrological dynamics

Time-lag between SMOS water fraction & TRMM rainfall



Time-lag between SMOS water fraction & in-situ discharge at outlet



Conclusions

The future of Hydrology…*a strategy for integrated observations*

- Integrating observations (CATDS, SWOT aval, ….)
  - to establish a more complete system description
- Integrating model components
  - to build an earth modeling system
- Integrating research results
  - to establish end-user solutions
- Data Integration
  - to allow for spatial and temporal rectification and to allow for the intercomparison and quality evaluation of different models and observation data
- Data-Model Integration
  - to constrain data and its errors by physical processes using four dimensional data assimilation techniques
- Solution Integration
  - to develop water cycle solutions by integrating observations into applications

The future of Hydrology*…a strategy for integrated observations*

The hydrological sciences community is making it’s mutation, as the atmospheric and ocean silences did before, by moving to **global multi-model and multi-sensors integrated modeling and assimilation systems.**

But this comes with **specific challenges** that need to be adressed like the complexity of the observed systems (spatial heterogeneity and temporal dynamics), and the impact of anthropogenic activities.

CNES is supporting this dynamic by contributing to innovative missions including the **SWOT** and the **SMOS** missions.

Thank you

Extra slides

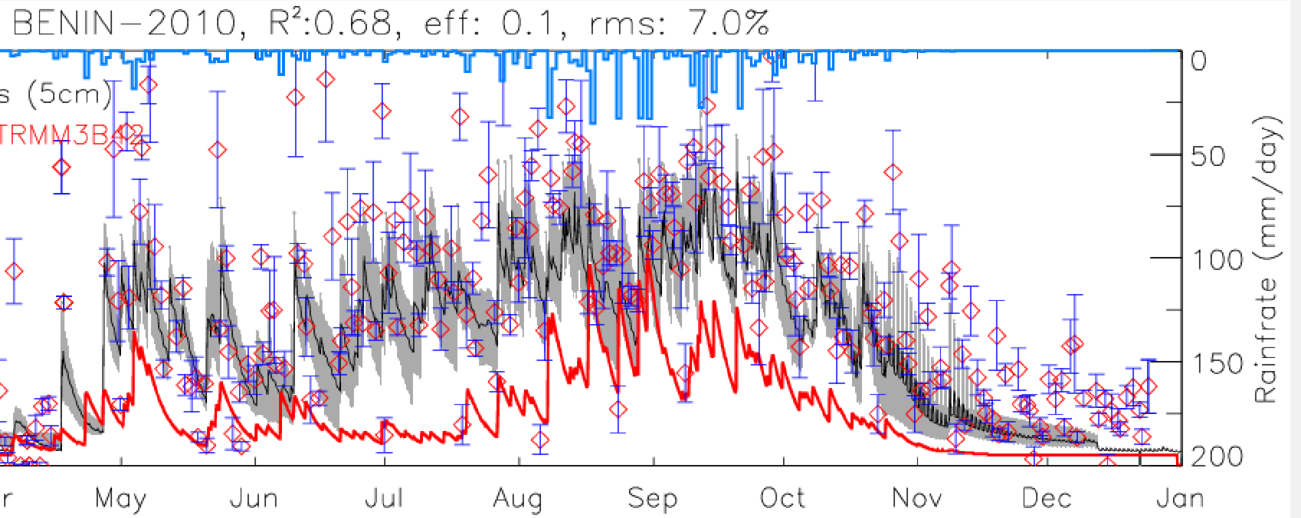
SMOS

Enhancing Rainfall products
LTHE

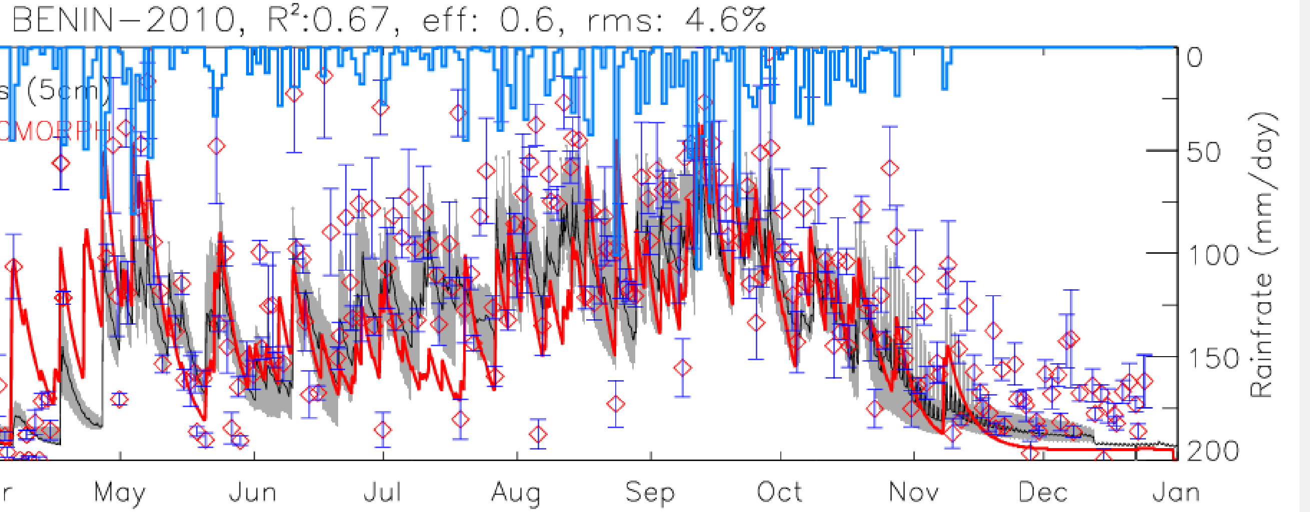
Estimated SSM <u>without</u> SMOS assimilation

Motivation:

using TRMM-3B42



using CMORPH

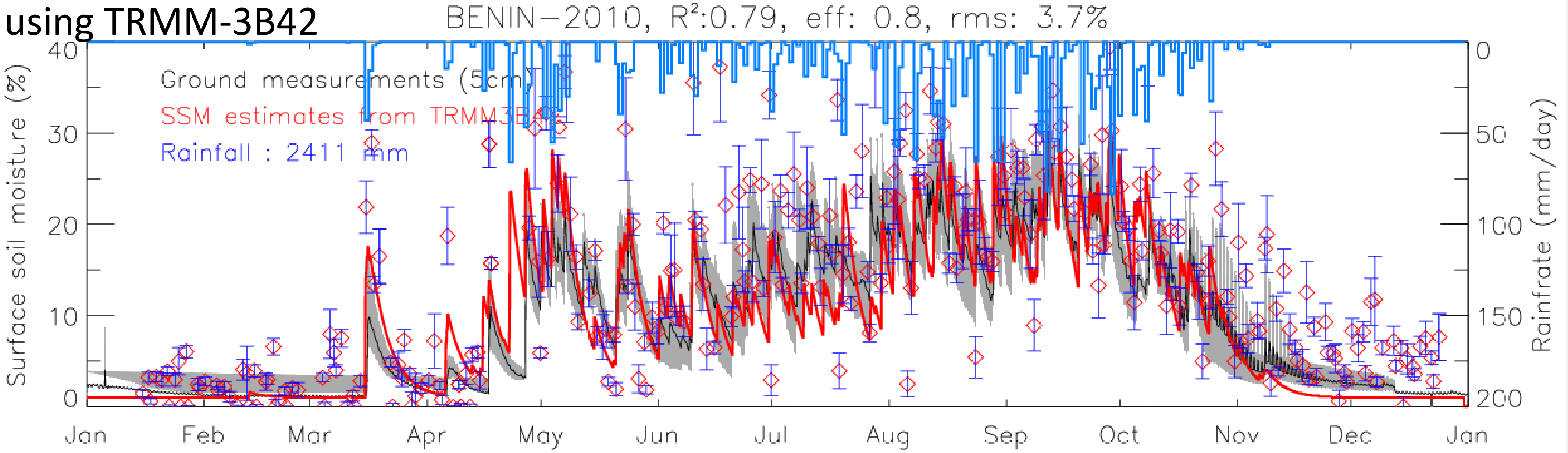


Pellarin T., Louvet S., Quantin G., Legout C., Al Bitar A., Kerr Y., Correcting Satellite Based Precipitation Products Using SMOS Measurement, 2014

