A CEOS Cryosphere Gap Analysis: Sea Level Change

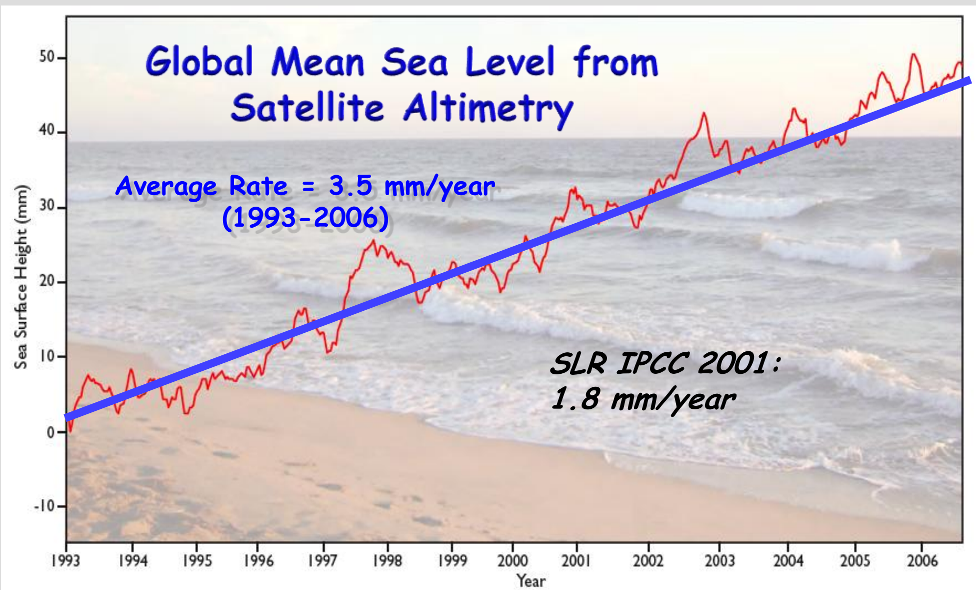
How will changes in the cryosphere impact sea level?

Jeff Key
NOAA/NESDIS, Madison, Wisconsin
IGOS Cryosphere Theme

Acknowledgements: Background information was provided by Stan Wilson (NOAA/NESDIS) and Konrad Steffen (University of Colorado). Ken Jezek (Ohio State University) and Mark Drinkwater (ESA) provided additional information.

Agenda Item 12.5

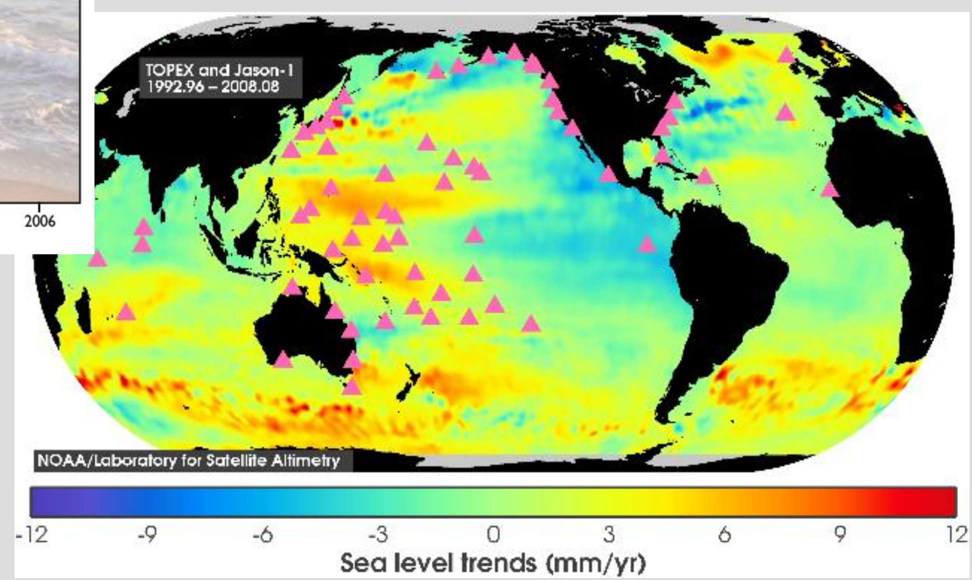
1. Background



(Mitchum and Nerem, 2007)

Sea level is rising…

though not the same everywhere



From NASA/CNES TOPEX/Poseidon & Jason missions, 1993 - 2008

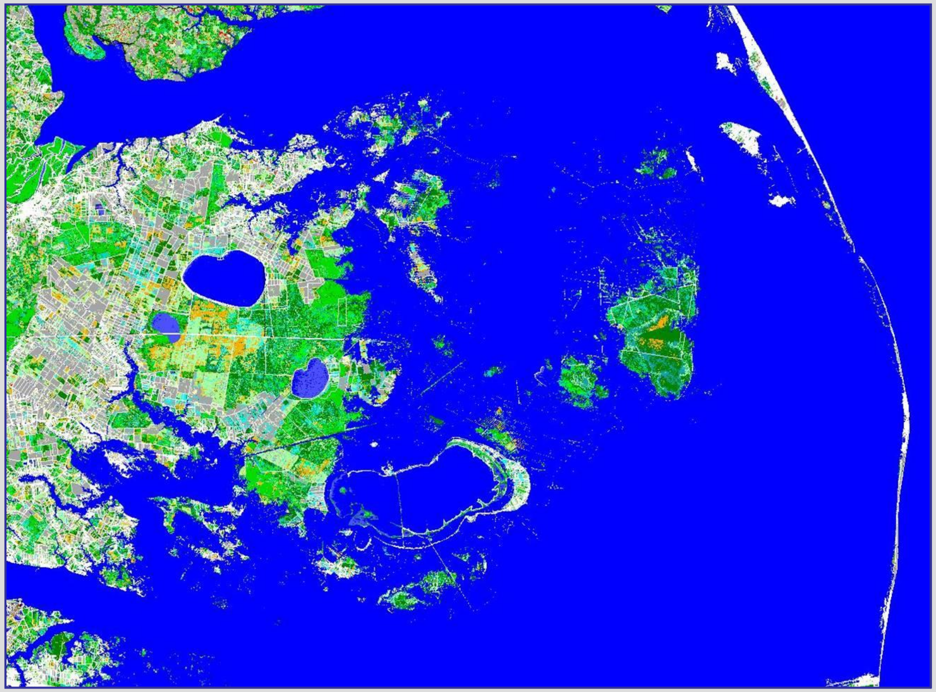
(Courtesy of Laury Miller, NESDIS)

Jason-class satellite altimetry is required to resolve the spatial variability of sea level rise in determining accurate global means.

