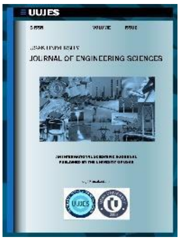

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*Research article*

# A STUDY ON THE TIDAL BEHAVIOR OF THE IZMIR BAY WITH AN OPEN-SOURCE MODEL

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## Abstract

In this paper, tidal behavior of Izmir Bay modeled by open source ADCIRC - Advanced Circulation Model. The source code of the ADCIRC installed on a local computer, the preparation of the files will be used as input required for the model simulation, the creation of the calculation grid, the coefficients representing the open boundary conditions, and the obtaining of the bathymetry data were made and cloud-based and open-access DesignSafe CI environment was also used to run the simulations. The results are compared with observed data at Izmir Mentes Mareograph Station and simulations of different time intervals and periods were graphed with the help of FORTRAN based FigureGen visualization tool.

***Keywords:*** *Modelling, Sea, Tide, ADCIRC.*



## 1. Introduction

It is important to consider the effects of tide in the study of sea movements. The effect of tide and atmospheric parameters must be considered as a whole on level changes and wave effects in the sea. At the same time, knowing the changes that may occur only with the tidal effect without being under atmospheric effects makes a more detailed examination possible.

According to Hendershott, ocean waters are affected by forces occurred because of gravity and tidal waves occurred for long period[1]. For a coastal area, currents and water heights

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occurred from tidal effects can be dominant or they can be observed as circulation in background which affects coastal dynamics in overall perspective. For lots of applications such as military operations, fisheries and navigation; prediction of tidal activities is a necessary component [2].

Izmir is the 3rd largest city or Turkey with a port which is very important to international trade and resides in an "L-Shaped" coastal area around the Izmir Bay. This "L-shaped" bay has a total length of 64 km; there are series of islands parallel to the west coast of the gulf and opens to the Aegean Sea in the north. [3]. With the help of ADCIRC model, tidal behavior of İzmir Bay can be modeled and predicted. Water levels and atmospheric parameters (atmospheric pressure and wind velocity) are being recorded in İzmir - Menteş Mareograph Station continuously for every 15 min. time interval and can be used to compare with model output data.

# 2. ADCIRC Model

ADCIRC model solves 2D or 3D time dependent, free surface circulation and transport problems. The model uses finite element method with unstructured grid, and it makes possible a flexible design even in very irregular shapes of coastal areas. Some of ADCIRC applications are; storm surge and flood prediction, tidal and wind driven circulation, near shore marine operations and material disposal studies [4].

## 2.1. Model Formulation

With using GWCE (Generalized Wave Continuity Equation), ADCIRC calculates water levels via the solution of the continuity and momentum equations which in a combined and differentiated form and solves the SWE (Shallow Water Equations) for water levels ζ and the vertically integrated momentum equations for currents $\vec{U}$.

The continuous Galerkin method (finite element) with linear $C_0$ triangular elements used to discretize and solve the SWE (Shallow Water Equations) on unstructured meshes, and it allows refine the elements in regions where has the largest solution gradients, locally.

Continuity and momentum equations;

$$\frac{\partial^2 \zeta}{\partial t^2} + \tau_0 \frac{\partial \zeta}{\partial t} + S_p \frac{\partial \tilde{J}_\lambda}{\partial \lambda} + \frac{\partial \tilde{J}_\phi}{\partial \varphi} - S_p U H \frac{\partial \tau_0}{\partial \lambda} - V H \frac{\partial \tau_0}{\partial \varphi} = 0 \tag{1}$$

where:

$$\tilde{J}_\lambda = -S_p Q_\lambda \frac{\partial U}{\partial \lambda} - Q_\varphi \frac{\partial U}{\partial \varphi} + f Q_\varphi - \frac{g}{2} S_p \frac{\partial \zeta^2}{\partial \lambda} - g S_p H \frac{\partial}{\partial \lambda}\left[\frac{P_s}{g\rho_0} - \alpha\eta\right] + \frac{\tau_{s\lambda,winds} + \tau_{s\lambda,waves} - \tau_{b\lambda}}{\rho_0} + (M_\lambda - D_\lambda) + U \frac{\partial \zeta}{\partial t} + \tau_0 Q_\lambda - g S_p H \frac{\partial \zeta}{\partial \lambda} \tag{2}$$

and

$$\tilde{J}_\varphi = -S_p Q_\lambda \frac{\partial V}{\partial \lambda} - Q_\varphi \frac{\partial V}{\partial \varphi} + f Q_\lambda - \frac{g}{2} S_p \frac{\partial \zeta^2}{\partial \varphi} - g S_p H \frac{\partial}{\partial \varphi}\left[\frac{P_s}{g\rho_0} - \alpha\eta\right] + \frac{\tau_{s\varphi,winds} + \tau_{s\varphi,waves} - \tau_{b\varphi}}{\rho_0} + \left(M_\varphi - D_\varphi\right) + V \frac{\partial \zeta}{\partial t} + \tau_0 Q_\varphi - g H \frac{\partial \zeta}{\partial \varphi} \tag{3}$$

and from the momentum equations integrated vertivally, the currents are obtained;

$$\frac{\partial U}{\partial t} + S_p U \frac{\partial U}{\partial \lambda} + V \frac{\partial U}{\partial \varphi} - fV = -gS_p \frac{\partial}{\partial \lambda}\left[\zeta + \frac{P_s}{g\rho_0} - \alpha\eta\right] + \frac{\tau_{S\lambda,winds} + \tau_{S\lambda,waves} - \tau_{b\lambda}}{\rho_0 H} + \frac{M_\lambda - D_\lambda}{H} \tag{4}$$

and

$$\frac{\partial V}{\partial t} + S_p U \frac{\partial V}{\partial \lambda} + V \frac{\partial V}{\partial \varphi} + fU = -gS_p \frac{\partial}{\partial \varphi}\left[\zeta + \frac{P_s}{g\rho_0} - \alpha\eta\right] + \frac{\tau_{S\varphi,winds} + \tau_{S\varphi,waves} - \tau_{b\varphi}}{\rho_0 H} + \frac{M_\varphi - D_\varphi}{H} \tag{5}$$

where

$H = h + \zeta$ is water depth (total); $\zeta$ is the deviation of the water surface from the mean; $h$ is bathymetric depth; $S_p = cos\varphi_0/cos\varphi$ is a spherical coordinate conversion factor and $\varphi_0$: is a reference latitude; $U, V$ are depth-integrated currents in the $x, y$ directions, respectively; $Q_\lambda = UH$ ; $Q_\varphi = VH$ are fluxes per unit width; $f$ is the Coriolis parameter; $g$ is gravitational acceleration; $P_s$ is atmospheric pressure at the surface; $\rho_0$ is the reference density of water; $\eta$ is the Newtonian equilibrium tidal potential and $\alpha$ is the effective earth elasticity factor; $\tau_{S\lambda,winds}, \tau_{S\lambda,waves}$ are surface stresses due to winds and waves, respectively; $\tau_b$ is bottom stress; $M$ are lateral stress gradients; $D$ are momentum dispersion terms; and $\tau_0$ is a numerical parameter that optimizes the phase propagation properties [5].

## 2.2. Unstructured Grid Generation

Unstructured grid offers advantages such as accuracy in representation of complex geology, high accuracy of simulation results and advantage in processing time [6].

Unstructured grid that will be used in ADCIRC has triangular calculation elements and nodes determined based on the finite element method. These points are expressed with the coordinate information of a predetermined georeference system and bathymetry data has adapted to the grid as 3rd dimension.

### 2.2.1. OceanMesh2D

OceanMesh2D is a MATLAB-based, object-oriented and open-source software used to create two-dimensional computational networks for sea, coastal and shallow water flow models [7]. With defined geographical coordinates, coastline data, topography and bathymetry information, OceanMesh2D can create an ADCIRC input file "fort.14" which contains ADCIRC compatible unstructured grid data.

OceanMesh2D program written with an object-oriented approach and it contains the 4 basic classes as follows.

1. Geodata: Processes geospatial data.
2. Edgefx: Configures the mesh size functions.
3. Meshgen: It creates the meshgen according to the mesh size functions and model boundaries.
4. Msh: It is used to store, write, read, analyze and visualize computational networks and auxiliary components for numerical simulation.

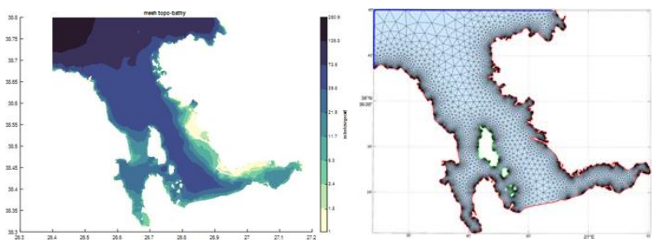
### 2.2.2. M_Map and nctoolbox

M_Map is a tool which contains map creation tools written for MATLAB [8]; nctoolbox is a MATLAB toolbox that provides access to common data model datasets (read-only) [9]. NETCDF-Java is the data access layer for nctoolbox which allows to access NETCDF, OPENDAP, HDF5, GRIB, GRIB2, HDF4 and other file formats and services using the same API.

### 2.2.3. GSHHS Shoreline Data and SRTM15+V2.1 DEM Data

GSHHS (A Global Self-consistent, Hierarchical, High-resolution Shoreline) is a globally consistent, hierarchical, high-resolution shoreline database [10]. SRTM15+ is a digital elevation model that contains bathymetry and topography data at a global scale, with a sampling interval of 15 angle-seconds, and a resolution of approximately 500m x 500m per pixel on the equator [11].

Coastline and bathymetry data are processed by OceanMesh2D and model domain obtained for defined parameters. Bathymetry data visualized by OceanMesh2D shown in Fig. 1. (a) and unstructured grid generated by OceanMesh2D shown in (b). This data also recorded as “fort.14” ADCIRC input file format to be used in simulations.



(a) (b)

**Fig. 1.** (a) Bathymetry data (b) Unstructured grid

## 2.3. Tidal Open Boundary Conditions

Tidal parameters for using as open boundary conditions of the ADCIRC model are obtained with MATLAB based TMD (Tidal Model Driver). “TMD (Tidal Model Driver) Tide Toolbox” is a MATLAB package created to access the harmonic components of the ESR/OSU family of tide models and make predictions for tide height and currents [12]. Interface of TMD is in Fig. 2. And open boundary nodes in TMD has shown in Fig. 3. Amplitude and phase values in open boundary nodes and “tide_fac.f” FORTRAN code used to obtain nodal attributes for calculation date and length. This information processed into the fort.15 input file containing the model parameters. 5 major tidal constituents selected for this model to determine tidal boundary conditions; properties of these constituents shown in Table 1.

