ASSESSING THE USE OF MULTI-MISSION OS TIDAL ESTIMATIONS FOR ESTUARIES IN THE NORTHERN GULF OF MEXICO

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Abstract - Measured water surface elevation (WSE) data are a critical for establishing initial and boundary conditions for hydrodynamic models. The lack of tidal stations that collect WSE and other data, oftentimes forces modelers to interpolate or extrapolate these critical data, generating undesired uncertainty in the output of hydrodynamic models. The inexistence of tidal stations in the Northern Gulf of Mexico is more evident than in other parts of the country. Oil-related disasters and other environmental issues have put in evidence the insufficient monitoring of the gulf. Satellite altimeters' capabilities for providing near real-time delivery of OST data could provide needed inputs to hydrodynamic models. This paper assesses the feasibility of using available ocean tide solutions (FES2004 and OTIS OSU) for providing water surface elevation boundary conditions to existing hydrodynamic models of estuaries located in the Northern Gulf of Mexico.

Index Terms - Tides, TOPEX, POSEIDON, FES2004, OTIS

I. INTRODUCTION

The idea of using satellite altimeter data for hydrodynamic modeling is not new. [1] assimilated satellite altimetry into a hydrodynamic model (FES94.1) assimilating empirical Topex/Poseidon (T/P) CSR2.0 tidal solution into the hydrodynamic model. [2] assimilated T/P data into the hydrodynamic model NAO99.0 for modeling ocean tides around Japan. [3] presented a computationally efficient relocatable system for generalized inverse modeling of barotropic ocean tides which required repeated solution of the forward and adjoint linearized shallow water equations (the same equations that are solved by hydrodynamic models). [4] assimilated T/P and other satellite altimeter data into the FUNDY5 hydrodynamic code for removing tides from satellite altimeter observations. [5] enriched a 3-D hydrodynamic model (Princeton Ocean Model, POM) with multi-mission satellite altimeter data.

Measured tide data are critical for establishing initial and boundary conditions for small-scale hydrodynamic models. Although coastal waters (estuaries, bays) receive fresh water inputs from rivers draining to the water body, tidal influences are felt miles upstream the incoming rivers. Hence, the water surface elevations and velocities calculated by hydrodynamic models for estuaries/bays and rivers are also strongly dependent on boundary conditions provided at open-ocean boundaries. However, the lack of tidal stations along the Northern Gulf of Mexico coast forces modelers to interpolate or extrapolate these critical data, generating undesired uncertainty in the output of hydrodynamic models.

The dearth of tidal stations in the Northern Gulf of Mexico is more evident than in other parts of the country. Several modeling efforts that characterized the hydrodynamics of estuaries in the area had to rely on the limited number of tidal monitoring introducing uncertainty bounds to the results that can be avoided if better WSE estimations were available [6][7][8][9]. Also, recent oil-related disasters and environmental issues such as sediment deposition, red tides, etc., have put in evidence the insufficient monitoring of the gulf. Satellite altimeters' capabilities for providing near real-time delivery of ocean surface topography data could provide needed inputs to hydrodynamic models of estuaries. This paper intends to assess the feasibility of using multi-mission OS tidal estimations for estuaries in an area of the Northern Gulf of Mexico close to Mobile Bay, Alabama.

This study will potentially be the seed for developing an operational application of satellite-altimetry-derived data for estimating tidal elevations for a region that lacks these critical data (the Northern Gulf of Mexico) in addition to contributing to research efforts and/or coastal management in other coastal estuaries in the US (and elsewhere) where tidal station data are scarce.

II. STUDY AREA

The area of interest in this review paper is Northern Gulf of Mexico's estuaries at or near Mobile Bay, Alabama (Fig. 1). The area is populated by several estuaries located along the coastal region of southern US states. Although most of the water bodies are located in the Mississippi –Alabama coast (Grand Bay, Mobile Bay, Weeks Bay), one estuary is located in Florida (Perdido Bay). Although several studies have been performed for assimilating satellite altimetry data into meso-scale hydrodynamic models of coastal waters, there are no studies focused on assimilating these kinds of data into small-scale estuary

hydrodynamic models.



Fig.1. Study area. Mobile Bay and several estuaries located along the coast of Mississippi and Alabama (including Perdido Bay FL).