While tide gauges [△] are poorly distributed, they are critical for calibration.

North Carolina's Albemarle Peninsula in 2100

(Animation)



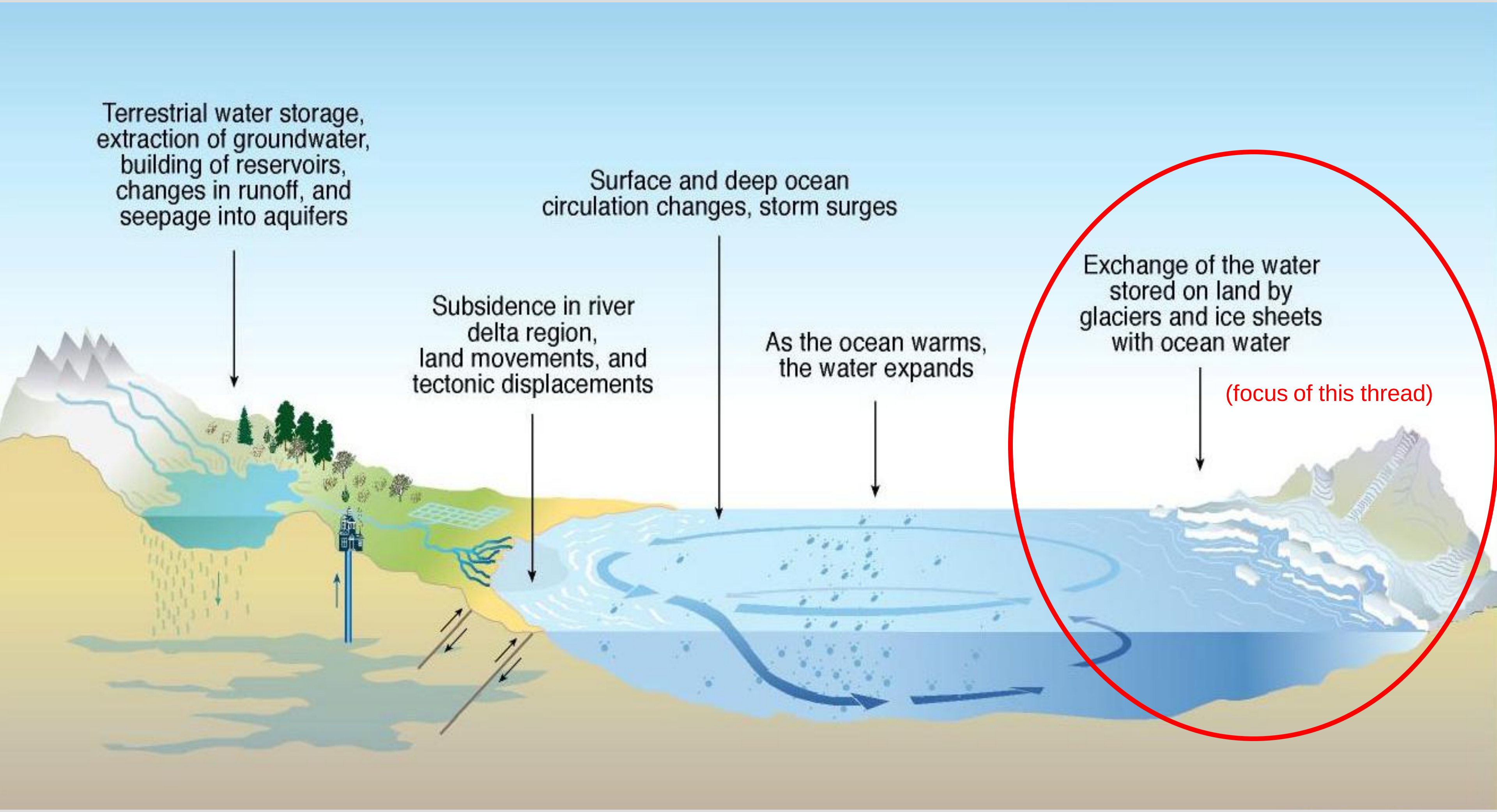
Right: Global sea level is currently predicted to increase from 30 to 80 cm by 2100 (AR4)

In this simulation, sea-level rise ranges from 10 to 80 cm

Below: **Impact of a 1 Meter Rise**

Miami Beach – Population Impacted: 88,000 *(Guerin, Thorp & Thompson, 2007)*

What Causes Sea Level Change?



