Response to the comments of reviewer #2:

We thank the reviewer for the time examining the manuscript and the valuable comments that have helped to improve the manuscript. We have carefully addressed the comments in the following response and provided some further analysis to clarify the reviewer's major concerns. The comments of the reviewer are in black and our response are in blue.

General comments:

In this manuscript, titled "Climate change overtakes coastal engineering as the dominant driver of hydrologic change in a large shallow lagoon", the authors describe the application of an unstructured modelling system to investigate hydrodynamics in the Peel-Harvey Estuary-Lagoon. Even if some may modelling studies dealing with lagoon's hydrodynamics have been already published, I particularly enjoyed reading this paper, which is clear, to the point and most interesting. The applied numerical model was properly applied and model results correctly presented and discussed. I particularly appreciate the multi-year investigation to separate the effects of climate change and engineering interventions. I recommend publication, subject to the authors addressing the major comments made below.

Specific concerns:

1. Even the model has been validated, the authors did not carry out any calibration of the model parameters. The authors adopt bottom drag coefficient values based on the area type and the estimated biomass of aquatic vegetation within the cell. The selected values are probably retrieved from previous studies and not calibrated for the specific site. To my opinion every model application need a calibration phase were the most important model parameters are properly tuned (as also highlighted by the sensitivity tests). Therefore, I suggest to perform a model calibration.

Response: Thank you for highlighting this aspect of the model setup. Ideally, we could adopt an automated calibration approach, aiming to minimize error in key model predictions using an objective function and a pre-determined acceptable criteria for model acceptability (e.g. Doherty and Johnston, 2003; Arhonditsis et al., 2008; Bahremand and Smedt, 2010). This approach has yet to receive widespread up-take in the hydrodynamic modelling community, particularly where 3-D models are employed to resolve variability in stratification, due to considerable computational burden running these models hundreds or thousands of times. Given the complex nature of the model domain that we wanted to adopt to resolve the river reaches to the tidal limit, and an individual run-time exceeding one-day per year, we therefore could not adopt an automatic optimization approach.

Instead, we adopted a structured hierarchical approach to calibration, similar to those described in Muleta and Nicklow (2004) and Hipsey et al. (2020), to manually calibrate the model. We first identified the key parameters of importance to the hydrology in the current study based on literature review and prior expert knowledge. In this stage, the key parameters were identified to be the bottom drag coefficient (which can vary spatially), the light extinction coefficient, bulk aerodynamic coefficients, and the mixing scheme options associated with the vertical turbulence model (in this case this is parameterized through the GOTM plugin). In the second stage, we evaluated a matrix of simulations, each with pre-determined parameter vectors and model options, by assessing model performance of each simulation against the observed salinity and temperature data at six stations within the estuary (at both surface and bottom levels), and the water elevation at the center of the Peel Inlet. For these we tabulated a summary of error metrics R, NSE and PBIAS, and used this to identify the final parameter options used for the validation simulations that were presented in the paper. The assessment was targeted, and included comparing performance of mixing models, against metrics relevant to the analysis such as stratification strength and hyper-salinity associated with evapo-concentration We also acknowledge issues in boundary condition data may affect the calibration, and we therefore spent considerable effort on the data quality control of the time-series of tide, weather, and catchment inputs to the model. In addition, the sensitivity of predictions to the selected environmental factors of air temperature, sea level mean height, and the bottom drag coefficient were performed.

We acknowledge that this approach is not necessarily providing the most optimum parameter set from a mathematical point of view, however, given other uncertainties in the spatial maps of vegetation (and therefore benthic drag) and potential error or bias in some of the assumed boundary conditions, it is our view that the model performance is close to the optimum and sufficiently accurate for the scale of our assessment. To address this in the paper, we therefore propose to add in the revised version a brief summary of the calibration approach and the results as supplemental material to this manuscript, and provide an improved discussion that describes to the known uncertainties and limitations of the model in this regard.

2. I suggest including some general information about tide characteristics, average freshwater discharge and main wind regimes in PHE in the site description section (2.1).

