IV. Alternative Modelling in MOHID Tagus Estuary

IV.1. Hypothesis 1 – Larger Domain 1

IV.1.1. Alternative domain 1 configuration

The horizontal grid characteristics of the alternative domain 1 are presented in Table IV-1.

Table IV-1: Horizontal grid characteristics for alternative domain 1 MOHID Tagus Estuary configuration used for Hypothesis 1 test.

Characteristics	Value
Location	Portuguese and Galician coasts
Spatial span	-12ºE to -6.15ºE 36ºN to 45ºN
Grid resolution	from 0.04ºx0.04º (boundary) to 0.02ºx0.02º (-10.5ºE to -8.5ºE and 38ºN to 40ºN)[a]
Number of cells	218x324

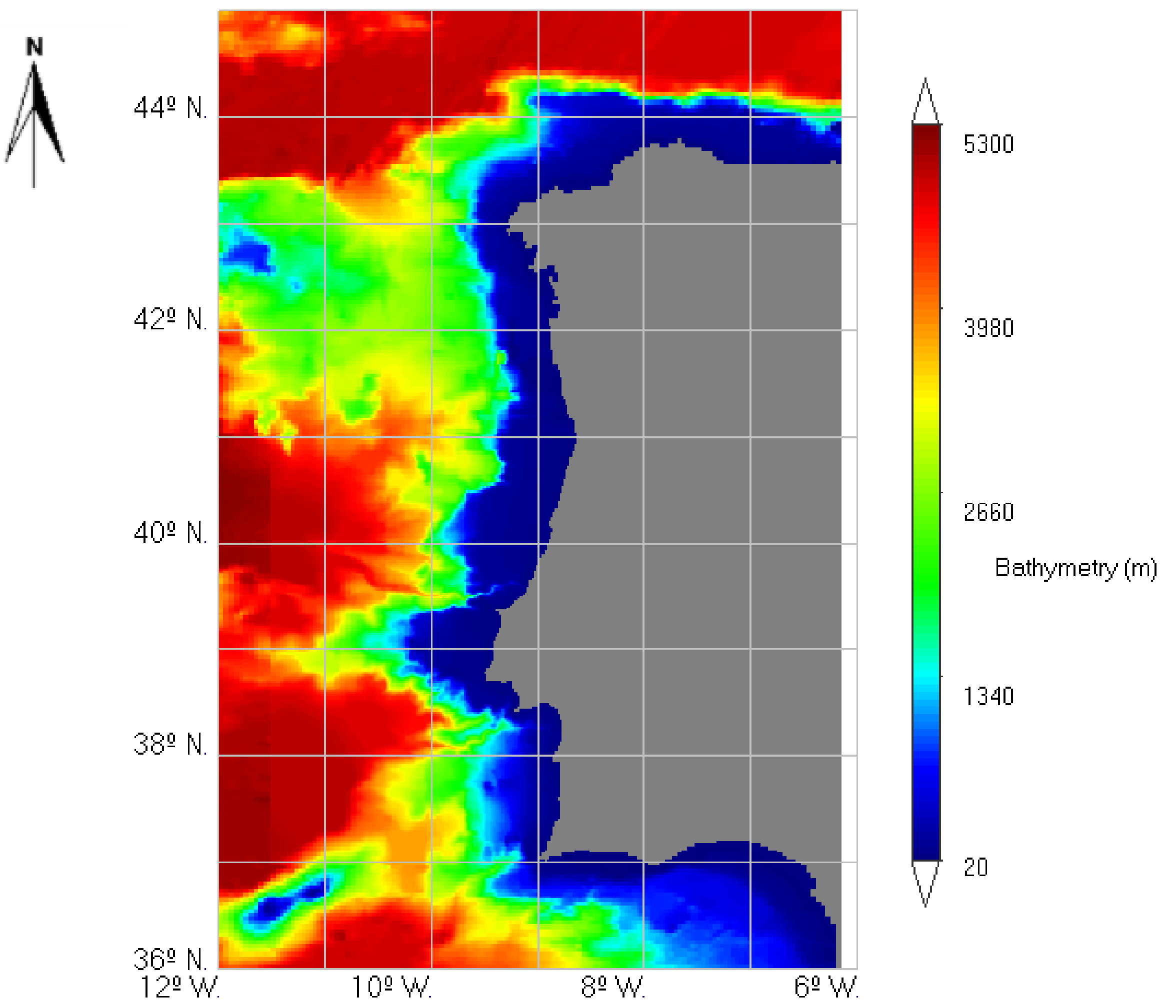
Notes: [a] between 43ºN and 45ºN the latitude resolution is constant valued 0.04º.

The higher resolution area of the alternative domain 1 is chosen as to coincide with the MOHID Tagus Estuary domain 2, so as to provide adequately detailed boundary conditions to this domain.

The bathymetry is presented in Figure IV-1 (see Chapter III for description of bathymetry data). It suffers a post-processing consisting in setting the minimum depth to 20m and closing the south east boundary, to avoid instabilities. The first adjustment is made to prevent discontinuities in the water level caused by very low depths and the occurrence of intertidal areas, which is incorrect to model given the resolution of the domain being considered. The second adjustment is made because in this area, due to the proximity of coastline, the bathymetry depths are small: this causes that tide levels imposed in the boundary can easily produce high velocities.

It is used 2D vertical resolution and tide forcing. The open boundary condition for this domain is established by considering the FES 95.2 solution as water level reference for a Blumberg and Kantha (1985) radiation condition, considering a decay time which ranges from 200s at open ocean cells to 1800s at the lower depths/near coastline cells. The remaining modelling conditions are according with the existent domain 1 MOHID Tagus Estuary configuration.

Figure IV-1: Portuguese and Galician coast bathymetry considered for alternative domain 1 MOHID Tagus Estuary configuration used for Hypothesis 1 test.



IV.1.2. Hypothesis test

For the test of the hypothesis, two simulations, of the existent and alternative domain 1 MOHID Tagus Estuary configurations, are made for the period 10/11/2004 0h – 30/11/2004 0h. The initialization of the model is as provided in Table IV-2.

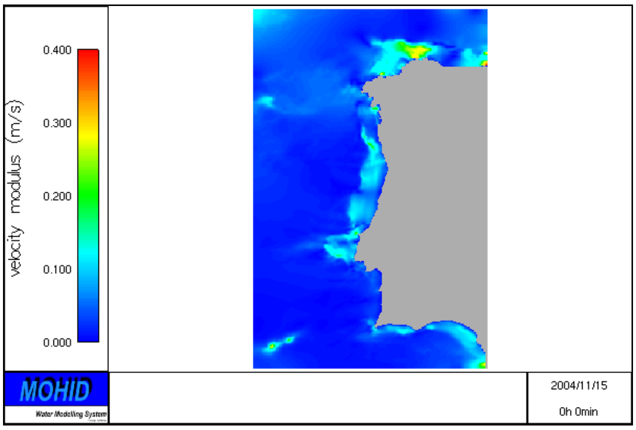
Table IV-2: Initial conditions for domain 1 model MOHID Tagus Estuary simulations used for Hypothesis 1 test.

Parameter	Initial condition
Water level	2.08m[a]
Velocity (meridional and zonal components)	0m/s
Tide forcing	Slowstart period[b] of 2 days

Notes: [a] average water level from long series of Cascais tide gauge measurements and constant mean sea level considered for tidal forcing; [b] in this period only a fraction of tide elevation is imposed, ranging from 0 at the beginning of period to 1 at the end of period.

The resulting velocity modulus field (Figure IV-2) is concurrent with previous knowledge of the area and with bathymetric features. In particular the amplification observed in front of the Portuguese region of Estremadura is according with previous results obtained with MOHID Tagus Estuary and with Sauvaget *et al.* (2000). The high velocities verified at the southeast boundary are probably derived from proximity of the artificially closed boundary and the consideration of the FES 95.2 solution in an area with small depths.

Figure IV-2: Velocity modulus field for alternative domain 1 MOHID Tagus Estuary configuration simulation for 15/11/2004 0h.



The contrast between the simulation results and tide predictions at several tide gauge locations (see Chapter III for details) from the fortnight 14/11/2004 0h – 30/11/2004 0h are presented in Table IV-3 for centered RMSE, considering all the data and those only in the neap and spring tide periods. In most of the locations, considering both simulations results, the centered RMSE amounts to 0.05m, representing less than 8% of tide amplitude, particularly in the locations adjacent to the Tagus Estuary (Sesimbra, Cascais) but also more south in Sado Baliza and Sines; the results, seem to be due to the larger horizontal grid resolution, are maintained in neap and spring tide periods. The error value in these locations seem to be limited by the bathymetry/horizontal grid resolution as Fortunato *et al.* (1999) find the smaller value of 0.02m RMSE in tide representation in Cascais using a high resolution finite elements model for Tagus Estuary and immediate adjacent coast and considering approximately the double of values (assessed every half hour) in RMSE calculation. Also in the relative proximity of Tagus Estuary, in Peniche the error is larger in the spring tide period (more than the double). This distinct behavior in neap and spring tides is an evidence of lack of variability in tide which is justified by the small number of tide components considered in this tide gauge (9 as shown in Chapter III) relative to the other locations (where components number is more than 20). It is striking to observe that in Sado Baliza the centered RMSE does not show variability from the neap to the spring tide periods: this is a sign that tide there is very affected by local conditions (bathymetry and coast line configuration). These results are qualitative similar to the ones found by Leitão (2003) for a 1997 simulation with a domain very similar to existent domain 1 MOHID Tagus Estuary configuration providing quantitative insight on the error description.

Table IV-3: Centered RMSE of existent and alternative domain 1 MOHID Tagus Estuary configurations relative to tide predictions. Values for neap tide, spring tide and total periods are presented. Statistics calculated from hourly values (385 for the total assessed period). Tide gauges presented from South to North.

Tide gauge	Centered RMSE per period (m) [a]					
	Neap tide (17/11/2004 – 23/11/2004)		Spring tide (23/11/2004 – 29/11/2004)		Total (14/11/2004 – 30/11/2004)	
	configuration		configuration		configuration	
	existent	alternative	existent	alternative	existent	alternative
Bonanza	-	0.12	-	0.14	-	0.14 (20%)
Guadiana	-	0.08	-	0.09	-	0.10 (14%)
Barra de Faro	-	0.03	-	0.07	-	0.06 (7%)
Sines	0.03	0.04	0.04	0.05	0.03 (5%)	0.04 (6%)
Sado Baliza	0.06	0.06	0.06	0.06	0.06 (7%)	0.06 (8%)
Sesimbra	0.03	0.03	0.04	0.05	0.04 (5%)	0.04 (6%)
Cascais	0.04	0.05	0.06	0.07	0.05 (7%)	0.06 (8%)
Peniche	0.06	0.06	0.16	0.16	0.13 (17%)	0.13 (17%)
Leixões	-	0.16	-	0.11	-	0.13 (16%)
Viana do Castelo	-	0.10	-	0.11	-	0.10 (13%)
Vigo	-	0.04	-	0.06	-	0.05 (6%)
Villagarcia	-	0.07	-	0.06	-	0.06 (7%)
Corunha	-	0.02	-	0.05	-	0.04 (4%)

Notes: - not inside the domain; [a] percentages represent the quotient between the centered RMSE and the average tide amplitude, expressed by standard deviation of tide prediction; in some of the tide gauges (Villagarcia, Vigo and Bonanza) the geographical coordinates are not in a model calculus cell, due to the resolution of the domain considered and also due to pre-processing work in bathymetry near coast line to avoid instabilities in simulations. In these cases, for validation is considered the result of the model for the nearest water cell, performing a shift in longitude.