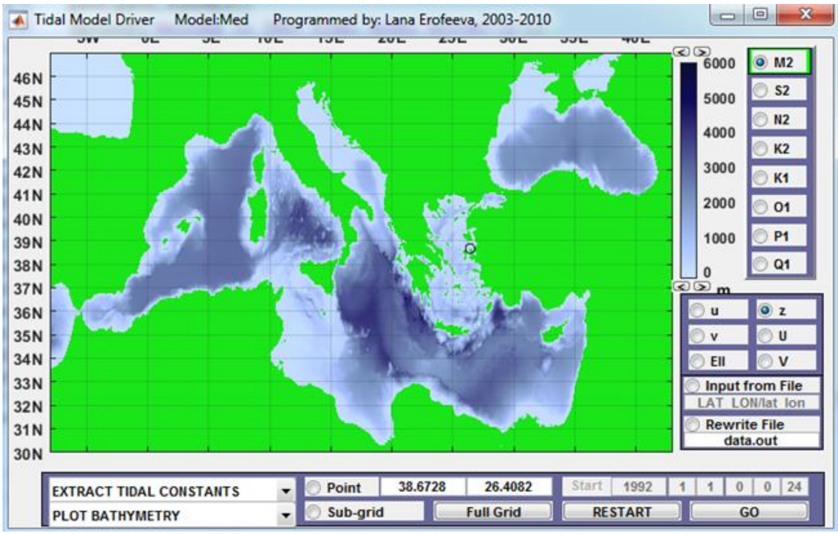



**Fig. 2.** MATLAB interface of Tidal Model Driver (TMD)

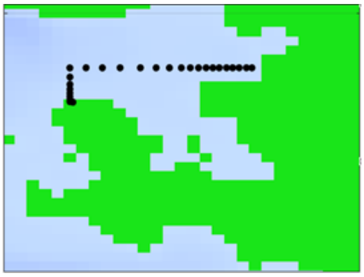


**Fig. 3.** Open boundary nodes in Tidal Model Driver (TMD)

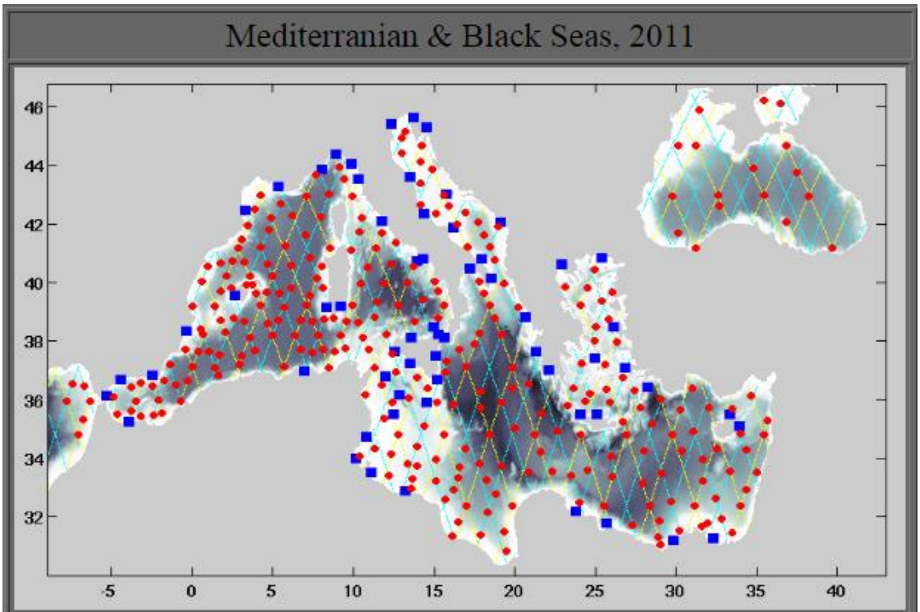
**Table 1**. Properties of 5 major tidal constituents in model

| Darwin Symbol | Type | Period (*hour*) | Speed (°/*hour*) | Doodson Number | NOAA Order |
|---|---|---|---|---|---|
| **M2** | Principal lunar semidiurnal | 12.4206012 | 28.9841042 | 255.555 | **1** |
| **S2** | Principal solar semidiurnal | 12 | 30 | 273.555 | **2** |
| **N2** | Larger lunar elliptic s.diurnal | 12.65834751 | 28.4397295 | 245.655 | **3** |
| **K1** | Lunar diurnal | 23.93447213 | 15.0410686 | 165.555 | **4** |
| **O1** | Lunar diurnal | 25.81933871 | 13.9430356 | 145.555 | **6** |

### 2.3.1. OSU TPXO-OTIS Regional Mediterranean Tidal Model

TPXO is a global, regional and local, barotropic tide model obtained by assimilating satellite altimetry and other data with OTIS [13].

The amplitude and phase values of the open boundary nodes in Izmir Bay obtained from "Mediterranean Regional Models" with using TMD MATLAB. General information about the OSU TPXO-OTIS Regional Mediterranean Tidal Model shown in Fig 4.




Bathymetry: GEBCO 1' database. Resolution: 1/30°; 1531x511 grid; OBC: TPXO7-atlas
Constituents: m2, s2, n2, k2, k1, o1, p1, q1
**Data assimilated:** Topex Poseidon 531 cycles (all available data); Topex Tandem 114 cycles (all available data) ~9000 data sites, ERS ~20000 data sites (m2 & k1 only)
**Data for validation (not assimilated):** 62 tide gauges from [Tsimplis et. al 1995] are shown with blue squares.
RMS misfit (cm) to the validationo tide gauges

| | M2 | S2 | K1 | O1 |
|---|---|---|---|---|
| RMS signal (cm) | 9.23 | 5.47 | 3.59 | 1.33 |
| RMS misfit (cm) | 0.94 | 0.84 | 0.85 | 0.58 |

**Fig. 4** OSU TPXO-OTIS Regional Mediterranean Tidal Model information

## 2.3.2. Nodal Parameters with "tide_fac.f" Fortran Program

Nodal parameters are used to consider the date and time interval when calculations will be performed. These parameters are "Nodal Factors" and "Equilibrium Arguments" which obtained from the formulation and tables in "Manual of Harmonic Analyses and Tides" of Paul Schureman [14]. Nodal factors are the reason of difference between the different dates (such as same months in different years) and will be taken into account with entering values in appropriate place in fort.15 ADCIRC input file which contains all initial parameters for the model.

The nodal parameters to be used in simulation are obtained with the help of Fortran program "tide_fac.f", which is among the ADCIRC model auxiliary tools. An example run of the code for 30 days of simulation starting at 00:00, 01.01.2020 shown below.

```
$ ./tide_fac.exe
 ENTER LENGTH OF RUN TIME (DAYS)
30
  ENTER START TIME - BHR,IDAY,IMO,IYR (IYR e.g. 1992)
00,01,01,2020
 TIDAL FACTORS STARTING:  HR- 0.00,  DAY-  1,  MONTH-  1  YEAR- 2020

 FOR A RUN LASTING    30.00 DAYS

 CONST   NODE      EQ ARG (ref GM)
 NAME   FACTOR     (DEG)
 K1    0.99979       1.23
 O1    0.99946     230.34
 P1    1.00000     349.87
 Q1    0.99946      62.13
 N2    1.00497      59.27
 M2    1.00497     227.48
 S2    1.00000       0.00
 K2    0.97870     182.43
```

### 2.3.3. İzmir - Menteş Mareograph Station

İzmir - Menteş station is a sea level measurement station with GNSS integrated radar sensor. General view of the measurement device is given in Fig. 5. Coordinates and other info of the station are given below.

Short Name: MNTS - Installation Date: 25.11.1985 00:00:00

Latitude: 38,42960155 - Longtitude: 26,72214568

**Fig. 5.** İzmir – Menteş Mareograph Station measurement device [15]

Amplitude values of M2, S2, K1, O1 tidal constituents for Mentes station obtained from different sources (TPXO Model Med used for simulations) are compared in Table 2.

**Table 2** Comparison - properties of 5 major tidal constituents in model

| Menteş Station Tidal Amplitudes (m) | M2 | S2 | K1 | O1 |
|---|---|---|---|---|
| IOS Method - Yüksel et. al. (2018) [16] | 0.0558 | 0.0405 | 0.0249 | 0.0138 |
| Yıldız et. al. (2003) [17] | 0.0577 | 0.0404 | 0.0254 | 0.0130 |
| TPXO Model Med | 0.0602 | 0.0355 | 0.0274 | 0.0139 |

### 2.4. DesignSafe Cyber Infrastructure (CI)

DesignSafe CI is a cloud-based platform for big data produced in natural hazards engineering research, which support data analysis, visualization and research workflow. ADCIRC model can also be used within this infrastructure. In this study, ADCIRC Version 52 serial mode in DesignSafe infrastructure is mostly used for simulations and supported with ADCIRC compiled on PC.

### 2.5. FigureGen Visualisation

FigureGen is a Fortran program that creates images for ADCIRC files [18]. It reads grid files (fort.14, etc.), nodal attributes files (fort.13, etc.) and output files (fort.63, fort.64, maxele.63, etc.). It plots contours, contour lines, and vectors. “maxele.63” output files of simulations are visualized with FigureGen to show maximum water levels during each of 30 days simulations for whole Izmir Bay area with contour lines filled with a color legend with 1 mm precision.

## 3. Results

Monthly results from ADCIRC simulations with only tidal open boundary conditions for 2020 and 2021 are compared with measured sea levels for every 30 min. at İzmir-Menteş Mareograph Station are compared in graphs and maximum water levels for each month are visualized by FigureGen. Results for each month (excluding March, October and December) has given with Fig. 6. to Fig 37. respectively. İzmir Menteş Mareograph Station water level comparison for January 2020 shown in Fig. 6. İzmir Bay maximum water levels (tide only) for January 2020 shown in Fig 7. İzmir Menteş Mareograph Station water level comparison for January 2021 shown in Fig. 8. İzmir Bay maximum water levels (tide only) for January 2021 shown in Fig 9. İzmir Menteş Mareograph Station water level comparison for February 2020 shown in Fig. 10. İzmir Bay maximum water levels (tide only) for February 2020 shown in Fig 11. İzmir Menteş Mareograph Station water level comparison for February 2021 shown in Fig. 12. İzmir Bay maximum water levels (tide only) for February 2021 shown in Fig 13. İzmir Menteş Mareograph Station water level comparison for April 2020 shown in Fig. 14. İzmir Bay maximum water levels (tide only) for April 2020 shown in Fig 15. İzmir Menteş Mareograph Station water level comparison for April 2021 shown in Fig. 16. İzmir Bay maximum water levels (tide only) for April 2021 shown in Fig 17. İzmir Menteş Mareograph Station water level comparison for June 2020 shown in Fig. 18. İzmir Bay maximum water levels (tide only) for June 2020 shown in Fig 19. İzmir Menteş Mareograph Station water level comparison for June 2021 shown in Fig. 20. İzmir Bay maximum water levels (tide only) for June 2021 shown in Fig 21. İzmir Menteş Mareograph Station water level comparison for July 2020 shown in Fig. 22. İzmir Bay maximum water levels (tide only) for July 2020 shown in Fig 23.

İzmir Menteş Mareograph Station water level comparison for July 2021 shown in Fig. 24. İzmir Bay maximum water levels (tide only) for July 2021 shown in Fig 25. İzmir Menteş Mareograph Station water level comparison for August 2020 shown in Fig. 26. İzmir Bay maximum water levels (tide only) for August 2020 shown in Fig 27. İzmir Menteş Mareograph Station water level comparison for August 2021 shown in Fig. 28. İzmir Bay maximum water levels (tide only) for August 2021 shown in Fig 29. İzmir Menteş Mareograph Station water level comparison for September 2020 shown in Fig. 30. İzmir Bay maximum water levels (tide only) for September 2020 shown in Fig 31. İzmir Menteş Mareograph Station water level comparison for September 2021 shown in Fig. 32. İzmir Bay maximum water levels (tide only) for September 2021 shown in Fig 33. İzmir Menteş Mareograph Station water level comparison for November 2020 shown in Fig. 34. İzmir Bay maximum water levels (tide only) for November 2020 shown in Fig 35. İzmir Menteş Mareograph Station water level comparison for November 2021 shown in Fig. 36. İzmir Bay maximum water levels (tide only) for November 2021 shown in Fig 37.

