Sea Level Observation
NOAA's Tide Station Network

Allison Allen, Stephen Gill, Lori Fenstermacher, Carolyn Lindley and Chris Zervas
NOAA Center for Operational Oceanographic Products and Services
NOAA National Ocean Service, Silver Spring MD

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1. Abstract

NOAA's Center for Operational Oceanographic Products and Services (CO-OPS), within the National Ocean Service (NOS), operates and maintains the National Water Level Observation Network (NWLON), a network of 210 long-term tide stations. These stations represent the longest continuous sea level time series in the U.S. and provide critical information on sea level trends and variability as an indicator of climate change. *In situ* observations from this tide station network support both local and global sea level measurement, and provide input to the Global Sea Level Observing System (GLOSS). Over the past several years, CO-OPS has contributed to NOAA's implementation of a Global Ocean Observing System (GOOS) for Climate, as outlined in the NOAA Climate Program Office Program Plan. Specifically, CO-OPS observations and analysis directly support the "Tide Gauge Station" subsystem of the Climate Observation System, though the applications extend beyond climate variability to include marine transportation, hazard warning, weather prediction, inundation modeling, and ecosystem monitoring.

2. Project Summary

The National Oceanic and Atmospheric Administration (NOAA) Center for Operational Oceanographic Products and Services (CO-OPS) operates and maintains a network of 210 long-term, continuously operating coastal water level stations on all U.S. coasts and in the Great

Lakes. This National Water Level Observation Network (NWLON) also includes stations on Pacific and Caribbean ocean islands, U.S. territories, and possessions. Many of these stations have now been in operation for over 100 years, with a few in operation for over 150 years. NOAA, through CO-OPS, has the national legal authority for coastal tides, tidal currents, and water levels, and is the U.S. leader on relative sea level information for all parts of the U.S. The operation of these stations, and their long period of record, is critical to understanding sea level rise and climate variability, both on a global and local scale. Tide gauge records provide relative sea level trends critical for coastal zone management, engineering, and long-term planning and decision-making on a local and national scale. They also provide calibration for satellite altimeters to better understand and measure global sea level changes caused by thermal expansion and changes in freshwater input. While the period of record for satellite altimeters is relatively short, tide gauge records exist for several decades, giving us a better understanding of what changes we have seen, and how that reflects future variability in sea level due to climate change. All NWLON stations are multi-purpose, providing both long-term and real-time water level information to support multiple user communities, including navigation, hazard warning and mitigation, and coastal zone management. In the climate community alone, immediate users of this data include climate researchers, NOAA and federal partners who use the information to develop climate mitigation strategies for coastal communities or for management decisions, coastal managers responsible for implementing climate change response and mitigation strategies, the general public, climate modelers requiring local information to downscale global models and develop local projections, and many others. All CO-OPS data are available real-time, and products, including long-term trends and monthly and annual means, are available through the CO-OPS *Sea Levels Online* web site, and are archived at all three Global Sea Level Observing System (GLOSS) archive centers. The data are also available through the Permanent Service for Mean Sea Level. Twenty-seven NWLON stations currently comprise the U.S. contribution to the core GLOSS network, and forty-five are part of the GLOSS-Long Term Trend (LTT) network. CO-OPS also supports the Global Earth Observation System of Systems (GEOSS) by providing on-line sea level trends and analysis for 114 international GLOSS-LTT stations by operating and maintaining the GLOSS-ALT tide gauges at Oil Platform Harvest for satellite altimeter calibration and evaluation, and by maintaining the long-term tide station at Bermuda. These efforts directly support the NOAA Office of Climate Observation (OCO) deliverable with respect to sea level: to identify changes resulting from trends and variability in climate. Failure to continue operation of CO-OPS' observing systems, update long-term time series, and analyze sea level trends on a national and global scale would cause a large gap in the Global Ocean Observing System for Climate and negatively impact understanding of both local and global sea level changes as an indicator of climate change.

3. Scientific Accomplishments

Accomplishments by CO-OPS in the area of climate variability can be divided into three primary tasks, as outlined in the 2009 work plan delivered by CO-OPS to OCO in November 2008. 2009 work was primarily a continuation of the work begun in previous years. All three tasks support the Office of Climate Observation's sea level deliverable. These tasks are:

- Develop and implement a routine annual sea level and extreme event analysis reporting capability that meets the requirements of the Climate Observation Program [Reported separately as an analysis project.]

- Upgrade the operation of selected National Water Level Observation Network Stations to ensure continuous operation and connection to geodetic reference frames. [Reported here.]

- Operate and maintain water level measurement systems on Platform Harvest in support of calibration of the TOPEX/Poseidon and Jason-1 satellite altimeter missions. [Reported here.]