Moving further from the Tagus Estuary mouth to the South are found comparable good centered RMSE results in Barra de Faro tide gauge, with similar results to Cascais in spring tides and considerably better results in neap tide (half value). This is a good result from the model having into account that the horizontal grid resolution is there smaller (3km whereas in Cascais it is approximately 2km). However the centered RMSE presents large values in Guadiana and Bonanza tide gauges, persistent in neap and spring tide periods; the number of tidal components considered at these locations is relatively large particularly in Bonanza (37 as presented in Chapter III). North to Peniche, error is also found to be large in Leixões, which also has a large number of tide components into consideration (35). This tide gauge is located in the transition zone between bathymetries with different raw data quality: at south the detailed data from the existent domain 1 MOHID Tagus Estuary configuration, in the north the lower resolution data from ETOPO 2’. In Viana do Castelo the number of tide components is small (9) which should justify the bad results of the centered RMSE. In the Galician tide gauges small error results, comparable to the values found in the proximity of the

Tagus Estuary, are found. Due to the smaller grid resolution in these locations, particularly in Corunha, this good model performance is considered to be a direct result of the detailed bathymetric data used for bathymetry construction in this area. Since a less detailed bathymetric data is used at Barra de Faro with similar centered RMSE and grid resolution this is an evidence that the tidal dynamics in Barra de Faro is less pronounced, which from the observation of Figure IV-1 seems to be a consequence of a less pronounced continental shelf slope. Given the good model performance in the Galician coast, the bad results at Guadiana and Bonanza seem to be a direct consequence of the consideration of the FES 95.2 solution in the small depths of the continental shelf but also of the complexity of the tidal hydrodynamics in the case of Bonanza, where the Guadalquivir River freshwater outflow has a determinant influence in tidal dynamics as reported by Fanjul *et al.* (1998).

Both simulations provide very similar results in the tide gauges present in both domain configurations (Sines, Sado Baliza, Sesimbra, Cascais, Peniche), although the alternative configuration seems to perform generally slightly worse. The difference, which amounts to 1cm and 1% of tide amplitude, is not considered appreciable to justify the rejection of the alternative domain, due to the potential for description of coastal and continental shelf hydrodynamics more adequately in 3D configurations than the existing domain 1 configuration. Both domain 1 configurations are therefore comparable in the Tagus Estuary mouth and adjacent coast and as such it is found no support for Hypothesis 1.

The bias of the simulations error is not assessed here as it is very affected by the mean sea level considered for tide predictions, which depends of the length of the time periods in tide gauge measurements and in model results, which is different from tide gauge to tide gauge and from measurements to model results. Nevertheless, it is referred for reference that in Cascais the bias is about 2cm in neap tides and largely bellow 1cm in spring tides, in both simulations.

IV.1.3. Tide representation in alternative domain 1

The tide representation in the alternative domain 1 configuration is further investigated by making a simulation for the one year period 01/03/1999 0h – 15/03/2000 0h, a period in which tide gauge measurements are available for Sines and specific time tide components are derived. Also, a simulation for the same period is considered using the astronomical tide generation forces explicitly in the model, to assess the importance of this forcing, although Kantha and Clayson (2000) refer it to be important only in domains larger than 1000km (the alternative domain 1 has a maximum spatial span for approximately 900km). The water level results in the period 15/03/1999 0h – 15/03/2000 0h are harmonically analysed to verify the capacity of the model to represent the major amplitude tide harmonic components in terms of amplitude and phase, thus following the methodology used by Sauvaget *et al.* (2000) and Fanjul *et al.* (1998), respectively for the Portuguese and Spanish coasts.

Although the results for every tide gauge location are presented, the results are mainly validated considering tide gauges where tide components have been estimated from long time series of measurements (one year or larger) - Bonanza, Sines, Cascais, Leixões, Vigo, Villagarcia and Corunha – since in these cases the tidal components are calculated with a higher precision.

The tide components of higher amplitude at the Tagus Estuary mouth according to Cascais tide gauge measurements (Figure IV-3) are M_2, S_2, N_2, K_2, K_1 and O_1; these components generally dominate the tide amplitude although the dominance is lower in shallower locations and larger in deeper locations, as exemplified by the distributions in Bonanza (where bathymetry amounts to 20m) and in Leixões (where bathymetry amounts to nearly 100m). The alternative domain 1 configuration representation of these components is assessed in terms of amplitude and phase, is presented in Figure IV-4 and Figure IV-5.

Both measurements and the simulations show the increase of tide amplitude and phase from South to North of the semi diurnal dominant components (M_2, S_2, N_2 and K_2) as found in the work of Sauvaget *et al.* (2000); the amplitudes of M_2, S_2 and N_2 from Sines to Viana do Castelo are also very consistent with the values found by these authors. It can be observed that the model generally overestimates tide amplitude for the semi diurnal components M_2, S_2 and N_2 in the entire coast (Figure IV-4), especially in M_2. This is probably the result of lack of bathymetry resolution to decrease through bottom shear stress the tidal energy: in tide gauges located at high bathymetry resolution or quality (Tagus Estuary mouth, Galician coast) the amplitude over estimation is smaller (about 5 cm in M_2) while at the south of the domain in Bonanza and Guadiana the amplitude over estimation amounts to 10cm in M_2 and S_2, representing more than 10% of the component amplitude as derived by the measurements; the error in Bonanza is concurrent with the Fanjul *et al.* (1998) model results for the location. Overall the amplitude error in these components represent less than 7% in M_2 and less than 5% in S_2 and N_2, except at the Southern tide gauges. In what refers to the phase of these semi diurnal components are well estimated by the model except in punctual cases of Bonanza, Barra de Faro, Peniche, Leixões and Viana do Castelo, with a 5º degrees error (underestimation in the most noticeable cases of Bonanza and Leixões). This error is considered to be due to deficient bathymetry resolution.

Figure IV-3: Amplitude of sea level for different harmonic components from tide gauge measurements at Bonanza, Cascais and Leixões. Only components with amplitude above 1cm are shown.