III. LITERATURE REVIEW

Possibly due to the existence of so many hydrodynamic and empirical ocean models using satellite altimeter data for either predicting tides or removing tide effects from satellite observations of the ocean surface, [10] conducted an evaluation of barotropic ocean tide corrections computed using several models (EOTO8a, FES2004, GOTo0.2, GOT4.7, NAO.99b, TPXO.6.2, TPXO.7.1, TPXO.7.2, OSU06). The study was performed for several regions of the world, the Gulf of Mexico (GOM) among them. The results for the GOM showed that percentages of disagreement of the models' output with respect to in-situ measured tidal heights ranged between 9.76% to 31.41%. The authors attributed these discrepancies to the Gulf of Mexico loop currents that transport warm water not captured by large-scale hydrodynamic models.

A. Satellite altimetry in the study area

The problem of satellite altimetry in coastal regions is illustrated in Figures 2 and 3. Figure 2 (after [11]) shows the comparison between Topex/Poseidon measured tidal heights vs heights measured at a coastal tidal station.

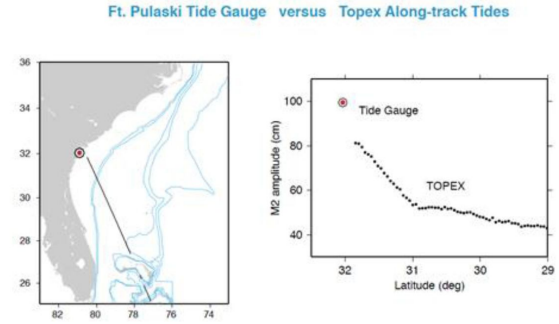


Fig.2. Comparison between Topex/Poseidon measured tidal heights vs heights measured at a coastal tidal station. Ft. Pulaski Tide gauge versus Topex along-track tides (after [11]).

At the left side of the figure, the Topex track is shown in reference to the geographical location of the tide gauge. The right-hand side shows a comparison of T/P M2 tide and M2 measured at the nearest tidal station (Ft. Pulaski, FL) In this particular case, the Topex track passes very near the tidal station allowing a straightforward comparison of measurements and corrections to T/P derived M2 values. However, for the Mississippi-Alabama-Northern-Florida gulf coast (Figure 3) T/P satellite tracks are far away from estuaries that are of environmental/regulatory interest (Mobile Bay, AL, Grand Bay, MS, Weeks Bay, Perdido Bay FL).

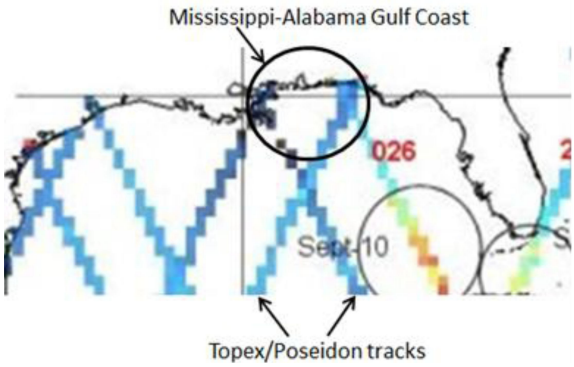


Fig. 3. Topex along-tracks along the Mississippi-Alabama gulf coast and Mobile Bay area (after [12],[13]).

The limitations of large-scale tidal models for generating estimations of tidal heights for the Northern Gulf of Mexico (especially for the Mississippi-Alabama gulf coast) is seen more evidently in Figure 4. This figure was generated by the Colorado Center for Astrodynamics Research [14] Real-Time Altimetry Project for the Gulf of Mexico. CCAR maps are produced from Jason, TOPEX/Poseidon (T/P), Geosat Follow-On (GFO), ERS-2 and Envisat altimeter data processed in near real-time.

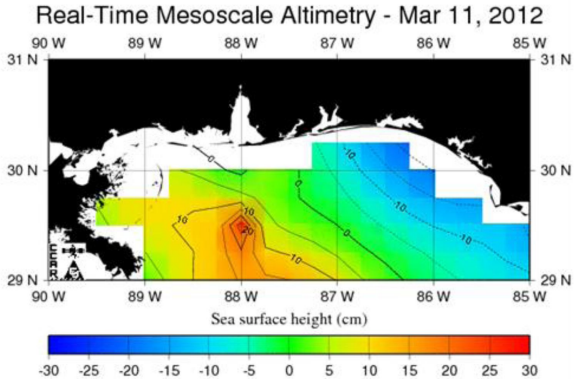


Figure 4. Real-time altimetry for the Northern Gulf of Mexico and Mobile Bay area (after [14]).

