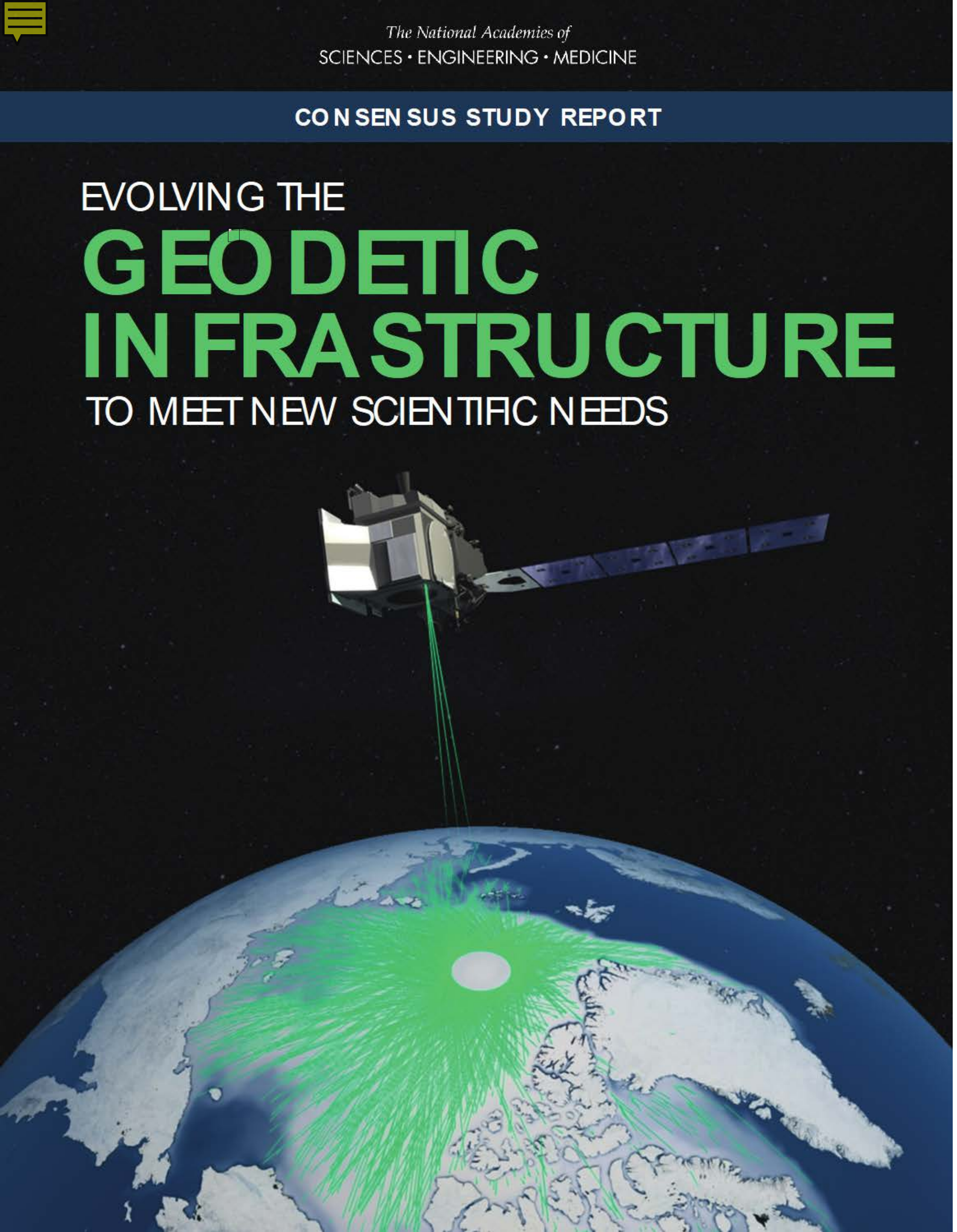



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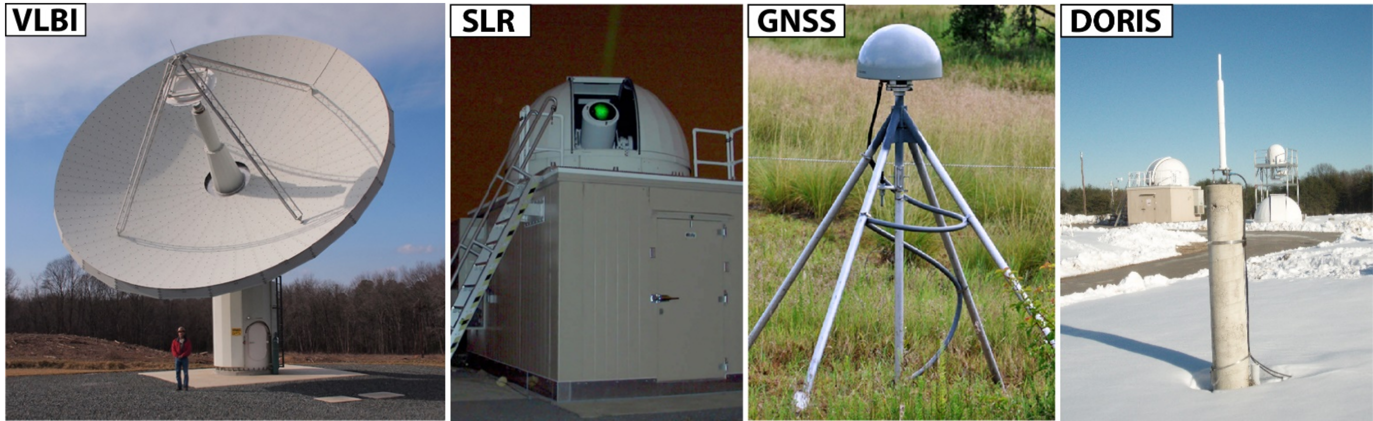
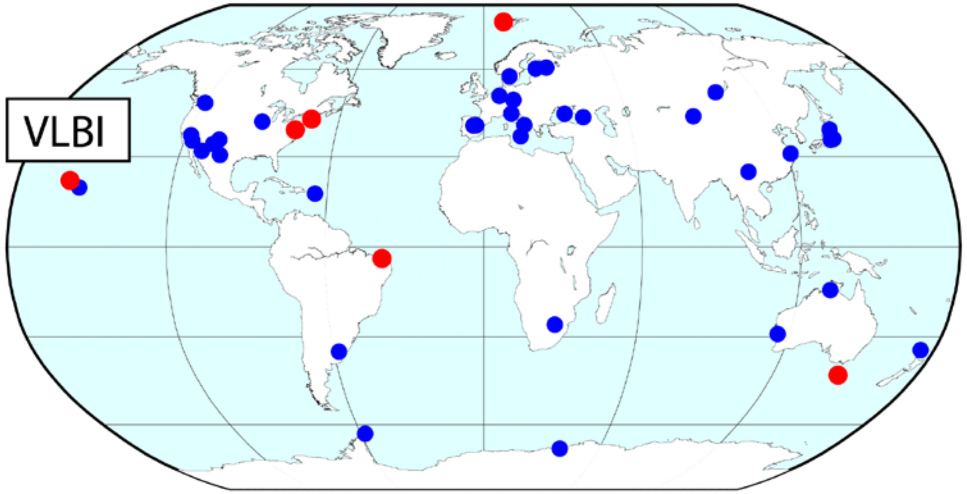
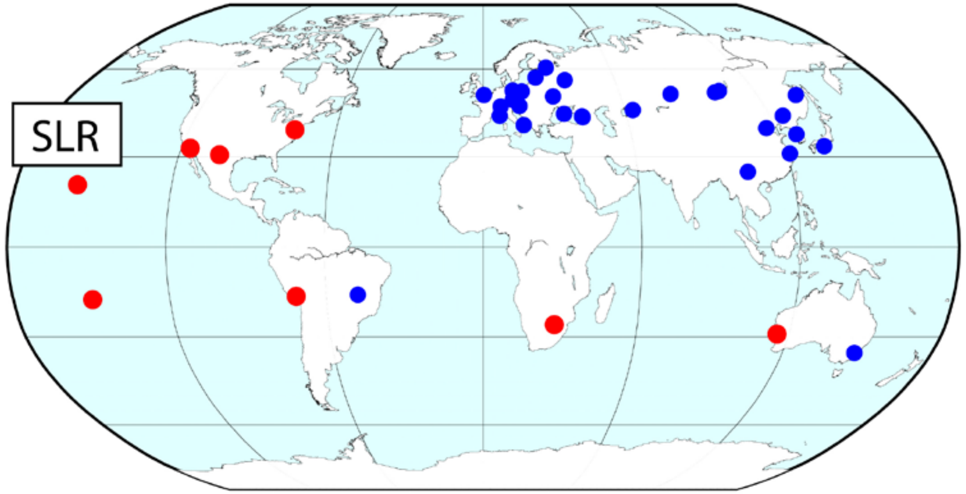


# Geodetic Infrastructure (GI)

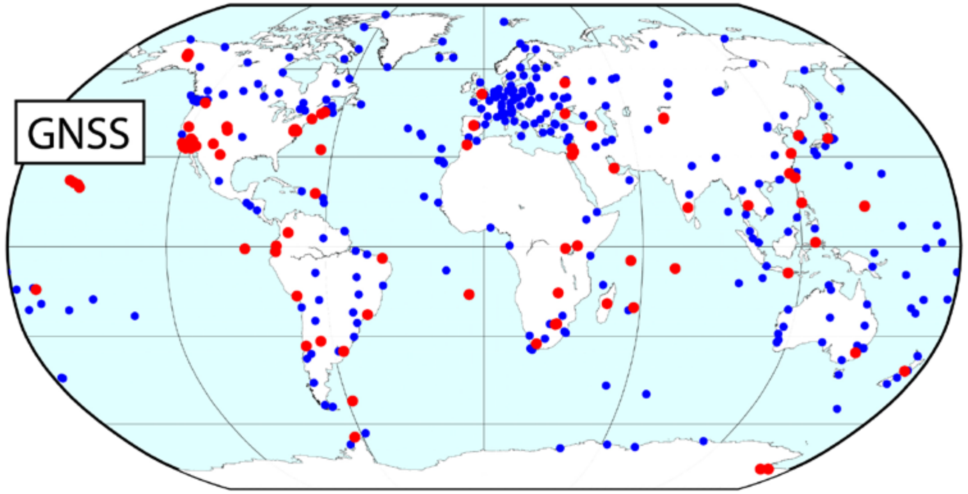
[Frank Lemoine, personal communication;
Carey Noll, personal communication;
https://space-geodesy.nasa.gov]

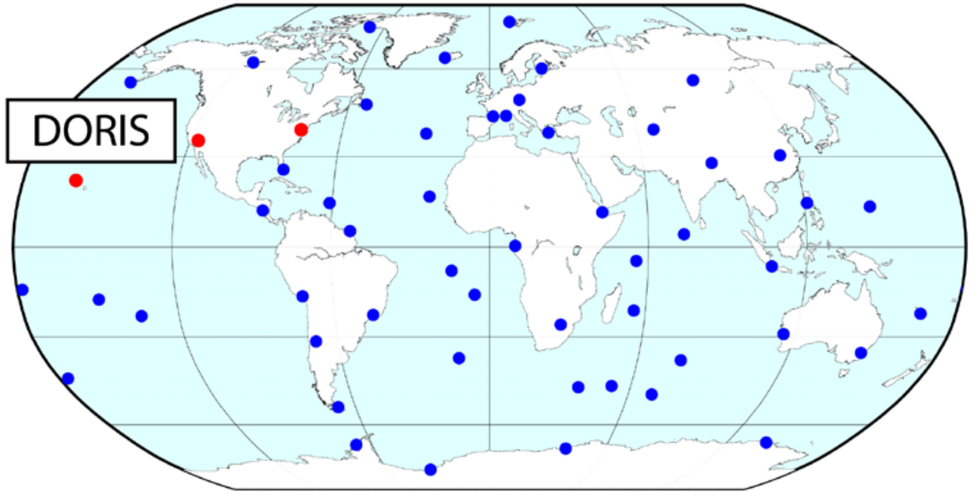



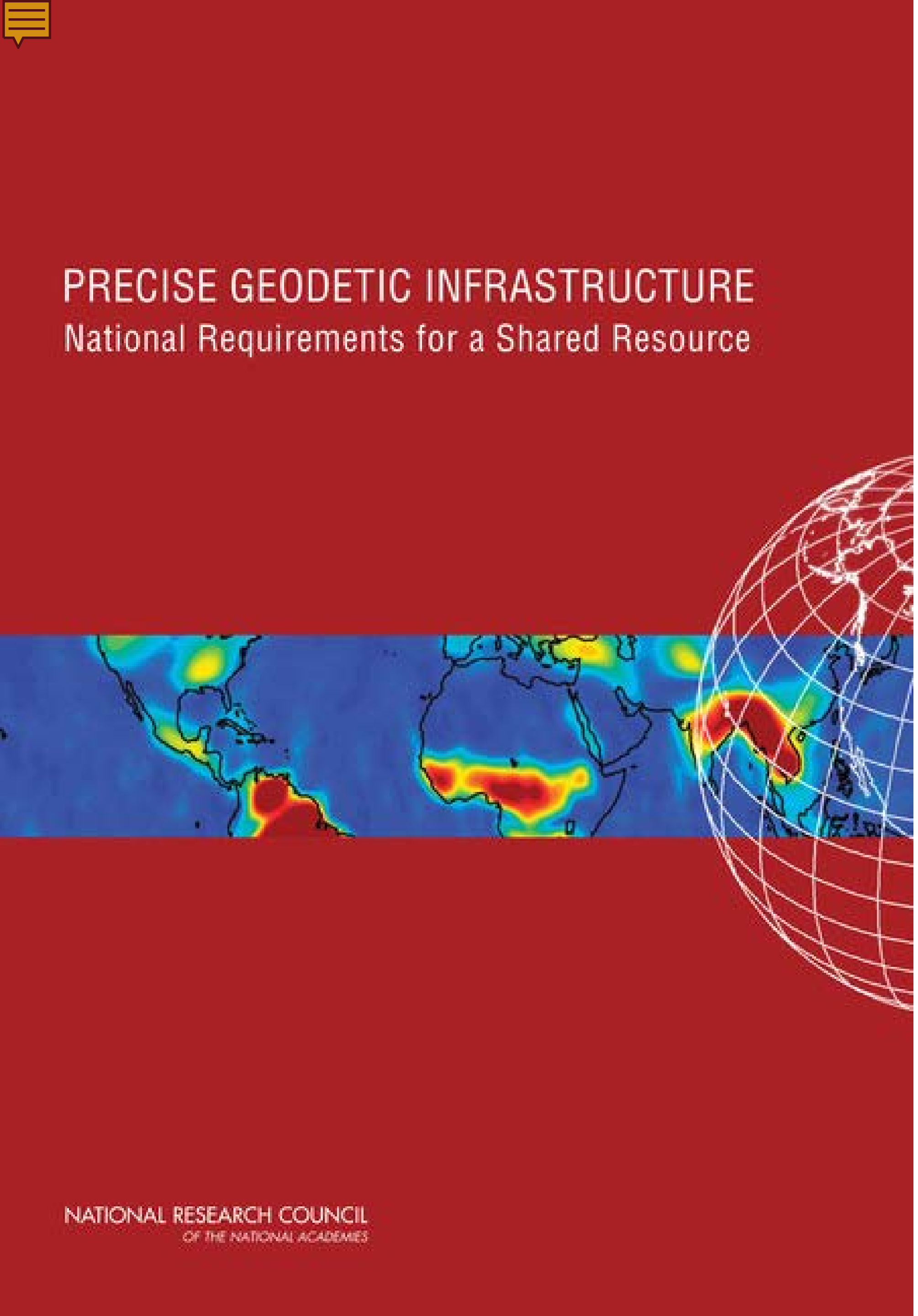




**red** – NASA, US

**blue** – International



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[NRC, 2010]


Thriving on Our Changing Planet
A Decadal Strategy for Earth Observation from Space
#EarthDecadal
The National Academies of
SCIENCES
ENGINEERING
MEDICINE

[NRC, 2017]

# Recommendations - Observables

**Recommendation 3.2:** NASA should implement a set of space-based observation capabilities based on this report's proposed program (which was designed to be affordable, comprehensive, robust, and balanced) by implementing its portion of the program of record and adding observations described in Table S.2, "Observing System Priorities." The implemented program should be guided by the budgetary considerations and decision rules contained in this report and accomplished through five distinct program elements:

1. *Program of record.* The series of existing or previously planned observations, which must be completed as planned. Execution of the ESAS 2017 recommendation requires that the total cost to NASA of the program of record flight missions from fiscal year (FY) 2018-FY27 be capped at $3.6 billion.
2. *Designated.* A program element for ESAS-designated cost-capped medium- and large-size missions to address observables essential to the overall program, directed or competed at the discretion of NASA.
3. *Earth System Explorer.* A new program element involving competitive opportunities for cost-capped medium-size instruments and missions serving specified ESAS-priority observations.
4. *Incubation.* A new program element, focused on investment for priority observation capabilities needing advancement prior to cost-effective implementation, including an innovation fund to respond to emerging needs.
5. *Earth Venture*. Earth Venture program element, as recommended in ESAS 2007, with the addition of a new Venture-continuity component to provide opportunity for low-cost sustained observations.

