GSICS Microwave Subgroup Workshop

Satellite Observations for Global Water Cycle

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1. Science and Application Importance

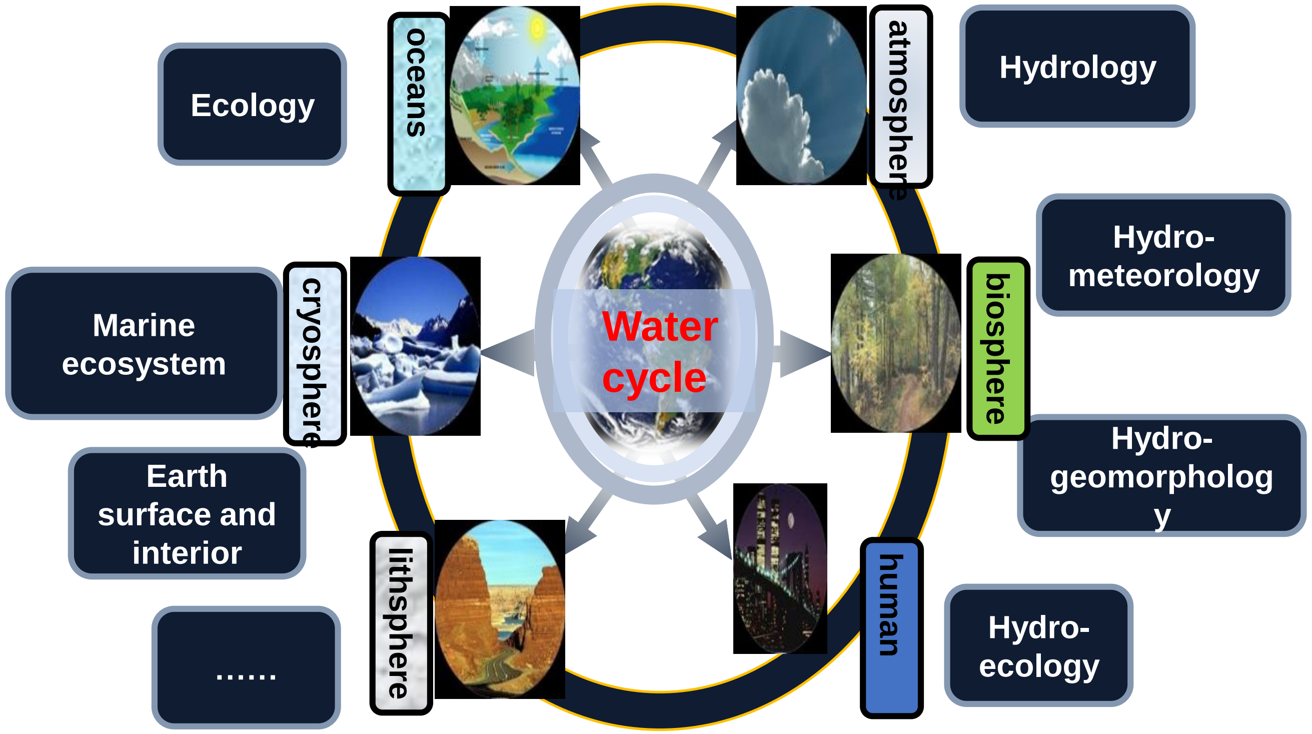
Water cycle is the one of natural key processes of Earth System, that links the most of atmospheric, surface, hydrological, and eco-system processes. *Understanding water cycle* from an integrated Earth-system perspective is a frontier research issue. Monitoring, understanding, and predicting their changes are critical to science, application, and society benefits.

Science Questions:

1） Characteristics of spatio-temporal distributions and their change at global and regional scales?

2） Water Cycle-Climate feedbacks ?

3） Water cycle acceleration at regional to global scales?



1. Project on Satellite Constellations of Water Cycle for Global Change (2021-2025)

Goal: Establish the global water cycle observatory (GWCO) to advance our understanding of water cycle changes, its consequences and impacts on applications and social benefits

International co-operation is an important function: establish an international infrastructure of observing system and analysis capacity with world experts, research groups and agencies

Technical Approach: build satellite based global water cycle observatory (GWCO) using current and future Chinese and International satellites, not only the parameters but also the water cycle system measurements

Institutions +national research projects

1. National Satellite Meteorological Center
2. National Satellite Ocean Application Service
3. National Space Science Center, CAS
4. State Key Laboratory of Remote Sensing Science, CAS/MOST

2. Build Water Cycle System Observatory

Characteristics of the Spatial-Temporal Distribution of Water Cycle Components

Hydro-climatology 50-100km， Hydro-meteorology 4-15km resolution

Strong Variability in Time：

- Precip./vapor
- Ocean Evaporation

Strong Variability in Space：

- Freeze/Thaw
- SWE
- Soil Moisture

Weak Variability：

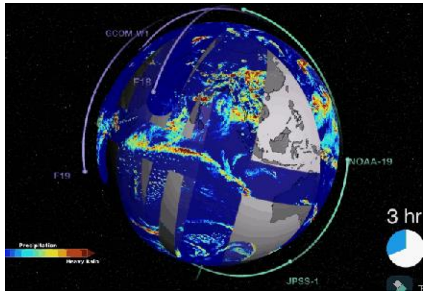
- Sea salinity
- Polar Ice

Water Cycle	Temporal Resolution	Ideal Spatial Resolution	Minimum Requirement	Obs, Error
Precip./vapor	1-2hour	1km	25km	1 mm hr-1
Sea Evap.	1-2hour	10km	25km	15 W m-2
Soil moisture	2-3day	100m-1km	50km	0.04 m^3/m^3
Sea salinity	6-10day	30km	100km	0.1-0.2 psu
FT	2-3day	100m-1km	50km	10-20 %
SWE	2-3day	100m-1km	50km	10 %
Water body	3-7day	30m	1km	1000 m2
Underground water	1month	50km	300km	~
Land ET	1-2hour	30m-1km	5km	30 W m-2
runoff	1-2hour	~	~	~

2. Build Water Cycle System Observatory

Precipition

The global observation capability of China microwave missions in polar and inclined orbits, including dual frequency precipitation radar, can obtain observational data globally with 3-5 hours. With international available satellites, temporal precipitation data can achieve at 2-3 hours.



China

FY-3D MWRI	FY-3F MWRI	FY-3G MWRI	FY-3R MWRI	FY-3R PR
10-89GHz	10-118GHz	10-118GHz	10-183GHz	13/36GHz
2017-	2021-	2023-	2022-	2022-

