Ocean Bottom Pressure

Preamble / Introduction

Ocean bottom pressure (OBP) is the total pressure resulting from the weight or mass of the column of seawater and the overlaying atmosphere. Indeed, both fluctuations in the atmospheric sea level pressure, in the dynamic topography, and fluctuations in the mass of the fluid column between the unperturbed surface and bottom contribute to the observed OBP variability. Therefore, the OBP variability is tightly connected with sea surface height variability, which is also directly affected by atmospheric loading and the hydrological cycle. OBP serves as a proxy of ocean mass variability - a key parameter needed in many geophysical applications such as large-scale ocean circulation or variability in the Earth's gravity field. Overall, observations of OBP significantly contribute to understanding the characteristics, dynamics, and temporal variability of many important oceanographic and geophysical phenomena. While OBP is highly valuable as a stand-alone parameter, synergisms abound when OBP observations are combined with measurements of other variables. Despite the importance of OBP, it is severely under-sampled globally and regionally because it cannot be directly measured remotely. Presently, OBP can only be inferred from GRACE data. Sensors on the seafloor are required to remain in place for years to measure the scales required for most applications.

In combination with relative or absolute sea-level (SL) observations, such as from satellite altimetry, OBP observations reveal the key mass component of long-time-scale SL changes. That is, thermal expansion, deducible from changes in water temperatures, does not change the mass of the water column, and so is not observed in OBP. However, glacier and ice cap melting does increase the mass of the oceans, in a complex pattern across the globe, and so is observed in OBP. Distributed OBP observations, with proper consideration of sensor drift as well as vertical land movement like all relative SL observations, will enable the definition of how water column mass varies geographically, helping test climate change model predictions. OBP observations are becoming more valuable now as opposed to 10 years ago because methods are being tested to self-calibrate OBP sensors, which promises to eliminate the problem of long-term drift that has hampered their use for studying interannual and longer time scale variability.

Defining the geographical structure of mass changes in the oceans is also an objective of the GRACE satellite mission (Gravity Recovery and Climate Experiment). However, GRACE provides only a coarse horizontal resolution of bottom pressure and is only valid far from continental boundaries. GRACE is sensitive to scales of variability longer than at least a few hundred kilometers. Its orbit leads to time-space scale aliasing issues and trade-offs between temporal and spatial resolution. Distributed OBP sensors will provide observations with high resolution in time, unlike GRACE, and can provide better horizontal resolution where desired, such as under the strongest elements of the ocean circulation system (e.g. DONET array).

In fact, due to the dominant balance of forces between the horizontal gradients of pressure and the velocity structure of currents at periods longer than a day, accurate OBP observations can provide estimates of both basin-wide modes of transport between OBP sensors located on opposing continental slopes and local bottom current amplitudes related to local energetic circulation features when deployed in proximity. All of these observations are needed to improve the accuracy of numerical models of global ocean circulation. Deriving transports from pressure gradients is such a fundamentally important issue that it was one of the principal arguments for the construction and launch of GRACE. The value of distributed OBP observations is very similar to and greatly complements, the value of the GRACE missions. OBP improves the calibration and validation of the GRACE Follow-On and subsequent remote sensing missions.

A distinct advantage of OBP sensors will be their ability to resolve well in time and in space, through regional arrays, the variability of large-scale circulation on time scales of days, weeks, and months, especially at latitudes poleward of ~40^{o} where surface and deep flows are most tightly linked. At periods less than a day, OBP is sensitive to even the weakest gravitational tides, internal tides and other internal waves, tsunamis and other infragravity waves, and storm surges. Observing tsunamis is a critical task for GOOS. The determination of very accurate tidal constants, including secular changes, is possible due to low geophysical "noise" at the seafloor, and is essential to de-aliasing and correcting other measurements, especially those from satellites or SL sensors, and provides essential context for studies of the structure of Earth's crust.

Using OBP observations to study oceanic phenomena goes hand in hand with studying the vertical deformation of the seafloor. Rates of uplift of subsea volcanos can be many tens of cm per year; coseismic tectonic deformation at subduction zones can lead to sudden vertical seafloor movements up to meters, and interseismic rebound can account for vertical movements at rates of several cm/yr for years after the seismic event.

