As shown in Figure 2, the VDatum software (Milbert, 2002) encodes a four-step traversal path along a minimal spanning tree whose nodes represent the vertical datums grouped into 3D ellipsoidal datums, orthometric datums, and tidal datums: (1) transformations from the 3D ellipsoidal-based reference system datums to the NAD83 (NSRS2007/CORS96) primary datum; (2) transformation between the NAD83 (NSRS2007/CORS96) primary 3D reference system datum and the NAVD 88 primary orthometric datum; (3) transformations between NAVD 88 and the MSL primary tidal datum; and (4) transformations between MSL and the tidal datums. Conversions between the 3D ellipsoidal datums apply 14-parameter Helmert transformations which ascribe the three-dimensional distance, rotation, and scale changes. Data that are referenced to the NAD27 horizontal datum are transformed to NAD83 (NSRS2007/CORS96). The topography of the sea surface (TSS) for each region relates NAVD 88 and local MSL. The TSS is generated by spatially interpolating the NAVD 88-to-MSL differences at water level stations. The NAD83 (NSRS2007/CORS96) and NAVD 88 primary datums are related directly by the user's selection of the following geoid models: GEOID99 (Smith and Roman, 2000, 2001), GEOID03 (Roman et al., 2004), or GEOID09. More information about the 3D reference frame and orthometric datum transformations may be found on the VDatum project webpage, http://vdatum.noaa.gov.

As there are many different types of models and sources of data involved with development of each VDatum application, standard operating procedures (SOP) were created to provide quality control and consistency to the process (Hess, 2007). For VDatum these procedures for development were grouped into the following categories: (1) selecting the region of application, (2) creating VDatum files, (3) placing VDatum files on the Web, (4) updating existing VDatum files, and (5) researching future developments. Creation of the transformation files through modeling and data analysis is addressed in category 2. Standard operating procedures for this category are further broken down into data acquisition, tidal datum modeling, creation of the VDatum gridded tidal datum files, generation of the gridded topography of the sea surface, and quality control and archival. Once a regional application has been developed, the SOP also provides steps to take in validating the quality of the transformation files. This involves not only comparing the transformations against available tidal and geodetic data, but also ensuring that the values are consistent where different VDatum applications overlap. A more detailed list of topics addressed in the SOP for creating VDatum files is provided in Figure 3.

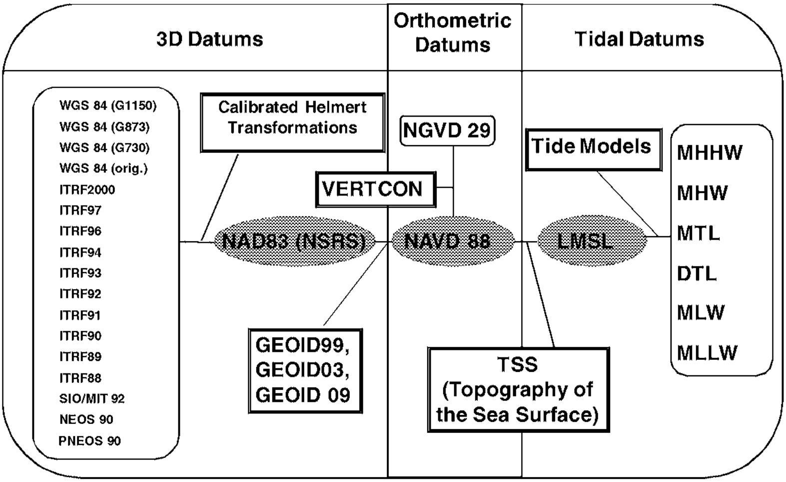

Figure 2. Vertical datum transformation "roadmap" supported in VDatum. Transformation models/equations are shown by the rectangles with double lines.

As vertical datums change over time in regards to both the data and models used in their determination, the VDatum team is evaluating how best to incorporate these changes seamlessly in its operations. Data updates that need to be reflected in an operational VDatum product include changes or new additions of water level gauges, geodetic bench marks, and GPS-determined ellipsoid-based reference heights. Relative sea level change needs to be accounted for through updates on the National Tidal Datum Epoch or to a more frequent adjustment in areas of rapid change, such as in the Gulf of Mexico. Updates to each of the modeling components in VDatum also need to be incorporated in a systematic manner as prescribed in the SOP.

While the SOP has procedures for providing quality control of the transformations, there still is uncertainty in these values. Therefore, the VDatum team has developed the first phase of an approach for evaluating this uncertainty for each of the available VDatum regional applications. Sources of uncertainty were evaluated for each of the components shown in Figure 2. For this evaluation, the standard deviation is the primary statistical variable used to quantify the random uncertainty in both the source data used to establish the vertical datums and of the transformations (double boxed rectangles in Figure 2) between them.