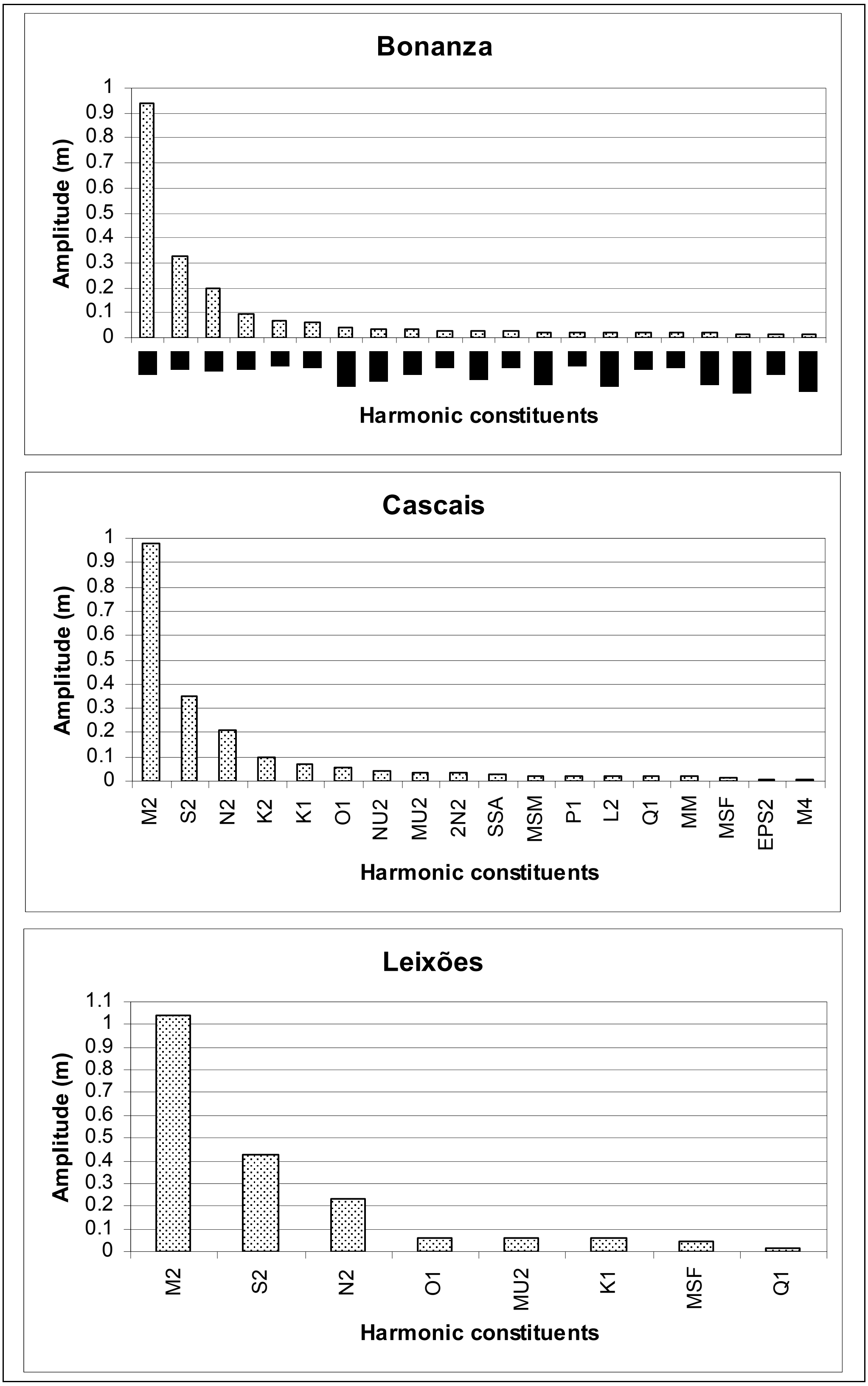
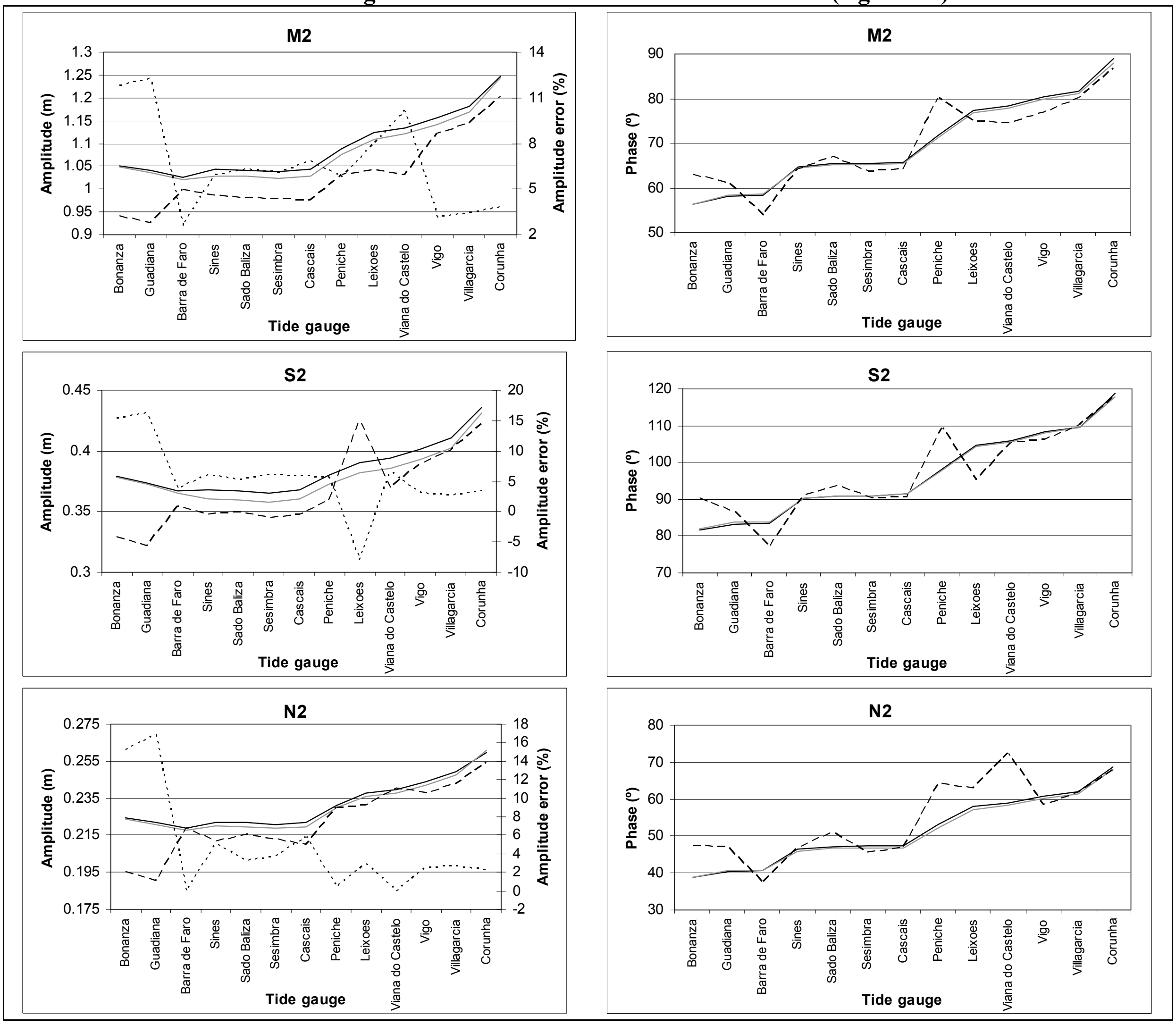
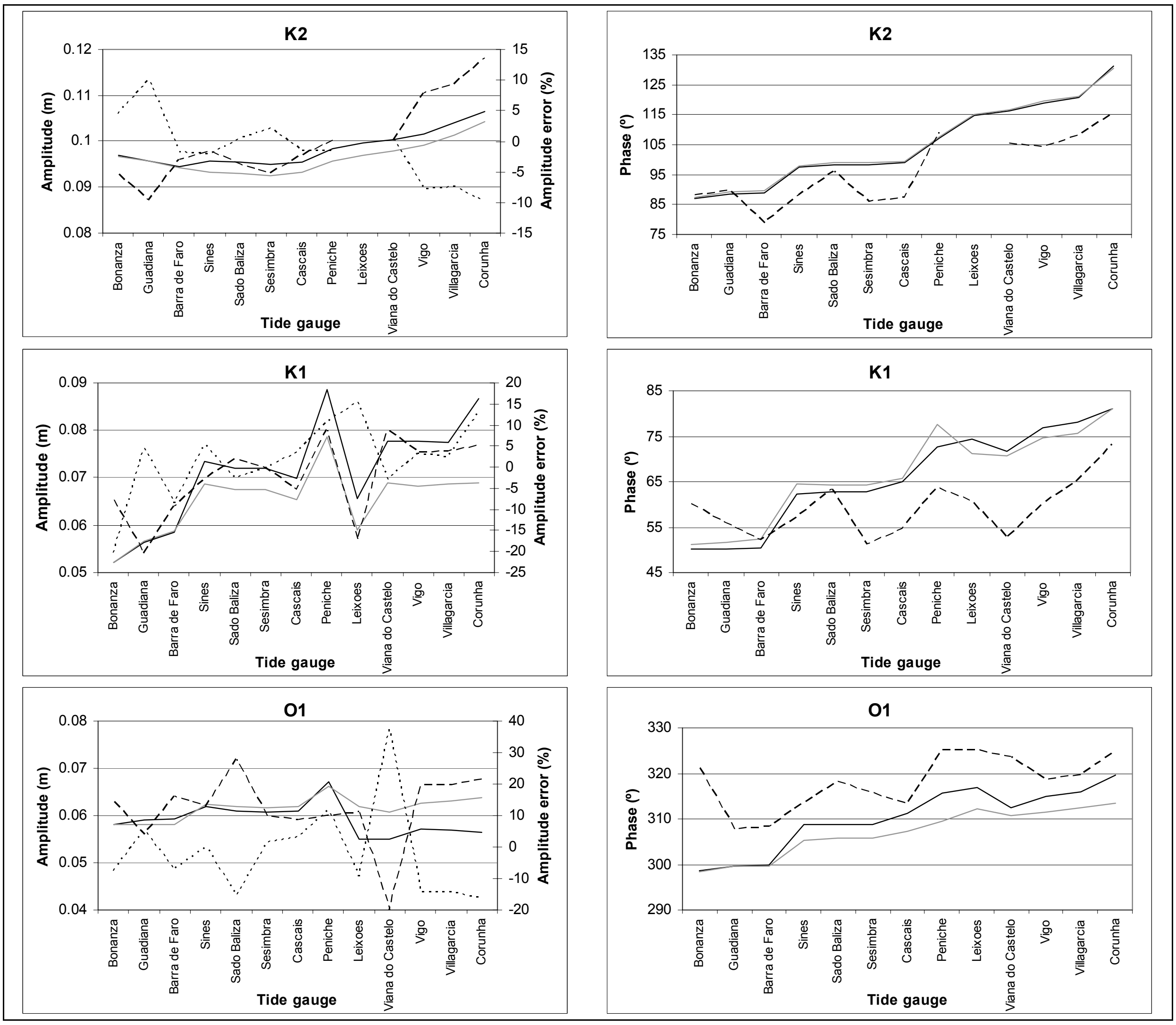


Figure IV-4: Amplitude and phase of M_2, S_2 and N_2 tide components at tide gauges in the Portuguese and Galician coasts as provided by measurements and alternative domain 1 MOHID Tagus Estuary configuration. Results from harmonic analysis of simulation results (15/01/1999-15/02/2000) and tide gauge measurements (several periods) are shown: dash line is measurements, black line is simulation without tide generation forces, grey line is simulation with tide generation forces (left axis); dot line is error of simulation without tide generation forces relative to measurements (right axis).



As for components K_2 and the diurnal K_1 and O_1 components (Figure IV-5) the over and under estimation of the amplitude is very variable in the coast, but amounting to less than 1cm. However there is a trend for the tide gauges located in the borders of the domain, Bonanza and Guadiana in the South and the Galician tide gauges in the North, to verify a large amplitude error (representing more than 10% of the component amplitude) relative to the inner tide gauges (where the error magnitude is typically less than 5% of the specific component amplitude). This can be a product of the lower resolution of the horizontal grid but also to the proximity of the domain boundaries where the FES 95.2 solution, less appropriate in the shallow areas is considered. The phase is in these components less well described than in the dominant semi diurnal components in the entire domain, with phase being overestimated in simulations in the K_2 and K_1 components and underestimated in the O_1 component. Errors are larger in the diurnal components, amounting to nearly 20% for K_1 in Viana do Castelo and for O_2 in Bonanza. The large phase errors are not judged to be due to bathymetry resolution and are thought to be due to other shallow water effects not accounted by the model.

Figure IV-5: Amplitude and phase of K_2, K_1 and O_1 tide components at tide gauges in the Portuguese and Galician coasts as provided by measurements and alternative domain 1 MOHID Tagus Estuary configuration. Results from harmonic analysis of simulation results (15/01/1999-15/02/2000) and tide gauge measurements (several periods) are shown: dash line is measurements, black line is simulation without tide generation forces, grey line is simulation with tide generation forces (left axis); dot line is error of simulation without tide generation forces relative to measurements (right axis). K_2 component data is not available in measurements for Leixões.

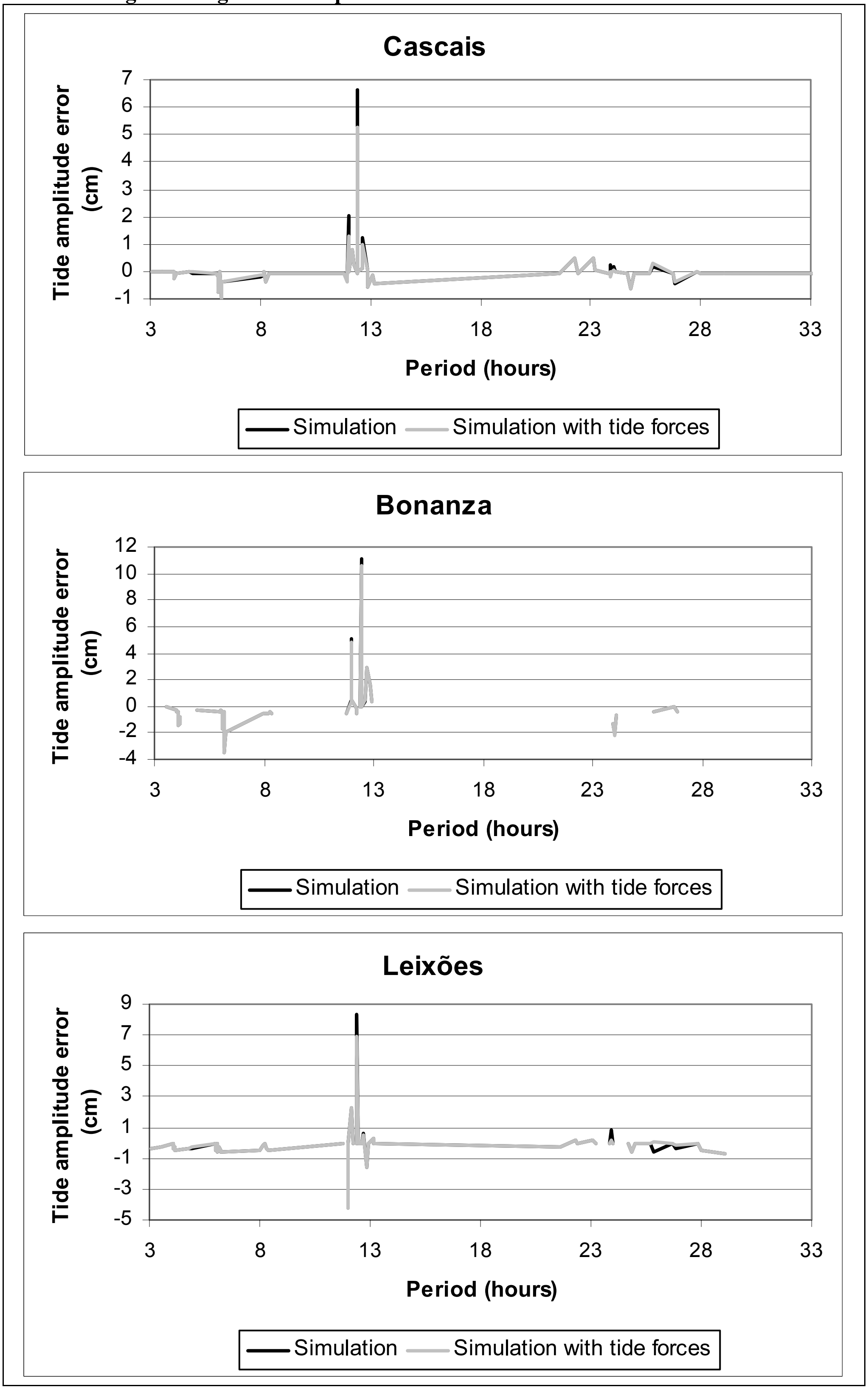


The influence of the consideration of the tide generation forces directly in the modelled hydrodynamics amounts to about 1cm decrease of tide amplitude in the semi diurnal components and K_1 and of an increase of amplitude in approximately the same amount in O_1. The effects in the phase are negligible in semi diurnal components although in diurnal components K_1 and O_1 it can cause considerable larger phase errors which can reach 5 degrees in some locations north of Barra de Faro, which is concurrent with the findings of Sauvaget *et al.* (2000) for the same area. Not always the inclusion of the tide generation forces causes a lower error relative to measurements, particularly in the diurnal components.