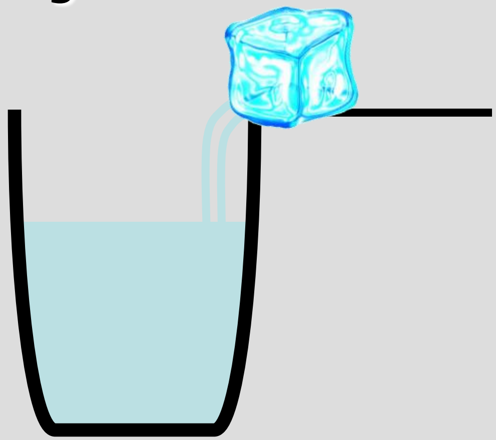
Addition of Water from Melting Ice

(Animation)

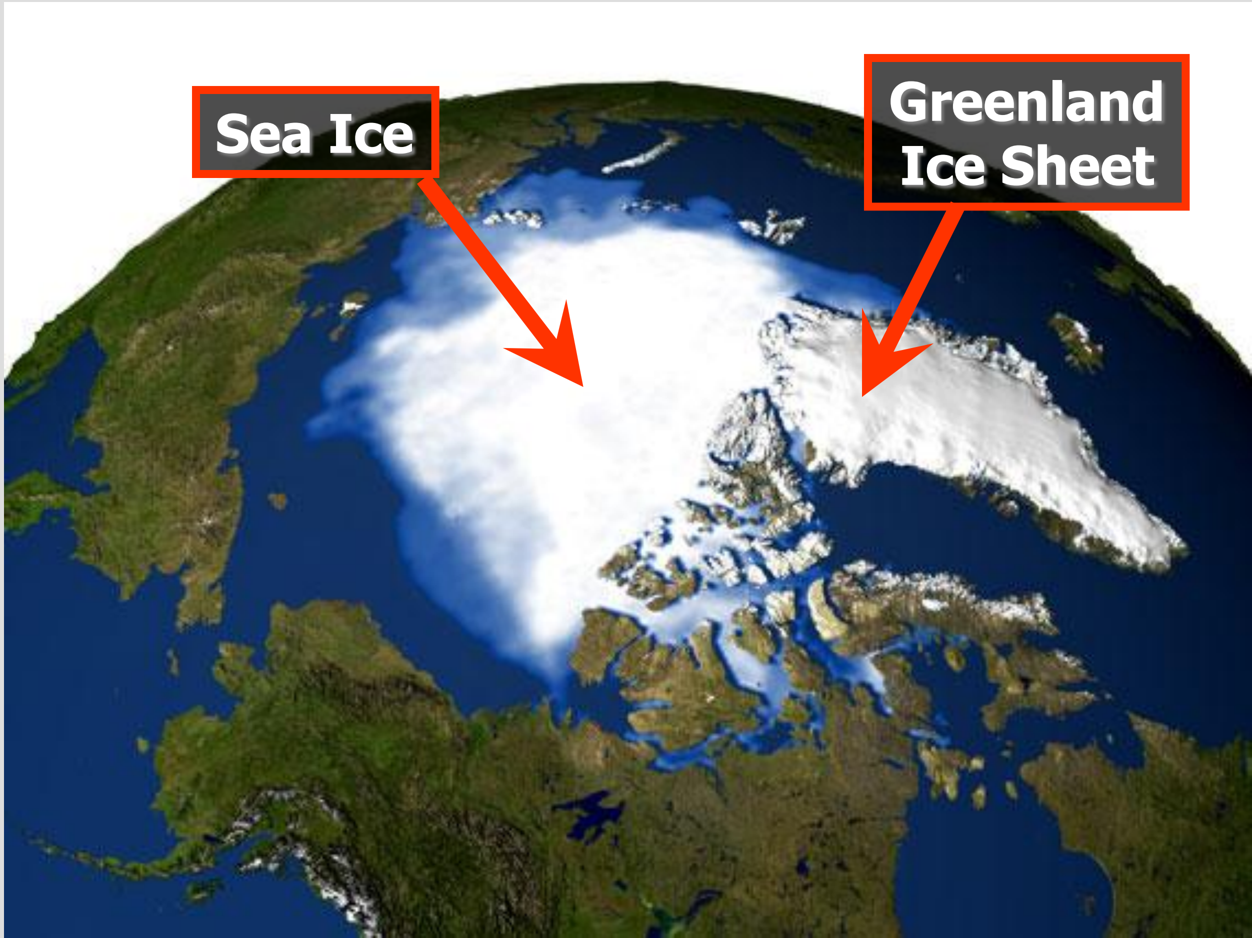
Sea Ice Melt

Does NOT raise sea level

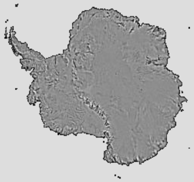
Melting *Land* ice does!



