Long-term observations of ocean circulation with cables as sensors

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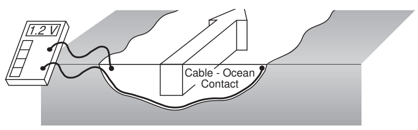
Abstract. Of the existing observational records using submarine cables as sensors of the ocean circulation, two of the longest are the time series in the Straits of Florida at 27N, and the HAW-1 observations of the voltage between the Hawaiian island of Oahu and Point Arena in Northern California. The history and context of the measurements are summarized, and emerging indications of connections to large-scale patterns of climate variability are briefly discussed.

1 Introduction

In both the North Atlantic and North Pacific oceans, variability of the extratropical ocean-atmosphere system on decadal to interdecadal scales is increasingly recognized as an important factor in climate and ecosystem variations of large societal impact. These include weather and climate phenomena such as temperature, precipitation, and storminess over areas that range as far south as the Sahel and the Nordeste of Brazil, as well as large scale shifts in fisheries and coastal ecosystems [e.g. Cayan et al., 1998, Francis et al., 1998; Mantua et al., 1997; Malmberg and Blindheim, 1994]. Interaction with shorter-scale variability, and with other large scale climate patterns are also a topic of active research [e.g. Barnett et al., 1999].

The mechanisms of the variations in question are far from well understood. A significant role of sea surface temperatures in the forcing is indicated by some recent studies [e.g. Mehta et al., 2000; Rodwell et al., 1999], and links with relatively slow variations of the large scale ocean circulation have long been suggested [e.g. Bjerknes, 1964; Latif and Barnett, 1996]. Other studies, however, do not find such mechanisms necessary. Observational data with a bearing on these questions are scarce. To quote from a discussion of coupled decadal variability in the Pacific sector and its predictability in the recent *'Implementing US CLIVAR 2001-2015'*, "Several plausible theories invoke very different atmospheric, oceanic, and coupled mechanisms. However, we lack long and comprehensive data records, particularly from the ocean, to test these theories or quantify many of the pathways and processes that regulate transport and exchanges of heat and freshwater in the coupled system." Observations of low-frequency variations in electric potential between points on the Earth's surface by means of cable voltages (Fig. 1) are part of a very small set of long-term observations capable of yielding information relevant to these questions. They offer qualities of spatial integration, temporal continuity, and potentially long duration that complement the sampling strategy of many other oceanographic data.

Figure 1: Seawater in motion across the geomagnetic field generates voltage differences between points on the surface of the Earth [Faraday, 1832; Stommel, 1948]. These can be measured by voltmeters whose leads consist of insulated cables with endpoints in contact with local ground or seawater, using the cable as a very long voltmeter lead [e.g. Sanford, 1971; Chave and Luther, 1990; Larsen, 1992].



2 North Atlantic: the Florida Current

The warm Florida Current flows northward between the Florida peninsula and the Bahama Banks, feeding the Gulf Stream and ultimately transporting its heat and salt into the far North Atlantic. The Current contains both the wind-driven North Atlantic subtropical gyre circulation and the upper ocean return flow of the thermohaline meridional overturning circulation [Schmitz and Richardson, 1991; Wilson and Johns, 1997].

Cable-based observations of this important link of the North Atlantic ocean's heat transport came of age during NOAA's Subtropical Atlantic Climate Studies (STACS) program in the 1980s. Cable voltage measurements across the Straits of Florida at at 27^{o}N had been initiated during 1969-1974 using a retired cable between Jupiter Inlet, Florida, and Settlement Point, Grand Bahama [Sanford, 1982] (Fig. 2). More or less continuous monitoring was maintained during 1982-1998 using both retired and in-use telephone cables [Larsen, 1991, 1992, Fig. 3]. Intercomparison with dropsonde transport observations established a linear relation between voltage and transport at this location [e.g. Larsen and Sanford, 1986; Leaman et al., 1987]. Measurements were continued during the 1990s under the auspices of the Atlantic Climate Change Program (ACCP), relying on the in-service Florida-Bahama cable between West Palm Beach and Eight Mile Rock, Grand Bahama, after the Jupiter cable had broken beyond repair in 1991.

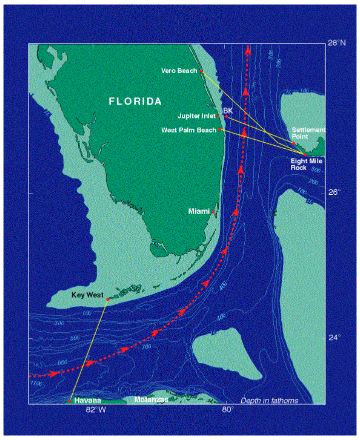


Figure 2: The Straits of Florida and the location of the cables used for voltage measurements during the STACS and ACCP programs.

