Appendix I – Descriptive statistics

Table Ap-1: Descriptive statistics for mean sea level (m) for Cascais tide gauge location for period 16/02/1972 12h to 07/10/1972 21h from tide gauge measurements, MOHID Tagus Estuary simulation results for domain 0 and nested domain 1 and inverted barometer formulation. Mean sea level is equal to the tide residuals of measurements and simulation results. Statistics calculated from hourly values except the results from inverted barometer which are calculated from values every 6 hours.

Mean sea level at Cascais	Average	Standard deviation	Maximum	Minimum
Measurements[a]	2.15	0.08	2.50	1.84
Model simulation:				
Domain 0	2.04	0.05	2.21	1.93
Domain 1	2.06	0.08	2.36	1.74
Inverted barometer formulation	2.04	0.05	2.23	1.94

Notes: [a] statistics for values every 6 hours have the same results, except the maximum, which is 2.46m.

Table Ap-2: Descriptive statistics for mean sea level (m) filtered to remove perturbations with period bellow 30h for tide gauge measurements. Statistics are calculated from tide residuals for the period 01/11/1972 0h - 31/01/1973 22h. Tide gauges indicated from open ocean (Cascais) to Tagus River (Vila Franca de Xira).

Tide gauge	Average	Standard deviation	Maximum	Minimum
Cascais	2.19	0.06	2.34	2.05
Paço de Arcos	2.18	0.07	2.40	2.05
Trafaria	2.23	0.08	2.45	2.08
Cacilhas	2.15	0.07	2.39	2.04
Lisboa	2.22	0.06	2.42	2.12
Cabo Ruivo	2.26	0.07	2.46	2.14
Seixal	2.21	0.06	2.43	2.10
Montijo	2.25	0.07	2.48	2.11
Alcochete	2.28	0.08	2.52	2.14
Ponta de Erva	2.22	0.09	2.49	2.03
Vila Franca de Xira	2.48	0.10	2.78	2.27

Table Ap-3: Descriptive statistics for mean sea level (m) filtered to remove perturbations with period bellow 30h for domain 2 MOHID Tagus Estuary simulation with tide forcing. Domain 2 with actualized bathymetry and nested in alternative domain 1 configuration developed to test Hypothesis 1. Statistics are calculated from tide residuals for the period 01/11/1972 0h - 31/01/1973 22h. Tide gauges indicated from open ocean (Cascais) to Tagus River (Vila Franca de Xira).

Tide gauge	Average	Standard deviation	Maximum	Minimum
Cascais	2.08	0.00	2.09	2.06
Paço de Arcos	2.08	0.00	2.09	2.06
Trafaria	2.08	0.00	2.09	2.06
Cacilhas	2.07	0.00	2.08	2.05
Lisboa	2.08	0.00	2.09	2.06
Cabo Ruivo	2.10	0.01	2.11	2.09
Seixal	2.10	0.01	2.11	2.08
Montijo	2.10	0.00	2.11	2.08
Alcochete	2.12	0.01	2.13	2.10
Ponta de Erva	2.22	0.02	2.25	2.16
Vila Franca de Xira	2.42	0.04	2.52	2.31

Table Ap-4: Descriptive statistics for mean sea level (m) filtered to remove perturbations with period bellow 30h for domain 2 MOHID Tagus Estuary simulation with tide forcing and inverted barometer effect. Domain 2 with actualized bathymetry and nested in alternative domain 1 configuration developed to test Hypothesis 1. Statistics are calculated from tide residuals for the period 01/11/1972 0h - 31/01/1973 22h. Tide gauges indicated from open ocean (Cascais) to Tagus River (Vila Franca de Xira).

Tide gauge	Average	Standard deviation	Maximum	Minimum
Cascais	2.01	0.04	2.12	1.90
Paço de Arcos	2.01	0.05	2.12	1.90
Trafaria	2.01	0.04	2.11	1.89
Cacilhas	2.00	0.04	2.11	1.88
Lisboa	2.00	0.04	2.11	1.89
Cabo Ruivo	2.03	0.05	2.14	1.92
Seixal	2.03	0.05	2.14	1.92
Montijo	2.03	0.05	2.14	1.92
Alcochete	2.05	0.04	2.19	1.96
Ponta de Erva	2.15	0.04	2.25	2.04
Vila Franca de Xira	2.36	0.06	2.56	2.22

Table Ap-5: Descriptive statistics for meteorological parameters from Guia meteorological station measurements for the period 15/01/2005 0h – 28/02/2005 23h. Statistics calculated from hourly values.

Tide gauge	Average	Standard deviation	Maximum	Minimum
Temperature (ºC)	11.0	2.8	19.9	4.1
Solar radiation (W/m^2)	143	211	736	0
Relative humidity (0-1)	0.6	0.2	0.9	0.1
Zonal wind velocity (m/s)	-1.22	1.64	5.40	-6.24
Meridional wind velocity (m/s)	-1.26	1.91	7.81	-9.74

Table Ap-6: Descriptive statistics for meteorological parameters from MM5 model highest resolution results for location of Guia meteorological station for the period 15/01/2005 0h – 28/02/2005 23h. Statistics calculated from hourly values interpolated for the domain 2 MOHID Tagus Estuary horizontal grid.

Tide gauge	Average	Standard deviation	Maximum	Minimum
Temperature (ºC)	10.8	2.2	15.2	4.9
Solar radiation (W/m^2)	126	204	737	0
Relative humidity (0-1)	0.7	0.1	1.0	0.4
Zonal wind velocity (m/s)	-3.33	3.76	8.52	-12.20
Meridional wind velocity (m/s)	-2.84	3.01	8.38	-10.47

Table Ap-7: Descriptive statistics for water level (m) state for tide gauge locations from the True Model simulation. Statistics are calculated from hourly domain 2 results for the period 01/11/1972 0h - 31/01/1973 17h. Tide gauges indicated from open ocean (Peniche) to Tagus River (Vila Franca de Xira).

Tide gauge	Average	Standard deviation	Maximum	Minimum
Peniche	2.08	0.79	3.92	0.37
Sesimbra	2.08	0.75	3.83	0.45
Cascais	2.08	0.76	3.84	0.45
Paço de Arcos	2.08	0.78	3.81	0.42
Trafaria	2.08	0.80	3.85	0.36
Cacilhas	2.05	0.85	3.98	0.27
Alfeite	2.09	0.86	4.02	0.25
Lisboa	2.07	0.86	3.99	0.25
Cabo Ruivo	2.10	0.89	4.09	0.24
Seixal	2.11	0.87	4.07	0.42
Montijo	2.09	0.89	4.09	0.25
Alcochete	2.13	0.91	4.17	0.21
Ponta de Erva	2.23	0.80	4.20	1.18
Póvoa de Santa Iria	2.25	0.79	4.20	0.94
Vila Franca de Xira	2.53	0.55	4.24	1.61

Table Ap-8: Descriptive statistics for zonal velocity state (m/s) for tide gauge locations from the True Model simulation. Statistics are calculated from hourly domain 2 results for the period 01/11/1972 0h - 31/01/1973 17h. Tide gauges indicated from open ocean (Peniche) to Tagus River (Vila Franca de Xira).

Tide gauge	Average	Standard deviation	Maximum	Minimum
Peniche	-0.0101	0.0265	0.0545	-0.0745
Sesimbra	-0.0003	0.0018	0.0134	-0.0060
Cascais	0.0011	0.0185	0.0709	-0.0872
Paço de Arcos	-0.0217	0.1395	0.1842	-0.3660
Trafaria	-0.0039	0.3866	0.7057	-0.6941
Cacilhas	-0.0474	0.6627	1.0833	-1.4792
Alfeite	-0.0052	0.0174	0.0742	-0.0482
Lisboa	0.0379	0.5429	1.0352	-1.0427
Cabo Ruivo	0.0138	0.1251	0.2504	-0.2092
Seixal	-0.0003	0.0093	0.1188	-0.1191
Montijo	-0.0145	0.3232	0.6257	-0.7063
Alcochete	0.0016	0.0746	0.1514	-0.1544
Ponta de Erva	-0.0173	0.1483	0.3605	-0.2211
Póvoa de Santa Iria	-0.0230	0.0616	0.1378	-0.1412
Vila Franca de Xira	-0.0277	0.0190	-0.0017	-0.0735

Table Ap-9: Descriptive statistics for meridional velocity state (m/s) for tide gauge locations from the True Model simulation. Statistics are calculated from hourly domain 2 results for the period 01/11/1972 0h - 31/01/1973 17h. Tide gauges indicated from open ocean (Peniche) to Tagus River (Vila Franca de Xira).

Tide gauge	Average	Standard deviation	Maximum	Minimum
Peniche	0.0177	0.0360	0.1221	-0.0605
Sesimbra	-0.0005	0.0040	0.0181	-0.0114
Cascais	-0.0021	0.0479	0.1511	-0.2125
Paço de Arcos	-0.0203	0.1334	0.1778	-0.3502
Trafaria	-0.0140	0.0078	0.0039	-0.0357
Cacilhas	0.0129	0.0131	0.0556	-0.0104
Alfeite	0.0021	0.0085	0.0235	-0.0290
Lisboa	0.0222	0.1030	0.2299	-0.1633
Cabo Ruivo	0.0140	0.1352	0.2657	-0.2280
Seixal	0.0056	0.3435	0.5794	-0.7829
Montijo	0.0008	0.0108	0.0254	-0.0260
Alcochete	0.0012	0.0859	0.1755	-0.1817
Ponta de Erva	-0.0189	0.1410	0.3497	-0.2424
Póvoa de Santa Iria	-0.0234	0.0680	0.1481	-0.1551
Vila Franca de Xira	-0.1382	0.2995	0.4824	-0.5782

Table Ap-10: Descriptive statistics for water level state (m) for tide gauge locations from the Free-run simulation. Statistics are calculated from hourly domain 2 results for the period 01/11/1972 0h - 31/01/1973 17h. Tide gauges indicated from open ocean (Peniche) to Tagus River (Vila Franca de Xira).

Tide gauge	Average	Standard deviation	Maximum	Minimum
Peniche	2.07	0.87	4.85	-0.35
Sesimbra	2.08	0.80	3.99	0.07
Cascais	2.08	0.80	4.19	0.16
Paço de Arcos	2.08	0.80	4.26	0.10
Trafaria	2.07	0.83	4.06	0.06
Cacilhas	2.05	0.86	4.02	0.05
Alfeite	2.08	0.88	4.10	-0.06
Lisboa	2.06	0.87	4.01	0.04
Cabo Ruivo	2.10	0.89	4.06	0.07
Seixal	2.12	0.86	4.07	0.36
Montijo	2.09	0.88	4.05	0.12
Alcochete	2.13	0.91	4.22	0.04
Ponta de Erva	2.24	0.80	4.24	1.18
Póvoa de Santa Iria	2.25	0.78	4.26	0.93
Vila Franca de Xira	2.53	0.55	4.28	1.59

Table Ap-11: Descriptive statistics for zonal velocity state (m/s) for tide gauge locations from the Free-run simulation. Statistics are calculated from hourly domain 2 results for the period 01/11/1972 0h - 31/01/1973 17h. Tide gauges indicated from open ocean (Peniche) to Tagus River (Vila Franca de Xira).

Tide gauge	Average	Standard deviation	Maximum	Minimum
Peniche	-0.0100	0.0360	0.1052	-0.1124
Sesimbra	-0.0007	0.0057	0.0246	-0.0198
Cascais	0.0013	0.0209	0.0954	-0.0936
Paço de Arcos	-0.0227	0.1447	0.2321	-0.3971
Trafaria	-0.0039	0.3935	0.8792	-0.8005
Cacilhas	-0.0631	0.6803	1.3614	-1.6932
Alfeite	-0.0031	0.0241	0.1201	-0.0847
Lisboa	0.0341	0.5612	1.2284	-1.1821
Cabo Ruivo	0.0161	0.1307	0.3465	-0.2510
Seixal	0.0004	0.0224	0.3601	-0.2787
Montijo	-0.0203	0.4126	0.9675	-1.1781
Alcochete	0.0034	0.0981	0.2834	-0.1934
Ponta de Erva	-0.0177	0.1625	0.3994	-0.3841
Póvoa de Santa Iria	-0.0234	0.0650	0.1720	-0.1576
Vila Franca de Xira	-0.0278	0.0186	-0.0011	-0.0727

Table Ap-12: Descriptive statistics for meridional velocity state (m/s) for tide gauge locations from the Free-run simulation. Statistics are calculated from hourly Domain 2 results for the period 01/11/1972 0h - 31/01/1973 17h. Tide gauges indicated from open ocean (Peniche) to Tagus River (Vila Franca de Xira).

