



Evaluating VDatum in Coastal National Parks

Cape Cod National Seashore

Natural Resource Report NPS/NCBN/NRR—2017/1460



ON THE COVER

A survey grade GPS device used to obtain elevation data at Coast Guard Beach overlooking Nauset Marsh in Cape Cod National Seashore.

Photograph courtesy of Michael Bradley.

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Executive Summary

The accuracy of tidal datum elevations provided by NOAA's VDatum software package (version 3.2) is investigated for Cape Cod National Seashore (CACO). All available water level observations that could be referenced to the orthometric datum NAVD88, from NOAA, USGS, and the National Park Service (NPS) in the vicinity of the park, were used in the comparison. For observational sites lacking published NOAA values, datum elevations were computed and corrected to the 1983-2001 National Tidal Datum Epoch (NTDE), the Epoch used for VDatum, using standard NOAA methodologies. The estimate of the uncertainties in computed datum elevations, arising from uncertainties in the observations, instrument elevations, and the computation of datums from short (less than 19 years) records is approximately 0.079 m. The corresponding uncertainty in datum elevations from VDatum, estimated by NOAA, is approximately 0.132 m in this region.

Comparisons between observed and VDatum elevations were performed for mean high and low water (MHW and MLW), mean higher high and lower low waters (MHHW and MLLW), as well as mean sea level (MSL). The performance of VDatum was extremely variable. At open water sites, where there is a relatively deep (deeper than the oceanic tidal range) connection to the ocean or Cape Cod Bay, VDatum elevations were accurate to within 0.07 m. However, at sites lacking a deep connection to open water VDatum was highly inaccurate, especially for the low water datums (MLW and MLLW) and MSL. Averaged over all sites without a deep connection, low water datums were in error by approximately 1.6 m and the root-mean-square error in MSL was about 0.75 m. These uncertainties far exceed the VDatum uncertainty estimates.

Since the NPS requires datum accuracy of 0.05-0.10 m for their management activities, the results of this study indicate that VDatum is inadequate in at least some of the shallow, constricted areas of CACO. At the present time, therefore, it appears that for accurate datum elevations in these areas water level observations (such as those used in this report) and subsequent calculation of datum elevations will be needed.

Acknowledgments

We would like to thank Kelly Medeiros (National Park Service) for providing water level observations in the CACO region. Other observational data were obtained from the United States Geological Survey. The accepted datum information as well as some of the observations used in this study were obtained from NOAA's Center for Operational Products and Services. We thank James Lynch and Neil Winn for helpful comments on an earlier draft of this report.

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Introduction

Coastal National Parks in a changing climate have a pressing need for accurate measures of present sea level with respect to the vertical orthometric datum (NAVD88) that is used as the reference level for land elevation measurements. Because the oceanic tidal response is spatially variable, the height of tidal datums relative to NAVD88 is not, in general, spatially uniform. NOAA's National Ocean Service (NOS) has responded to the need for accurate datum information in coastal regions with the development of the VDatum transformation tool (<http://vdatum.noaa.gov>) that can be used to convert between various vertical datums (e.g. from tidal datums to NAVD88). VDatum coverage is available for all Northeast coastal National Parks including Cape Cod National Seashore (CACO), but it is not *a priori* clear whether the accuracy of vertical datum elevations is sufficient for park management activities. This report presents an analysis of the accuracy of VDatum in the Cape Cod National Seashore region. This work represents a continuation of previously published work for other coastal National Parks (Ullman et al., 2016).

NOAA's development of VDatum was performed on a regional basis, and for each region, uncertainty estimates were provided. For the CACO area, part of the Gulf of Maine region, the maximum uncertainty in a vertical transformation from an ellipsoidal datum to a tidal datum was estimated as approximately 0.13 m (NOAA, 2012). However, because this estimate represents an average over the entire Gulf of Maine region, it may not be representative of the accuracy of VDatum within the relatively small CACO area. Thus, the present work focused on the evaluation of VDatum using all available water level observations in and near the park with the objective of providing a local estimate of VDatum uncertainty. Although some of these data were used by NOS as model constraints in the creation of the regional VDatum solution, most of the data sets used in this report are from "independent stations" in the sense that they can be used to produce a measure of VDatum uncertainty that is independent of the VDatum development.

Methods

Data Sources

Datum elevations (relative to NAVD88) in the CACO region were computed using VDatum (version 3.2) on a grid, with spacing of 100 m. These data were used to produce maps showing the spatial structure of the vertical elevation of the datums as well as the mean tidal range (MHW-MLW). Estimates of the uncertainties in tidal datum elevations provided by VDatum have been provided by NOAA for each VDatum region in the form of maximum cumulative uncertainty (MCU) (NOAA, 2012). The elevation uncertainty for a particular tidal datum includes the uncertainties involved in the transformations between various datums (e.g. NAD83 to NAVD88) as well as the uncertainties in the source data for these datums. Maximum cumulative uncertainty for a VDatum region is the maximum of the uncertainties associated with a transformation from the International Terrestrial Reference Frame through NAD83, NAVD88, and mean sea level to each of the tidal datums. Maximum cumulative uncertainty was estimated as 0.132 m for CACO (NOAA, 2012).

Within coastal park regions, published tidal datum elevations may be available from two different sources: (1) NOS NWLON sites where datums are computed using a full 19-year sea level record, and (2) NOS historical sites where short-term (several months to a year or more) data were obtained in the past and where datum elevations were subsequently computed using procedures developed by NOS to compute datums using short time series (NOS, 2003). Datum elevations from these sites were typically used in the construction of the VDatum solutions so these data do not provide useful independent checks on the performance of VDatum. In the previous analysis of VDatum in other northeast coastal parks, the differences between published and VDatum-derived datum elevations were found to be extremely small (Ullman et al., 2016).

More useful data, from the standpoint of the evaluation of VDatum, are those from independent stations where the elevation of the sensor is known relative to NAVD88. Although they are potentially useful in assessing the tidal range predictions of VDatum, for the analysis presented here we excluded data from sensors with unknown NAVD88 elevations. Data from three distinct sensor types were encountered and each required slightly different preprocessing procedures to produce time series of water surface elevation. The first sensor type is the Microwave Water Level (MWL) system used by NOAA/NOS. This system provides direct measurements of the water surface elevation. The second sensor type, a bubbler system, used at United States Geological Survey (USGS) sites, measures the subsurface pressure at a known elevation relative to atmospheric pressure (i.e. the pressure relative to the surface). This pressure is converted to a water surface elevation using an assumed or measured water density with the hydrostatic equation. The third sensor type provides a measure of the absolute subsurface pressure at a known elevation. This measurement must first be converted to pressure relative to the surface using measured atmospheric pressure, with subsequent conversion to water surface elevation as described above.

An important consideration when comparing observational- and VDatum-derived datum elevations relative to NAVD88 is the uncertainty associated with these estimates. For the observational estimates, the uncertainty is composed of three components, the uncertainty in the estimate of the

instrument elevation relative to NAVD88, the uncertainty in the water surface elevation measurement, and the uncertainty in the datum elevation relative to the instrument computed from records shorter than a tidal epoch. The last of these components, the uncertainty arising from the use of short data records, has been estimated using the results from Bodnar (1981) as described below.

The uncertainty in instrument elevation relative to NAVD88 depends on the particular methodology used to determine the elevation. Because the data used in this report come from a variety of sources and because the details of the instrument leveling were not available to us in all cases, for most cases we use a conservative estimate based on the assumption that elevations were obtained using GPS techniques. The elevation uncertainty is estimated by quadratically combining the uncertainties in the transformation from an International Terrestrial Reference Frame (ITRF) to NAVD88 via NAD83 and the inherent uncertainties in NAD83 and NAVD88. This information was obtained from the NOAA document "Estimation of Vertical Uncertainties in VDatum" (NOAA, 2012) and results in an estimated uncertainty in elevation of 0.076 m.

The accuracy of water level measurements depends to some extent on the methodology. The MWWL is accurate to less than 0.01 m except in the presence of large waves (Boon et al., 2012). Based on published instrument specifications the other instruments used for collection of the data used in this report (e.g. Onset Hobo, YSI 6600), these measurements also appear to be accurate to approximately 0.01 m. We thus use 0.01 m as the nominal water level measurement accuracy.

Data Processing

The computation of tidal datums from time series of water surface elevation, typically measured at 6-minute intervals, was performed using the NOS standard algorithms as described in NOS publications (NOS, 2003). These procedures were coded in MATLAB for this project and will be briefly described here.

The first step of the process is to fill short gaps (less than 4 hours duration) using piecewise cubic spline interpolation. The next step is the so-called "tabulation" of the tides, whereby the times and heights of all high and low tides are identified and each tide is characterized as either a "higher" or "lower" high or low tide. The details of the tabulation procedure (S. Gill, NOS Center for Operational Oceanographic Products and Services, personal communication) are described in Appendix A. Next the lunitidal interval, defined as the interval of time between the moon's transit over the Greenwich meridian and the tide (NOAA, 2000), is determined for each tide. Times of the moon's transit were obtained from the Multiyear Interactive Computer Almanac (U.S. Naval Observatory, 2005). The final step in the processing of the raw 6-minute data is the production of an hourly-averaged surface elevation time series by application of a 1-hour running-mean filter and subsequent resampling at a 1-hour interval.