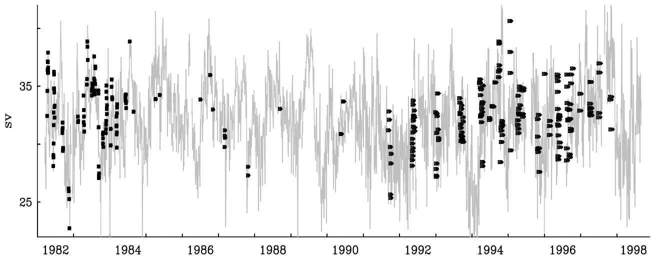


Figure 3: Daily values of voltage derived Florida Current transport (line), and profiling-derived transport observations (dots), courtesy of J. Larsen. Tides and externally generated signals have been removed from the voltage time series by use of the robust remote reference methods of Larsen et al. [1996], corrections associated with the use of an in-service cable after 1990 have been applied using the methods of Larsen [1991], and the profiling data have been used to estimate the calibration factor converting voltage to transport.

The Florida Current record is now long enough to show decadal changes of several Sverdrup (10^6 m^3/s), and to suggest correlations with the dominant low frequency climate signal in the North Atlantic, the North Atlantic Oscillation (NAO), and with principal modes of Atlantic sea surface temperature variability (Fig. 4) [Baringer and Larsen, "Update from Florida Current Transport time series, 27^{o}N in the Atlantic"; Flosadóttir et al, "Florida Current transport 1969-2001", in preparation]. The volume of the Florida Current is in fact large enough that it could replace all of the North Atlantic surface water down to 100 m within one year, so transport variations of the size observed could indeed have a significant influence on the North Atlantic temperature. The cable data suggest links between variations of the Florida Current transport, large scale variations of sea surface temperature, and the strength of the winter westerlies as reflected by the changes in the NAO index. However, it is important to note that because of the decadal to interdecadal timescales involved, it has taken nearly a two decade long time series to begin to cover a single cycle of this important climate signal. At least twice as long a time series is needed even to begin to resolve the signals involved with any confidence. Efforts are being made to re-evaluate some older data, to see if the time series can be extended further back in time. Most importantly, efforts are also being made to continue this important

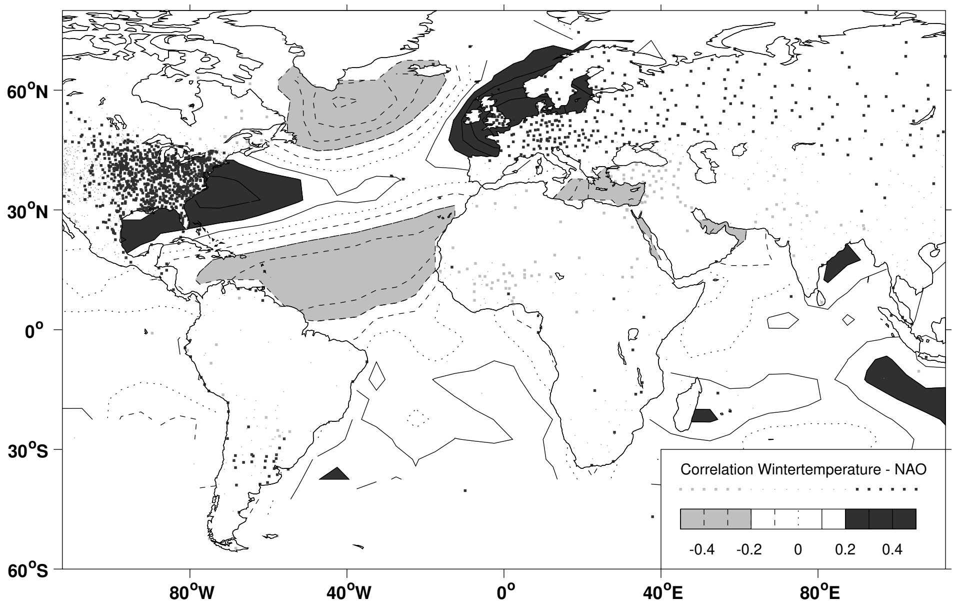
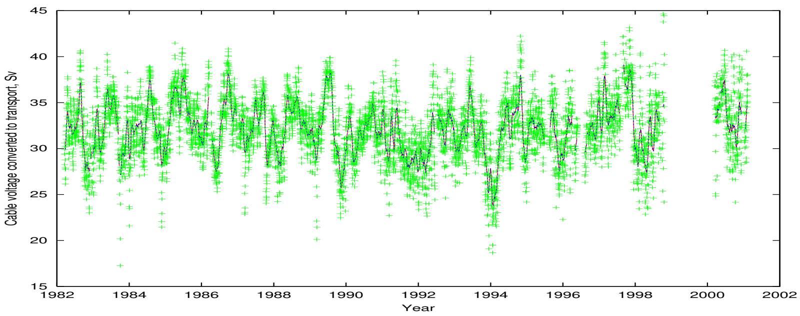


Figure 4: Regression between winter sea and land surface temperature and the NAO index showing a 'tripole' pattern (courtesy of M. Visbeck and H. Cullen, Atlantic CLIVAR implementation plan). A similar pattern results from regression with the cable voltage.

climate time series for a contribution of observational input to the debate over climate mechanisms that was touched on in the introduction.