Resolving OBP with corrections for the oceanographic effects and sea level change can provide important information on the changing shape of the seafloor and tectonic processes associated with great megathrust earthquakes that cause large tsunamis and significant hazards. At the same time, any interpretation of OBP data as evidence for sea level change must include knowledge of the tectonic activity at the site of the pressure observation (or vice-versa) as the tectonic uplift and subsidence rates can be similar to the rate of sea level change.

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Variable Information	
Name of EOV	Ocean Bottom Pressure (OBP)
Sub-Variables[1]	in-sensor bottom pressure - the raw pressure measurement (e.g., in units of volts or frequency) in-sensor temperature - the internal temperature measurement that is essential in obtaining a useful pressure in-sensor bottom pressure and temperature are combined using calibration equations to produce OBP
Derived Variables[2]	Water column mass; basin-wide integrated mass transports as a function of depth; arrays of local absolute velocity profiles; very high accuracy sea level tidal constituents; real-time tsunami amplitudes and travel times for tsunami forecasts; infragravity waves for de-aliasing satellite measurements and as proxies for swell wave trends; torques on the solid earth.
Supporting Variables[3]	SSH; seawater density profiles (temperature and salinity); air pressure; vertical land movement; gravity; geopotential
Contact/Lead Expert(s)[4]	Platforms Deep-ocean Assessment and Reporting of Tsunamis (DART) Ocean Observatories Initiative (OOI) Regional Cabled Network (RCN) Ocean Networks Canada (ONC) Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET) Aloha Cabled Observatory (ACO) Moorings (e.g., see OceanSITES) Joint Task Force (JTF) of the ITU, the WMO, and UNESCO/IOC; Science Monitoring And Reliable Telecommunications (SMART) cables GRACE Follow-On Mission Products DOOS OBP Task Team

[1] 'Sub-variables' are variables observed or known from instrumentation or metadata and used to calculate the desired EOV or ECV.
[2] 'Derived Variables' are variables derived from the EOV or ECV
[3] Supporting variables are those which are needed to deliver the EOV or ECV
[4] Contact experts should include experts or teams for platforms and for products

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Requirements Settings*					
Responsible GCOS/GOOS Panel	OOPC				
Reporting Mechanism	GCOS Implementation Plan/Status Reporting to UNFCCC				
Readiness Level [5]	Mature Level 8. [Several basin-scale and regional telemetering networks fully operational, e.g., DART; OOI RCN; ONC; DONET; ACO.]				
Phenomena to Capture	Sea Level	Circulation	Fronts and Eddies	Tides	Infragravity Waves and Tsunamis
Temporal Scales of the Phenomena (order)	Week to decade	Week to decade	Day to month	Hour to week	Minute to hour
Horizontal Scales of the Phenomena (order)	10 km to 10,000 km	10 km to 10,000 km	1 km to 100 km	10 km to 10,000 km	1 km to 1,000 km
Magnitudes of the Signals of the Phenomena (order)	0.01 dbar to 1.0 dbar	0.01 dbar to 1.0 dbar	0.01 dbar to 1.0 dbar	0.001 dbar to 1.0 dbar	0.001 dbar to 1.0 dbar

[5] See FOO readiness table on last page
*Table is relevant for in-situ technologies that measure OBP.