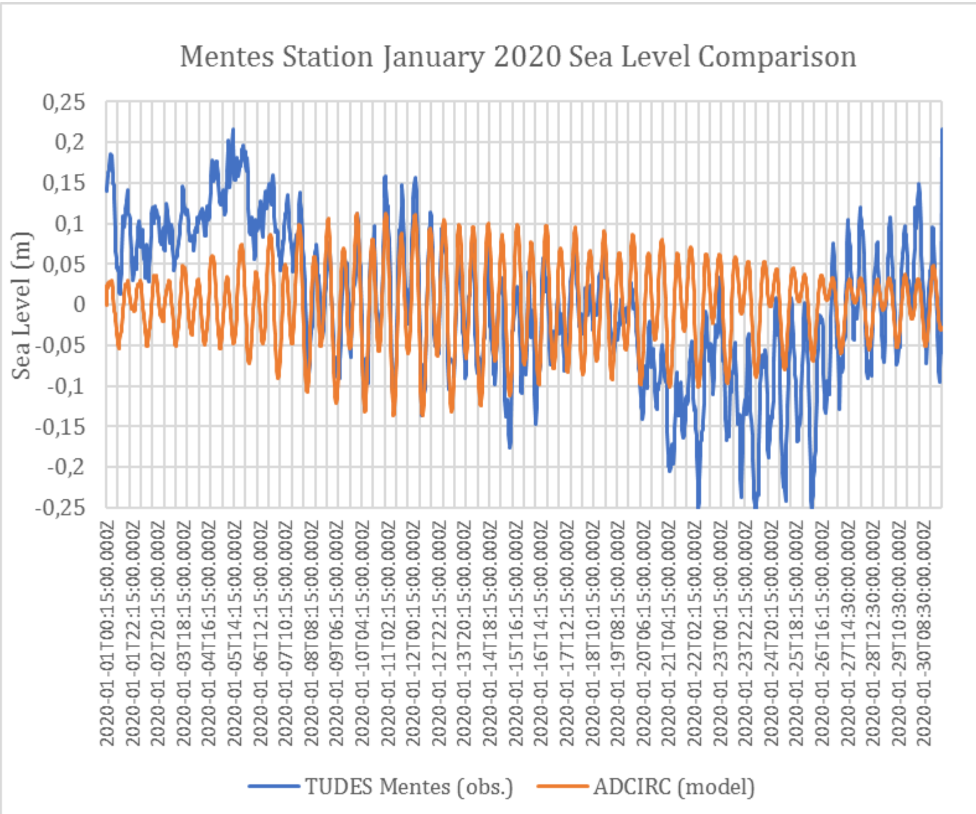



**Fig. 6** İzmir Menteş Mareograph Station water level comparison for January 2020

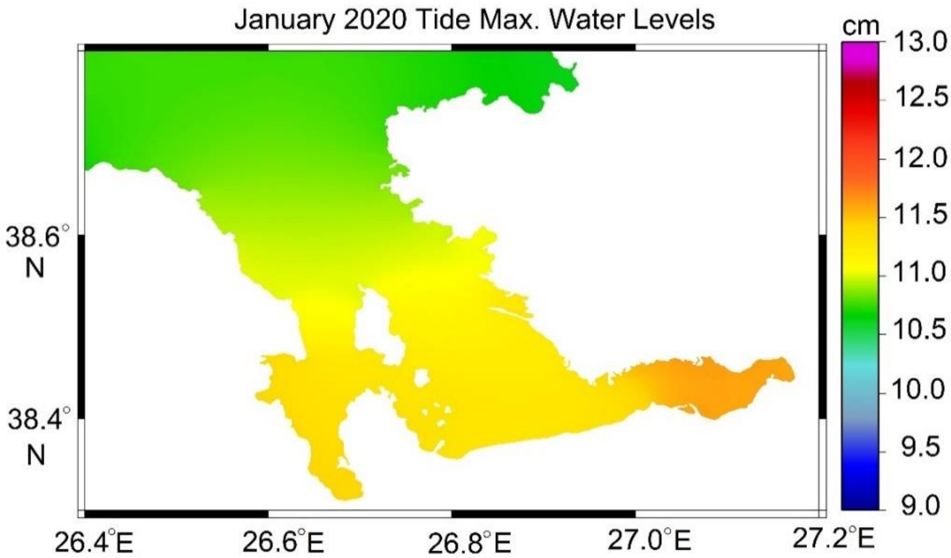



**Fig. 7** İzmir Bay maximum water levels (tide only) for January 2020

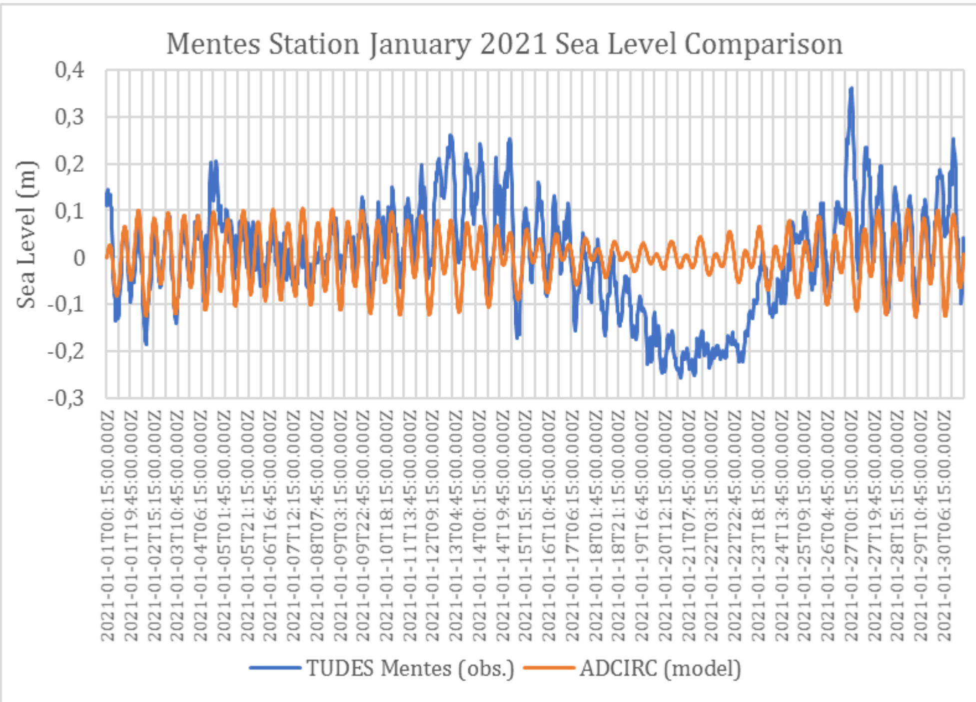



**Fig. 8** İzmir – Menteş Mareograph Station water level comparison for January 2021

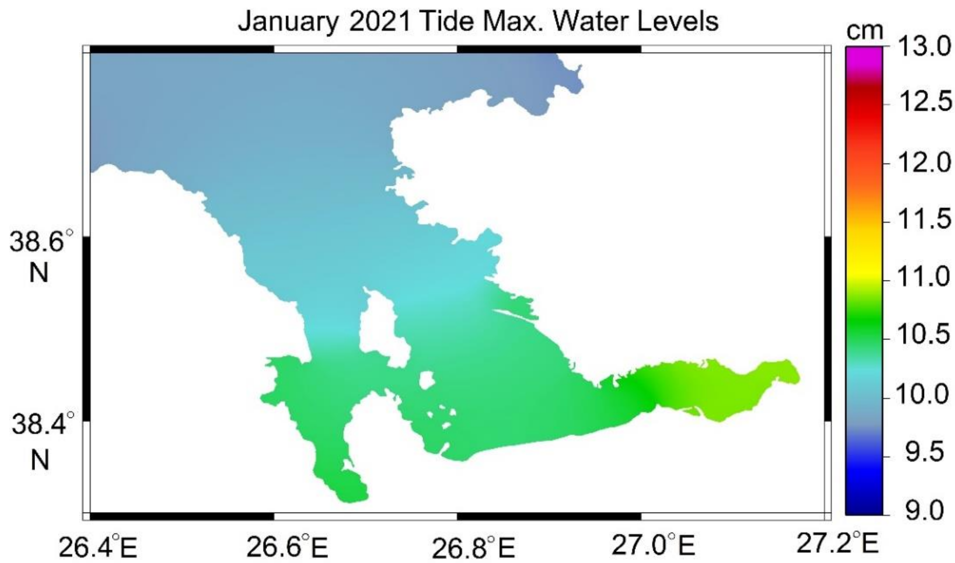



**Fig. 9** İzmir Bay maximum water levels (tide only) for January 2021

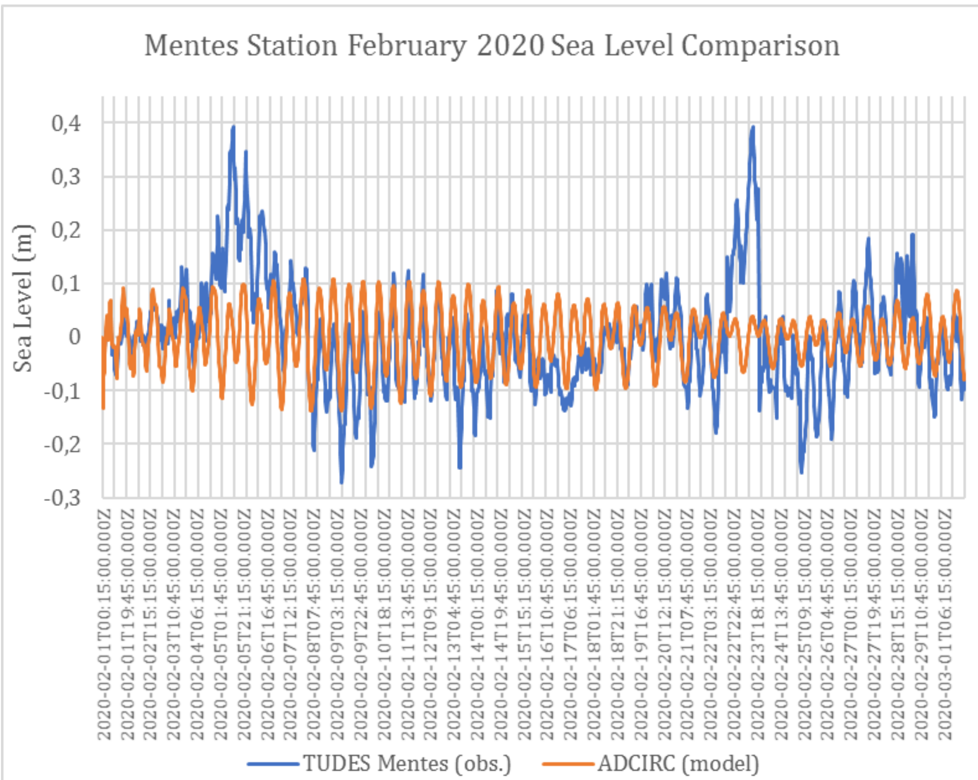



**Fig. 10** İzmir – Menteş Mareograph Station water level comparison for February 2020

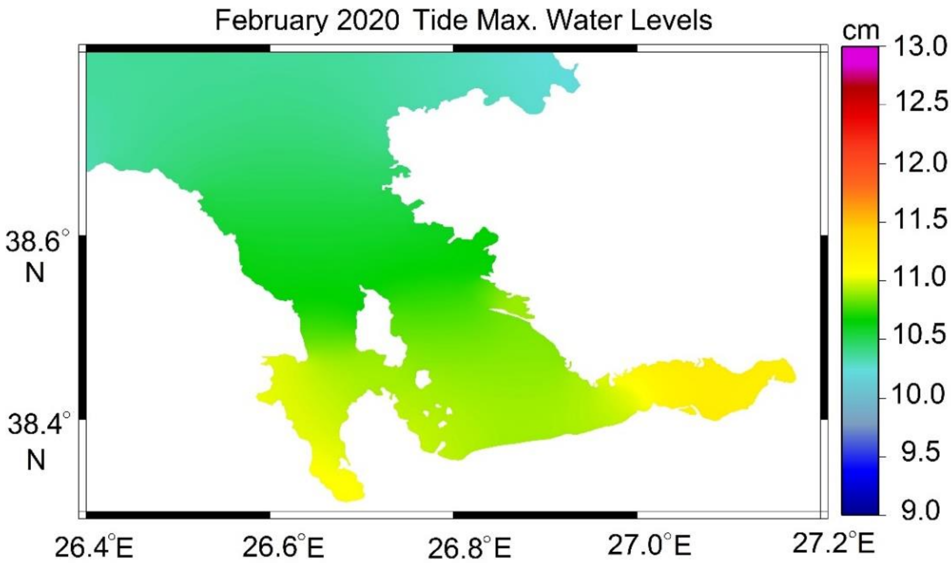



**Fig. 11** İzmir Bay maximum water levels (tide only) for February 2020

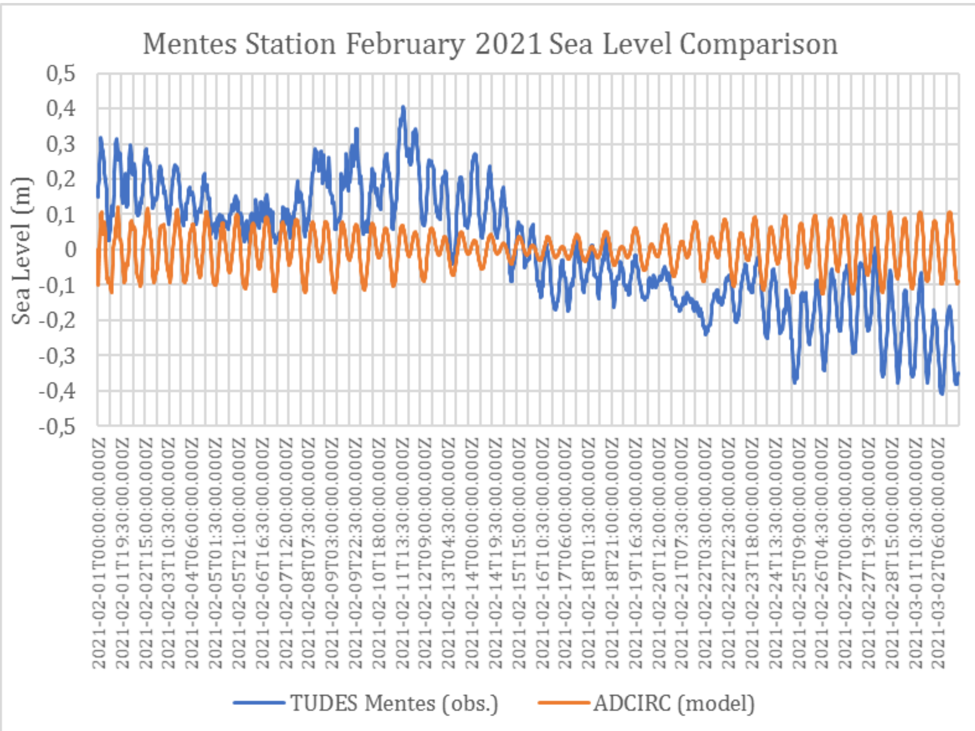



**Fig. 12** İzmir – Menteş Mareograph Station water level comparison for February 2021

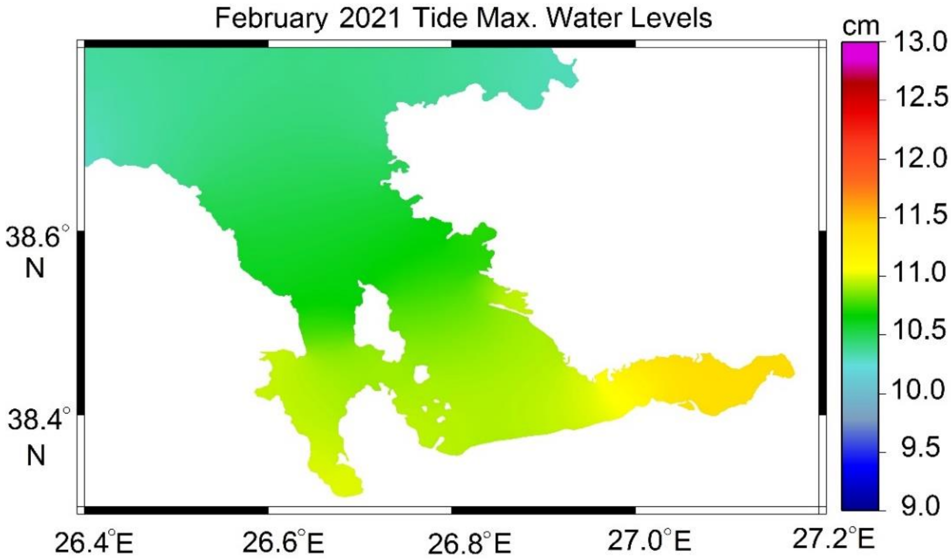



**Fig. 13** İzmir Bay maximum water levels (tide only) for February 2021

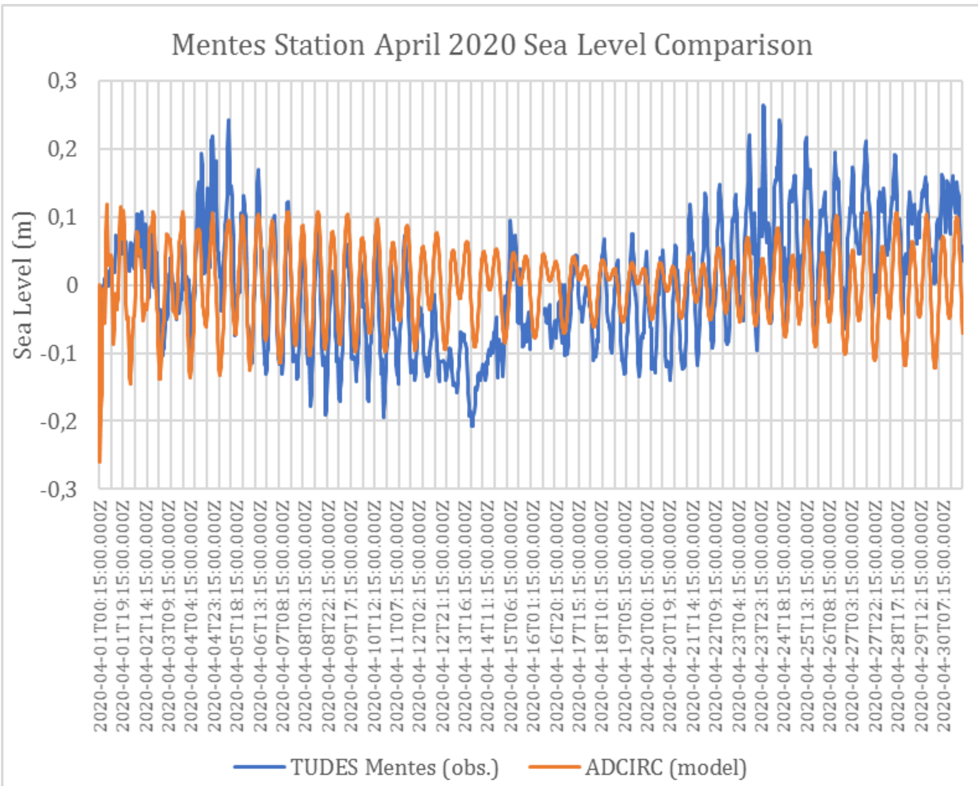