After a break in the measurements due to retirement of the Florida-Bahamas cable from active telephone service during 1999, the cable was reterminated and observations were resumed from the Grand Bahama end in March, 2000 (Fig. 5, http://www.pmel.noaa.gov/wbcurrents/cabletransport.html). The observations are now being maintained by a team of researchers at JISAO/PMEL in Seattle and NOAA/AOML in Miami (A.H Flosadóttir, W.D. Wilson, and M.O. Baringer). Efforts are being made by some of the same researchers (A.H. Flosadóttir, W.E. Johns, and W.D. Wilson) to add submarine cable and sea level measurements of transport through the passages of the southeastern Caribbean Sea, also an important link in both the wind-driven and thermohaline circulations of the North Atlantic. Pressure gauges have been put in place, but voltage observations, using the East Caribbean Fibre System cable across the Grenada Passage between Trinidad and Grenada, were delayed by repeated cable faults during the cable's first years of service. Sections of the cable have now been re-laid, and negotiations are in progress with the cable owners for installation of voltage recorders. Comparison with a lengthening record from the retired CAM-1 cable between the island of Madeira and the coast of Portugal [Santos et al., 2000] will also be of interest.

Figure 5: Daily and monthly values of voltage derived Florida Current transport, 1982 through January, 2001.



3 HAW-1

In the North Pacific, a network of long cable voltage measurements was put in place over the 1990's by scientists in the USA and Japan. The western part of this network is currently maintained by the group of H. Utada at the Earthquake Research Institute of the University of Tokyo as part of the Japanese Ocean Hemisphere Project [Utada et al., this volume]. Measurements in Hawaii and California were initiated by researchers at Lucent Technologies' (formerly AT&T) Bell Laboratories and Woods Hole Oceanographic Institution [e.g. Chave et al., 1992; Lanzerotti et al., 1992, 1993]. The longest of these is the HAW-1 voltage time series, started in April of 1990. The system originally consisted of two cables, HAW-1 North and HAW-1 South, about 4000 km long and separated by approximately 120 km along most of the path. At the eastern termination, they shared a telecommmunications silicon-iron ground rod in seawater contact near the beach at Pt. Arena, N. California. At the western end, HAW-1 N remained terminated at the original sea-earth ground in Hanauma Bay, Oahu, while HAW-1 S had, since a break in early 1991, made contact between the copper conductor and seawater at the cable break a short distance offshore [Lanzerotti et al., 1992]. The north cable suffered a break off California in 1999. The south cable remained intact, but was disconnected from the data recording equipment shortly afterwards due to construction at the Point Arena cable station. Reconnection was delayed by further disturbance of the cable station access by drill pipe operations for landing of the Japan-US cable system in late 2000, but the cable has now been reconnected back to the cable station and is ready for the resumption of observations.

At periods of approximately a week to a few months, work with the first few years of data has established coherence between the HAW-1 voltage and atmospheric pressure, wind stress, and wind stress curl data [e.g. Fujii and Chave, 1999], consistent with evidence of wind-driven motions reaching great depths in the North Pacific from the BEMPEX experiment and other evidence [e.g. Luther et al., 1991; Niiler and Koblinsky, 1985; Koblinsky et al., 1989]

To look at longer-term signals, the left hand panel of Fig. 6 places the cable in relation to patterns of large scale ocean and atmospheric variability, showing the approximate location of HAW-1 superimposed on contours of the first EOF of winter sea level pressure (SLP), 1899-1997, after Minobe and Mantua [1999]. This mode exhibits SLP changes associated with variability of the Aleutian Low, and explains 43.6% of the total variance. It is closely related with the Pacific Decadal Oscillation [e.g. Mantua et al., 1997, Zhang et al., 1997]. The right panel of Fig. 6 shows a comparison of the 1990-1997 variability in the low-passed voltage time series for HAW-1 N, sea level differences between Hawaii and Northern California, and the Pacific Decadal Oscillation (PDO) Index. The sea level differences are differences of pressure-corrected deviations from the 1975-1995 mean sea level from the Integrated Global Ocean Services System (IGOSS) Sea Level Program in the Pacific (ISLP-Pac) as provided by the University of Hawaii Sea Level Center. The PDO index used here (other variants exist) is the temporal variation of the first EOF of sea surface temperature poleward of 20N, using data covering most of the 20th century, provided courtesy of N. Mantua. The sign of the PDO is defined so that a positive change corresponds with a strengthening Aleutian Low, and the voltage polarity is such that a positive change corresponds with increased equatorward transport.