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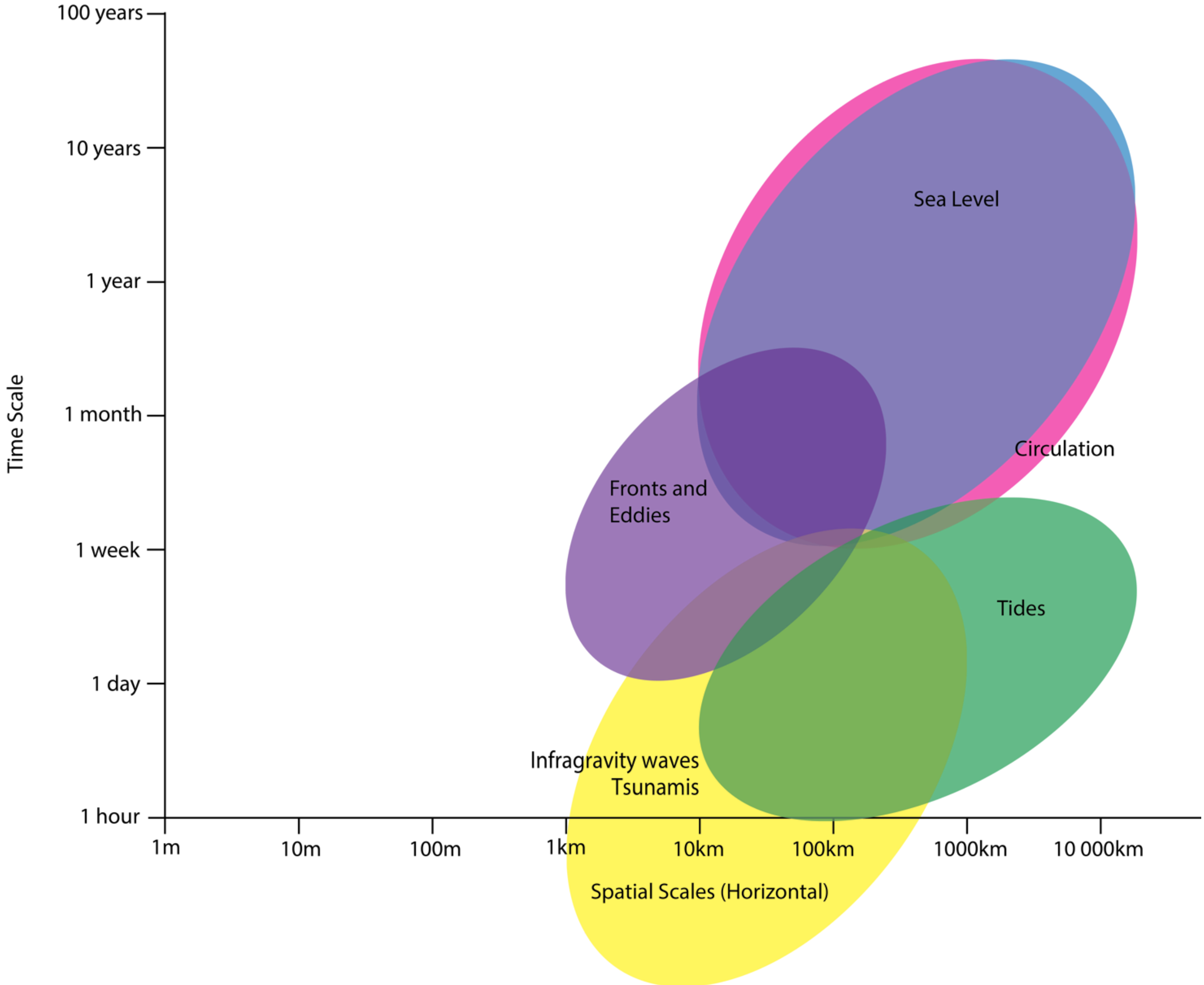

Figure 1: Temporal and spatial scales of phenomena to be addressed by current observing capacity

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Observation Deployment & Maintenance				
Observing Elements[6]	**DART Stations**	**DONET, OOI RCN, ONC, ACO**	**Moorings (OceanSITES, DBCP)**	**GRACE**
Relevant measured parameter	Pressure	Pressure	Pressure	Gravity perturbations
Measurement Type	in-situ	in-situ	in-situ	remote
Sensor(s)/Technique	SBE 54 Tsunami Pressure Sensor	SBE 54 and Paroscientific Nano-resolution Digiquartz Pressure Transducer	Paroscientific Digiquartz Pressure Transducer, e.g., incorporated in PIES instrument./	Inversion of relative positions and speeds of paired satellites.
Phenomena addressed	Infragravity waves Tsunamis Tides Sea level	Infragravity waves Tsunamis Tides Eddies Sea level	Tides Fronts and eddies Circulation Sea Level	Circulation Sea Level
Readiness Level	Mature Level 8	Mature Level 8	Mature Level 8	Mature Level 9
Spatial sampling	Specific locations; 100's of km spacing and up	Specific locations; 1 km to 100's of km spacing	Point samples; fixed locations at tens of km spacing and up	100's of km
Temporal sampling	15 s to 15 min	1 Hz	Better than 1 Hz to several samples per hour	Monthly gridded maps
Special Characteristics/ Contributions	Real-time at 15 min; delayed at 15 sec	Sparse regional networks; real-time	Sparse global network; delayed data availability.	Global coverage; 1-2 month delayed delivery
Requirements or Random Uncertainty estimate (units, one standard dev).	< 0.005 dbar over an hour	< 0.005 dbar over an hour	< 0.005 dbar over an hour	Variable and uncertain

