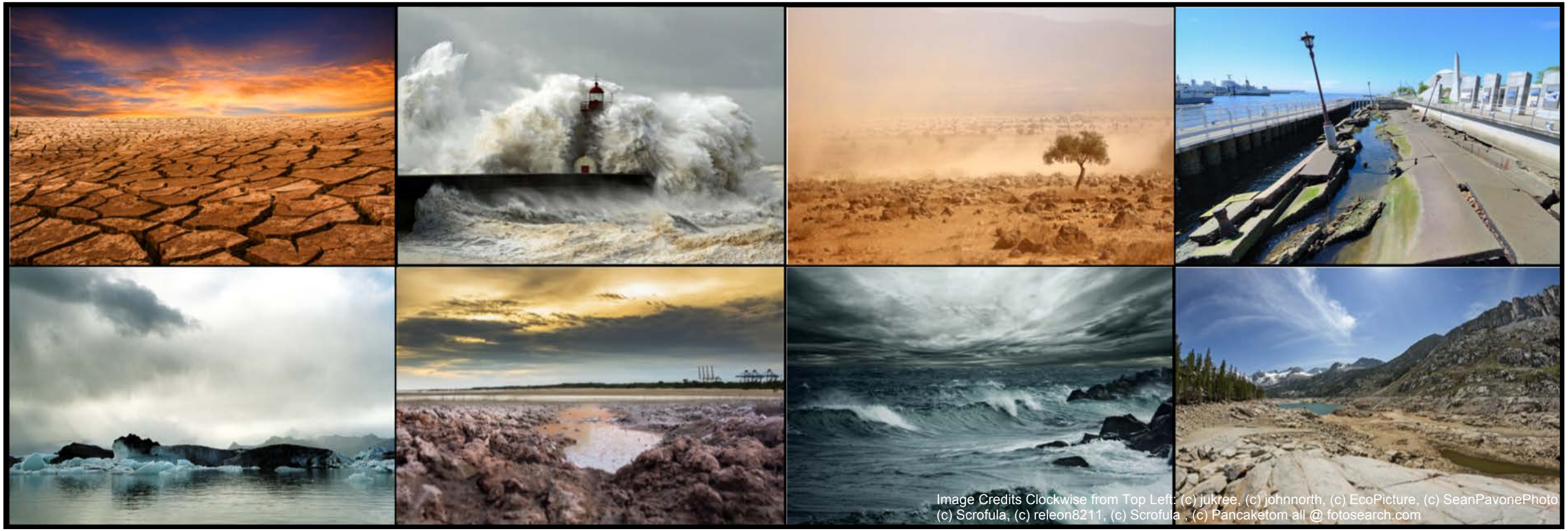


Mass Change Designated Observable Science and Applications Traceability Matrix

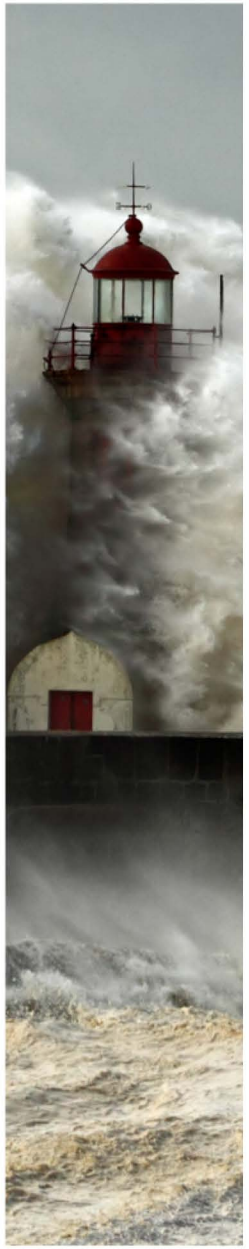
The Mass Change Study Team[1,2,3,4,5]

[1]Jet Propulsion Laboratory, California Institute of Technology
[2]NASA Ames Research Center
[3]NASA Goddard Space Flight Center
[4]NASA Headquarters
[5]NASA Langley Research Center

February 13, 2020

Overview of the SATM process

- The following slides summarize the traceability of 15 science and applications objectives listed in the Decadal Survey (DS) that can be addressed by measurements of Mass Change (MC) to suggested measurement parameters.
- Each objective is characterized with the following:
  - Importance: This is given in the DS
  - Utility: Prescribes the relative importance of MC in addressing the objective.
  - Suggested measurement parameters for Baseline and Goal scenarios. Baseline supports full science objectives, while Goal will support additional science. The measurement parameters include a targeted:
    - Spatial Resolution
    - Temporal Resolution
    - Accuracy