Response: Comment accepted. We are rewording the paragraph in the site description section to include more detailed description as below:

"The estuary experiences a micro-tide regime, with a range < 1m. The tide is dominated by the lunar diurnal constituents (K1, O1) contributing 87% of the tide potential energy, followed by the solar diurnal constituent (P1), principal lunar semidiurnal constituent (M2), and principal solar semi-diurnal constituent (S2) (Table 1). The coastal catchment of the estuary is drained by three major river systems: the Serpentine, Murray and Harvey Rivers (on average contributing 16.4%, 46.5%, and 30.8% to the total flow, respectively), and numerous minor drains (contributing 6.3% to the total flow) (Kelsey et al., 2011). Gauged flow rate data for Murray River were available from 1970 to present, while for Serpentine River and Harvey River were available from 1982 to present. For the missing periods in the gauged flows (year 1970 and 1978 for Serpentine River and Harvey River) and the ungauged drains, the output from the Source (eWater®) catchment modelling platform (Kelsey et al., 2011; Welsh et al., 2013), operated by the Western Australia 204 Department of Water and Environmental Regulation, was used."

Table 1. Principal tidal constituents for Fremantle tide record

Constituents	Potential Energy (%)	Amplitude (m)	Greenwich phase lag (degrees)	Frequency (cycles per hour)
K1	61.08	0.156	324	0.0418
O1	25.95	0.101	308	0.0387
P1	6.06	0.049	314	0.0416

M2	3.53	0.0374	323	0.0805
S2	3.37	0.0365	334	0.0833

The wind regime will be further explained in the data section. We used a combination of weather station records and regional weather models to produce the wind conditions, and we have undertaken a further investigation into the wind regimes from these three sources. As shown in the figure below, the wind regimes of these data sources showed similar distribution in wind magnitudes and directions, though the winds in the Mandurah station record are relatively smaller when compared to other two sources. We will integrate the figure in the revision and indicate the selection of meteorological sources could have influence the results in the years after 2001.

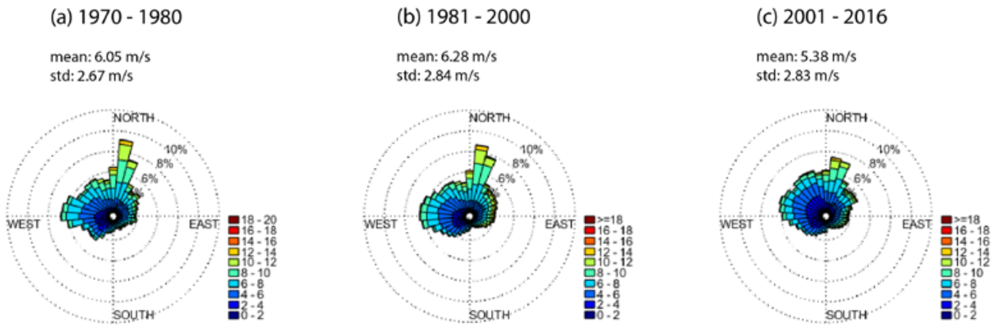

Figure 1. Rose plot of wind condition in years of (a) 1970-1980, obtained from the Halls Head weather station; (b) 1981-2000, obtained from the WRF weather model; and (c) 2001-2016, obtained from the Mandurah weather station.

3. A detailed description of the open sea boundary conditions used in the simulations is needed.

Response: Comment accepted. We will add an open sea boundary condition description in the model set up section as below: “The water level at the ocean boundary was specified with the Fremantle gauge station record, while the velocity was calculated internally based on a radiation condition”.

4. Please provide a more detailed description of the retention time computation (number of replicas per year, boundary conditions, initial conditions, treatment of the tail of the concentration decay when the simulation is shorted than the retention time, . . .). The work of Li et al. (2019) is not present in the reference list.

Response: Comment accepted. For each selected year, the modelling simulation started from 1st September of the previous year, giving a 4-month spin-up period, and the results from 1st January to the end of the selected year were used for analysis. The initial condition of water temperature and salinity was interpolated from the field data when they were available (years 1985-2016), except the years 1970 and 1978 when no field data was available and so the same initial condition as for 1985 was adopted.