Tide gauge	Average	Standard deviation	Maximum	Minimum
Peniche	0.0197	0.0434	0.1485	-0.1116
Sesimbra	-0.0019	0.0206	0.0825	-0.0915
Cascais	-0.0041	0.0734	0.2223	-0.3010
Paço de Arcos	-0.0211	0.1389	0.2225	-0.3827
Trafaria	-0.0144	0.0082	0.0043	-0.0422
Cacilhas	0.0135	0.0149	0.0617	-0.0223
Alfeite	0.0015	0.0123	0.0388	-0.0494
Lisboa	0.0220	0.1070	0.2807	-0.1933
Cabo Ruivo	0.0161	0.1407	0.3634	-0.2745
Seixal	0.0082	0.3856	0.7920	-1.0662
Montijo	0.0013	0.0130	0.0319	-0.0340
Alcochete	0.0026	0.1120	0.3242	-0.2167
Ponta de Erva	-0.0195	0.1602	0.4480	-0.5264
Póvoa de Santa Iria	-0.0239	0.0734	0.1914	-0.1651
Vila Franca de Xira	-0.1388	0.2993	0.5181	-0.5733

Table Ap-13: Descriptive statistics for water level state error (m) for tide gauge locations from the Free-run simulation. Error is considered as difference between the Free-run and the True Model results. Statistics are calculated from hourly Domain 2 results for the period 01/11/1972 0h - 31/01/1973 17h. Tide gauges indicated from open ocean (Peniche) to Tagus River (Vila Franca de Xira).

Tide gauge	Average	Standard deviation	Maximum	Minimum
Peniche	-0.01	0.37	1.25	-1.31
Sesimbra	0.00	0.26	1.01	-0.74
Cascais	0.00	0.24	0.75	-0.85
Paço de Arcos	0.00	0.20	0.73	-0.78
Trafaria	0.00	0.17	0.58	-0.52
Cacilhas	-0.01	0.15	0.55	-0.56
Alfeite	-0.01	0.18	0.62	-0.67
Lisboa	-0.01	0.15	0.51	-0.55
Cabo Ruivo	0.00	0.13	0.54	-0.40
Seixal	0.02	0.11	0.48	-0.34
Montijo	0.00	0.12	0.50	-0.37
Alcochete	0.00	0.14	0.52	-0.53
Ponta de Erva	0.01	0.10	0.46	-0.47
Póvoa de Santa Iria	0.00	0.11	0.56	-0.53
Vila Franca de Xira	0.00	0.07	0.44	-0.42

Table Ap-14: Descriptive statistics for zonal velocity state error (m/s) for tide gauge locations from the Free-run simulation. Error is considered as difference between the Free-run and the True Model results. Statistics are calculated from hourly Level 2 results for the period 01/11/1972 0h - 31/01/1973 17h. Tide gauges indicated from open ocean (Peniche) to Tagus River (Vila Franca de Xira).

Tide gauge	Average	Standard deviation	Maximum	Minimum
Peniche	0.0002	0.0271	0.0914	-0.0942
Sesimbra	-0.0003	0.0054	0.0249	-0.0203
Cascais	0.0001	0.0109	0.0361	-0.0400
Paço de Arcos	-0.0011	0.0317	0.1269	-0.1075
Trafaria	0.0000	0.0937	0.3609	-0.3066
Cacilhas	-0.0157	0.2265	0.8485	-0.7400
Alfeite	0.0020	0.0201	0.1201	-0.0664
Lisboa	-0.0038	0.1731	0.6632	-0.6145
Cabo Ruivo	0.0024	0.0477	0.1940	-0.1777
Seixal	0.0007	0.0209	0.3941	-0.2373
Montijo	-0.0058	0.2716	0.9251	-0.9688
Alcochete	0.0018	0.0667	0.2456	-0.2169
Ponta de Erva	-0.0004	0.0735	0.3622	-0.3087
Póvoa de Santa Iria	-0.0003	0.0246	0.1636	-0.0966
Vila Franca de Xira	-0.0001	0.0027	0.0150	-0.0127

Table Ap-15: Descriptive statistics for meridional velocity state error (m/s) for tide gauge locations from the Free-run simulation. Error is considered as difference between the Free-run and the True Model results. Statistics are calculated from hourly Domain 2 results for the period 01/11/1972 0h - 31/01/1973 17h. Tide gauges indicated from open ocean (Peniche) to Tagus River (Vila Franca de Xira).

Tide gauge	Average	Standard deviation	Maximum	Minimum
Peniche	0.0020	0.0296	0.1161	-0.0948
Sesimbra	-0.0014	0.0202	0.0834	-0.0943
Cascais	-0.0020	0.0595	0.2099	-0.2773
Paço de Arcos	-0.0008	0.0332	0.1223	-0.1131
Trafaria	-0.0004	0.0040	0.0130	-0.0162
Cacilhas	0.0005	0.0068	0.0305	-0.0252
Alfeite	-0.0006	0.0103	0.0307	-0.0512
Lisboa	-0.0001	0.0309	0.1202	-0.1132
Cabo Ruivo	0.0020	0.0492	0.1972	-0.1817
Seixal	0.0026	0.1927	0.7441	-0.7607
Montijo	0.0004	0.0077	0.0335	-0.0371
Alcochete	0.0013	0.0757	0.2611	-0.2435
Ponta de Erva	-0.0006	0.0850	0.5346	-0.4380
Póvoa de Santa Iria	-0.0005	0.0300	0.1795	-0.1141
Vila Franca de Xira	-0.0006	0.0571	0.3523	-0.3271

Appendix II – Analysis of water discharges in Tagus Estuary

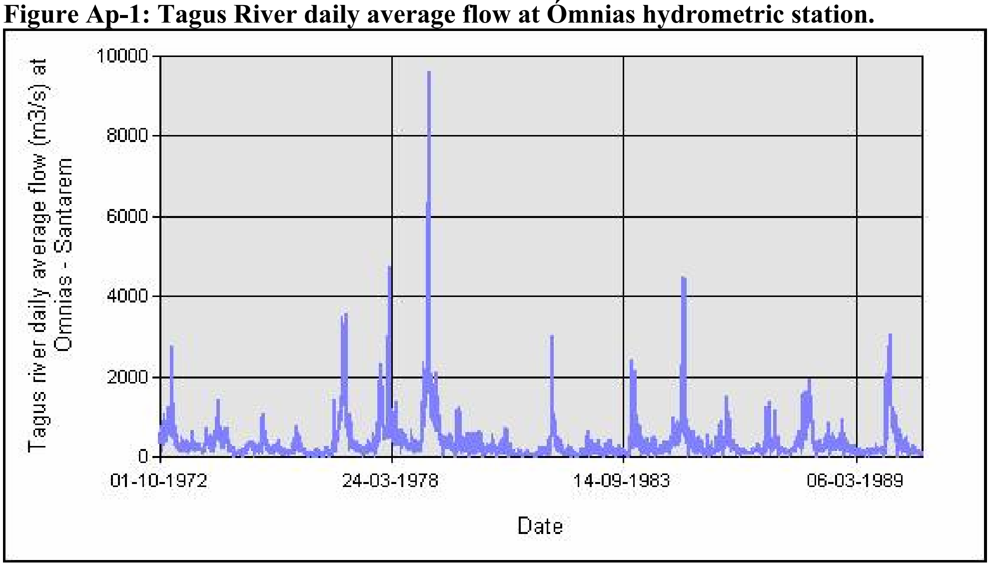
The average values for water discharges flow in the Tagus Estuary, considered in MOHID Tagus Estuary modelling, are presented in Table Ap-16: they reveal that the Tagus River is dominant discharge in terms of flow.

Table Ap-16: Average flow of main water discharges in the Tagus Estuary.

River		Wastewater discharge	
Name	**Default flow (m^3/s)**	**Name**	**Default flow (m^3/s)**
Tagus	187.2	Mutela	0.301
		Portinho da Costa	0.259
		Quinta da Bomba	0.707
		Alcântara	1.985
Sorraia	39.5	Chelas	0.608
		Alhos Vedros	0.009
		Moita	0.175
		Palhais	0.793
Trancão	6	Montijo	0.139

From the evolution of an historical time series of daily average flows for nearly 30 years of Ómnias, in Figure Ap-1, it can be observed that Tagus River flow presents high variability, so that although flows in the period generally remained bellow the 1000 m3/s, it was observed a maximum daily average flow of 9605 m^3/s in this particular period. It is also noted that the yearly peaks are observed approximately in the autumn/winter season. These results show that it is important to use a detailed Tagus River flow in modelling, particularly in the autumn/winter season.

Figure Ap-1: Tagus River daily average flow at Ómnias hydrometric station.



Appendix III – Tide representation of actualized domain 2 bathymetry

A simulation of MOHID Tagus Estuary 2D configuration is made considering the alternative enlarged domain 1 developed for research on Hypothesis 1 and the actualized bathymetry of domain 2, using the modelling conditions of the existent MOHID Tagus Estuary system and river flows as indicated in Chapter III and only tide as forcing for the period 01/10/1972 0h to 31/01/1973 0h. The water level results for the two months period 01/11/1972 0h to 31/12/1973 22h at tide gauge locations in the Tagus Estuary are contrasted with the tidal part of tide gauge measurements, presented in Chapter III, for assessment of tide representation. The results for bias and centered RMSE are presented in Table Ap-17.

Table Ap-17: Bias and centered RMSE between domain 2 MOHID Tagus Estuary 2D configuration and tidal part of tide gauge measurements. Domain 2 with actualized bathymetry and nested in alternative domain 1 configuration developed for Hypothesis 1 test. Measurements are harmonically analysed to obtain tidal part. Statistics are calculated from hourly values for the period 01/11/1972 0h - 31/12/1973 22h. Tide gauges indicated from open ocean (Cascais) to Tagus River (Vila Franca de Xira).