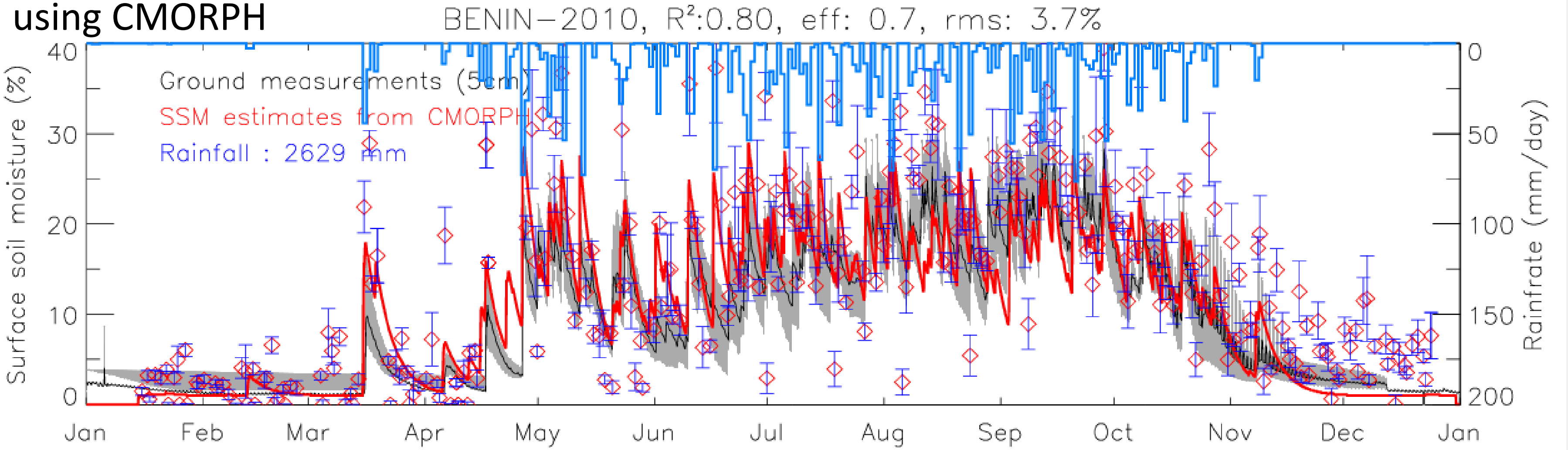
Estimated SSM <u>with</u> SMOS assimilation