As shown in Figure 4, Real-Time Altimetry Project for the Gulf of Mexico produces altimetry data that very coarse near the coast of the Northern Gulf of Mexico. Finer resolution altimetry for the Mississippi-Alabama gulf coast would enhance greatly the applicability of satellite altimeter data for estimating the hydrodynamic regime of small scale estuaries in the region, such as Mobile Bay, Grand Bay, Weeks Bay), and Perdido Bay.

B. Tidal solutions from satellite altimetry

FES2004

This solution uses the barotropic ocean tide corrections computed from FES2004 and OTIS (OSU Tidal Inversion Software). FES2004 is the latest version of the Finite Element Solution tide model called FES. It is a fully revised version of the global hydrodynamic tide solutions initiated by the works of Christian Le Provost in the early nineties [1]. This new version is based on the resolution of the tidal barotropic equations on a new global finite element grid (~1 million nodes) which leads to solutions independent of in situ and remote-sensing data [13]. The accuracy of these solutions was improved by assimilating tide gauge and altimetry data (T/P and ERS-2) through a revised "representer" assimilation method. 15 tidal constituents are distributed on 1/8° grids (amplitude and phase). Twenty-eight other constituents are taken into account by the means of a specific admittance method and a long period wave computation. A new prediction algorithm is distributed within the FES2004 package to provide tidal heights at any location of the world ocean.

OTIS solutions

OTIS implements the efficient "representer" calculation scheme, which forms the basis for a practical relocatable tidal data inversion package. OTIS includes software for generating grids, prior model covariances, and boundary conditions; for solving linear shallow water equations by direct factorization; for tidal processing of TOPEX/POSEIDON altimeter data; for solution of the GI problem; and for computation of posterior error bars. The methods implemented in OTIS are described in detail in [3].

FES2004 and OTIS solutions are available for public download.

C. Existing hydrodynamic models in the study area

Although there are several modeling studies of estuaries along the Northern Gulf of Mexico in this paper we will concentrate on modeling efforts that used the Environmental Fluid Dynamics Code, because it is arguably the most commonly applied model to Gulf of Mexico estuaries for regulatory purposes.

The EFDC model is a public-domain surface water modeling system incorporating fully integrated hydrodynamics, for 1D, 2D, or 3D simulations of rivers, lakes, reservoirs, estuaries, coastal seas, and wetlands (Tetratech, 2002). It is currently used by federal, state and local agencies, consultants and universities.

Ongoing or recent EFDC applications include the Back Bay of Biloxi, MS [16]; Bay St. Louis, MS [17], Escatawpa and Pascagoula Rivers, MS [18]; Mobile Bay, AL [19][20]; Weeks Bay, AL [7][9], Grand Bay [8], Fish River and Weeks Bay [6] and many others. Some of these estuary hydrodynamic models were used to estimate the amount, fate, and transport of oil and dispersants in estuarine environments [9] for several estuaries along the Gulf Coast. Figure 8 shows the results achieved for Grand Bay estuary.

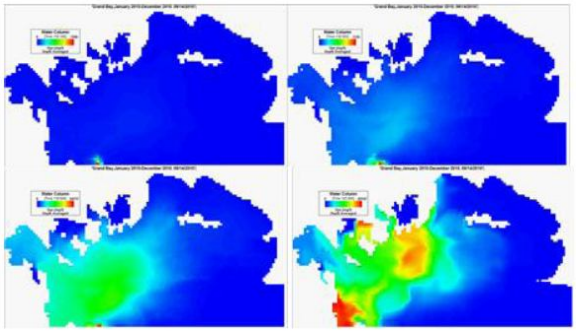


Figure 8. Dye transport experiment using the EFDC model application to Grand Bay, MS. A constant dye concentration is applied at 3 cells located in the lower left ocean boundary (after [9]).

In [9], an EFDC hydrodynamic and dye-transport model consisting of 5202 cells was developed for the Grand Bay (MS) estuary. Several experiments were performed to assess the capabilities of the developed EFDC model application. Constant dye concentrations were applied to several locations along the ocean boundary (Figure 8). The model was set up to receive point-source dye concentrations or non-point source dye concentrations along all the ocean boundary cells (105 cells in total).

