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# Obtaining instantaneous water levels relative to a geoid with a 2D storm surge model

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ABSTRACT

Current and new applications of 2D storm surge models such as the Dutch Continental Shelf Model (DCSM) require that the models provide proper estimates of the instantaneous water levels expressed relative to a particular geoid, rather than only the tide and surge components expressed relative to the ill-defined model's zero height surface. For DCSM, this is realized by adding the depth-averaged horizontal baroclinic pressure gradients to the model equations, which are derived from 4D salinity and temperature fields provided by the Proudman Oceanographic Laboratory hydrodynamic model (POL's hindcast). The vertical datum of the extended model is fixed to that of the European Gravimetric Geoid model 2008 (EGG08). This is done by an adjustment of the model parameters that depend on the choice of the reference surface (e.g., bathymetry) and by referring the water levels along the open boundaries to this reference surface. Using different numerical experiments we investigate the effects on the water levels of several approximations we have made during the implementation. The ability of the model to reproduce both the mean sea level (MSL) and instantaneous water levels is assessed by a comparison with the MSL derived from POL's hindcast as well as with instantaneous water levels acquired by various radar altimeter satellites. From this comparison we conclude that our modeled MSL is in good agreement with the MSL derived from POL's hindcast; the standard deviation of the differences is below 2 cm. However, larger differences in MSL are observed when comparing the model output with the MSL derived from radar altimeter data. They are attributed to either geoid errors or errors in the used salinity and temperature fields. The root mean squared (rms) differences between observed and modeled instantaneous water levels over the entire model domain varies from 9 cm for data acquired by the TOPEX satellite to 11 cm for data acquired by the GFO-1 satellite. These numbers improve to 8–10 cm on the North Sea, for data acquired by the TOPEX and ERS-2 satellites, respectively. These numbers are a factor two to three larger than the expected accuracy of water levels derived from radar altimeter data (which is $\sim 4$ cm). About 25% of these differences can be explained by a bias between the modeled and observed water levels of a single satellite pass. These biases are attributed to errors in the applied correction for the net steric expansion/contraction of the global oceans as this is not captured by DCSM that makes use of the Boussinesq approximation, as well as other errors in model and data.


## 1. Introduction

In this paper, we aim to obtain proper estimates of the instantaneous water levels in a uniquely defined 3D coordinate system (e.g., the European Terrestrial Reference System ETRS89 in combination with the GRS80 ellipsoid) from a 2D storm surge model. In the North Sea, characterized by strong tides and storm surges, such models are often used for real-time prediction of tides and surges. The models typically solve the depth-integrated shallow water equations, assuming that the water density is uniform in both space and time (Heaps, 1983; Engedahl, 1995; Vested et al., 1995; Flather, 2000). Ignoring this "baroclinic forcing" is motivated by the fact that both the magnitude and temporal variability of the associated steric sea level changes in the North Sea are much lower than the dominating tide and surge signals. Hence, these variations are not relevant to short-term storm surge predictions, though some pragmatic approaches exist to account for the dominant time-varying contribution (see Section 3 for an example).

A further "limitation" is that storm surge models, usually, do not provide absolute water levels, i.e., water levels in a 3D coordinate system. Such water levels can be easily obtained as soon as the model's reference surface is uniquely described in a 3D coordinate system. Often, this surface is identified with mean

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sea level (MSL) (e.g., Mouthaan et al., 1994; Heemink et al., 2002; Iliffe et al., 2007; Dodd et al., 2010), which can be described in a 3D coordinate system by making use of radar altimeter data. However, while the dynamics of the models usually assume zero horizontal gravity components, this interpretation cannot be correct. Indeed, vanishing horizontal gravity components imply the model's vertical reference surface is an equipotential surface of the Earth's gravity field (a so-called geop). This has already been noticed by Hughes and Bingham (2008). Geops close to MSL (so-called geoids) are often used as natural reference surface for onshore height systems, see Hofmann-Wellenhof and Moritz (2005) for a thorough introduction or Meyer et al. (2006) for a brief summary. Like the MSL, a geoid is an observable reference surface that can be uniquely described in a 3D coordinate system. Since both the model's reference surface and a geoid are geops, the most natural way to obtain a model that provides absolute water levels is when the model is adjusted such that its reference surface can be identified with a geoid.

Until now, one dealt with this issue in a pragmatic way in case properly referenced water levels are required. For example, to assess the predicted height of the water level induced by a predicted storm surge in order to decide whether or not storm surge barriers need to be closed, absolute water levels relative with respect to the onshore height system reference surface (a geoid) are necessary. These are obtained by evaluating the predicted surge at the locations of nearby tide gauge stations of which the tide gauge benchmarks are known in the onshore height system. Here the predicted surge, computed as the difference between two model runs with as driving forces (i) astronomical tide and meteorology (wind and mean sea level pressure variations) and (ii) astronomical tide only, is added to the predicted astronomical tide, obtained by a harmonic analysis of the tide gauge data using a pre-defined set of tidal constituents. Indeed, since the constituents are directly derived from the observed water levels (that contain the sum of all effects including steric), the derived zero-frequency constituent represents the total MSL expressed relative to the vertical reference surface of observed water levels. Consequently, the water levels obtained by adding the predicted surge to the predicted tide will be properly referenced. Moreover, this approach even accounts for a part of the time-varying steric sea level changes, since this variability has energy at the same frequencies of some tidal constituents used in the harmonic analysis.