Note that there is currently no central data archive in the observational datasets list in the above table. However, within the regional activities listed the data formats and procedures are coordinated. The following shows the spatial distribution of current OBP sensors.

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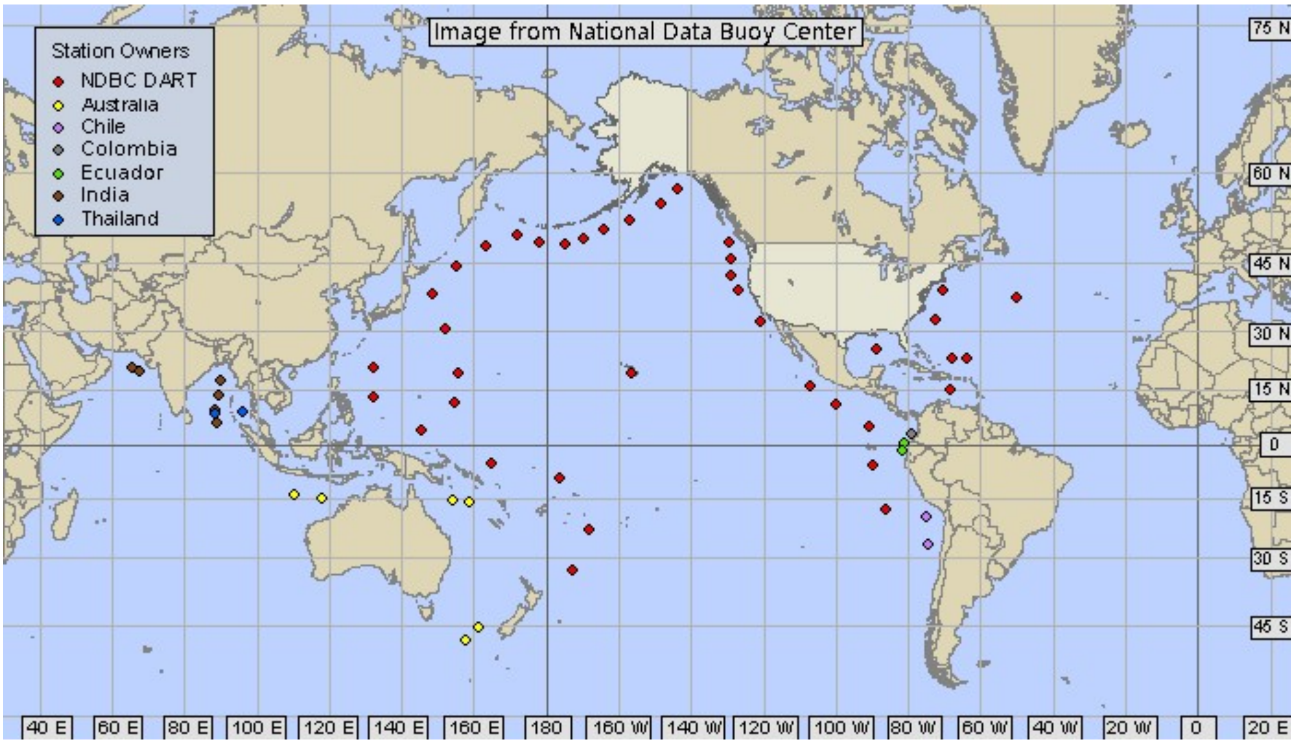