<u>Results:</u>

using TRMM-3B42

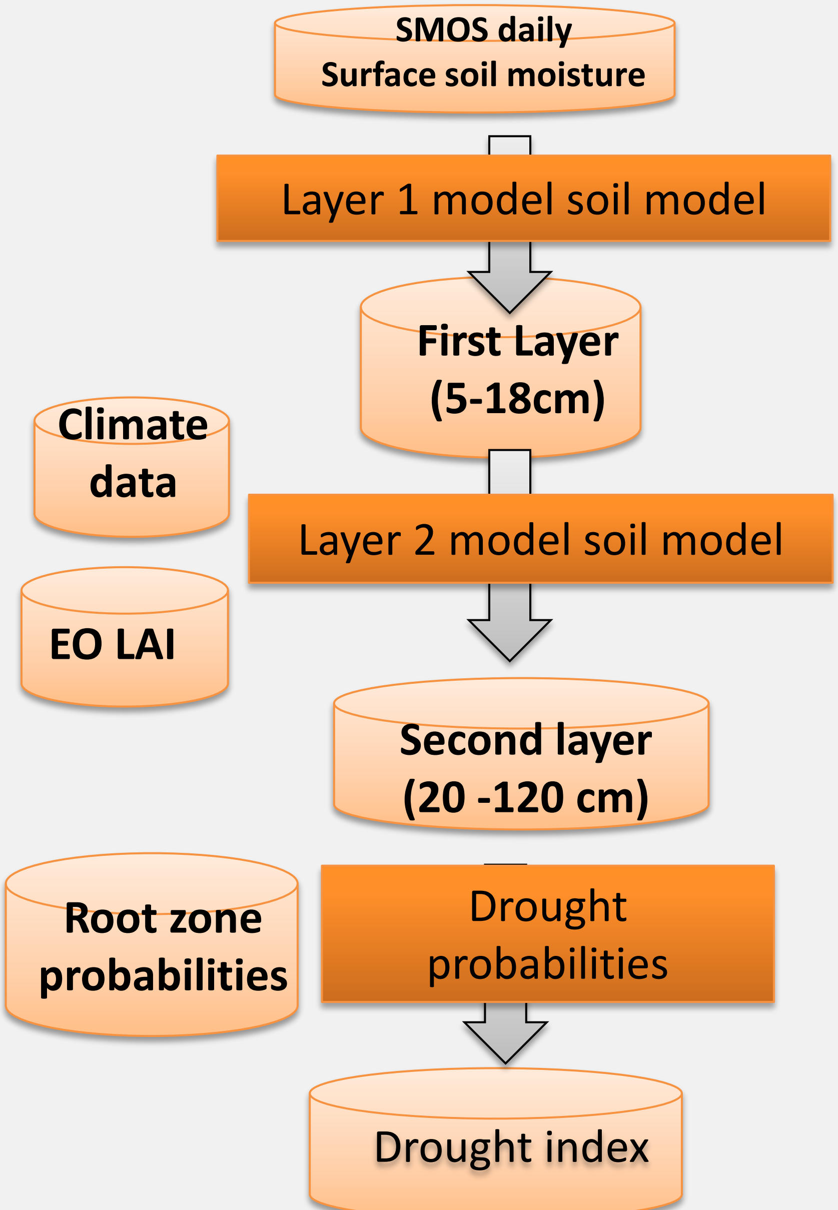


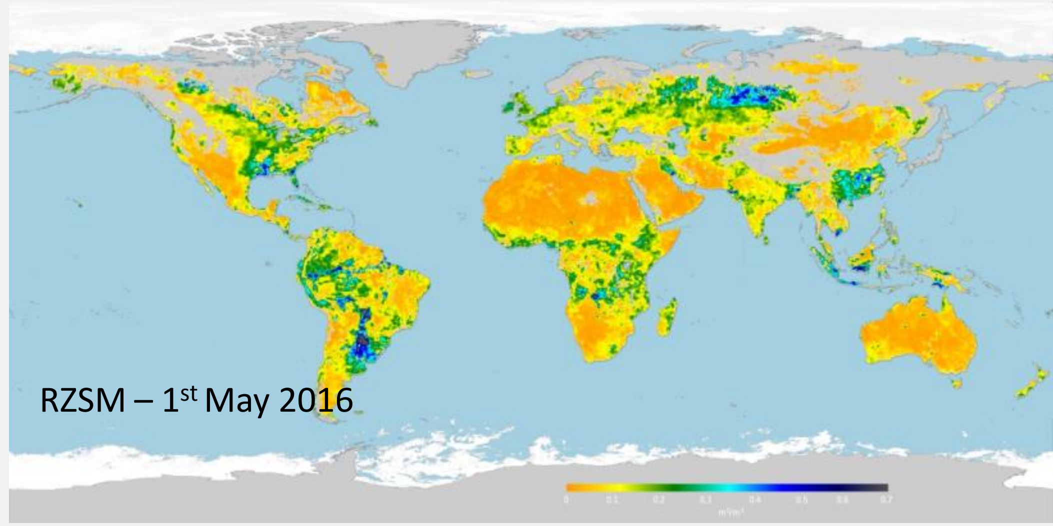
using CMORPH

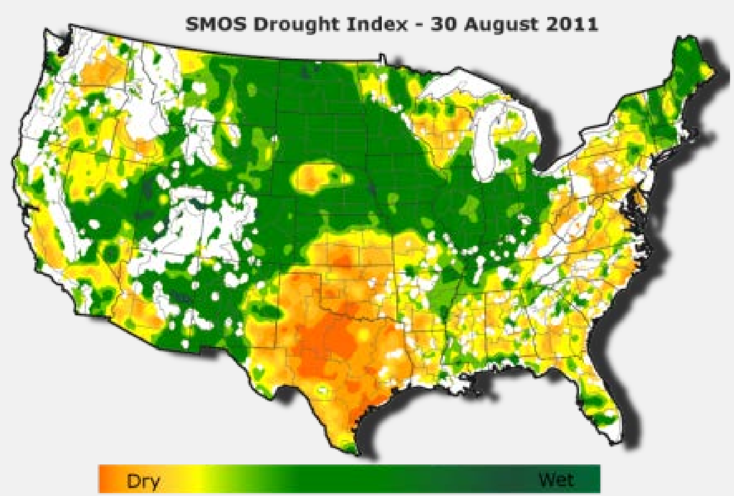


[Pellarin T.](), Louvet S., Quantin G., Legout C., Al Bitar A., Kerr Y., Correcting Satellite Based Precipitation Products Using SMOS Measurement, 2014

From surface to root zone SM using SMOS data

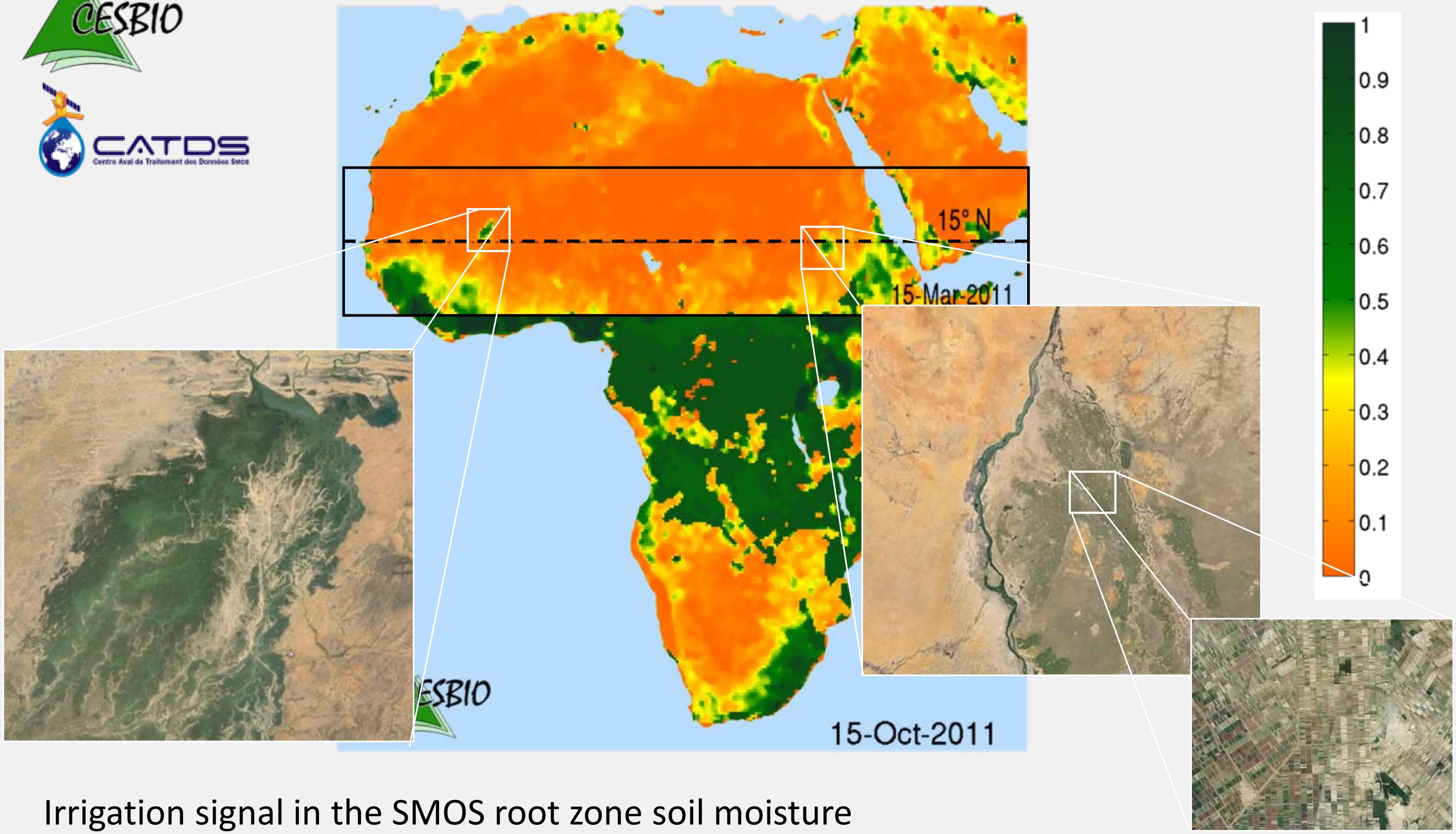






(Al Bitar et al., 2013)