In [6] a nested hydrodynamic model of the Fish River, a tributary of the sub-estuary Weeks Bay located in Mobile Bay, Alabama was developed. The Environmental Fluid Dynamics Code (EFDC) and a novel dynamic-coupling tool were used to link three EFDC hydrodynamic models corresponding to Mobile Bay, Weeks Bay, and the Fish River.

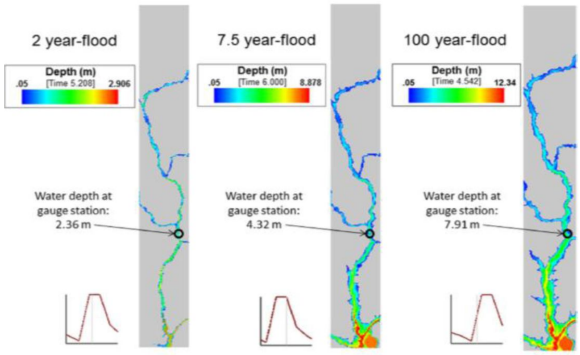


Figure 9. Nested hydrodynamic model of the Fish River, a tributary of the sub-estuary Weeks Bay located in Mobile Bay, Alabama. 2-year to 100-year floods were simulated. Inundation areas for each flood were identified (after [6].

The dynamically-coupled models were used to simulate inundation scenarios for combinations of 2-, 7.5-, 10-, 25-, and 100-year floods, and the hurricane surge that occurred during hurricane Katrina.

The sample EFDC model applications summarized above show that whenever there is ocean altimetry data available, it is possible to generate useful estuary hydrodynamic models. Updated altimetry datasets generated using multi-mission would allow to also update current estuary models for purposes of environmental management or flood assessment and prediction.

IV. PROPOSED METHODOLOGY

Based on the above described tidal solutions and the current EFDC model applications to estuaries in the Northern Gulf of Mexico, it is proposed here a methodology for using multi-mission tidal data to generate ocean boundary conditions that could be used by estuary models.

The method would consist of using two regional (large-scale) tide models for providing boundary conditions to EFDC hydrodynamic models of: 1) Mobile Bay and surrounding Mississippi-Alabama gulf coast, and 2) several small estuaries located along the Mississippi Alabama Gulf Coast (Grand Bay, Mobile Bay, Perdido Bay). This will allow the comparison of results through a range of estuary sizes and computational mesh complexity (see Figure 9).

The boundary conditions (BCs) provided by the large-scale FES2004 and OTIS models will be introduced at the cells located in the ocean boundaries of each of the existing EFDC models (see Figure 7). The FES2004 and OTIS models were chosen based on the evaluation of ocean tide models presented in [10]. FES2004 achieved one of the lowest levels of disagreement (11.95 %) with in-situ tide measurements, while OTIS (a purely empirical estimation) was reported to have the highest level of disagreement (31.41%) from all models included in the study.

The methodology for assimilation of satellite altimeter data would be modified from [22], [23], and [25]. Figure 8 shows a flowchart illustrating the methodology.

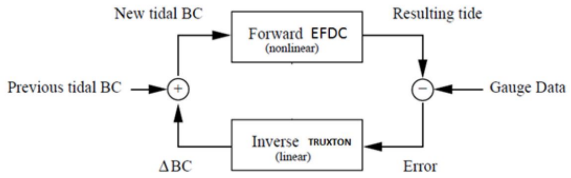


Figure 8. Methodology for assimilation of satellite altimeter data into EFDC estuary models.

The assimilation of vertically averaged satellite altimeter data would be conducted via an iterative inversion strategy. The method assumes that the open boundary condition specified as barotropic elevation is not perfectly known. The prior estimates for boundary conditions generated by the OTIS or FES2004 models would be used to drive the nonlinear forward hydrodynamic model (EFDC). The differences between tidal gauge measurements and EFDC predictions will be input to the inverse model (TRUXTON), which will compute corrections to the boundary conditions in order to reduce the error differences. The next forward model run uses newly obtained BCs and the process is iterated until no further improvement in the missing BCs is possible.
The inverse model TRUXTON is a 2D linear, harmonic, barotropic, frequency domain model [25]. TRUXTON is an exact inverse of a linearized, frequency-domain 2D version of QUODDY which adopts mixing and bottom stress coefficients generated by the forward model (Dunphy et al., 2005). Therefore, TRUXTON only approximates the inversion of EFDC and the iteration is required to make up for this approximation.