Our study adopted a ‘water age’ method to calculate the water retention time, which is defined as the time of a water parcel has spent since entering the model domain through one of the boundaries (Zimmerman, 1988; Monsen et al., 2002). The modelled water age was initially set to be 0 across the domain, then the water age in each computational cell was computed as a conservative tracer subject to a constant increase with time (i.e. $d\tau/dt = 1$, where τ is the water age, and t is the time, in addition to advection and mixing), with the boundary values of τ set to 0. While the water age method has an advantage of presenting the spatial heterogeneity of water retention (Monsen et al., 2002), this method is different to the water renewal time, which is calculated by the rate of tracer decaying within the study domain. Therefore the treatment of the tail of the concentration decay is not applicable in our study (further explanation of the difference between the water age and water flushing time methods is provided in the response to the next comment related to mixing efficiency). We will seek to integrate this information more clearly into the model set up section in the revision.

Apologizes for the missing reference of Li et al., (2019). The work of Li et al. (2019) was cited in the methodology section as a reference for the water age method. The full description of this reference is “Li, Y., Feng, H., Zhang, H., Sun, J., Yuan, D., Guo, L., Nie, J., Du, J. (2019), Hydrodynamics and water circulation in the New York/New Jersey Harbor: A study from the perspective of water age, Journal of Marine Systems, 199, doi.org/10.1016/j.jmarsys.2019.103219". We will add this reference in the revision of the manuscript.

5. Since the author is already computing the water retention time and the bulk flushing time, I strongly suggest to investigate the variation of the mixing efficiency of the lagoon. This will allow the author to investigate the effect of climate change and cut-opening not only on the sea-lagoon exchange (flushing), but also on the internal mixing processes. As far as I understood, the retention time computed by the author is similar to the water renewal time estimated by Umgiesser et al. (2014). According to Umgiesser et al (2014), the ratio between the bulk flushing time and the mean renewal time can be interpreted as an index of the mixing behaviour of the basin (i.e. mixing efficiency, ME). ME ranges between 0 and 1 and is equal to 1 in case of a fully mixed system (renewal time becomes equal to flushing time). In the theoretical case of ME = 0, the water masses entering the lagoon do not mix at all with the inner waters, and the renewal time goes to infinity.

Response: Thank you for the recommendation of the reference of Umgiesser et al. (2014), which compared the water retention time in 10 Mediterranean lagoons. We have carefully read this reference and found it a valuable reference to this research. The work of Umgiesser et al. (2014) adopted two hydrodynamic time parameters, one is water renewal time (WRT) and the other water flushing time (WFT). In their models, they set the initial tracer concentration to be 1 across the study domain, then calculate the WRT and WRF as the rate of tracer reduction. Because these two time parameters use the same mathematical method to calculate the retention time, they can then define the mixing efficiency (ME) as the ratio between WFT and WRT, and compared this mixing character between different lagoons.

We have found the method in this study attractive to study the mixing in lagoon estuaries, though we note that the water age method we used is theoretically different to the water renewal time method, and they cannot be compared directly to the bulk flushing time

(Zimmerman, 1988; Monsen et al., 2002). Although our current simulation outputs cannot reveal the mixing efficiency with the water age method, we find this concept is valuable to compare the mixing character before and after the construction of the artificial channel, as well as under wet and dry conditions. Therefore, we propose to carry further simulations using the tracer decay method so we can compute the WRT and WFT metrics in the Peel-Harvey Estuary. The inter-comparison of mixing efficiency changes affected by the climate and artificial channel will be presented and discussed, and placed in context of the Umgiesser et al. (2014) results.

6. In commenting the possible future changes in PHE hydrodynamics, please consider also that these coastal environments can act as sentinel systems for observation of global change (see ad example Ferrarin et al., 2014).

Response: Comment accepted. We thank the reviewer for the recommendation of the reference of Ferrarin et al., (2014). This paper is a valuable reference to the current manuscript. It showed that Mediterranean lagoons are sensitive to the climate change as they amplify the salinity and temperature changes expected for the open sea. It also showed that the coastal lagoon systems are under stress of not only the human activities but also the climate change. Therefore, the research of climate change on coastal systems has implications on more general scope. The Peel-Harvey Estuary, in this scope, can work as a valuable example for assessing climate change because it has a long historical record of its hydrology since 1980s, and the local system has experienced a notable change due to the consistent drying climate. We will integrate this response into the revision to enhance the discussion of the roles of lagoons in global climate change studies.

Minor comments:

1. Change hydrologic to hydrological

Response: Comment accepted.