Droughts in the horn of africa in 2011

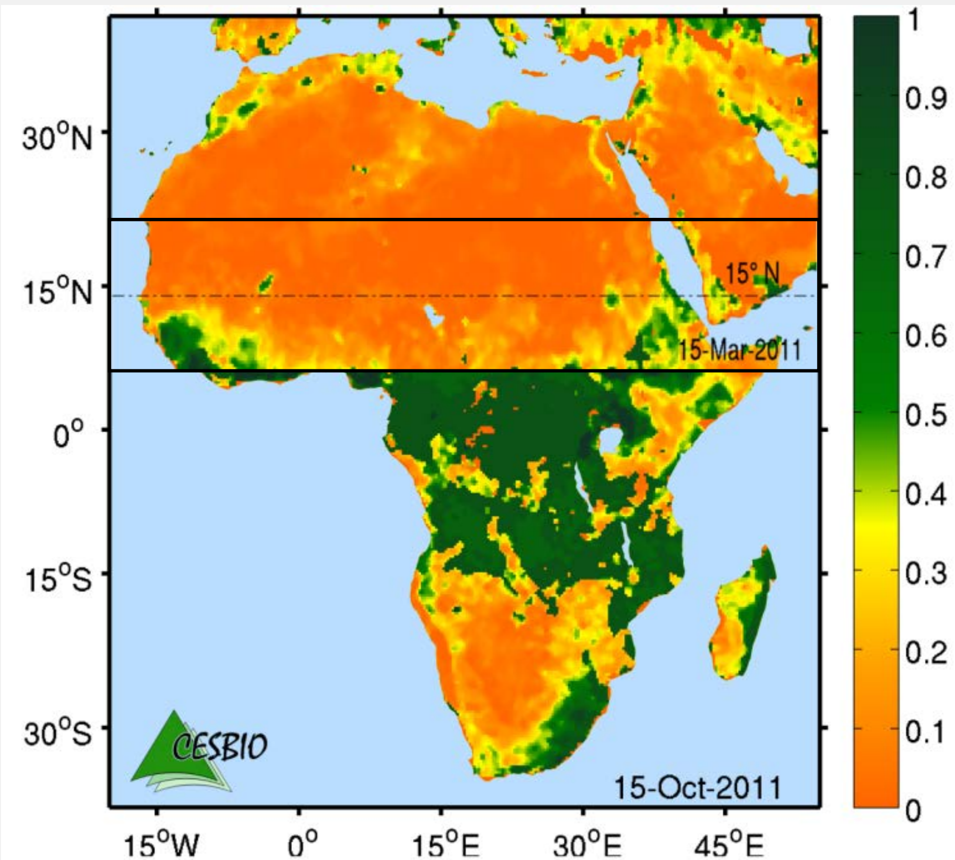


Irrigation signal in the SMOS root zone soil moisture

ahmad.albitar@cesbio.cnes.fr

Drought Index vs NDVI

Drought in the horn of Affrica



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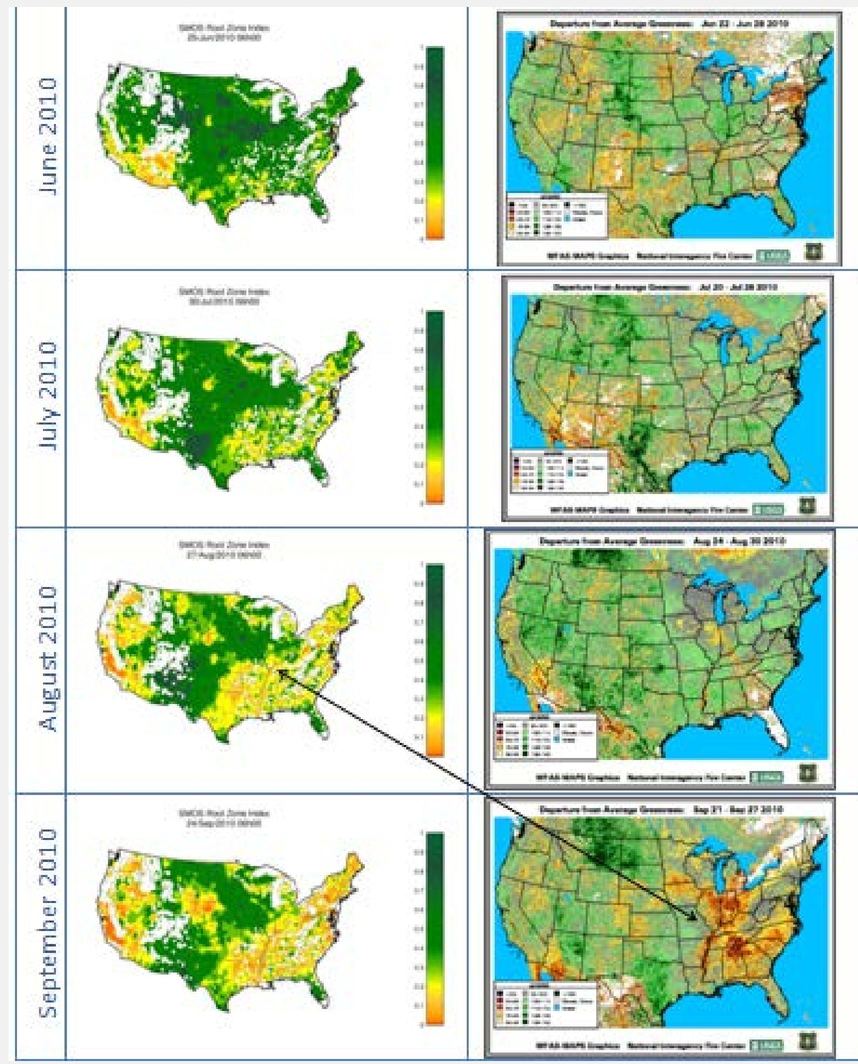
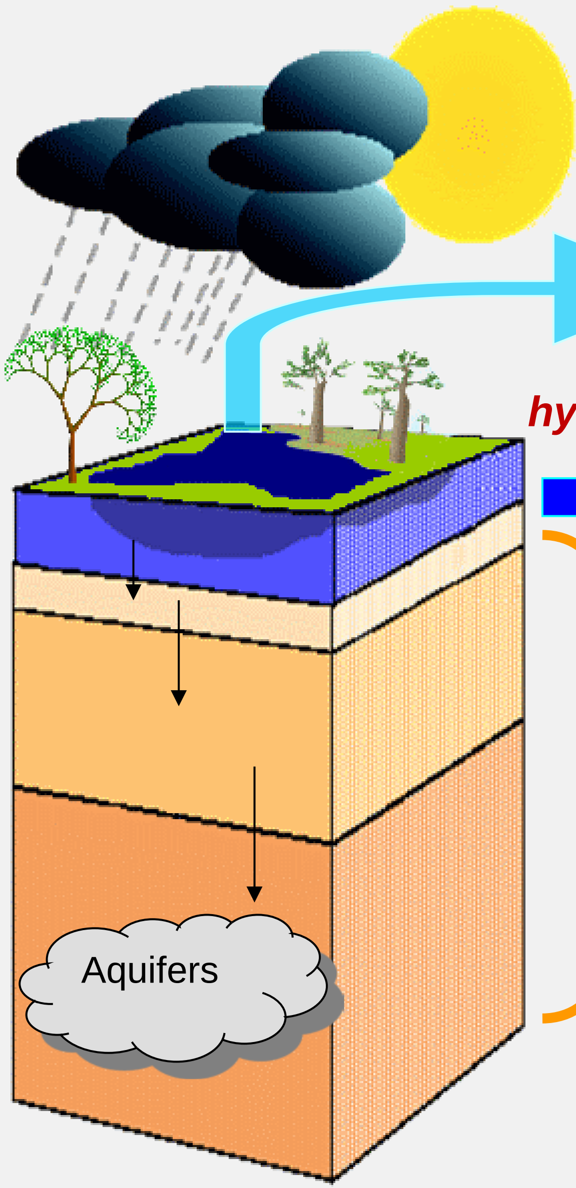
SMOS Drought Index AVHRR NDVI