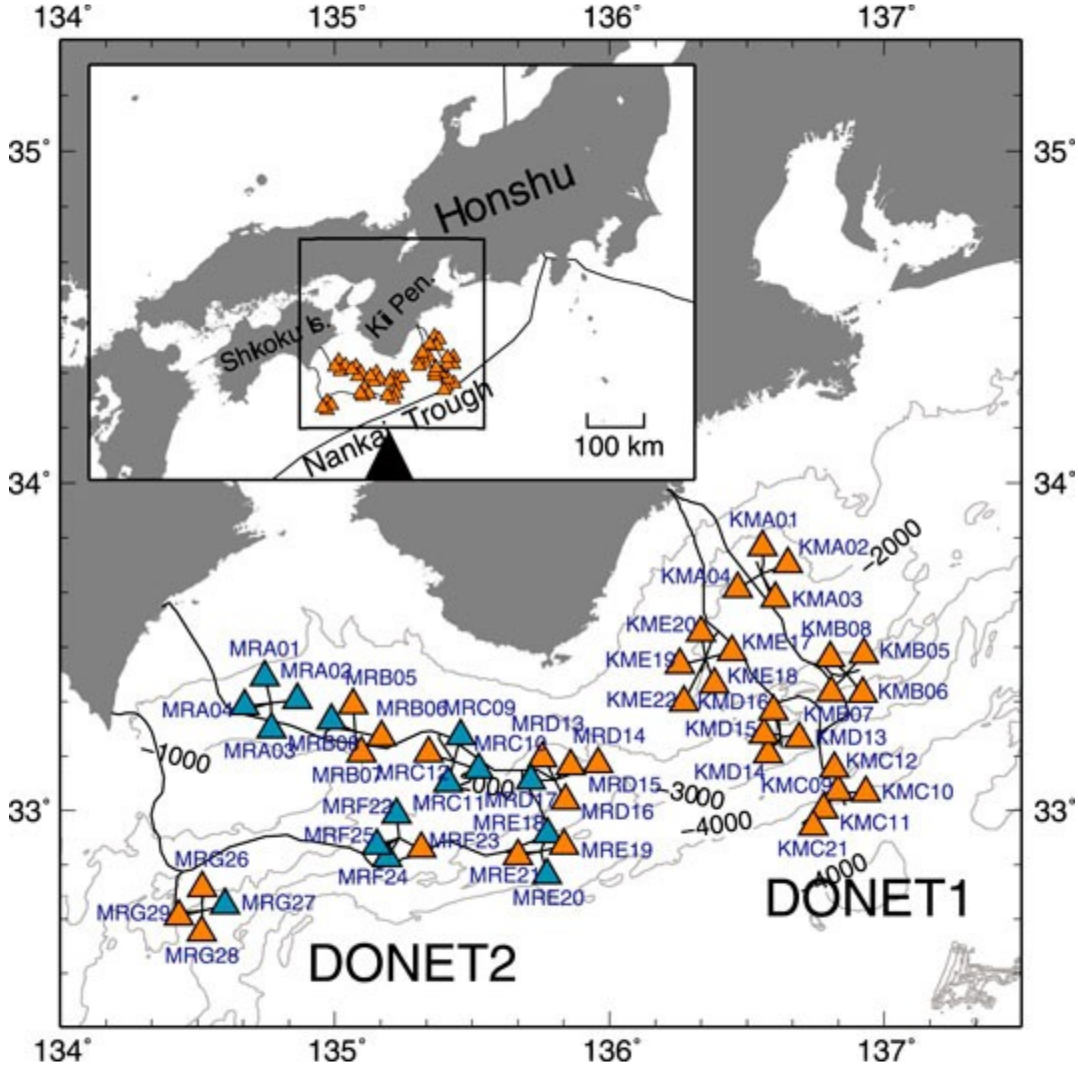
[6] If applicable, in a separate paragraph please describe how the networks interact with each other. For example, one network might be very sparse but it provides the most accurate data which are used to improve the calibration in other networks.