Marine mission

HY-2B	HY-2E	HY-2G
6-36GHz	6-36GHz	6-89GHz
2018-	2021-	2023-

International

GPM GMI	GPM DPR
10-183GHz	13/36GHz
2014-	2014-

Other Missions

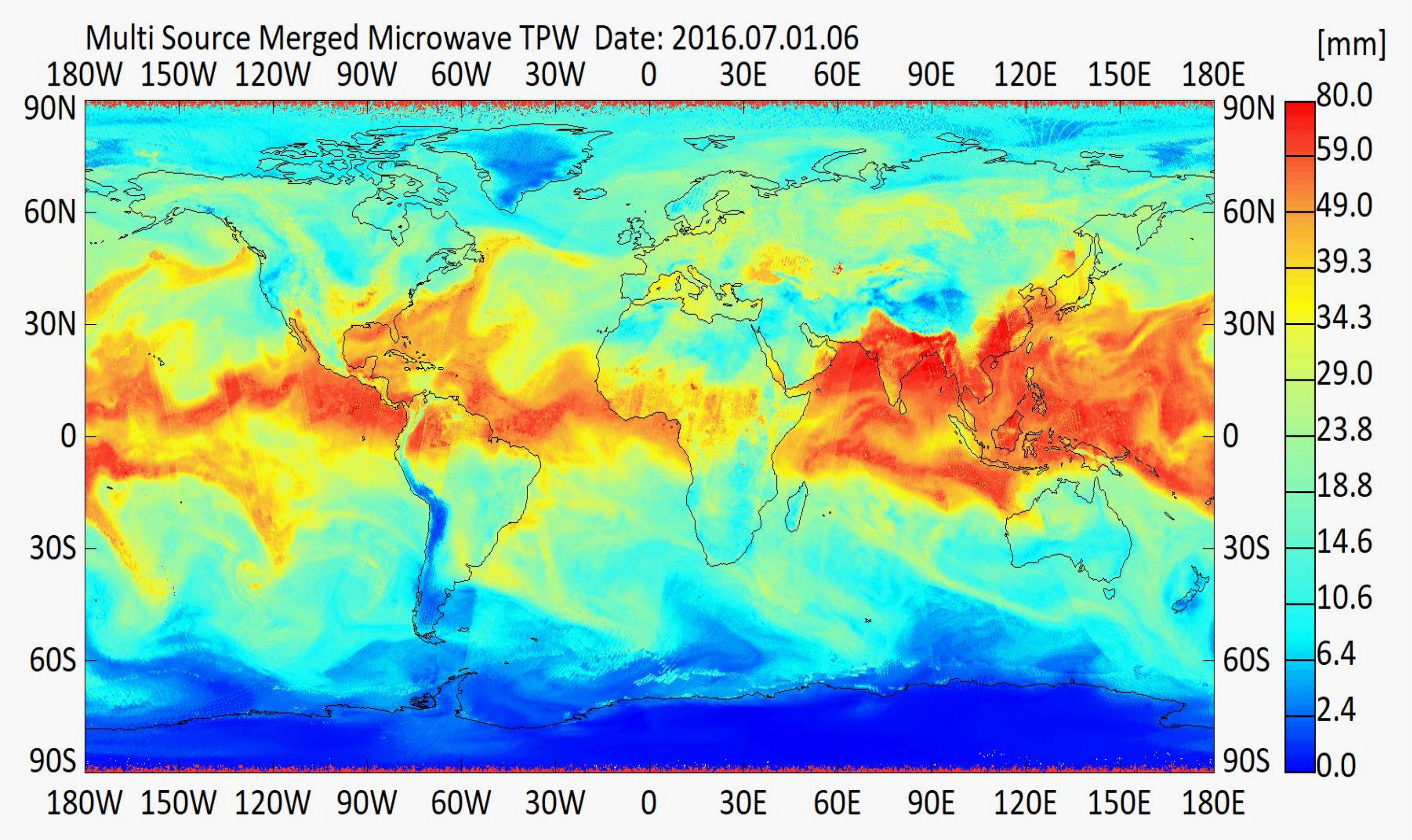
GCOM-W1 AMSR2	DMSP-F16 SSMIS	DMSP-F17 SSMIS	DMSP-F18 SSMIS	DMSP-F19 SSMIS	Coriolis WindSat
6-89GHz	19-183GHz	19-183GHz	19-183GHz	19-183GHz	6-37GHz
2012-	2003-	2006-	2009-	2014-	2003-

But algorithms need to be improved. Combining with Geostationary orbit Infrared sounders to improve temporal resolution (10-30 min), but accuracy is less than microwave.

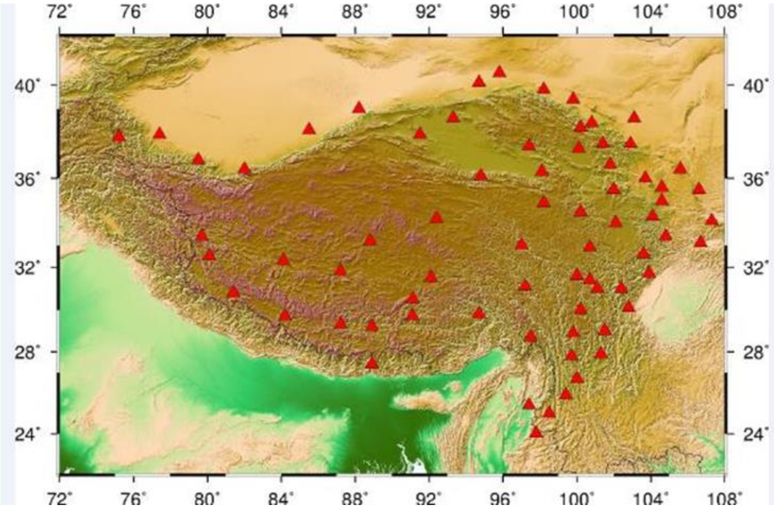
2. Build Water Cycle System Observatory

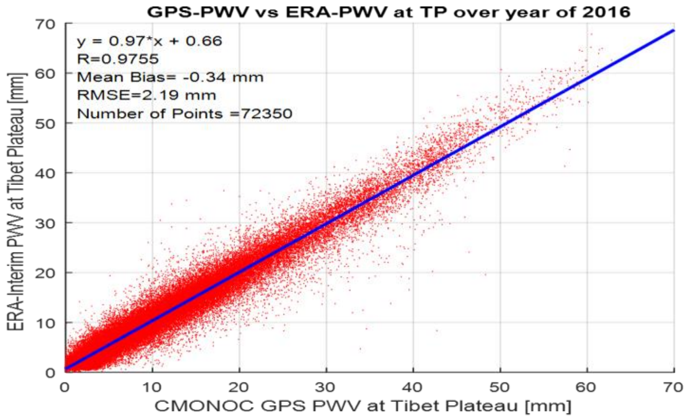
Water Vapor

Merged Microwave Water Vapor Product (3h)



Validation with GPS observations

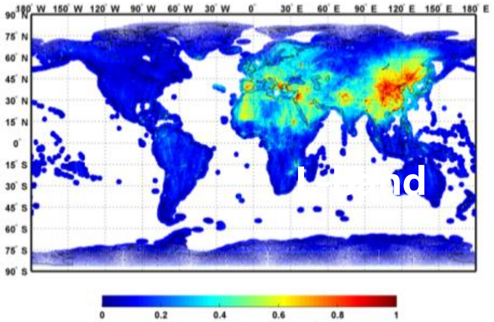




2. Build Water Cycle System Observatory

Soil Miosture L-band SMOS

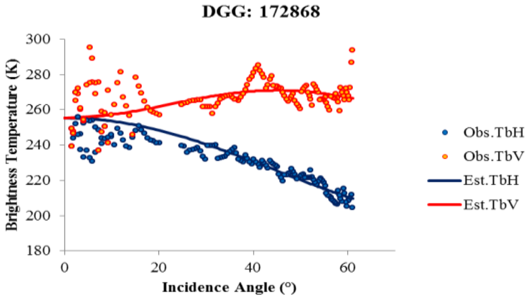
Improved algorithm



Eurasia

SMOS Brightness temperature

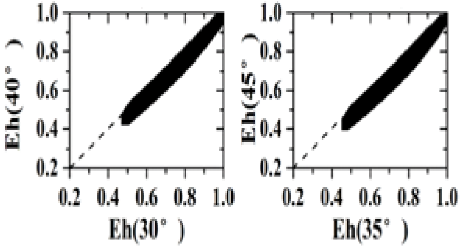
1) A new processing method to reduce radio interference significantly