After the detection and tabulation of individual tides and the production of the hourly water level time series, monthly mean quantities are computed. Monthly mean sea level (MSL) is defined as the average over the month of the hourly mean sea level. Monthly mean high water intervals (HWI) and low water intervals (LWI) are respectively calculated as averages of the lunitidal intervals for high tides and low tides. The monthly mean high water (MHW) and low water (MLW) are computed as

the averages of the heights of all the high tides and all the low tides respectively. Similarly, monthly mean higher high water (MHHW) and lower low water (MLLW) are respectively averages of tide heights over all higher high tides and lower low tides. From these values, a number of other quantities are computed (see Figure 1 for a graphical representation):

<i>Mean Tide Level</i>	$MTL=0.5*(MHW+MLW)$	(1)
<i>Diurnal Tide Level</i>	$DTL=0.5*(MHHW+MLLW)$	(2)
<i>Mean Range</i>	$Mn=MHW-MLW$	(3)
<i>Great Diurnal Range</i>	$Gt=MHHW-MLLW$	(4)
<i>Diurnal High Water Inequality</i>	$DHQ=MHHW-MHW$	(5)
<i>Diurnal Low Water Inequality</i>	$DLQ=MLW-MLLW$	(6)

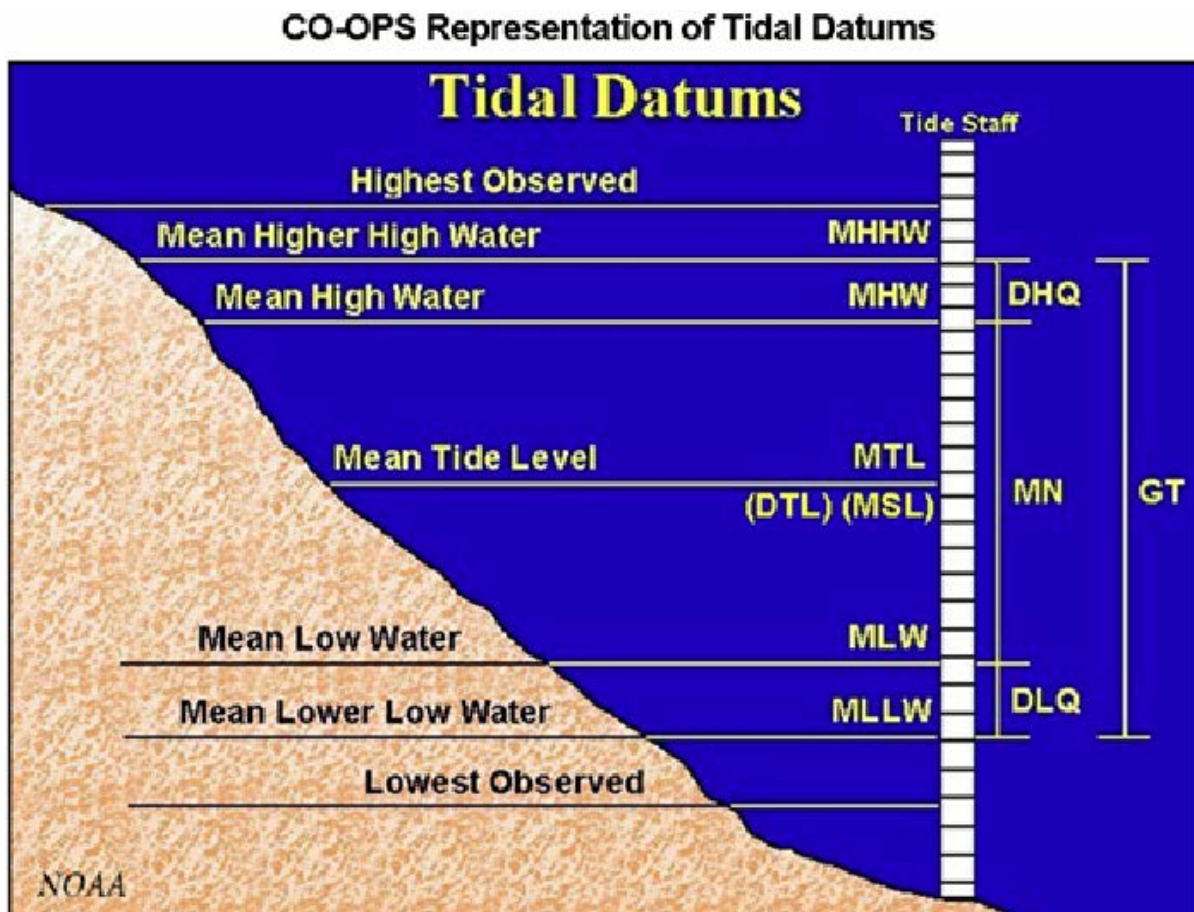


Figure 1. Terminology associated with tidal datums.

Tidal Datum Computation

Tidal datums are defined as mean values over a specific 19-year period designated as a National Tidal Datum Epoch (NTDE) (NOS, 2003). The present NTDE is the period from 1983 to 2001. At long-term NWLON stations, where the required 19-year dataset is available, datums are computed directly by averaging monthly mean values over the entire NTDE. To derive datum elevations at a location with a shorter data record (the target station), monthly mean values are compared with values from a nearby long-term station, denoted as the control station. Published datum elevations (so-called accepted datums) at the control station are used as baseline elevations. Computed datum elevation differences between the target and control station, over the time period of the target observations, are used with the accepted datum elevations at the control site to determine datum elevations at the target site. For sites along the U.S. East Coast, NOS uses the Modified-Range Ratio Method (NOS, 2003) for this "simultaneous comparison" procedure. The steps in this procedure are outlined in Appendix B (see NOS (2003) for more detail and worked examples).

Although present-day tidal datums are computed based on the 1983-2001 NTDE, it should be noted that the datum correction procedure should largely remove the effect of long-term sea level rise from datums computed from recent observations. This is because the accepted datums at NWLON control stations, based on 1983-2001 observations are used as baseline elevations for estimation of datums at short-term stations. To illustrate how the correction procedure removes long-term sea level rise from the datum elevations, the equation for the corrected MSL at a target site (see Appendix B) can be rewritten as:

$$MSL_T^{Corr} = MSL_C^{Acc} - \langle MSL_C \rangle + \langle MSL_T \rangle, \quad (7)$$

where MSL_T^{Corr} is the corrected MSL at the target site, MSL_C^{Acc} is the accepted MSL at the control site and $\langle MSL_C \rangle$ and $\langle MSL_T \rangle$ are the averaged MSL, over the observational time period, for the control and target sites respectively. The first two terms on the right hand side of the above equation represent the correction to the observed MSL value at the target site (the 3rd term on the right hand side). This correction is the difference between the accepted MSL value at the control site, representing mean sea level over the NTDE (1983-2001 in the present case), and the average value over the observational period. If we neglect seasonal or other short-term fluctuations in sea level and assume that MSL is varying only on long time scales associated with sea level rise, then the correction is equal to minus the sea level rise. In other words, the amount of sea level change at the control site between the NTDE and the time of the observations, which is assumed to be equal to the sea level change at the target site, is subtracted from the observed MSL at the target site. This corrects the target MSL datum to the time period of the NTDE and thus removes the effect of sea level change. However, if the sea level change at the target and control sites is not equal, then the correction will not adjust the target datums to the NTDE levels but will be in error with a magnitude equal to the difference in sea level change between the two sites. The difference between observed and corrected datums is important to understand for management applications such as the determination of the elevation of marsh surfaces relative to tidal datums (in this case it is most relevant to know where present sea level stands).

The analysis software developed for this project was tested by applying it to the computation of datum elevations at a NOAA short-term station where published datum elevations are available. The published datum elevations for the water level station at Chatham, MA (site number 8447435) are based on observations from 01 September 2009 to 31 August 2011. Water level observations for this time period were obtained for the Chatham location and for the water level station at Nantucket Island (site 8449130), which was the control tide station for the NOAA datum computation at Chatham. These observations were processed as described above and in Appendices A and B to tabulate the tides, compute monthly datum elevations, and to correct the Chatham datums. The computed datum elevations at Chatham agreed with the published values to within 0.002 m, indicating that the processing was faithfully replicating the NOAA procedures.

Estimates of datum elevations from short data records using the method of simultaneous comparison with a control NWLON station are subject to uncertainties or errors that vary inversely with the record length at the target station (Swanson, 1974). Swanson (1974) quantified the errors for different record lengths and presented results averaged over different U.S. coastal regions. Subsequent work by Bodnar (1981) indicated that the variability of the errors could be described as functions of several easily estimated variables (e.g. distance between target and control sites and tidal phase difference between the sites). To characterize the computational uncertainties in the datum elevation estimates in this report, the Bodnar relation for the uncertainty in MHW is used.

In addition to the uncertainties associated with the method of simultaneous comparison, additional uncertainties in computed datum elevations arise from errors in the observations themselves and in the measurements of the instrument elevations relative to NAVD88. The overall accuracy of datum elevations, resulting from the combination of the computational uncertainties and the uncertainties in instrument elevation and the water level measurements can be expressed as:

$$\Delta z_{overall} = \pm \sqrt{\Delta z_{comp}^2 + \Delta z_{elev}^2 + \Delta z_{meas}^2} \quad (8)$$

where $\Delta z_{overall}$ is the overall accuracy, Δz_{comp} is the accuracy of the computation (from the Bodnar relations), Δz_{elev} is the accuracy of the instrument elevation, and Δz_{meas} is the measurement uncertainty (0.01 m). Estimates of the overall accuracies will be presented in the Results section.

Data

Cape Cod National Seashore (CACO) is located on Cape Cod, a peninsula extending eastward into the Atlantic Ocean from southeastern Massachusetts. The National Seashore includes parts of the outer Cape (the northward-pointing arm) from Nauset Beach near Chatham in the south to the northern tip of the Cape. For this report, we made use of water level records at various sites in and near the National Seashore (see Table 1 and Figure 2). There is a NOAA National Water Level Observation Network (NWLON) station at Chatham near the southeastern region of the park as well as two sites recently set up by the United States Geological Survey (USGS) on Cape Cod Bay (Provincetown and Sesuit Harbor). In addition, the National Park Service (NPS), provided observations of various durations at three sites within the national seashore on the Cape Cod Bay side of the park (Herring River, and two sites at Hatches Harbor) and one site at Meetinghouse Pond, north of Chatham (outside of the park boundaries). All of the water level records were referenced to NAVD88. All of the stations except for Provincetown, Sesuit Harbor, and Chatham were "independent" stations in the sense that these data were not used for the creation of VDatum in this region (Yang et al., 2013). Note, however, that the USGS observations at Provincetown and Sesuit Harbor used in our study were not used in that process, although prior observations by NOAA at these sites were used.