# Earth Surface and Interior - Measurements

1. **Terrestrial Reference Frame** – VLBI, SLR and GNSS (e.g. satellite tracking)

2. **Crustal Deformation** – InSAR and GNSS (strain rate < 100 nanostrain/yr = 1 mm/yr/10 km; weekly revisit)

3. **Bare-Earth Topography** spacecraft (5-10m (h), 1 m (v)) and aircraft LIDAR (1-5m (h), 0.1m (v))

4. **Hyperspectral Imaging** (~200 bands, vis – IR 30 m (h); ~20 bands,TIR 60 m (h); 14-16 days revisit)

5. **Time-variable gravity**

# Recommended NASA Priorities: Designated

| TARGETED OBSERVABLE | SCIENCE/APPLICATIONS SUMMARY | CANDIDATE MEASUREMENT APPROACH | Designated | Explorer | Incubation |
|---|---|---|---|---|---|
| **Aerosols** | **Aerosol properties, aerosol vertical profiles, and cloud properties** to understand their direct and indirect effects on climate and air quality | Backscatter lidar and multi-channel/multi-angle/polarization imaging radiometer flown together on the same platform | X | | |
| **Clouds, Convection, & Precipitation** | **Coupled cloud-precipitation state and dynamics** for monitoring global hydrological cycle and understanding contributing processes | Radar(s), with multi-frequency passive microwave and sub-mm radiometer | X | | |
| **Mass Change** | **Large-scale Earth dynamics** measured by the changing mass distribution within and between the Earth's atmosphere, oceans, ground water, and ice sheets | Spacecraft ranging measurement of gravity anomaly | X | | |
| **Surface Biology & Geology** | **Earth surface geology and biology,** ground/water temperature, snow reflectivity, active geologic processes, vegetation traits and algal biomass | Hyperspectral imagery in the visible and shortwave infrared, multi- or hyperspectral imagery in the thermal IR | X | | |
| **Surface Deformation & Change** | **Earth surface dynamics** from earthquakes and landslides to ice sheets and permafrost | Interferometric Synthetic Aperture Radar (InSAR) with ionospheric correction | X | | |

# Tasks

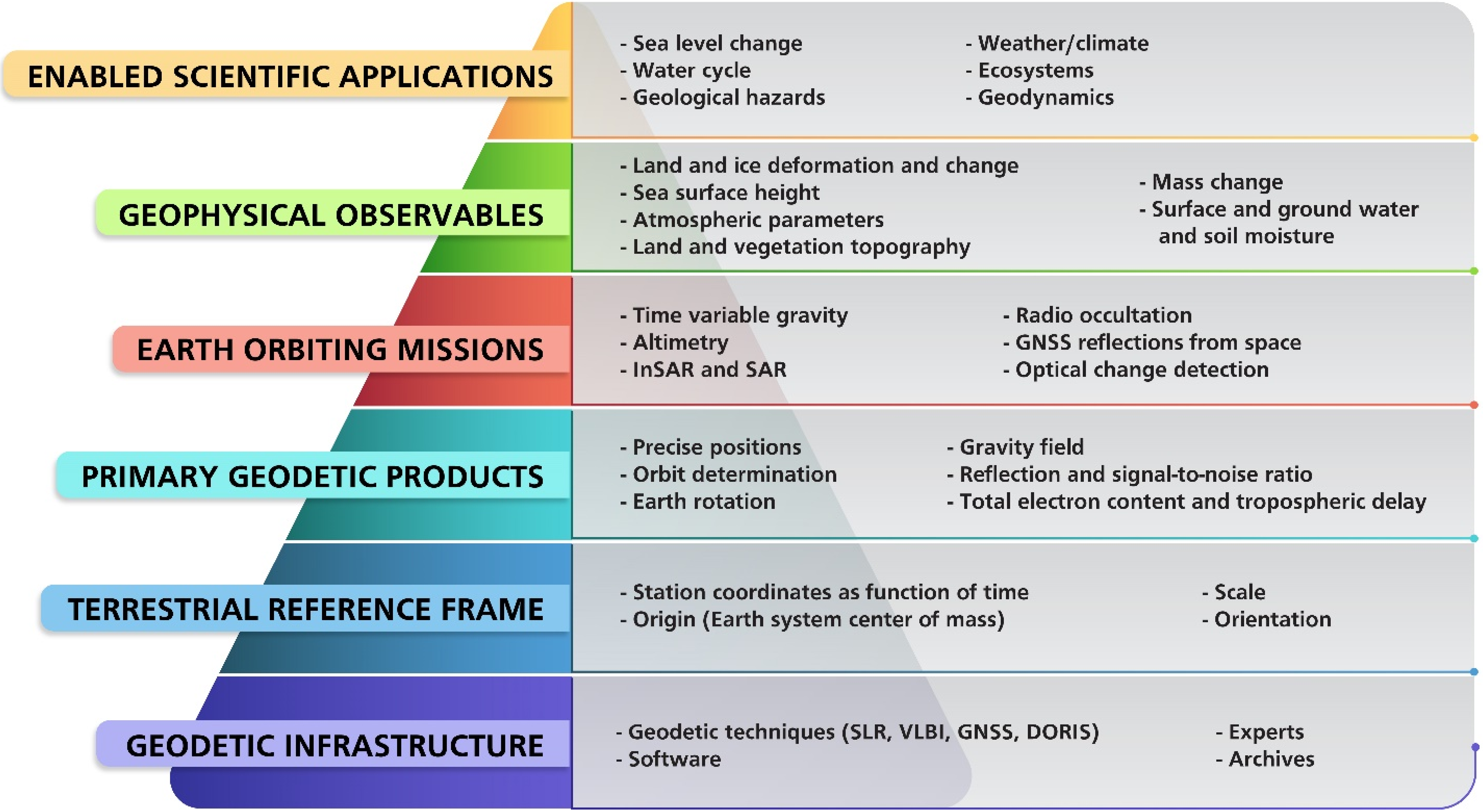
**1. Summarize progress** in maintaining and improving the geodetic infrastructure, as detailed in the recommendations in Precise Geodetic Infrastructure: National Requirements for a Shared Resource (NRC, 2010), and aspirations for future improvements through, for example, new technology and analysis. (meeting in DC October, 2018)

**2. Identify science questions from the 2017 Decadal Survey** on Earth Science and Applications from Space (NASEM, 2018) that depend on geodesy, and describe the connections between these questions, associated measurement requirements, and geodetic data.

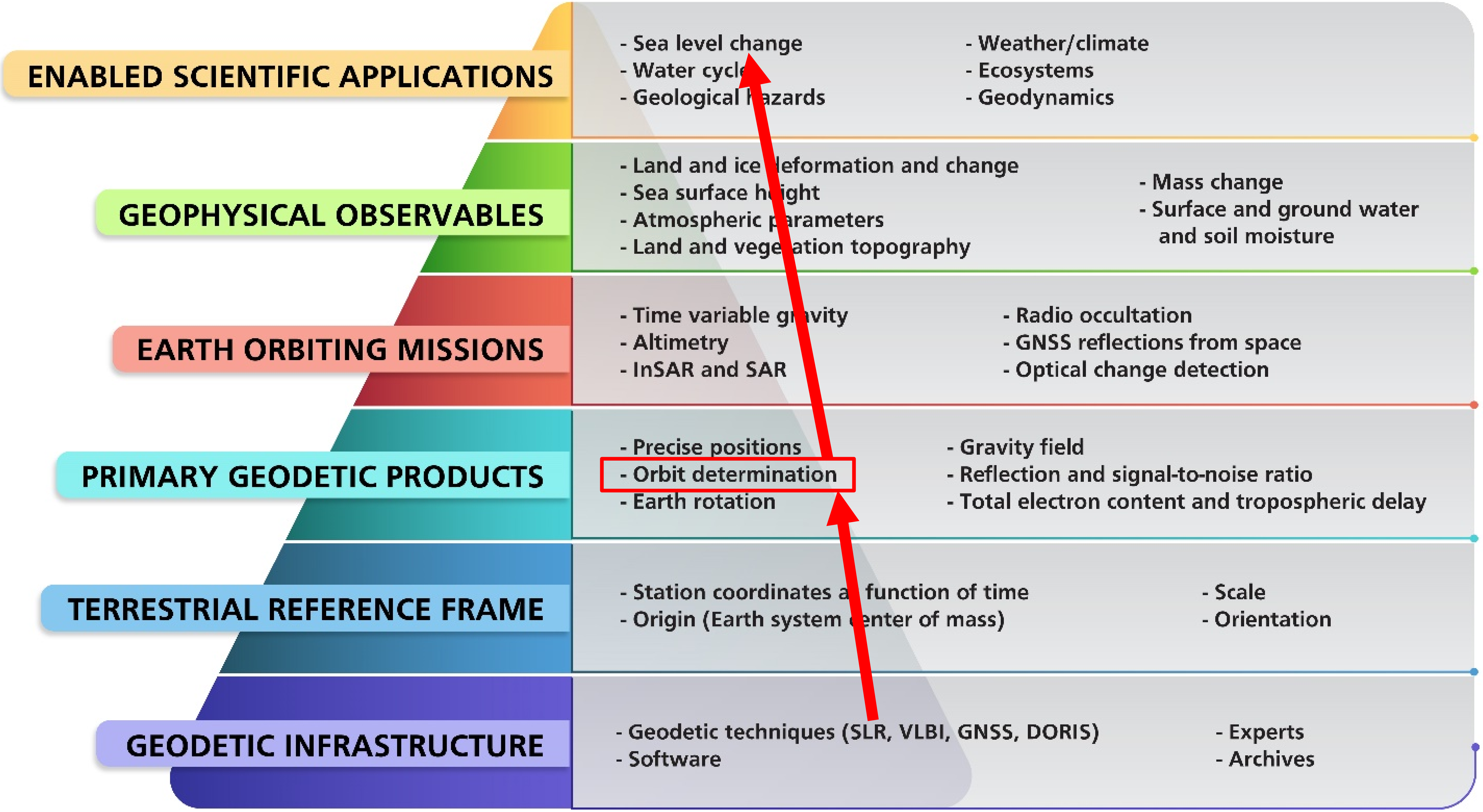
**3.** Discuss the elements of these science questions that **drive future requirements for the terrestrial reference frame**, Earth-orientation parameters, and satellite orbits, and identify what geodetic infrastructure changes are needed to help answer the questions. (workshop in Irvine, February 2019)

**4. Identify priority improvements to the geodetic infrastructure** that would facilitate advances across the science questions identified in Task 2.

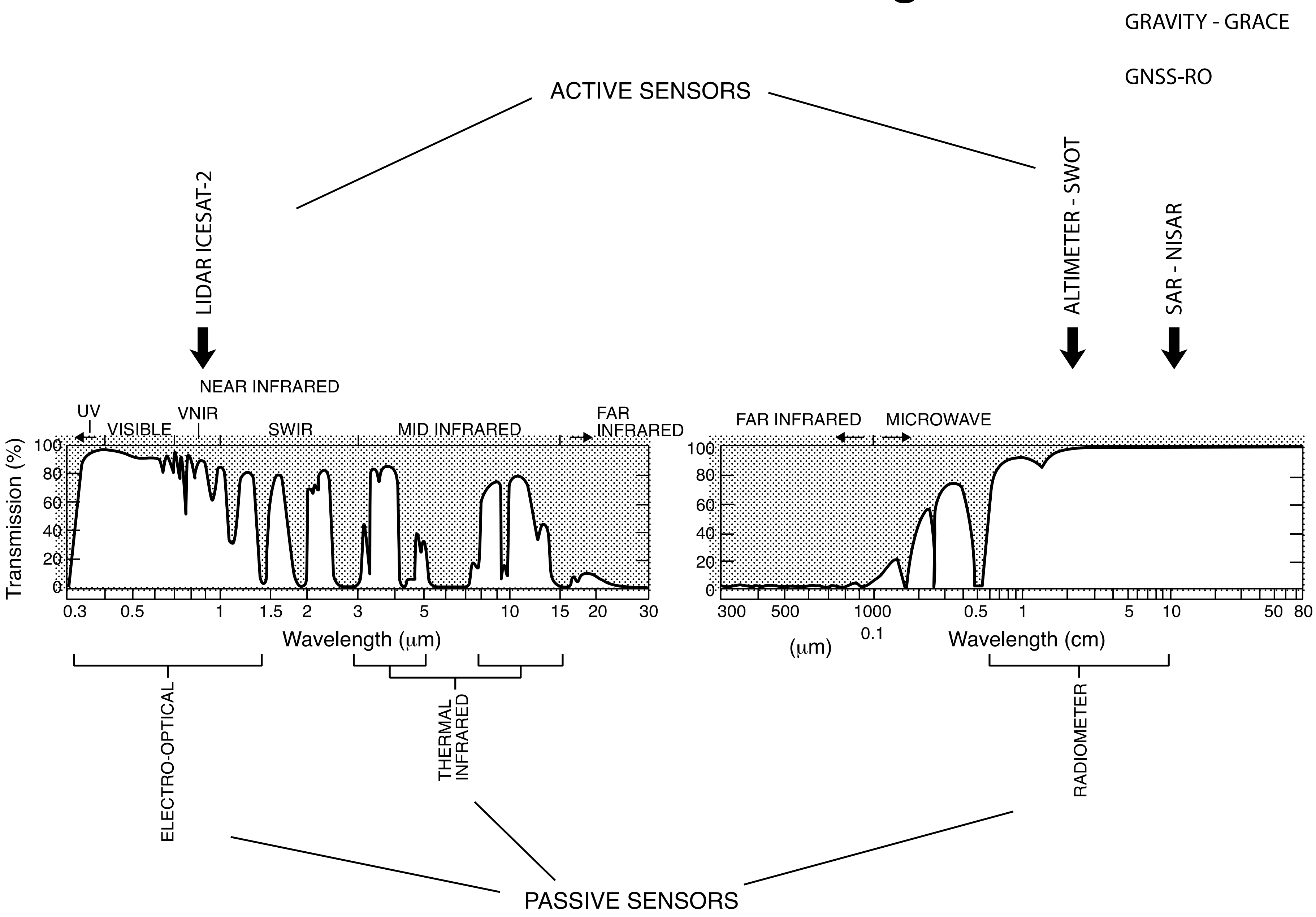
# Science Enabled by the Geodetic Infrastructure



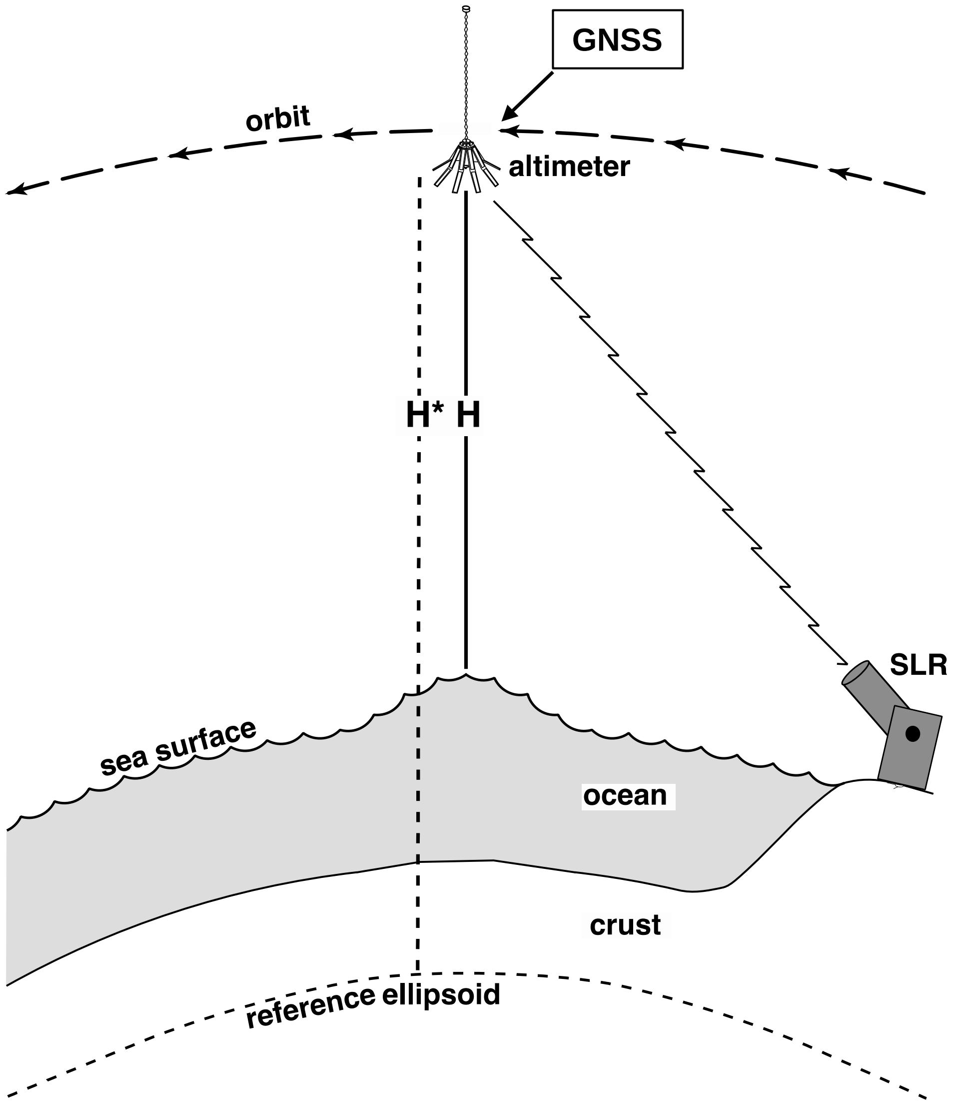
# Science Enabled by the Geodetic Infrastructure



# **Active** and Passive Remote Sensing



# All active sensors require precise (cm) orbits

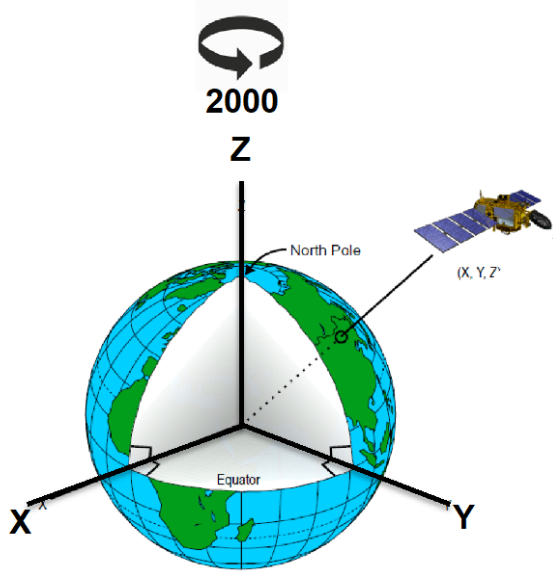



Ocean Science Topography Science Team (OSTST), November 2019:

“recommends that agencies and mission advisory groups developing future radar altimeter missions consider including the three independent positioning systems (SLR, GNSS, DORIS) to ensure highest possible orbit accuracy and widest possible use of the data over all surfaces.”