3.1 Tide Station Upgrade and Geodetic Connections

There are several coastal and island NWLON stations critical to the Global Ocean Observing System for Climate. The operation and maintenance of the ocean island stations of the National Water Level Observation Network (NWLON) has been increasingly more difficult over time due to the slow abandonment of the island facilities by the U.S. Department of Defense, at which some of the stations reside. Finding routine and/or cost-effective flights can be difficult, yet these stations require high standards of annual maintenance to ensure the integrity of their long term data sets. Annual maintenance is extremely important, especially in light of the fact that corrective maintenance is logistically very difficult and expensive. Therefore, over the past few years, the focus of CO-OPS contribution to the Global Ocean Observing System for Climate has been on upgrading hardware and software at 11 identified critical ocean island sites, creating redundancy in data collection to ensure continuous time series, improving communications where necessary, and establishing geodetic connections and continuous GPS monitoring sites where they do not currently exist. Establishing a geodetic connection, and monitoring rates of land motion at sea level observation points is critical in understanding the mechanisms contributing to local rates sea level rise and better quantifying rates of global change. All of this work supports the OCO deliverable to identify changes resulting from trends and variability in climate. Observations are critical to this sea level work.

In 2009, work on this task involved two primary components. First, equipment was purchased to be installed at Adak, Alaska in FY10, in order to provide redundancy at this remote location. In accordance with this effort, two additional data collection platforms will be installed. Second, the installation of a Continuously Operating Reference System (CORS) was planned for Midway Island, as well as the establishment of a geodetic connection using GPS. However, the work at Midway was not completed prior to the end of FY09 due to difficulty with the timing of the contract mechanism, travel logistics, and technical challenges with the site's infrastructure. Work on both tasks will be completed in FY10 through no additional funding to OCO. We were also notified that there is a CORS operating at Adak, Alaska, which had been tentatively planned for the CO-OPS 2011 Work Plan, and will no longer be necessary. Due to the work done in 2009, the priority work to upgrade and establish geodetic connections at the Pacific, Alaska, and Caribbean island sites is nearly complete (see Table 1).

Table 1. Status of Ocean Island NWLON Station Upgrades and Improvements

Station	Upgraded	Geodetic Connection	CORS Operating
Guam	Yes	Yes	Yes
Kwajalein	Yes	Yes	Yes
Pago Pago	Yes	Yes	Yes
Wake Island	Yes	Yes	No*
Midway	Yes	No*	No**
Adak	No*	Yes	Yes
Bermuda	Yes	Yes	Yes
San Juan, PR	Yes	Yes	Yes
Magueyes Island, PR	Yes	Yes	Yes
Charlotte Amalie, VI	Yes	Yes	Yes
St. Croix, VI	Yes	Yes	Yes

* Will be completed in FY10 without additional funding requested
** Will be completed in FY10 through FY10 Work Plan and Budget Request

3.2 Satellite Altimeter Support

Support for the TOPEX/Poseidon satellite altimeter mission began with installation of an acoustic system and a digibub system on Platform Harvest in 1992 (see Figure 1). System operations include provision of water level measurements relative to the satellite altimeter closure analysis reference frame for calibration monitoring (see B. Hanes et al, Special Issue of Marine Geodesy, 2003 "The Harvest Experiment: Monitoring Jason-1 and TOPEX-Poseidon from a California Offshore Platform"). CO-OPS' special support for this site has included a vertical survey on the Platform necessary to relate the water level sensor reference zeros (near the bottom catwalk) to the GPS reference zero (located up top at the helipad on the Platform). Continuous data are required to monitor effects of waves on the water level measurements and to ensure provision of data during the times of altimeter over flights every ten days, so care is taken to ensure accurate and reliable data collection and dissemination. Raw and verified 6-minute interval water level data are posted on the CO-OPS web-site.

Figure 1. Platform Harvest Calibration Site at which NOAA tide gauges are located.

The original acoustic system was replaced by a digibub pressure system prior to the Jason-1 altimeter launch. These two digibub pressure tide gauge systems have been collecting continuous water level data streams surveyed into the Platform and Satellite Orbit Reference frames. In 2009, CO-OPS replaced one of the two nitrogen tanks and digibub systems with an air pump, which is a safer, more reliable, and more cost-effective system for long-term maintenance. Both systems were not replaced at once in order to ensure continuous operation and monitor the success of the air pump at this site prior to a full replacement. This system has performed well and will allow for easier, safer, and more cost-effective maintenance in the future. The 2010 work plan will reflect plans to replace the remaining digibub system with an air pump system, though the primary components for this upgrade were purchased in 2009.

Annual OCO funding is used to cover travel to and routine emergency maintenance of this site, as well as and water level and ancillary sensor calibrations. Without this funding, this site could not be maintained. This site is critical for calibration of the satellite altimeters for global sea level observation and measurement.