**Fig. 14** İzmir – Menteş Mareograph Station water level comparison for April 2020

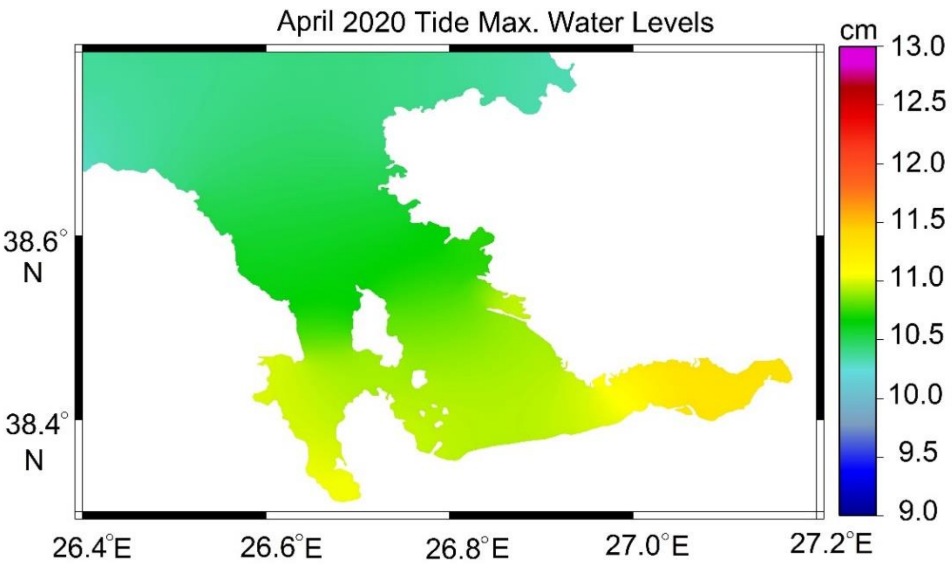



**Fig. 15** İzmir Bay maximum water levels (tide only) for April 2020

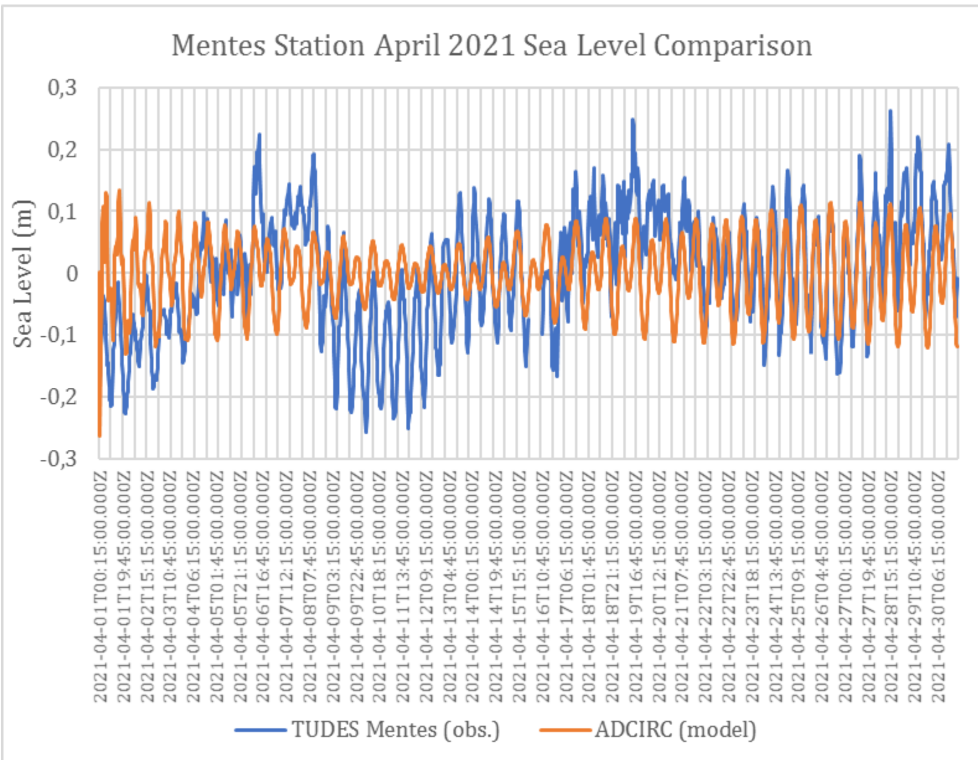



**Fig. 16** İzmir – Menteş Mareograph Station water level comparison for April 2021

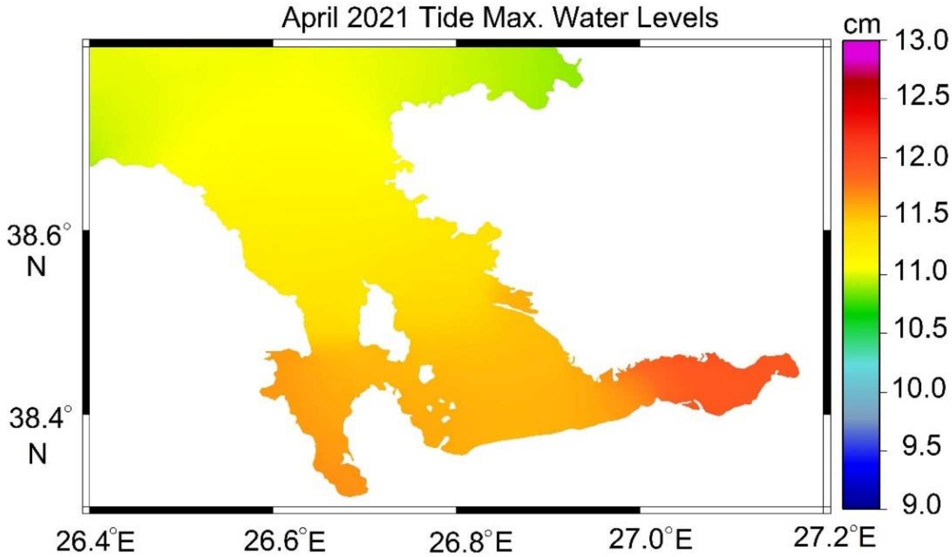



**Fig. 17** İzmir Bay maximum water levels (tide only) for April 2021

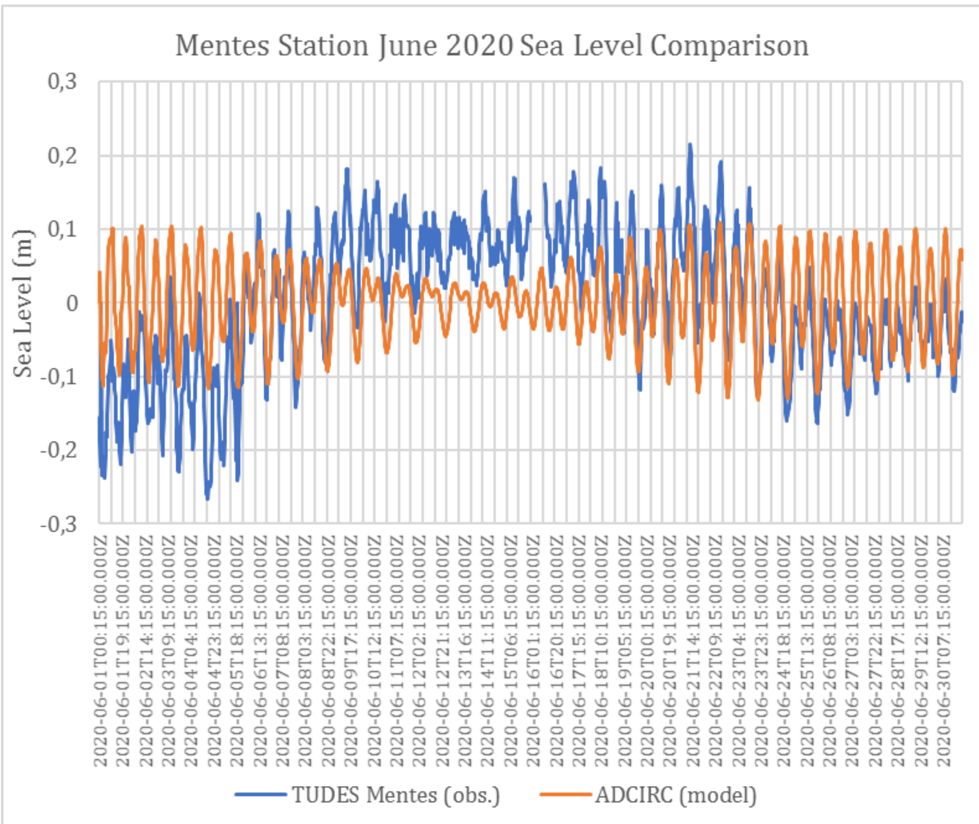



**Fig. 18** İzmir – Menteş Mareograph Station water level comparison for June 2020

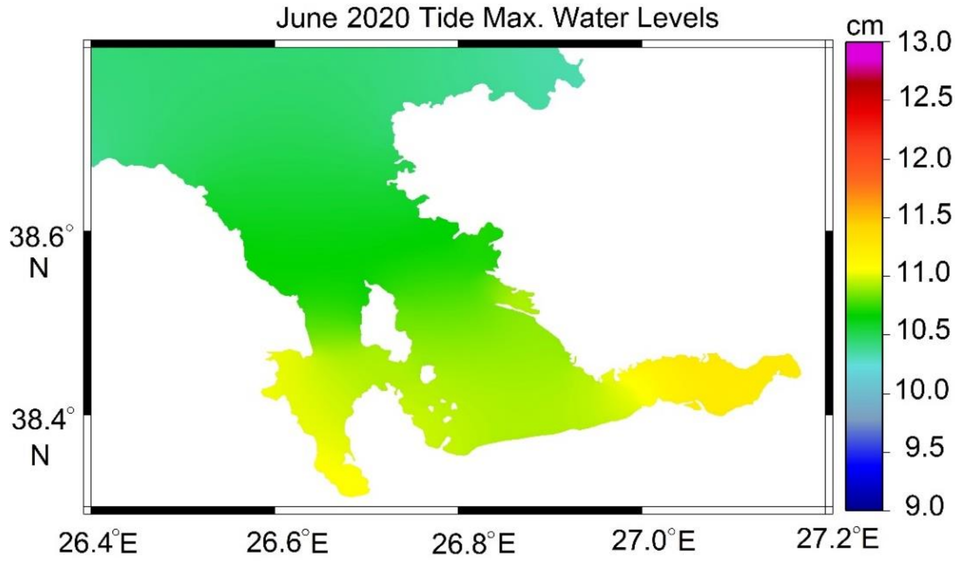



**Fig. 19** İzmir Bay maximum water levels (tide only) for June 2020

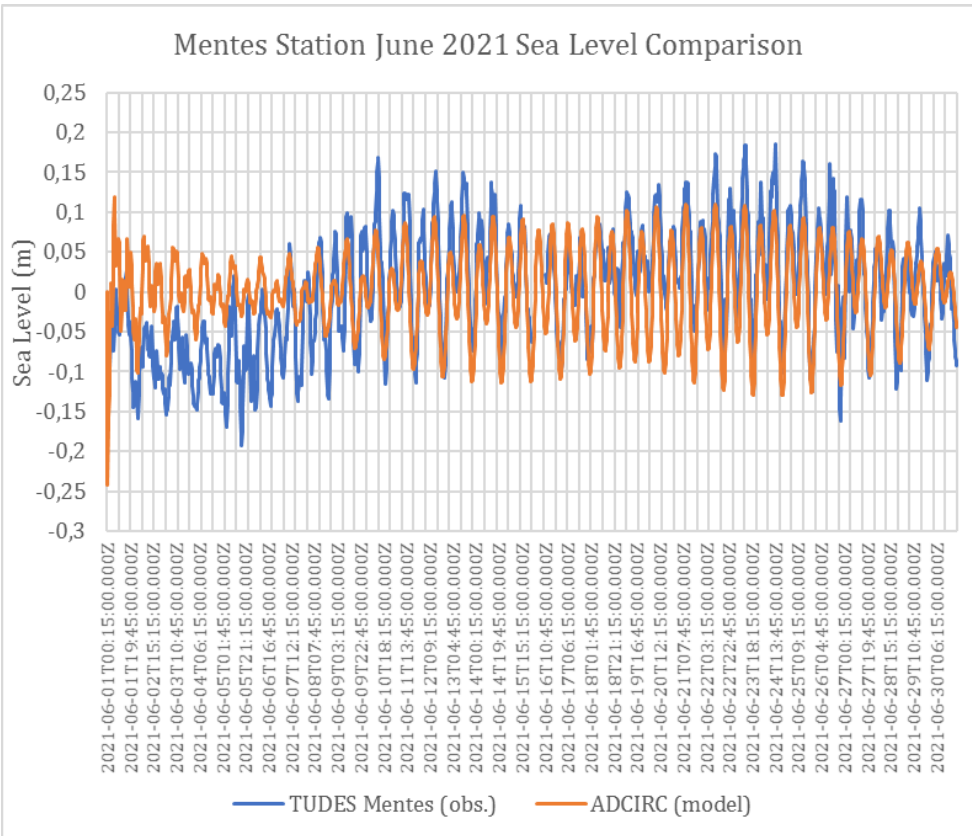



**Fig. 20** İzmir – Menteş Mareograph Station water level comparison for June 2021

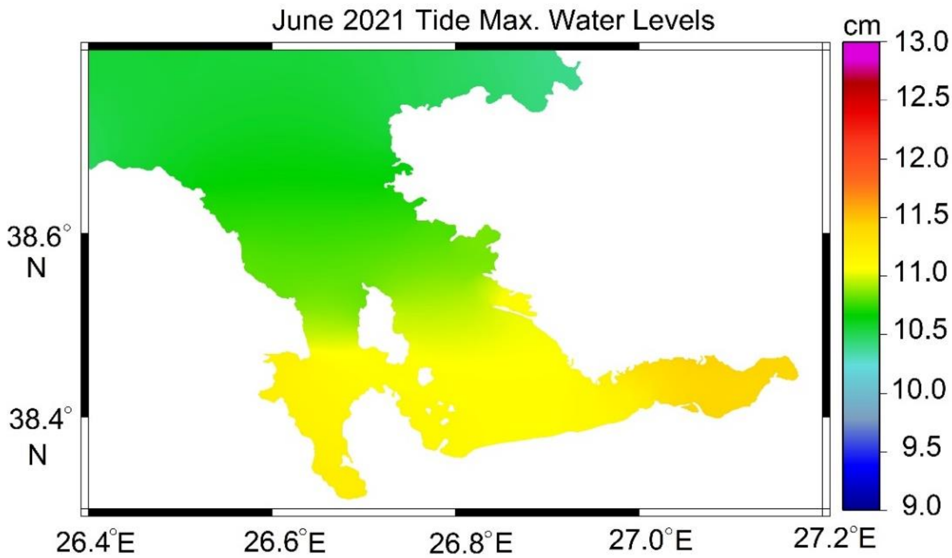



**Fig. 21** İzmir Bay maximum water levels (tide only) for June 2021

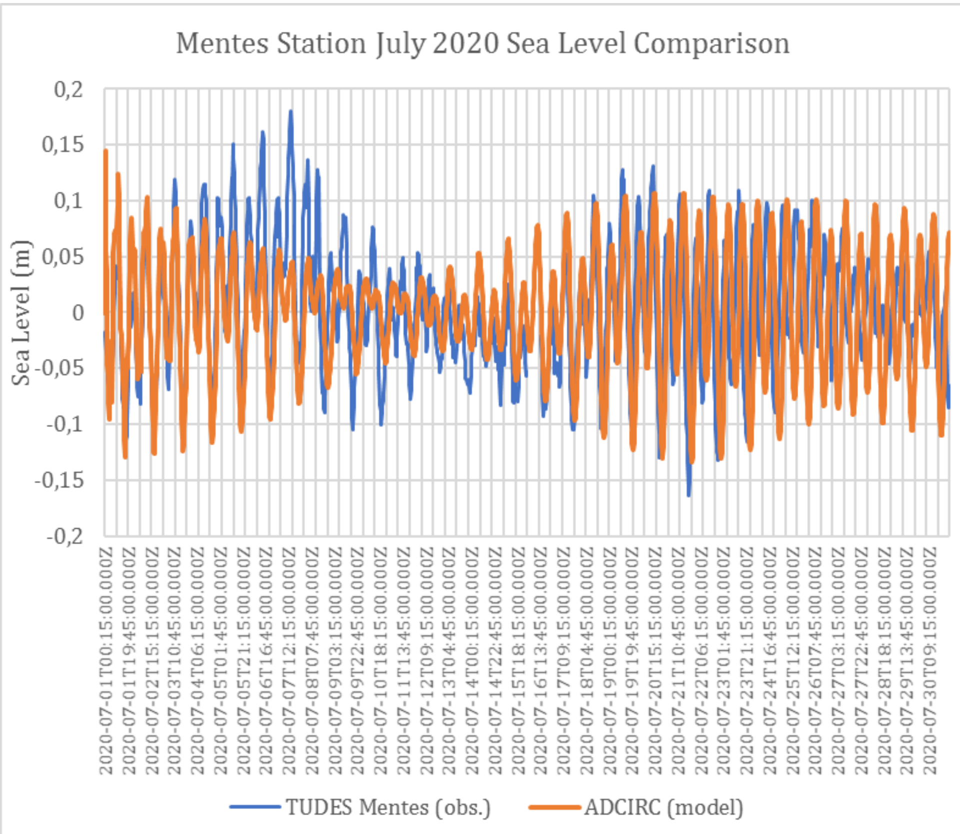