To apply the methodology to the study area, the iterative correction of the boundary conditions would be performed by comparison with the EFDC model tidal predictions at these stations: Dauphin Island, Fowl River, Middle Bay Light House, Bayou La Batre, Mobile State Docks, and Perdido Pass. When the iterative process produces negligible differences between measured and EFDC-estimated tidal heights, the boundary conditions will be considered corrected. To validate the corrected boundary conditions, the EFDC model will be used for predicting tidal heights at these stations: Fort Morgan, Bon Secour Bay, Weeks Bay, Grand Bay (NERRS), and Meaher Park. The validation will consist of comparing FDC predictions to tidal heights measured at those stations. Since this study is focused in assessing the use of satellite-altimeter-derived tidal data at the estuary scale, the use of tidal station data will be done at two levels: 1) tidal station data used for correcting boundary conditions, and 2) tidal data stations used for validation of the technique.

CONCLUSIONS

In general, the studies reviewed for this paper coincide in that estimations for coastal areas can be improved greatly with better bathymetry characterization. Higher resolution grid and improved bathymetry may resolve the small scale localized effects of strong topographic features. The literature review shows that FES 2004 and OTIS solutions may help overcome the inexistence of tidal stations in the area, and current absence of high resolution bathymetric information.

The fact that both, FES2004 and OTIS, are in the public domain makes them attractive to explore further the feasibility of using them for generation of tidal heights that could be used by estuary models in the Northern Gulf of Mexico. Future studies should seek applying the methodology outlined in this review paper.

REFERENCES

[1] Le Provost, C., Lyard, F., Molines, J.M., Genco, M.L. & Rabilloud, F. 1998. A hydrodynamic ocean tide model improved by assimilating a satellite altimeter-derived data set. Journal of Geophysical Research, 103, 5513–5529.

[2] Koji Matsumoto, Takashi Takanezawa and Masatsugu Ooe, 2000. Ocean Tide Models Developed by Assimilating TOPEX/POSEIDON Altimeter Data into Hydrodynamical Model: A Global Model and a Regional Model around Japan, Journal of Oceanography. Volume 56, Number 5, 567-581, DOI: 10.1023/A:1011157212596.

[3] Egbert, G.D. & Erofeeva, S. 2002. Efficient inverse modelling of barotropic ocean tides. Journal of Atmospheric and Oceanic Technology, 19, 183–204. http://volkov.oce.orst.edu/tides/

[4] Foreman, M.G.G., Thomson, R.E., Smith, C.L., 2000. Seasonal current simulations for the western continental margin of Vancouver Island. Journal of Geophysical Research 105 (C8), 19, pp. 665–19,698.

[5] Han, G., S. Paturi, B. de Young, Y. Yi, and C.-K. Shum, 2010. A 3-D Data-Assimilative Tidal Model of the Northwest Atlantic. Atmosphere-Ocean 48 (1) 2010, 39–57, doi:10.3137/OC303.2010

[6] Alarcon V. J., Johnson, D., McAnally, W., van der Zwaag, J., Irby, D., Cartwright, J., 2014. Nested hydrodynamic modeling of a coastal river applying dynamic-coupling. Water Resources Management, 28(10), 3227-3240. DOI: 10.1007/s11269-014-0671-6

[7] Alarcon, V. J., McAnally, W. H., and Pathak, S., 2012. Comparison of Two Hydrodynamic Models of Weeks Bay, Alabama. Lecture Notes in Computer Science, LNCS 7334, 589-598. DOI: 10.1007/978-3-642-31075-1_44.

[8] Alarcon, V. J., and McAnally, W. H., 2012. Using Hydrodynamic Modeling for Estimating Flooding and Water Depths in Grand Bay, Alabama. Lecture Notes in Computer Science, LNCS 7334, pp. 578-588. DOI: 10.1007/978-3-642-31075-1_43

[9] Alarcon, V. J., Xiong, Y., Martin, J., McAnally, W., 2011. Amount, Fate, and Transport of Oil and Dispersants in Estuarine Environments. http://coaps.fsu.edu/pub/eric/BP%20NGI%20Phase%20II/MSU/Understand/New%20CUA%20Fate&%20transport%20Modelalarcon_xiong_martin.pdf