SLR – satellite laser ranging

# Terrestrial Reference Frame (TRF)



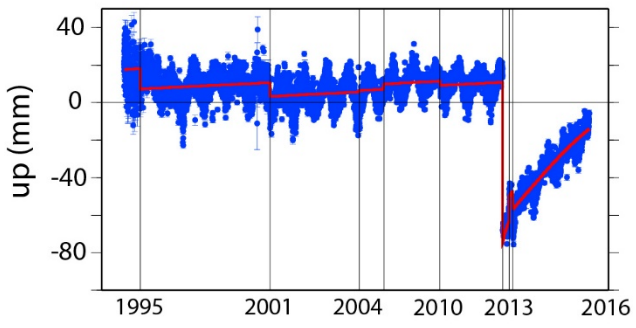

- Origin, orientation, and scale defined by the Geodetic Infrastructure (7-parameters)
- Allows diverse geodetic measurements to be linked over space and time
- Changes over a wide range of time scales as mass is redistributed over Earth's surface

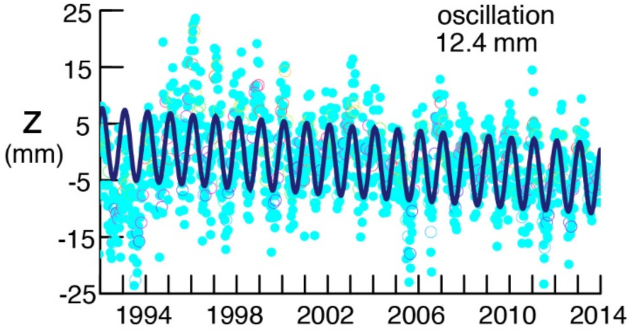
**increasing time scale**

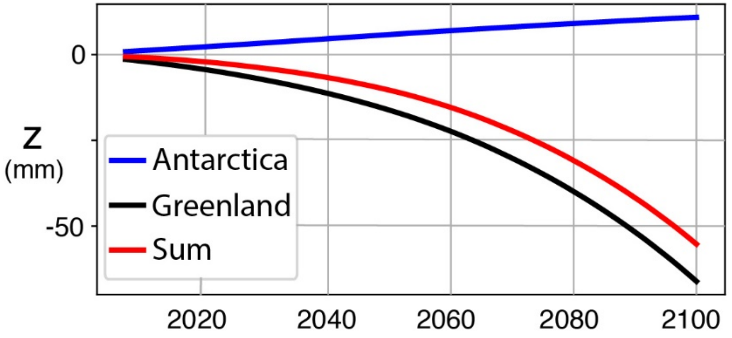
**sudden earthquake**

**annual snow/water**

**century ice sheet melting**



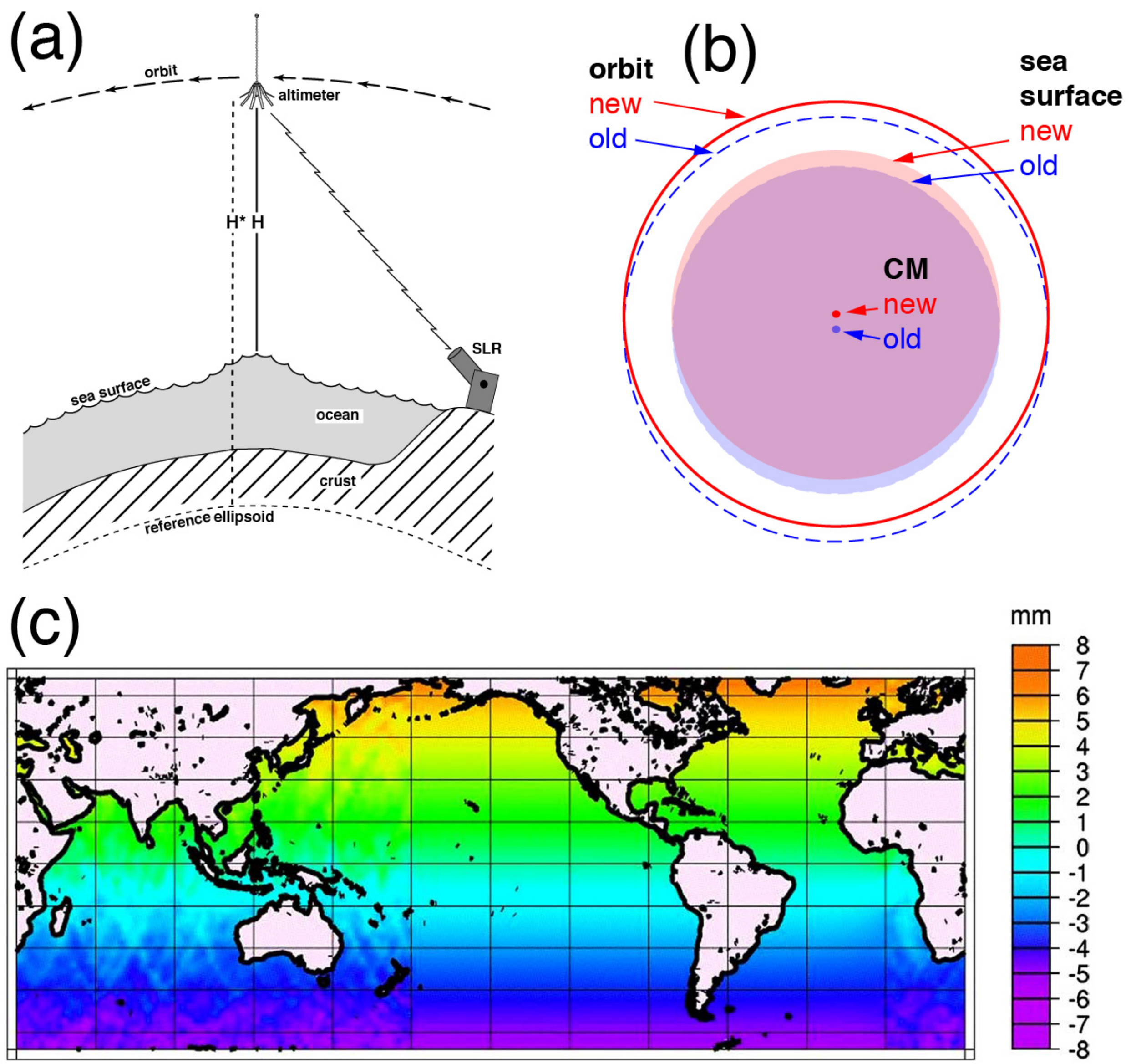

[Altamimi et al., 2016; Argus personal communication; Adhikari et al., 2015]

# Relative Contributions to TRF

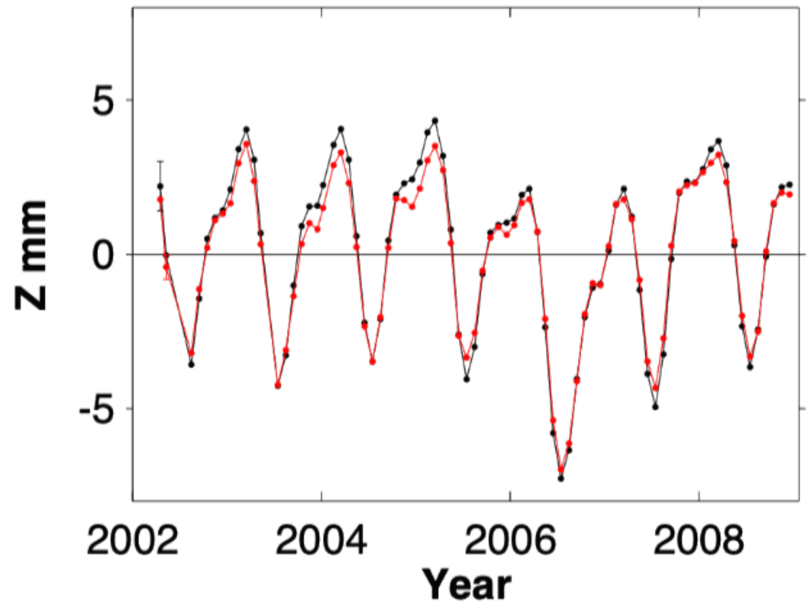
[Altamimi, 2016;
Haines et al., 2015,
Argus, personal communication]

| technique | VLBI | SLR | GPS |
|---|---|---|---|
| celestial frame (UT1) | **strong** | weak | weak |
| scale | **strong** | **strong** | medium |
| geocenter | weak | **strong** | medium |
| geographic density | weak | weak | **strong** |

# Direct connection between TRF error and sea level error




[Morel and Willis, 2005]




Motion of the CM of the Earth due to seasonal variations in water loading
[Wu et al., AGU 2019]

# All active sensors require precise (cm) orbits

These decadal survey missions would be **space junk** if their tracking systems failed.

Scientific payoff of these missions is directly related to the accuracy of their orbits.

| SATELLITE | JASON-3 | GRACE-FO | ICESAT-2 | COSMIC-2 | SWOT | NISAR |
|---|---|---|---|---|---|---|
| LAUNCH<br>LIFETIME | 2016<br>5+ | 2018<br>5+ | 2018<br>3-7 | 2019<br>5+ | 2021<br>3+ | 2022<br>3-10 |
| TRACKING | GNSS, SLR, DORIS | GNSS, SLR | GNSS, SLR | GNSS, SLR, DORIS | GNSS, SLR, DORIS | GNSS, SLR |
| ACCURACY* | 10 mm | < 20 mm | 4 mm/yr | 20-30 mm | < 30 mm | 40–70 mm |
| PRECISION* | .1 mm/yr | < 2 μm | < 30 mm | < 0.2 mm/s** | 2.5 mm | 3.5 mm/50km |

* Accuracy/precision values are based on actual or projected performance.
**This is really a clock stability requirement. $10^{-12}$ over 200 seconds.

# **TASK 1.** Summarize progress in geodetic infrastructure since 2010

United States continues to make a strong contribution to the international geodetic infrastructure. **Four areas of concern**:

**1)** Accuracy of NASA's next-generation VLBI and SLR systems not validated with long-term data-driven studies (peer reviewed)

**2)** Few fundamental or SLR stations have been added. Especially needed in the southern hemisphere

**3)** Highly-accurate, national GNSS observing system has not been developed that could both serve as the U.S. realization of and connection to the ITRF

**4)** Aging workforce puts U.S. at risk:

a) not meeting needs of U.S. geodesy programs
b) not maintaining a leadership role in geodesy

**TASKS 2 and 3.** Science questions from the 2017 Decadal Survey that depend on geodesy and elements that drive future requirements for the TRF

Themes from workshop February 2019:

- Sea level change
- **Terrestrial water cycle**
- Geological hazards
- Weather and climate
- Ecosystems

**Discipline scientists and geodesists worked together to determine geodetic requirements**

# Terrestrial Water Cycle

**Decadal Survey science questions:**

**H-2. How do anthropogenic changes in climate, land use, water use, and water storage interact and modify the water and energy cycles** locally, regionally, and globally and what are the short- and long- term consequences?

**H-4. How does the water cycle interact with other Earth System processes** to change the predictability and impacts of hazardous events and hazard chains (e.g., floods, wildfires, landslides, coastal loss, subsidence, droughts, human health, and ecosystem health), and how do we improve preparedness and mitigation of water-related extreme events?

**S-6. How much water is traveling deep underground** and how does it affect geological processes and water supplies?

# Elastic Loading vs. Aquifer Compaction

**Elastic response to water load**

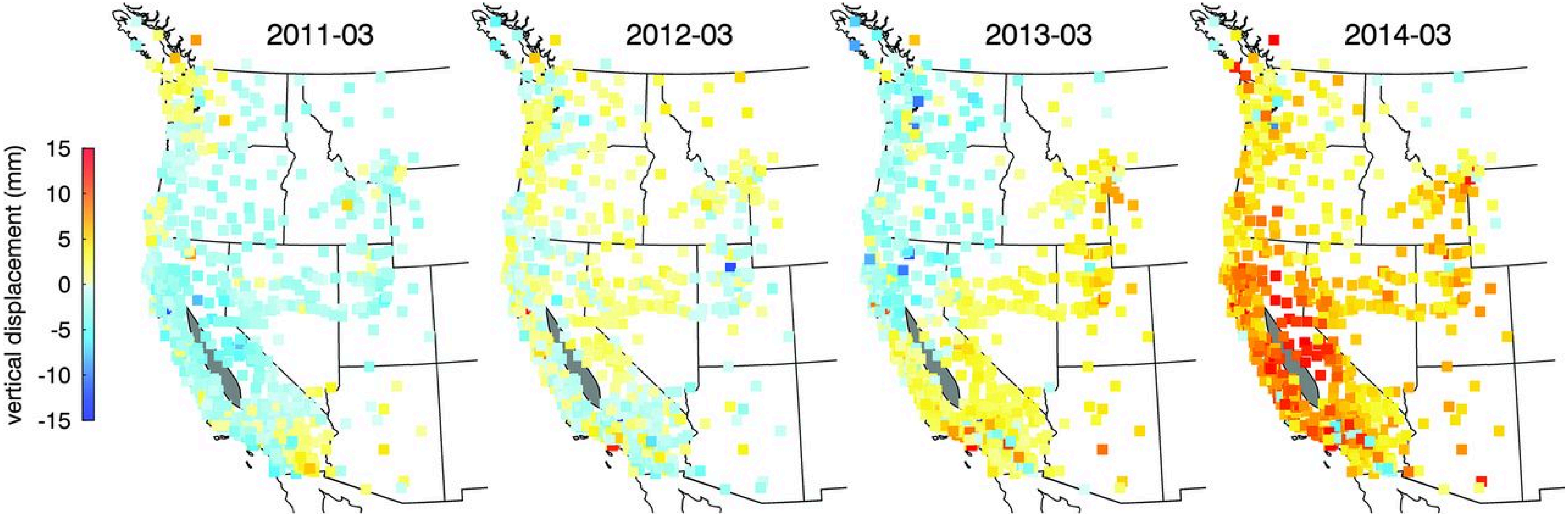

**Mountains subside in elastic response to snow or water load**
**81% of GPS sites**

**Porous response to groundwater change**

**Aquifers expand/compact as groundwater fills/drains pores in silts, sands, and gravels of aquifer**
**10% of GPS sites**

[Argus, personal communication]

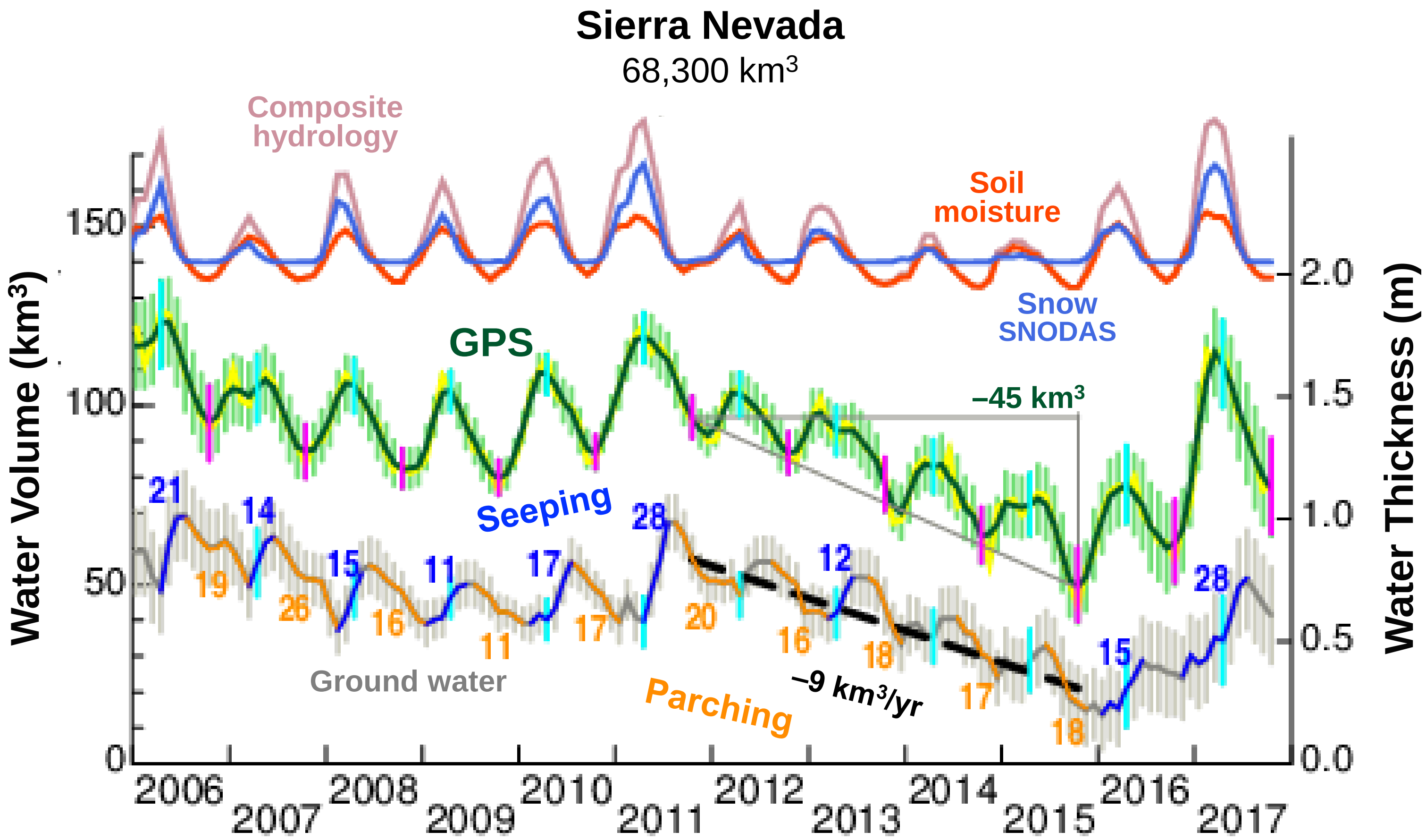
# Elastic Loading




Vertical land displacements observed by GPS in the western United States from March 2011 through March 2014.