Tide gauge	Bias		Centered RMSE	
	(m)	(%)[b]	(m)[c]	(%)[d]
Cascais	-0.09[a]	-4	0.09[a] (0.08)	13
Paço de Arcos	-0.20	-9	0.05 (0.11)	7
Trafaria	-0.24	-10	0.07 (0.11)	9
Cacilhas	-0.15	-7	0.05 (0.08)	5
Lisboa	-0.22	-10	0.04 (0.08)	5
Cabo Ruivo	-0.23	-10	0.10 (0.13)	11
Seixal	-0.17	-8	0.07 (0.10)	8
Montijo	-0.21	-9	0.06 (0.10)	7
Alcochete	-0.11	-5	0.10 (0.17)	11
Ponta de Erva	-0.05	-2	0.33 (0.35)	34
Vila Franca de Xira	-0.10	-4	0.37 (0.37)	41

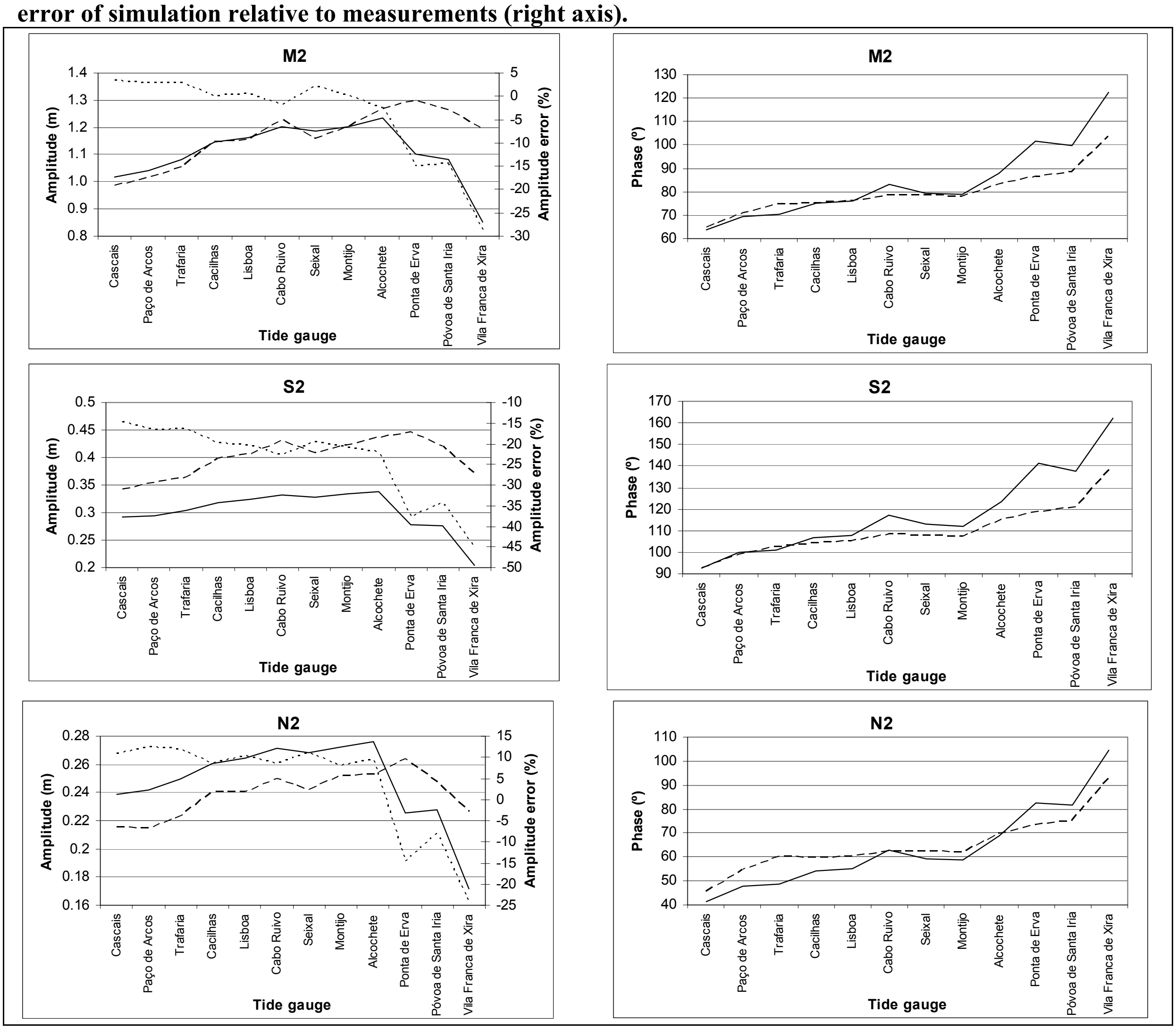
Notes: [a] tidal part of measurements without considering K_2 component (could not be estimated by harmonic analysis); [b] percentage represented by bias relative to average value of tidal part of measurements; [c] in brackets is presented the value assessed for the full measurement (tide and non tide parts); [d] percentage represented by centered RMSE relative to standard deviation of tidal part of measurements; measurement period used for harmonic analysis is nearly one year for all tide gauges except Cascais where only four months are available.

In all the tide gauge locations the model underestimates the average water level detected in measurements, as the bias is always negative. However, this is more noticeable in areas where the circulation is more constrained such as the estuary exit channel (Trafaria, Cacilhas, Lisboa) and the channels of central estuary (Seixal and Montijo), where bias represents approximately 10% of average water level in measurements. Comparatively, the coast (Cascais), the unconstrained areas of central and upper estuary (Alcochete and Ponta de Erva) and the inner delta of Tagus River (Vila Franca de Xira) present very small bias (5% or less). These results suggest that the bias is due to average mean sea level difference: having into account that approximately the same bias could be observed in domain 1 results in Cascais for the early and mid 1972 (Table Ap-1 and section IV.2.2.) with a bathymetry resolution considerably smaller (2km versus 300m) this is not due to a bathymetry resolution problem; it could be instead a sign that the average mean sea level imposed at the boundary of domain 1 (or of domain 0 of section IV.2.2.) is incorrect. This provides evidence that mean sea level time variability is a relevant issue for hydrodynamic modelling at the Tagus Estuary, at least in its central and lower part.

The representation of tide variability is indicated by the centered RMSE values. The result for Cascais indicates that domain 2 presents a lower performance in representing tide that domain 1 (see section IV.1.2.), however this is thought to be mostly due to the fact that the only a period of four months of measurements comprising the simulation period is available for Cascais tide gauge: the harmonic analysis could not estimate the K_2 component of tide which has an important amplitude of 10cm and the tidal part of measurements thus does not account for the variability due to this component. Differently from the spatial pattern of the bias, the tide seems to be less well represented in the upper estuary, particularly at the mouths of rivers Tagus and Sorraia (Vila Franca de Xira and Ponta de Erva) where the error amounts to more than 30% of measurements tide variability. As the effect of river flow variability is present in model results and not in the reconstructed tidal part of measurements it is important to contrast the centered RMSE relative to the tidal part of measurements and the centered RMSE relative to the full water level of measurements: in both Vila Franca de Xira and Ponta de Erva the centered RMSE change is not appreciable which suggests that the large value is not due to the river flow misrepresentation but instead due to tide misrepresentation. At middle and lower estuary the centered RMSE values are considerably smaller, with very good values of 5% centered RMSE in the border of the estuary exit channel (Lisboa and Cacilhas). These results indicate that the actualization of the domain 2 bathymetry with more detailed bathymetry coastline data does not reduced significantly the weak representation of tide in the upper estuary noted by Fernandes (2005).

The simulation results from 01/11/1972 0h to 31/01/1973 0h (three months) are harmonically analysed to investigate further the tide misrepresentation. The amplitude and phase results for the three larger amplitude tide components, M_2, S_2 and N_2, are presented in Figure Ap-2. In all three semi diurnal components it is verified, in both measurements and simulation results, an increase of amplitude from ocean to inner estuary till Ponta de Erva and after a decrease till the Tagus River, which is according with the results of Fortunato *et al.* (1999). The representation of the M_2 component is very good in amplitude and phase (within 5% error in amplitude and less than 5º in phase) till Ponta de Erva. In Cascais domain 2 provides a big improvement in the representation of this component whereas in domain 1 results an amplitude error of more than 5cm is observable. However, from Ponta de Erva to Vila Franca de Xira the M_2 representation is greatly degraded, both in amplitude with underestimations of 20% and in phase with errors of 20º. The horizontal grid resolution in these locations is smaller and so the underestimation is probably due to a bathymetric misrepresentation of the area with estuarine channels represented as larger than reality, supporting the indication of Fernandes (2005). In S_2 and N_2 the degree of representation in the model is weaker with errors again more expressive in the upper estuary reaching 40% and 15% underestimations of amplitude, respectively.

Figure Ap-2: Amplitude and phase of M_2, S_2 and N_2 tide components at tide gauges in the Tagus Estuary and adjacent coast as provided by measurements and domain 2 MOHID Tagus Estuary configuration. Domain 2 is nested in alternative domain 1 MOHID Tagus Estuary configuration developed for Hypothesis 1. Results from harmonic analysis of simulation results (01/11/1972-31/01/1973) and tide gauge measurements (several periods) are shown: dash line is measurements, black line is simulation; dot line is error of simulation relative to measurements (right axis).



The results for the dominant diurnal components, K_1 and O_1, and the dominant shallow water component M_4 in Cascais are presented in Figure Ap-3. The diurnal components are generally overestimated by the model, especially in the estuary exit channel where K_1 and O_1 amplitudes are

35% and 8% larger than in measurements. However in term of phase the K_1 is not degraded by the model except in the upper estuary where the phase is overestimated by 20º. Together with the overestimation of the phase in semi diurnal components this indicates that the tidal wave arrives later in the simulation relative to the measurements in these locations, which indicates bathymetry inadequacy. As for the shallow water component M_4, while it is found a distribution of amplitude across the estuary according to Fortunato *et al.* (1999), with a big increase in the estuary exit channel, in both measurements and simulation, it is also verified a quantitatively weak representation in all the tide gauge locations, with the simulation providing a coarse underestimation (50% or more) in locations till the upper estuary where a large overestimation is perceived in Vila Franca de Xira. In this location this result suggests that an excessive energy transfer from M_2 to M_4, possibly due to the excessively large channels represented in bathymetry and also to inadequate intertidal areas description, since them affect determinately the creation of this component according with Fortunato *et al.* (1999). Since outside the estuary the increase of resolution from 2km to 300m is not adequate for the model to produce the M_4 component (with almost 100% underestimation in Cascais provided by domain 2 and domain 1) these results suggest that even there the bathymetry resolution is not adequate to represent this shallow water component.

The distribution of amplitude error per tide period is presented in Figure Ap-4 for Cascais and the two tide gauge locations presenting weaker tide representation: Ponta de Erva and Vila Franca de Xira. In the case of Cascais, it can be observed that domain 2 comparatively to domain 1 (see section IV.1.2.) presents a reduced overestimation of most semi diurnal components but providing underestimation of one component (S_2) which is not observed in domain 1 results. However, the diurnal components present now a larger overestimation than in domain 1. The shallow water components do not show appreciable changes of error, evidencing that the increase of resolution from domain 1 to domain 2 is not sufficient in this respect. As for Ponta de Erva, Figure Ap-4 indicates that the amplitude error is grossly concentrated in the semi diurnal band, which is greatly underestimated, explaining clearly the large centered RMSE presented in the Table Ap-17. The shallow water components misrepresentation concentrates not only in the M_4 overestimation but in a M_6 underestimation (almost 100% error), clearly suggesting that M_2 energy is being transferred in the wrong way. The distribution of amplitude error observed for Vila Franca de Xira is very similar (Figure Ap-4) except that the M_6 component is now better described. The gross underestimation of semi diurnal components also explains the large centered RMSE in Table Ap-17 as being due to tide misrepresentation.

The validation of the tide representation of domain 2 MOHID Tagus Estuary shows that tide is reasonably well represented in the central and lower parts of the Tagus Estuary and in adjacent coast, although the model cannot produce significant amplitude error in shallow water components, but that in the upper estuary the tide representation is not adequate, with the error concentrating in semi diurnal tide amplitude underestimation and misrepresentation of shallow water components. The results validation evidences that bathymetry resolution is the main cause for this poor tide representation, which provides a quantitative fundament for Fernandes (2005) indication. The research also finds that error is not biased in this area although a significant bias is found in the lower and middle estuary, suggesting a misspecification of mean sea level at the domain 1 boundary.

Figure Ap-3: Amplitude and phase of K_1, O_1 and M_4 tide components at tide gauges in the Tagus Estuary and adjacent coast as provided by measurements and domain 2 MOHID Tagus Estuary configuration. Domain 2 is nested in alternative domain 1 MOHID Tagus Estuary configuration developed for Hypothesis 1. Results from harmonic analysis of simulation results (01/11/1972-31/01/1973) and tide gauge measurements (several periods) are shown: dash line is measurements, black line is simulation; dot line is error of simulation relative to measurements (right axis).