**Fig. 22** İzmir – Menteş Mareograph Station water level comparison for July 2020

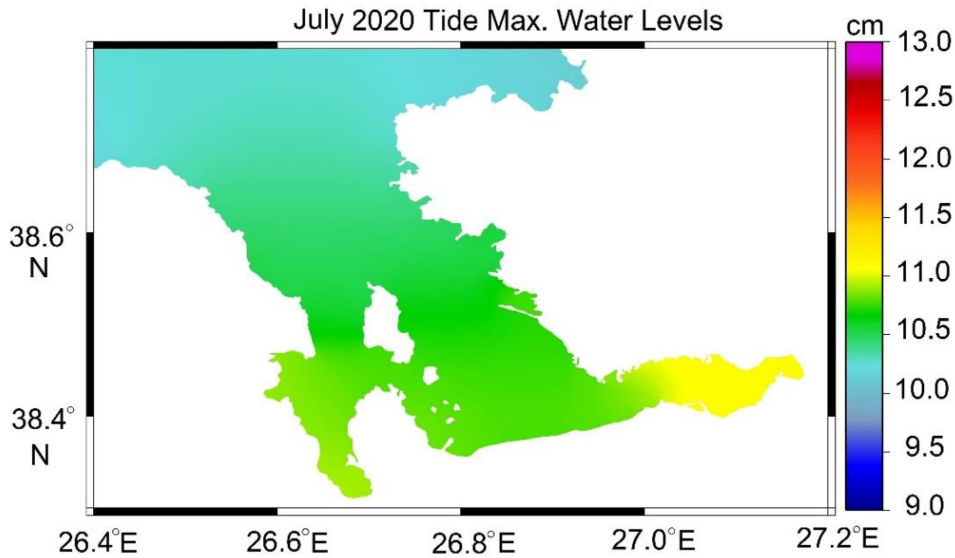



**Fig. 23** İzmir Bay maximum water levels (tide only) for July 2020

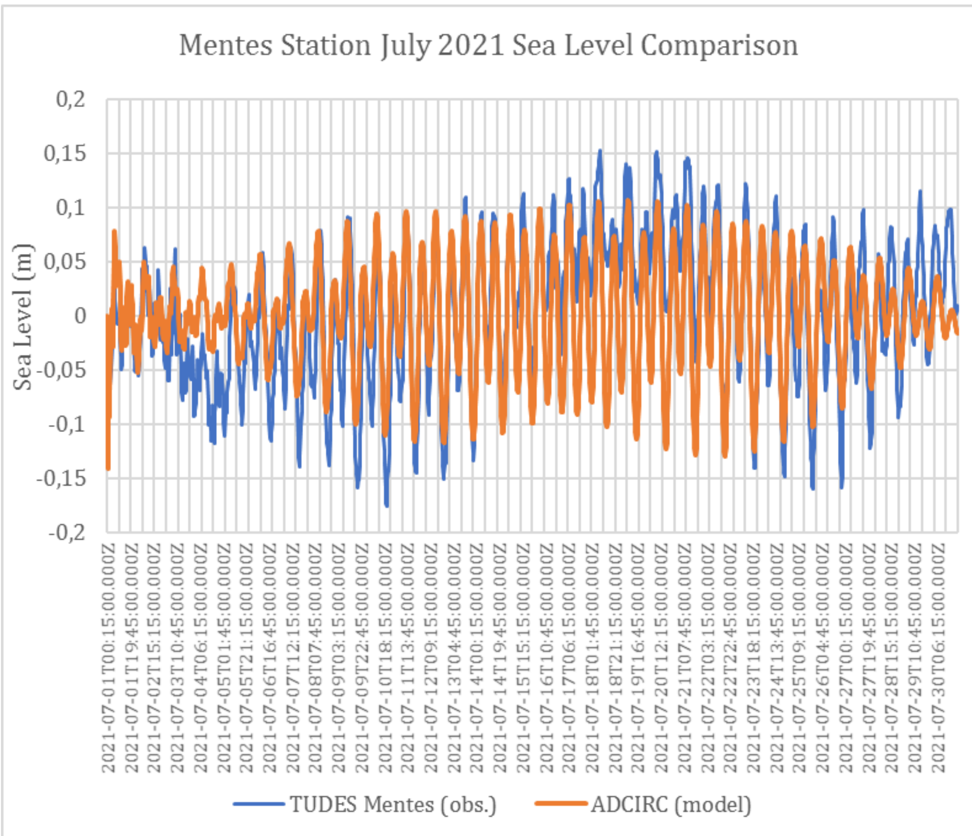



**Fig. 24** İzmir – Menteş Mareograph Station water level comparison for July 2021

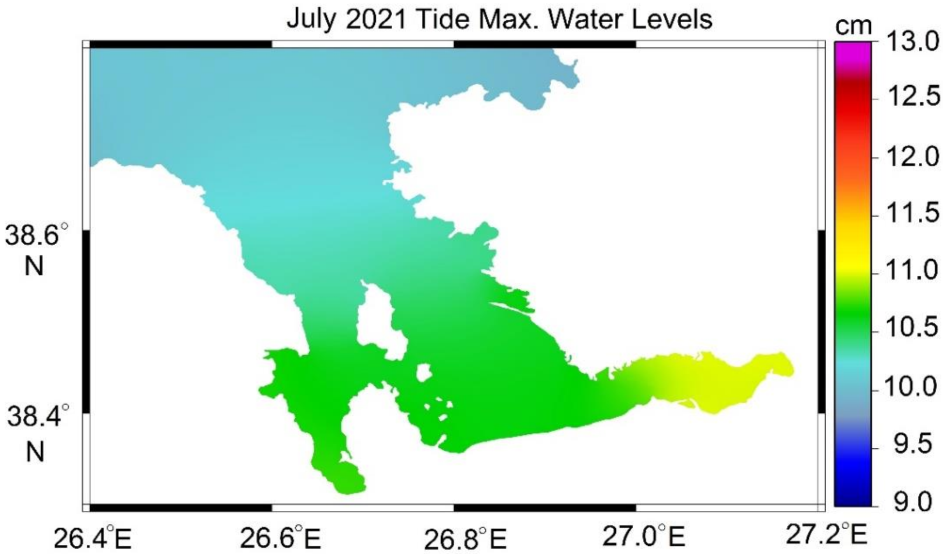



**Fig. 25** İzmir Bay maximum water levels (tide only) for July 2021

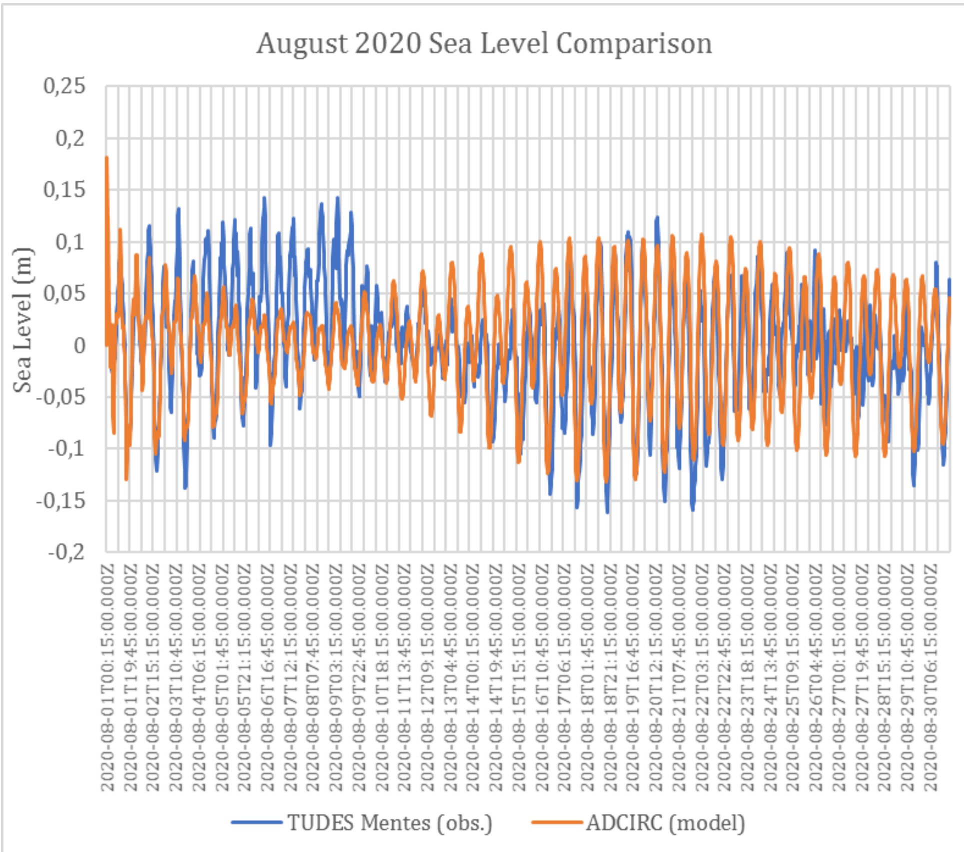



**Fig. 26** İzmir – Menteş Mareograph Station water level comparison for August 2020

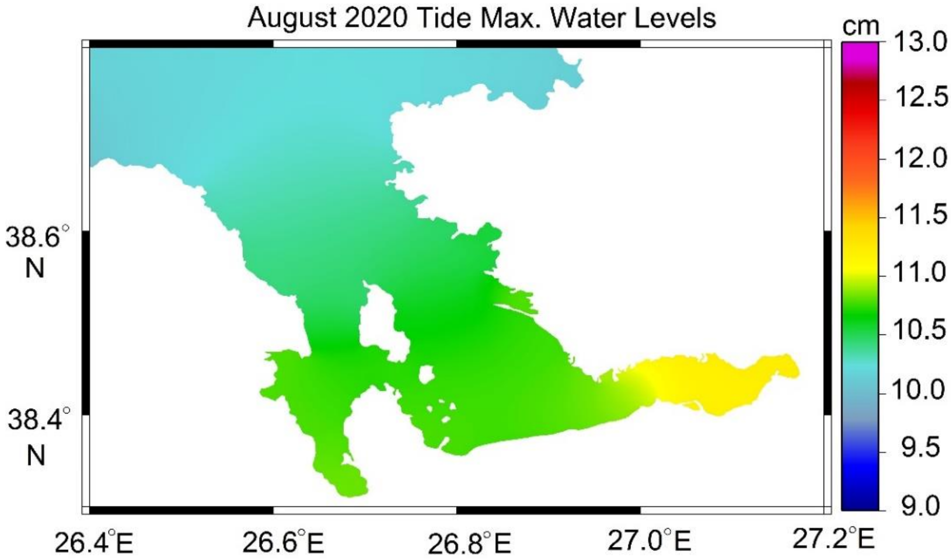



**Fig. 27** İzmir Bay maximum water levels (tide only) for August 2020

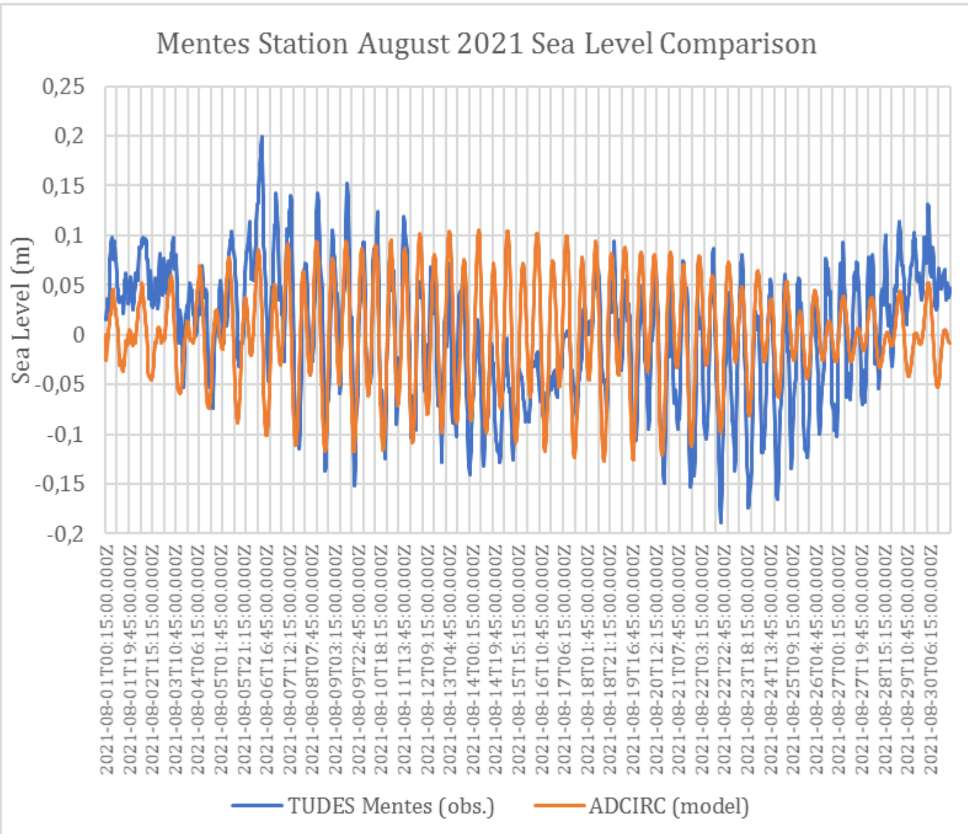



**Fig. 28** İzmir – Menteş Mareograph Station water level comparison for August 2021

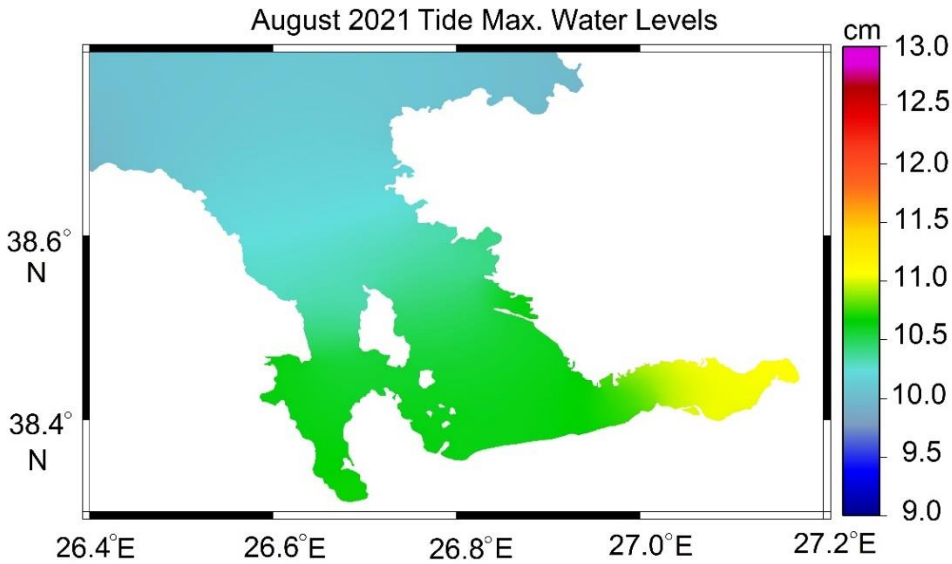



**Fig. 29** İzmir Bay maximum water levels (tide only) for August 2021

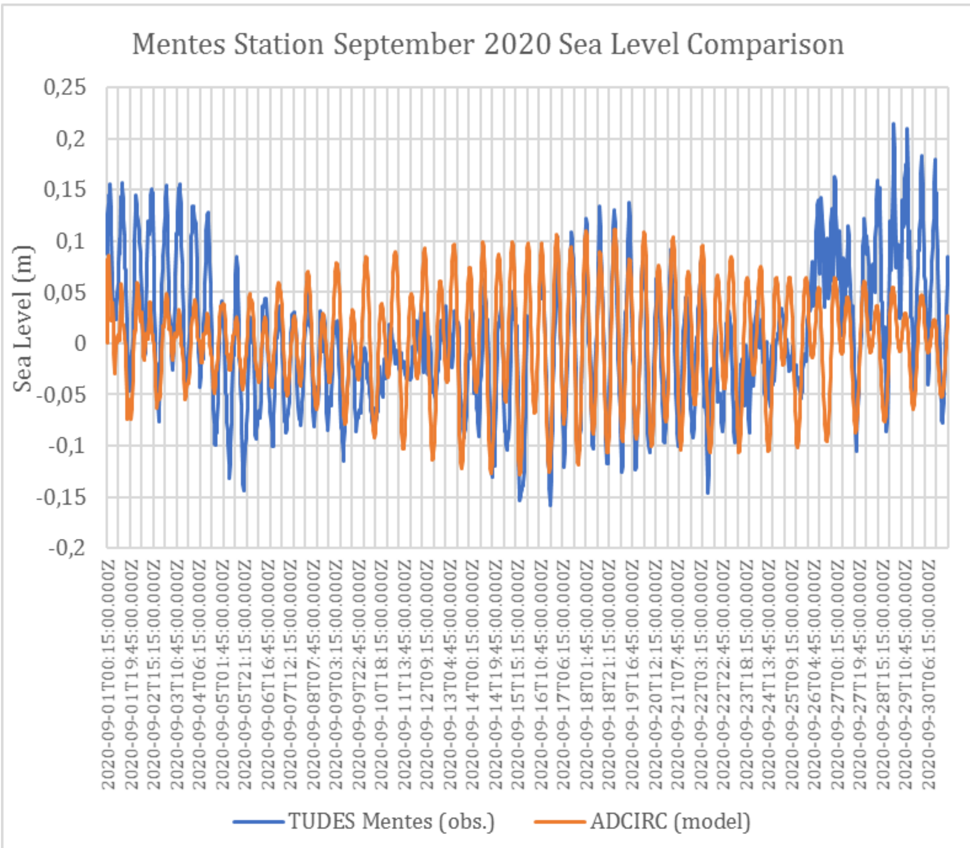