Space measurements for the water cycle



Precipitation, Energy → Vis, NIR, TIR, Radar

Land Surface

Water Surface

hydro network, water storage, Discharge, *Evapotranspiration*

Soil moisture → Radar and passive microwaves

Ground water → Gravimetry

Direct or indirect measurements

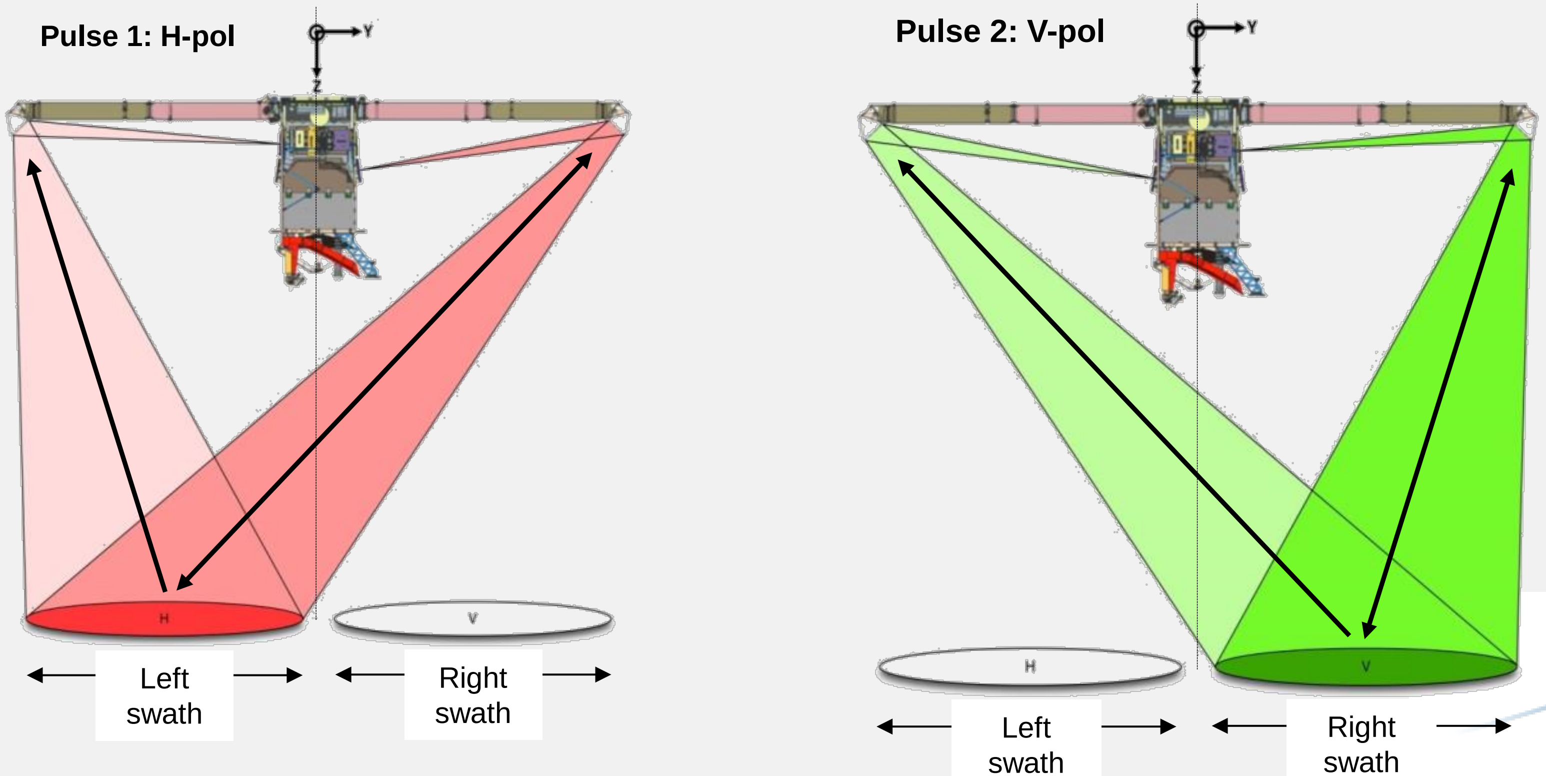
SWOT KARIN main products for hydrology

KaRIn will generate about 7Tb of data per day, which will be processed on ground to generate the following products :

- Level 0: Instrument Telemetry
- Level 1: Sensor data.
  - SWOT Low Resolution (Ocean Data) – OBP partial interferograms.
  - SWOT High Resolution (Land data) – full resolution complex interferograms in radar coordinates, phase flattened. (Images are internal product)
- Level 2 : Users level.
  - SWOT Low Resolution (Ocean Data) : Swath of sea surface height, slope, height uncertainty and backscatter
  - SWOT High Resolution (Land data) : Geolocated water mask with Surface Water height, slopes with uncertainties,
  - SWOT High Resolution Enhanced: Discharge on river database, flood plain on long-term data collection

KaRIN OPERATION

- To form the required baseline, KaRIn will deploy two 5-m-long and 0.25-m-wide reflectarray antennas on opposite ends of a 5 m boom; both antennas transmit and receive radar pulses.
- The interferometer is a dual-swath system, alternatively illuminating the left and right 50 km swaths on each side of the nadir track. KaRIn will make near-nadir measurements at Ka-band (0.84-cm wavelength, 35.75-GHz center frequency).



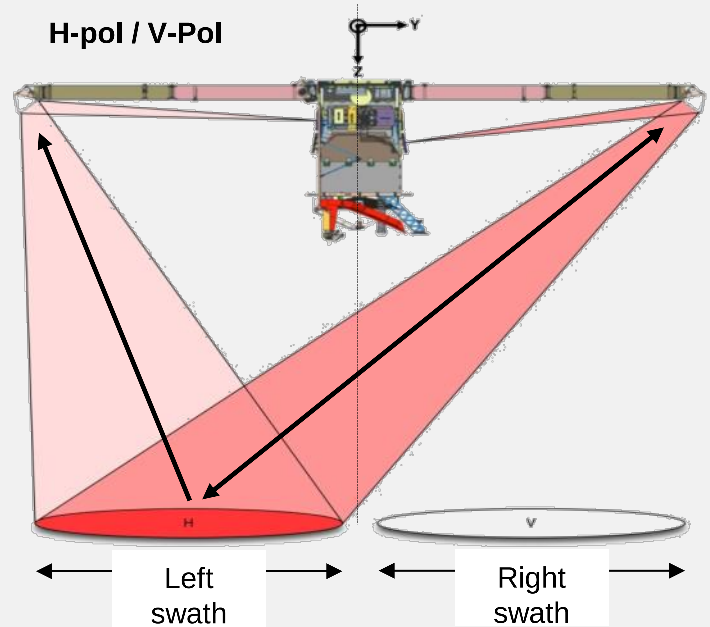
SWOT Mission FACT SHEET

Mission Science

Oceanography: Characterize the ocean mesoscale and sub-mesoscale circulation at spatial resolutions of 15 km and greater.

Hydrology: To provide a global inventory of all terrestrial water bodies whose surface area exceeds $(250m)^2$ (lakes, reservoirs, wetlands) and rivers whose width exceeds 100 m (rivers).

- To measure the global storage change in fresh water bodies at sub-monthly, seasonal, and annual time scales.
- To estimate the global change in river discharge at sub-monthly, seasonal, and annual time scales.



Mission Architecture

- Ka-band SAR interferometric (KaRIn) system with 2 swaths, 50 km each
- Produces heights and co-registered all-weather imagery
- Use conventional Jason-class altimeter for nadir coverage, radiometer for wet-tropospheric delay, and GPS/DORIS/LRA for POD.
- On-board data compression over the ocean (1 km^2 resolution).