At the Tagus Estuary mouth the tide amplitude error is concentrated in the semi diurnal band of the period amounting to 7cm in M_2, as observed in Figure IV-6 for Cascais tide gauge. The use of tide generation forces in the domain can reduce the overestimation of amplitude in this band but the results suggest that it could also increase the error in the diurnal band. Apart from the semi diurnal band the most significant amplitude error is verified in the 6 hours period in M_4, which results from M_2 due to energy transference in shallow waters: the amplitude is underestimated by 1cm in the simulation (tide generation forces provide no influence here), which is precisely the magnitude of the M_4 amplitude derived from measurement at this location. While M_4, as a shallow water component, is not provided by the FES 95.2 solution in the domain boundary, Figure IV-6 indicates that the model is not capable to generate this component (which is the 18^{th}) at the estuary mouth, suggesting that some of the over estimation of the semi diurnal band amplitude can be due to this lack of energy transfer. This is a strong indicator that bathymetry in Cascais has deficiencies, in terms of grid resolution or raw bathymetric data.

The results of harmonic analysis can also be used to investigate further the relatively large centered RMSE observed in Bonanza and Leixões. The distribution of the tide amplitude error according with the tide period for these locations is presented in Figure IV-6. In the case of Bonanza the semi diurnal band presents again a large amplitude overestimation by the model. In this case the effect of the tide generation forces is less significant. Again the M_4 component is approximately entirely disregarded by the model, which fails to transfer the energy from M_2 to generate this component: the error now amounts to near 4cm, approximately the value of this component amplitude in this location. M_4 represents in Bonanza the 9^{th} most important component in term of amplitude (Figure IV-3), a sign of the important effect of the relatively large continental shelf width in tide hydrodynamics. This coarse underestimation evidence an inadequate accounting of the bathymetry effect in the model is also reproduced in 4 hours period components as the M_6, again a component derived from M_2; this model behavior is though to be due besides from bathymetry resolution also to this location being very close to the boundary where the global tide solution is imposed as this model response is not observed in the modelling study of Fanjul *et al.* (1998) which place the model domain boundary much more to south. An important error of nearly 2cm is also observed in K_1.

Figure IV-6: Tide amplitude error of alternative domain 1 MOHID Tagus Estuary configuration simulation as a function of tide period in Cascais, Bonzanza and Leixões. Results from harmonic analysis of simulation results (15/01/1999-15/02/2000) with and without tide generating forces are presented.



In the case of Leixões, no appreciable error beyond the semi diurnal band is verified, where both over and underestimations of amplitude are observed according to component. Tide generation forces can reduce some of the overestimation. These results in Leixões suggest that the major problem in tide representation in Leixões is not the lack of energy transfer to shallow water components, as in Bonanza, but instead a deficient propagation of semi diurnal components from other areas of the domain, which can result from the different quality of bathymetry raw data in the area referred before.

The results of the alternative domain 1 MOHID Tagus Estuary configuration after one year simulation show the existence of an accumulation of velocity perturbations at the northeast boundary of the domain, expressed by velocities comparable in magnitude to the ones normally observed in front of the Estremadura region. This is probably the result of the accumulation of errors in the simulation which are driven to northeast boundary by tide and are not dissipated due to the open boundary condition. This could mean that diffusion through turbulence is not sufficiently accomplished in modelling or that the decay times specified at the north boundary are inadequate. To deal with the possibility of turbulence deficiency some tests are performed, in which a simulation is made using an increased turbulence's biharmonic coefficient (valued $1x10^{10}$) and, in another simulation, with increased bottom shear stress coefficient (0.003 instead of 0.0025). Also, an alternative configuration with larger decay times at the continental shelf is applied and tested. In all tests the simulation time period is the same as before. However, the results of these tests do not support for benefit of using these changes for the alternative domain MOHID Tagus Estuary configuration and are not shown here.

IV.2. Hypothesis 2 – Atmospheric Pressure Effect on Mean Sea Level

IV.2.1. Domain 0 configuration

In order to model explicitly the meteorological forcing effect on large scale circulation it is considered a domain 0 configuration for MOHID Tagus Estuary. This domain is based on an existent bathymetry for the North Atlantic Sea (92.25ºW – 7.25ºE, 12.75ºN – 72.75ºN) whose details are presented in Chapter III. The modelling conditions are those presented in Table IV-4.

Table IV-4: Model domain 0 configuration used to test research Hypothesis 2.

Modelling condition	Specification
Time discretization step (s)	600 (double splitting)[a]
Vertical discretization	2D
Processes modelled	Hydrodynamic (water level, velocity)
Flux	Barotropic
Imposed tide	-
Advection spatial discretization scheme	Upwind order 1
Discharges	-
Meteorological forcing	Sea level atmospheric pressure, wind (spatially variable)
Water properties	Density (constant)
Horizontal viscosity coefficient	20
Bottom shear stress coefficient	0.0025
Open boundary condition	Flather (1976) radiation (reference water level=2.08m[b] and reference barotropic velocity=0m/s)

Notes: [a] corresponding Courant number is nearly 8, which is smaller than the 17 which is observed in MOHID Tagus Estuary existent and alternative domain 1 and domain 2 configurations but is adequate for a first simulation; [b] mean sea level from long time series of Cascais tide gauge measurements, assumed for domain 1 tide forcing; - not considered.

As detailed in Chapter III, the meteorological forcing is provided by ECMWF ERA40 reanalysis, as no MM5 forcing is available for the time period of simulation. No tide modelling is performed as an adequate tide forcing could not be devised for the Equator open boundary.

IV.2.2. Large scale meteorological forcing effect on mean sea level

For studying the large scale meteorological forcing effect on coastal mean sea level a simulation is made of the alternative domain 1 MOHID Tagus Estuary configuration presented in the Table IV-1 nested in the domain 0 configuration presented previously, without tide simulation and considering in both domains the meteorological forcing from Table IV-4, for the period 15/01/1972 0h – 07/10/1972 21h. The initialization of the model is as are provided in Table IV-5.

Table IV-5: Initial conditions for domain 0 and nested domain 1 MOHID Tagus Estuary simulation used for Hypothesis 2 test.

Parameter	Initial condition
Water level	2.08m[a]
Velocity (meridional and zonal components)	0m/s

Notes: [a] average water level from long series of Cascais tide gauge measurements.

No domain 2 is considered because the interaction between tide, bathymetry and meteorological forcing is expected to be important and no tide forcing is considered in domain 0 and domain 1.

The tidal residuals of the water level simulation results for 16/02/1972 12h to 07/10/1972 21h for Cascais tide gauge location from both domains are contrasted with the tidal residuals obtained from the measurements available from this tide gauge for the simulation time period. The first simulation month is not analyzed to in order to discard potential spin-up effects.

The descriptive statistics of the simulation results and the measurements tidal residuals, provided in Appendix I, show that the simulation achieves a representation of the average mean sea level within 10cm of measurements, with the simulation underestimating the average mean sea level. The standard deviation of the mean sea level of the measurements (0.08m) is very well represented in domain 1 results, while underestimated in the domain 0. These results suggest also that average mean sea level representation in the model is not dependent of the horizontal grid resolution, as the domain 0 resolution is more than 10 times smaller than the domain 1 resolution, but is more influenced by the initial and open boundary conditions for water level. The horizontal grid resolution seems, however, to influence the representation by the model of the variability of mean sea level.

Given the difference in average mean sea level between the measurements and the simulation results, the domain 1 results represent adequately the extreme variation of mean sea level, which represents nearly 0.30m relative to the average mean sea level: in domain 0 the representation of extreme values is considerably smaller with the extreme variations of mean sea level representing about 0.15m relative to average mean sea level.

The descriptive statistics obtained for the results of the direct application of the inverted barometer formulation to Cascais tide gauge location (processed by the software application described in section IV.2.4), also presented in Appendix 1, are very similar to those obtained for domain 0, a result which confirms the adequacy of this formulation to represent the large scale meteorological forcing effect on mean sea level. This also evidences that the atmospheric pressure is more important that wind stress at the large scale.

These findings confirming that the determinant processes influencing mean sea level at the Tagus Estuary mouth are of meteorological origin and acting at the large and regional scales. According with the classification of storm surges for Cascais of Gama *et al.* (1994) the extreme variation of mean sea level observed in this period corresponds to a significant storm surge (from 26 to 34cm). Since the simulation period is mainly concentrated in the summer season, when storms are usually less pronounced, these extreme variations of mean sea level outline the importance of meteorological induced mean sea level changes at the estuary mouth.

The model simulation error statistics obtained for Cascais tide gauge are summarized in Table IV-6. It is interesting to note that while the overall variability of the measured mean sea level is as seen better represented by domain 1 than by domain 0 results, the centered RMSE is 2cm larger in the domain 1. The bias represents less than 5% of average mean sea level of measurements while centered RMSE is large relative to the mean sea level variability.

Table IV-6: Bias and centered RMSE of domain 0 and nested domain 1 of MOHID Tagus Estuary simulation and inverted barometer formulation used for Hypothesis 2 test relative to tide gauge measurements of mean sea level in Cascais. Statistics calculated from hourly values of mean sea level, except for the inverted barometer formulation which are calculated from values sampled every 6 hours.

Mean sea level	Bias (m)[a]	Centered RMSE (m)
Model simulation:		
Domain 0	-0.10 (5%)	0.06
Domain 1	-0.09 (4%)	0.08
Inverted barometer formulation	-0.11 (5%)	0.06

Notes: [a] percentages represent the quotient between the bias and the average mean sea level of measurements.

These results evidence that the large frequencies of variability are not well represented by the model simulation, which is perhaps a consequence of the low time resolution of the meteorological forcing (6 hours resolution) or of the importance of non linear interactions between tide, meteorological forcing and bathymetry affecting mean sea level at the regional scale.