[Borsa et al., 2014]

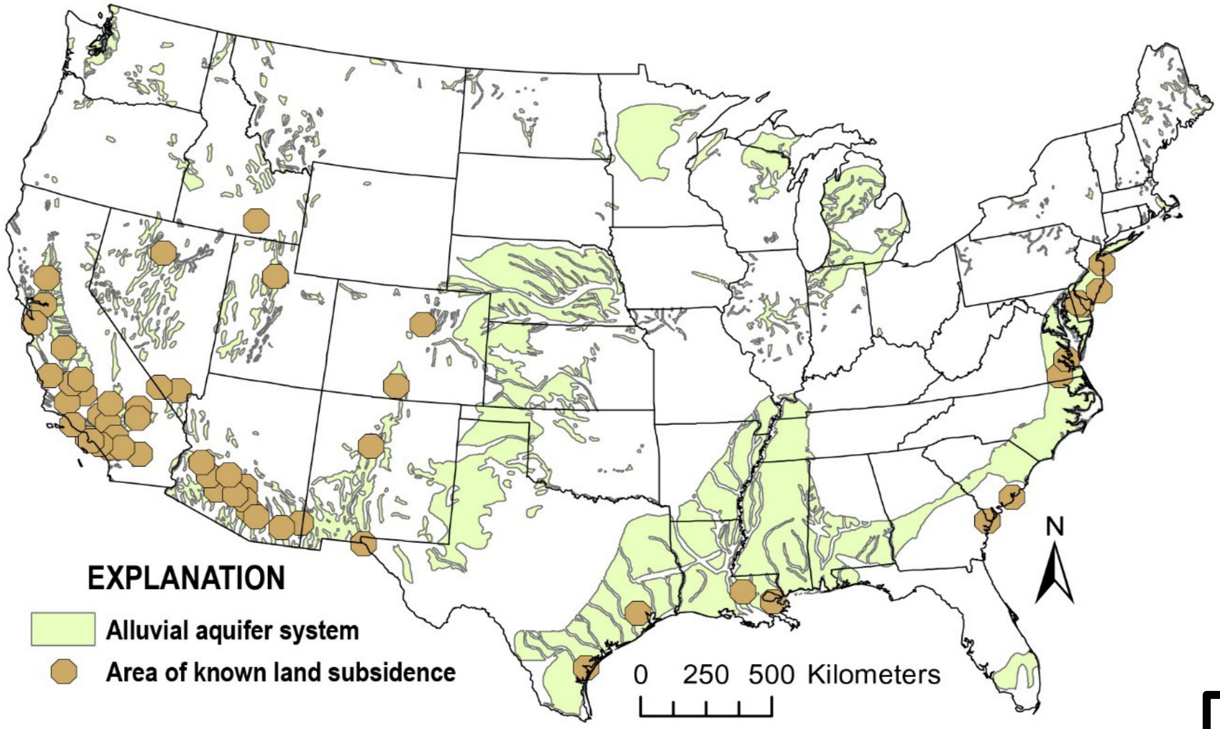
# Hydrology models greatly underestimate water loss




Sierra Nevada lost 45 ± 21 $km^3$ of groundwater during drought of October 2011-October 2015, exceeding the 6 $km^3$ of soil moisture lost in hydrology model estimates

[Argus et al., 2017]

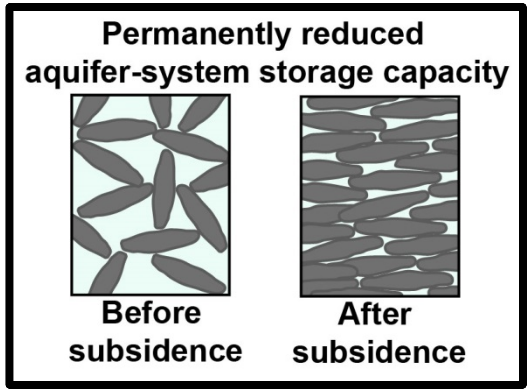
# Aquifer-System Compaction (Land Subsidence)




- **123,000 km$^2$ of U.S. land and waterways** impacted by land subsidence caused by aquifer-system compaction

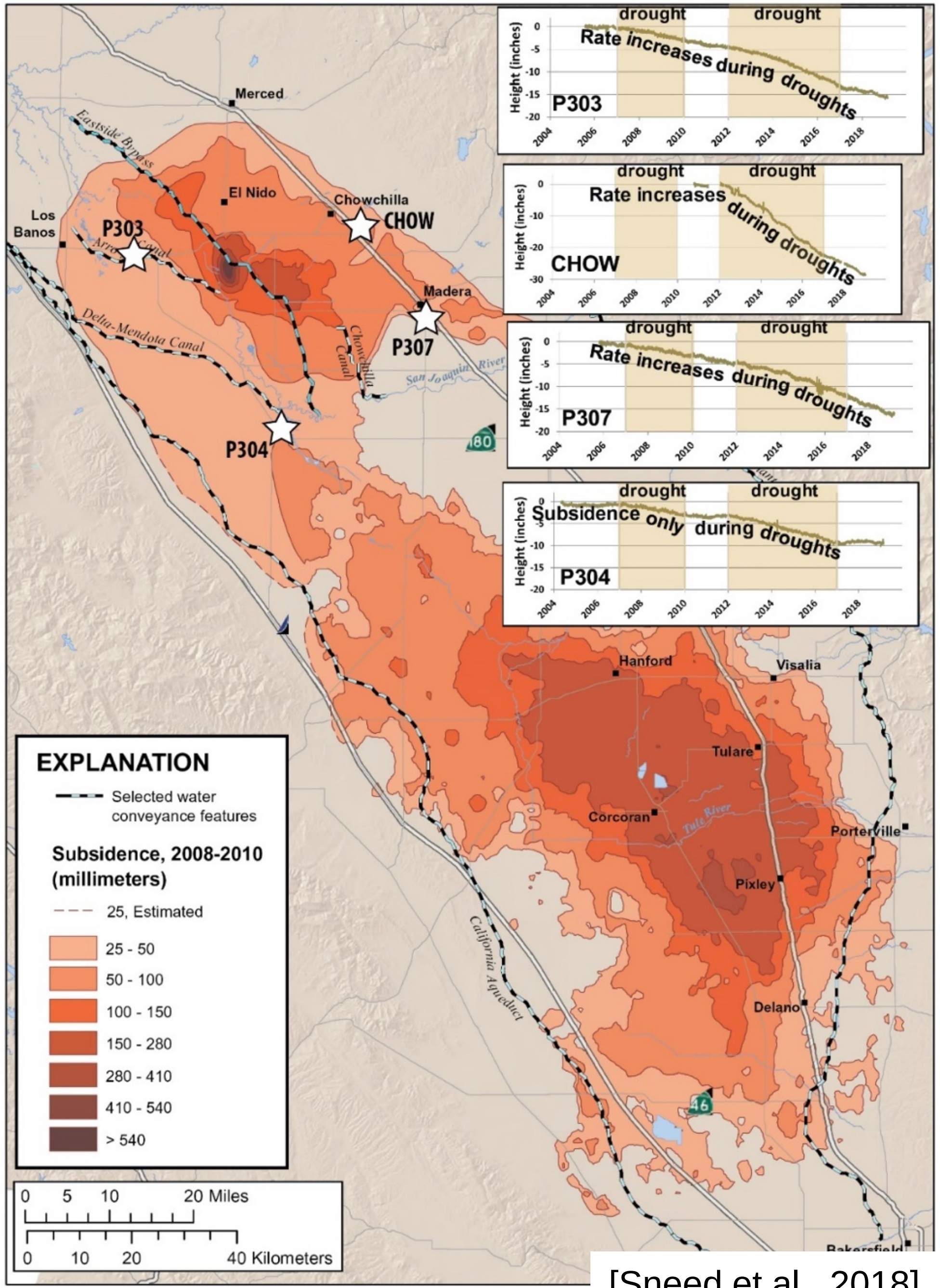
**Damages infrastructure and natural resources**

- Reduces water conveyance capacity & freeboard, etc.
- Roads, rails, bridges, pipelines, wells, etc.
- Reduces aquifer-system storage capacity
- Ground failures (fissuring/faulting)
- Impacts to wetland, riparian, and aquatic ecosystems




[Sneed et al., 2018]

# Land Subsidence in San Joaquin Valley, CA




[Sneed et al., 2018]

- Among highest subsidence rates in the world during 2012-16 drought (0.3 m/yr)
- Major canals have lost as much as 60% conveyance capacity
- Land subsidence areas and rates constantly change and need to be tracked

# Terrestrial Water Cycle

## Maintenance of Geodetic Infrastructure

- Maintain current stability of ITRF
- Maintain InSAR orbit accuracy to 20 mm radially and 60 mm along-track
- Maintain robust global distribution of high-quality GNSS stations, analysis products, and software
- Continue support for high-accuracy GNSS analysis software
- Support antenna phase calibrations
- Support automated GNSS processing services
- Maintain geodetic expertise to maintain institutional knowledge & technical capabilities

## Enhancements to Geodetic Infrastructure

- **Add GNSS stations in western United States to geodetic infrastructure**
  - **~40 km spacing, with more stations in watersheds or areas without traditional hydrological measurement networks**
  - Meet highest standards for data quality, site design, stable monumentation, and metadata
  - Would improve accuracy of local surveys (e.g., aircraft lidar).

# Sea-Level Change

**Decadal Survey science questions:**

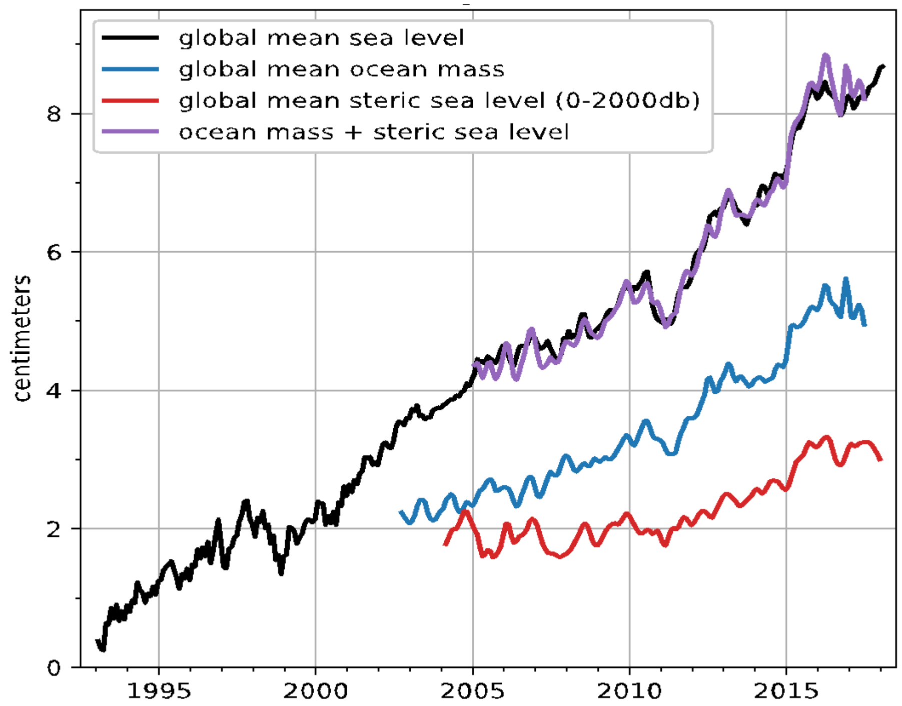
**C-1. How much will sea level rise, globally and regionally**, over the next decade and beyond, and what will be the role of ice sheets and ocean heat storage?

**S-3. How will local sea level change along coastlines** around the world in the next decade to century?

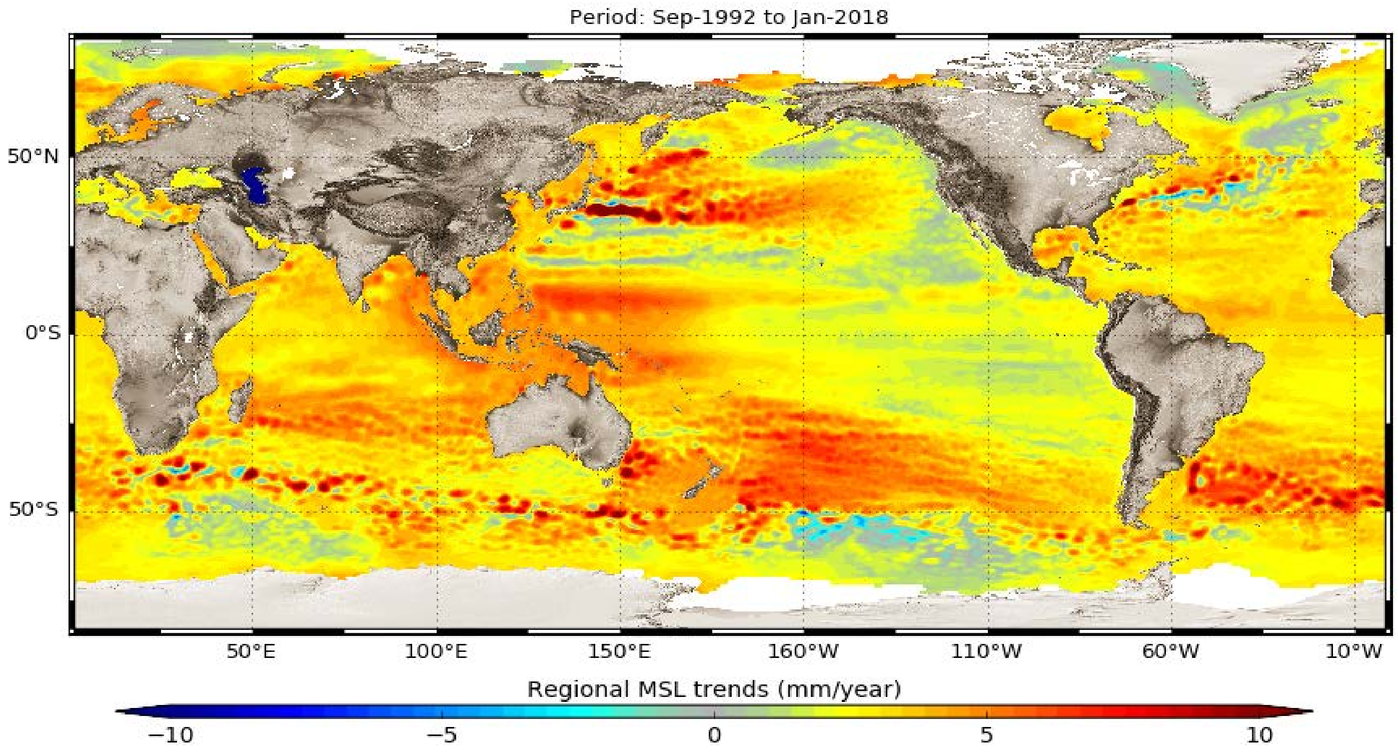
**C-6.** Can we significantly improve seasonal to decadal forecasts of societally relevant climate variables?

**H-1.** How is the water cycle changing? Are changes in evapotranspiration and precipitation accelerating, with greater rates of evapotranspiration and thereby precipitation, and how are these changes expressed in the space-time distribution of rainfall, snowfall, evapotranspiration, and the frequency and magnitude of extremes such as droughts and floods?

# Global and Regional Sea Level Change




[Leuliette and Nerem, 2016]

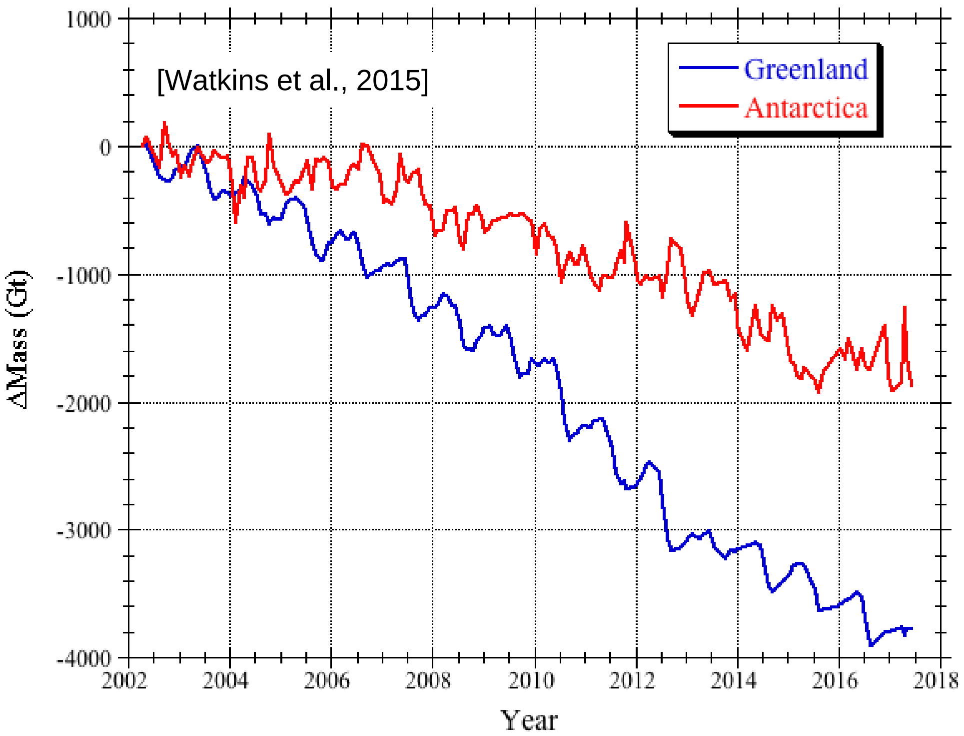


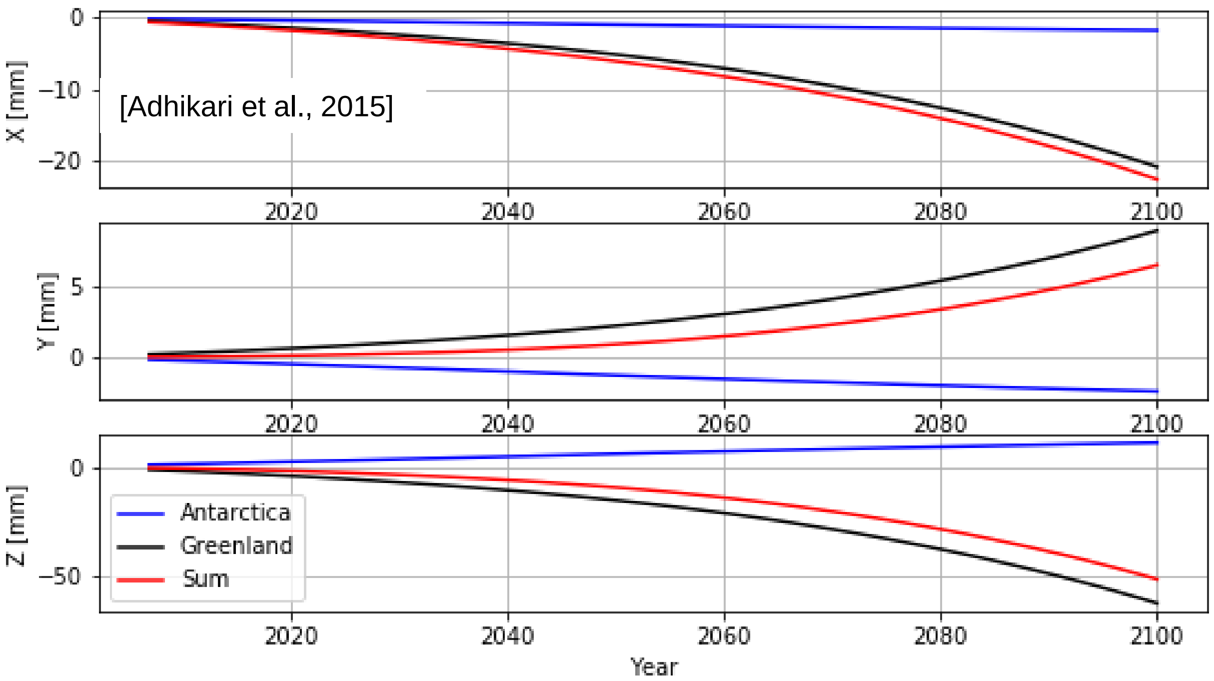

[Copernicus Marine Environment Monitoring Service]

Absolute sea level measured by temporally overlapping series of satellite altimeters.  Tide gauges with GNSS vertical land measurements provide 10-100 year accuracy.