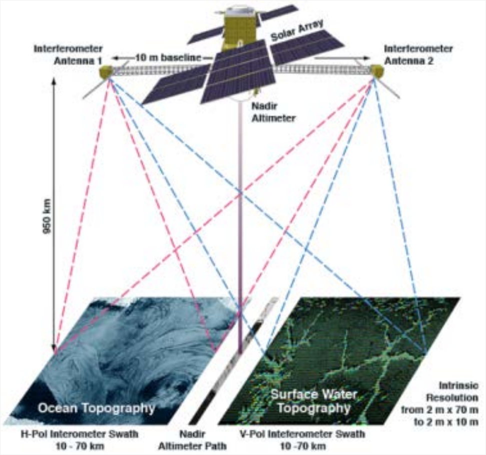
- Partnered mission : CNES/ NASA /CSA/ UKSA
- Science mission duration of 3 years
- Calibration orbit: 857 km, 77.6º Incl., 1 day repeat
- Science orbit: 891 km, 77.6º Incl., 21 day repeat
- Flight System: ~2000kg, ~1900W
- Launch Vehicle: NASA Medium class
- Target Launch Readiness: Apr. 2021

SWOT Mission *Motivations*

- Recommended
  - by the US Decadal Survey based on Water/Hydrosphere Concept
  - In the frame of the CNES Scientific Prospective Seminar (Biarritz, March, 2009)

- Cooperation USA/France/Canada
  - **An emblematic Project of** France-USA cooperation **: more than 20 years cooperation in Space Altimetry**

- The SWOT mission is a partnership between two communities, hydrology and oceanography



SWOT mission motivations

The Surface Water and Ocean Topography (SWOT) Mission is being jointly developed by NASA and CNES, with contributions from the Canadian Space Agency (CSA) and United Kingdom Space Agency (UKSA).

The SWOT mission will provide valuable data and information that will benefit society in two critical areas; freshwater on land, and the oceans' role in climate change.

It will fulfill important observations of the amount and variability of water stored in global lakes, reservoirs, wetlands, and river channels and will support derived estimates of river discharge.

SWOT will also provide critical information necessary for water management, particularly in international hydrological basins.

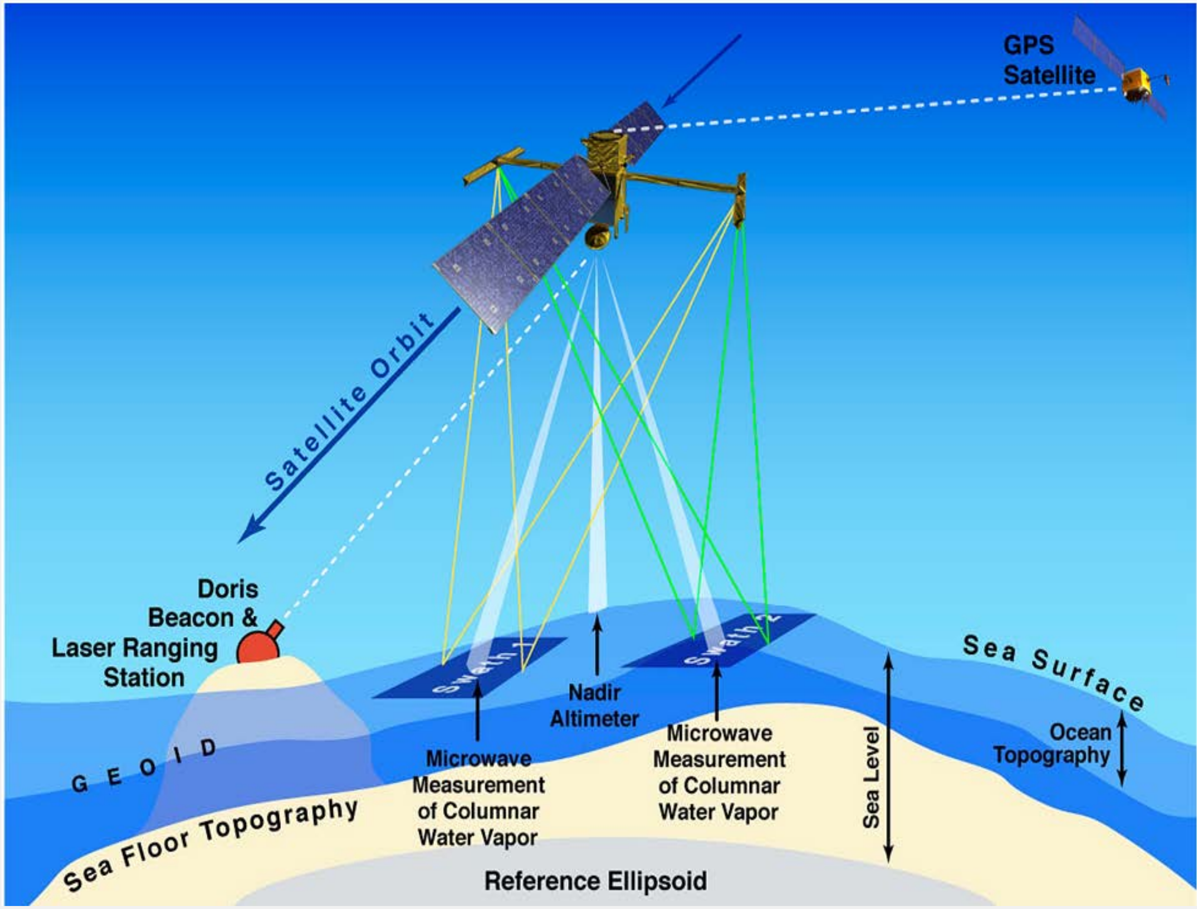
SWOT is scheduled to launch in April 2021 with newly developed wide-swath altimetry technology, the Ka-band Radar Interferometer (KaRIN) instrument.

THE SWOT MEASUREMENT PAYLOAD

The core technology for SWOT is the KaRIN SAR radar Interferometer, complemented with a suite of instruments:

- a nadir-looking conventional altimeter, a three-frequency microwave radiometer), as well as global positioning system (GPS) receivers and a DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) transponder for precise orbit determination.

KaRIN will measure elevations at high precision and spatial resolution. The payload complement will be used for calibration and to obtain a cross calibrated data set with traditional altimeters.