Decadal Survey Science and Application Objectives for Mass Change

A Diverse Set of Objectives Spanning Three Panels

Climate Variability and Change

- C-1a: Global Sea Level — H
- C-1c: Ice Sheet Mass Change — H
- C-1b: Ocean Heat — H
- C-7d: Dynamical Ocean State — L
- C-1d: Regional Sea Level — H
- C-7e: Ocean Circulation — L

Global Hydrological Cycles and Water Resources

- H-1a: Water Balance Closure — H
- H-2c: Groundwater Recharge — H
- H-3b: Water Availability & Storage — H

Earth Surface and Interior

- S-1b: Earthquakes — H
- S-4a: Landscape Changes — M
- S-3a: Glacial Isostatic Adjustment/Local Sea Level — H
- S-5a: Earth Energy Flow — VL
- H-4c: Drought Monitoring — M
- S-6b: Groundwater Flux — M

DS Prescribed Weights [Importance]

- Most Important — Highest weight
- Very Important — Medium weight
- Important — Lower Weight

Mass Change Utility

H: High
M: Medium
L: Low
VL: Very Low

→ Science Performance Targets

Suggested Measurement Parameters for Baseline

Weighting Combines Decadal Survey Importance with Mass Change Utility | Most Important Parameter Is Underlined | Units: Equivalent Water Height

Climate Variability and Change

- C C-1a: **(300 km)²**; 15 mm Monthly O
- C C-1c: **(300 km)²**; 40 mm Monthly I
- C C-1b: **(300 km)²**; 15 mm Monthly O
- C C-7d: (300 km)²; 15 mm Monthly O
- C C-1d: **(300 km)²**; 15 mm Monthly O
- C C-7e: (300 km)²; 15 mm Monthly O

Global Hydrological Cycles and Water Resources

- H-1a: (1000 km)²; **10 mm** Monthly L
- H-2c: **(450 km)²**; 25 mm Monthly L
- H-3b: **(450 km)²**; 25 mm Monthly L
- C H-4c: (450 km)²; 25 mm **Monthly** L

Earth Surface and Interior

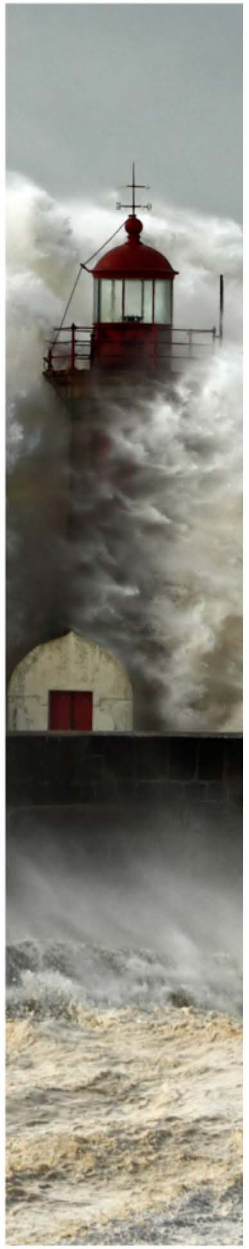
- S-1b: **(300 km)²**; 25 mm Monthly G
- S-3a: (300 km)²; **25 mm** Monthly G
- S-4a: **(300 km)²**; 25 mm Monthly G
- S-5a: (20,000 km)²; **1mm** Monthly G
- S-6b: **(450 km)²**; 25 mm Monthly L

C: Continuity explicitly recommended in Decadal Survey

Highest Weight | Medium – High Weight | Medium Weight | Medium-Low Weight | Low Weight

G: Global
O: Ocean
L: Land
I: Ice

→ Science Performance Targets



Suggested Measurement Parameters for Goal

Weighting Combines Decadal Survey Importance with Mass Change Utility | Most Important Parameter Is Underlined | Units: Equivalent Water Height

Climate Variability and Change

- C C-1a: **(100 km)²**; 15 mm Monthly O
- C C-1c: **(100 km)²**; 10 mm Monthly I
- C C-1b: **(100 km)²**; 15 mm Weekly O
- C C-7d: **(50 km)²**; 10 mm; Monthly O
- C C-1d: **(100 km)²**; 15 mm Monthly O
- C C-7e: **(50 km)²**; 10 mm; Monthly O