3.3 National Water Level Observation Network Data Availability

In 2009, data availability from the National Water Level Observation Network was 97.7%. All CO-OPS real-time and long-term water level data and sea level trends are available through several channels. Real-time water level data are available for all CO-OPS tide gauges via the internet, web services, and the Global Telecommunications System. All raw and verified data and products, standards and procedures, and data analysis reports can be accessed through http://tidesandcurrents.noaa.gov. Data can also be accessed through the IOOS web portal at http://opendap.co-ops.nos.noaa.gov/content/. Sea level products are also available online, through the CO-OPS *Sea Levels Online* web site for U.S. (http://tidesandcurrents.noaa.gov/sltrends/sltrends.shtml) and global (http://tidesandcurrents.noaa.gov/sltrends/sltrends_global.shtml) stations. Data are archived

regularly in-house, and sea level data sets are provided to all GLOSS archive centers for U.S. GLOSS stations. One-minute water level data are archived weekly at the NOAA National Geophysical Data Center in Boulder, CO.

4. Education and Outreach

Through FY2009, CO-OPS participated in a number of independent education and outreach efforts focused on increasing understanding of global and local sea level rise rates and mechanisms, and how to utilize this information to understand and plan for climate variability. CO-OPS provided technical input to policy guidance and science programs, including the U.S. Army Corps of Engineers Engineering Circular EC 1165-2-211 for Incorporating Sea-Level Change Considerations in Civil Works Programs (USACE, 2009) and in a NOAA lead author role for Climate Change Science Program's Synthesis and Assessment Product 4.1 (Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region (CCSP, 2009)). The primary CO-OPS role involved incorporating long-term relative sea level trends from tide gauge observations into planning and engineering guidance to understand and mitigate climate change impacts. In FY09, CO-OPS hosted a team from the Caribbean Community Climate Change Centre to provide a week of training and technology transfer on tide gauge operation, with a focus on climate applications, including monitoring the stability of gauges and long-term sustainability of observation sites. CO-OPS supported a National Centers for Coastal Ocean Science (NCCOS) grant proposal for an educational display on sea levels and climate change at the Pine Knoll Shores Aquarium in North Carolina. CO-OPS has also been working with the NOS Office of Education to incorporate sea level rise information into science guides (SciGuides) for elementary school and high school science teachers, and has upgraded their Sea Levels Online website with more user-friendly descriptions to enhance public understanding and utilization of sea level trends. CO-OPS provided input on sea-level change issues to the NOAA Office of Coastal and Resource Management Coastal Strategy document "Recommendations for Interim Guidance for Considering Climate Change Impacts in Coastal Habitat Restoration, Land Acquisition, and Facility Development Investments." Finally, CO-OPS has conducted a number of briefings and trainings focused on sea level and climate change, highlighting CO-OPS' role as the legal authority on mean sea level for the U.S., the role of coastal tide stations in global sea level observation, and how to find and utilize local sea level trends.

5. Publications and Reports

5.1. Publications by Principal Investigators

CCSP, 2009: *Coastal Sensitivity to Sea-Level Rise: A focus on the Mid-Atlantic Region.* A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. [James G. Titus (Coordinating lead Author), K. Eric Anderson, Donald R. Calhoon, Dean B. Gesch, Stephen K. Gill, Benjamin T. Guitierrez, E. Robert Thieler, and S. Jeffress Williams (Lead Authors)]. U.S. Environmental Protection Agency, Washington, D.C., USA, 320 pp.

An update to the following NOAA Technical Report CO-OPS 36 has been completed and undergone internal review. It will be titled Sea level variations of the United States, 1854-2006.

Zervas, C. E., 2001: *Sea level variations of the United States, 1854-1999.* U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service, ix, 186 p. pp.

5.2. Other Relevant Publications

Merrifield, M.A., R.S. Nerem, G.T. Mitchum, L. Miller, E. Leuliette, S. Gill, and P.L. Woodworth, 2009: Sea level variations, 2008 annual assessment [in "State of the Climate in 2008"]. *Bull. Amer. Meteor. Soc.*, 90, p 562-65.

USACE, 2009: Water Resource Policies and Authorities Incorporating Sea-Level Change Considerations in Civil Works Programs, CECW-CE Circular No. 1165-2-211, Department of the Army, U.S. Army Corps of Engineers, Washington D.C., 1 July 2009, 26pp.

NOAA, 2009: Annual report series 2003 - 2007, the Ocean Observing System for Climate, NOAA Office of Climate Observation, Silver Spring, MD. [available on line at: http://www.oco.noaa.gov/index.jsp]

Sweet, W., C. Zervas, and S. Gill, 2009: Elevated East Coast Sea Level Anomaly: June-July, 2009. NOAA Technical Report NOS CO-OPS 051, 30pp.

Szabados, M., 2008: Understanding Sea Level Change, American Congress on Surveying and Mapping Bulletin No. 236, December 2008, p 10-14.