2017 Decadal Survey called for determining **global mean sea-level rise to within 0.5 mm/year** over a decade and **regional sea-level change to within 1.5–2.5 mm/year** over a decade.

# Ice Sheet and Glacier Mass Changes



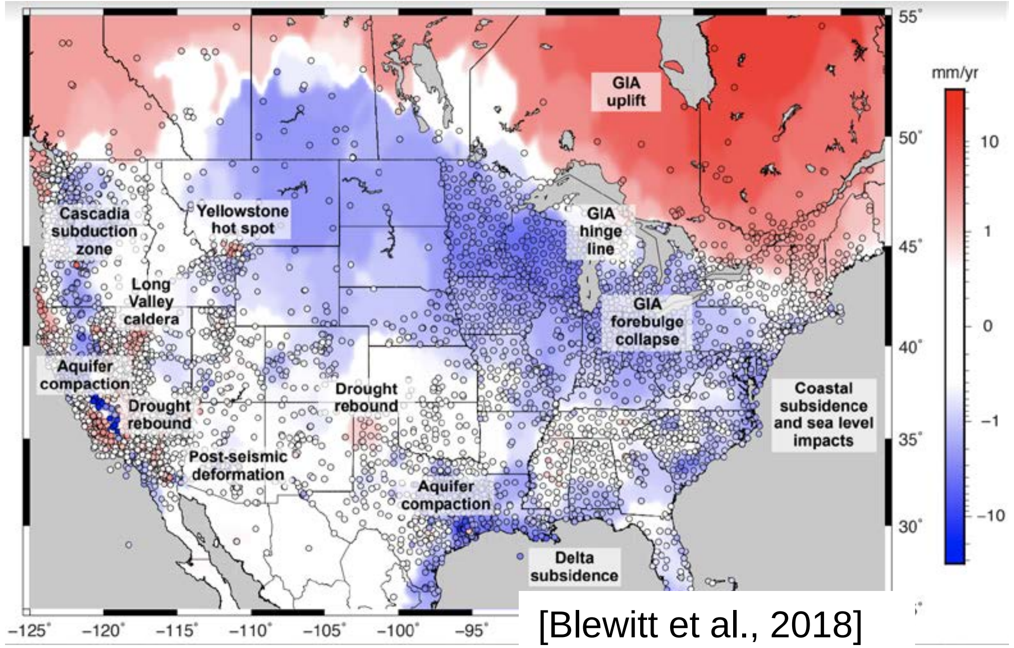




Ice sheet mass changes require multiple measurements:

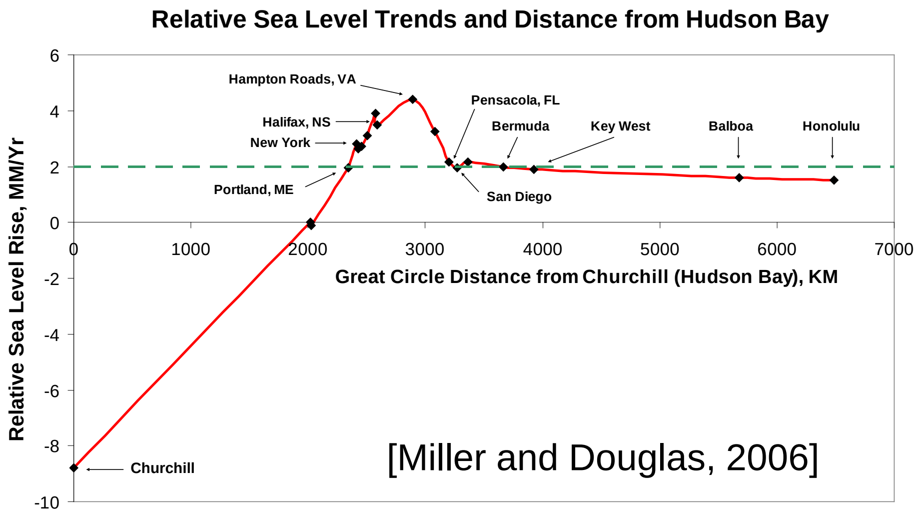
- monthly gravity change (e.g., GRACE), GIA correction, ice sheet elevation (e.g., ICESAT-2, CRYOSAT-2), ice stream velocity (i.e., NISAR), visco-elastic rebound (e.g., GNSS)

Mass loss of Greenland and Antarctic ice sheets over the next 100 years will cause large CM motions, so need to maintain absolute accuracy of TRF.

# Relative Sea Level and Vertical Land Motion




[Blewitt et al., 2018]




[Miller and Douglas, 2006]

**Relative sea level at coastlines = sea level rise + land subsidence/uplift**

**Causes of vertical land motion:**

- extraction of groundwater or hydrocarbons
- sediment compaction
- glacial rebound
- tectonics

Need long-term stable GNSS sites with 0.5 mm/yr vertical accuracy

InSAR can fill GNSS gaps in coastal areas

# Sea-Level Change

## Maintenance of Geodetic Infrastructure

- Maintain tide gauge record to achieve 0.1 mm/yr averaged over a decade
- Altimeter orbit determination requirement: 10–20 mm radial position. Ice-sheet flow-rate measurements using InSAR requirement: 3-D better than 0.1 m
- Maintain current accuracy of low degree and order geopotential field
- Maintain and enhance ancillary models and corrections for altimetric satellites

## Enhancements to Geodetic Infrastructure

- **Improve TRF accuracy to 1 mm and drift in TRF origin to < 0.1 mm/yr.**
- **Improve accuracy of Z-component of the CM. Depends on successful tracking of SLR in southern hemisphere**
- **Install GNSS stations at tide gauges** to achieve absolute vertical land motion requirement of better than 0.5 mm/yr.
- Encourage use of GNSS reflectometry to expand number of worldwide tide gauges defined in the ITRF

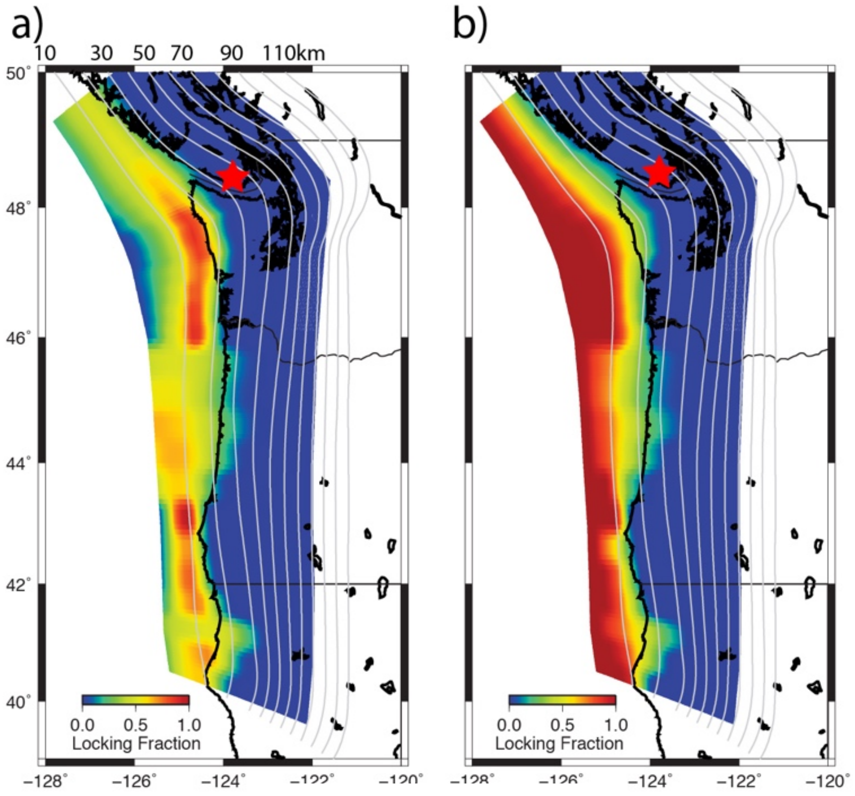
# Geological Hazards: Earthquakes and Volcanoes

**Decadal Survey science questions:**

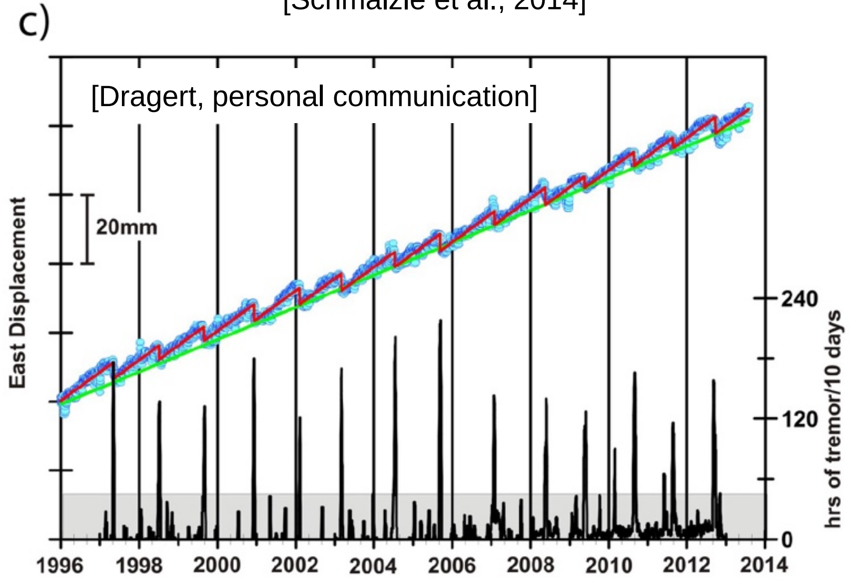
**S-1.** How can large-scale geological hazards be accurately forecast in a socially relevant time frame?

**S-2.** How do geological disasters directly impact the Earth system and society following an event?

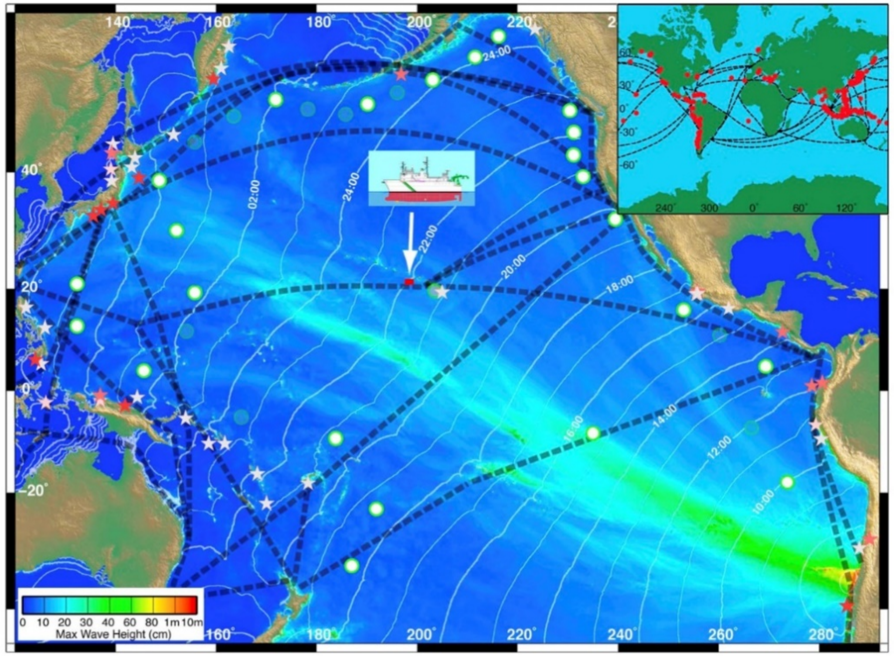
# Seismic hazard: Cascadia Subduction Zone



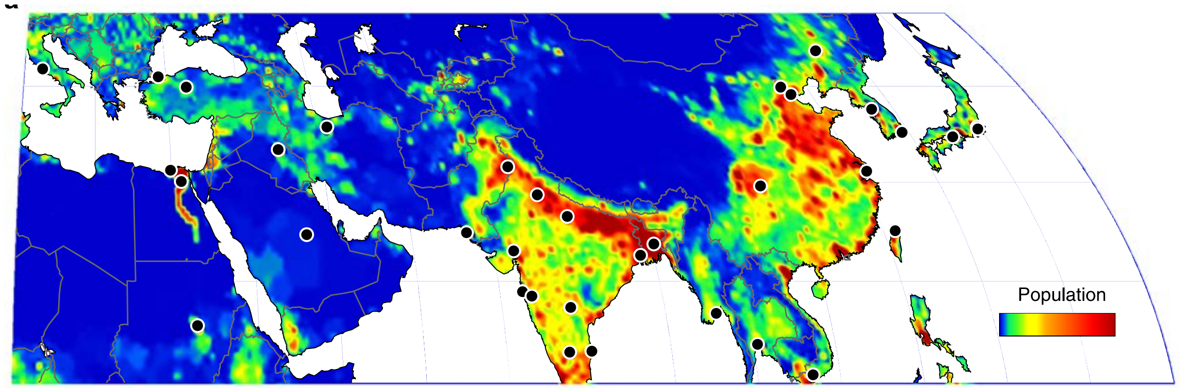

[Schmalzle et al., 2014]




- Mw 8.7-9.2 earthquake/tsunami in 1700
- Recurrence interval 300-900 yr
- Coastal forests subsided ~2 m
- Predicted tsunami wave > 3m in Pacific Northwest, Alaska, Hawaii, Guam, etc.



# Seismic hazard: Strain-rate mapping



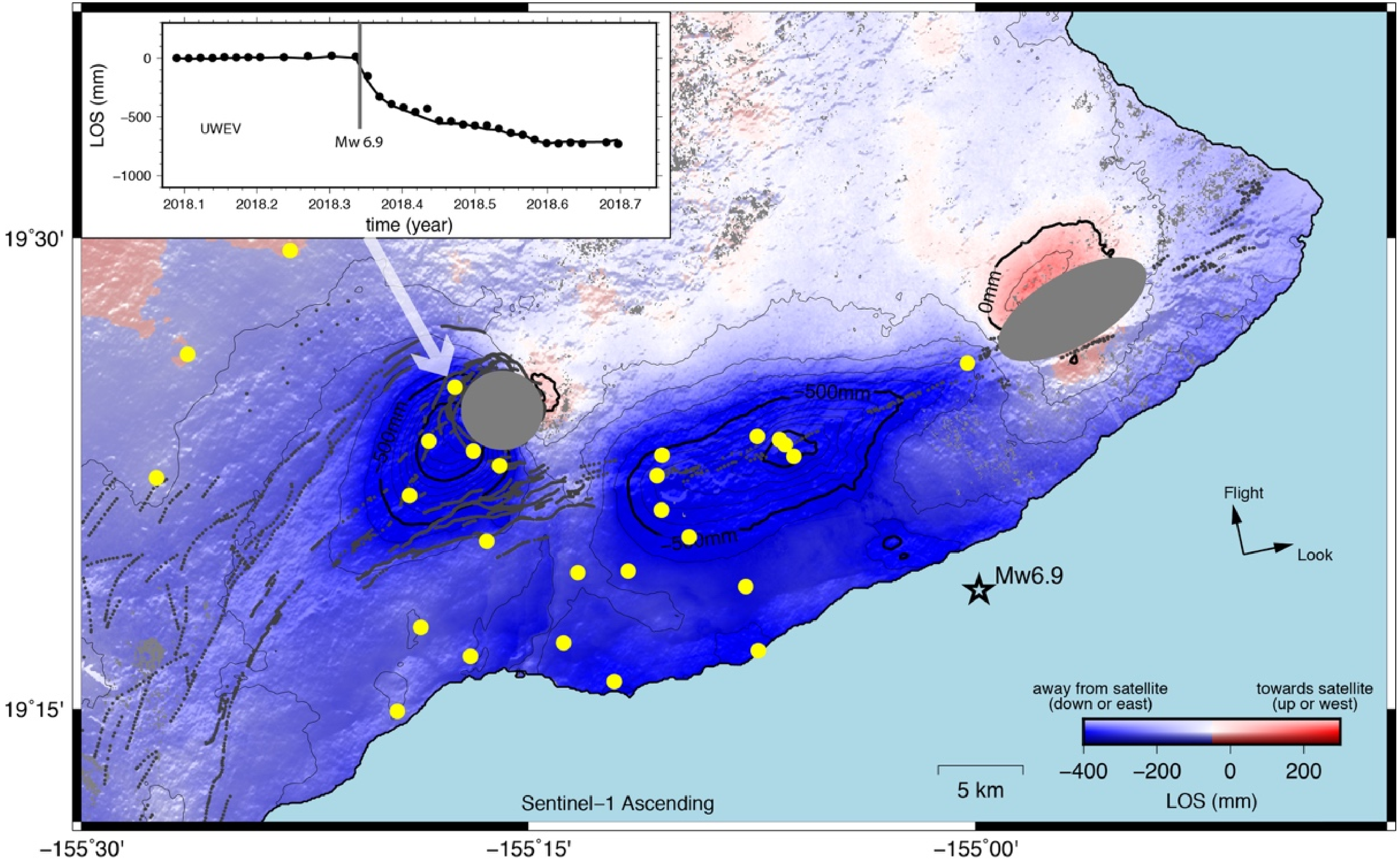

[Elliot et al., 2016]

Large continental earthquakes mainly occur where strain rate > 50 nanostrain/yr (0.5 mm/yr over 10 km distance)

GNSS at < 50 km spacing provides absolute vector time series

InSAR at < 12 day intervals provides spatial coverage to resolve partly locked faults