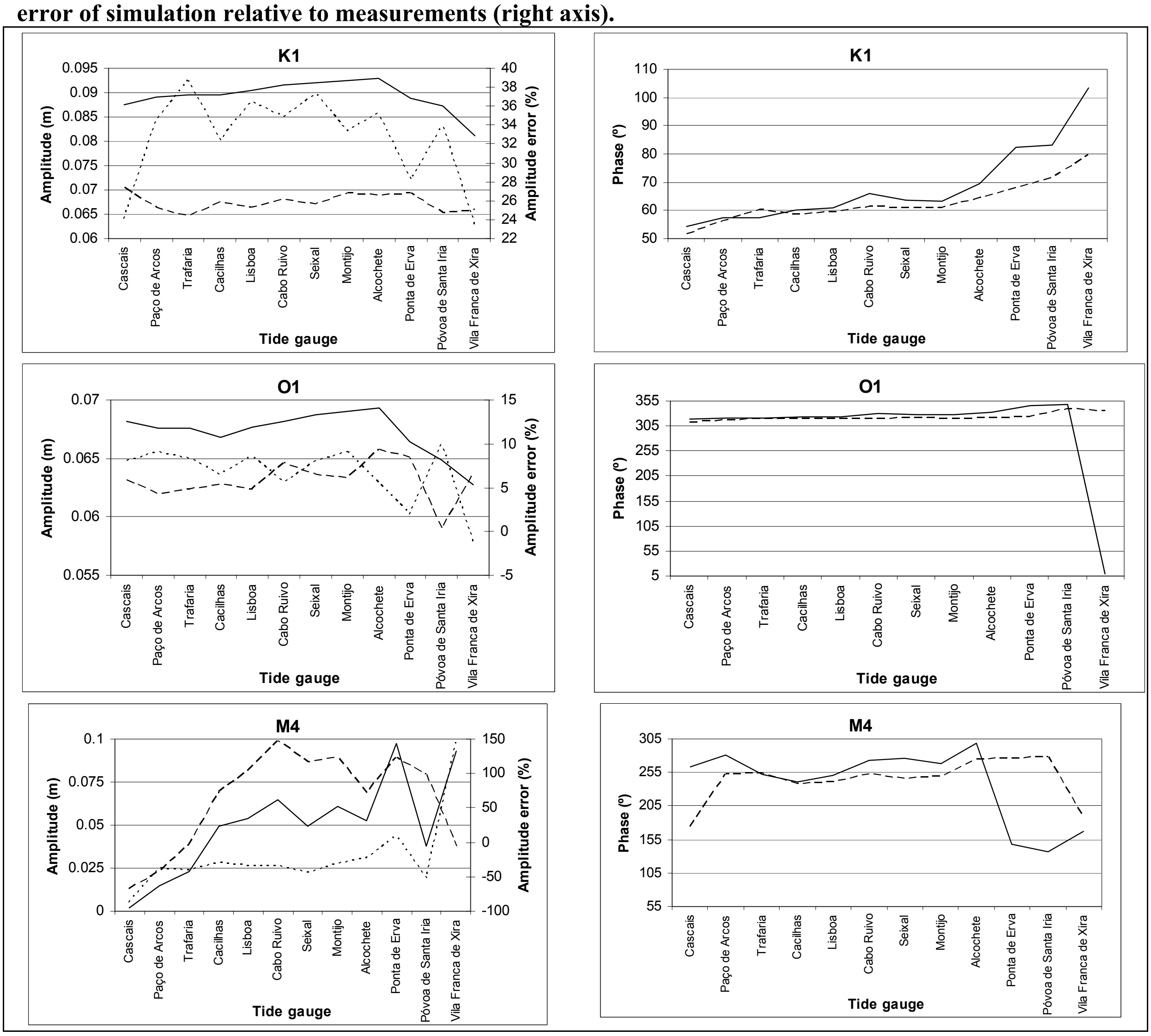
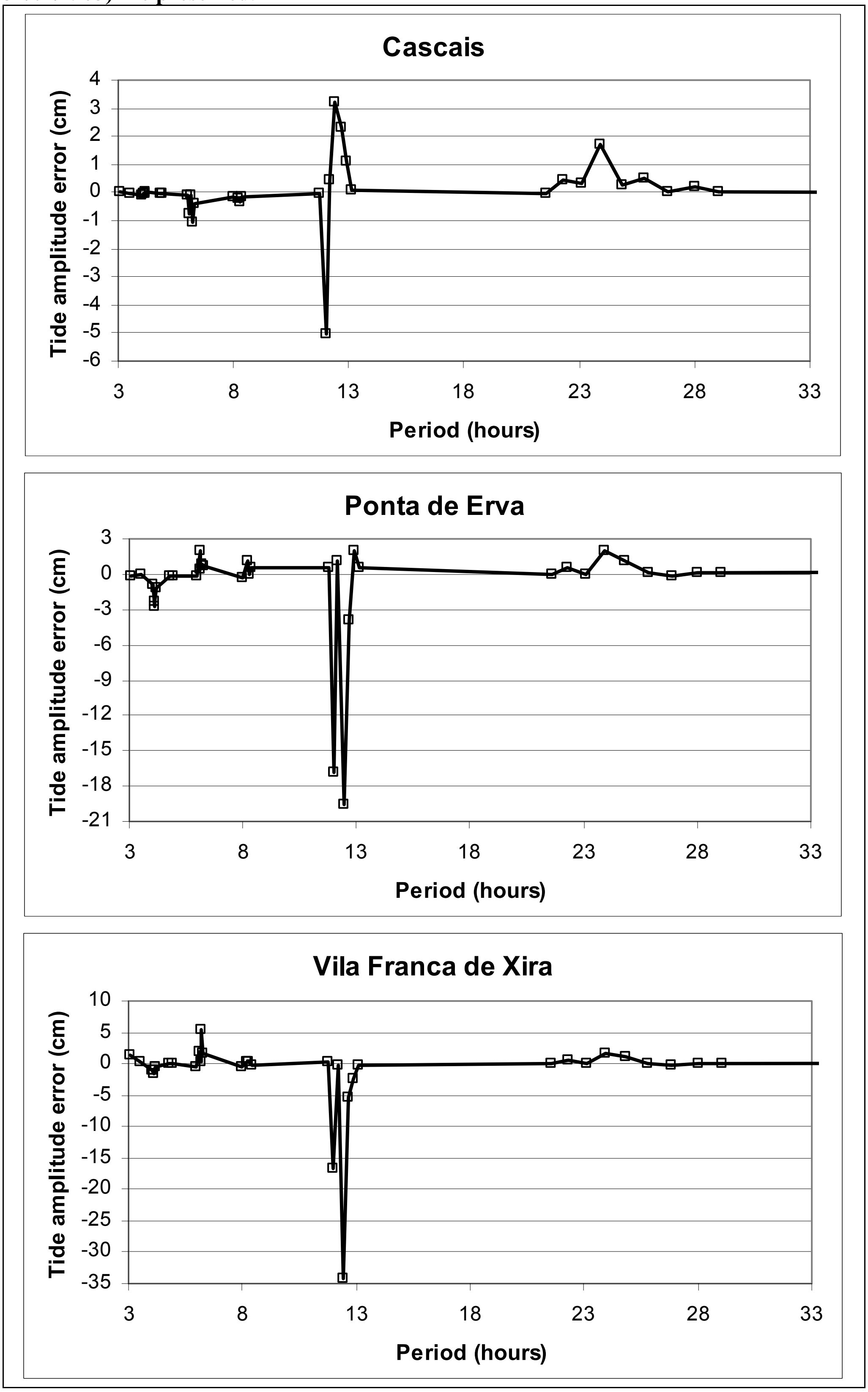


Figure Ap-4: Tide amplitude error of alternative domain 2 MOHID Tagus Estuary configuration simulation as a function of tide period in Cascais, Ponta de Erva and Vila Franca de Xira. Results from harmonic analysis of simulation results (01/11/1972-31/01/1973) are presented.

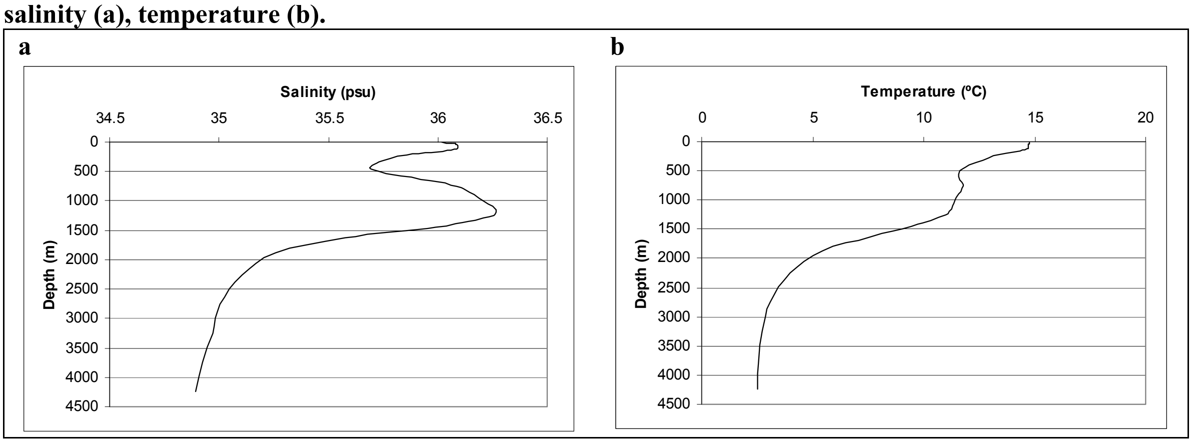


Appendix IV – Development of alternative domain 2 configuration vertical discretization

The alternative vertical discretization is developed to make the average depth difference between adjacent cartesian vertical layers similar to the density difference verified in adjacent depths in the density profile to be considered as reference for open boundary or initialization. In this situation, when MOHID Water interpolates property values from climatology profiles to the model layers, the density will have a similar vertical gradient to climatology and so instability occurrence in model simulations is minimized.

The density profile is calculated from the salinity and temperature profiles (Figure Ap-5), following the UNESCO (1981) equation of state used in MOHID Water simulations (correction for pressure is applied in density calculation). This is made for the February profile provided by Levitus (1982) and the corresponding density profile is presented in Figure Ap-6, presenting an approximately constant gradient. In Figure Ap-7 is presented the depth of the density profile as function of the relative density change (assuming the surface density as 1 and reducing the others to it).

Figure Ap-5: Water properties depth profiles for month February from Levitus (1982) climatology: salinity (a), temperature (b).



Comparatively to the climatology density profile, the existent 3D domain 2 MOHID Tagus Estuary configuration presents a very rough discretization at the bottom (layer depths can be observed in Table Ap-18), inducing a considerably higher density gradient than in climatology, as is visible in Figure Ap-7. The alternative discretization must thus be more detailed at the bottom. At surface it is convenient to maintain the fine discretization since it is important to calculate correctly the hydrodynamics and water quality, especially at low depth areas inside the estuary. It should also be taken care so that there is a smooth transition of depths between layers.

Improved results for the velocity field of running the domain 2 MOHID Tagus Estuary configuration with the 43 layers' MERCATOR model vertical discretization, namely in the canyons in the vicinity of Tagus Estuary, evidence the advantage in variability representation of increasing largely the number of layers above the 11 layers.

Having into account the available computational resources it is chosen to develop a vertical discretization with the higher number of layers compatible with a maximum computational cost of double the current cost of running the existent domain 1 and domain 2 MOHID Tagus Estuary configurations. To find the advisable maximum depth of the layers (and the layer number) a linear regression analysis is performed for the relative density profile: the slope of the linear regression is the approximate density gradient, which has value 207.13m as presented in Figure Ap-7. Thus, maximum layer depth should be about 200m.

Considering a near surface vertical discretization according with the current configuration of domain 2 and also trying to approximate the resolution of the MERCATOR system discretization at depths where canyons are located (depth range of 1000-2000m) a new vertical discretization was reached with 33 layers (Table Ap-18). The average depth per layer for this vertical discretization is presented in Figure Ap-7. It can be seen that the depth difference of the final layers is similar to the density difference observed in climatology. For the first layers the difference is smaller, which is a consequence of the higher detail required near surface to model other parameters than density.

Following the success of this methodology it is developed by the author a new software application for generating cartesian vertical discretizations for MOHID Water applications, called CreateVerticalResolution, which is useful for development of new baroclinic MOHID Water applications in MARETEC group.

Figure Ap-6: Density profile calculated through the UNESCO (1981) equation of state for month February from Levitus (1982) climatology.