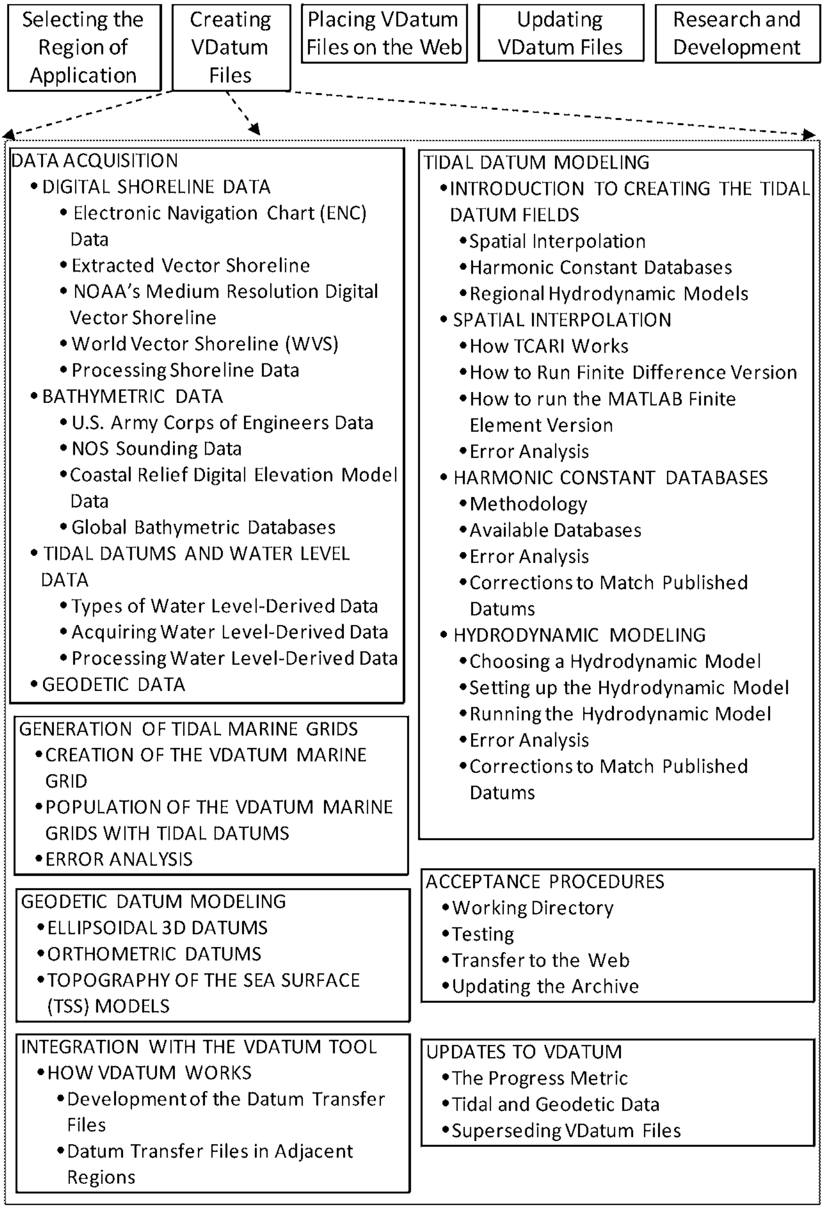

Figure 3. Standard operating procedures itemized for creating VDatum files.

For the tidal datum transformations, the modeled results are corrected to match the tidal datums derived from observations located within the tide model domain. However, there may be some stations that are not included in this correction process, as they may be located outside of the model domain. At stations where the model has been corrected, errors in the tidal datums should be equivalent to errors in computing the datums from observations. At locations away from those NOAA observations used in the corrections to the tidal datum fields, it is more difficult to determine errors. These errors are affected by a variety of factors, including variations in the tidal range, tidal phase differences, bathymetric and coastal features, the density and proximity of nearby stations used in the corrections, and more. NOAA is currently investigating better approximations of these spatially varying errors. These methods include selective removal of data to determine the sensitivity of the corrected fields and various spatial interpolation methods that are guided by the results of the underlying hydrodynamic model of the tides.

To best approximate the tidal datum transformation uncertainties at the present time, though, the preferred approach is to compute the standard deviations of the differences between the tidal datums computed from the uncorrected model and from the observations. Statistics on these errors can provide the user with a sense for what the errors could potentially be at locations away from the stations. It is important to keep in mind that larger model-data errors in any coastal domain are more likely to be seen in upstream river environments, marshes, and areas where the tides may change more rapidly.

Uncertainty estimates for each of the VDatum regions as well as further details on the uncertainty analysis for the other VDatum transformations and source data may be found in the report available from the following VDatum webpage: http://vdatum.noaa.gov/docs/est_uncertainties.html.