The error statistics obtained for the results of direct application of the inverted barometer formulation, also shown in Table IV-6, are again very similar to the simulation domain 0 results, confirming that the use of this formulation is capable to convey the fundamental quantitative results of an effective modelling of large scale hydrodynamics driven by atmospheric pressure and wind forcing. This provides an evidence of support for Hypothesis 2.

IV.2.3. Actualization of domain 2 bathymetry

The domain 2 bathymetry is, while maintaining the horizontal grid resolution, actualized with more detailed bathymetric data inside and at the mouth of the Tagus Estuary; the other areas of the domain are informed by bathymetric data from the existent MOHID Tagus Estuary domain 1 bathymetry and ETOPO 2' data as detailed in Chapter III. The coastline description is also more detailed.

This bathymetry (Figure IV-7) is outside the estuary overall very similar to the existent domain 2 configuration bathymetry. However, inside the estuary it is noted, as presented in Figure IV-8, a better description of the estuarine channels.

The performance of this bathymetry in representing tide using the modelling conditions of the existent domain 2 MOHID Tagus Estuary 2D configuration (only tide forcing) but nested in the alternative domain 1 configuration presented in section IV.1 is presented in Appendix III. It is found an adequate representation of tide in the coast, estuary exit channel and mid estuary but a large error in the upper estuary at Ponta de Erva and Vila Franca de Xira, not solving the error problem of the existent domain 2 MOHID Tagus Estuary in this respect indicated by Fernandes (2005). The research presented in Appendix III finds that this error concentrates in the semi diurnal band of tide period and is found evidence that this error is due to bathymetry resolution. Also, the model cannot adequately produce the dominant shallow water components of tide both in the upper estuary and the coast. Important average mean sea level differences exist between the tide gauge measurements and the model results, especially at the estuary exit channel.

Figure IV-7: Actualized bathymetry of domain 2 MOHID Tagus Estuary configuration used for Hypothesis 2 test.

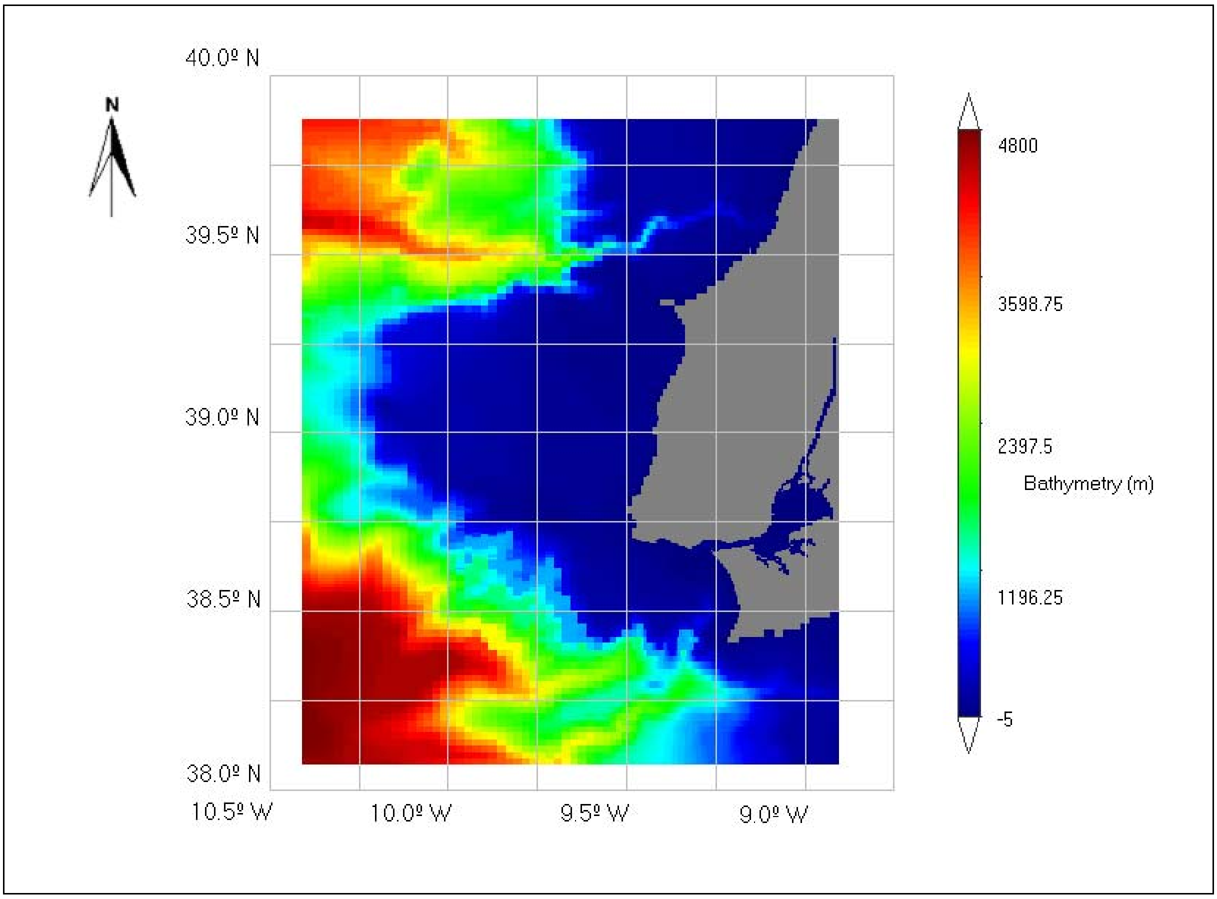
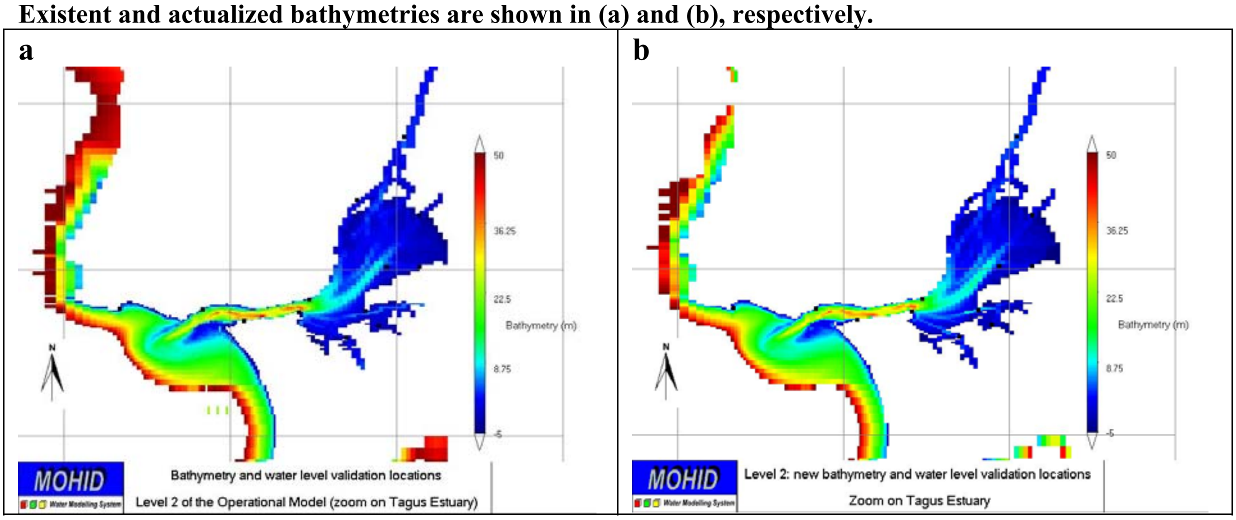


Figure IV-8: Existent and actualized bathymetries of domain 2 MOHID Tagus Estuary configuration. Existent and actualized bathymetries are shown in (a) and (b), respectively.



IV.2.4. Alternative domain 1 configuration

In order to test Hypothesis 2 is developed an alternative domain 1 configuration accounting the atmospheric pressure effect on large scale circulation. This configuration is based in the alternative domain 1 configuration developed for the test of Hypothesis 1 and, as referred in Chapter III, is developed considering the inverted barometer formulation.

A mean sea level time series is generated from the atmospheric pressure time evolution for each water level locations considered as reference in the Blumberg and Kantha (1985) open boundary condition of domain 1. The mean sea level time series is generated according with the following expression derived from Cañizares (1999):

$$\zeta_p = -0.000101 * (P - P_{ref}) \qquad \text{(IV.1)}$$

Where ζ_p is the change in mean sea level caused by atmospheric pressure (m), P is the atmospheric pressure at sea level (Pa) and P_{ref} is the reference atmospheric pressure which is taken to be 101330 Pa (Dorandeu and Le Traon, 1999; Cañizares, 1999, Choi *et al.*, 2003).

The calculation of mean sea level time series is performed by a software application developed in this work, called InvertedBarometer (see Appendix X), which receives as input the tidal components file in MOHID format used to supply the tide boundary reference in MOHID Water and sea level atmospheric pressure data in MOHID HDF5 file. The application calculates the mean sea level by adding the change in mean sea level derived from atmospheric pressure to the reference mean sea level considered at each tide gauge location in tidal components file. The output of this application is a new tidal components file with specification of time variable mean sea level and a set of mean sea level time series, one per each tide gauge considered in the tidal components file. MOHID Water then interpolates the tide and mean sea level data from the tide gauges to the domain open boundary to be taken as reference to the Blumberg and Kantha (1985) boundary condition.

The alternative domain 1 configuration is thus constituted by the alternative domain 1 configuration developed for Hypothesis 1 test and the time series for mean sea level produced from atmospheric pressure time variable fields by InvertedBarometer application.

IV.2.5. Hypothesis test

In order to test the effect of atmospheric pressure on mean sea level evolution observed in the Tagus Estuary and adjacent coast two simulations of MOHID Tagus Estuary are made for the period from 01/10/1972 0h to 31/01/1973 0h: one with the domain 2 with actualized bathymetry (section IV.2.3) nested in the alternative domain 1 configuration of section IV.1.1. with only tide forcing and another with the domain 2 with actualized bathymetry nested in the alternative domain 1 configuration of section IV.2.4. with tide forcing and the atmospheric pressure effect in mean sea level. River flows are also considered as detailed in Chapter III. The atmospheric pressure data used to generate the mean sea level at the boundary is provided by ECMWF ERA40 reanalysis, as explained in Chapter III.

The model initialization conditions for domain 1 are as provided in Table IV-2. Those for domain 2 are presented in Table IV-7.

Table IV-7: Initial conditions for domain 2 MOHID Tagus Estuary simulations used for Hypothesis 2 test.

Parameter	Initial condition
Water level	2.08m[a]
Velocity (meridional and zonal components)	0m/s

Notes: [a] average water level from long series of Cascais tide gauge measurements.

The water level results of both simulations from 01/11/1972 0h to 31/01/1973 0h (three months) are harmonically analysed and tidal residuals are produced as explained in Chapter III. The same procedure is used to produce the tide residuals from measurements of 11 tide gauges available for approximately one year in the Tagus Estuary and adjacent coast (Chapter III). The tidal residuals of simulations are then contrasted with the tide residuals from measurements. Since the harmonic analysis of the simulation results is only made for three months data the tide components K_2 and P_1 cannot be estimated and are not taken into account in the production of tidal residuals from simulations. These components are however taken into account for the production of the measurements tidal residuals. As these are important semi diurnal and diurnal component of tide at the Tagus Estuary area with amplitude of several centimetres (see section IV.1.3.) and the meteorological forced mean sea level oscillations should amount to several tens of centimetres (section IV.2.2) in order to assess more correctly the atmospheric pressure influence on mean sea level the tidal residuals of simulations and measurements are filtered to remove perturbations of mean sea level with period bellow 30 hours, which should be very much affected by insufficient detiding.