**Fig. 30** İzmir – Menteş Mareograph Station water level comparison for September 2020

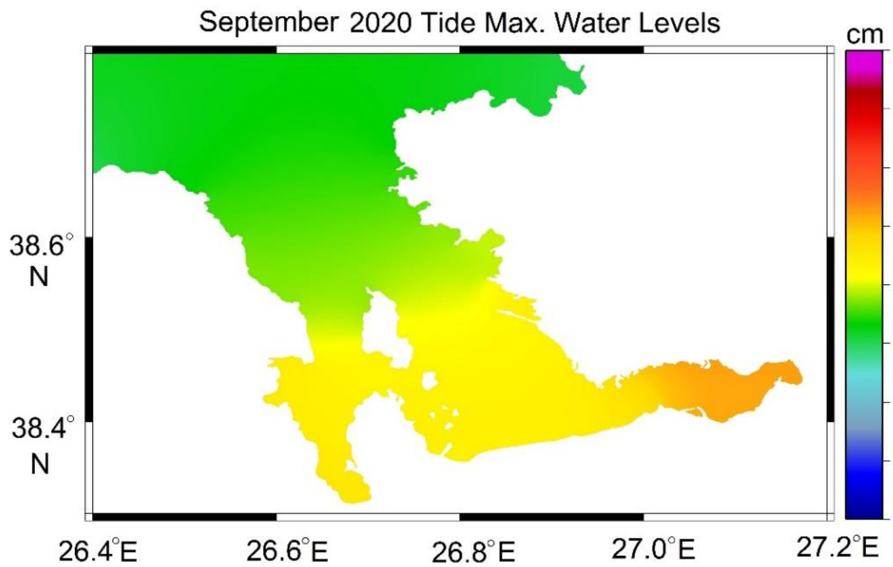



**Fig. 31** İzmir Bay maximum water levels (tide only) for September 2020

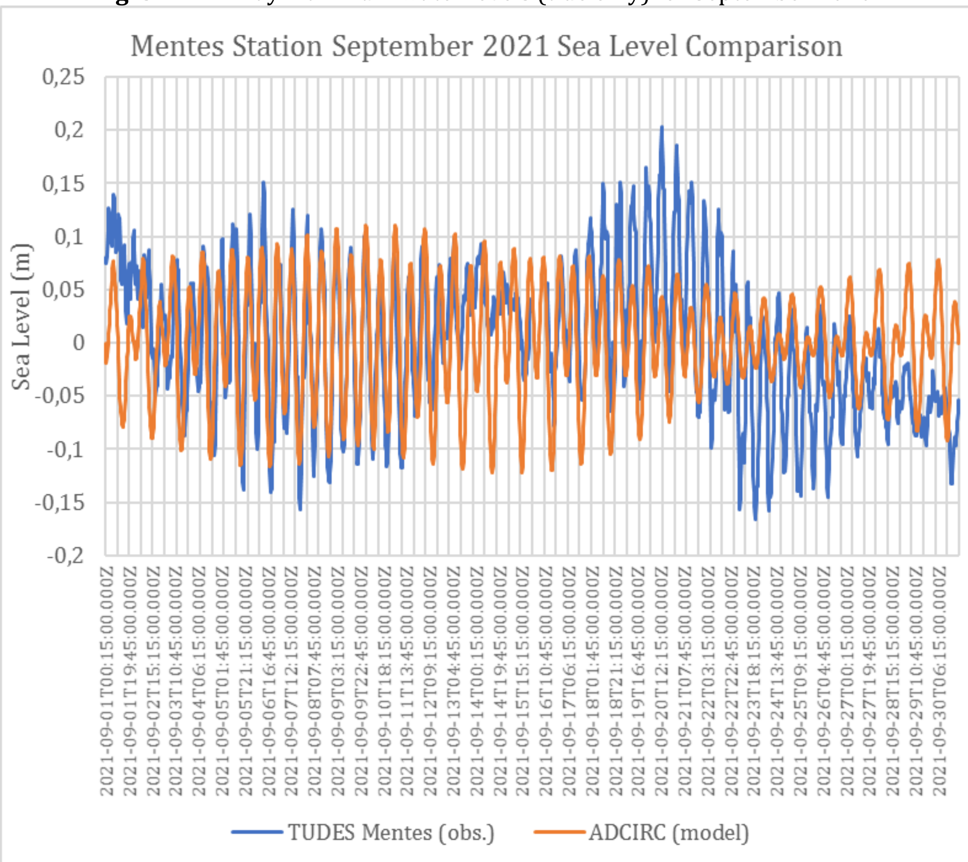



**Fig. 32** İzmir – Menteş Mareograph Station water level comparison for September 2021

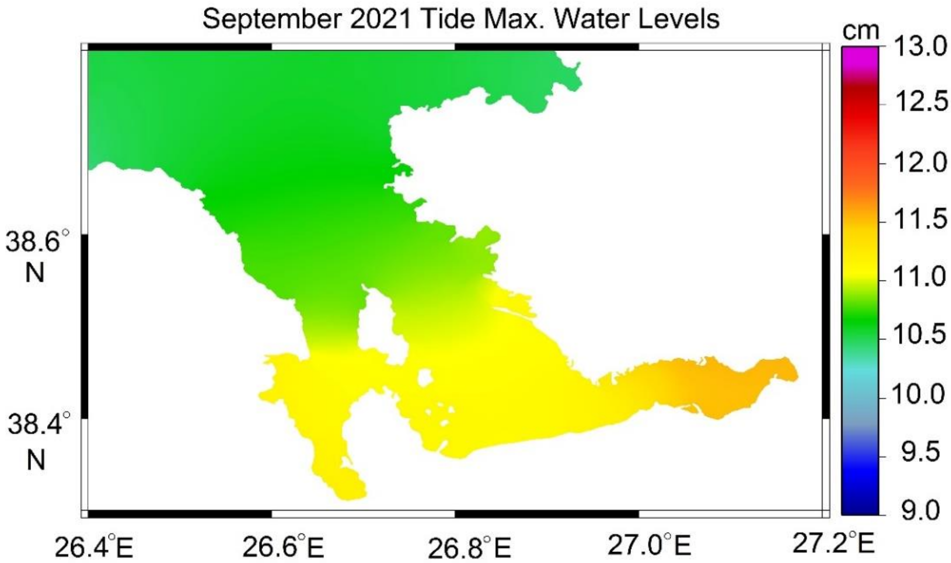



**Fig. 33** İzmir Bay maximum water levels (tide only) for September 2021

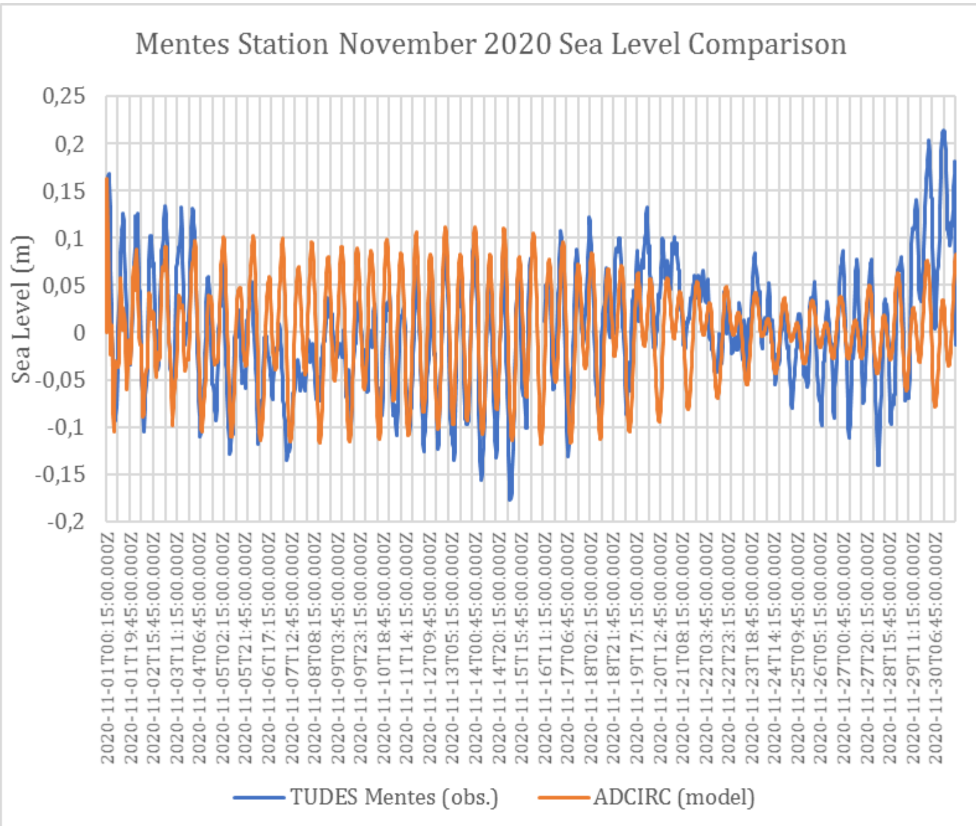



**Fig. 34** İzmir – Menteş Mareograph Station water level comparison for November 2020

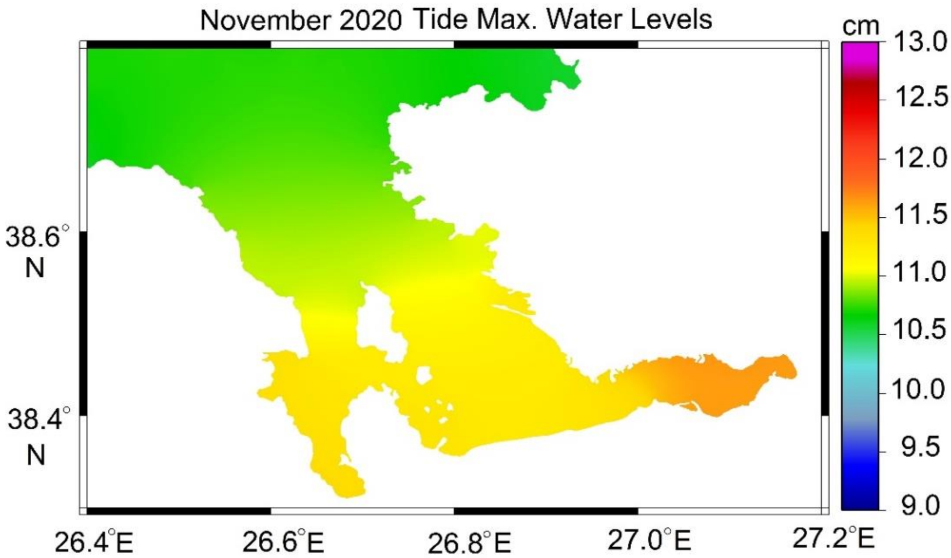



**Fig. 35** İzmir Bay maximum water levels (tide only) for November 2020

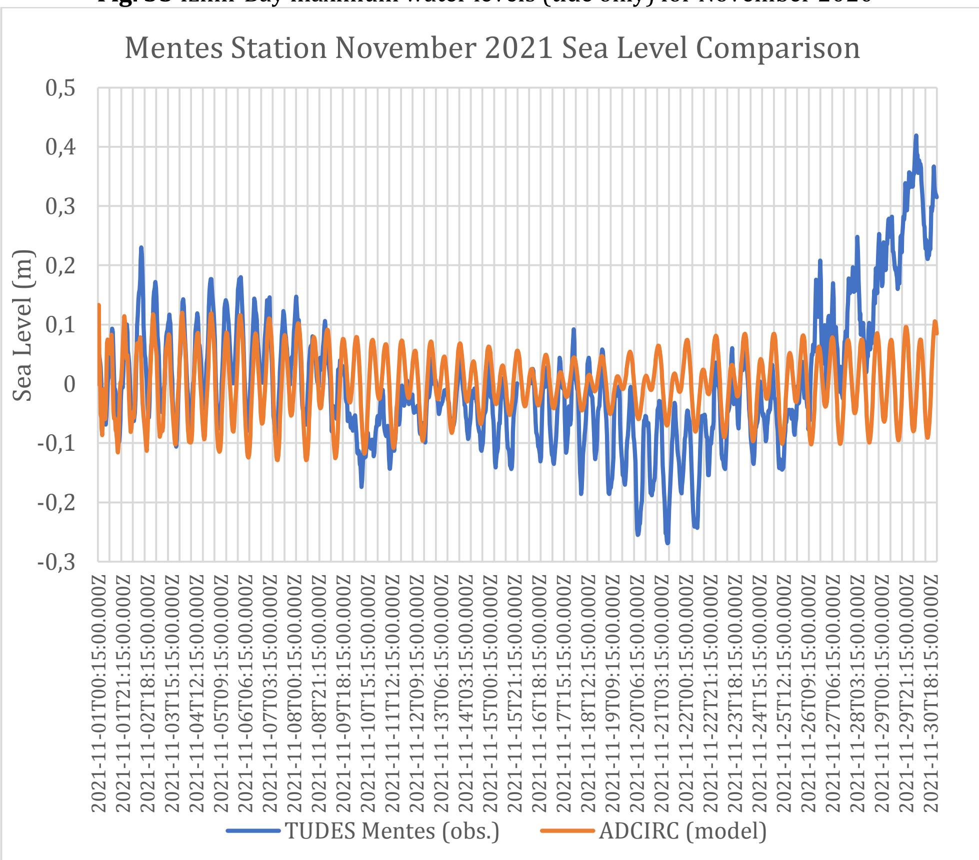



**Fig. 36** İzmir – Menteş Mareograph Station water level comparison for November 2021

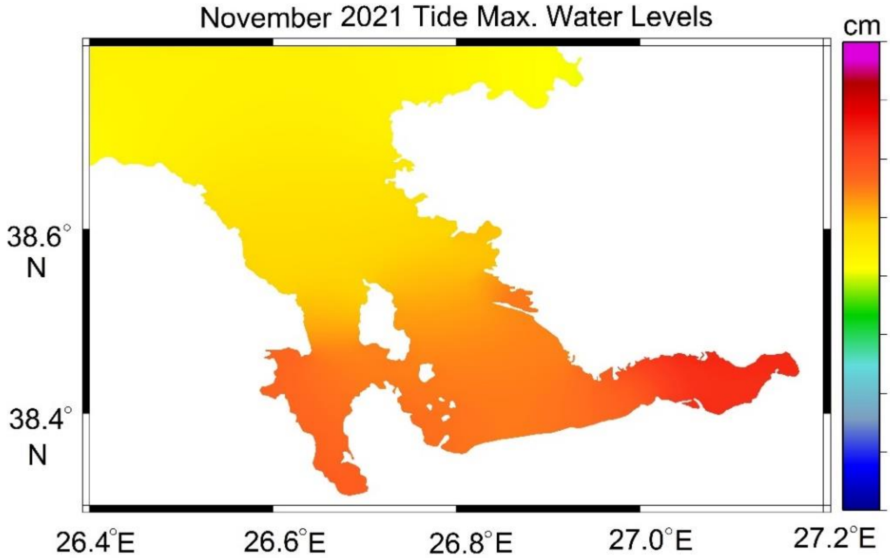