# Volcanic Hazard: 2018 Kilauea Eruption



# Geological Hazards: Earthquakes and Volcanoes

## Maintenance of Geodetic Infrastructure

- **Maintain current stability of TRF at 0.5 mm/yr globally**
- Track InSAR/lidar satellites at accuracy of 20 mm radially and 60 mm along-track
- **Maintain geodetic infrastructure to support monthly gravity change measurements of 1 microgal at spatial resolution of 300 km or better**
- Maintain GNSS station density of ~20 km in areas of high strain rate to bring InSAR measurements into an absolute frame at 0.5 mm/yr accuracy
- Maintain free and open access to all data used in formulating TRF

## Enhancements to Geodetic Infrastructure

- **Improve reference frame to quickly accommodate global-scale motions associated with very large earthquakes**
- Maintain and enhance a globally distributed set of GNSS sites to measure plate-boundary deformation to 0.5 mm/yr accuracy
- Ensure at least two open software development efforts for each geodetic method
- Transition processing of all geodetic data to automated analysis
- Encourage free and open access to all GNSS and InSAR data

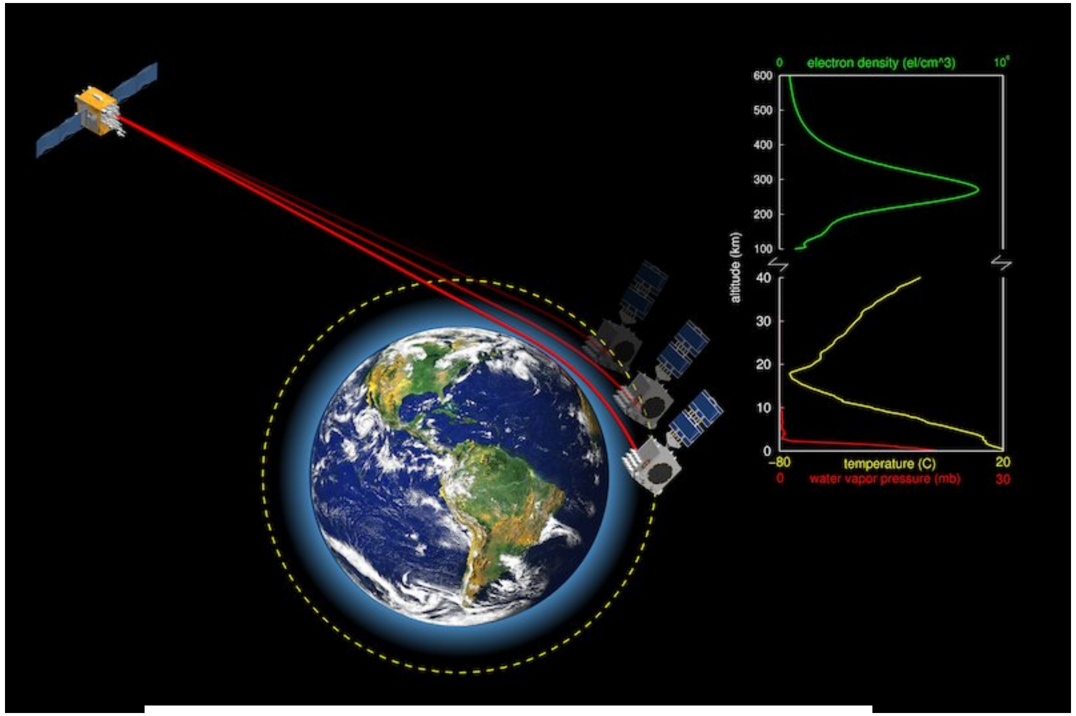
# Weather and Climate

**Decadal Survey science questions:**

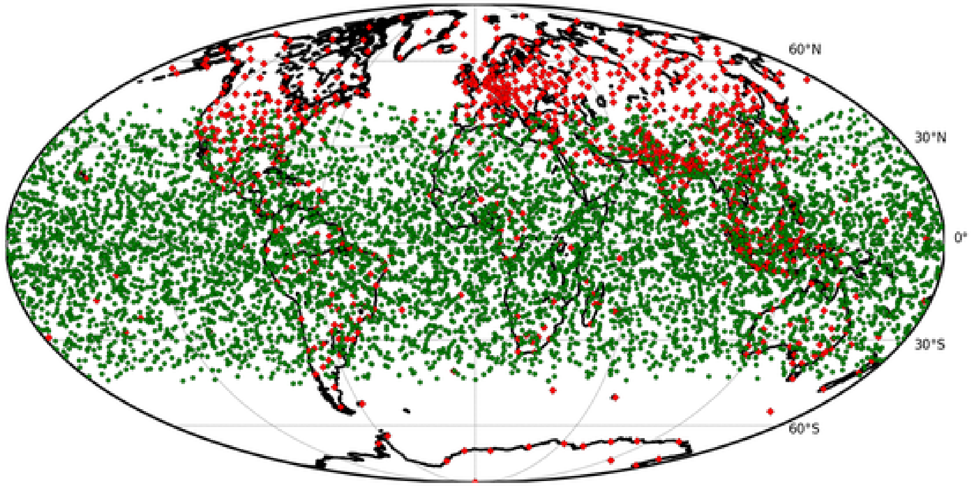
**W-2.** How can environmental predictions of weather and air quality be extended to seamlessly **forecast Earth system conditions at lead times of 1 week to 2 months**?

**C-2.** How can we reduce the uncertainty in the amount of future warming of the Earth as a function of fossil fuel emissions, **improve our ability to predict local and regional climate response to natural and anthropogenic forcings**, and reduce the uncertainty in global climate sensitivity that drives uncertainty in future economic impacts and mitigation/adaptation strategies?

# GNSS – Radio Occultation




[https://www.cosmic.ucar.edu/what-we-do/cosmic-2/]



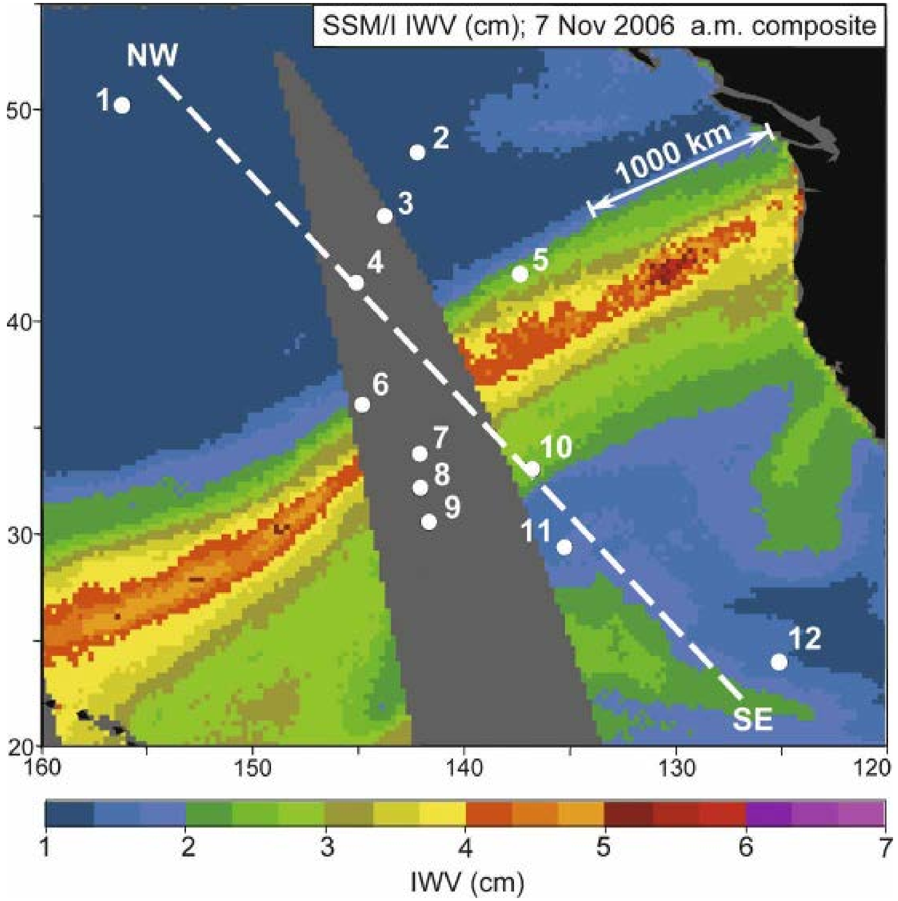

Improves sampling over oceans and mid-atmosphere.

Provides “anchor” measurements for microwave and infrared observations and improves bias corrections applied to satellite radiance measurements.

[Anthes et al., 2008]

# Weather

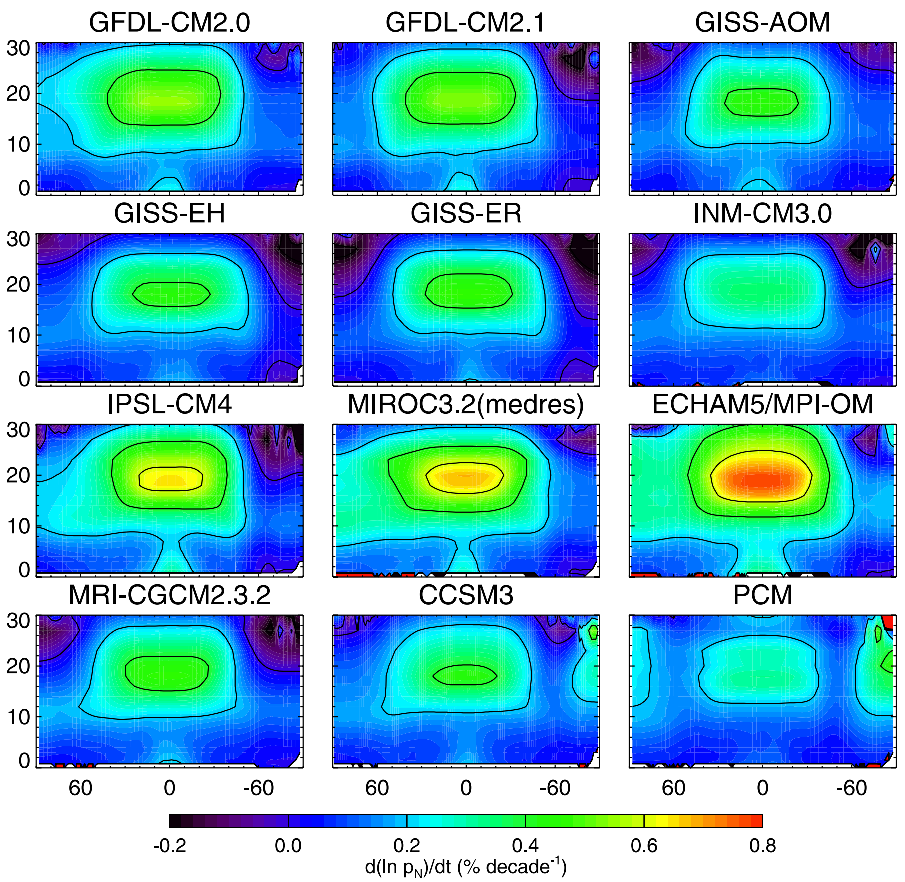
[Neiman et al., 2008]




GNSS-RO provides vertical profiles of "atmospheric river" not available from other methods (e.g., SSM/I)

# Climate

[Leroy et al., 2006]




GNSS-RO highly-accurate, long-term record of mid-atmospheric temperature variations

# Weather and Climate

### Maintenance of Geodetic Infrastructure

- Maintain robust global distribution of GNSS stations providing **free, open, and near-real-time raw observational data**
- Support IGS analysis products, including **accurate orbits and clocks**
- Maintain geodetic expertise for institutional knowledge and availability of trained personnel

### Enhancements to Geodetic Infrastructure

- **Upgrade global IGS sites to achieve GPS-like accuracies for other constellations (e.g., Galileo).** Would dramatically increase number of radio occultations for weather and climate applications
- Improve modeling of GNSS observables, including attitude information, satellite metadata and radiation force models.

# Ecosystems

**Decadal Survey science questions:**

**E-1. What are the structure, function, and biodiversity of the Earth's ecosystems**, and how and why are they changing in time and space?

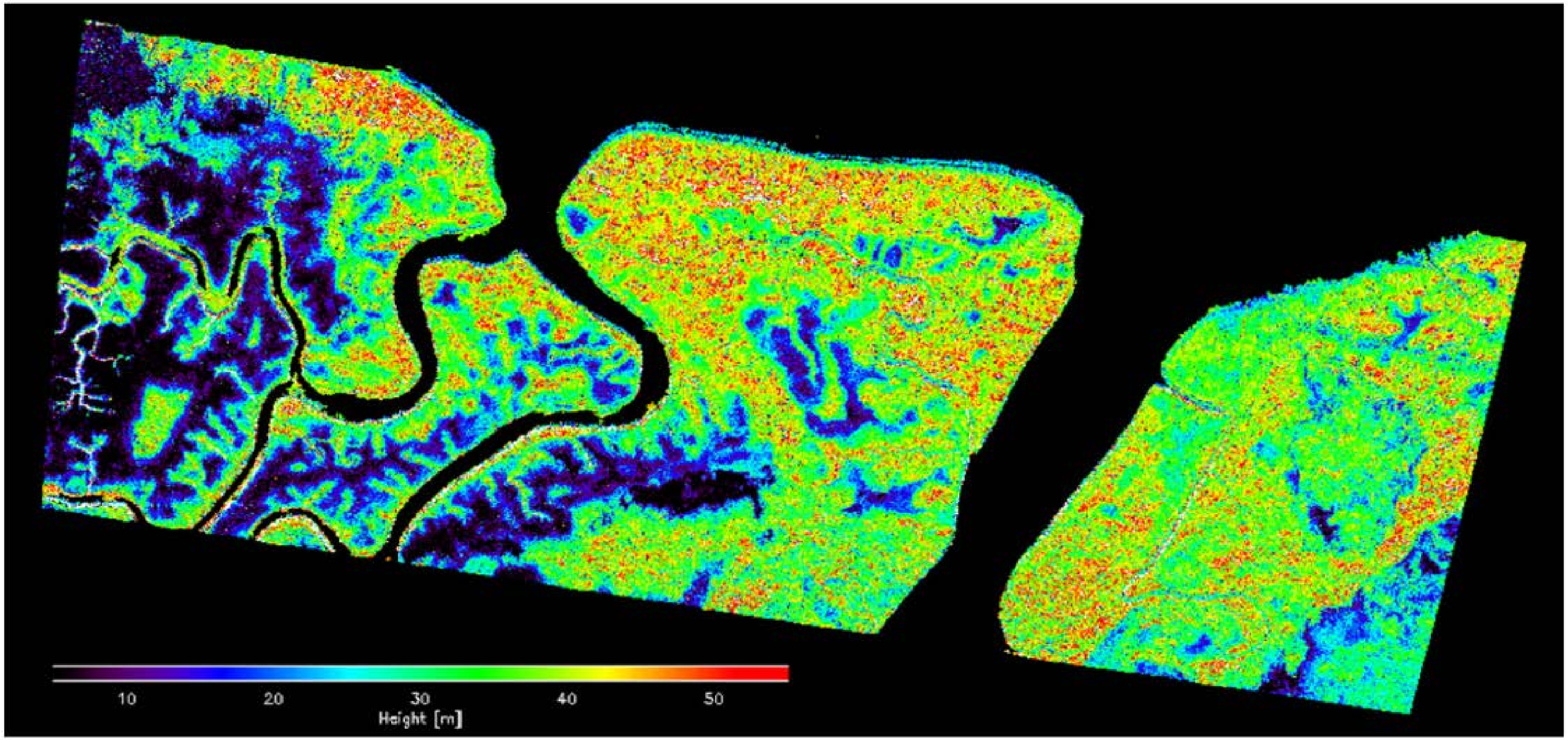
**E-2. What are the fluxes (of carbon, water, nutrients, and energy)** between ecosystems and the atmosphere, the ocean and the solid Earth, and how and why are they changing?

**E-3.** What are the fluxes (of carbon, water, nutrients, and energy) within ecosystems, and how and why are they changing?

**E-4.** How is carbon accounted for through carbon storage, turnover, and accumulated biomass? Have all of the major carbon sinks been quantified and how are they changing in time?

**S-4.** What processes and interactions determine the rates of landscape change?

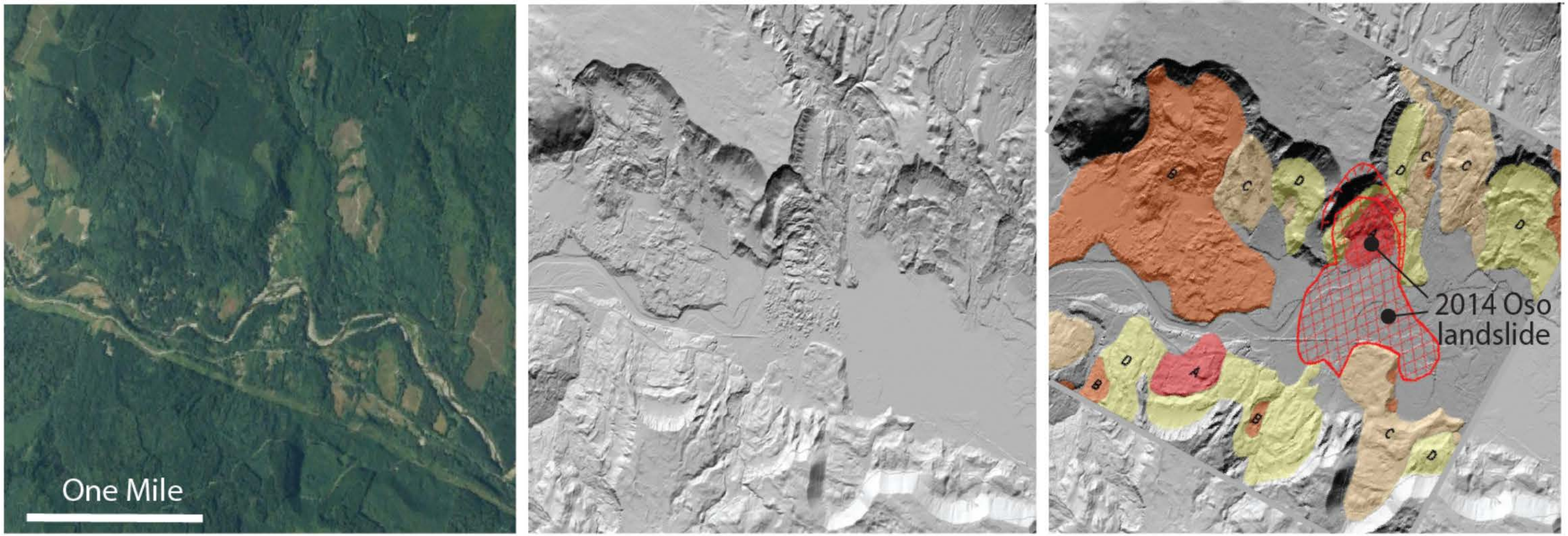
# Vegetation Dynamics




[Quegan et al., 2019]

Active remote sensing by polarimetric SAR, InSAR, and lidar are providing new measurements of biomass changes.