Comparison of the cable voltage and sea level differences in Fig. 6 suggests that flow variability is a major contributor to the cable voltage. This is also supported by an exploratory comparison of the first few years of cable data with Sverdrup transport from SSMI winds by S. Howden (personal communication). The size of the voltage variations, if entirely attributed to transport variations corresponds to sizeable transport variations on the order of several Sverdrup (using rough estimates based on calibration factors from numerical modeling in the North Atlantic). The vertical component of the geomagnetic field is stronger toward the California end of the cable than near Hawaii by a factor of roughly 2, so that cross-cable flow near California is sensed more strongly than flow near Hawaii. Upper ocean temperature can also affect the weighting of different parts of the flow field, but this would be unlikely to be large enough to account for the size of the observed voltage variations [e.g. estimates in Luther and Chave, 1993, and Flosadóttir et al., 1997b]. Comparison of the cable voltages and sea level differences with the PDO index curve is also interesting. While there is far from a perfect correlation, at the longest timescales represented there appears to be a correspondence between periods of strengthening/weakening trends in the PDO and the cable voltage, the latter leading the SST-based PDO index by a few months.

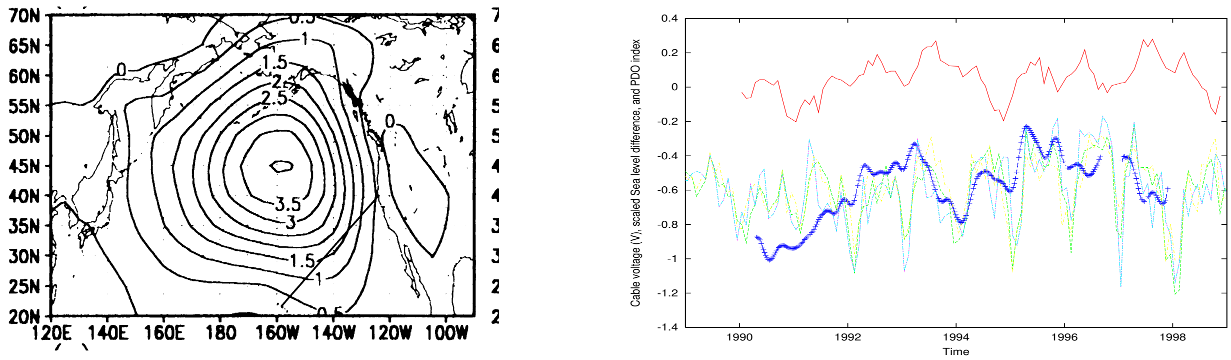


Figure 6: Left panel: The approximate path of HAW-1 superimposed on the spatial pattern of the first EOF of sea level pressure in winter season (December-February) over the North Pacific (120E-90W), after Minobe and Mantua [1999].

Right panel: Low-passed time series for HAW-1 North cable voltage (pluses), monthly values of Hawaii-Northern California sea level differences (dashed curves), provided by the University of Hawaii Sea Level Center, and the Pacific Decadal Oscillation (PDO) index, (courtesy of N. Mantua, top curve, solid). The voltage in V has been reversed so that a positive change corresponds to increased equatorward transport, low-passed to produce monthly values, and shifted by -0.1 V for a visual offset from the PDO index, which has been divided by 10. Sea level differences in meters have been multiplied by 2, and shifted by -0.6 so that they roughly overlay the cable voltage series. The three curves are Honolulu minus Crescent City, Hilo minus Crescent City, and French Frigate Shoal minus San Franscisco.

The implication of this preliminary comparison is that the strong spatial filtering inherent in the cable voltages is serving to bring out features of the large scale ocean transport variability that are related to the PDO and its associated large scale changes in winds over the North Pacific. As in the case of the North Atlantic, with lengthening time series, these observations may provide a unique source of input into the debate over the mechanisms of climate variability on decadal to interdecadal scales. Currently, however, the HAW-1 time series observations are in a state of uncertainty. As of this writing, there is no funding in place for continuation of the time series. For the time being, a presence at the cable stations is being maintained, some necessary field work has been done to avert permanent disconnection of the longest time series (HAW-1) in late 2000, and efforts are being made through the University of Washington to obtain funding to continue the observations. It would indeed be a loss if the measurements were to come to a stop at this juncture, just as the longest of the time series begin to reach a length sufficient for analysis of climate-related signals, and just as a background level has been established during the past decade's phase of the Pacific Decadal Oscillation, possibly on the verge of its next major interdecadal regime shift.

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