DART:



Credit from NDBC: https://www.weather.gov/jetstream/dart_max

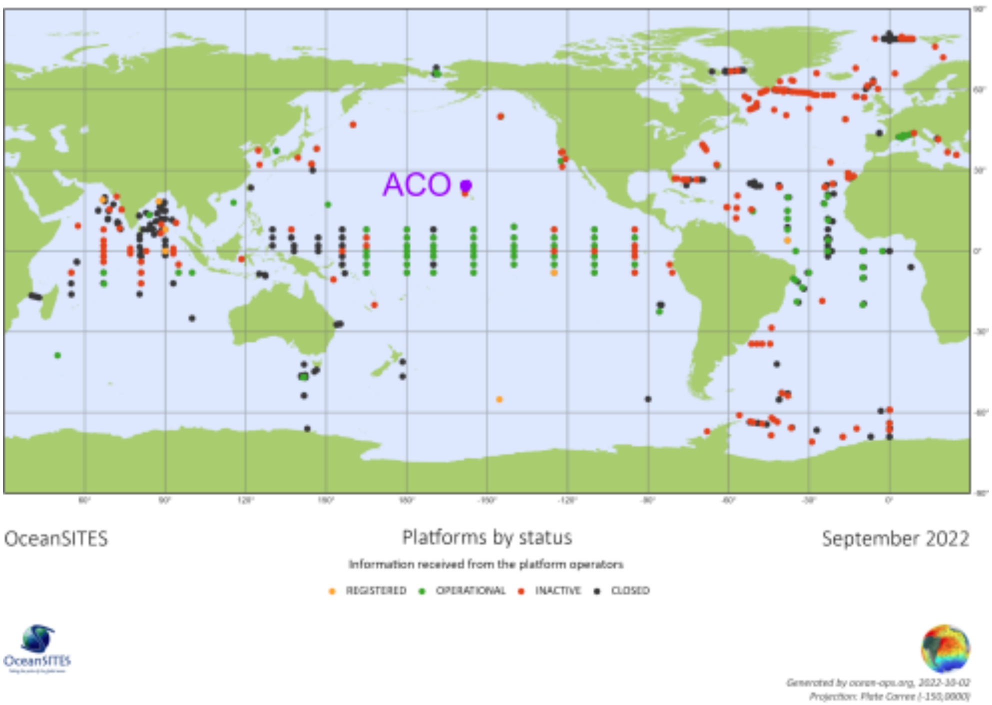
DONET:



Adapted from Matsumoto and Araki, (2021) Drift Characteristics of DONET Pressure Sensors Determined From *In-Situ* and Experimental Measurements, Frontiers in Earth Science, doi:10.3389/feart.2020.600966

OOI assets: the ONC assets are co-located with the regional cabled observatory in the Northeast Pacific near the Endurance array.

OCEANSITES/DBCP, ACO is located 100 km North of Hawaiʻi.



Future Observing Elements	
Observing Elements	Pressure sensors on telecommunications cables (SMART)
Phenomena addressed	Infragravity waves Tsunamis Tides Eddies Circulation Sea level
Readiness Level[1]	Level 2
Spatial sampling	50 km along cable
Temporal sampling	1 Hz and better
Special Characteristics or Contribution	Coincident with temperature sensor and 3-axis accelerometer
Estimated time when part of the observing system	2025
Relevant measured parameter(s)	Pressure
Sensor(s)/Technique	Pressure sensor
Random Uncertainty estimate (units, 1 standard deviation).	< 0.005 dbar