Temperature correction

Surface emissivity

surface reflectance at different incident angles



$$TB_h(\theta_2) = a_h(\theta_1,\theta_2)\cdot V_{atth}(\theta_2) + V_{eh}(\theta_2) - b_h(\theta_1,\theta_2)\cdot\frac{V_{atth}(\theta_2)}{V_{atth}(\theta_1)}\cdot V_{eh}(\theta_1) + b_h(\theta_1,\theta_2)\cdot\frac{V_{atth}(\theta_2)}{V_{atth}(\theta_1)}\cdot TB_h(\theta_1)$$

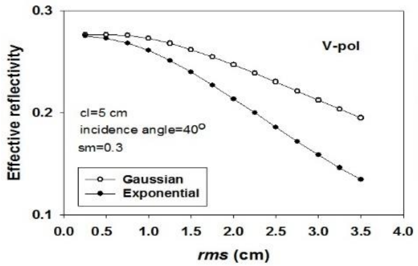
Ah Microwave vegetation index Bh

2) New technique to separation vegetation and soil signals

Veg. → **VOT**

Soil → **SM**, **Roughness**

Influence of different roughness functions



3) Parameterized model of surface reflectance considering different roughness functions

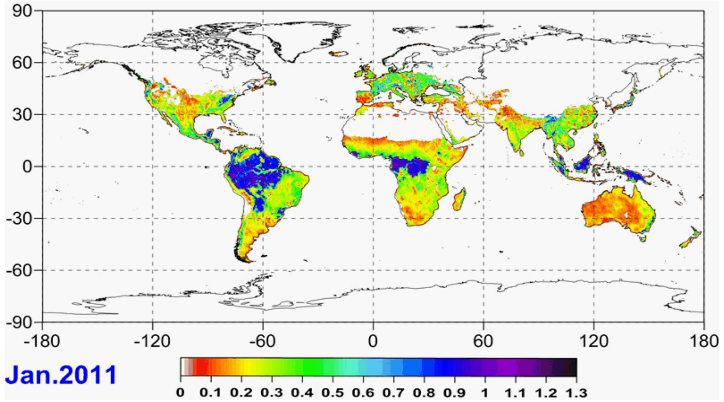
$$Sr = (K\cdot rms)^{2-N}\cdot(rms/cl)^N$$

2. Build Water Cycle System Observatory

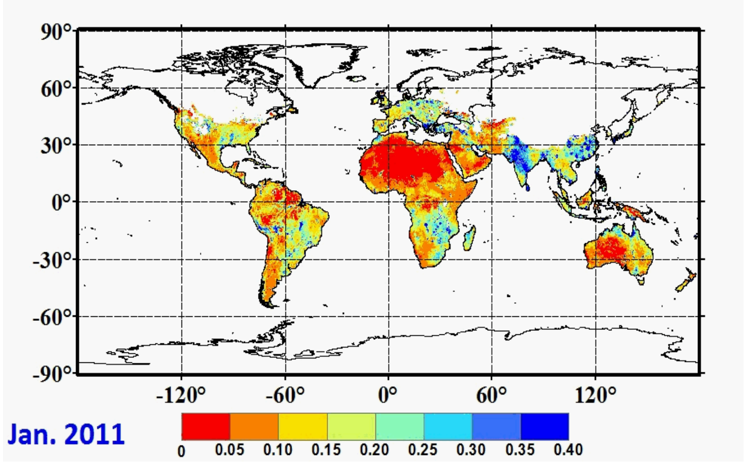
Soil Miosture SMOS

New results

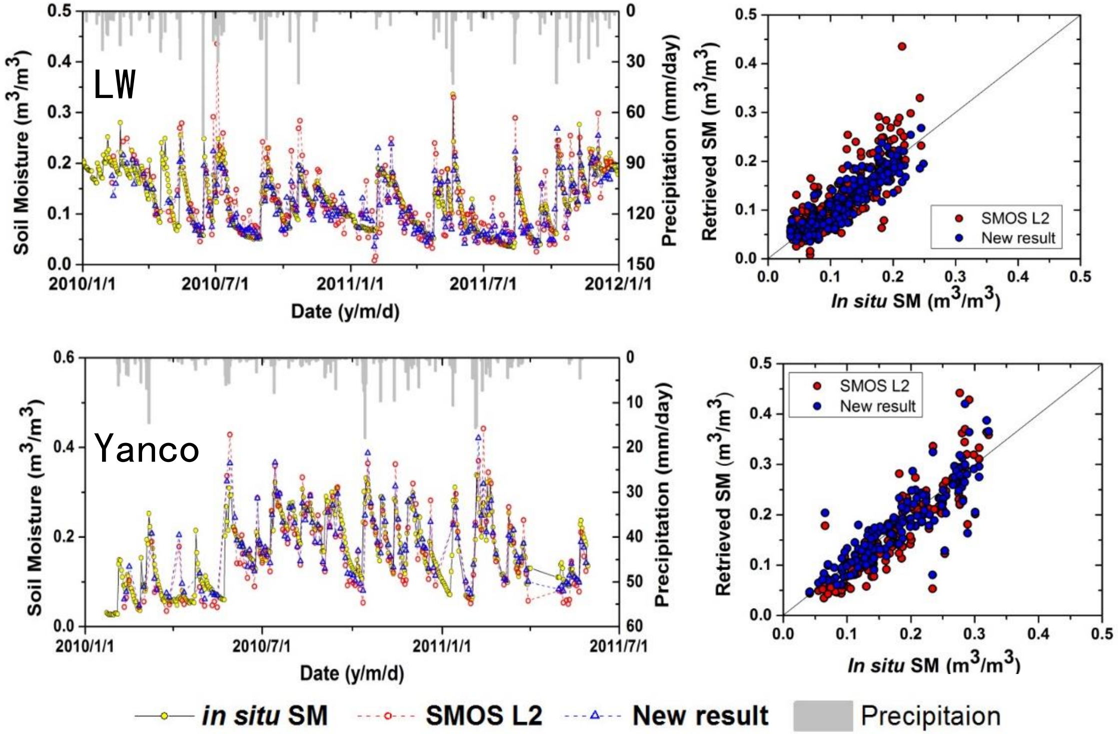
Vegetation optical thickness



Soil moisture



Two soil moisture standard verification sites



		RMSE	R^2
LW	SMOS L2	0.040	0.661
	New result	0.024	0.811
Yanco	SMOS L2	0.045	0.753
	New result	0.038	0.760

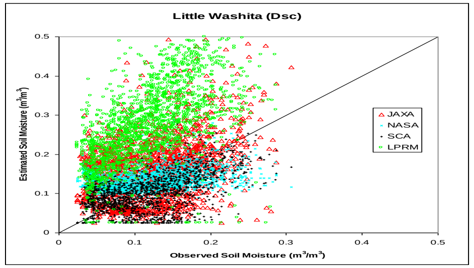
Verification results show that it has higher accuracy of soil moisture estimation than SMOS

2. Build Water Cycle System Observatory

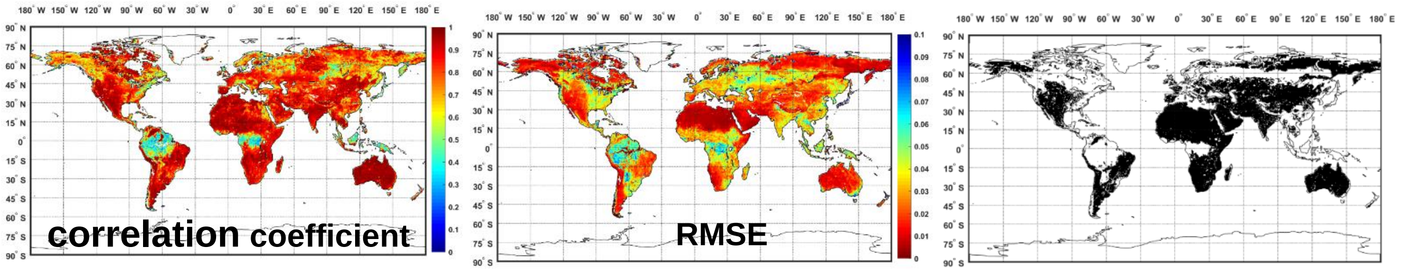
Soil Miosture C-X bands

Problem: Current & Historical data (C-and X-band) cannot meet the accuracy needs of water cycle and global change studies.