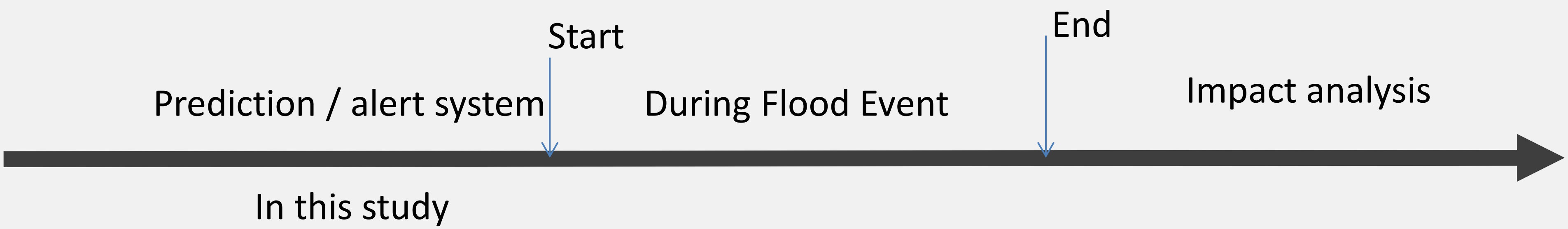
SWOT – An ambitious and challenging mission

- **Scientific Stakes : Leading scientific innovation**
  - New technologies on board SWOT allow the collection of unprecedented oceanographic and hydrographic data on a global scale
    - Essential contribution of SWOT: spectacular gain in spatial resolution from ~ 100 km to100 m or more
- **Applications Stakes: Providing information on freshwater**
    - Beyond the scientific contribution to a better understanding of the water cycle, SWOT could have an economic and social impact through the development of new applications
- **Technological Stakes: New path for satellite altimetry**
  - The SWOT mission is a breakthrough in the field of space altimetry
    - The instrument KaRIN is the main innovation of the SWOT mission and presents a significant technical challenge

Flood Risk mapping

Motivation

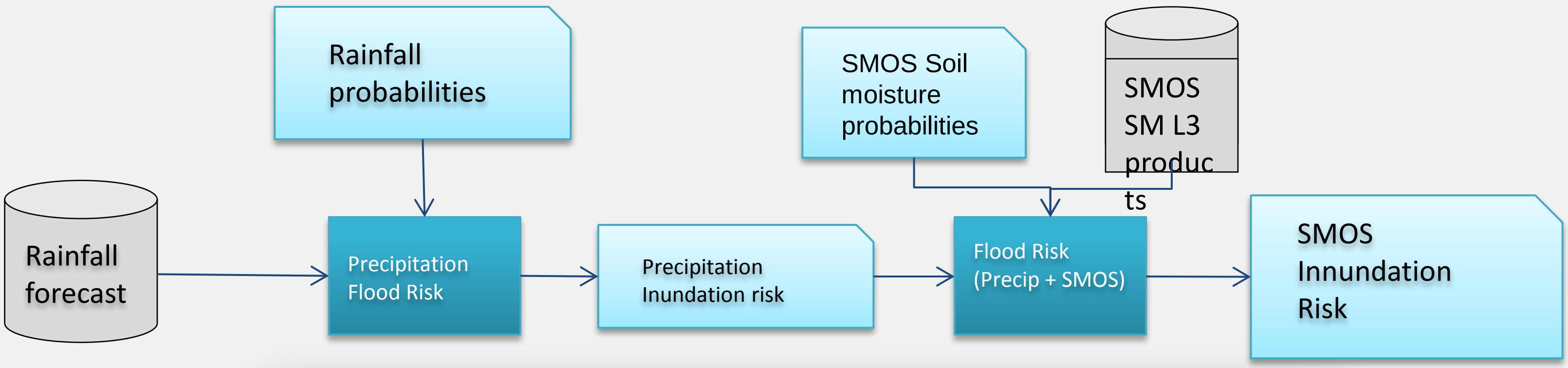
- Flood can be classified to several types : Hurricans, storm surge, heavy rainfall …
- Soil moisture is expected to play a role for heavy rainfall flood, but this remains an open question in hydrology.
- Here we consider that soil moisture conditions can increase or decrease the flood risk:
  - saturated soils increase risk for floods
  - Soil moisture is a proxy for rainfall
  - Land surface / atmospheric coupling (Koster et al.)