Global Hydrological Cycles and Water Resources

- H-1a: (3 km)²; **10 mm** Monthly L
- H-2c: **(50 km)²**; 10 mm Monthly L
- H-3b: **(200 km)²**; 25 mm Monthly L
- C H-4c: (50 km)²; 1.5 mm **Weekly** L

Earth Surface and Interior

- S-1b: **(200 km)²**; 12 mm Monthly G
- S-3a: (200 km)²; **10 mm** Monthly G
- S-4a: **(200 km)²**; 12 mm Monthly G
- S-5a: (20,000 km)²; **.01mm** Monthly G
- S-6b: **(100 km)²**; 10 mm Monthly L

C: Continuity explicitly recommended in Decadal Survey

Highest Weight | Medium – High Weight | Medium Weight | Medium-Low Weight | Low Weight

G: Global
O: Ocean
L: Land
I: Ice

→ Science Performance Targets

Performance Targets Derived from Community Interpretation: C1-a

DS Science Objective – C-1a
[**MOST IMPORTANT**]

C-1a. Determine the global mean sea level rise to within 0.5 mm yr-1 over the course of a decade

Necessary Observables

Sea surface height
Terrestrial reference frame
Ocean mass distribution

Relative Importance of MC [Utility]

High. MC provides a unique measurement of global ocean mass change

Performance Targets

Baseline
(300 km)^2; 15 mm EWH, Monthly

Goal
(100 km)^2; 15 mm EWH, Monthly

Key measurement parameter is underlined

Community interpretation and justification for performance target

Baseline: Specified in DS Appendix B

Goal: Higher spatial resolution will reduce land leakage errors which are one of the dominant sources of error in determining global ocean mass.

Performance Targets Derived from Community Interpretation: C-1b

DS Science Objective C-1b [**MOST IMPORTANT**]	Necessary Observables	Relative Importance of MC [Utility]	Performance Targets
C-1b. Determine the change in the <u>global oceanic heat uptake</u> to within 0.1 Wm-2 <u>over the course of a decade</u>	Sea surface height <u>Ocean mass distribution</u> Ocean temp and salinity profile	High. Ocean heat uptake is related to total minus mass component. Serves as independent measurement of planetary heat uptake	Baseline <u>(300 km)^2</u>; 15 mm EWH; Monthly Goal <u>(100 km)^2</u>; 15 mm EWH; Weekly

Community interpretation and justification for performance target

Key measurement parameter is <u>underlined</u>

<u>Baseline:</u> Specified in DS Appendix B

<u>Goal:</u> Higher spatial resolution will reduce land leakage errors which are one of the dominant sources of error in determining global ocean mass. Higher temporal resolution will allow for understanding the role of the ocean in the Earth's energy budget at short time scales.

(1 mm/yr corresponds to 0.75 W/m2)

Performance Targets Derived from Community Interpretation: C1-c

DS Science Objective – C-1c [**MOST IMPORTANT**]	Necessary Observables	Relative Importance of MC [Utility]	Performance Targets
C-1c. Determine the changes in <u>total ice sheet mass balance</u> to within 15 Gton/yr over the course of a decade and the changes in surface mass balance and glacier ice discharge with the same accuracy over <u>the entire ice sheets, continuously, for decades to come</u>	<u>Ice sheet mass</u> Ice sheet velocity Ice sheet elevation Ice sheet thickness, ice shelf thickness Ice sheet bed elevation, ice shelf cavity shape <u>Ice sheet surface mass balance</u>	High. Ice sheet mass change is directly measured through MC	Baseline <u>(300 km)^2</u>; 40 mm; Monthly Goal <u>(100 km)^2</u>; 10 mm; Monthly

Community interpretation and justification for performance target

<u>Baseline:</u> Consistency with program of record

<u>Goal</u>: Specified in DS Appendix B. Higher spatial resolution to resolve glacier outlets for separation of drainage basins

Key measurement parameter is <u>underlined</u>

Pail et al, 2015, Bonin and Chambers, 2015

Performance Targets Derived from Community Interpretation: C-1d

DS Science Objective C-1d
[**VERY IMPORTANT**]