# Lateral Transport




[Haugerud, 2014]

Lidar can provide “bare earth” topography to reveal present and past landslides as well as the vertical structure of the vegetation.

# Ecosystems

**Maintenance of Geodetic Infrastructure**

- Maintain current TRF
- Maintain orbit determination: 10–20 mm orbit accuracy, 40–70 mm along-track accuracy, and mm/yr orbit stability
- Sustain gravity measurements for accurate geocenter

**Enhancements to Geodetic Infrastructure**

- **Additional L5 base stations ~30 km spacing in remote areas** (needed for aircraft lidar)
- Training and cyberinfrastructure to support new technologies

# Common Themes for Maintaining and Enhancing the Geodetic Infrastructure

- Accuracy and stability of the TRF
- Accuracy and stability of the satellite orbits
- Accuracy of the low-degree geopotential harmonics
- Augmentation of the GNSS Network (e.g., ~40 spacing for hydrology)
- Supporting software, models, data, and expertise

# Priority improvements to the geodetic infrastructure

1. **Finalize deployment and testing of next-generation VLBI and SLR systems** and complete deployment of multi-GNSS to:
    - achieve balance of geodetic measurement techniques between northern and southern hemispheres
    - document errors in the systems
    - improve ability to estimate their positions accurately and automatically

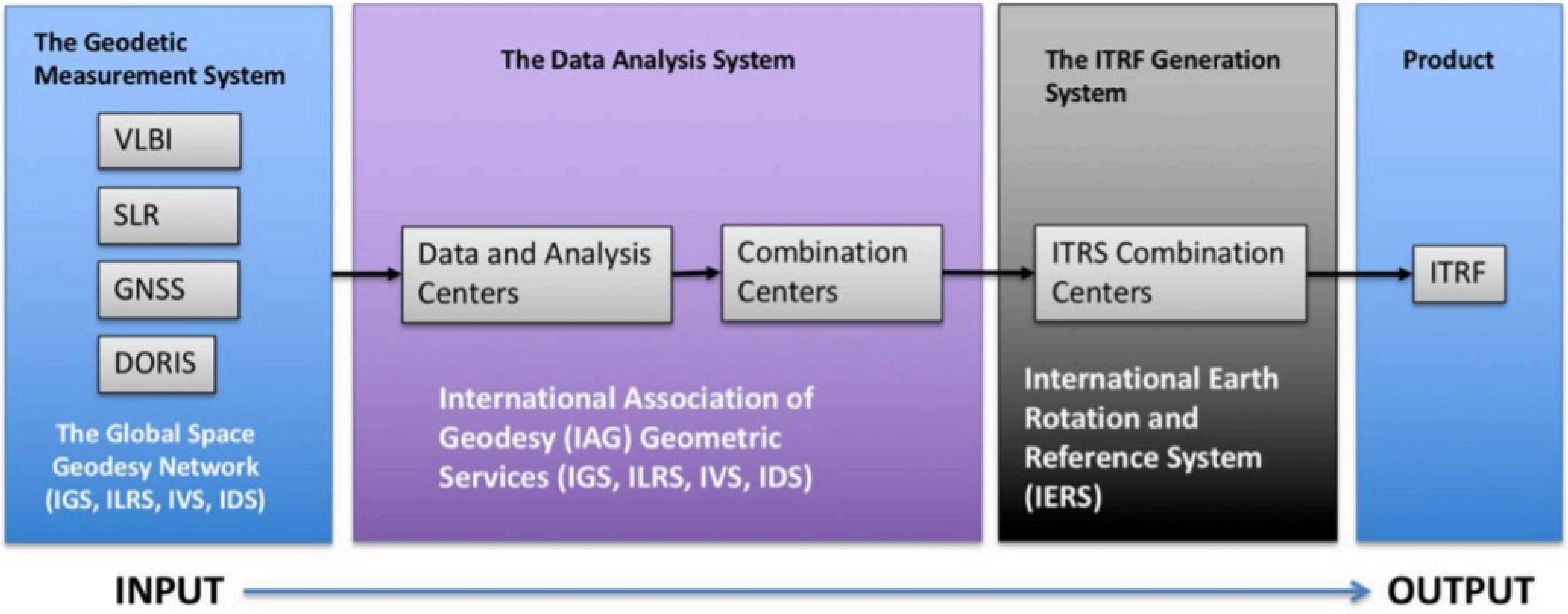
2. **Increase capabilities for measuring center of mass motions** expected over the next 100 years due to melting of ice sheets

3. **Work with international community to implement a fully time-dependent TRF** that accommodates both annual and sudden changes in locations of fundamental stations

# Questions?

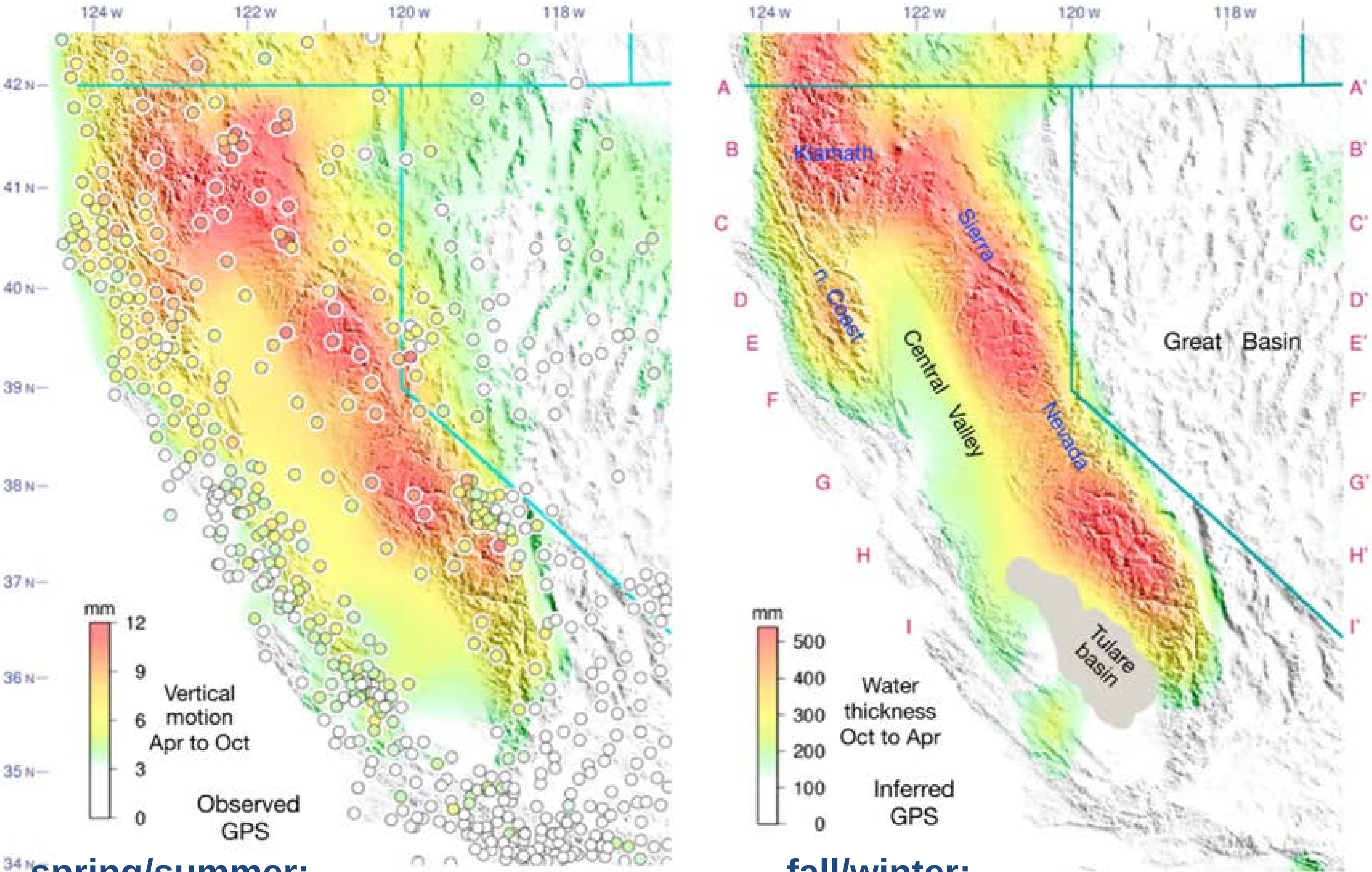
# Extra

# Geodetic Services




[Lemoine, personal communication]

# Elastic Loading

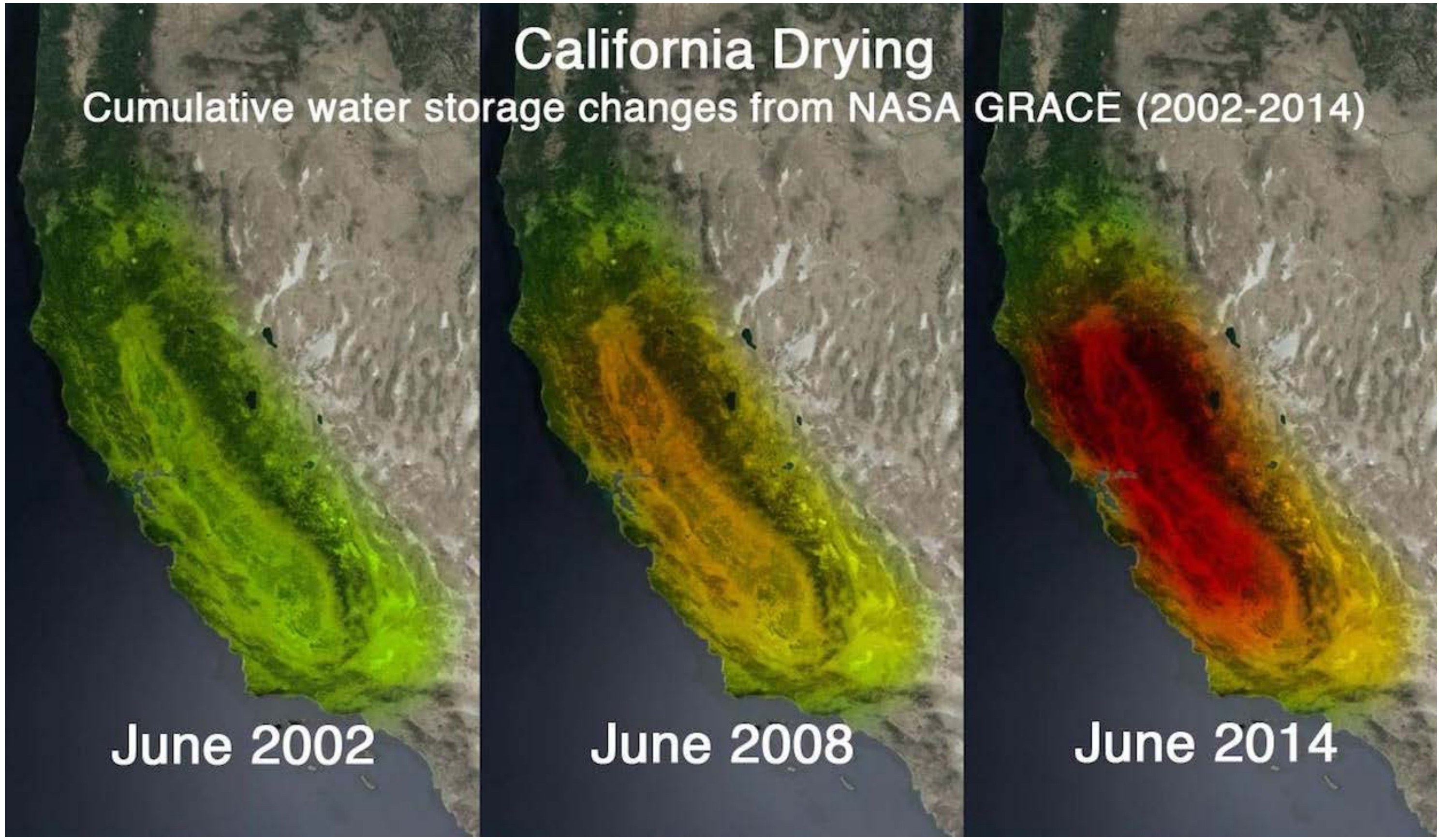



**spring/summer:**
**reduced terrestrial water storage**

**fall/winter:**
**increased terrestrial water storage**

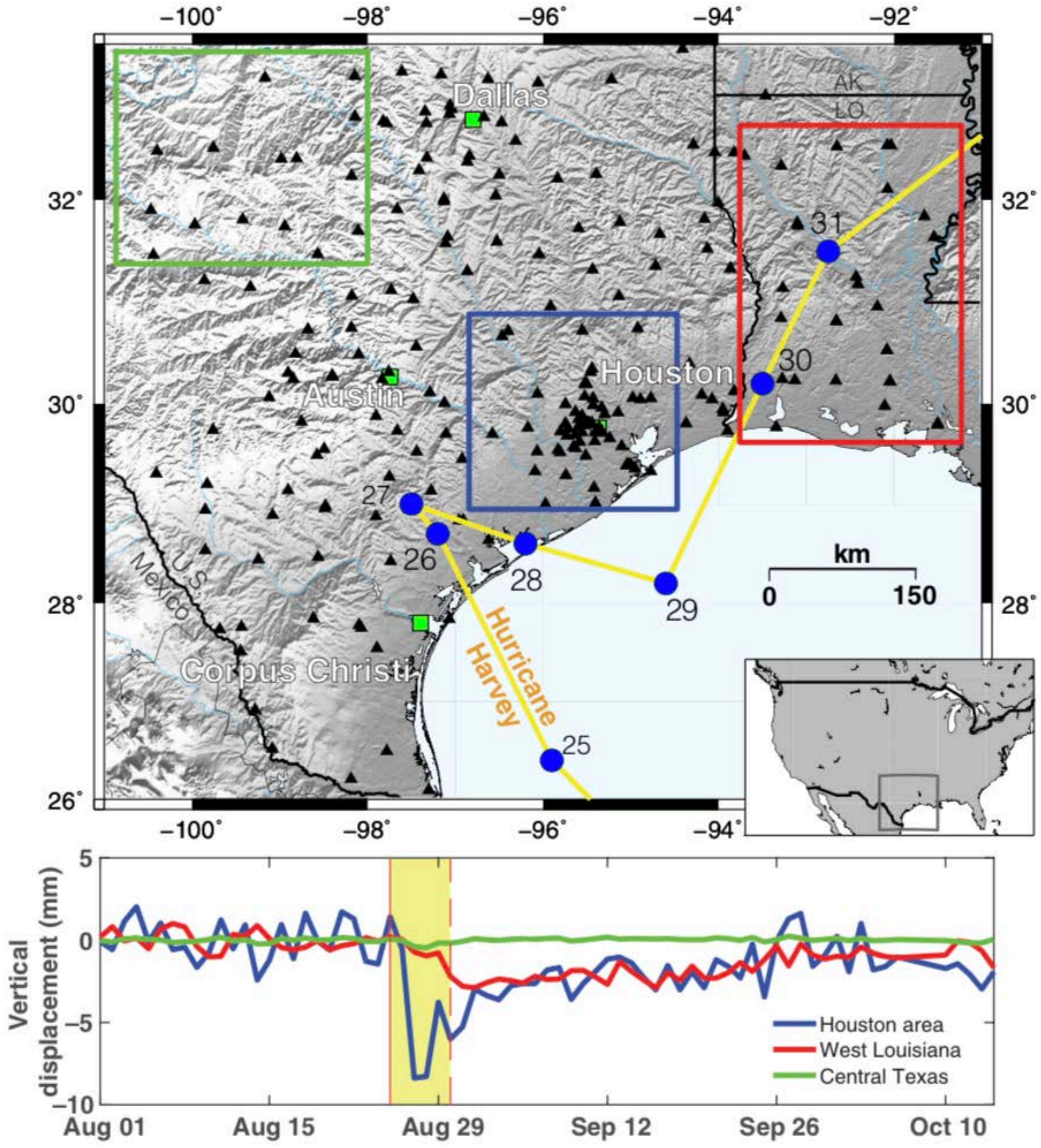
[Argus et al., 2014]

# Water cycle monitoring with satellite gravity – GRACE-FO




- Gravity-change measurements interpreted as change in the total water storage at >300 km scales subseasonally
  - Used to study drought conditions and flood potential
- Needs to be supplemented with other information from the geodetic infrastructure (SLR)
  - Geocenter motion is one of the largest sources of uncertainty
  - Low-degree harmonics estimates are essential to support continuity between space missions