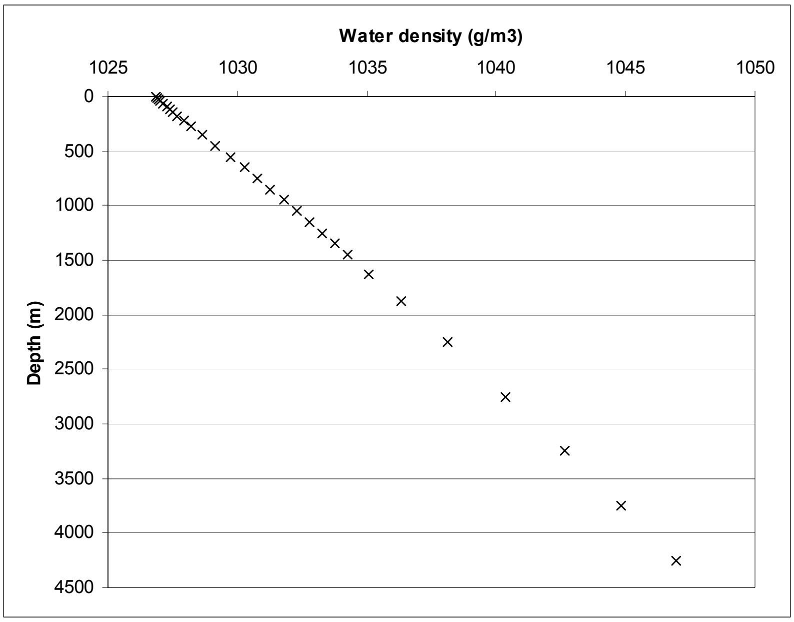


Figure Ap-7: Average depth of model layer in the current and new vertical discretization of Level 2 of the Tagus Estuary Model. Layers are presented from surface (number 1) to depth.

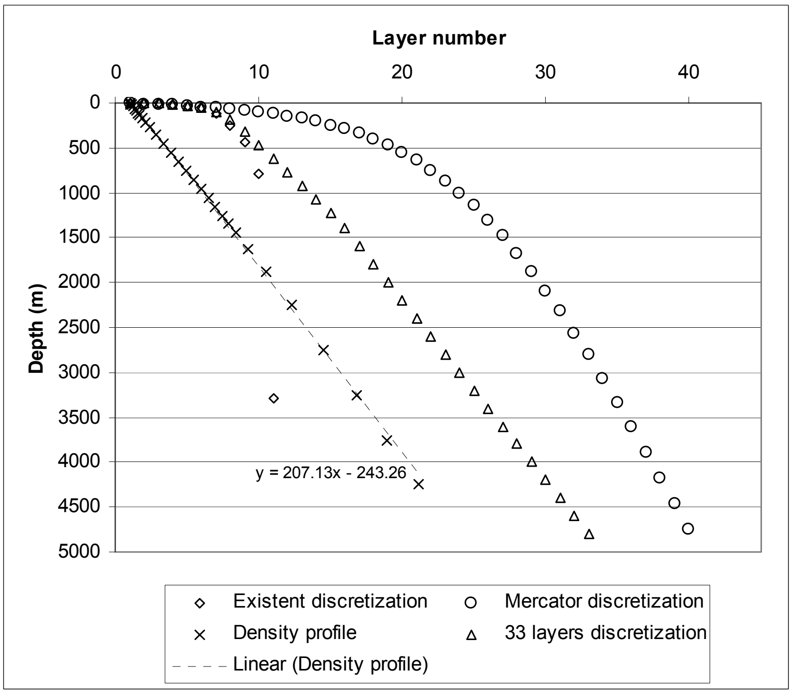


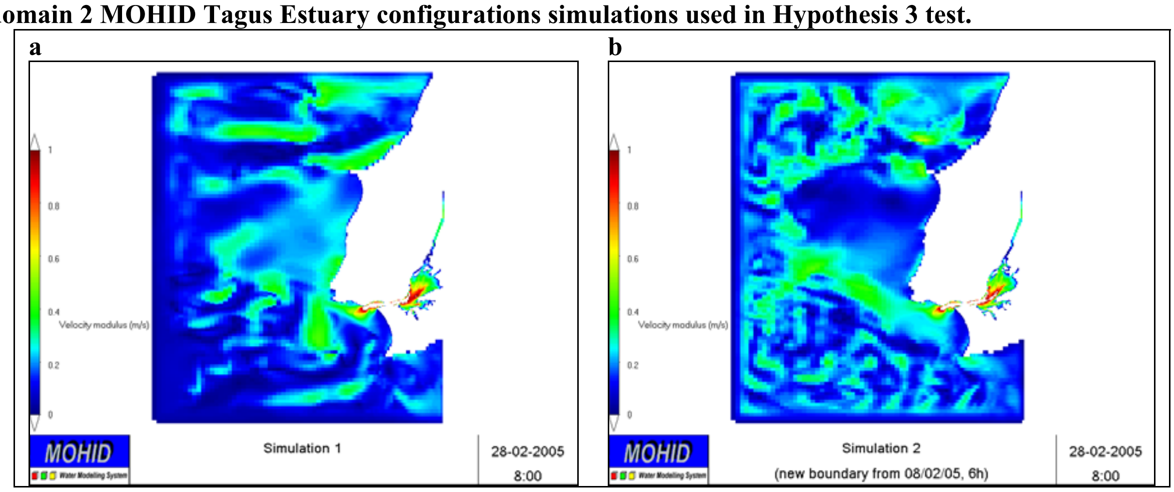
Table Ap-18: Existent and alternative vertical discretizations for domain 2 MOHID Tagus Estuary configuration. Presented layer depth for each discretization. Layers are presented from depth (number 1) to surface.

Layer number	Current layer depth (m)	MERCATOR 43 layers depth (m)	33 layers depth (m)
1	4500	302.01	200
2	510	300.21	200
3	200	297.49	200
4	150	294.83	200
5	130	291.11	200
6	20	287.3	200
7	15	282.26	200
8	10	276.96	200
9	5	270.24	200
10	4.9	263.09	200
11	0.1	254.39	200
12	-	245.15	200
13	-	234.31	200
14	-	222.94	200
15	-	210.08	200
16	-	196.9	200
17	-	182.54	200
18	-	168.26	200
19	-	153.27	150
20	-	138.89	150
21	-	124.32	150
22	-	110.86	150
23	-	97.64	150
24	-	85.88	150
25	-	74.61	150
26	-	64.93	120
27	-	55.81	75
28	-	48.26	20
29	-	41.17	15
30	-	35.52	10
31	-	30.17	5
32	-	26.09	4.9
33	-	22.13	0.1
34	-	19.27	-
35	-	16.37	-
36	-	14.43	-
37	-	12.31	-
38	-	11.02	-
39	-	9.46	-
40	-	8.65	-
41	-	7.49	-
42	-	7.01	-
43	-	6.26	-

Appendix V – Qualitative discussion of velocity results of alternative 3D domain 2 configuration

It is immediately visible from Figure Ap-8 that surface velocity shows different variability patterns in both domain 2 configurations of MOHID Tagus Estuary. In fact, the large kinetic energy observed in the continental shelf area between the Roca and Espichel capes (Estremadura Promontory) in the existent configuration results is considerably transferred, in the alternative configuration results, to areas of the continental shelf slope. In these areas the alternative configuration results show a pattern of internal waves which seems to be dependent of the vertical stratification of density imposed through the newtonian relaxation to climatology, as a simulation with the same stratification but without computation of baroclinic flow does not originate this pattern.

Figure Ap-8: Surface velocity modulus fields (m/s) for 28/02/05 8h from existent (a) and alternative (b) 3D domain 2 MOHID Tagus Estuary configurations simulations used in Hypothesis 3 test.

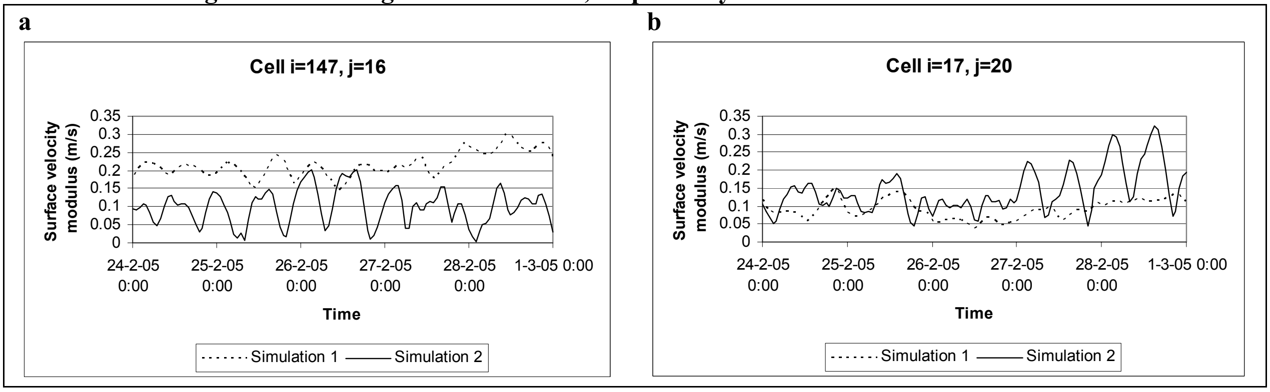


In Figure Ap-9 is presented the time evolution of the surface velocity modulus at two cells where large kinetic energy activity is observed, one located in the north continental shelf slope area and the other in the south continental slope area in the period from 24/02/05 0h – 01/03/05 0h. From this evolution it is verified that the tidal signal appears amplified in the alternative configuration results, with velocity perturbations having dominant semidiurnal period, providing evidence that these perturbations are of tidal origin.

Following the Leitão (2003) classification of the Estremadura Promontory and the Lisbon Canyon as areas of strong generation of internal tides, it is probable that these internal waves are realistic and of barotropic tide origin. Also, these internal waves only appear in the velocity field and not in the water level field, which is an expected behavior of internal tide according with Kantha and Clayson (2000);

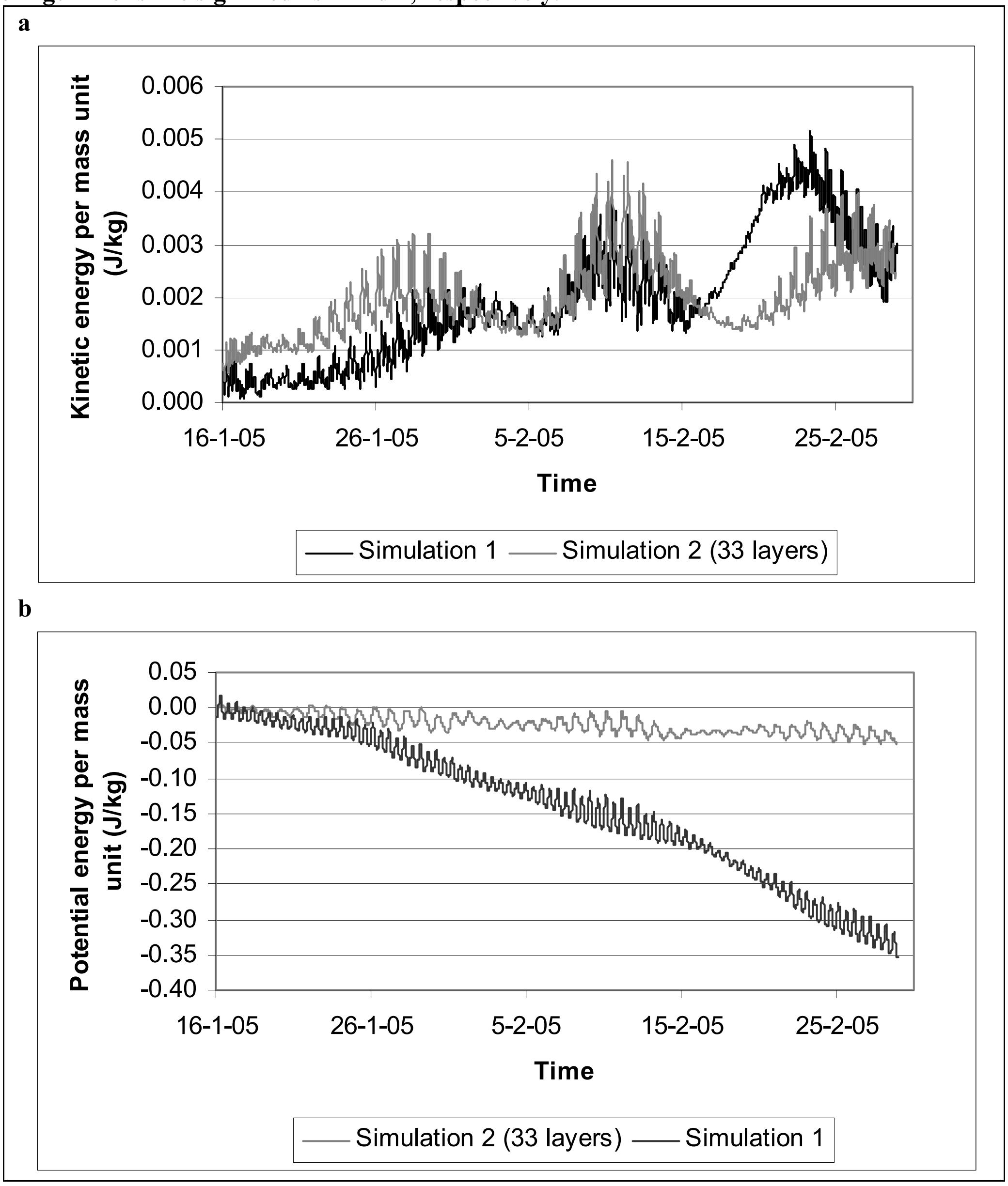
the same authors state that the currents associated with internal tides are of comparable magnitude to the ones of barotropic tides, which is also observed in Figure Ap-8.