C-1d. Determine regional sea level change to within 1.5- 2.5 mm/yr over the course of a decade (1.5 corresponds to a ~(6000 km)^2 region, 2.5 corresponds to a ~(4000 km)^2 region)

Necessary Observables

Sea surface height
Vertical land motion
Ocean mass distribution
Wind vector

Relative Importance of MC [Utility]

High. MC provides a unique measurement of ocean mass change

Performance Targets

Baseline
(300 km)^2; 15 mm; Monthly

Goal
(100 km)^2; 15 mm; Monthly

Key measurement parameter is underlined

Community interpretation and justification for performance target

Baseline: Specified in DS Appendix B

Goal: Higher spatial resolution will reduce land leakage errors which are one of the dominant sources of error in determining regional ocean mass.

Importance of obtaining sea level fingerprints (enabled by satellite gravimetry observations) in addition to directly observing regional ocean mass changes is noted. These performance targets will additionally enable the resolution of sea level fingerprints.

Performance Targets Derived from Community Interpretation: C-7d

DS Science Objective C-7d [IMPORTANT]	Necessary Observables	Relative Importance of MC [Utility]	Performance Targets
C-7d. Quantify the linkage between the dynamical and thermodynamic state of the ocean upon atmospheric weather patterns on decadal timescales. Reduce the uncertainty by a factor of 2 (relative to decadal prediction uncertainty in IPCC 2013). Confidence level: 67% (likely).	Ocean velocity, temperature, salinity, wind stress Ocean bottom pressure	Low. Mass change is a secondary observable for this objective.	Baseline (300 km)^2; 15 mm; Monthly Goal (50 km)^2; 10 mm; Monthly

Key measurement parameter is underlined

Community interpretation and justification for performance target

Baseline: Consistency with the current Program of Record

Goal: Specified in the Decadal Survey (Appendix B). Higher spatial resolution will allow for resolution of major oceanic fronts.

Performance Targets Derived from Community Interpretation: C-7e

DS Science Objective C-7e [IMPORTANT]	Necessary Observables	Relative Importance of MC [Utility]	Performance Targets
C-7e. Observational verification of models used for climate projections. Are the models simulating the observed evolution of the large scale patterns in the atmosphere and ocean circulation, such as the frequency and magnitude of ENSO events, strength of AMOC, and the poleward expansion of the sub-tropical jet (to a 67% level correspondence with the observational data)?	Ocean velocity, temperature, salinity, wind stress Ocean bottom pressure	Low. Mass change is a secondary observable for this objective.	Baseline (300 km)^2; 15 mm; Monthly Goal (50 km)^2; 10 mm; Monthly

Community interpretation and justification for performance target

Baseline: Consistency with the current Program of Record

Goal: Specified in the Decadal Survey (Appendix B). Higher spatial resolution will allow for resolution of major oceanic fronts.

Key measurement parameter is underlined

Performance Targets Derived from Community Interpretation: H-1a

DS Science Objective H-1a
[**MOST IMPORTANT**]

H-1a. Develop and evaluate an integrated Earth System analysis with sufficient observational input to accurately quantify the components of the water and energy cycles and their interactions, and to close the water balance from headwater catchments to continental-scale river basins.

Necessary Observables

Precipitation
Evapotranspiration
Runoff
Terrestrial Water Storage Mass Change.

Relative Importance of MC [Utility]

High. dTWS is essential to closing the water budget and only a mass change measurement can provide it.

Performance Targets

Baseline
(1,000 km)^2; 10 mm; Monthly

Goal
(3 km)^2; 10 mm; Monthly

Key measurement parameter is underlined

Community interpretation and justification for performance target

Baseline: Consistency with the current program of record, allowing water budget closure at continental, monthly and annual scales with less than 10% (of precipitation) total uncertainty.

Goal: Improved spatial resolution enabling water budget closure at the scale of headwater catchments.

Performance Targets Derived from Community Interpretation: H-2c

DS Science Objective H-2c [**MOST IMPORTANT**]	Necessary Observables	Relative Importance of MC [Utility]	Performance Targets
H-2c. Quantify how changes in land use, land cover, and water use related to agricultural activities, food production, and forest management affect water quality and especially <u>groundwater recharge</u>, threatening sustainability of future water supplies.	Terrestrial water storage change and either (1) simplifying assumptions; or (2) precipitation, solar radiation, soil moisture, land cover and irrigation information, and a hydrological model.	High. dTWS can be used to infer dGW (with auxiliary info or assumptions). GW discharge is also needed to compute GW recharge as a residual.	Baseline <u>(450 km)^2</u>; 25 mm; Monthly Goal <u>(50 km)^2</u>; 10 mm; Monthly

Key measurement parameter is <u>underlined</u>

Community interpretation and justification for performance target

<u>Baseline:</u> Consistency with the current program of record, which has supported estimates of dGW at regional scales.