VDatum and the Community Modeling Framework

The tide modeling products and work associated with VDatum are considered community tools by the VDatum team. When a regional tide modeling project for VDatum is completed and the associated work has been analyzed and documented, the modeling work and expertise is made available to other community modeling efforts. An example of this has been making the grids developed for the tide models available to be used in other modeling efforts. Through NOAA's Coastal Storms Program, an effort is underway to develop an unstructured grid catalog (UGC) that would serve as a public repository to/from which users could submit/download unstructured grids for hydrodynamic modeling purposes.

The UGC will first be developed for grids in the Gulf of Mexico region. The vision for the UGC in the future is one that will evolve into a nationwide tool and could potentially include structured grids as well. Unstructured grids have been developed in the Gulf of Mexico for a variety of hydrodynamic modeling applications by different agencies, for different mandates, at different scales. Once a model study is complete, there has traditionally been no central mechanism through which the grids and associated project metadata could be catalogued and potentially archived. Considering the amount of work that can go into creating high quality grids, these are valuable resources for the following reasons: (1) it is useful for communities and other modelers to know what has been developed in a given area and for what purpose; (2) shared grid resources can help reduce redundancy in development of new model applications; (3) the grids may be used and/or modified to address different purposes than how the grid was used for its original intent; (4) an unstructured grid catalog pushes forward the concept that model inputs and metadata are an important regional and national asset for identifying storm surge risk and protection of life and property.

The UGC is therefore intended to provide modelers, coastal managers, and funding agencies with a mechanism for the sharing of grids and information about projects to help identify modeling gaps and redundancies. A workshop was held in March 2009 to assess the community interest in the UGC and learn what types of requirements would help make this a successful project. A summary paper of the workshop findings is being circulated to community groups for review, and development of the UGC is commencing so as to be publicly available in 2010. While initial population of the UGC will most likely be from modeling groups (such as the VDatum program) from federal agencies, the goal is to encourage community participation from federal/state/local governments, academia, and the private sector.

The VDatum program has also been active in community efforts aimed at developing consistency in approaches to accurately referencing data and projects to vertical datums. An example of this participation has been coordination with the U.S. Army Corps of Engineers' national effort to update all projects to vertical datums consistent with NOAA's definitions. A Comprehensive Evaluation of Project Datums (CEPD) program was led by the USACE to provide training and guidance to their districts through a collaborative effort with NOAA. Results from the CEPD were further incorporated into the USACE Actions for Change program to implement a nationwide datum and subsidence standard methodology for the Corps, initiate and populate a database, provide and update guidance manuals containing references to elevations and datums, develop a certification process and provide training to reach certification, and develop a standard methodology for updating geodetic and water level information within projects. This interagency collaboration is a critical step towards consistent vertical referencing of data, projects and models that will improve the community effort of standardizing methodology and lead to fewer errors associated with vertical referencing procedures.

Conclusion

The VDatum program involves input components from different sources of data and models, and coordination of expertise from oceanography, geodesy, and hydrodynamic modeling is required to develop a methodology for creating and updating VDatum applications. Standard operating procedures have therefore been developed to help guide this development and operational maintenance. One of the components that the VDatum SOP addresses is the development of tide modeling applications in the computation of spatially varying tidal datums. Tide models are primarily developed using the ADCIRC hydrodynamic model with high resolution grids in coastal and estuarine U.S. waters. Once a model is completed, validated, and adjusted, it is then transferred into operations within the VDatum software. The VDatum team encourages practices that support the legacy of these modeling applications through the community framework. Through NOAA's Coastal Storms Program, a community tool to share the unstructured grids is underway in the Gulf of Mexico. This unstructured grid catalog is intended to facilitate community participation and is designed to evolve into a nationwide tool. Similar community practices are being followed in sharing expertise and methodologies relating to vertical datum computations and transformations, as exemplified by collaboration with agencies such as the U.S. Army Corps of Engineers. Working towards this community framework will continue so as to encourage efficiency towards scientific advancement and dissemination of the products of that science to the public.

Acknowledgments

We would like to thank those in CO-OPS and NGS who have worked extensively over several years to create and supply data to this project. We would also like to thank the USACE Vertical Control Project Delivery Team for leading the collaborative effort in updating vertical control on USACE projects and implementing a methodology for continuing this coordination into the future. We would also like to thank NOAA's Coastal Storms Program for supporting the development of the unstructured grid catalog in the Gulf of Mexico. Thanks as well to the UGC workshop participants for supporting this as a community effort.