Although such pragmatic approaches to account for steric water level variations and to obtain absolute water levels suffice for storm surge applications, they are not adequate for additional applications in coastal engineering, hydrography and geodesy. For example, one major drawback of the above described workaround to obtain absolute water levels is that it can only be applied at those tide gauge stations whose benchmarks are fixed in a 3D coordinate system. For some applications this is not sufficient; these need estimates of the instantaneous water levels expressed relative to a well-defined geoid everywhere. Of course, other workarounds can be found, but from a conceptual point of view this is not satisfactory. It is much clearer if these can be avoided and the definition of the model's vertical datum becomes an intrinsic feature of the model itself. Moreover, avoiding workarounds is needed to satisfy the higher and ever increasing accuracy requirements. The following examples of applications require sub-decimeter accuracy for instantaneous and mean water level computations.

One hydrographic application, thoroughly treated in Slobbe et al. (in press), is the derivation of the separation between the chart datum (CD) and a reference ellipsoid in coastal waters and estuaries. Such a "separation model" is needed to enable the reduction of observed water depths to CD using GNSS (Wöppelmann et al., 1999; FIG Commission 4 Working Group 4.2, 2006; Dodd and Mills, 2011; Turner et al., 2010). In deep water, the ellipsoidal heights of CD are obtained by adding to the ellipsoidal heights of MSL the separation between MSL and CD derived from a global ocean tide model. Along the coast and in estuaries, however, no ellipsoidal heights of MSL are available due to a lack of reliable radar data. Since the geoid is globally defined, the most straightforward approach to obtain the ellipsoidal heights of CD is by modeling CD directly relative to the geoid and add this separation model to the geoid undulations. In Slobbe et al. (in press), it is also shown that in the North Sea, the low water levels frequently deviate from the adopted CD. As suggested by technical resolution 3/1919 of the International Hydrographic Organization (IHO) (International Hydrographic Organization, 2011), in such a case another surface might be used as CD. In Slobbe et al. (in press), a CD is proposed that is defined as a level which is exceeded with a given fixed probability. In order to compute the ellipsoidal heights of this surface, a model is required that provides instantaneous water levels expressed relative to a geoid. Another application, relevant to a broader community, is to reference water levels at offshore locations properly. Currently, these water levels refer to MSL, which is realized by adjusting them to the mean computed over the measurement period. This period, however, needs to be sufficiently long before the initial mean can be computed and the data can be used. Furthermore, while only by averaging over longer time spans the mean gets closer to the actual MSL, the datum is commonly recalculated over time, resulting in discontinuities in the time series. By using a properly referenced model that includes steric effects, the water levels can be expressed relative to the geoid from the first measurement day.

To a first approximation, instantaneous water levels relative to a particular geoid can be obtained in a post-processing step by adding to the modeled water levels the time-mean steric water levels expressed relative to that geoid (the dominant time-variable steric water level variations can be added using conventional workarounds (Section 3)). This contribution needs to be derived from a circulation model whose model domain comprises that of the 2D storm surge model being used (no reliable radar data are available in coastal zones and estuaries). However, irrespective whether observations or a model is used, the main problem is that all contributions to the time-mean water levels other than steric (mainly astronomical tide and the contribution induced by meteorological forcing) need to be excluded. As long as the astronomical tide and meteorological forcing contributions on the one hand and the steric contribution on the other hand are linearly additive, excluding their contributions from the total time-mean water levels is straightforward. This is, however, not likely. Anyway, unless we have access to the model used to compute the total time-mean water levels, we cannot obtain the time-mean water levels induced by tide and meteorological forcing only. Deriving them using our 2D storm surge model comes down to a replacement of its mean water levels by those obtained from the circulation model. As a consequence, any contribution of the 2D storm surge model to an improved representation of the mean water levels is ignored, which is undesirable. Besides that, another important disadvantage of this approach is that the steric contribution is assumed to be static. This means not only that the modeled water levels lack the time-varying contribution of the water density gradients, but also that the modeled water levels become dependent on the time span used to compute the time-mean steric water levels.

In this paper, we present an alternative approach to obtain a 2D storm surge model that provides estimates of the instantaneous water level relative to a particular geoid. Basically, the approach involves two steps. First, we explicitly add to the model the baroclinic forcing by adding the depth-averaged baroclinic pressure gradient terms as diagnostic variables computed from