Figure Ap-9: Time evolution of surface velocity modulus results for i=147, j=16 cell (a) (north continental shelf slope) and i=17, j=20 cell (b) (south continental shelf slope) from 24/02/05 0h to 01/03/05 0h in existent and alternative 3D domain 2 MOHID Tagus Estuary configurations simulations. Existent and alternative configurations are signalled as 1 and 2, respectively.



The time evolution of the average kinetic and potential energy of the domain in both 3D domain 2 configurations is presented in Figure Ap-10. It is found that the internal waves cause a larger kinetic energy per unit of mass in the alternative configuration results than the one verified in the existent configuration in the first fortnight of simulation. However, while the kinetic energy after this period seems to evolve in the alternative configuration with neap (small energy) and spring (large energy) cycles oscillating over an approximately constant energetic level, the existent configuration kinetic energy evolution seems to oscillate over a non constant time-increasing level. This increasing kinetic energy trend reflects in a decreasing potential energy trend, particularly evident in Figure Ap-10 b. This is evidence that the stratification conditions of the existent configuration are highly unrealistic and seem to promote, together with the interaction with meteorological forcing (the cooling effect of air temperature), the vertical movement of water masses (increase kinetic energy) which overall become colder and thus more dense (decrease potential energy). The stratification conditions of the alternative configuration appear more realistic as no such long term energy transfers are observable. However, it is still noted a small decreasing trend in potential energy which should be the result of a slight inconsistency between the stratification conditions and the meteorological forcing.

Figure Ap-10: Kinetic energy per mass unit (a) and potential energy per mass unit (b) evolution in existent and alternative 3D domain 2 MOHID Tagus Estuary configurations simulation results from 16/01/05 0h, to 28/02/05 23h50. Existent and alternative configurations are signalled as 1 and 2, respectively.



Note: the first day of simulation (15/01/05) is not presented as it corresponds to the period of gradual connection of tide, baroclinic forces and wind forcing; in potential energy per unit mass is considered the approximation of in the beginning of each run to consider the potential energy equal to the 10 minutes before value (the last value in the previous run)[124].

[124] This should affect more the presented values for the alternative MOHID Tagus Estuary configuration due to the consideration of smaller runs in this simulation (usually 2 days while in current MOHID Tagus Estuary configuration they usually length one week).

Appendix VI – Validation of the meteorological forcing used in model simulations to test Hypothesis 3

In this appendix is presented the validation of the MM5 meteorological forcing with hourly measurement data obtained at the Guia meteorological station.

This study follows the work of Fernandes (2005) who contrasted the 2004 time series used for forcing MOHID Tagus Estuary with measurements from this station. However, since the Guia meteorological data and the forcing time series do not refer to the same spatial location but are distant nearly 0.25º in longitude the comparison performed by this author could only be coarse.

In Table Ap-20 are provided statistics for the contrast of atmospheric variables used for forcing 3D domain 2 MOHID Tagus Estuary configuration as measured by the Guia meteorological station and as provided by MM5 higher resolution results interpolated for domain 2 horizontal grid for station location. In Appendix I are presented the descriptive statistics of meteorological measurements and model results for this location.

Table Ap-19: Bias and centered RMSE for meteorological parameters of MM5 model relative to Guia meteorological station for the period 15/01/2005 0h – 28/02/2005 23h at the location of the meteorological station. The statistics are calculated from the MM5 model results interpolated to the domain 2 MOHID Tagus Estuary configuration horizontal grid; are considered hourly measurements and model results.

Meteorological parameter	Bias		Centered RMSE	
	absolute	relative (%)[a]	absolute	relative (%)[b]
Temperature (ºC)	-0.2	-2	1.7	59
Solar radiation (W/m^2)	-16.3	-11	82.9	39
Relative humidity (0-1)	0.1	20	0.1	71
Zonal wind velocity (m/s)	-2.11	173	2.83	173
Meridional wind velocity (m/s)	-1.58	125	2.01	105

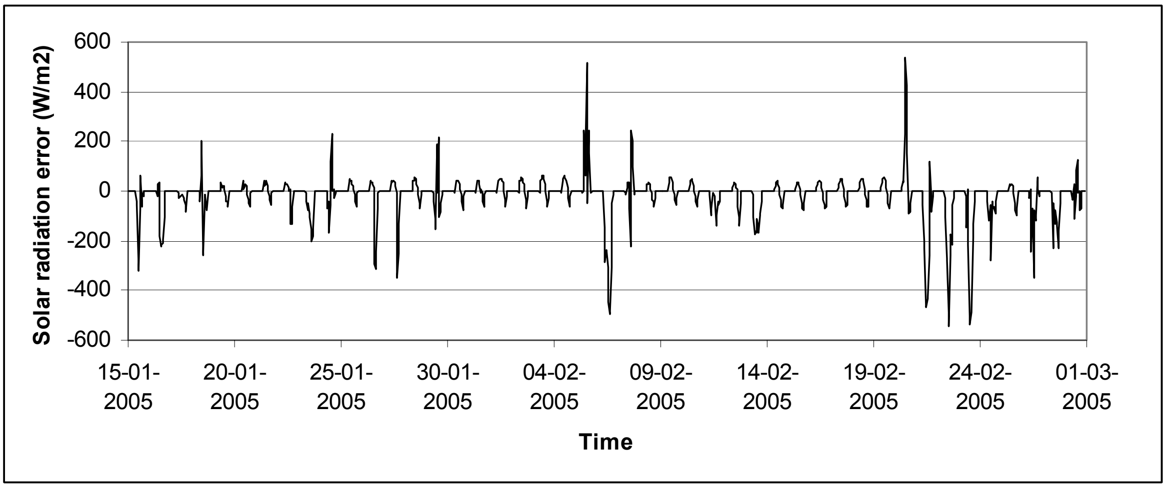
Notes: [a] percentage represented by bias relative to measurements average value; [b] percentage represented by centered RMSE relative to measurements standard deviation.

In terms of bias it is verified that the MM5 forcing underestimates the values of temperature and solar radiation. While the temperature underestimation is bellow 5%, the solar radiation underestimation represents more than 10%. The other meteorological parameters verify overestimations in the MM5 results, especially the wind velocity, with more than 100% bias.

From the descriptive statistics in Appendix I Table Ap-5 and Table Ap-6 it is found that the variability is larger in the meteorological station measurements in all parameters except wind. The centered RMSE values are due then essentially to lack of variability in all parameters except the wind where the centered RMSE is due to excess variability (more than 100% error in both components). The smaller variability in the meteorological station and the relative overestimation of MM5 in wind is observed by Fernandes (2005) and since the present contrast is performed for the same location this is important evidence that this discrepancy is due to the effect of Sintra Mountain area not resolved by MM5, an hypothesis referred by this author. The lack of variability in temperature, which Fernandes (2005) accounted in his data as the effect of contrasting a water location and a land location conjugated with the fact that the MM5 has a deficient sea temperature boundary condition, seems to be in this case the result of model coarse resolution and also of this boundary condition problem.

The centered RMSE of MM5 forcing is less expressive in radiation. In fact, it is found that this radiation error concentrates in specific periods, where it reaches considerable values (relative to the average Guia Meteorological Station value) in days 5/02/05, 6/02/05, 20/02/05, 21/02/05, 22/02/05 and 23/02/05 as can be seen by the error time series presented in Figure Ap-11.

Figure Ap-11: Time evolution of solar radiation error of MM5 forcing relative to Guia meteorological station measurements for period from 15/01/2005, 0h, to 28/02/2005, 23h.

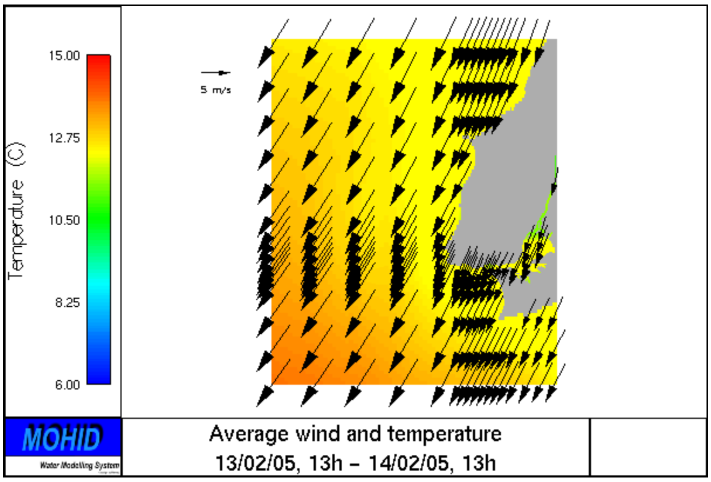


The time series of MM5 results used to provide the meteorological forcing in the existent 3D MOHID Tagus Estuary configuration simulation is compared with the values of the high resolution domain MM5 cell containing its location, as observation of meteorological forcing used for both existent and the alternative 3D MOHID Tagus Estuary configurations simulations evidenced the existence of discrepancies between the two sources at the time series location. This comparison showed that the time series used for forcing the existent configuration simulation has lower variability than the MM5 obtained time series in all variables. Research on why this is verified resulted in the finding that the times series used in existent configuration is the vertical average of the model layer closer to surface and the alternative configuration forcing is relative to the surface values. The wind velocity is overestimated by 30%, the relative humidity underestimated by 15% and air temperature overestimated by 10%. The bias in solar radiation is largely bellow 5%.