Table 1. Water level stations in the CACO region used for analysis. Instrument elevation accuracy (Δz_{instr}) is the estimate of the uncertainty in the instrument elevation relative to NAVD88. Computed datum accuracies (Δz_{comp}) were estimated using the formulae for MHW datum accuracy in Bodnar (1981) using the indicated control stations. If the control station is not a NOAA NWLON station with a 19-year data record, the quoted accuracy also accounts for the uncertainty in the datum elevation at the control site (denoted by asterisks).

Site	Operator	Inst. Type	Time Range(s)	Record Length (mon)	NWLON Control Station	Instrument Elevation Accuracy (m)	Computed Datum Accuracy (m)	Used for VDatum
Provincetown	USGS	Bubbler System	06/01/2015-05/31/2016	12	Boston	0.076	0.016	no ¹
Sesuit Harbor	USGS	Bubbler System	06/01/2015-05/31/2016	12	Boston	0.076	0.017	no ¹
Chatham	NOAA	MWWL	09/01/2009-08/31/2011	24	Nantucket	0.076	0.012	yes
Herring River	NPS	YSI 6600	05/05/2015-06/18/2015	2	Boston	0.076	0.020	no
Hatches Harbor Unrestricted	NPS	HOB0 U20	07/21/2015-10/19/2015	3	Boston	0.076	0.017	no
Hatches Harbor Restricted	NPS	HOB0 U20	07/21/2015-10/23/2015	3	Boston	0.076	0.018	no
Meetinghouse Pond	NPS	YSI 6600	01/18/2012-02/05/2013	12	Chatham	0.076	0.016*	no

¹Note that although the USGS data from the Provincetown and Sesuit Harbor sites were not used in the creation of VDatum, observations at these sites from prior NOAA tide gauge deployments were used in that process. The station latitudes and longitudes are given in Appendix C, Table 4.

CACO Water Level Stations

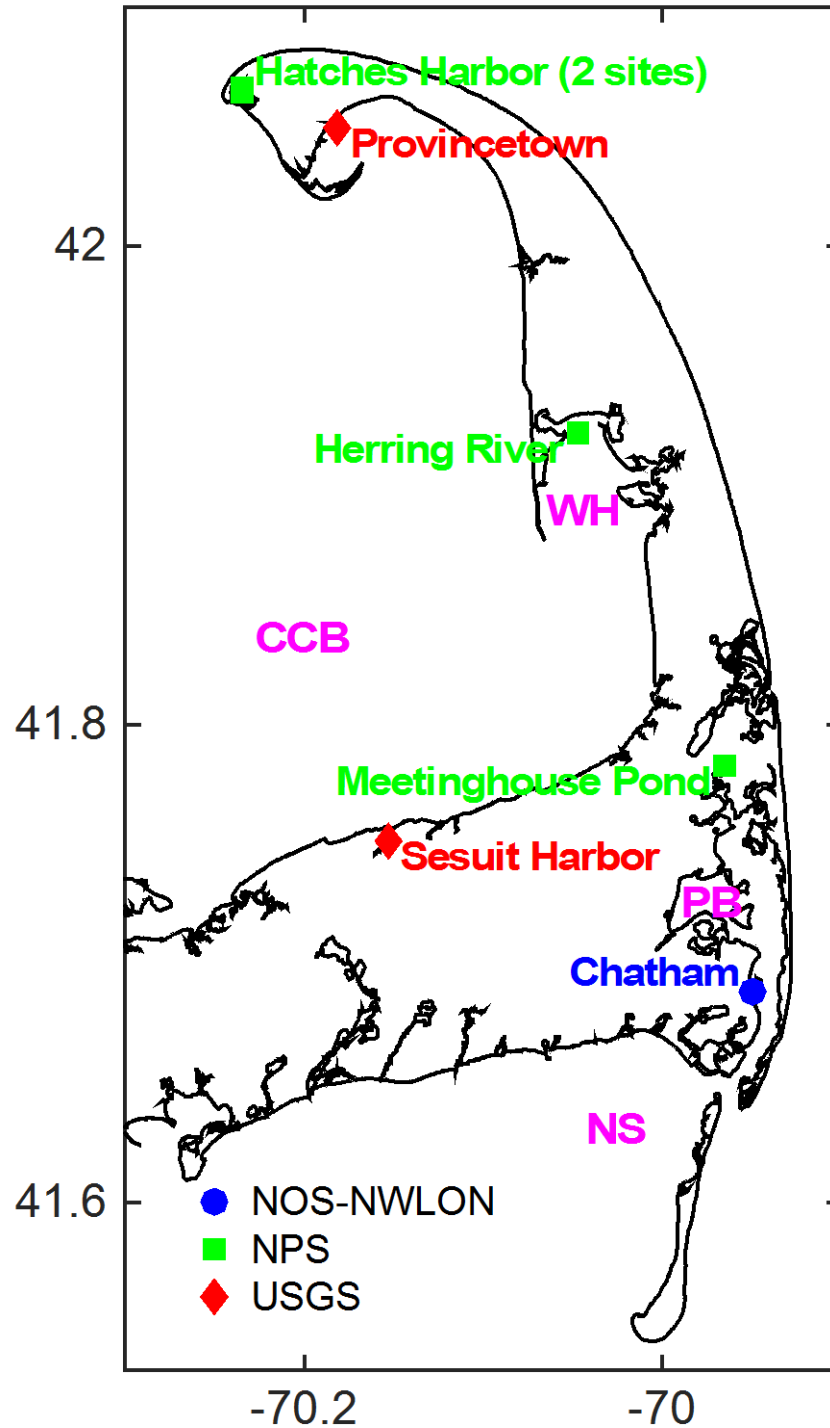


Figure 2. Water level stations in the Cape Cod National Seashore region. The sites are denoted by colored symbols, where the colors indicate the operator of the station. Place names referred to in the text are abbreviated as follows: Nantucket Sound (NS), Pleasant Bay (PB), Cape Cod Bay (CCB), and Wellfleet Harbor (WH).

The two sites at Hatches Harbor are designated as "unrestricted" and "restricted" (Table 1) based on their location in relation to an old dike constructed in the 1930s that completely prevented tidal exchange landward of its location. As shown in Figure 3, the dike is located at the head of a narrow, shallow tidal channel that connects to Cape Cod Bay. The dike has recently been opened by the construction of a culvert that allows exchange between the portions of Hatches Harbor on either side (Smith et al., 2008). The unrestricted site is located just seaward of the culvert, while the restricted site is on the landward side (Figure 3).



Figure 3. Satellite image of the Hatches Harbor region of CACO. The tide gauge locations are indicated by the pin symbols. The tidal connection with Cape Cod Bay is via a shallow tidal channel with entrance near the lower right corner of the map. The inset map shows a zoomed in view of the tide gauge area. An old dike that restricts tidal connectivity to the area around the "restricted" site is seen as the linear feature running from northwest to southeast.

Results

The uncertainty in the elevation of a particular tidal datum is composed of three components: (1) the uncertainty in the instrument elevation relative to the orthometric datum NAVD88, (2) the uncertainty in estimating the datum elevation from short (compared to the 19-year tidal epoch) elevation records, and (3) the accuracy of the water surface measurement relative to the instrument (Ullman et al., 2016). Estimates of components (1) and (2) are given in Table 1. Component (3) was estimated by Ullman et al., 2016 to be approximately 0.01 m, which is much smaller than the uncertainties associated with the instrument elevations and the datum computation (Table 1). From Table 1, the mean uncertainty in computed datum elevation is 0.017 m. Combining this value quadratically with the estimates of instrument elevation uncertainty (0.076 m) from Table 1 and the 0.01 m measurement accuracy yields an overall uncertainty estimate for datum elevations relative to NAVD88 as 0.079 m. This value can be compared with the cumulative uncertainty estimate for VDatum-derived datum elevations provided by NOAA. Averaged over the entire Gulf of Maine VDatum region, the maximum cumulative uncertainty in datum elevations was estimated as 0.132 m (NOAA, 2012).

Maps of datum elevations in the CACO region derived from VDatum illustrate the spatial variability of datum elevations across the area (Figures 4-6). Mean sea level drops by 0.05-0.075 m from the ocean side to the Cape Cod Bay side (Figure 4). This variation is opposite in sign to what is typically observed in other coastal regions (e.g. see Ullman et al., 2016 for examples from other coastal national parks) where sea level generally rises from the ocean towards inner embayments. The mean tidal range (difference between MHW and MLW; Figure 4) increases from just over 2 m in the ocean to approximately 3 m on the western side of Cape Cod in Cape Cod Bay. The tidal range within Pleasant Bay (the embayment at the southeast corner of the Cape) is 0.2-0.4 m lower than the range in the ocean to the east. A similar reduction in tidal range occurs in Nantucket Sound (south of Cape Cod).

Corresponding to the increase in tidal range from the ocean side to the Bay side, the high tide datums (MHW and MHHW; Figure 5) increase in elevation by 0.3-0.4 m from the east side to the west side of Cape Cod. Low tide datum elevations (MLW and MLLW; Figure 6) decrease by 0.4-0.5 m from the ocean side to the Bay side. The opposite occurs between the ocean and Pleasant Bay and Nantucket Sound. Both of these locations exhibit lower high water datums and higher low water datums than are observed in the ocean to the east of Cape Cod.

Comparison of datum elevations from VDatum and from observations at the sites listed in Table 1 show that VDatum provides accurate estimates at some sites and very poor estimates at others (Figures 7-13). At Chatham, the only site in which the observations we used were also used in the VDatum creation process, agreement between VDatum elevations and our estimates is very good, with differences less than 0.03 m for all datums (Figure 9). At Provincetown (Figure 7) and Sesuit Harbor (Figure 8), stations that used NOAA datum elevations as input to the VDatum process (note that we used more recent USGS observations at these sites), the agreement is slightly worse. At these

sites high water datums from VDatum are low by about 0.07 m, MSL is low by approximately 0.04 m, and low water datums are low by 0.01-0.03 m.