The descriptive statistics of the filtered tide residuals are presented in Appendix I. Besides the important mean sea level differences between the simulation and measurements already referred in section IV.2.3., it is important to note that both simulations present a smaller variability of the mean sea level (expressed by the standard deviation) than measurements in every tide gauge locations. This could be the result of unaccounted dynamical effects in simulation or a too coarse bathymetry resolution: since only perturbations with period larger than 30 hours are being accounted in variability local effects of wind and river flow are not though to be very important and it is more probable that the variability difference be due to the second factor. The difference of variability of mean sea level from the coast (Cascais) to upper estuary (Ponta de Erva, Vila Franca de Xira) is improved in the simulation with the inverted barometer effect, approaching the variability difference observed in measurements, evidence that this effect is important in explaining the mean sea level variability in the coast and lower estuary and that in the upper estuary the river flow should be the determinant factor affecting mean sea level. The extreme mean sea level values are not as significant as those verified in the time series from Cascais tide gauge considered in section IV.2.2. which is probably the result of the filtering step used.

The statistics for the contrast between the tidal residuals of measurements and both simulations are presented in Table IV-8. In this contrast besides the centered RMSE is also used the correlation coefficient since the higher frequency perturbations of mean sea level have been filtered and the representation error of the model (due to limited grid resolution) is assumed less important for smaller frequencies and also because the Hypothesis 2 involves a correlation in time in mean sea level evolution of model and measurements.

In terms of centered RMSE, Table IV-8 evidences that the consideration of the inverted barometer effect causes little change in the model performance in the upper estuary (Vila Franca de Xira and Ponta de Erva) and in some locations of mid estuary (Montijo, Alcochete). These are areas near river discharges (upper estuary) or affected by river discharges through intertidal movements (Montijo and in some degree Alcochete): in these areas the gross of the error seems therefore to be caused by other effects such as river flow and bathymetry representation. In the upper estuary, the slight degradation of the model representation of mean sea level (more than 5% increase in centered RMSE) is an indicator of bathymetry misrepresentation, which is thought to be due to too low resolution which causes that the atmospheric pressure effect propagates too much in the upper estuary, which is not supported by measurements. However, in most locations of the mid estuary, end estuary channel and coast the account of the inverted barometer effect causes a significant reduction of mean sea level error with centered RMSE improvements more than 5% especially in the coast, in Cascais and Trafaria, but also in the mid estuary narrow channels, in Seixal. This is evidence that the mid estuary areas where the circulation is very much constrained by bathymetry should be very much affected by storm surges occurring at the estuary mouth, particularly in situations of spring tide. Contrastingly, in Lisboa, which is more close to the end of the estuary than Seixal, the inverted barometer effect is not important, probably due to the relatively larger depth of bathymetry.

Table IV-8: Centered RMSE and correlation coefficient of domain 2 MOHID Tagus Estuary mean sea level results relative to mean sea level measurements in several tide gauges. Statistics calculated from hourly values of mean sea level, obtained from tidal residuals filtered to remove the perturbations with period bellow 30 hours.

Tide gauge	Centered RMSE				Correlation coefficient[c]	
	without inverted barometer effect		with inverted barometer effect		without inverted barometer effect	with inverted barometer effect
	(m)	(%)[a]	(m)	(%)[a,b]		
Cascais	0.06	102	0.05	78 (-24)	-0.22	0.63
Paço de Arcos	0.07	101	0.06	92 (-9)	-0.22	0.44
Trafaria	0.08	101	0.07	85 (-16)	-0.20	0.53
Cacilhas	0.07	101	0.06	95 (-6)	-0.11	0.40
Lisboa	0.06	101	0.06	100 (-1)	-0.11	0.36
Cabo Ruivo	0.07	103	0.07	92 (-11)	-0.32	0.44
Seixal	0.07	103	0.06	87 (-16)	-0.28	0.53
Montijo	0.08	101	0.07	99 (-2)	-0.12	0.32
Alcochete	0.08	102	0.08	107 (5)	-0.22	0.15
Ponta de Erva	0.09	98	0.10	106 (8)	0.20	0.06
Vila Franca de Xira	0.11	104	0.11	111 (7)	0.13	0.10

Notes: [a] percentages represent centered RMSE relative to standard deviation of mean sea level part of measurements; [b] in parentesis are presented the percentual difference of the second simulation percentage centered RMSE relative to the first simulation percentage centered RMSE; [c] all correlation coefficient values are statistically significant relative to the 1% significance level (Emery and Thomson, 2001).

While providing significant error reductions the inverted barometer effect importance is perhaps more visible in the correlation coefficient values, which measure the concordance of time evolution of mean sea level between simulations and measurements. In the simulation made not accounting the inverted barometer effect the mean sea level in measurements and model results in inversely correlated, except in the upper estuary (Ponta de Erva and Vila Franca de Xira), where river flow becomes the dominant effect as seen in the analysis of centered RMSE values. This situation evidences that important effects affecting mean sea level variability in most of the estuary and adjacent coast are being neglected by the model. The correlation coefficients obtained for the results of simulation accounting for the inverted barometer effects, which are positive and generally with larger absolute value, show the large scale effect of atmospheric pressure on circulation is one of these important effects. The pattern of relative correlation coefficient values within the estuary and coast perfectly match the pattern found in the centered RMSE, with the effect being more important in explaining the variability outside the estuary and in Seixal. It is now possible to note that the effect is also important in Lisboa, although the error in this location should be dominated by other effects. In Ponta de Erva the correlation coefficient verifies a decrease with the inclusion of the inverted barometer effect providing more evidence that bathymetry is not being adequately represented in the model.

These contrast results provide consistent support for usefulness of Hypothesis 2 in explaining mean sea level variability with period 30 hours or larger at the coast and lower and mid estuary. This hypothesis seems not to be important in explaining the upper estuary variability. They also provide strong support for the barotropic velocity variability found by Leitão (2003) near Cascais to be due to the large scale effect of atmospheric pressure on circulation as suggested in Chapter III.

IV.3. Hypothesis 3 – Vertical Stratification

IV.3.1. Alternative 3D domain 2 configuration

The alternative 3D domain 2 configuration developed to test Hypothesis 3 is constituted by the existent 3D domain 2 configuration (Chapter II) using the actualized bathymetry presented in section IV.2.3. and the altered modelling conditions presented in Table IV-9.

Table IV-9: Model alternative 3D domain 2 MOHID Tagus Estuary configuration used to test research Hypothesis 3. Only modelling conditions with changes relative to the existent 3D domain 2 MOHID Tagus Estuary configuration presented in Chapter II are shown.

Modelling condition	Specification
Vertical discretization	33 layers (cartesian)
Processes modelled	Hydrodynamic (water level, velocity, temperature, salinity)
Advection spatial discretization scheme	TVD Superbee
Discharges	Hourly values for Tagus and Sorraia river, daily average for Trancão
Meteorological forcing	Spatially variable: wind, solar radiation, air temperature, heat fluxes, relative humidity
Water properties	Density, temperature, salinity (polynomial interpolation calculation of baroclinic density gradient integral)
Open boundary condition	Temperature and salinity: null gradient with reference solution provided by Levitus (1982) climatology; newtonian relaxation for climatology in the 11 outmost boundary cell frames, except the north boundary of continental shelf, with decay times ranging from 900s (boundary) to 7200000s (inside)[a] Water level and velocity: Flather (1976) radiation with reference solution provided by domain 1, flow relaxation scheme for velocity, with decay times ranging from 900s (boundary) to 7200000s (inside)[a], to domain 1 solution

Notes: [a] decay times established considering existent domain 2 MOHID Tagus Estuary configuration flow relaxation scheme decay times.

The use of Levitus (1982) climatology for providing the open boundary stratification, the use of TVD advection, discharges and spatially variable meteorological forcing are related to previous research results and data availability and are discussed in Chapter III.

The improved vertical discretization, representing a three-fold change in layers number, is required so that large density changes between adjacent vertical layers are not verified, as they would cause instabilities in the model. The methodology used for this discretization development is presented in Appendix IV.

Since the profile from climatology does not present adequate spatial and time variability to be considered directly as reference for open boundary condition for temperature and salinity it is used a newtonian relaxation, following the discussion presented in Leitão (2003). Having into account a first test of the alternative 3D domain 2 MOHID Tagus Estuary configuration, the relaxation is performed in all boundary except for the nearest to land north boundary and the nearest to the south boundary, with depths smaller that 100m. At these boundary, full relaxation is considered till a bathymetry depth of 750m, no relaxation is considered from a bathymetry depth of 100m to coastline, and a relaxation time transition is performed in the area in between. The consideration of these bathymetry values is informed by the analysis of currents and temperature at surface and depth in the first results of this model configuration, which indicated the existence an inadequate representation of temperature variability in the continental shelf with the use of newtonian relaxation.

The spatially variable meteorological forcing of the alternative domain 2 configuration is obtained from MM5 model results.

IV.3.2. Hypothesis test

The test of Hypothesis 3 is made by performing two model simulations of 3D domain 2 MOHID Tagus Estuary configuration: one for the existent domain 2 configuration nested in the existent domain 1 configuration and another for the alternative domain 2 configuration (section IV.3.1.) nested in the alternative domain 1 configuration (section IV.1.1.). Since both domain 1 configurations provide similar performance in tide representation as seen in section IV.1. it is used the existent domain 1 configuration for nesting the existent domain 2 configuration, to assess the differences of both complete domain 1-domain 2 configurations. These simulations are made for the period 15/01/2005 0h – 01/03/1973 0h with the modelling conditions described before (Chapter II for existent configurations and sections IV.3.1. and IV.1.1. for the alternative configurations).

The initialization of the model is as provided in Table IV-10. Because the modelling conditions are different the initialization is not equal in both simulations but whenever possible the same initial conditions are used, to minimize the effect of a different initialization. The use of wind forcing gradual connection is mostly determined by the use of spatially variable wind, in order for the correct surface circulation to be achieved in the alternative configuration simulation; it is also used for the existent configuration simulation for consistency. The gradual connection of baroclinic forces follows from the discussion of Leitão (2003) of the usefulness of this option to avoid instabilities in model initialization in stratified conditions. Finally the gradual connection of tide elevation is reduced from the two days, used in sections IV.1. and IV.2., to one day to be consistent with the wind forcing connection and the ramp period, as satisfying results are obtained.

Table IV-10: Initial conditions for domain 1 and domain 2 MOHID Tagus Estuary simulations used for Hypothesis 3 test.