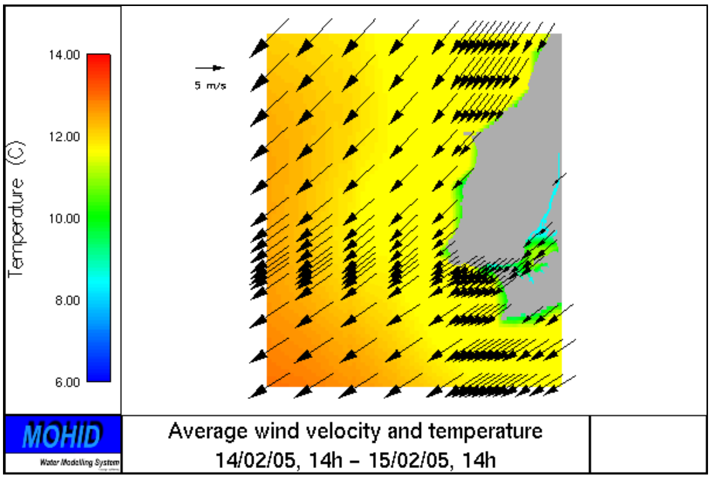
Appendix VII – Average wind velocity and air temperature forcing in alternative 3D domain 2 configuration for the period 13/02/2005-19/02/2005

Figure Ap-12: Average wind velocity and air temperature forcing for periods 13/02/05 13h – 14/02/05 13h (a), 14/02/05 14h – 15/02/05 14h (b) and 15/02/05 13h – 16/02/05 13h (c).

a



b



c

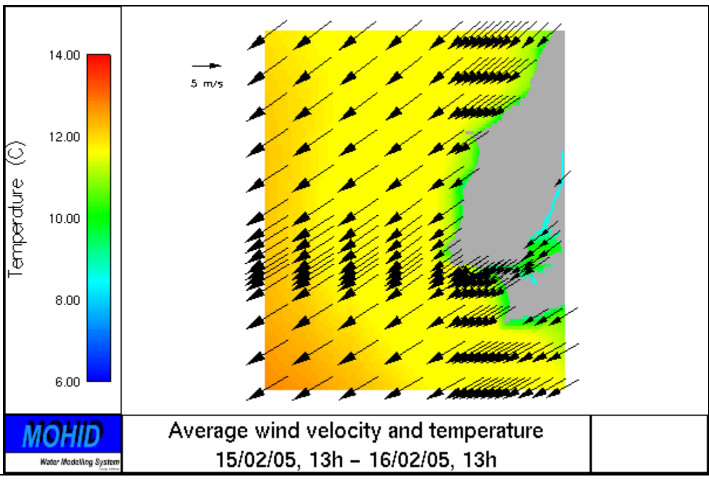
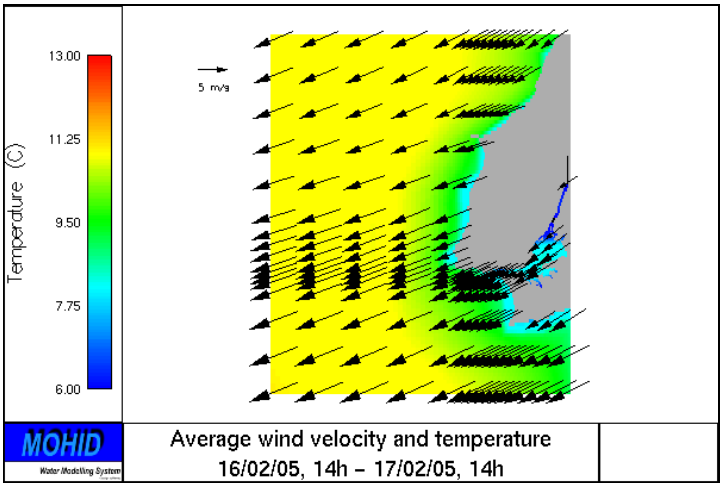
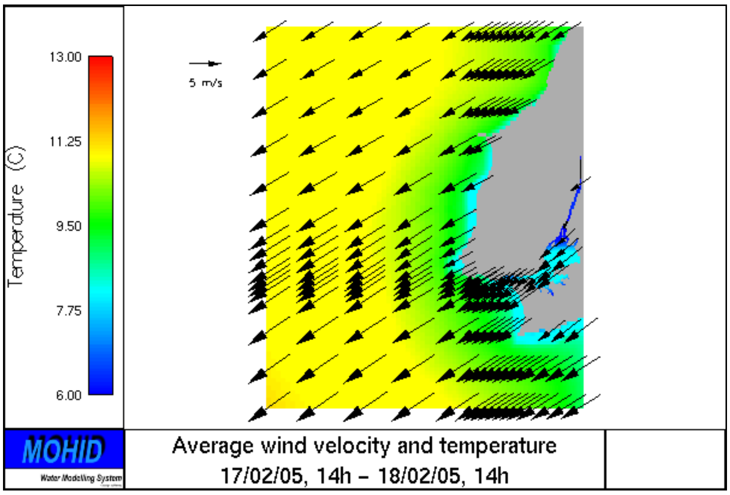


Figure Ap-13: Average wind velocity and air temperature forcing for periods 16/02/05 14h – 17/02/05 14h (a), 17/02/05 14h – 18/02/05 14h (b) and 18/02/05 13h – 19/02/05 13h (c).

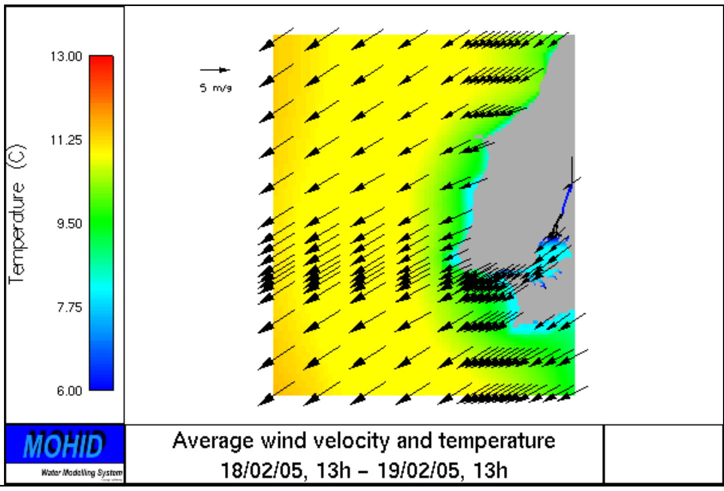
a



b



c

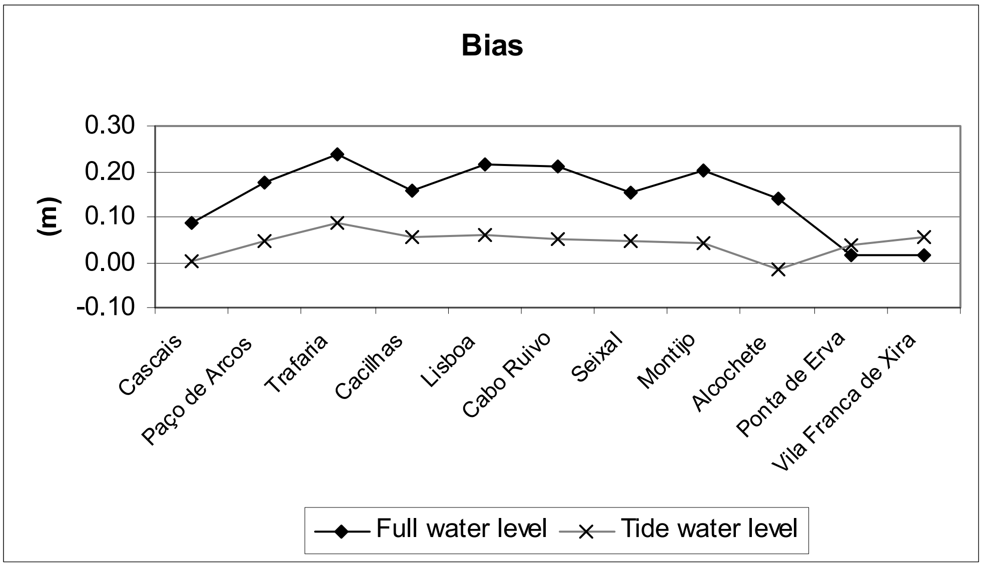


Appendix VIII – Analysis of True Model state error

A first comparison between the True Model and the tide gauge measurements is made. In Figure Ap-14 and Figure Ap-15 are presented the statistics of this comparison, respectively for bias and centered RMSE, obtained considering the full water level or only its tidal part[125]. Only the tide gauges with measurements in the period from 01/11/1972 to 31/01/1973 are considered.

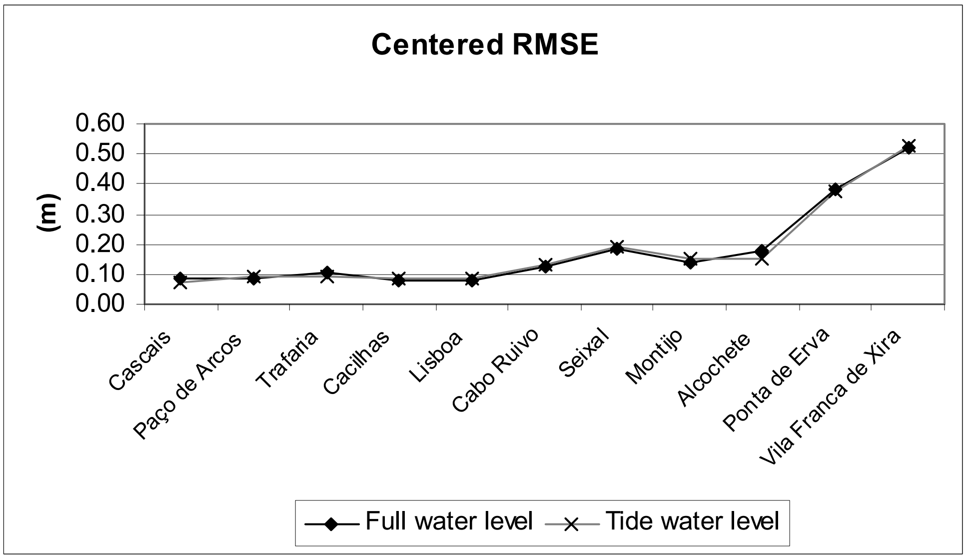
It can be observed that the True Model and the measurements are more concurrent outside the estuary and are more disagreeing in the channel areas at the Tagus River inner delta (Ponta de Erva, Vila Franca de Xira). The bias is concentrated in the non tidal part of water level in most tide gauge locations, except in the case of the locations in the Tagus River inner delta, where it is concentrated in the tidal part of water level, revealing deficiencies in tidal representation.

Figure Ap-14: Bias between water level time series from True Model Domain 2 results and measurements for tide gauge locations (ordered from the open sea to inside the Tagus Estuary) considering the period from 01/11/1972 to 31/01/1973.



[125] Obtained performing harmonic analysis considering approximately one year data for measurements and three months data for True Model results.

Figure Ap-15: Centered RMSE between water level time series from True Model Domain 2 results and measurements for tide gauge locations (ordered from the open sea to inside the Tagus Estuary) considering the period from 01/11/1972 to 31/01/1973.



Appendix IX – Analysis of Perturbed Model state error

In this Appendix is presented the analysis of the Perturbed Model simulation error at tide gauges locations intended to verify if there is support for the assumption of a normal probability distribution for this error made in Kalman filter methods. The importance of this information is two-fold: on one hand it means that in the state variables having an error not normally distributed it can be expected the state error to be difficultly corrected with data assimilation using a Kalman filter scheme and constituting a way to validate the scheme performance; on the other hand, because the Perturbed Model model configuration is created from the True Model configuration by adding a normally distributed white noise, this informs of the state variables for which the model dynamics, responsible for the error evolution, is very non linear (those presenting important normal distribution departures) and the state variables for which this dynamics, although using a non linear model, are approximately linear (those presenting approximate normal distribution characteristics).

The normally distribution assumption can be verified by analysing the normalized error and looking for normal distribution characteristics: null average, null skewness (third order moment of the distribution), kurtosis (forth order moment of the distribution) valued 3 and 95% of the values with absolute value smaller or equal to 2. In Table Ap-20, Table Ap-21 and Table Ap-22 presented these descriptive statistics for normalized error for water level, zonal velocity and meridional velocity, respectively. Considering reasonable threshold levels, these results show that important departures from the normal distribution can be observed in some of the state properties in some tide gauges, expressed essentially by extreme skewness and kurtosis departures.