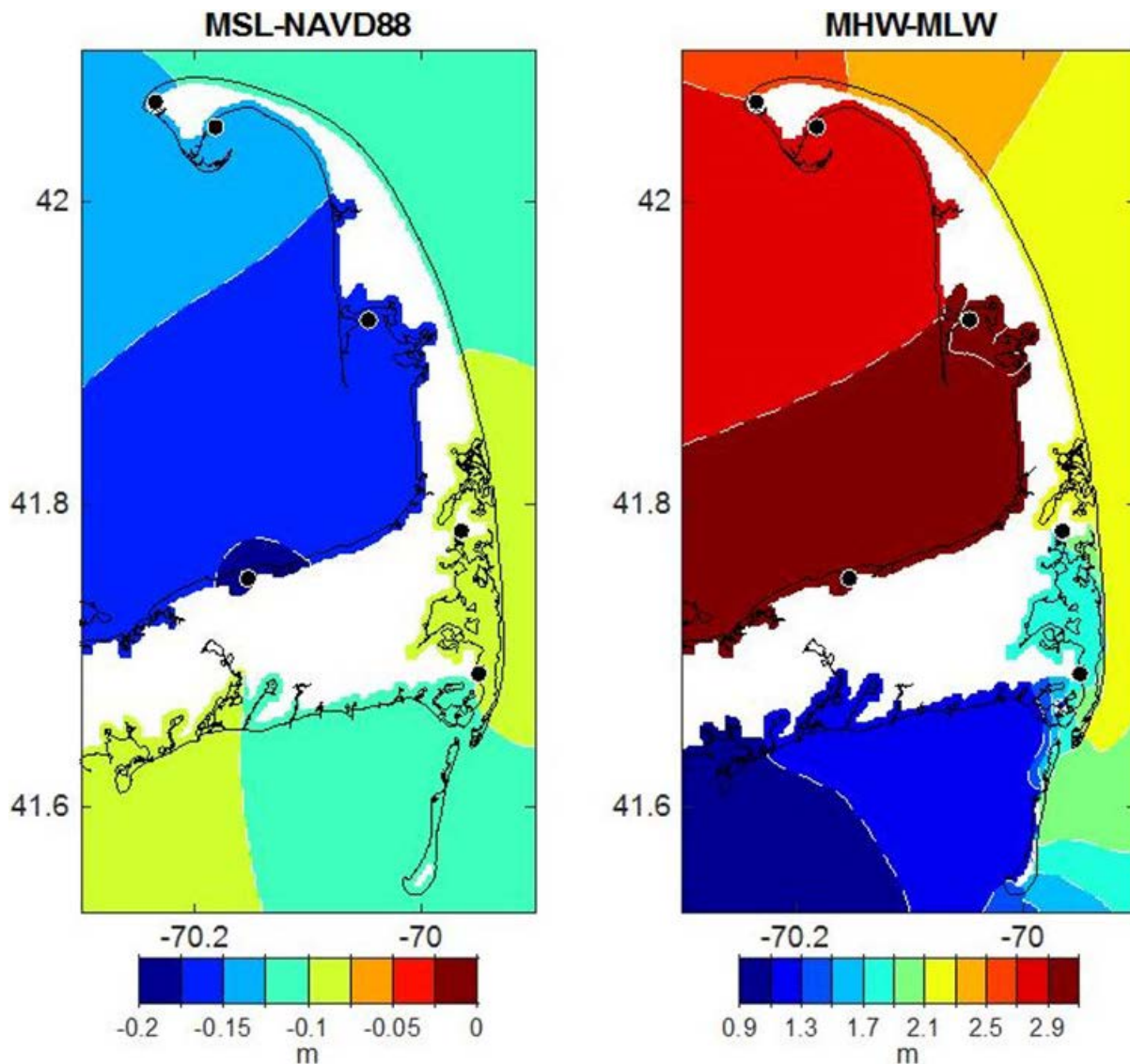


Figure 4. Mean sea level relative to NAVD88 (left) and mean tidal range (right) in the CACO region from VDatum. The black dots show the locations of the water level stations used in the analysis.

At the independent station Herring River (Figure 10), a site in Wellfleet Harbor that is relatively deep, all VDatum elevations are high in comparison to the observations by 0.04-0.08 m. At the two sites in Hatches Harbor (Figures 11-12), datum elevations from VDatum are very different from our observation-based estimates. At the Hatches Harbor Unrestricted site, all VDatum elevations are low, by 0.20-0.25 m for high water datums, 0.80 m for MSL, and approximately 1.7 m for the low water datums. At the Hatches Harbor Restricted site, the high water datums from VDatum are within about 0.05 m of the observed values. However, MSL at this site is low in VDatum by approximately 1.0 m and the low water datums are low by 2.0-2.1 m.

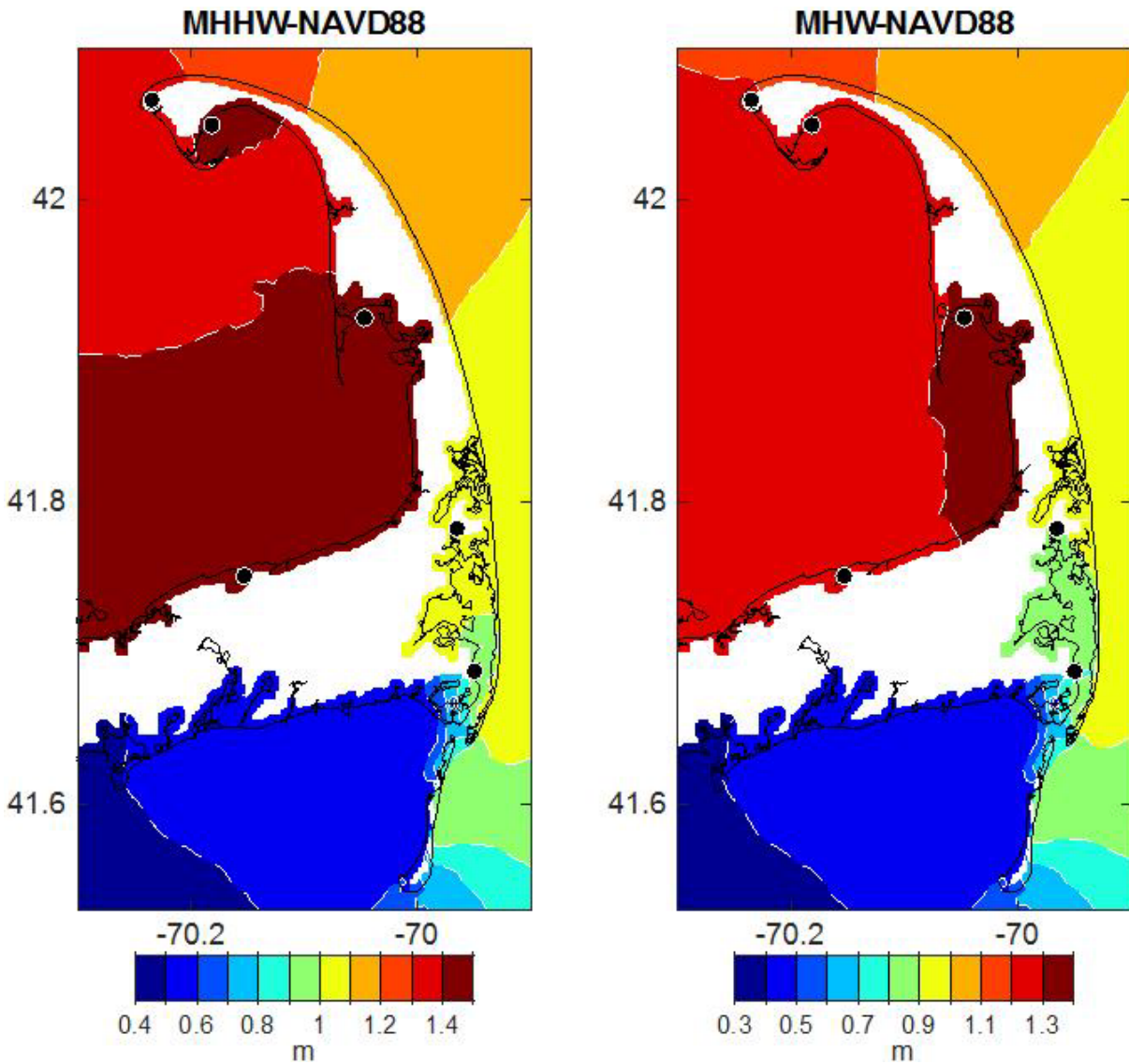


Figure 5. Mean higher high water (left) and mean high water (right) in the CACO region relative to NAVD88 from VDatum. The black dots show the locations of the water level stations used in the analysis.