So does iceberg calving



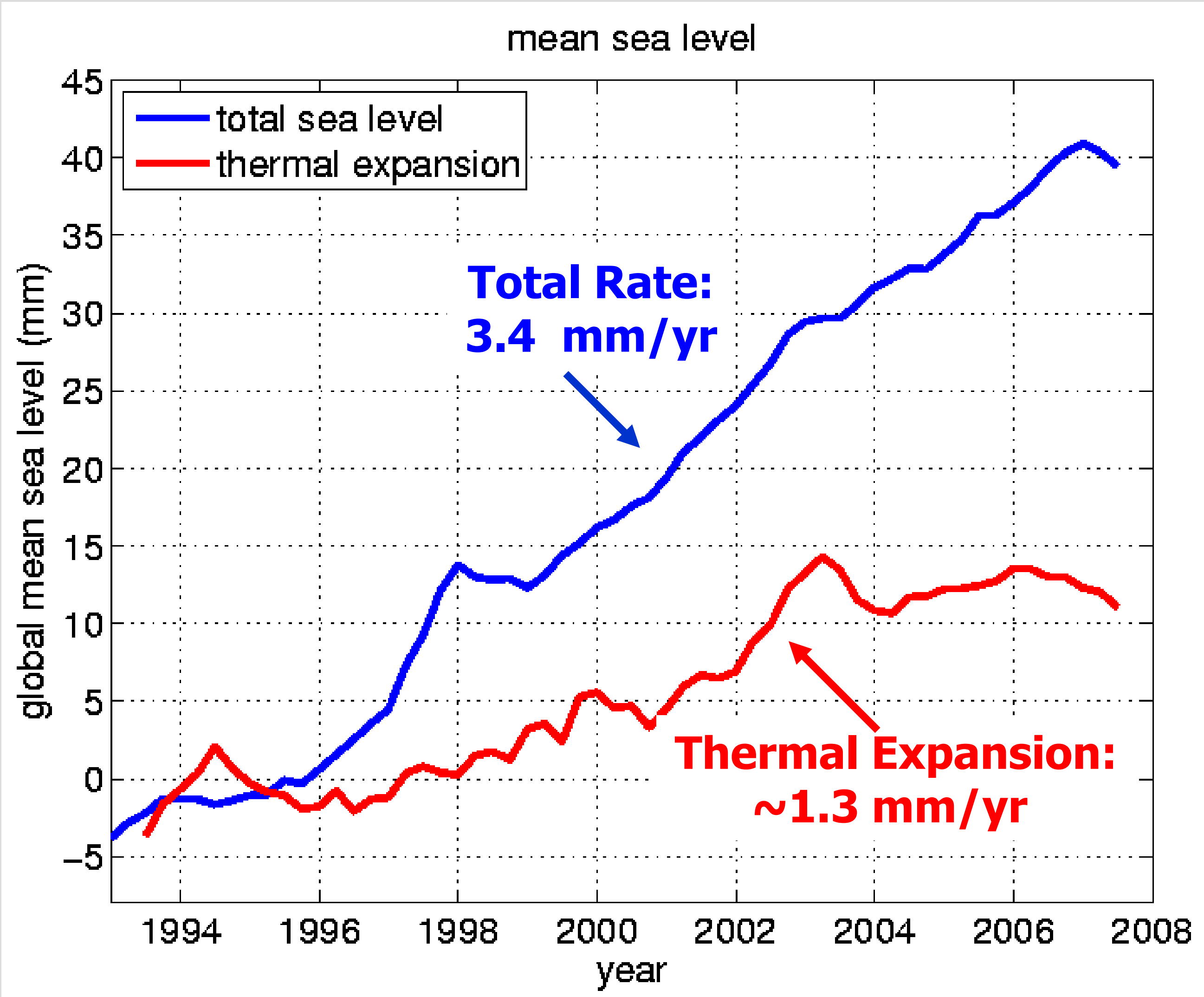
Potential Sea Level Change Contributions



	Potential	Recent*
Thermal expansion	~1 m	1.2-1.6 mm/yr
Mountain glaciers	0.5 m	~0.9 mm/yr
Greenland ice sheet	7 m	~0.5 mm/yr
Antarctic Ice sheet	60 m	~0.4 mm/yr
Land water storage	< 0.5 m	?

**"Recent" means 1993 - 2006 as measured by satellite altimeters.*

Observed mean sea level rise and the portion due to changes in volume



Most of this difference is due to melting ice

Estimated change in volume due to thermal expansion

(Courtesy of Josh Willis, JPL)

2. Products, Services, and Users

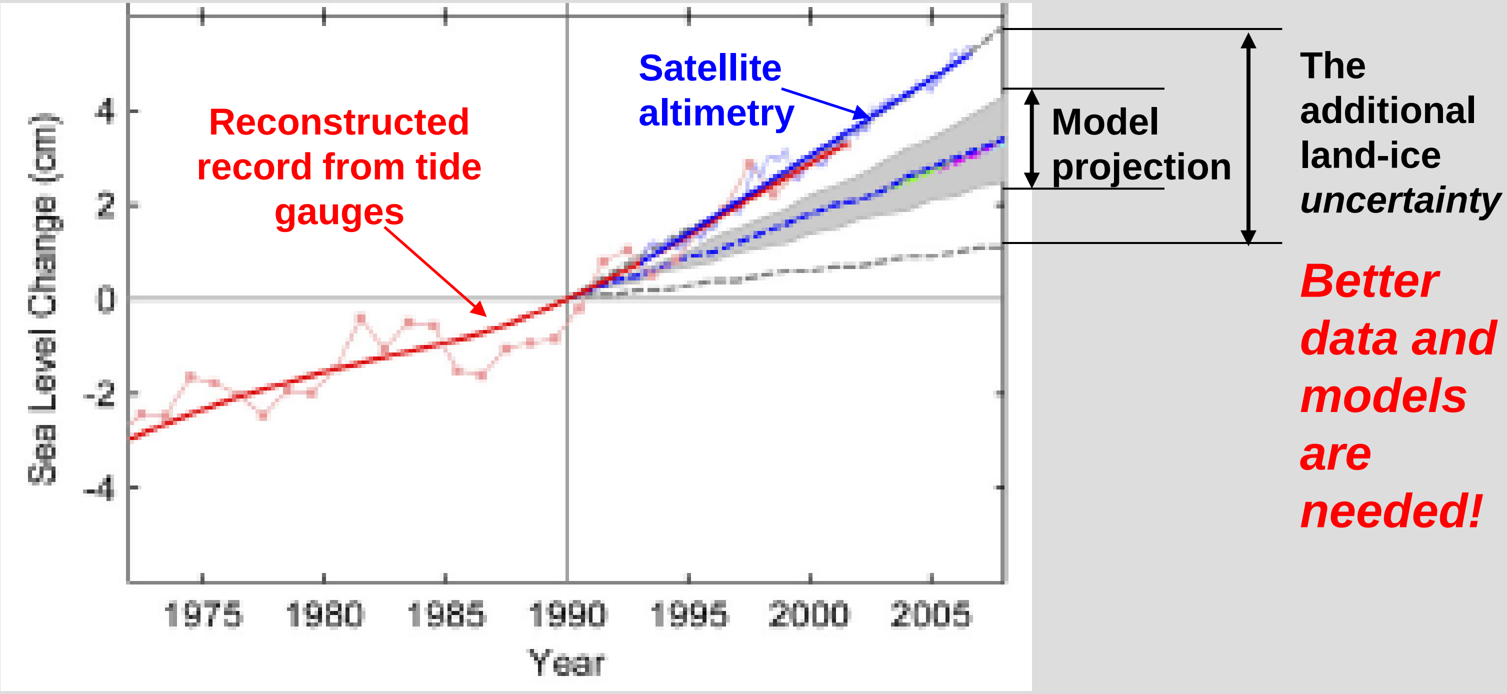
Products and Services
- Sea level obs and/or trends, e.g., NOAA NOS, IPCC reports
- Impact maps and physical assessments, e.g., EPA reports
- Economic assessments and mitigation strategies

Users
- Policymakers
- Resource managers
- City planners
- Public works engineers
- Media

- Satellite products:
  - Sea level
  - Gravity
  - Ice sheet and glacier motion, thickness, etc.