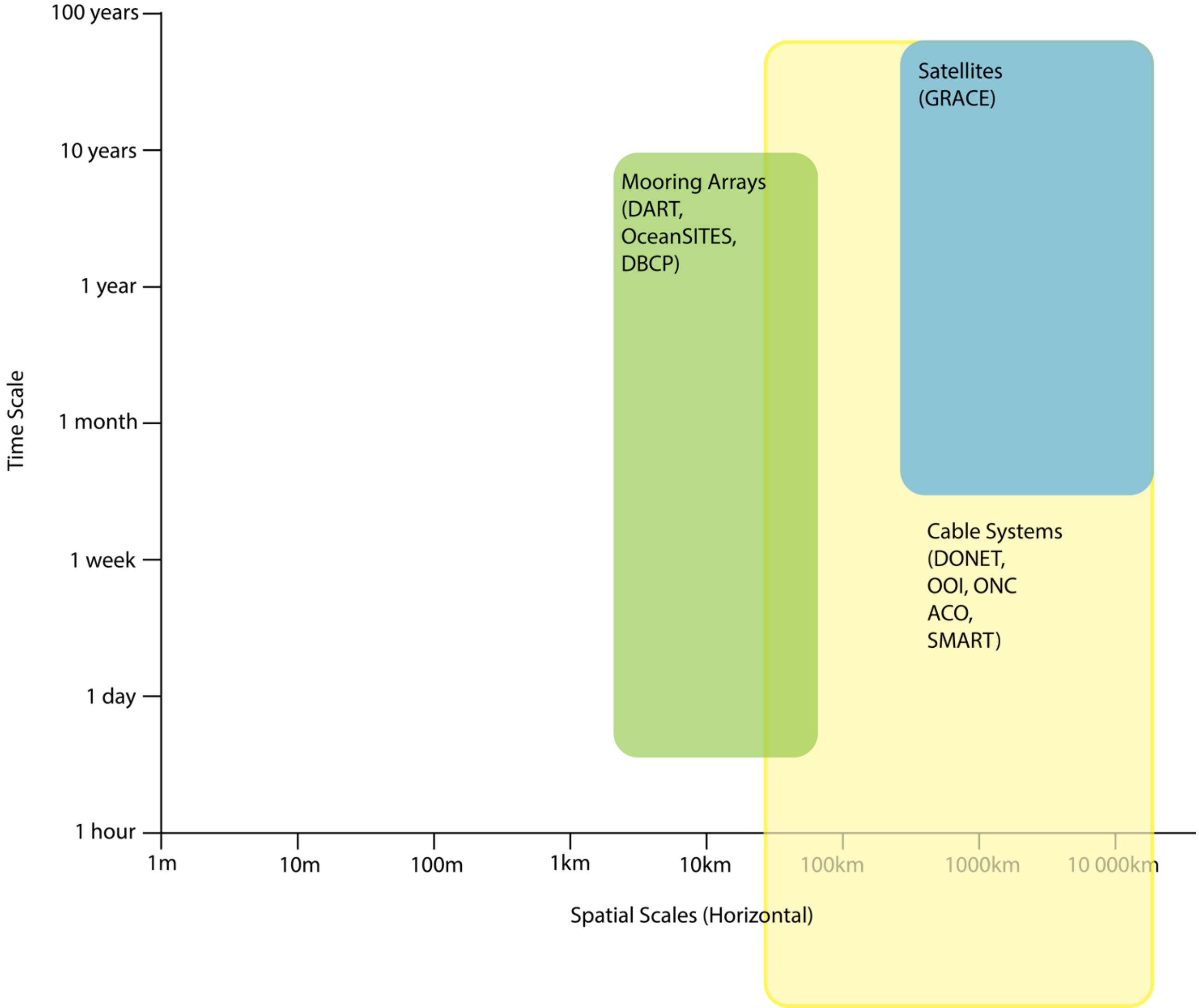


Figure 3. Resolved observation scales of the component networks.

Data & Information Creation[7]				
	DART Stations	**DONET, OOI & ONC, ACO**	**Moorings (OceanSITES, DBCP)**	**GRACE gridded**
Readiness Level[1]	Mature Level 9	Mature Level 9	Mature Level 9	Mature Level 9
Oversight & Coordination	NOAA/NCEI, IOC	NSF, OOI, JAMSTEC	OceanSITES	NASA JPL; CSZ; GFZ
Readiness status of Metadata	Mature Level 9	Mature Level 9	Mature Level 9	Mature Level 9
Data Centre/ repository	NDBC (real-time): NCEI (delayed):	DONET OOI ONC ACO	OceanSITES	NASA JPL
Data Stream delivery and QC…	QC by PMEL/NCTR; Time series delivered by NCEI and IOC	DONET OOI ONC ACO	OceanSITES Delayed mode	NASA JPL
Derived Products	SSH	Seafloor pressure; nano-resolution seafloor pressure	SSH	Gridded geopotential; mass above in units of liquid water equivalent thickness.

[7] If there are too many products (i.e. SST), describe each type of product.