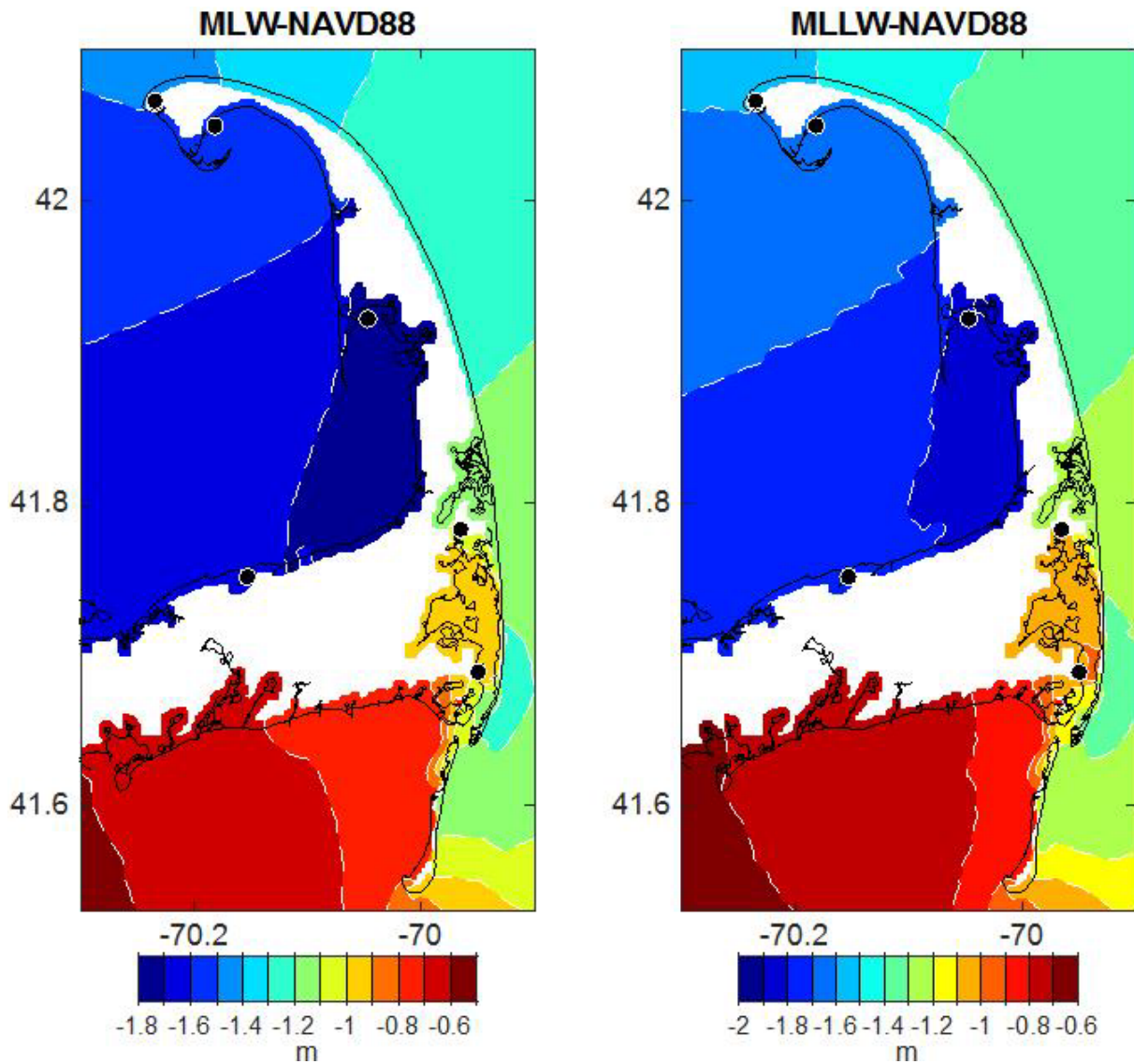


Figure 6. Mean low water (left) and mean lower low water (right) in the CACO region relative to NAVD88 from VDatum. The black dots show the locations of the water level stations used in the analysis.

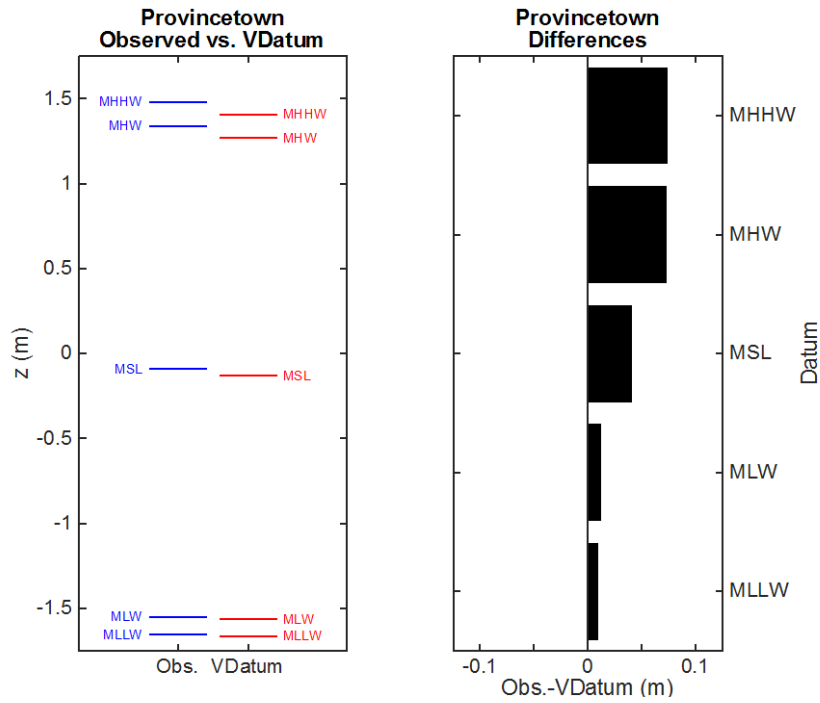


Figure 7. Comparison of datum elevations relative to NAVD88 ($z = 0$) between observations (blue) and VDatum (red) for the USGS Provincetown site. The elevation differences for these datums are shown in the right panel.

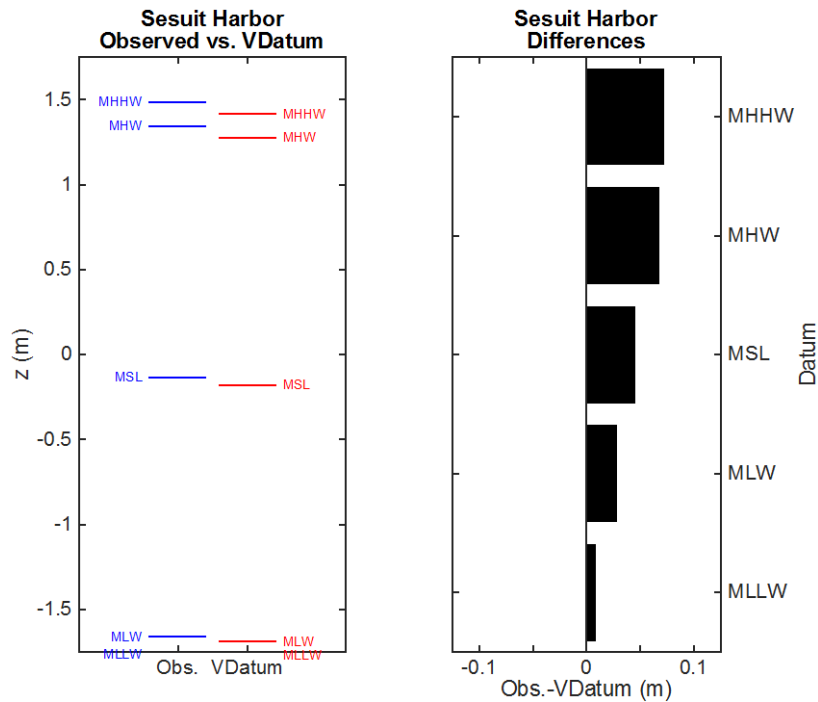


Figure 8. Comparison of datum elevations relative to NAVD88 ($z = 0$) between observations (blue) and VDatum (red) for the USGS Sesuit Harbor site. The elevation differences for these datums are shown in the right panel.

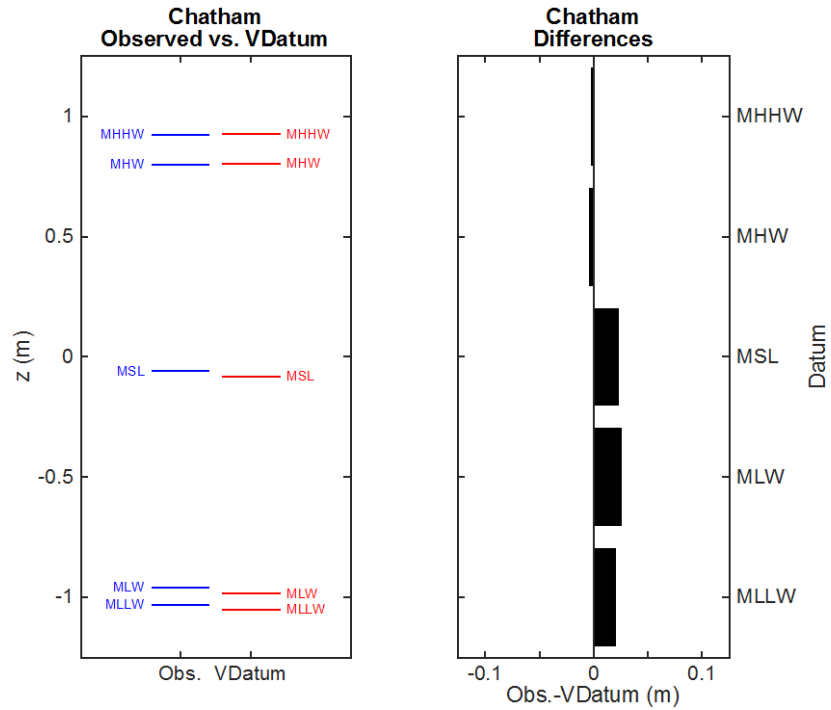


Figure 9. Comparison of datum elevations relative to NAVD88 ($z = 0$) between observations (blue) and VDatum (red) for the NOAA NWLON Chatham site. The elevation differences for these datums are shown in the right panel.