[10] Fok, H. S., H. B. Iz, C. K. Shum, Y. Yi, O. Andersen, A. Braun, Y. Chao, G. Han, C. Y. Kuo, K. Matsumoto, and Y. T. Song, 2010. Evaluation of Ocean Tide Models Used for Jason-2 Altimetry Corrections, Marine Geodesy, Volume 33, Supplement 1, 2010, pp 285-303, DOI: 10.1080/01490419.2010.491027

[11] Ray, R. D., 2008. Thoughts on Tidal Corrections for SWOT, NASA Goddard Space Flight Center, http://bprc.osu.edu/water/Meetings_WATERHM/SubMesoscale_April2008/presentations-day3/RAY.pdf

[12] AVISO, 2012a. Hurricane Ike seen by Jason-2. http://www.aviso.oceanobs.com/en/news-storage/news-detail/index.html?tx_ttnews[tt_news]=349&tx_ttnews[backPid]=276&cHash=vxxjemisap

[13] AVISO, 2012b. FES (Finite Element Solution)- Global tide. http://www.aviso.oceanobs.com/index.php?id=1279

[14] Colorado Center for Astrodynamics Research, CCAR, 2012. Real-Time Altimetry Project: Gulf of Mexico Near Real-Time Altimeter Viewer. http://argo.colorado.edu/~realtime/gsfc_gom-real-time_ssh/

[15] Tetratech, Inc. Draft user's manual for environmental fluid dynamics code Hydro Version (EFDC-Hydro) Release 1.00. Tetra Tech, Inc., Fairfax, Virginia, 2002.

[16] MDEQ. 2002. "Fecal Coliform TMDL for the Back Bay of Biloxi and Biloxi Bay Coastal Streams Basin Harrison and Jackson Counties, Mississippi," Department of Environmental Quality, Office of Pollution Control, Jackson, Mississippi

[17] MDEQ. 2001. "Fecal Coliform TMDL for St. Louis Bay, Jourdan River (Phase Two), and Wolf River (Phase Two)." Coastal Streams Basin. Hancock, Harrison, and Pearl River Counties, Department of Environmental Quality, Office of Pollution Control, Jackson, Mississippi.

[18] Huddleston, D.H., Z. Liu and W. L. Kingery. 2007. "Application of St. Louis Bay water quality model to develop TMDLs for tributaries," Prepared for Mississippi Department of Environmental Quality, Office of Pollution Control, Jackson, Mississippi, June 2007.

[19] Rodriguez Borrelli, Hugo, James M. Greenfield, and Jamie Miller. 2006. "Using Biology and Hydrodynamics to Establish a Site Specific Dissolved Oxygen Criterion for the Escatawpa River And Estuary – Gulf Of Mexico," Presented at the XXX Congreso Interamericano De Ingeniería Sanitaria Y Ambiental, Punta del Este – Uruguay

[20] Wool, T.W. 2003. "TMDL Development for a Stratified Shallow Estuary: Mobile Bay Case Study," U.S. Environmental Protection Agency, Region 4, Presented at TMDL 2003

[21] Wool, Tim A., Steven R. Davie, Yuri M. Plis, and John Hamrick. 2004. "The Development of a Hydrodynamic and Water Quality Model to Support TMDL Determinations and Water Quality Management of a Stratified Shallow Estuary: Mobile Bay, Alabama," U.S. Environmental Protection Agency, Region 4, Atlanta, GA. 2004.

[22] He, R., and J. L. Wilkin (2006), Barotropic tides on the southeast New England shelf: A view from a hybrid data assimilative modeling approach. Journal of Geophysical Research: Oceans, Volume 111, Issue C8, CiteID C08002 l.

[23] Gecek, S. and T. Legovic, 2010. Towards carrying capacity assessment for aquaculture in the Bolinao Bay, Philippines: A numerical study of tidal circulation. Ecological Modelling, 221 (2010) pp. 1394–1412.

[24] Dunphy, M., F. Dupont, C. G. Hannah, D. Greenberg. Validation of a Modelling System for Tides in the Canadian Arctic Archipelago. Canadian Technical Report of Hydrography and Ocean Sciences 243, Ocean Sciences Division, Maritimes Region, Fisheries and Oceans Canada. Bedford Institute of Oceanography, Dartmouth, N.S. Canada.

[25] Lynch, D. R. and Hanah, C. G., 2001. Inverse Model for Limited-Area Hindcasts on the Continental Shelf. Journal of Atmospheric and Oceanic Technology 18(6) DOI: 10.1175/1520-0426(2001)018<0962:IMFLAH>2.0.CO;2

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