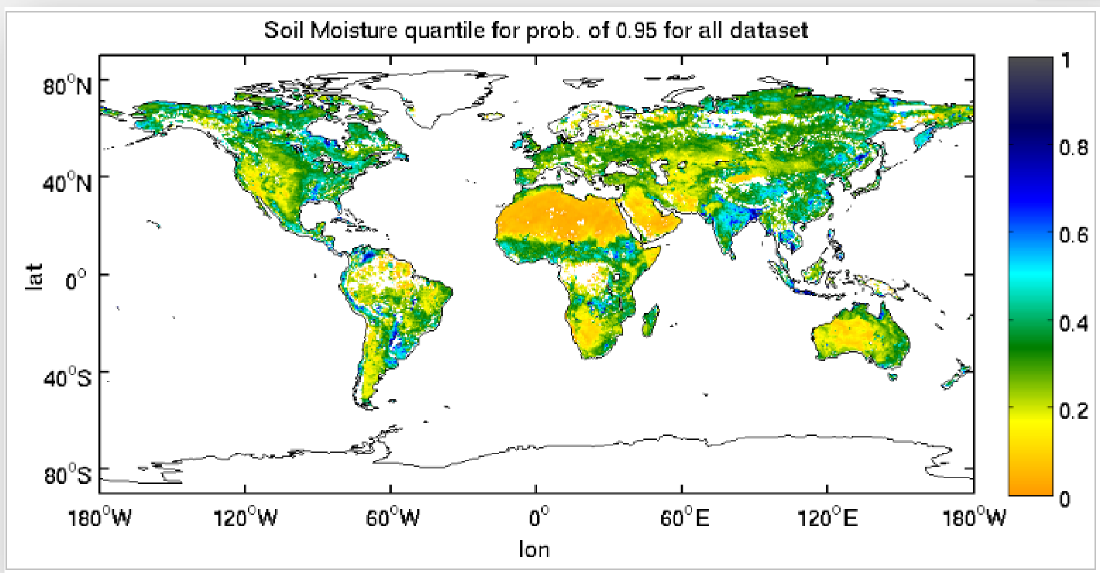


SMOS Flood Risk Forecast

Methodology

Leveraging inundation risk based on SMOS soil moisture prior knowledge



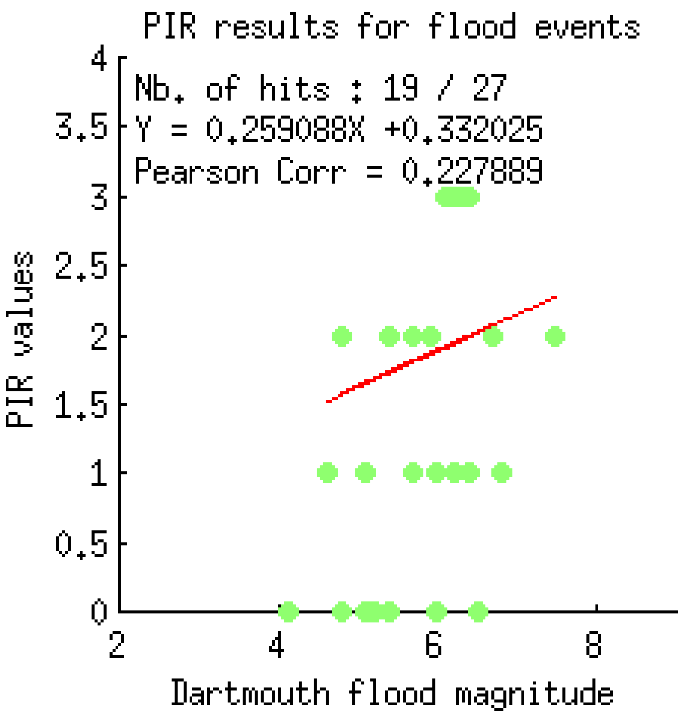


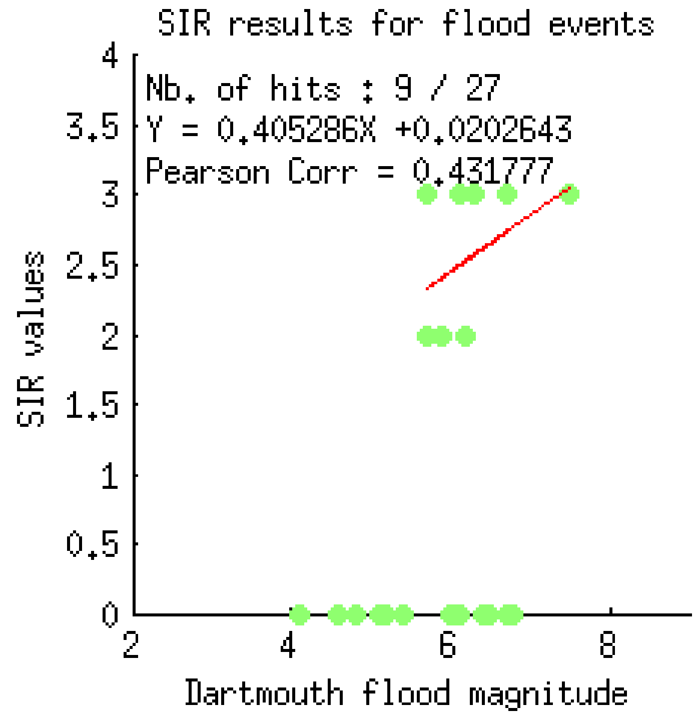
Al Bitar A., Chone A., S. K. Tomer, CESBIO

SMOS Flood Risk Forecast

Results

- Compare with the Dartmouth Flood Observatory
- Dartmouth magnitude of the flood against the Precipitation inundation risk and the SMOS inundation risk.





- Results show that the Precipitation Inundation risk is underperforming.
- But also that the use of SMOS globally enhances the risk product except in A

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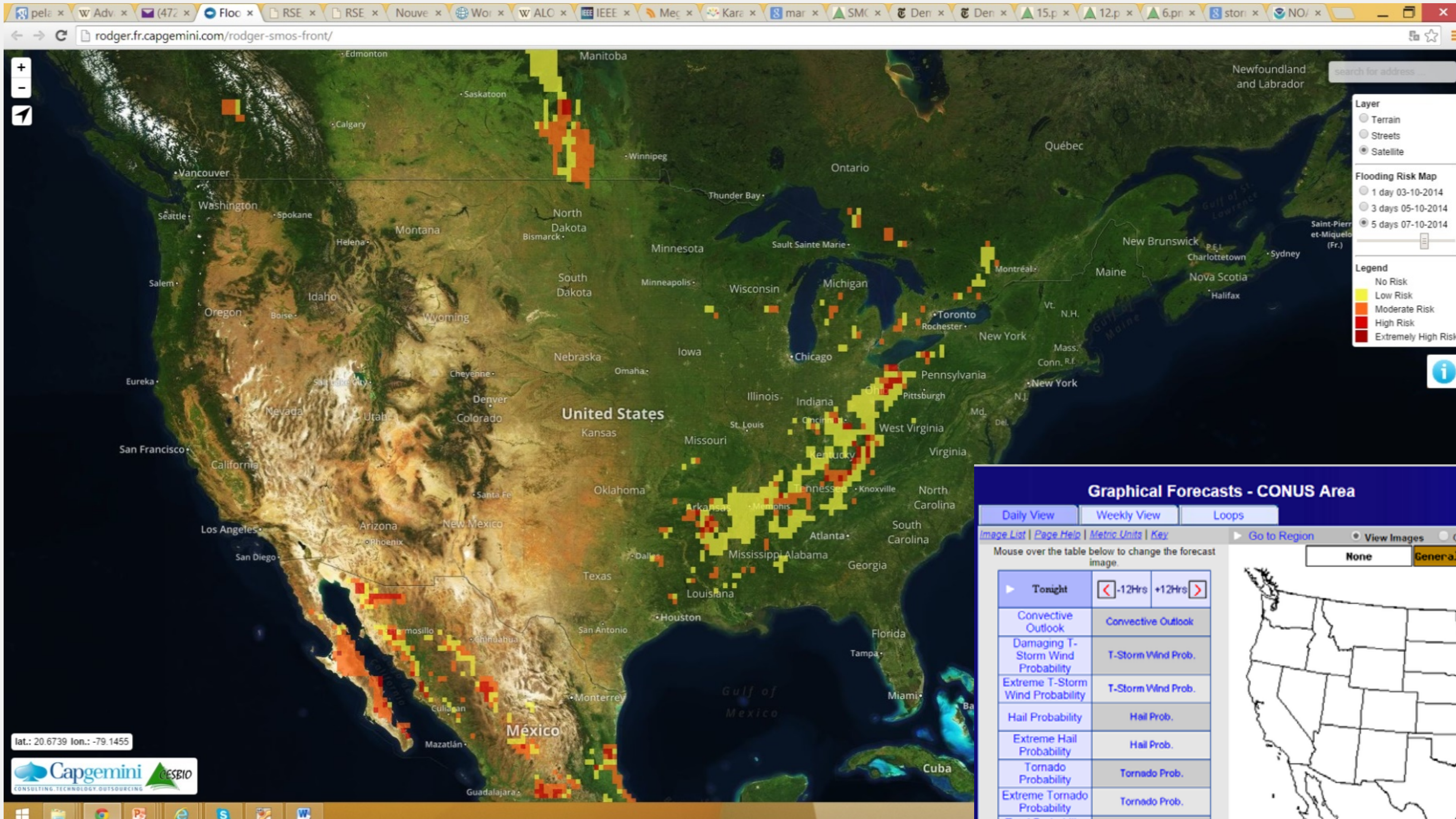
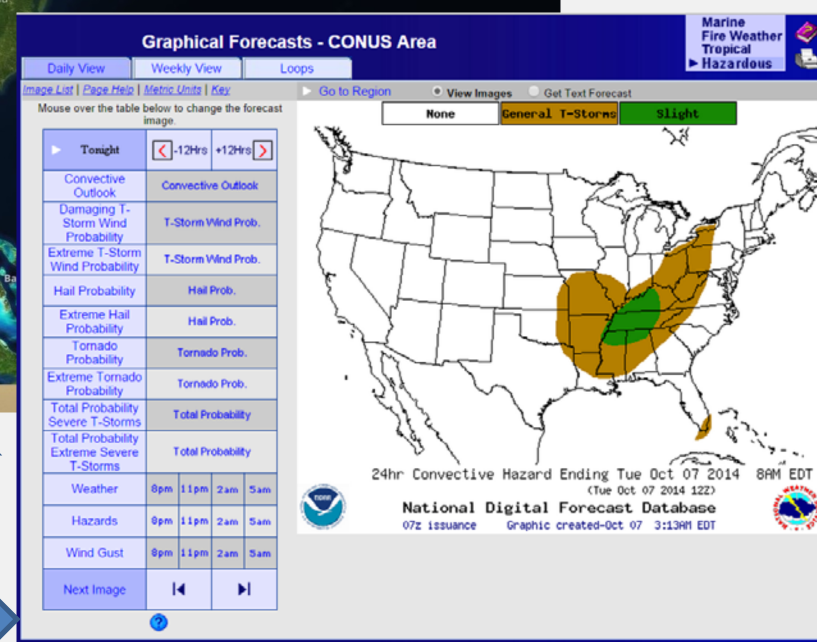
Operational implementation by CapGemini and CESBIO





SMOS flood risk Today 07 Oct. 2014 at 12h45 for the next 5 days

Storm risk by NOAA Today 07 Oct. 2014 at 12h45