LW station calibration based on 7-yr data and 4-algorithms



Eg., SMOS/SMAP **L-band retrieval of soil moisture** and **AI** are used to develop algorithms of AMRS (C- and X-band) and FY-3 (X-band). Results show the accuracy of AI with similar as L-band instrument, especially in non-forest areas.



SMAP meet accuracy (4%) at shaded areas, while retrieval shows problem at forests, cites, polar and water cover areas.

Globe

CC	RMSE	Bias
0.80	0.029	0.0017

No-forest Regions

CC	RMSE	Bias
0.92	0.014	0.001

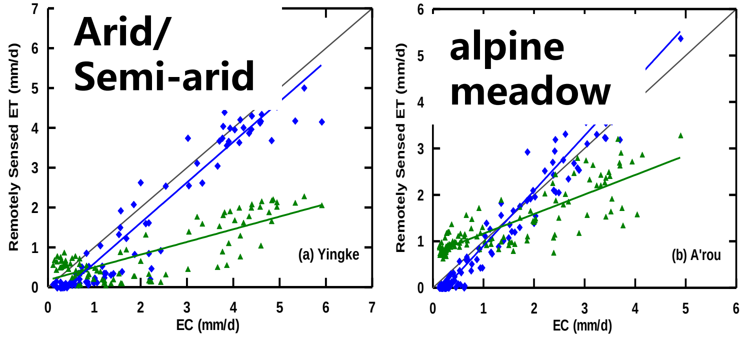
Producing the better SM products for 2002-currents: AI and machine learning offer great opportunities throughout historical longer-time series SM data.

2. Build Water Cycle System Observatory

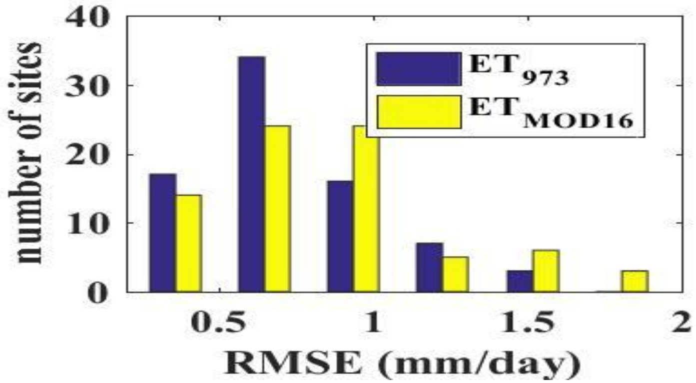
Evapotranspiration

ET-Monitor is mainly driven by remote sensing observations (Jia et al.)

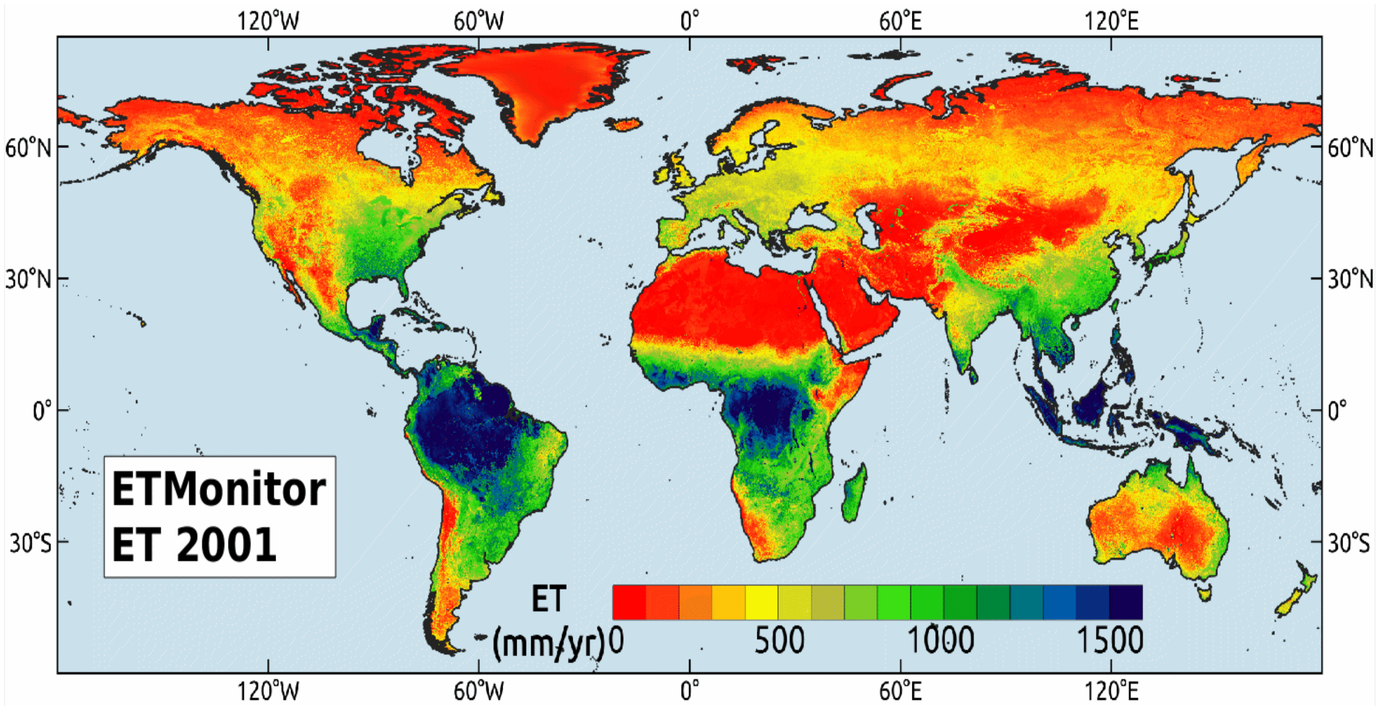
Role of soil moisture



Accuracy comparison with MODIS at 79 sites



Annual ET since 2001 (mm/yr)



The global ET product at 1km and daily scale since 2001.

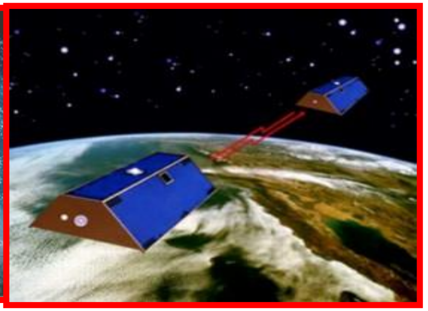
2. Build Water Cycle System Observatory

Water Storage

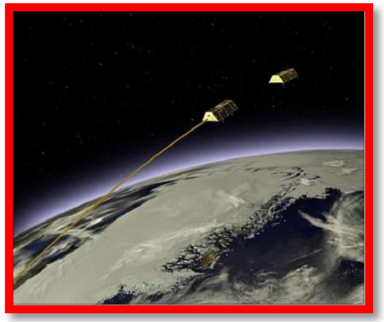
Water storage is one of the 4 water balance components. Gravity satellites have made many achievements in the detection of changes in water storage, groundwater, glacier melting, sea level changes.