- Modelers
- Climatologists

Intergovernmental Panel on Climate Change projects* sea level to rise ~30-80 cm by 2100

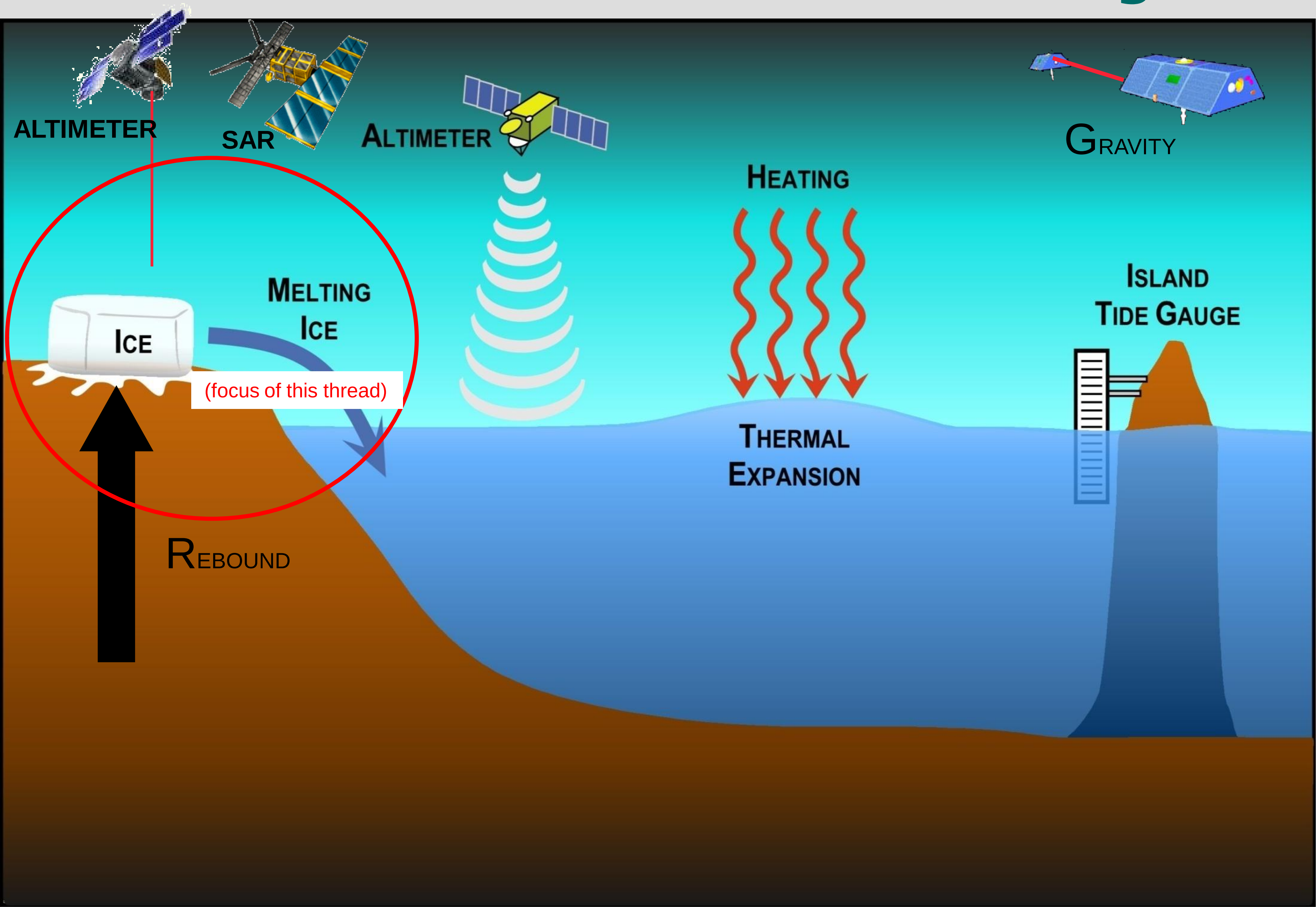


But the observed sea level is rising at the upper limit of the earlier IPCC projection!

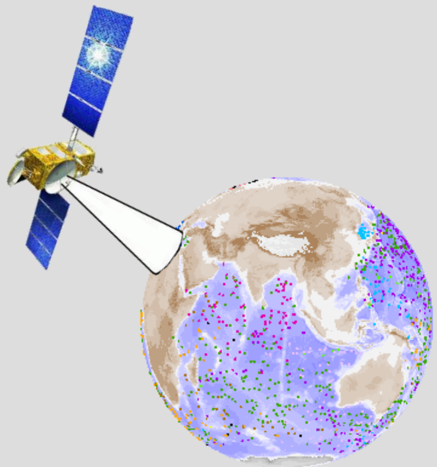
*4th Assessment Report

(Rahmstorf et al., Science, 2007)