<u>Goal:</u> From Decadal Survey Table 6.3: "Groundwater storage, at basin scale (50 km or better)".

Performance Targets Derived from Community Interpretation: H-3b

DS Science Objective H-3b [IMPORTANT]

H-3b. Monitor and understand the coupled natural and anthropogenic processes that change water quality, fluxes, and storages in and between all reservoirs (atmosphere, rivers, lakes, groundwater, and glaciers), and response to extreme events.

Necessary Observables

Numerous terrestrial water cycle observations including terrestrial water storage change (MC).

Relative Importance of MC [Utility]

High: Monitoring and understanding dTWS provides clues to the natural and anthropogenic processes that control water storage changes and fluxes.

Performance Targets

Baseline
(450 km)^2; 25 mm; Monthly

Goal
(200 km)^2; 25 mm; Monthly

Key measurement parameter is underlined

Community interpretation and justification for performance target

Baseline: Consistency with the current program of record, which has supported estimates of dTWS at regional scales.

Goal: Improved spatial resolution would allow for quantification of dTWS at scales that better support process understanding.

Performance Targets Derived from Community Interpretation: H-4c

DS Science Objective H-4c
[IMPORTANT]

H-4c. Improve drought monitoring to forecast short-term impacts more accurately and to assess potential mitigations.

Necessary Observables

Precipitation (GPM, A-CCP), soil moisture (SMAP, SMOS), water storage change (MC), surface waters (SWOT), vegetation health and evapotranspiration (imagers).

Relative Importance of MC [Utility]

Medium: Terrestrial water storage anomalies are useful indicators of drought, particularly when downscaled and temporally extrapolated via data assimilation.

Performance Targets

Baseline
$(450\ km)^2$; 25 mm;
Monthly

Goal
$(50\ km)^2$; 1.5 mm;
Weekly

Key measurement parameter is underlined

Community interpretation and justification for performance target

Baseline: Consistency with the current program of record, which has supported quasi-operational groundwater and soil moisture drought monitoring with the aid of data assimilation.

Goal: Enables drought monitoring at the spatial and temporal scales that water managers need without data assimilation; see Decadal Survey Table 6.4.

Performance Targets Derived from Community Interpretation: S1-b

DS Science Objective – S-1b
[**MOST IMPORTANT**]

S-1b. Measure and forecast interseismic, preseismic, coseismic, and postseismic activity over tectonically active areas on time scales ranging from hours to decades.

Necessary Geophysical Observables	Relative Importance of **MC** [Utility]	Performance Targets
Land-surface deformation Large scale gravity change Reference frame Topography Land-cover change	High. MC provides a unique measurement for constraining long-wavelength post-seismic processes	Baseline (300 km)^2; 1 μGal or 25 mm EWH, Monthly Goal (200 km)^2; 0.5 μGal or 12 mm EWH, Monthly

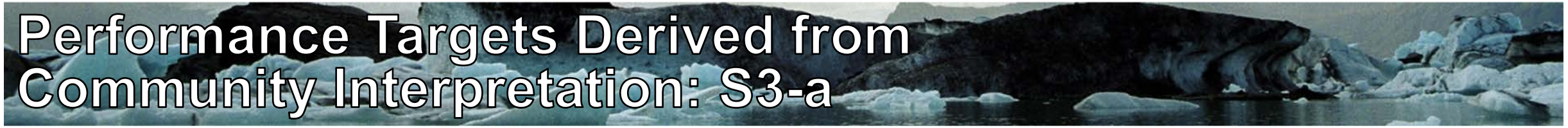
Key measurement parameter is underlined

Community interpretation and justification for performance target

Baseline: Consistency with the current Program of Record is needed for decadal-scale post-seismic and other seismic cycle processes

Goal: Improved spatial resolution and accuracy will enable better resolution of key seismic cycle processes and detection of M<8.1 events

Performance Targets Derived from Community Interpretation: S3-a



DS Science Objective S-3a
[**MOST IMPORTANT**]

S-3a. Quantify the rates of sea-level change and its driving processes at global, regional, and local scales, with uncertainty < 0.1 mm yr-1 for global mean sea-level equivalent and <0.5 mm yr-1 sea-level equivalent at resolution of 10 km.