**Fig. 37** İzmir Bay maximum water levels (tide only) for November 2021

## 4. Conclusion

ADCIRC model performed on İzmir Bay driven with tidal open boundary conditions obtained from TMD with unstructured grid generated with OceanMesh2D by using GSHHS Shoreline Data and SRTM15+V2.1 DEM Data. 30 days of simulation runs performed for each month in 2020 and 2021.

Maximum water levels occurred only with 5 major tide effects obtained and visualized by FigureGen. Water levels for each 30 min. are obtained from both İzmir – Menteş Mareograph Staton and ADCIRC model are compared in graphs. Maximum water level changes between 10-12 cm. Data from model and observations are similar in stable meteorological conditions (less amount of change in atmospheric pressure and wind velocity), especially in summer.

Atmospheric conditions are important as tides in water behavior and must be considered. For example, under the low atmospheric pressure conditions, water level rises, and barometric surge occurs. With high speed of wind velocity, waves and fluctuations can be observed. These effects must be included as model input for a fully compatible results with observed data. Meteorological conditions should be considered for data analyze; as a future work, observed sea level data can be re-analysed with methods which isolates atmospheric pressure effect.

By combining tidal effects with meteorological forces obtained from ERA5 database (wind velocities and atmospheric pressure), meteorological conditions will also be considered as forcing conditions and meteorological input files for model will be generated with a Python code. Simulations with coupled ADCIRC-SWAN model is also planned for future of this work.

Water levels and atmospheric data of İzmir from 4 different stations also will obtained from Dokuz Eylul Marine Science Institute and will be used for validating the ERA5 atmospheric data and ADCIRC output data at different locations.

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