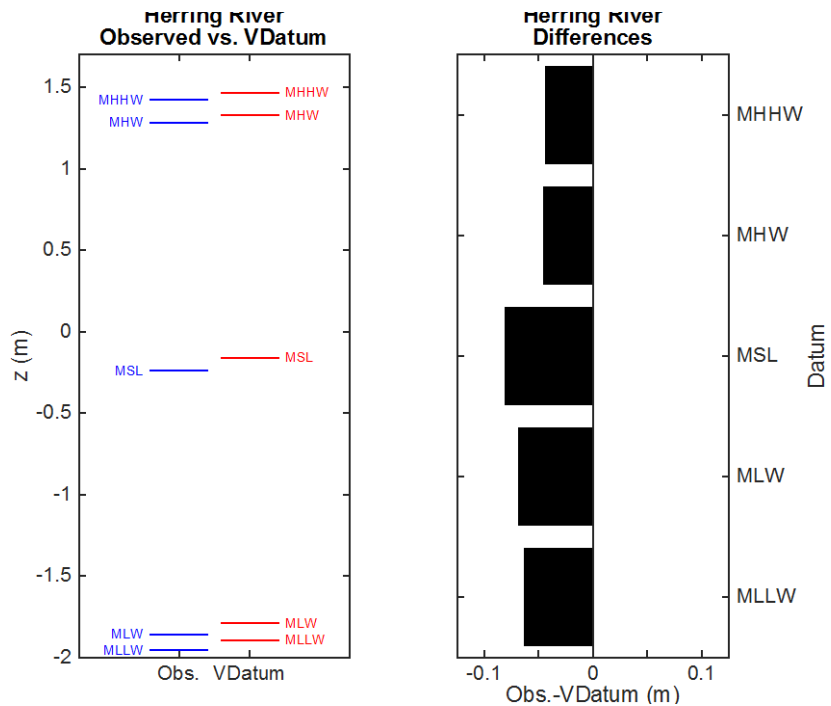


Figure 10. Comparison of datum elevations relative to NAVD88 ($z = 0$) between observations (blue) and VDatum (red) for the NPS Herring River site. The elevation differences for these datums are shown in the right panel.

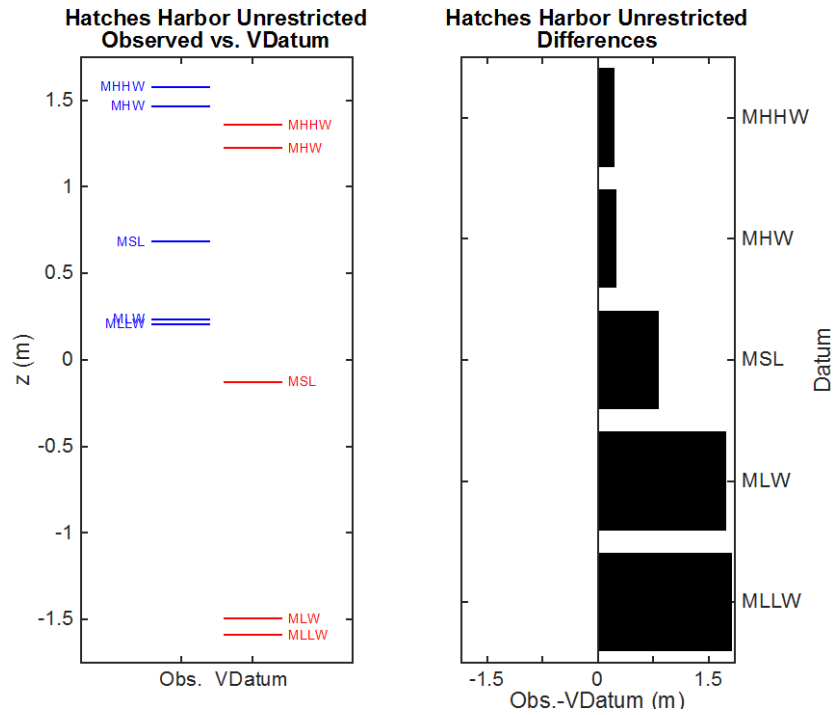


Figure 11. Comparison of datum elevations relative to NAVD88 ($z = 0$) between observations (blue) and VDatum (red) for the NPS Hatches Harbor Unrestricted site. The elevation differences for these datums are shown in the right panel.

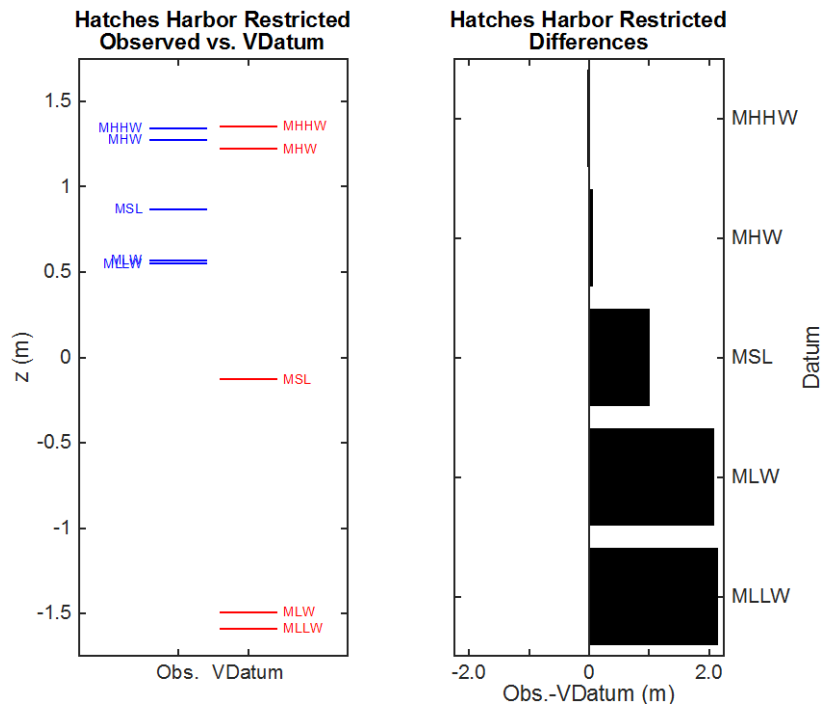


Figure 12. Comparison of datum elevations relative to NAVD88 ($z = 0$) between observations (blue) and VDatum (red) for the NPS Hatches Harbor Restricted site. The elevation differences for these datums are shown in the right panel.

A similar inaccuracy in VDatum is seen at the Meetinghouse Pond site, located at the head of Pleasant Bay. High water datums at Meetinghouse Pond are high relative to observationally-derived datums by 0.07-0.08 m (Figure 13). However MSL in VDatum is low by about 0.17 m and low water datums are low in VDatum by 0.50-0.55 m.

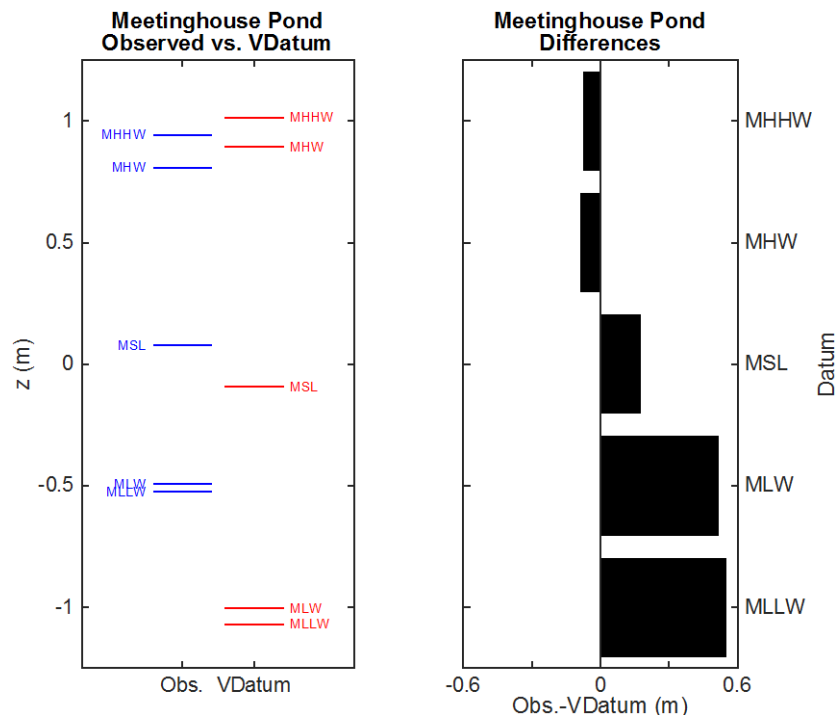


Figure 13. Comparison of datum elevations relative to NAVD88 ($z = 0$) between observations (blue) and VDatum (red) for the NPS Meetinghouse Pond site. The elevation differences for these datums are shown in the right panel.

Differences between observational datum elevations and VDatum values are shown in map form in Figures 14-16. These figures emphasize that VDatum in the CACO region is highly inaccurate in the Hatches Harbor area and the Meetinghouse Pond area but that differences are small at all other sites.