Necessary Geophysical Observables

Surface melt
Ice topography
Snow density
<u>Gravity</u>
3-D Surface deformation on ice
Sea-surface height
Terrestrial reference frame
In situ temperature/salinity
Ice velocity
High-resolution topography

Relative Importance of MC [Utility]

High. MC is an essential component of global GIA estimates

Performance Targets

Baseline
(300 km)^2; <u>25 mm EWH</u>; Monthly

Goal
(200 km)^2; <u>10 mm EWH</u>; Monthly

Community interpretation and justification for performance target

<u>Baseline:</u> Consistency with the current Program of Record is needed to estimate GIA and to separate GIA from other signals

<u>Goal:</u> Specified in the Decadal Survey (Appendix B)

Key measurement parameter is <u>underlined</u>

Importance of obtaining sea level fingerprints (enabled by satellite gravimetry observations) to address this objective is noted. These performance targets will additionally enable the resolution of sea level fingerprints.

Performance Targets Derived from Community Interpretation: S-4a

DS Science Objective – S-4a
[**MOST IMPORTANT**]

S-4a. Quantify global, decadal landscape change produced by abrupt events and by continuous reshaping of Earth's surface due to surface processes, tectonics, and societal activity.

Necessary Geophysical Observables

Bare-earth topography
Land-surface deformation

Changes in optical surface characteristics

Mass change
Rain and snow fall rates
Reflectance for freeze/thaw

Relative Importance of MC [Utility]

Medium. Mass movement as discussed in other elements (earthquake related mass movement, ice mass change, and hydrological flux)

Performance Targets

Baseline
(300 km)^2; 1 uGal or 25 mm; Monthly

Goal
(200 km)^2; 0.5 uGal or 12 mm; Monthly

Key measurement parameter is underlined

Community interpretation and justification for performance target

Baseline: Consistency with the current Program of Record is needed for abrupt to decadal-scale seismic and other processes

Goal: Improved spatial resolution and accuracy will enable better resolution of key processes and detection of M<8.1 events

Performance Targets Derived from Community Interpretation: S-5a

DS Science Objective S-5a
[**VERY IMPORTANT**]

S-5a. Determine the effects of convection within the Earth's interior, specifically the dynamics of the Earth's core and its changing magnetic field and the interaction between mantle convection and plate motions. For MC: Determine exchange of angular momentum between core and mantle from Earth rotation parameters. Measure mean pole coordinates to within 50 μas

Necessary Geophysical Observables	Relative Importance of MC [Utility]	Performance Targets
Earth Orientation Parameters Mass Change Reference frame; Center of Mass	Very Low. VLBI is the primary necessary observable. SLR is a secondary necessary observable.	Baseline (C_{21}/S_{21}): $(20{,}000\ km)^2$; Monthly 2E-11 = 1 mm EWH Goal (C_{21}/S_{21}): $(20{,}000km)^2$; monthly 2E-13 = .01 mm EWH

Key measurement parameter is underlined

Community interpretation and justification for performance target

Baseline: Consistency with the current Program of Record. This is defined as the agreement between C21/S21 derived from SLR and satellite gravimetry

Goal: Improved accuracy of 2E-13 will allow for the determination of the angular offset between the Earth's figure axis and the mean mantle rotation axis to within 50 μas (*Wahr*, 1987)

Performance Targets Derived from Community Interpretation: S-6b

DS Science Objective S-6b [IMPORTANT]	Necessary Geophysical Observables	Relative Importance of MC [Utility]	Performance Targets
S-6b. Measure all significant fluxes in and out of the groundwater system across the recharge area (see also See also H-2c, recharge rates)	Soil moisture, Snow WE, rainfall Gravity Topography Deformation from fluid fluxes* Land-surface deformation	Medium. MC provides global, long-wavelength gravity change	Baseline $(450\ km)^2$; 25 mm; Monthly Goal $(100\ km)^2$; 10 mm; Monthly

Community interpretation and justification for performance target

Baseline: Consistency with the current Program of Record

Goal: Specified in the Decadal Survey (Appendix B)

Key measurement parameter is underlined