Operational Gravity satellites

CHAMP
2000 – 2010



GRACE
2002 – 2017

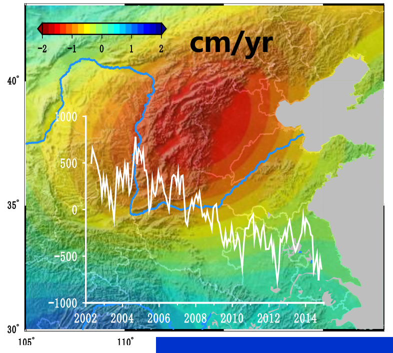


GRACE-Follow On
2018 – 2025

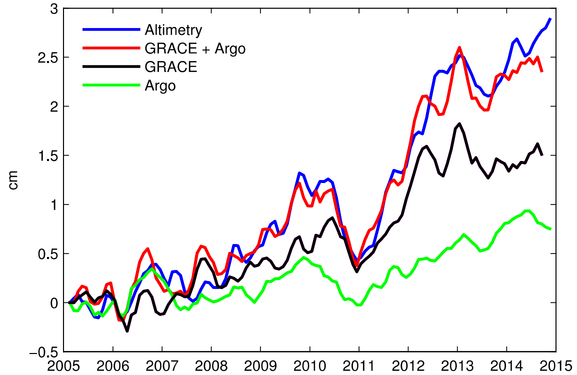
Mission Planed in China

- **Tianqin-2** (~2025)

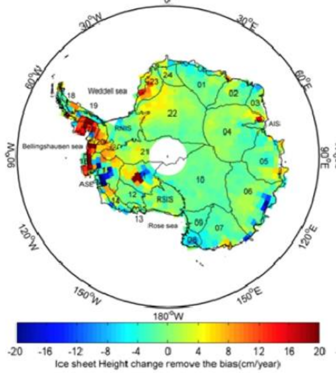
Groundwater Loss in North China

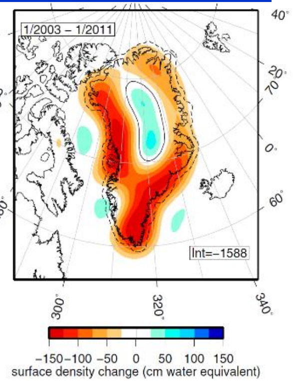


Sea level change



Glacier mass change

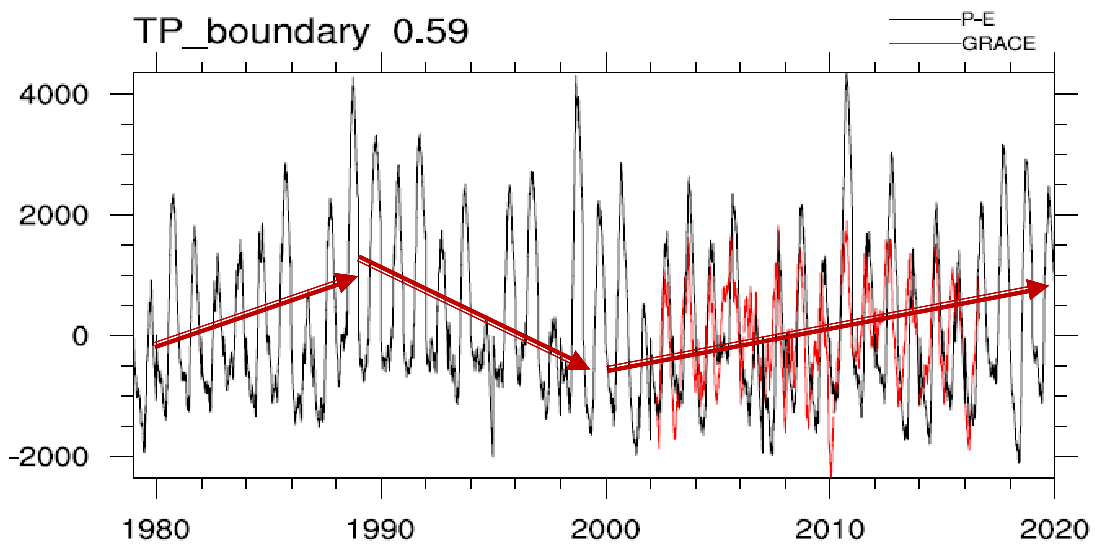




2. An Example in Water Balance Study

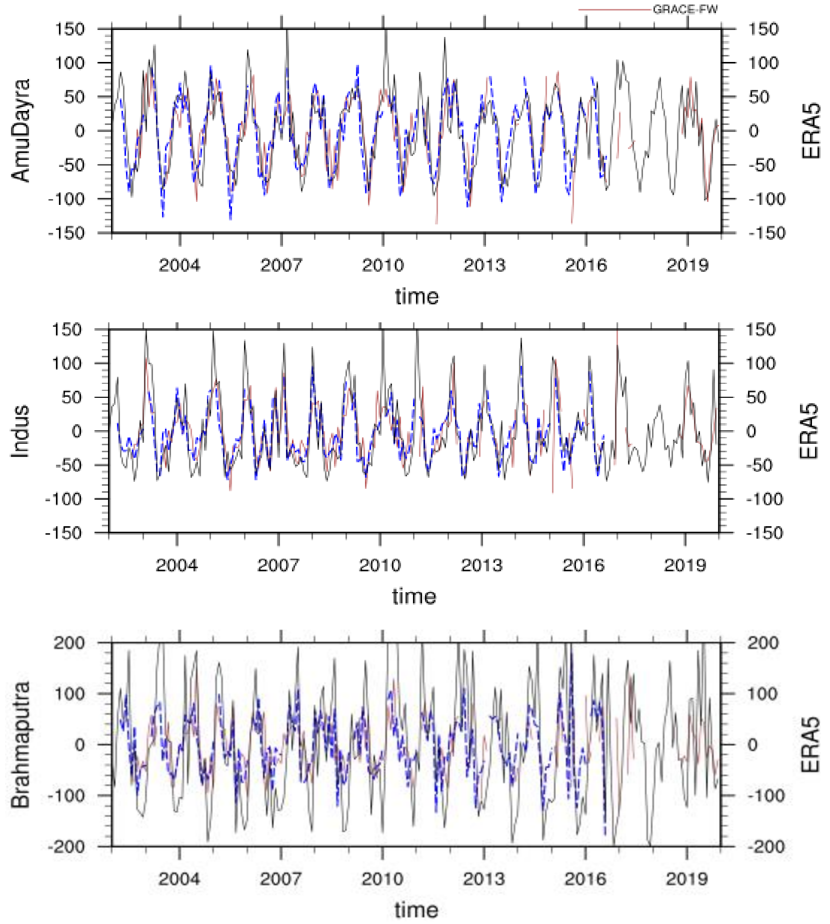
Water Storage

Anomaly analysis over Tibet Plateau: P-ET（1979-2019，ERA5）vs Terrestrial Water Storage（2002-2016).



Results: 1) TWS has Strong annual and seasonal variabilities, at similar level as P-ET;
2) Important observation on water balance studies and supporting integrated surface-ground water assimilations.