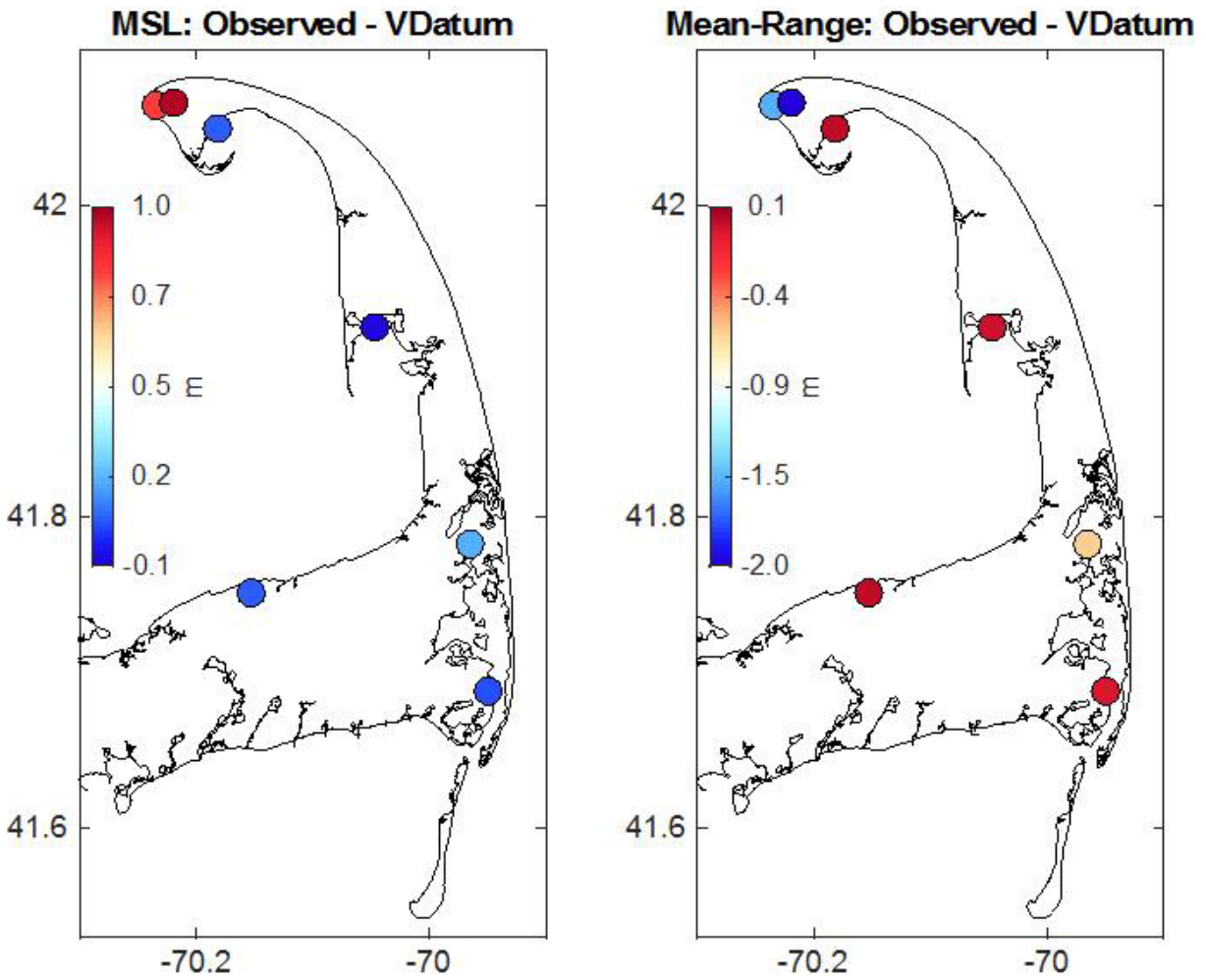


Figure 14. Map views of differences between observed and VDatum MSL (left) and mean tidal range (right), where the colored symbols indicate the difference. Note that the location of the Hatches Harbor Restricted site has been shifted slightly eastward to make it visible.

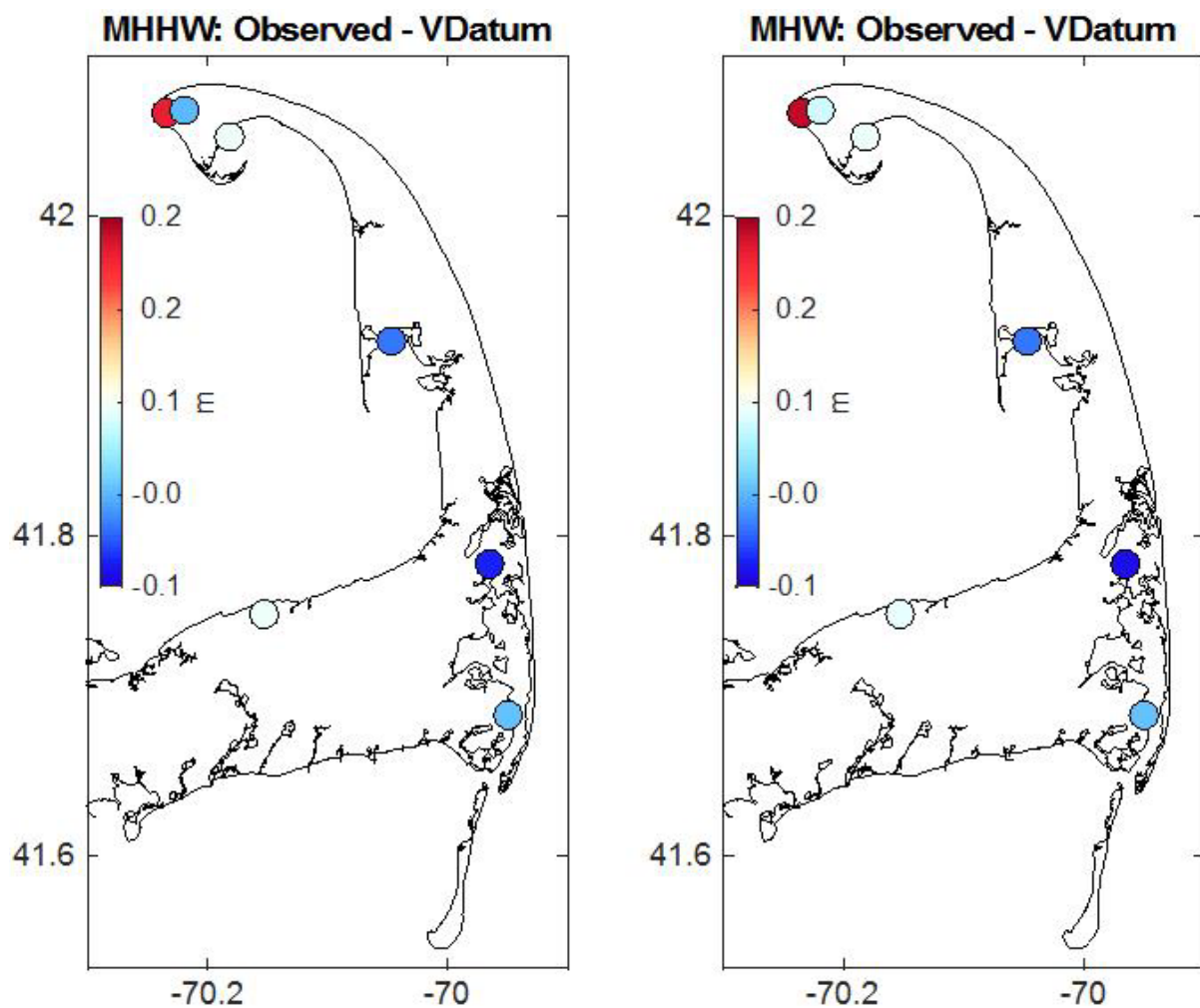


Figure 15. Map views of differences between observed and VDatum MHHW (left) and MHW (right), where the colored symbols indicate the difference. Note that the location of the Hatches Harbor Restricted site has been shifted slightly eastward to make it visible.

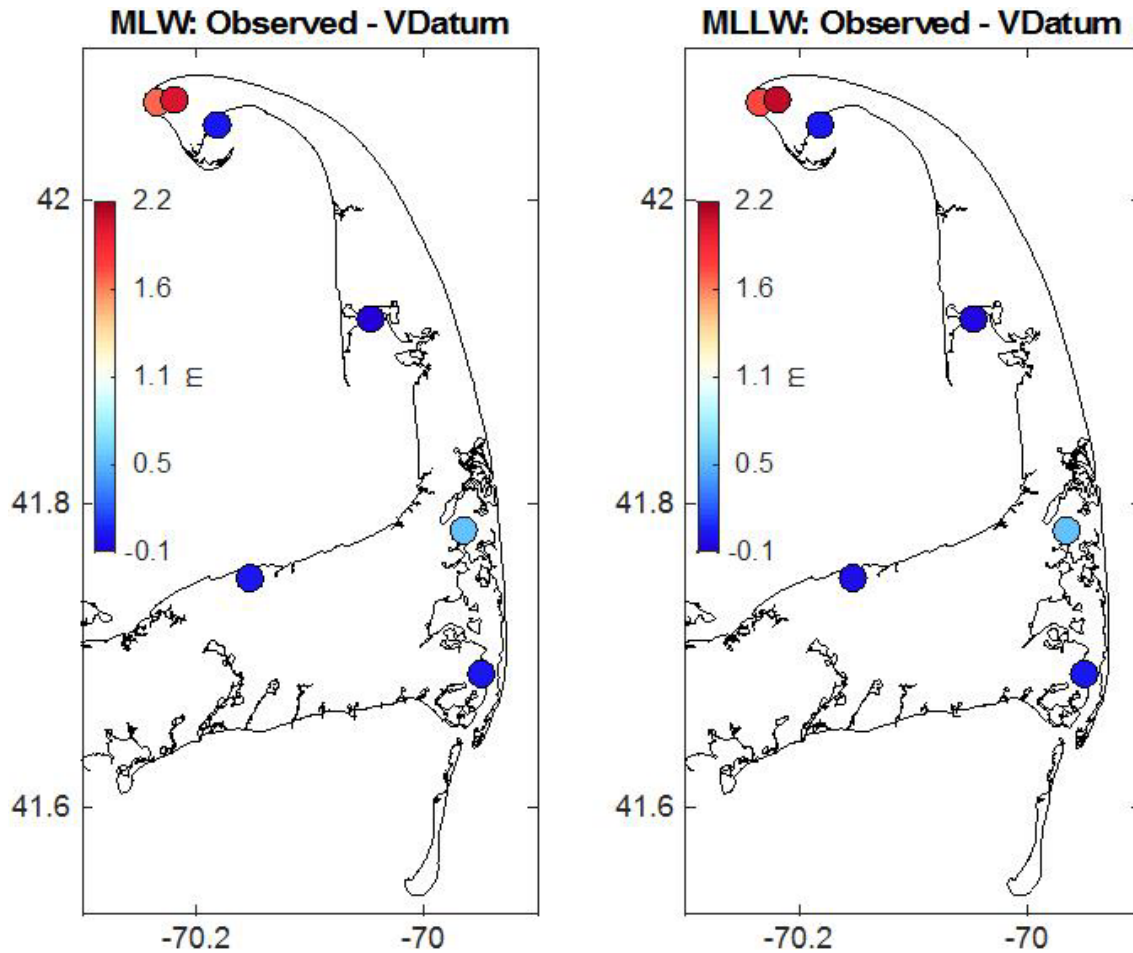


Figure 16. Map views of differences between observed and VDatum MLW (left) and MLLW (right), where the colored symbols indicate the difference. Note that the location of the Hatches Harbor Restricted site has been shifted slightly eastward to make it visible.