Parameter	Initial condition configuration	
	existent	alternative
Water level	2.08m[a]	2.08m
Velocity (meridional and zonal components)	0m/s	0m/s
Salinity (domain 2)	Tagus Estuary: boxes with 2, 10, 20, 30 p.s.u. (from Tagus River to sea) Elsewhere: 36 p.s.u.	Tagus Estuary: boxes with 2, 10, 20, 30 p.s.u. (from Tagus River to sea) Elsewhere: climatology profile[b]
Temperature (domain 2)	16ºC	climatology profile (Levitus, 1982)
Density (domain 2)	constant with depth (1026.73 g/m$^{3)}$	variable with depth (corrected for pressure)
Tide forcing (domain 1)	Slowstart period of 1 day[c]	Slowstart period of 1 day[c]
Wind forcing	Gradual connection (0-100%) for 1 day period	Gradual connection (0-100%) for 1 day period
Baroclinic forces (domain 2)	-	Gradual connection (0-100%) for 1 inertial period (19 hours)[d]

Notes: [a] average water level from long series of Cascais tide gauge measurements and constant mean sea level considered for tidal forcing; [b] spatially variable default value (a vertical profile in this configuration) is an improvement of MOHID Water code performed in this research work; [c] in this period only a fraction of tide elevation is imposed, ranging from 0 at the beginning of period to 1 at the end of period; [d] option RAMP (Leitão, 2003).

A fortnight period is considered for model spin up from initial conditions and the simulations results from 01/02/2005 are contrasted with CTD measurements of thermal and saline stratification taken in 01/02/2005 at several locations near Guia wastewater outfall (see Chapter III) and MODIS Level 2 SST images (see Chapter III).

Tide representation is not assessed because the configurations are already validated by Leitão (2003) and Fernandes (2005), in the case of existent domain 2 configuration, and in Appendix III, in the case of the alternative domain 2 configuration, and the tide representation is barotropic by nature and should not be significantly affected by baroclinic and 3D dynamic effects. Also, velocity results are not analyzed in this work, as validation data is unavailable. In Appendix V are discussed succinctly the surface velocity patterns obtained in the alternation 3D configuration simulation results which seem to derive from the occurrence of internal tides at the continental shelf slope.

Since the CTD measurements are concentrated in a small area of domain 2 only for one day it is chosen to assess the representation of stratification of the model relative to measurements considering all measurement points in calculating statistics. This is made for the three layers of the model with average depths 2.55m, 15m and 27.5m (layers 32, 30 and 29), present in all measurement locations. The contrast results are presented in Table IV-11.

Table IV-11: Bias and centered RMSE for temperature and salinity of existent and alternative 3D domain 2 MOHID Tagus Estuary simulations used for Hypothesis 3 test relative to CTD measurements near the Guia wastewater outfall. Measurements are linearly interpolated for model vertical layers average depths for statistics calculation. 11 measurements with longitude ranging from -9.43ºE to -9.57ºE and latitude from 38.67ºN to 38.70ºN, from which 10 are located in the continental shelf.

Depth (m)	Temperature (ºC)				Salinity (ºC)			
	Bias[a]		Centered RMSE[b]		Bias[a]		Centered RMSE[b]	
	configuration		configuration		configuration		configuration	
	existent	alternative	existent	alternative	existent	alternative	existent	alternative
2.55	1.00	0.11	0.32	0.27	-0.34	-0.03	0.25	0.14
	(7%)	(1%)	(134%)	(116%)	(-1%)	(0%)	(310%)	(177%)
15	1.35	0.26	0.19	0.20	-0.19	-0.03	0.13	0.10
	(10%)	(2%)	(95%)	(102%)	(-1%)	(0%)	(189%)	(146%)
27.5	1.43	0.26	0.19	0.19	-0.12	-0.04	0.12	0.10
	(10%)	(2%)	(120%)	(122%)	(0%)	(0%)	(183%)	(142%)

Notes: [a] percentages represent bias relative to average of measurements interpolated to model layer average depths; [b] percentages represent centered RMSE relative to standard deviation of measurements interpolated to model layer average depths.

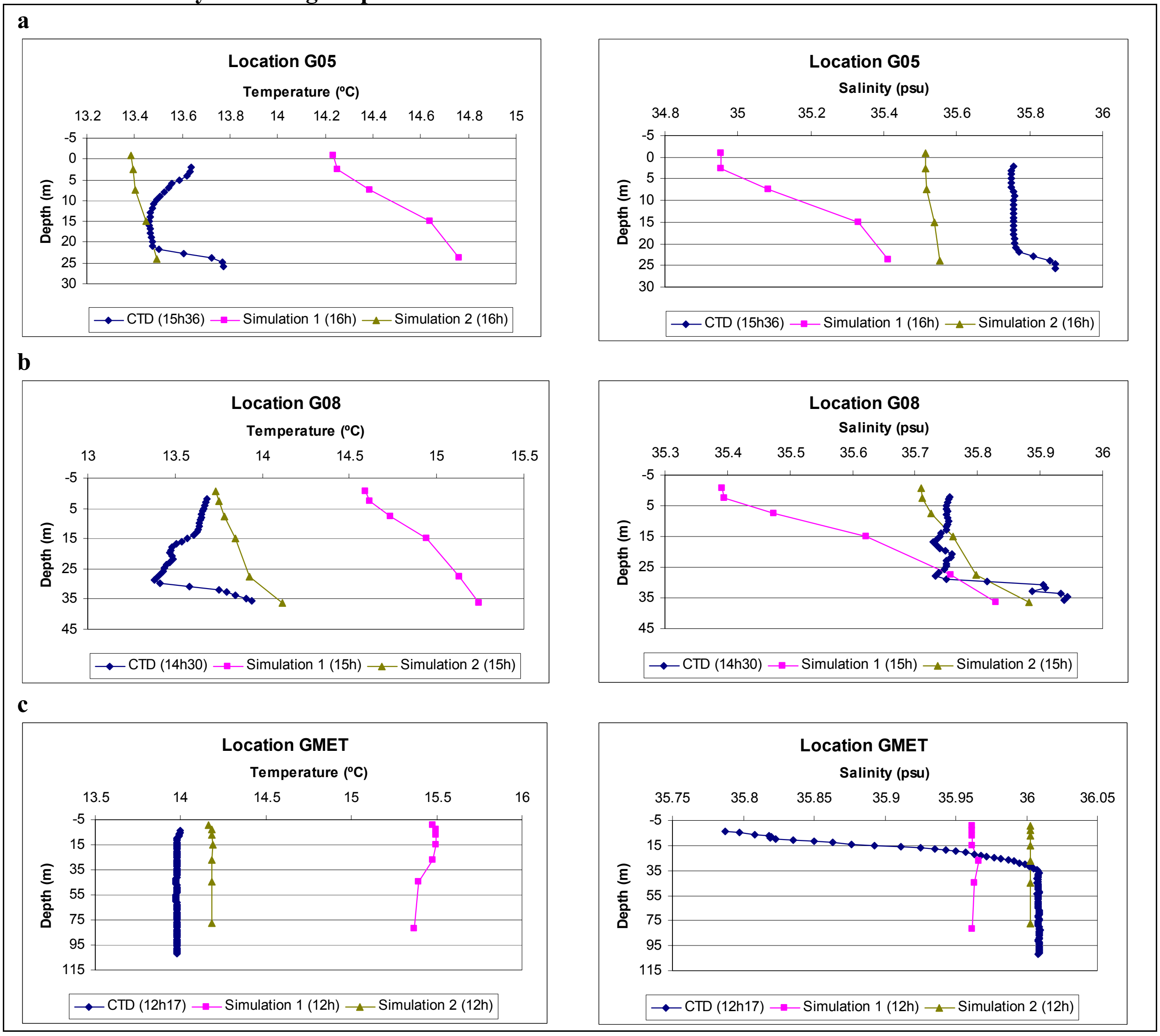
It is observed that the existent domain 2 configuration simulation results presents a bias of more than 5% of average measurement value for temperature at all the depths analyzed but more accentuated in the two larger depths. This bias is probably the result of considering a constant temperature of 16ºC in the whole water column at the initial time and in the boundary, which is too high temperature for the depths analyzed. A similar behavior of a model configuration very similar to the existent domain 2 configuration is observed by Leitão (2003) for depth 20m although in a location more close to the Tagus Estuary mouth and the constant vertical temperature value assumed for the initial time pointed by this author as the cause. This bias is almost completely removed by the use of the alternative domain 2 configuration (bias represent 2% or less of measurement average value). The same bias is not so important in salinity, in both configurations, a result which seems to suggest that relationship between vertical distribution of temperature and salinity in the existent domain 2 configuration is not very realistic, at least for the two larger depths. The better performance of the model in salinity representation is probably due to the proximity to the Tagus Estuary where the fresh water flow should be adequately represented. Also, it is expected that the ocean stratification in this area is essentially driven by temperature (Leitão, 2003) as can also be observed in the climatology stratification for February presented in Appendix IV.

However, both configurations results present a large centered RMSE both in temperature and salinity evidencing that the variability of measured stratification is not adequately represented by the model. For this statistical indicator the salinity verifies the larger error. The use of the climatology stratification as initial and boundary condition while achieving generally large error reductions in temperature and salinity in the first depth and in salinity in the two larger depths cannot reduce this error to acceptable levels. The effect of the alternative configuration in the larger depth temperature is nearly negligible and it seems to cause a slightly larger error in the case of the intermediate depth temperature. This suggests that the climatology may not be adequate near coast or that a larger simulation time is required for the model to create a more realistic stratification based on the meteorological forcing and the river flows. The existence of a transient regime of this type is suggested by the potential energy per unit mass evolution as presented in Appendix V. The work of Leitão (2003) suggests that a period of 14-25 days is adequate for a model similar to the existent 3D domain 2 MOHID Tagus Estuary configuration to evolve from schematic initial conditions to realistic representation of temperature and salinity at the estuary mouth according to CTD measurements. However, the CTD measurements considered by this author refer to locations more near the estuary mouth and the Tagus River flows (300-1000m^3/s) in his study are larger than the ones verified in this work (generally lower than 50m^3/s).

The bias and centered RMSE statistics provide a concise view of both domain 2 configurations performances. However it is important to assess with more detail the performance in stratification representation in specific locations. In Figure IV-9 are presented the vertical profiles of temperature and salinity as represented in model simulations and as present in CTD measurements for three locations: the location closest to the Tagus Estuary mouth (G05), the location closest to the Guia wastewater outfall (G08) and the location most offshore (GMET). These locations are representative of the locations spanned by measurements.

At the location more close to the estuary (G05) the alternative configuration provides a considerably better representation of the measurements vertical distribution of temperature and salinity, both in quantitative and qualitative terms: the temperature at the 15m depth is almost coincidental and the near surface and near bottom temperature differences (within 0.4ºC) are smaller than the ones observed for the existent configuration; as for salinity the alternative configuration reduces considerably the underestimation of salinity of the existent configuration (to less than 0.4 p.s.u. underestimation), especially near surface, and provides an almost constant salinity profile as verified in the measurements; only near bottom the measurements profile is not followed which is most probably a result of lack of vertical resolution. At surface the remaining underestimation should be a consequence of an incorrect fresh water plume from the estuary possibly caused by inadequate resolution of wind forcing. The validation of the meteorological forcing with the Guia meteorological station measurements provides in Appendix VI provides evidence that the wind velocity is overestimated by the MM5 model for this area: this overestimation and the fact also presented there that the wind for the simulation period is predominantly from Northeast justifies that the extent to West and South of the fresh water plume can be exaggerated in the model results as a consequence of surface shear stress. This should also explain the lower near surface values observed in the alternative configuration results relative to the measurements. Overall, this performance of the alternative configuration provides an error which is within or even smaller than the ones found by Leitão (2003) in locations near the Tagus Estuary mouth.