2. Line 13-15: I suggest to remove this statement since is not valid in general.

Response: Thank you for pointing out this. We did not mean that artificially channel is a common engineering intervention of many estuarine lagoons. We will reword the text as: "The introduction of artificial channel is a fundamental engineering measure to enhance flushing and alter the hydrology of estuarine lagoon systems, however, the effects from the interaction of climate change with artificial channels have not been well evaluated."

3. For the water inflow rate and fluxes I would suggest to use m3 instead of GL.

Response: Comment accepted. We will check through the manuscript to use the SI units consistently.

4. I suggest to remove Figure 11, because the results are clearly explained in the text.

Response: Thank you for the suggestion. While we agree that the results of salinity stratification are explained in the text, we still think the Figure 11 can work to provide a quantitative evaluation of the salinity stratification in space and time, therefore help the readers to better understand the heterogeneity and evolution of stratification. As stratification is also a key character of the estuary hydrology, we would suggest to keep this figure in the manuscript, but subject to finalization of the discussion.

Reference:

Arhonditsis, G. B., Perhar, G., Zhang, W., Massos, E., Shi, M., Das, A., 2008, Addressing equifinality and uncertainty in eutrophication models, Water Resour. Res., 44, W01420, doi:10.1029/2007WR005862.

Bahremand, A., Smedt, F.D. 2010, Predictive Analysis and Simulation Uncertainty of a Distributed Hydrological Model, Water Resources Management volume 24, 2869–2880.

Doherty, J., Johnston, J.M., 2003. Methodologies for Calibration and Predictive Analysis of a Watershed Model, Journal of the American Water Resources Association (JAWRA), 39(2):251-265.

Ferrarin, C., Bajo, M., Bellafiore, D., Cucco, A., De Pascalis, F., Ghezzo, M., Umgiesser G., 2014, Toward homogenization of Mediterranean lagoons and their loss of hydrodiversity, Geophys. Res. Lett., 41, 5935–5941, doi:10.1002/2014GL060843.

Hipsey, M.R., Gal, G., Arhonditsis, G.B., Carey, C.C., Elliott, J.A., Frassl, M.A., Janse, J.H., de Mora, L., Robson, B.J. A system of metrics for the assessment and improvement of aquatic ecosystem models. Environ. Model. Soft 2020, 128, 104697.

Kelsey, P., Hall, J., Kretschmer, P., Quiton, B. and Shakya, D.: Hydrological and nutrient modelling of the Peel-Harvey catchment, Water Science Technical Series, Report no. 33, Department of Water, Western Australia., 2011.

Li, Y., Feng, H., Zhang, H., Sun, J., Yuan, D., Guo, L., Nie, J., Du, J., 2019, Hydrodynamics and water circulation in the New York/New Jersey Harbor: A study from the perspective of water age, Journal of Marine Systems, 199, doi.org/10.1016/j.jmarsys.2019.103219.

Monsen, N. E., Cloern, J. E., Lucas, L.V., Monismith, S.G., 2002. A comment on the use of flushing time, residence time, and age as transport time scales. Limnology & Oceanography, 47:1545–1553.

Muleta, M.K., Nicklow, J.W., 2004, Sensitivity and uncertainty analysis coupled with automatic calibration for a distributed watershed model, J. Hydrol., 306, 127–145.

Umgiesser, G., Ferrarin, C., Cucco, A., De Pascalis, F., Bellafiore, D., Ghezzo, M., Bajo, M., 2014, Comparative hydrodynamics of 10 Mediterranean lagoons by means of numerical modeling, J. Geophys. Res. Oceans, 119, 2212–2226, doi:10.1002/2013JC009512.

Welsh, W.D., Vaze, J., Dutta, D., Rassam, D., Rahman, J.M., Jolly, I.D., Wallbrink, P., Podger, G.M., Bethune, M., Hardy, M.J., Teng, J., Lerat, J., 2013, An integrated modelling framework for regulated river systems, Environ. Model. Softw., 39, 81–102, doi:10.1016/j.envsoft.2012.02.022.

Zimmerman, J.T.F., 1988. Estuarine residence times, p. 75–84. In B. Kjerfve [ed.], Hydrodynamics of estuaries. V. 1. CRC Press.