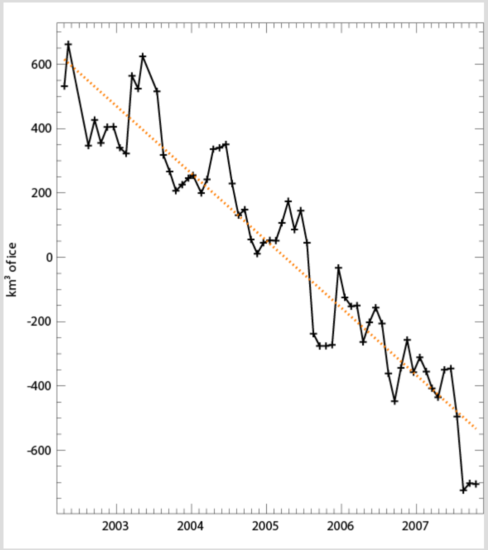
3. Measurements of Sea Level Change

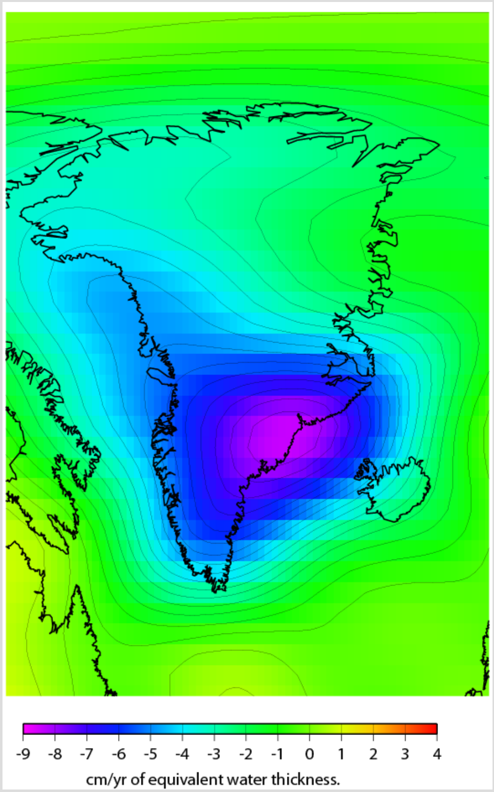


Measuring Total Sea Level with Jason

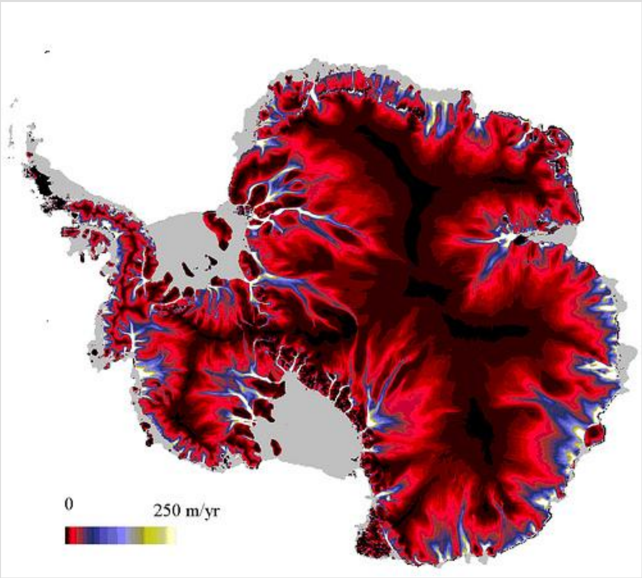


Changes in Gravity from GRACE





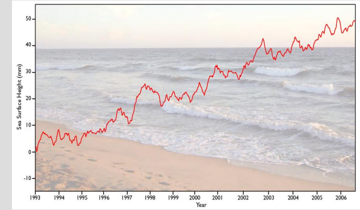
(Courtesy of John Wahr and Isabella Velicogna, 2008)



Ice Sheet Change from SAR and Altimetry

Altimetry and interferometric SAR (InSAR) can be used to map the velocity of ice sheets, providing a more detailed picture of how they will impact sea level.

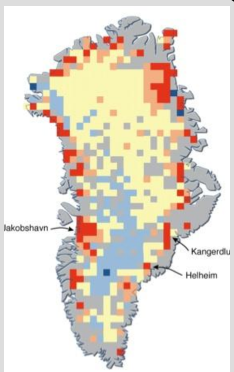
Cryosphere "Thread"



Societal Benefit

Decision Topic

How will changes in the cryosphere impact sea level?



Information Products and Services

- Societal impact reports
- Sea level trends
- Glacier and ice sheet state
- Glacier and ice sheet elevation change, surface melt, gravity, etc.
- Cryosphere monitoring and assessments

→

- EPA impact reports
- IPCC Scenario Impact Assessments
- Research products (e.g., GRACE mass change, passive microwave melt, ice velocity)
- WMO Global Cryosphere Watch
- World Glacier Monitoring Service

Science Knowledge and Models

- Fully coupled ice sheet models (currently inadequate)
- Regional models that represent glacier variability
- Climate Models (accumulation, ablation currently inadequate)

→

Research models, e.g., Community Ice Sheet Model

Climate models & reanalyses:

- ECMWF, NCEP, JMA reanalyses
- Hadley Centre
- NOAA GFDL (Princeton) Global Coupled Climate Model
- NASA GISS Global Climate Model

Variable	2009	2010	2011	2012	2013	2014	2015	2016	
Ice margin	A, B, C	A, B, C	A, B, C	A, B, C	A, B, C	A, B, C	A, B, C	A, B, C	A C
Surface accumulation	F, D	F, D	F, D	F, D	F, D	F, D	F, D	F, D	F
Surface elevation	E	E	E	E	E	E	E	E	E
Snow grain size and shape	A	A	A	A	A	A	A	A	A
Surface temperature	A	A	A	A	A	A	A	A	A
Surface albedo	A	A	A	A	A	A	A	A	A
Surface velocity field	C	C	C	C	C	C	C	C	C
Ice thickness									
Ice sheet morphology	B, C	B, C	B, C	B, C	B, C	B, C	B, C	B, C	B
Surface melt extent	F, D	F, D	F, D	F, D	F, D	F, D	F, D	F, D	F
Mass change	G	G	G	G	G	G	G	G	G