Links & References	
Links (especially regarding Background & Justification)	Bernard, E., and V. Titov, 2015: Evolution of tsunami warning systems and products, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 373. http://doi.org/10.1098/rsta.2014.0371 Bertin et al., 2018: Infragravity waves: From driving mechanisms to impacts, Earth-Science Reviews, Volume 177, 774-799, ISSN 0012-8252, https://doi.org/10.1016/j.earscirev.2018.01.002 Hughes et., 2018: A window on the deep ocean: The special value of ocean bottom pressure for monitoring the large-scale, deep-ocean circulation. Progress in Oceanography 161:19-46. https://doi.org/10.1016/j.pocean.2018.01.011 Rohith et al., 2019: Basin-wide sea level coherency in the tropical Indian Ocean driven by Madden–Julian Oscillation, Nature Communications, 10:1257, https://doi.org/10.1038/s41467-019-09243-5
Links for Contributing Networks	DART: https://nctr.pmel.noaa.gov/Dart/ DONET: http://www.jamstec.go.jp/donet/e/ OOI: https://oceanobservatories.org ONC: http://www.oceannetworks.ca/ ACO: http://aco-ssds.soest.hawaii.edu OceanSITES: http://www.oceansites.org JTF SMART Subsea Cables: https://www.itu.int/en/ITU-T/climatechange/task-force-sc/Pages/default.aspx GRACE: https://grace.jpl.nasa.gov
Data References	DART NDBC (real-time): https://www.ndbc.noaa.gov/dart.shtml NCEI (delayed): https://www.ngdc.noaa.gov/hazard/DARTData.shtml DONET Data Portal: http://www.jamstec.go.jp/scdc/top_e.html OOI RCN Data Portal: https://oceanobservatories.org/data-portal/ ONC Data Portal: http://www.oceannetworks.ca/data-tools ACO Data Portal: http://aco-ssds.soest.hawaii.edu/ftp.html OceanSITES Data Portal: http://www.oceansites.org/data/index.html GRACE gridded data: https://grace.jpl.nasa.gov

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FRAMEWORK PROCESSES BY READINESS LEVELS

Readiness Levels	Requirements Processes	Coordination of Observational Elements	Data Management & Information Products
Mature			
Level 9 "Sustained"	Essential Ocean Variable: • Adequate sampling specifications • Quality specifications	System in Place: • Globally • Sustained indefinitely • Periodic review	Information Products Routinely Available: • Product generation standardized • User groups routinely consulted
Level 8 "Mission qualified"	Requirements "Mission Qualified:" • Longevity/stability • Fully scalable	System "Mission Qualified:" • Regional implementation • Fully scalable • Available specifications and documentation	Data Availability: • Globally available • Evaluation of utility
Level 7 "Fitness for purpose"	Validation of Requirements: • Consensus on observation impact • Satisfaction of multiple user needs • Ongoing international community support	Fitness-for-Purpose of Observation: • Full-range of operational environments • Meet quality specifications • Peer review certified	Validation of Data Policy • Management • Distribution
Pilot			
Level 6 "Operational"	Requirement Refined: • Operational environment • Platform and sensor constraints	Implementation Plans Developed: • Maintenance schedule • Servicing logistics	Demonstrate: • System-wide availability • System-wide use • Interoperability
Level 5 "Verification"	Sampling Strategy Verified: • Spatial • Temporal	Establish: • International commitments and governance • Define standardized components	Verify and Validate Management Practices: • Draft data policy • Archival plan
Level 4 "Trial"	Measurement Strategy Verified at Sea	Pilot project in an operational environment	Agree to Management Practices: • Quality control • Quality assurance • Calibration • Provenance
Concept			
Level 3 "Proof of concept"	Proof of Concept via Feasibility Study: • Measurement strategy • Technology	Proof of Concept Validated: • Technical review • Concept of operations • Scalability (ocean basin)	Verification of Data Model with Actual Observational Unit
Level 2 "Documentation"	Measurement Strategy Described • Sensors • Sensitivity • Dependencies	Proof of Concept: • Technical capability • Feasibility testing • Documentation • Preliminary design	Socialization of Data Model • Interoperability strategy • Expert review
Level 1 "Idea"	Environment Information Need and Characteristics Identified: • Physical • Chemical • Biological	System Formulation: • Sensors • Platforms • Candidate technologies • Innovative approaches	Specify Data Model • Entities, Standards • Delivery latency • Processing flow

Figure 9. A Detailed View of Framework Processes for Varying Levels of Readiness.

Framework Processes and Readiness Levels (from the Framework for Ocean Observing [FOO]).

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