At 3 drainage Basin scale



At AmuDayra, Indus, Brahmaputrae basins, CC are 0.83，0.87，0.69, respectively

2. Build Water Cycle System Observatory

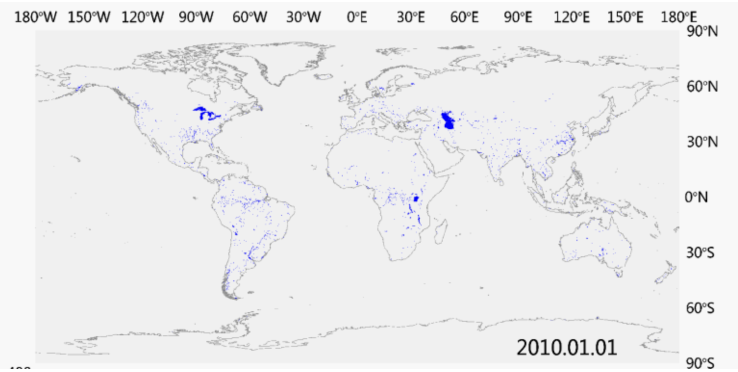
Lakes

Complete the analysis of water observation capacity and data products from China and international optical satellites

Many optics have been used to observe the water bodies

Satellite Type	Satellite sensors characteristics	Water and water quality monitoring applications	Typical domestic satellite remote sensor	Typical foreign satellite remote sensor
Landsat satellites	high spatial resolution, multispectral	Monitoring of small water body	GF1-PMS, GF2-PMS, GF6-PMS	Worldview2/3, SPOT6/7
Landsat satellites	wide swath, multispectral	The dynamic monitoring of small and medium-sized water	GF1-WFV, GF6-WFV	Sentinel2, Landsat8
Landsat satellites	hyperspectral	High precision monitoring of small and medium-sized water	ZY1E-AHSI	PRISIMA, DESIS
Sea-Viewing Satellites	wide swath, multispectral	The dynamic monitoring of large lake library	HY1C-COCTS	MODIS, VIIRS, OLCI

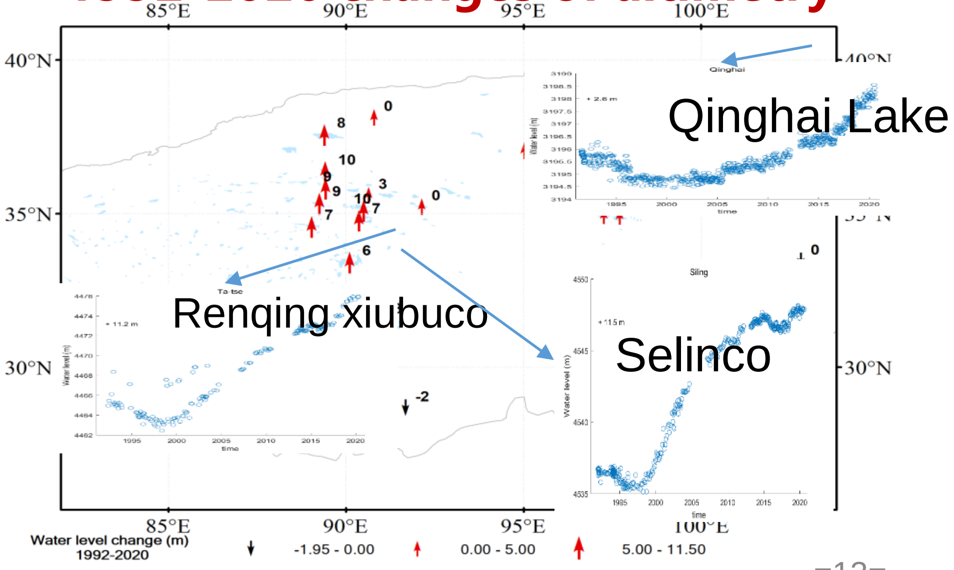
2013 daily water bodies dynamics



Available altimetry satellites

Satellite	Launch Institutions	Launch Date	Mission Status	Altitude (km)	Inclination (°)	Repeat Cycles (day)	Frequency	Product Types
CryoSat-2	ESA	2010	Ongoing	717	92	369	Ku	LRM, SAR,SARIN
HY-2A	China	2011	Ongoing	971	98.5	14	Ku, C	LRM
SARAL	ISRO/CNES	2013	Ongoing	800	98.5	35	Ka	LRM
Jason-3	NASA/CNES	2016	Ongoing	1336	66	10	Ku, C	LRM
Sentinel-3A	ESA	2016	Ongoing	815	98.6	27	Ku, C	SAR
Sentinel-3B	ESA	2018	Ongoing	815	98.6	27	Ku, C	SAR
ICESat-2	NASA	2018	Ongoing	500	92	91	Laser	---
HY-2B	China	2018	Ongoing	973	99.3	14	Ku, C	LRM
GF-7	China	2019	Ongoing	505	99	5	Laser	---
HY-2C	China	2020	Ongoing	958	66	10	Ku, C	LRM
Sentinel-6A	ESA/NASA/CNES	2020	Ongoing	1336	66	10	Ku, C	SAR

1992-2020 changes of altimetry



3. A Proposed Water Cycle Satellite Mission

- ◆ **Approved mission** by CNES and CNSA in Nov. 2019, but delayed. Looking for other opportunities (domestic and international)
- ◆ **Objectives:** high-resolution, high-precision and simultaneous observation of key elements of water cycle (soil moisture, ocean salinity, snow water equivalent, and soil freeze/thaw)
- ◆ **Technical Approach**： Two-Dimensional Synthetic-Aperture Radiometers (similar technique as SMOS)
  - ◆ Multi-frequency (L/X/Ka) and multi-angular (0º-60º) capabilities
  - ◆ Significantly improved sensitivity of the radiometer with one magnitude of order, and the spatial resolution is increased by 4-10 times (current microwave radiometers at 25-40 km)

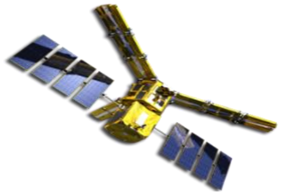
Payload configuration and technical parameters			
Payload	Payload function	Advantages	Current capability
L band	1. Soil moisture 2. ocean salinity	1. Soil moisture (10km, 0.04m³/m³) 2. Ocean salinity (0.1ppm, 30km, 3-6 day)	1. 0.04-0.06m³/m³,25km-40km 2. 0.2 ppm, >1º, monthly
X band	High resolution soil moisture for non-forest area, veg correction, LST, SST	1. Soil moisture for non-forest area (2-3km, 0.04m³/m³) 2. Background signal for SWE and change detection for F/T	1. Missing km scale SM, SWE, and FT 2. SWE and FT (25 km)
Ka band	SWE, FT, LST, atmospheric correction for SSS	2-3km SWE and FT	

3. Advantages for Ocean Salinity

Current

SMOS (2009) : target accuracy monthly 0.1-0.4psu/200km

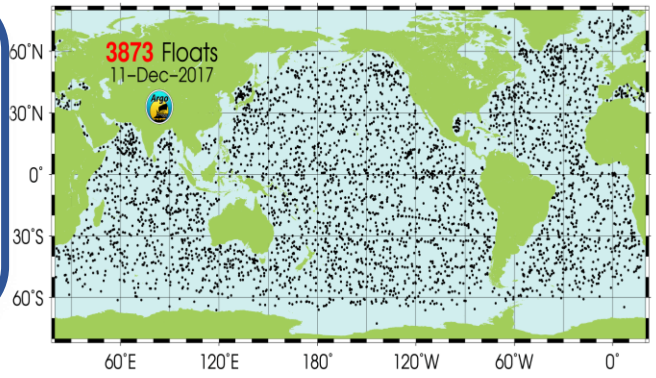
Aquarius (2015) : L-Band Active & Passive , target accuracy monthly 0.2psu/150km