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Barotropic Tides and Tidal Datums in Florida Coastal Waters

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The present study simulates barotropic tides and currents in the Florida (FL) coastal waters and the Straits of Florida (SFL) using a high-resolution, two-dimensional version of the Advanced Circulation model (ADCIRC –2DDI). The model domain spans from eastern Gulf of Mexico (GOM) across the SFL to the entire Southern Atlantic Bight (SAB). The finite-element model grid consists of 353,718 nodes and 622,367 triangular elements, with a resolution ranging from 16 m to 41 km. A finely resolved spatial model resolution is an important factor to ensure realistic reproductions of tidal and current fields.

The fields of tidal harmonics, current ellipses, tidal datums, energy fluxes, and the bottom friction dissipation rates are derived from the modeled water level and current time series. The results indicate favorable model-data agreement. In addition to reproducing tidal and current fields, this study focuses on examining the tidal dynamics and energetics over the SFL and its adjacent waters. This study reveals an amphidromic point of the principle solar constituent (K_1) centered around the Bimini Island. It is located offshore the southeast Florid Shelf; its formation is attributed to superposition of tides propagating in opposite directions.

This study identifies that energy in the SFL originates from the SAB. The energy flux is attributed predominantly to the principle lunar semidiurnal constituent (M_2). It propagates into the Straits through three pathways: along the east FL shelf (EFS); a deep channel between islands in the northern Bahamas; and the northeast coast of Cuba. Across the Straits the energy flux progresses from east to west. Once into the eastern GOM, it turns rapidly to a northward direction, then finally turning eastward onto the west FL shelf (WFS).

The shallow, nearshore regions display the strongest energy dissipation rate of the entire domain. The areas of less than 10 m water depth dissipates about 5 GW energy, accounting for over 75 percent of the total tidal energy loss over the entire model domain. Of the rest 25 percent energy loss, waters between 10-50 m depths make 24 percent and even deeper waters cause the remaining 1 percent.

1. Introduction

Florida coastal waters consist of three geographical regions of distinctive tidal dynamic

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features: the WFS along the northeast coast of the GOM; the SFL in the south; and the EFS in the east (Figure 1). Each region exhibits distinctive bathymetric and coastline features. The WFS is broad and gently sloped; it spans over 500 km in the along-shore direction from the Big Bend (BB) to the Florida Bay (FB) and 300 km in the across shelf direction. The isobaths in the area are aligned with local shorelines.

In contrast, the EFS has a limited shelf extension, with an average breadth less than 50 km. The shelf floor displays an upside down triangular shape: being as wide as 200 km in its northern end in the middle SAB and gradually narrow down to nearly immediately hugging the coast in the south. It has a smooth coastline without immense embayments or rough bends. The SFL connects the GOM and the Atlantic Ocean, oriented in a zonal direction. It extends about 250 km in the meridional direction and is bordered by the FL keys in the north and the Cuba coast in the south.

Due to particular geographical locations and bathymetric and coastal line features, the three areas demonstrate distinctive tidal characteristics. As a continuum of the SAB, the EFS belongs to the SAB tidal regime (Blanton et al., 2004). The M_2 constituent dominates the tide in the area. Both semidiurnal and diurnal tides propagate southward parallel to the shoreline in a Kelvin wave-like manner with greater amplitudes on the right-hand (shoreward) side. Along the shelf, the M_2 amplitude reduces monotonically from 1 m in the central SAB to less than 0.3 m over the southern Shelf, whereas the K_1 amplitude reduces from 0.15 m to less than 0.05 m. While the tidal dynamics in the broad SAB has been studied comprehensively (Blanton et al., 2004), many aspects of the tidal dynamics in the southern EFS, such as impacts of the Bahamas on the local tides and tidal energy fluxes, remain unclear.

Over the WFL, the semidiurnal constituents exhibit spatial variability, whereas the diurnal constituents appear to be rather uniform (He and Weisberg, 2002). The former approaches the coast in directions normal to local isobaths. It displays considerable spatial variability, with nearly 1-m tides in the BB and southwest of the Pavillion Keys. In contrast, the diurnal tides propagate from southeast to northwest parallel to local isobaths with nearly constant amplitudes. It is noted that the finest model grid resolution in past studies are 2-6 km (He and Weisberg, 2002), which is insufficient to resolve the fine coastline line features and prohibits accurate reproduction of the tidal fields (Blanton et al., 2004). To overcome the shortcoming, models with higher spatial resolution are needed.

Evidently, the SFL represents a transition region between the north Atlantic and the GOM and plays a crucial role in connecting the EFS and WFS tidal regimes. However, its tidal dynamics are much less studied compared with the WFS and EFS cases. The tidal atlas by Mukai et al., (2002) indicates that the M_2 amplitude reduces from 0.2 m in the east to 0.1 m in west, whereas the K_1 tide remains nearly unchanged. Its tidal dynamics must experience heavy impacts from both tidal regimes. However the influence on and its role in associating the EFS and WFL regimes remain unclear. Questions such as how the tidal energy is transferred through the Straits raise needs for detailed investigations.