The Hatches Harbor sites are located along a small tidal channel feeding a large salt marsh area that is bisected by the dike and culvert referred to above. The "restricted" site is located about 200 m landward of the culvert, while the "unrestricted" site is just seaward of the culvert. The restrictive nature of the culvert to tidal flow is apparent in Figures 11-12, where the observed tidal range is seen to decrease from approximately 1.25 m at the unrestricted site to about 0.75 m at the restricted site only 200 m distant. The entire Hatches Harbor marsh appears not to be resolved in the VDatum model grid (Yang et al, 2013). Thus the VDatum values at these locations would be interpolated from nearby values in the open Cape Cod Bay. It is not surprising that the tidal characteristics would change dramatically from Cape Cod Bay along a shallow channel leading to the location of these sites. If, as suggested from Google Earth imagery (Figure 3), the sea bed in the tidal channel leading to the Hatches Harbor sites is at an elevation higher than that of MLW in Cape Cod Bay (e.g. at Provincetown), then one would expect that at times around low tide the channel would behave as a river. In this case, the water level at low tide cannot become lower than the elevation of the bottom, thus the low water datums at the Hatches Harbor sites would be far higher than those in the open

Cape Cod Bay as can be seen by comparing the low water datum elevations at these sites (Figures 11-12) with those at Provincetown (Figure 7).

The Meetinghouse Pond site is located in a basin at the northern end of Pleasant Bay. The connection to Pleasant Bay is via a winding channel that appears to be quite shallow. Although Pleasant Bay is crudely resolved in the VDatum model grid, the detail does not appear to be sufficient to capture the small scale, shallow channel leading to Meetinghouse Pond. Thus it is likely that a situation similar to that in the Hatches Harbor region pertains here, whereby the water level at low tide cannot fall below the level of the bottom of the tidal channel leading to it. This interpretation is supported by comparison of observed tidal datums at Meetinghouse Pond and Chatham (located in southern Pleasant Bay). Figures 9 and 13 show that MHW is at approximately the same level (0.8 m above NAVD88) at these two sites, but MLW at Meetinghouse Pond is roughly 0.5 m higher than that at Chatham.

The observations available for this study can be separated into two groups, those from stations where the VDatum grid well resolves the bathymetry near the site and those where the VDatum grid appears to be inadequate in resolution. Tables 2 and 3 present respectively the averaged datum elevation errors over the well-resolved group of sites (eliminating the Chatham site which was used in the creation of VDatum) and the same averages over the poorly-resolved sites. At the well-resolved sites (Table 2), mean errors are small, ranging from -0.016 m for MLLW to 0.034 m for MHHW. RMS errors range between 0.037 m and 0.064 m. These errors are small in comparison to the regional VDatum error estimate of 0.132 m (NOAA, 2012). They are also smaller than the 0.079 m estimated uncertainty in datum elevation determined above. At the poorly-resolved sites (Table 3), mean errors range from 0.045 m for MHHW to 1.493 m for MLLW. RMS errors range from 0.134 m for MHHW to 1.643 for MLLW. The low water datums from VDatum at these sites are thus much less accurate than the high water datums. The RMS errors for the high water datums are roughly equivalent to the VDatum error estimate, while those for the low water datums are far larger.

Table 2. Overall averaged datum errors (observed minus VDatum) for the 3 sites in well-resolved portions of the VDatum domain that were not used in the creation of the VDatum solution (Provincetown, Sesuit Harbor, and Herring River). The RMS (root-mean-squared) error accounts for the errors regardless of sign.

Error Measure	MHHW (m)	MHW (m)	MSL (m)	MLW (m)	MLLW (m)
Mean	0.034	0.032	0.001	-0.010	-0.016
RMS	0.064	0.063	0.058	0.043	0.037

Table 3. Overall averaged datum errors (observed minus VDatum) for the 3 sites in poorly-resolved portions of the VDatum domain (Hatches Harbor Unrestricted, Hatches Harbor Restricted, and Meetinghouse Pond). The RMS (root-mean-squared) error accounts for the errors regardless of sign.

Error Measure	MHHW (m)	MHW (m)	MSL (m)	MLW (m)	MLLW (m)
Mean	0.045	0.070	0.660	1.434	1.493
RMS	0.134	0.151	0.749	1.582	1.643

Summary

VDatum in the CACO region was shown to be highly accurate (RMS errors of < 0.07 m) in relatively deep areas where the VDatum model grid accurately captures the bathymetric variability. However, in areas such as Hatches Harbor and Meetinghouse pond where narrow and shallow channels lead to open waters, VDatum does a poor job of estimating datum elevations. At these sites RMS errors for low tide datums are very large (RMS errors of ~ 1.6 m). High tide datums are more accurate (RMS errors of approximately 0.15 m) and are comparable to the VDatum error estimates. Mean sea level at these sites is in error by roughly 0.75 m (RMS).

These results indicate that VDatum cannot be used to accurately estimate tidal datums in shallower, more constricted areas in CACO. In these areas datum computation from observations, such as those used for this study, appears to be necessary to obtain accurate tidal datum elevations.

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Appendix A: Tide Identification and Tabulation Procedure

The procedure for identifying high and low tides in a 6-minute resolution water level record is based on NOS procedures as described by Stephen Gill of NOS (personal communication). The first step is to compute sums over half-hour intervals for the entire record. Sums resulting from less than 5 valid water level values are flagged as invalid. Each half-hour sum is subtracted from the sum from the next half-hour interval with the sign of the difference indicating whether the tide is rising (difference is positive) or falling (difference is negative). If either sum is invalid, the difference is denoted as invalid. If the sign of two consecutive differences changes, indicating that the tide has changed from rising to falling or the reverse, then a candidate tide (high or low) is indicated within the time window (1.5 hours). If a candidate tide is found, data within a time window centered on the central point of the middle half-hour period are analyzed to determine the tide height and time. A time window of 6.5 hours is used if the difference between the highest and lowest water levels within the window is less than or equal to 1 meter. Otherwise, a 2.5-hour window is used. The elevations within the chosen window are fit to a 5th order polynomial and the maximum (for a high tide) or minimum (for a low tide) value of this function is taken as the height of the tide and its time as the time of occurrence of that particular tide. This procedure is repeated for all candidate tides. After the heights and times of all tides have been determined, a screening procedure is applied to eliminate spurious tides. In this process, all tides occurring within 2 hours of another valid tide are removed and sequential highs/lows occurring less than 0.5 days after the previous high/low are removed.

After the identification of all tides in a record, the tides are tabulated into lower and higher low and high tides. For high tides, starting from the beginning of the record, pairs of high tides are compared and the higher of the two is designated as the higher high, with the other tabulated as the lower high. The same procedure is followed for low tides.

Appendix B: Modified Range Ratio Method of Simultaneous Comparison

The first step in the simultaneous comparison procedure is to obtain published datum elevations (so-called accepted datums) and the water surface elevation time series over the time period of the target station at the selected control station. Given monthly mean values of MSL, MTL, DTL, Mn, and Gt at a target station, the first step is to compute monthly mean values of these quantities at the control station for the same months. For MSL, MTL, and DTL, the monthly differences between target and control stations are averaged to get mean differences:

$$\Delta MSL = \langle MSL_T - MSL_C \rangle$$

$$\Delta MTL = \langle MTL_T - MTL_C \rangle$$

$$\Delta DTL = \langle DTL_T - DTL_C \rangle$$

where the subscripts T and C refer to the target and control stations respectively, and the angle brackets denote an average over all months. The mean differences are then used with the accepted datums at the control station to compute corrected datums at the target station:

$$MSL_T^{Corr} = MSL_C^{Acc} + \Delta MSL$$

$$MTL_T^{Corr} = MTL_C^{Acc} + \Delta MTL$$

$$DTL_T^{Corr} = DTL_C^{Acc} + \Delta DTL$$

where the superscripts *Corr* and *Acc* refer to corrected and accepted values.

For the tidal range quantities, Mn and Gt, monthly ratios are computed between target and control and these are then averaged to get mean range ratios:

$$RMn = \langle \frac{Mn_T}{Mn_C} \rangle$$

$$RGt = \langle \frac{Gt_T}{Gt_C} \rangle$$

The corrected ranges at the target station are then computed using the mean ratios and the accepted tidal range values at the control station:

$$Mn_T^{Corr} = Mn_C^{Acc} \times RMn$$

$$Gt_T^{Corr} = Gt_C^{Acc} \times RGt.$$

These corrected datums and tidal ranges at the target station are then used to compute corrected values of MHHW, MLLW, MHW, MLW:

$$MHHW_T^{Corr} = DTL_T^{Corr} + \frac{1}{2}Gt_T^{Corr}$$

$$MHW_T^{Corr} = MTL_T^{Corr} + \frac{1}{2}Mn_T^{Corr}$$

$$MLW_T^{Corr} = MTL_T^{Corr} - \frac{1}{2}Mn_T^{Corr}$$

$$MLLW_T^{Corr} = DTL_T^{Corr} - \frac{1}{2}Gt_T^{Corr}$$

Appendix C: Water Level Station Locations

Table 4. CACO water level station locations. Site numbers, if given, are the NOAA or USGS site identification numbers.

Site	Site Number	Longitude	Latitude
Provincetown-USGS	420259070105600	-70.1822	42.0497
Sesuit Harbor-USGS	414507070091400	-70.1539	41.7519
Chatham	8447435	-69.9500	41.6883
Herring River		-70.0475	41.9220
Hatches Harbor Unrestricted		-70.2357	42.0650
Hatches Harbor Restricted		-70.2340	42.0668
Meetinghouse Pond		-69.9653	41.7831

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

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