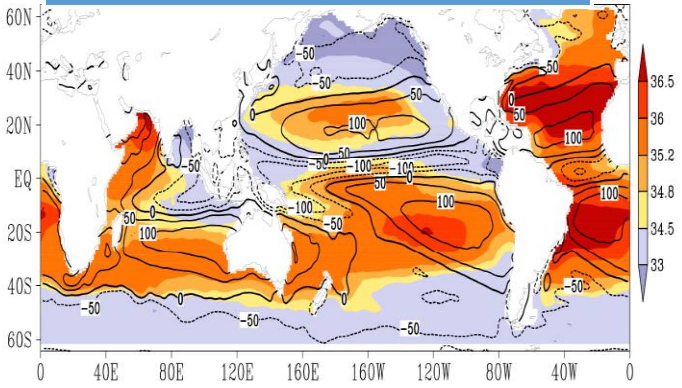
Science Requirements

Much higher spatio-temporal resolutions (3-6 days, better than 50 km) due to effects of sub-mesoscale process

ARGO network: average/300km



SSS correlation with P-E

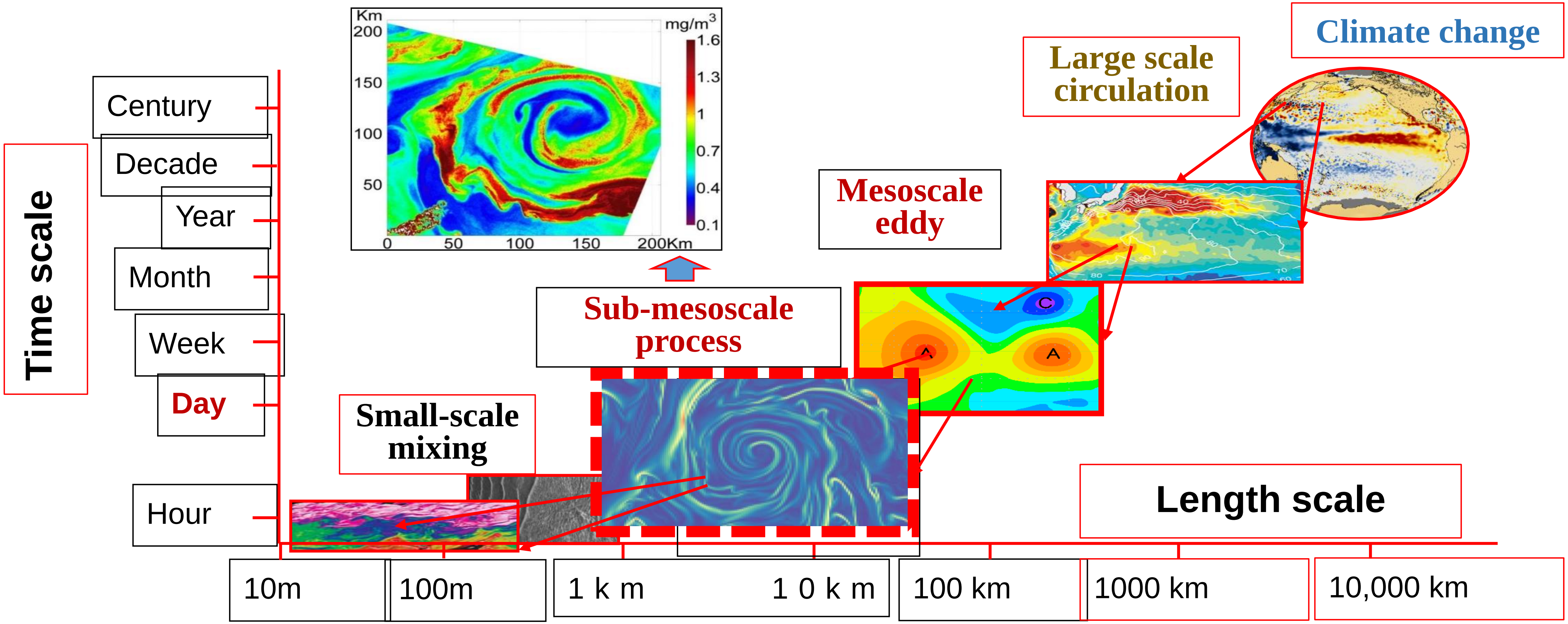


Advantages

Payload	Function
L-Band	Initial 10km -> average to 30km and 3-6 day
X-Band	Sea surface temperature (SST) for sub-mesoscale water and heat fluxes and high resolution roughness averaged from 2-3km
Ka-Band	High resolution atmospheric correction

3. Ocean multi-scale dynamic processes

Sub-mesoscale phenomena are widespread in the upper ocean, dominating more than 50% of the vertical flux of water，heat and carbon in the upper ocean



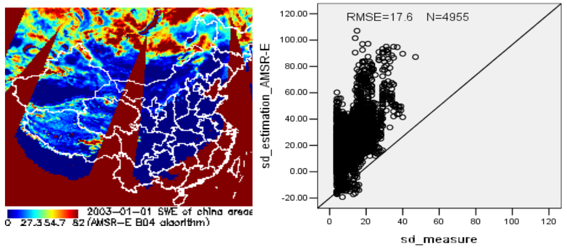
3. Advantages for Snow Water Equivalent

SWE

Current Status

SWE: SSMIS、AMSR2、FY-3
Spatial res. 20~50km, low accuracy due to mixed pixels

Example of satellite retrieval of SWE and its validation



Problems

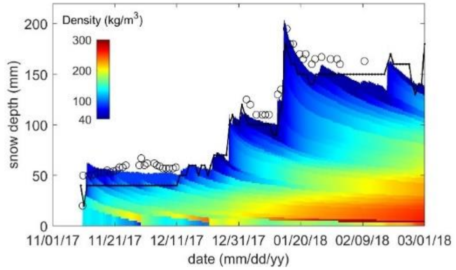
1) **Horizontal: need for high resolution – effect of surface inhomogeneity**
2) **Vertical: impact of snowpack structure, parameterization and background noise**

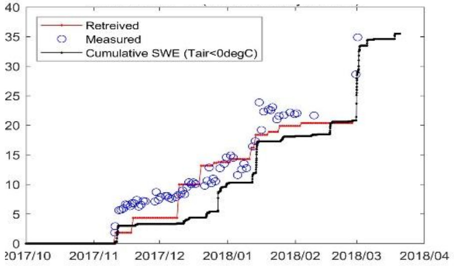
Payload Strategy

Payload	Function
L-band radiometer	Soil state, parameters and background noise under snow cover
X-band 2 – 3km	Providing background signal for brightness temperature difference; offering necessary condition for retrieving SWE
Ka-band 2 – 3km	Most suitable for retrieving SWE; possible for SWE retrieval using a combination of X- and Ka-bands

Field Experiment

Snow stratigraphy





Inversion test

Single-layer: RMSE: 9.2 mm

Multi-layer: RMSE: 2.7 mm

3. Advantages of Payload Design

Capable of measuring four target parameters simultaneously with **optimal bands** and correcting the impacts of **different interfering factors for science & application break through**

Parameter/Band	L-band	X-band	Ka-band
Sea Surface Salinity (SSS)	1. Highly sensitive to sea salinity, highly accurate retrieval based on multi-angle observation 2. Sea surface roughness 3. Faraday rotation correction (T3)	1. Measuring sea surface roughness 2. Measuring sea surface temperature	1. Acquisition of cloud liquid water and water vapor for better atmospheric correction
Surface Soil Moisture (SSM)	1. Highly sensitive to soil moisture variations 2. Minimizing vegetation effects	1. Retrieval of soil moisture over non-forested areas 2. Obtaining vegetation canopy characteristics	1. Retrieval of land surface temperature
Snow Water Equivalent (SWE)	1. Acquisition of soil surface parameters under snow cover	1. Providing background signal for brightness temperature difference in order to retrieve SWE	1. Best band for retrieving SWE 2. Atmospheric calibration
Freeze/Thaw (F/T)	1. Impact of frozen layer thickness	1. Highly sensitive to phase transition water content in the freeze-thaw process	1. Sensitive to temperature changes in the freeze-thaw process 2. Atmospheric calibration