For the reasons presented above it is worthwhile to discuss the state variables where these normal distribution departures exist. Considering the bathymetric features of the tide gauge locations (Table Ap-23) it is noted that these seem very connected with the non linear behaviour of the model. In water level field the response of the model is approximately linear in all locations, except in small depth intertidal or narrow estuarine channel locations (Seixal, Ponta de Erva and Povoa de Santa Iria), reflecting the effect of intertidal motion model accounting and bottom/side shear stress on local dynamics. In velocity fields the model introduced non linearities are more expressive, with about one third of the locations in the case of zonal velocity and one half of the locations in the case of meridional velocity presenting important normality departures: these arise in the same areas as in the water level field but also in other inside estuary small depth/channel (Vila Franca de Xira, Montijo, Cacilhas) or intertidal areas (Alfeite) or in relatively shallow coastal bays (Cascais, Sesimbra), where the shear stress and coastline configuration are expected to introduce non linearities in dynamics. An approximate linear behaviour of the model is observed in deep coast (Peniche), in the estuary exit channel (Paço de Arcos, Trafaria, Lisboa) and estuarine locations unconstrained by coastline or not significantly affected by intertidal movements (Cabo Ruivo, Alcochete). The horizontal grid resolution does not seem to be determinant for the non linear behaviour of the model, as similar resolution locations present different non linear behaviour.

The average of the error, i.e. the bias of the Perturbed Model state relative to the True state, is not significant in most locations and state properties when considered as a percentage of the error standard deviation: the important exception is the water level in Seixal, where the bias represent 14% of the error standard deviation.

Table Ap-20: Descriptive statistics for water level state normalized error for tide gauge locations from the Perturbed Model simulation. Normalized error is obtained by the quotient between error and error standard deviation. Statistics are calculated from hourly domain 2 results for the period 01/11/1972 0h - 31/01/1973 17h. Tide gauges indicated from open ocean (Peniche) to Tagus River (Vila Franca de Xira).

Tide gauge	Average	Skewness	Kurtosis	% Absolute values ≤ 2	Important departure from normal distribution[a]
Peniche	-0.03	-0.07	2.89	95.91	No
Sesimbra	0.01	0.01	2.91	95.82	No
Cascais	-0.01	0.00	2.81	96.00	No
Paço de Arcos	-0.01	0.13	2.97	95.91	No
Trafaria	-0.03	0.07	2.95	95.59	No
Cacilhas	-0.05	-0.10	3.28	94.60	No
Alfeite	-0.05	-0.01	3.19	95.41	No
Lisboa	-0.04	-0.06	3.20	94.96	No
Cabo Ruivo	0.01	0.07	2.95	95.55	No
Seixal	0.14	-0.01	3.22	94.69	Yes
Montijo	0.00	0.11	3.27	95.10	No
Alcochete	0.00	-0.08	3.29	94.91	No
Ponta de Erva	0.06	-0.08	4.89	93.64	Yes
Póvoa de Santa Iria	0.01	-0.16	4.96	94.28	Yes
Vila Franca de Xira	-0.03	-0.07	2.89	95.91	No

Note: [a] Yes if any of the following threshold levels is exceeded: 0.1 for absolute average, 0.5 for absolute skewness, 0.5 for absolute Kurtosis difference from 3, 1% for absolute value number; No if otherwise.

Table Ap-21: Descriptive statistics for zonal velocity state normalized error for tide gauge locations from the Perturbed Model simulation. Normalized error is obtained by the quotient between error and error standard deviation. Statistics are calculated from hourly domain 2 results for the period 01/11/1972 0h - 31/01/1973 17h. Tide gauges indicated from open ocean (Peniche) to Tagus River (Vila Franca de Xira).

Tide gauge	Average	Skewness	Kurtosis	% Absolute values ≤ 2	Important departure from normal distribution[a]
Peniche	0.01	0.01	2.99	95.37	No
Sesimbra	-0.06	0.13	4.46	94.50	Yes
Cascais	0.01	-0.05	2.93	95.28	No
Paço de Arcos	-0.03	0.04	3.20	95.05	No
Trafaria	0.00	0.11	3.41	95.32	No
Cacilhas	-0.07	-0.07	3.10	95.37	No
Alfeite	0.10	0.56	4.93	94.55	Yes
Lisboa	-0.02	-0.08	3.09	95.50	No
Cabo Ruivo	0.05	0.06	3.44	94.87	No
Seixal	0.03	5.65	126.25	97.68	Yes
Montijo	-0.02	-0.07	3.40	94.10	No
Alcochete	0.03	0.12	3.37	94.14	No
Ponta de Erva	-0.01	0.21	5.64	92.69	Yes
Póvoa de Santa Iria	-0.01	0.97	8.27	93.78	Yes
Vila Franca de Xira	-0.05	0.00	7.39	93.69	Yes

Note: [a] Yes if any of the following threshold levels is exceeded: 0.1 for absolute average, 0.5 for absolute skewness, 0.5 for absolute Kurtosis difference from 3, 1% for absolute value number; No if otherwise.

Table Ap-22: Descriptive statistics for meridional velocity state normalized error for tide gauge locations from the Perturbed Model simulation. Normalized error is obtained by the quotient between error and error standard deviation. Statistics are calculated from hourly domain 2 results for the period 01/11/1972 0h - 31/01/1973 17h. Tide gauges indicated from open ocean (Peniche) to Tagus River (Vila Franca de Xira).

Tide gauge	Average	Skewness	Kurtosis	% Absolute values ≤ 2	Important departure from normal distribution[a]
Peniche	0.07	0.13	3.13	95.37	No
Sesimbra	-0.07	-0.09	4.01	94.19	Yes
Cascais	-0.03	-0.21	3.55	95.05	Yes
Paço de Arcos	-0.02	0.05	3.02	95.46	No
Trafaria	-0.10	0.01	3.34	95.14	No
Cacilhas	0.08	0.73	5.14	93.55	Yes
Alfeite	-0.06	-0.32	3.98	94.82	Yes
Lisboa	0.00	-0.07	3.30	95.14	No
Cabo Ruivo	0.04	0.01	3.40	95.19	No
Seixal	0.01	-0.08	3.82	94.91	Yes
Montijo	0.05	0.03	3.94	94.50	Yes
Alcochete	0.02	0.12	3.25	94.87	No
Ponta de Erva	-0.01	0.23	7.48	93.87	Yes
Póvoa de Santa Iria	-0.02	0.79	6.76	93.78	Yes
Vila Franca de Xira	-0.01	-0.14	8.41	93.69	Yes

Note: [a] Yes if any of the following threshold levels is exceeded: 0.1 for absolute average, 0.5 for absolute skewness, 0.5 for absolute Kurtosis difference from 3, 1% for absolute value number; No if otherwise.

Table Ap-23: Departure from normal distribution of Perturbed Model error and bathymetric features of tide gauge locations. Tide gauges indicated from open ocean (Peniche) to Tagus River (Vila Franca de Xira).

Tide gauge	Important departure from normal distribution of Free-run error[a]	Grid resolution (mxm)	Bathymetry depth (m)	Type of location
Peniche	No	300x2000	56	Coast
Sesimbra	Yes (U, V)	600x2000	12	Coastal bay (southward)
Cascais	Yes (V)	500x300	7	Coastal bay (southward)
Paço de Arcos	No	400x300	5	Coast/estuary exit channel
Trafaria	No	300x300	11	Estuary exit channel
Cacilhas	Yes (V)	500x300	5	Estuary exit channel
Alfeite	Yes (U, V)	500x300	4	Intertidal
Lisboa	No	600x300	7	Estuary exit channel
Cabo Ruivo	No	700x500	3	Estuary
Seixal	Yes (WL, U, V)	700x300	-3	Narrow estuarine channel/intertidal
Montijo	Yes (V)	700x300	0	Estuarine channel/intertidal
Alcochete	No	700x500	1	Estuary
Ponta de Erva	Yes (WL, U, V)	700x500	0.5	Intertidal /riverside
Póvoa de Santa Iria	Yes (WL, U, V)	700x500	1	Narrow estuarine channel
Vila Franca de Xira	Yes (U, V)	700x1000	1	Estuarine channel/riverside

Note: [a] Yes if any of the following threshold levels is exceeded: 0.1 for absolute average, 0.5 for absolute skewness, 0.5 for absolute Kurtosis difference from 3, 1% for absolute value number; No if otherwise. WL = water level; U = zonal velocity; V = meridional velocity.

Appendix X – Software developments

For the work presented in this thesis several software developments are made. These developments range from the creation from root of new software applications to code changes of previously developed software applications. The new software developments are presented in Table Ap-24. These include pre-processing, post-processing and HDF5 files management tools. The changes processed on existent MOHID framework software are presented in Table Ap-25.

Table Ap-24: New software applications developed in this thesis work.

Application	General description	Link to users manual at MOHID wiki Internet site
Pre-processing:		
AssimilationPreProcessor[a]	Calculates initial covariance structure for SFEK and SEEK filter applications in MOHID Water. Performs EOF analysis of MOHID Water results in HDF5 format and the reconstruction of results based on a specific number of leading EOFs.	-
Inverted Barometer	Calculates mean sea level time series from atmospheric pressure data in HDF5 format. Prepares tide components file contemplating these time series for use in MOHID Water simulations accounting for the inverted barometer effect.	http://www.mohid.com/wiki/index.php?title=InvertedBarometer
Post-processing:		
ConvertToTimeSerie	Converts water level measurements files from Toga Center and Instituto Hidrográfico format to MOHID TimeSeries format.	-
HDF5 management:		
HDF5Exporter	Creates MOHID TimeSeries format files from data in HDF5 format.	http://www.mohid.com/wiki/index.php?title=HDF5Exporter
HDF5Extractor	Extracts data in specific time periods and for specific properties in HDF5 format from HDF5 files.	http://www.mohid.com/wiki/index.php?title=HDF5Extractor
HDF5Statistics	Calculates daily, monthly and period specific general statistics for data in HDF5 files. Outputs statistics in HDF5 format.	http://www.mohid.com/wiki/index.php?title=HDF5Statistics

Notes: [a] a more complete description is provided in Chapter VI; - not available.

Table Ap-25: Existent MOHID software applications altered in this thesis work.

Application	Change description
Pre-processing:	
ConvertToHDF5[a]	Creation of new modules ERA40Format and PatchHDF5Files. Module ERA40Format converts ERA40 data in NetCDF format to MOHID HDF5 format. Module PatchHDF5Files interpolates 2D data in several HDF5 files from one horizontal grid to another with different resolution considering a priority in HDF5 files use.
MOHID Base 1:	
Module Functions	Inclusion of operations required for sequential assimilation, namely the classification of properties from modules Hydrodynamic and WaterProperties, Cholesky decomposition and EOF analysis.
ModuleGlobalData	Registering of Module SequentialAssimilation.
MOHID Base 2:	
Module Geometry	Features for module variables storage for SEEK filter applications.
Module HorizontalGrid	Implementation of default value for simulation initialization provided by a vertical profile.
Module Map	Detection of isolated cells in bathymetry and correction of bathymetry to eliminate them. These cells in baroclinic modelling can lead to instabilities.
MOHID Water:	
Module Hydrodynamic	Inclusion of operations required for sequential data assimilation, namely the reading of keyword commanding sequential assimilation, allowing of module variables values change by data assimilation and features for module variables storage for SEEK filter applications. Allowance of output of velocity results in specific faces horizontal grids to HDF5 format.
Module Model	Inclusion of operations required for sequential data assimilation, namely the call of Module SequentialAssimilation subroutines.
Module SequentialAssimilation[b]	Module constructed from root, including sequential data assimilation core operations for SFEK and SEEK filter use in MOHID Water simulations.
Module WaterProperties	Inclusion of operations required for sequential data assimilation, namely the reading of keyword commanding sequential assimilation, allowing of module variables values change by data assimilation and features for module variables storage for SEEK filter applications.

Notes: [a] Users manual of theses modules at the MOHID wiki Internet site: http://www.mohid.com/wiki/index.php?title=ConvertToHDF5; [b]a more complete description is provided in Chapter VI.

Apart from the most recently developed software applications directed to data assimilation, most of these tools are extensively used in routine work at MARETEC research group and are contemplated in the programs of the two editions of MOHID framework course, which took place in Lisbon in 2006[126] and 2007[127]. Due to their usefulness, some of then have been further developed, through the inclusion of new functionalities, by other members of MARETEC team since their creation.

[126] Course information at the Internet site http://www.mohid.com/MOHIDCourse/Introduction.aspx.
[127] Course information at the Internet site http://www.mohid.com/MOHIDCourse2/.