# Heavy Precipitation Loading: Hurricane Harvey

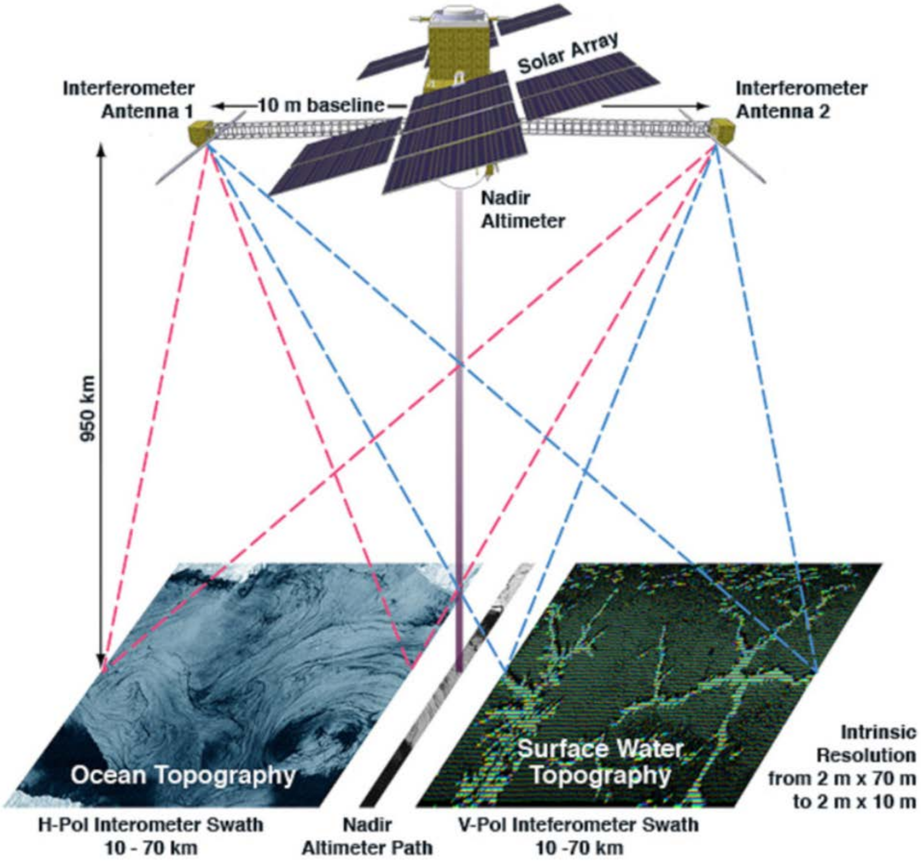


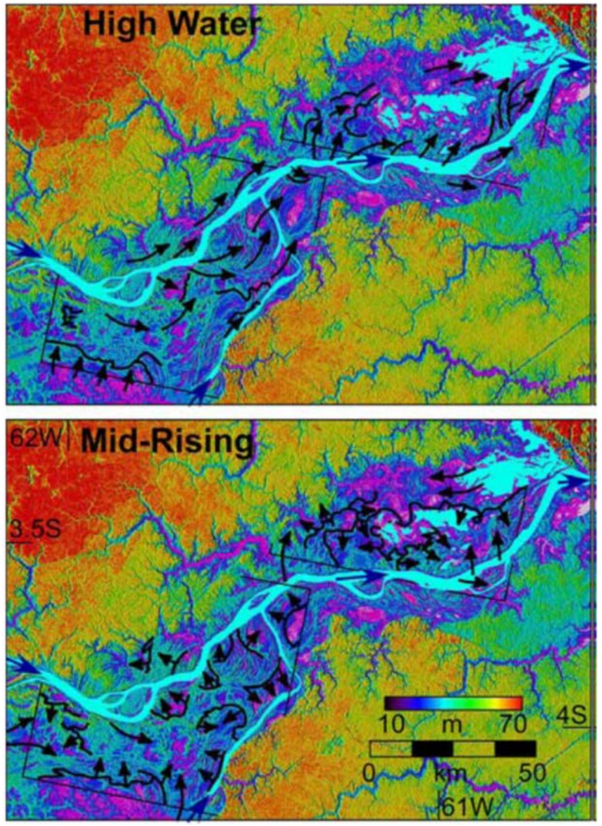

- Almost 100 km$^3$ of water deposited over several days
- Daily GNSS position analysis
  - Quantified the extent and magnitude of the 3-D elastic response to the sudden water load and of the gradual dissipation of the load
  - Further modeling distinguished whether the water was removed as runoff or through evapotranspiration

- **Demonstrates the power of continuous GNSS networks to improve flood forecasting by quantifying the spatial extent and evolution (drainage) of terrestrial water storage associated with extreme precipitation events.**

[Milliner et al., 2018]

# Surface water monitoring by satellite altimetry - SWOT

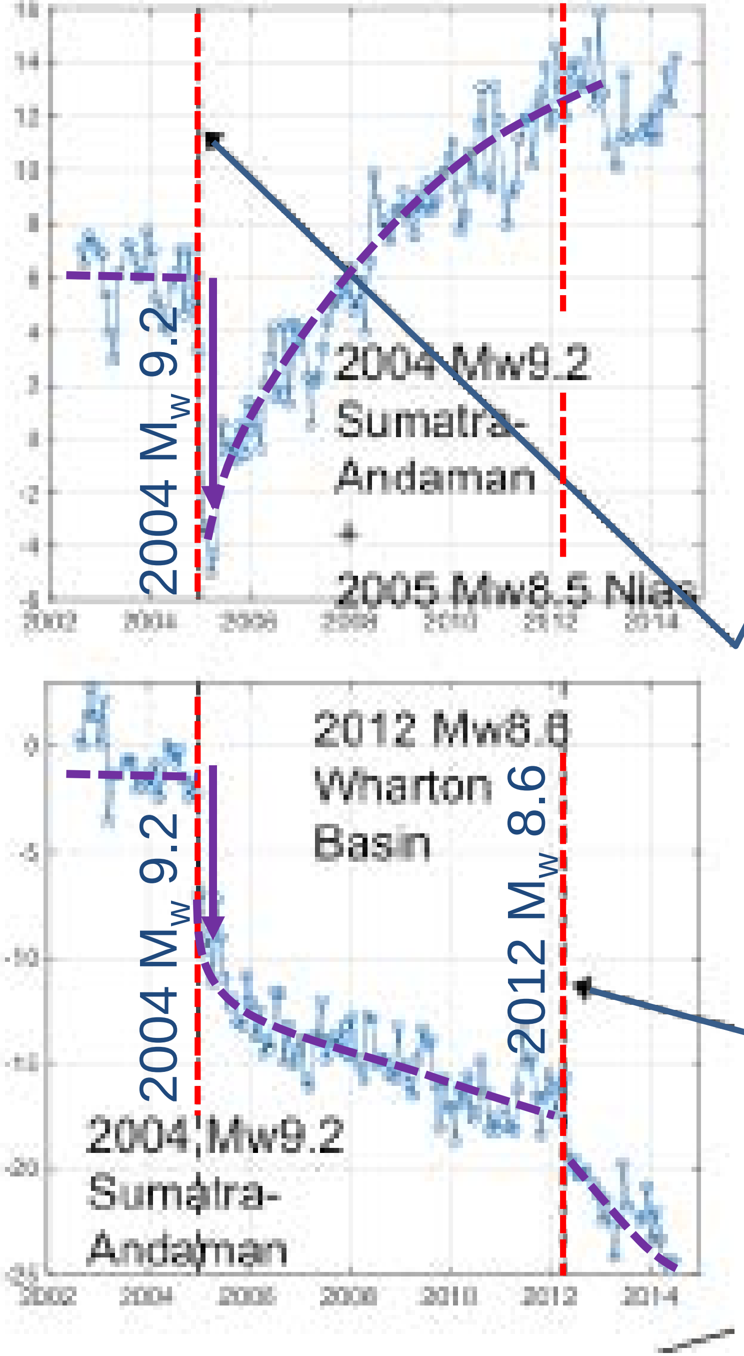


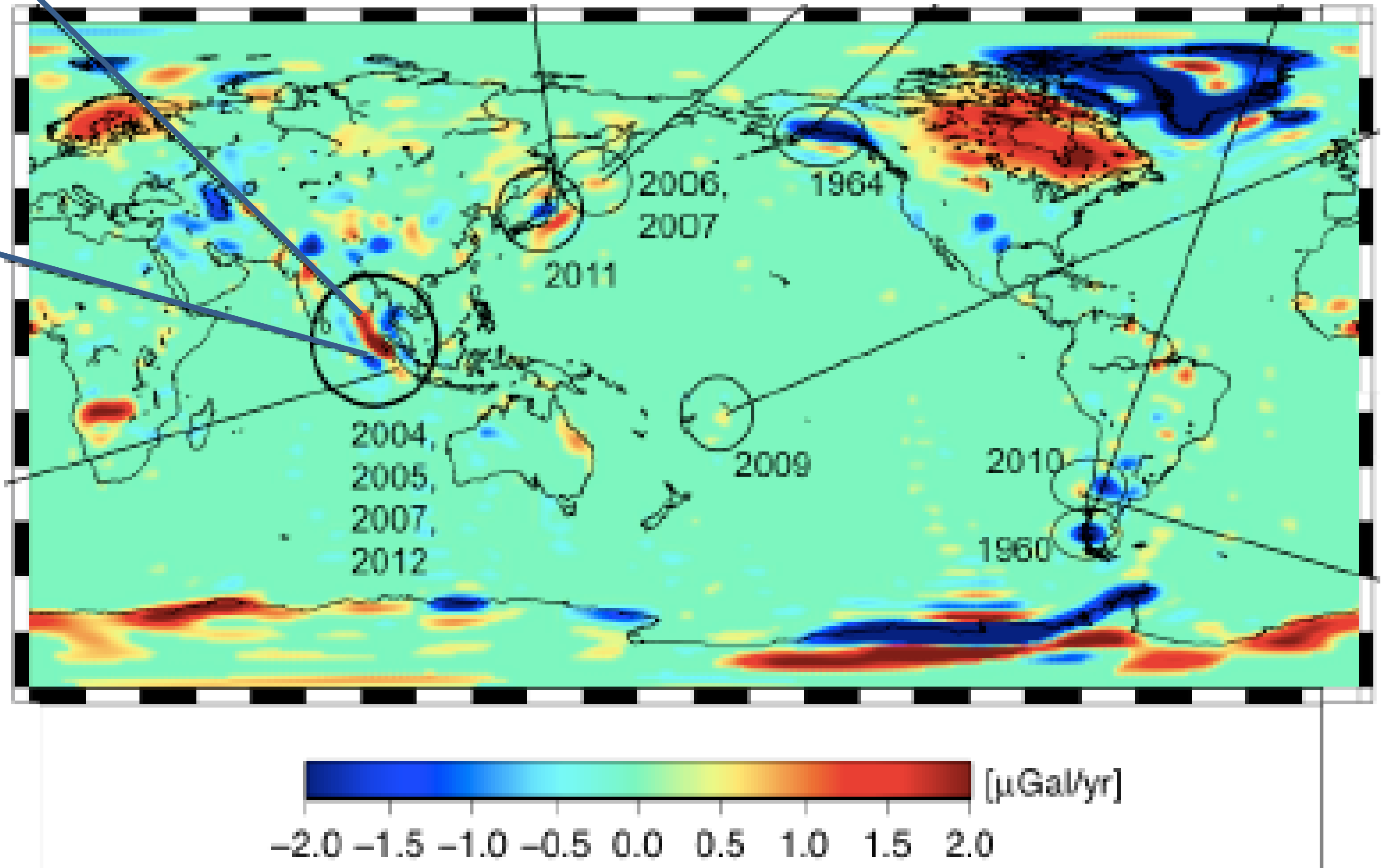




[Alsdorf et al., 2007]

- Monitor water-level changes over rivers, lakes/reservoirs, and floodplains
- Number of water gauges declining in many regions of the world; some basins ungauged
- Provides homogeneous and long-term monitoring of surface water levels and volumes (when combined with optical or radar imagery)

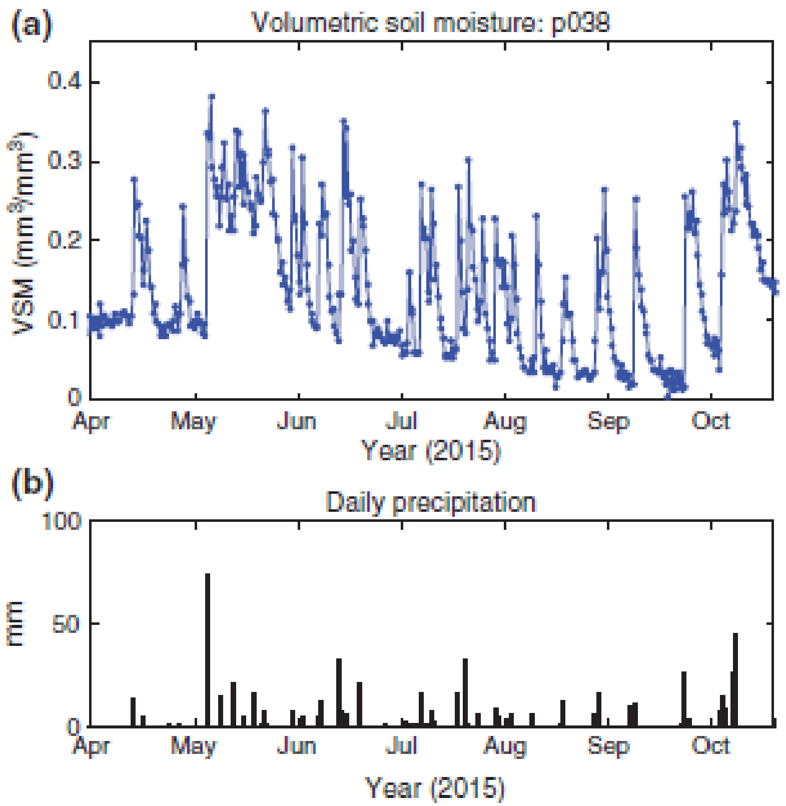
- ***Mass Changes: Compression; Dilation due to EQs***
- Two large earthquakes: 2004 & 2012
- Similar co-seismic change in 2004
- Opposite post-seismic (2004) trends
- Only Wharton Basin responds to 2012 EQ



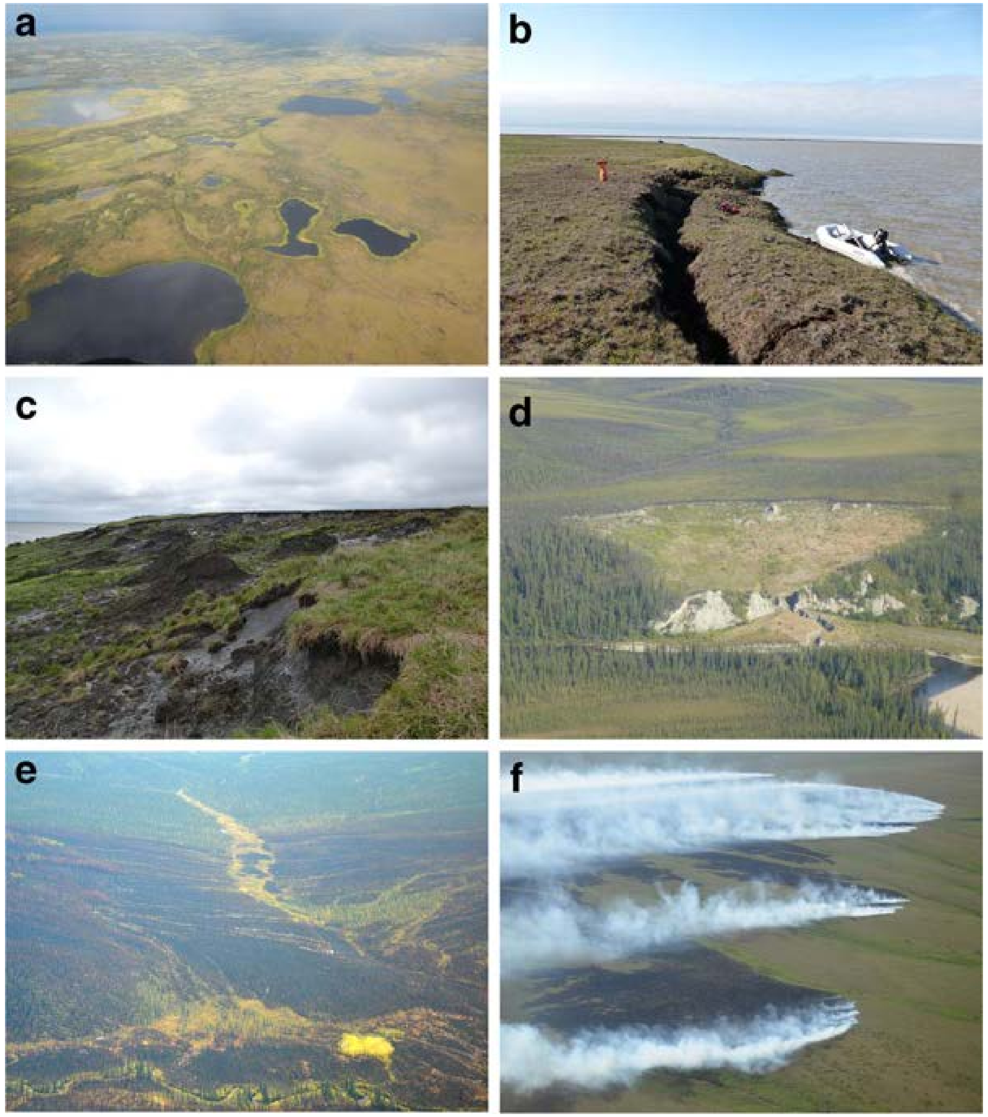

Linear trend estimates from GRACE gravity data

# Global Soil Moisture




[Larson, 2016]

# Permafrost




[Nitze et al., 2018]

**TASK 4.** Identify priority improvements to the geodetic infrastructure that would facilitate advances across the science questions identified in Task 2.

**TABLE A.1 Sea-Level Rise Reduced SATM**

| Question | Objective | Geophysical Observable | Measurement Parameters and *Geodetic Needs* |
|---|---|---|---|
| ***QUESTION C-1.*** How much will sea-level rise, globally and regionally, over the next decade and beyond, and what will be the role of ice sheets and ocean heat storage? | **C-1a.** Determine the global mean sea-level rise to within 0.5 mm/yr over the course of a decade. | Sea-surface height | Coverage: global or near global<br>Spatial: 7 km along track<br>Temporal: Every 10 days<br>Accuracy/Stability: 30 mm at 7 km, 1 mm/yr global<br><br>*Geodetic needs*<br>*POD: 10 mm RMS/0.1 mm/yr stability in height.*<br>*Altimeter drift: calibration via tide gauge network: requires 0.1 mm/yr (averaged over a decade) in TRF scale.*<br>*Wet troposphere: GNSS in complement of radiometers.* |
| | | Terrestrial reference frame | Temporal: Monthly<br>Coverage: Global every year<br>Accuracy/Stability: 1 mm, 0.1 mm/yr/decade<br><br>*Geodetic needs*<br>*Maintain core multi-technique sites over long term (20+ years) to ensure continuity over very long term (full altimeter record), improve stability of TRF to 0.1 mm/yr in origin and scale.*<br>*Monitor and quantify gravitational deformation of VLBI antennas.*<br>*Monitor and quantify SLR timing biases, range biases and center of mass offsets (e.g., T2L2).*<br>*Calibrate GNSS spacecraft antennas independent of frame.*<br>*Multi-technique POD to tie frame at the observation level.*<br>*Measurement and modeling of time-dependent earthquake-related deformation.*<br>*Explore multi-technique tropospheric parameter estimation.*<br>*To avoid degradation of TRF, consider experimenting with more frequent updates (e.g., Kalman filtering, monthly updates).*<br>*Develop inclusion of GNSS into geocenter and scale determination to provide independent uncertainty assessment.* |