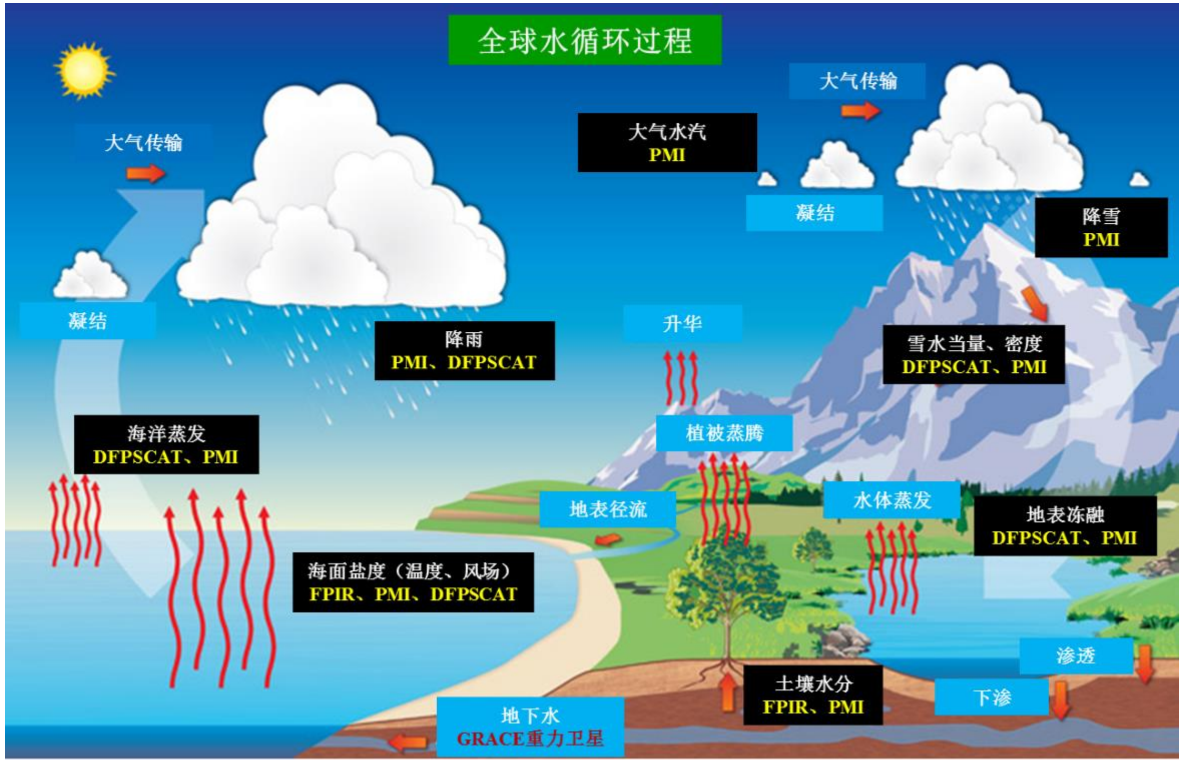
Vital | Synergetic | Supporting

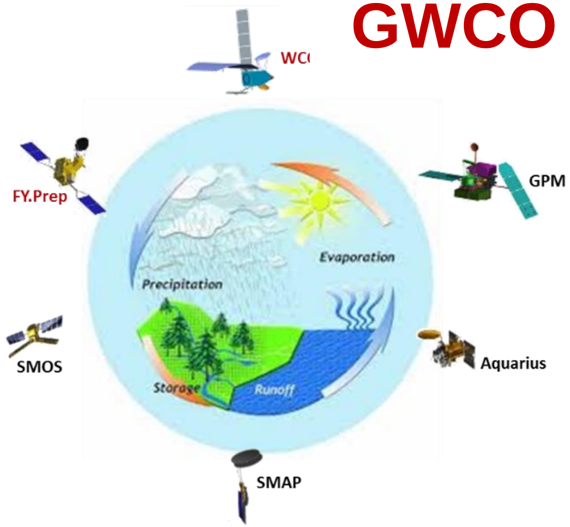
Summary

Global Water Cycle Observatory（GWCO） will establish capacity on monitoring of global water cycle system, not only on the specific parameters but also on the system. It will substantially advance understanding on the water cycle for global change studies and enhance the capacities for applications of UN SDGs.

The GWCO program builds foundation to a strategic framework between international partnerships. We would like to collaborate with you on GWCO, including collaborations on the water cycle mission, data processing, algorithm development, validation, science or SDG applications or any your interested objectives.

Thanks for your attention!





Outline

Water Cycle Observatory

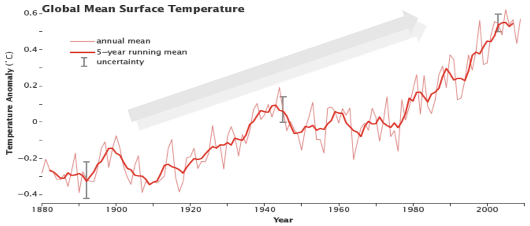
1. Introduction
2. Build Water Cycle System Observatory
3. A Proposed Water Cycle Satellite

1. Science and Application Importance

Impact of Global Climate Change on Water Cycle

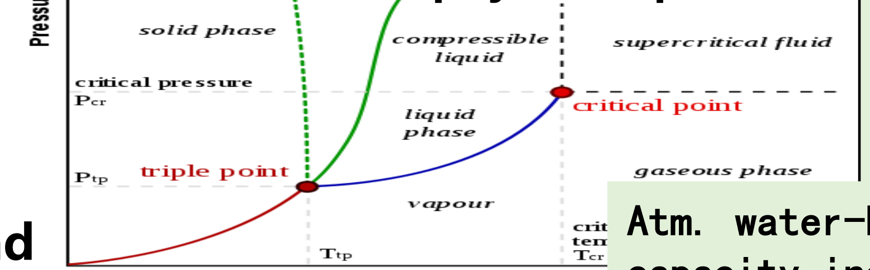
Expectations:

1. Changes in precipitation: less drizzles, more storms (more frequent and higher intensity), less snowfall;
2. Increases in evapotranspiration;
3. Changes in runoff intensity and characteristics



Temperature rises

Clausius-Clapeyron Equation



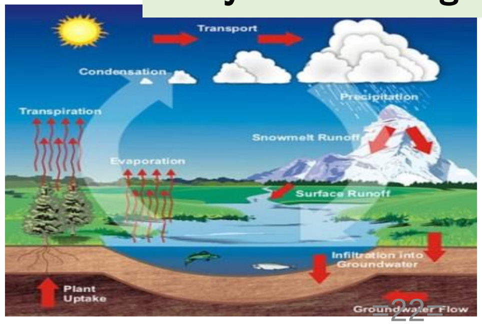
Atm. water-holding capacity increases

Increase of 6-7% in water-holding capacity of the atmosphere per degree Celsius

Consequences: Hydrological extreme events (droughts and floods) will be increased!

Feedback to Climate System: Water cycle system change will result in climate system change.

Water cycle system changes



Applications: Improved understanding and predicting water cycle processes and variation characteristics need to be urgently addressed for science and for their impacts on United Nation Sustainable Development Goals (UN SDGs) : water resources, food security, hydrological disasters...)