CEOS **measurements**

- Ice sheet/cap topography and rate of change
- Ice stream velocity
- Glacier extent
- Glacier and ice sheet mass balance
- Ice sheet calving rate
- Snow cover
- Ice surface energy budget
- Geoid measurements
- Continental rebound

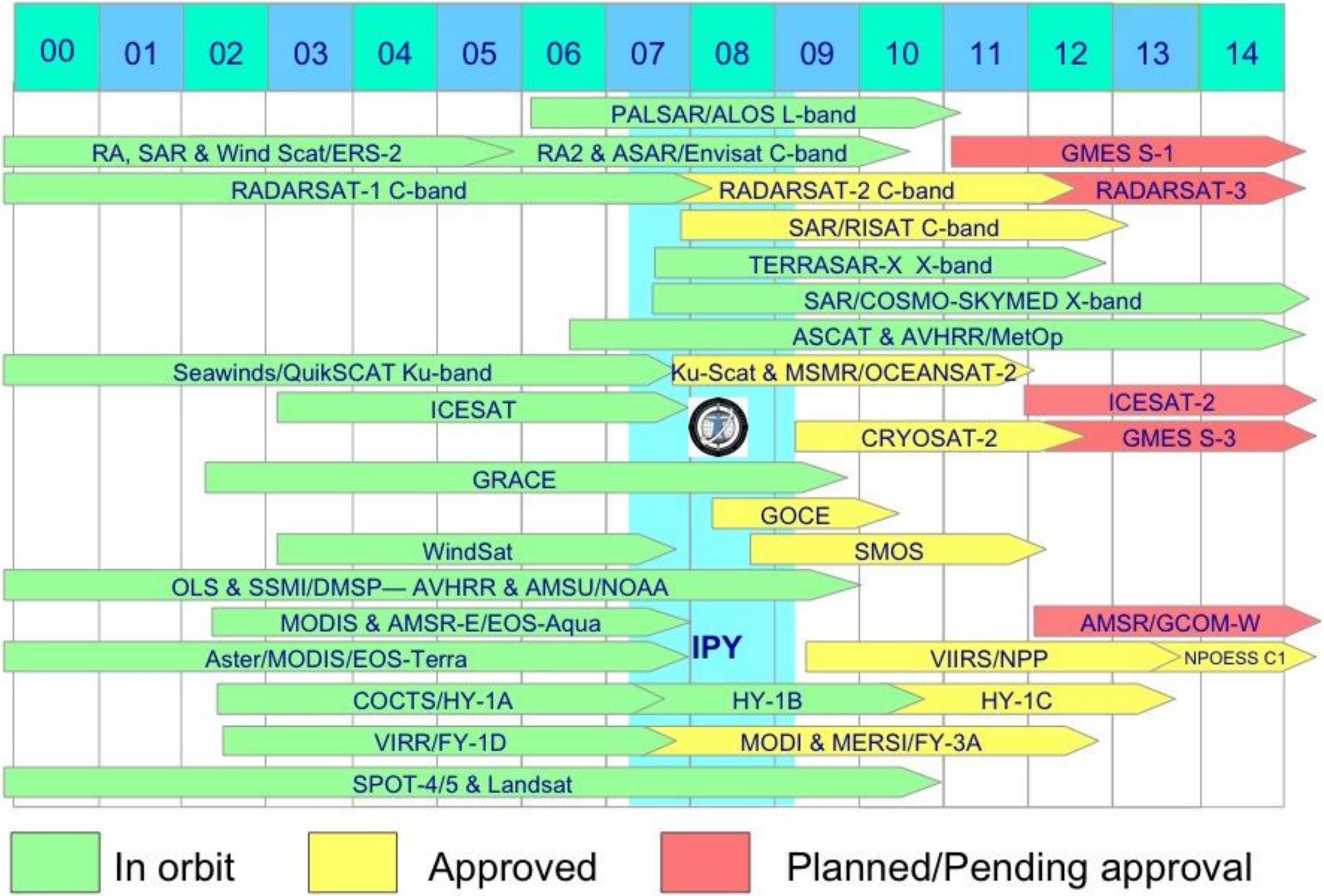
Measurements

Contributions from *N* CEOS **instruments** and *M* **missions.**

→

Instruments and Missions

Cryosphere Satellite Missions



Status of satellite systems for monitoring ice sheets, ice caps, and glaciers

Variable	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Notes
Sea level	E	E	E	E	E	E	E	E	E	E	E	E	1
Gravity/Mass change	G	G	G	G	G	G	G	G	G	G	G	G	2
Ice sheet elevation	E	E	E	E	E	E	E	E	E	E	E	E	3
Ice margin	A, B, C	A, B, C	A, B, C	A, B, C	A, B, C	A, B, C	A, B, C	A, B, C	A, B, C	A, B, C	A, B, C	A, B, C	
Surface accumulation	F, D	F, D	F, D	F, D	F, D	F, D	F, D	F, D	F, D	F, D	F, D	F, D	4
Surface velocity field	C	C	C	C	C	C	C	C	C	C	C	C	5
Surface melt extent	F, D	F, D	F, D	F, D	F, D	F, D	F, D	F, D	F, D	F, D	F, D	F, D	4
Snow grain size and shape	A	A	A	A	A	A	A	A	A	A	A	A	
Surface temperature	A	A	A	A	A	A	A	A	A	A	A	A	
Surface albedo	A	A	A	A	A	A	A	A	A	A	A	A	
Ice thickness													6
Ice sheet morphology	B, C	B, C	B, C	B, C	B, C	B, C	B, C	B, C	B, C	B, C	B, C	B, C	

Mission/sensor categories indicated in the table:

- ***A)*** ***Med-res vis/IR*** - 1: AVHRR, 2: MODIS, 3: HY-1, 4: FY-3, 5: VIIRS
- ***B)*** ***Hi-res vis/IR*** - 10: ASTER, 11: SPOT, 12: MERIS, 13: Landsat, 14: FORMOSAT, 15: GMES Sentinel-2
- ***C)*** ***Hi-res SAR*** - 20: Radarsat, 21: ERS-2 SAR, 22: Envisat ASAR, 23: ALOS-PALSAR, 24: TERRASAR-X, 25: COSMO-SKYMED, 26: RISAT, 27: GMES Sentinel-1
- ***D)*** ***Lo-res SAR*** – 30: ERS2 WindScat, 31: QuikScat, 32: Metop ASCAT, 33: Oceansat-2, 34: HY-2A Scat
- ***E)*** ***Altimeters*** - 40: ICESat, 41: CryoSat-2, 42: ERS-2 altimeter, 43: GMES Sentinel-3; Jason-1, -2
- ***F)*** ***Passive microwave*** - 50: SSM/I, 51: AMSR-E, 52: Windsat, 53: SMOS, 54: HY-2A
- ***G)*** ***Gravity*** - 60: GRACE, 61: GOCE

Colors: Green: sufficient satellite capabilities; Orange: suboptimal mission/sensor or sensor characteristics/availability is uncertain; Red: no sensor will be available

Notes:

1. Assumes that GMES Sentinel-3 will continue the Jason-series measurements.
2. No gravity mission planned after GOCE.
3. Gap between ICESat-1 and both ICESat-2 and CryoSat-2
4. Uncertainty in the characteristics of the NPOESS microwave sensor
5. While there are a number of SAR instruments, current and planned missions are generally not optimized for interferometric SAR (InSAR) measurements over ice sheets.
6. Ice sheet thickness measurements can be done with VHF and UHF radars (~5 MHz to ~500 MHz).

Recommendations for CEOS

There are three types of gaps (from Water Thread); the first two apply here:

1. missing variables (obs, sensors, missions)
2. missing products (lack of analysis and integration capability, model deficiencies)
3. missing services (data not being distributed, lack of local capacity)

- Assess the needs of the modeling community for satellite information that can aid in the prediction of sea level, from ice sheet models to GCMs.
- Develop new or improved cryosphere products that can be used as verification in large-scale models, e.g., surface accumulation, calving rate, and ice sheet thickness.
- Generate ice sheet surface topography and velocity products with increased spatial resolution using TANdem-X (first Terrasar-X: 2008; second in 2009).
- Make plans to continue the time series of spaceborne gravity observations for monitoring changes in ice sheet mass and its contribution to sea level rise.
- Make plans to continue ocean surface elevation measurements beyond Jason-2 and Sentinel-3b. *This is a current CEOS action. Outlook is positive.*
- Support a satellite mission that can provide information on snow accumulation, such as the candidate CoreH2O Earth Explorer mission (ESA) concept based on dual frequency (Ku- and X-band) SAR.

Recommendations for CEOS, cont.

- SAR interferometry (InSAR) is a major missing element in plans for cryospheric observations. Implement a virtual multi-frequency multi-polarisation SAR constellation with InSAR capability.
- A dedicated mission for precise mapping of *glacier* topography is a high priority. Single pass or short-repeat InSAR will provide coverage of all glaciers worldwide.
- Ice thickness measuring in situ and airborne radars (5-500 MHz) should be evolved into satellite systems. In the meanwhile, support aircraft missions for measuring ice thickness.
- Long-term continuation of Landsat/SPOT type missions, providing data at favorable costs, are needed to obtain global inventories of glaciers. Continue the acquisition of high (10 m) and moderate (250 m) resolution optical imagery for detecting rapid changes in ice shelves, ice streams and outlet glaciers and for measuring surface velocity as a complement to InSAR.
- Continue passive microwave observations of ice sheet surface melt through the re-inclusion of a passive microwave radiometer on NPOESS.
- The ice shelf-ocean interface is critical. However, no satellite method exists for measuring the ocean temperature profile. In situ measurements need to be combined with satellite-derive ice velocity, grounding lines, etc.

Linkages and Heritage

<u>GEO Tasks</u>

AR-09-03b (formerly CL-06-05): Advocating for Sustained Observing Systems; Legacy of the International Polar Year 2007-08 (WCRP)

AR-09-02a (formerly DA-07-03): Interoperable Systems for GEOSS; Virtual Constellations (CEOS)

CL-06-01a: A Climate Record for Assessing Variability and Change; Sustained Reprocessing and Reanalysis of Climate Data (CEOS, GCOS, WCRP)

<u>Heritage/References</u>

- IGOS Cryosphere Theme
- WCRP Climate and Cryosphere (CliC) project area #2 on sea level rise.
- G8 Summit Focus Areas - Climate
- WMO Global Cryosphere Watch
- World Glacier Monitoring Service
- IPCC Scenario Impact Assessments

Suggested Thread Team

Konrad Steffen, University of Colorado-Boulder
Mark Drinkwater, European Space Agency
Ken Jezek, Ohio State University
Waleed Abdalati, NASA Goddard Space Flight Center
Gino Casassa, Centro de Estudios Cientificios (Chile)
Vladimir Ryabinin, World Climate Research Programme

Why is this a good problem for CEOS?

- Hot topic: Sea level rise will impact millions of people at a huge cost.
- Uncertainty: The potential impact of the cryosphere on sea level is greater than anything other factor. Models do not accurately estimate sea level rise due largely to the uncertainty in the effect of changes in the cryosphere.
- Satellites are important:
  - We need new and innovative products
  - We need new measurements with current satellites (e.g., better glacier inventory with hi-res optical; better coordination of SAR sensors for InSAR)
  - We need to explore new technologies (e.g., P-band SAR for ice sheet thickness)