Figure IV-9: Temperature and salinity vertical profiles for locations G05 (a), G08 (b) and GMET (c) as provided by CTD measurements and existent and alternative 3D domain 2 MOHID Tagus Estuary configurations simulations (1 and 2, respectively) for day 01/02/2005. Simulation results are presented at model vertical layers average depths.



For the Guia wastewater outfall area (location G08) the alternative configuration is again more performing although the more complex stratification of measurements provides for a lower qualitative representation: while the near surface and near bottom quantitative values of measurements of temperature and salinity are adequately represented by the alternative configuration (and also by the existent configuration in what respects to near bottom salinity) the mid water column values, particularly at depths between 15m and 25m are not adequately represented, especially in temperature where an appreciable error of 0.5ºC is observed. In this case the lower performance of the model seems to be justified by the small vertical resolution of the model grid. At surface the underestimation of salinity is again justifiable by the deficiencies of wind forcing.

In the case of the most offshore location (GMET) the alternative configuration provides a good qualitative agreement with the measurements, providing for nearly constant with depth temperature and salinity profiles, which is more performing relative to measurements than the existent configuration, specially in depths larger than 35m. However this alternative configuration simulation cannot capture the fresher water mass near surface which is observed in measurements. This pattern in measurements suggests that the estuarine plume expands to small offshore in the model simulations. This could be again due to an inadequate quality or resolution of the wind forcing. The existent configuration approaches more the measurements near surface but this is supposed to be a coincidental behavior as in depth it is less performing than the alternative configuration.

The surface distribution of temperature representation in model simulations further assessed by contrasting with SST images, as referred. As presented in Chapter III the analyzed SST images refer the period 11/02/2005 – 25/02/2005. From these, a set of MODIS (Level 2) images from four consecutive days from 16/02/2005 to 19/02/2005 is presented in Figure IV-10 and Figure IV-11, together with the results for the surface layer of the existent and alternative domain 2 configurations. In this set of days it is shown in Appendix VI that the daily average wind is from Northeast; also the daily average air temperature verifies an accented cooling (nearly 4ºC) near coast. The MODIS images present a large variability of SST ranging from 16ºC in most of the domain 2 in day 16/02/2005 to situation of 3ºC differences throughout the domain and cold water (13ºC or less) near coast in days 17/02/2005 and 19/02/2005 to a situation of more homogeneous SST with approximately 14ºC near coast in day 18/02/2005. Due to the consistent Southwest ward winds it is probable that some of the reduced temperature events near coast may be due in part to mild upwelling, particularly in the center and south of the domain. It is thus a good period to assess the surface temperature spatial and time variability representation of the model.

In terms of spatial variability, it is possible to observe that the alternative configuration presents a larger variability than the existent configuration, which is seems mainly the result of the climatology stratification consideration. The areas with colder water near the coast, in the continental shelf facing the Estremadura Promontory and near the north boundary, persist throughout the period and are probably due water column mixing due wind action and climatology stratification, as no similar cooling is observed in the existent configuration results: since the spatial variability of the wind is small in the period considered (see Appendix VII), due to low spatial resolution of MM5 results, if this should be caused by simple meteorological cooling effect it should be apparent also in the existent configuration results. It is probable that the overestimation of the wind stress by MM5 (Appendix VI) should accentuate this mixing, while an excessive cooling due to incorrect air temperature or radiation seems less likely due to the relatively good representation of these meteorological parameters in MM5 results (Appendix VI).

Figure IV-10: SST fields from MODIS (Level 2) satellite images (a, b) and existent (c, d) and alternative (e, f) 3D domain 2 MOHID Tagus Estuary simulation results for 16/02/2005 12h55 – 13h and 17/02/2005 13h38 – 14h. Model simulation results are presented for the nearest time instant.

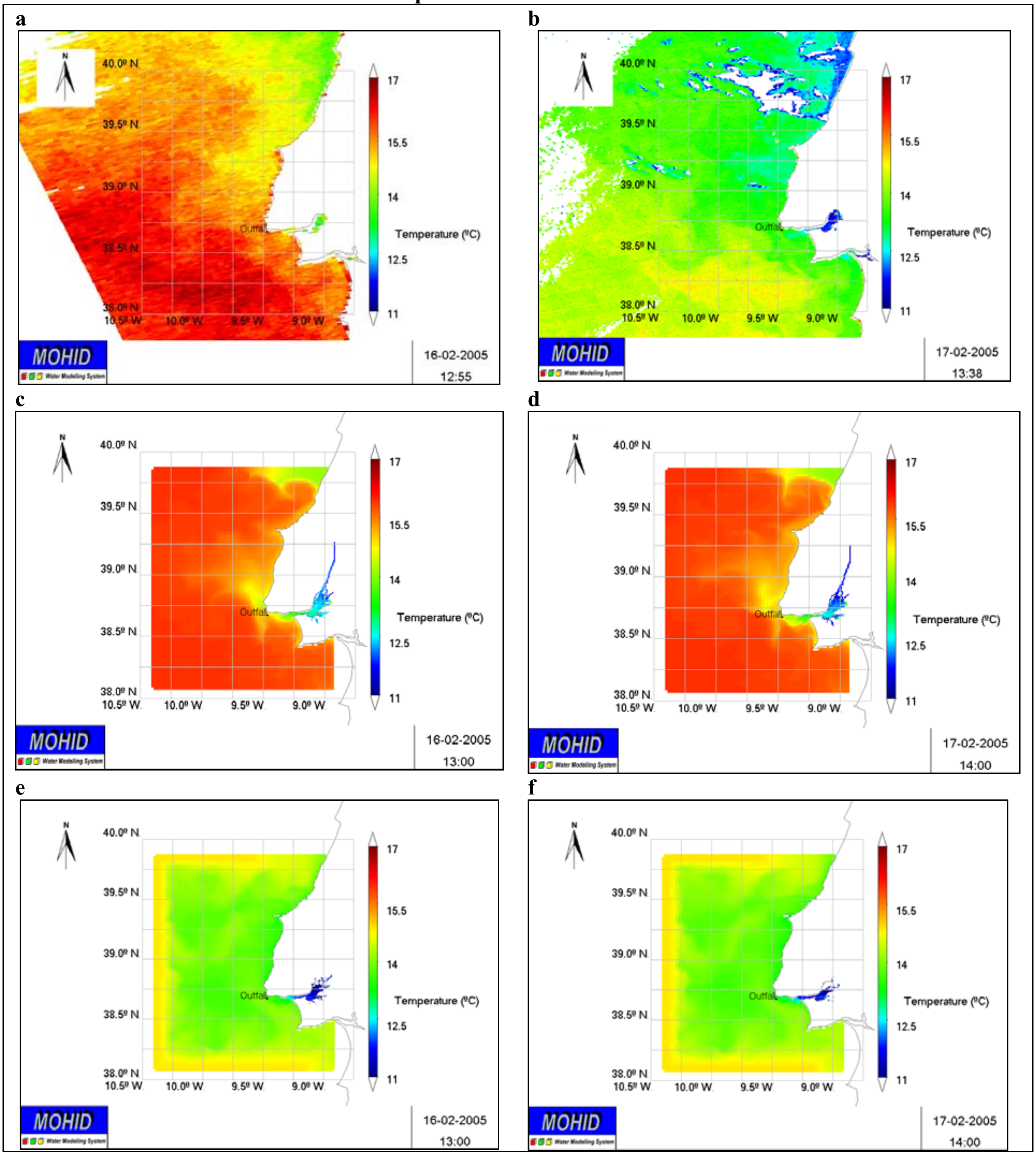
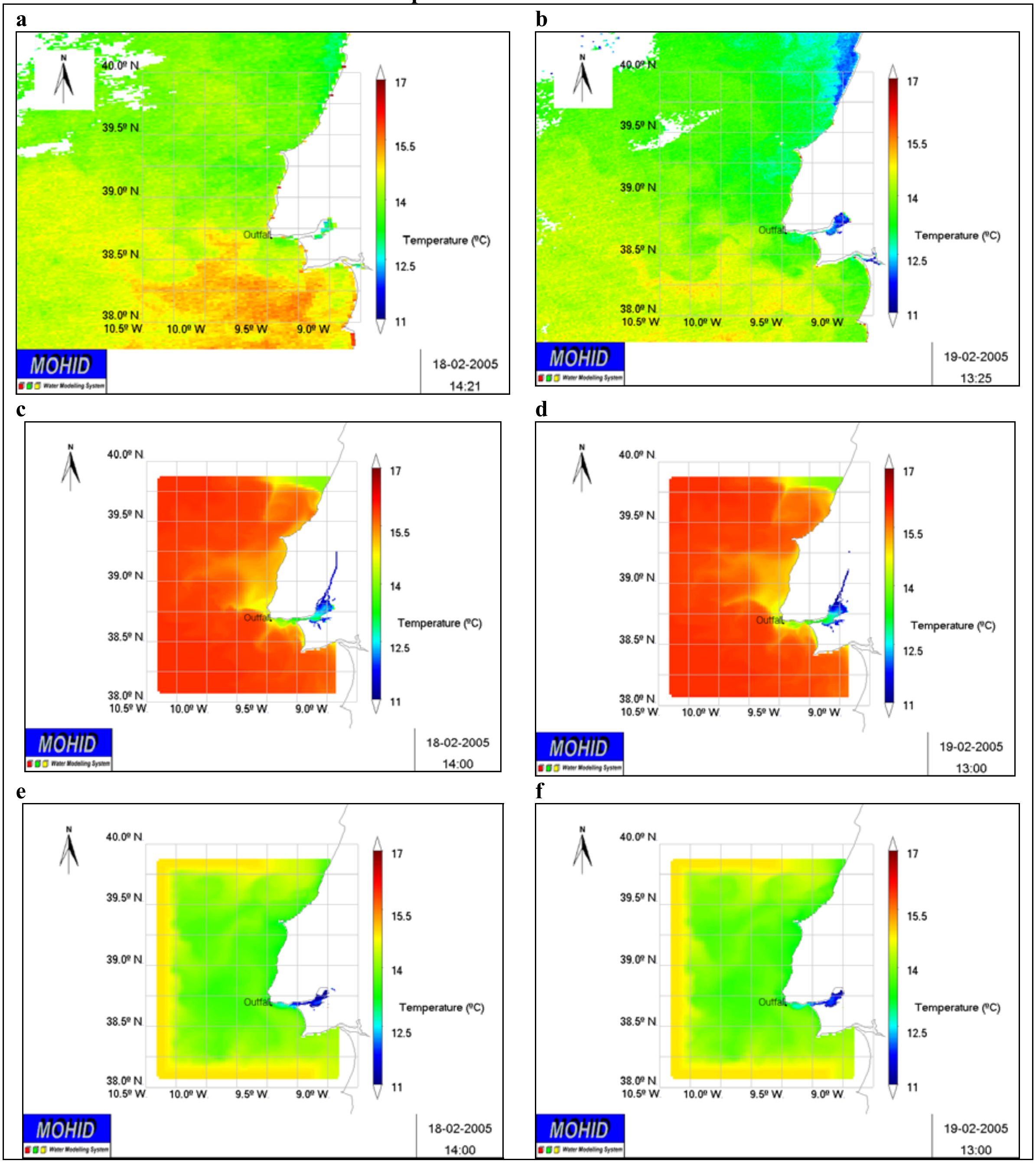
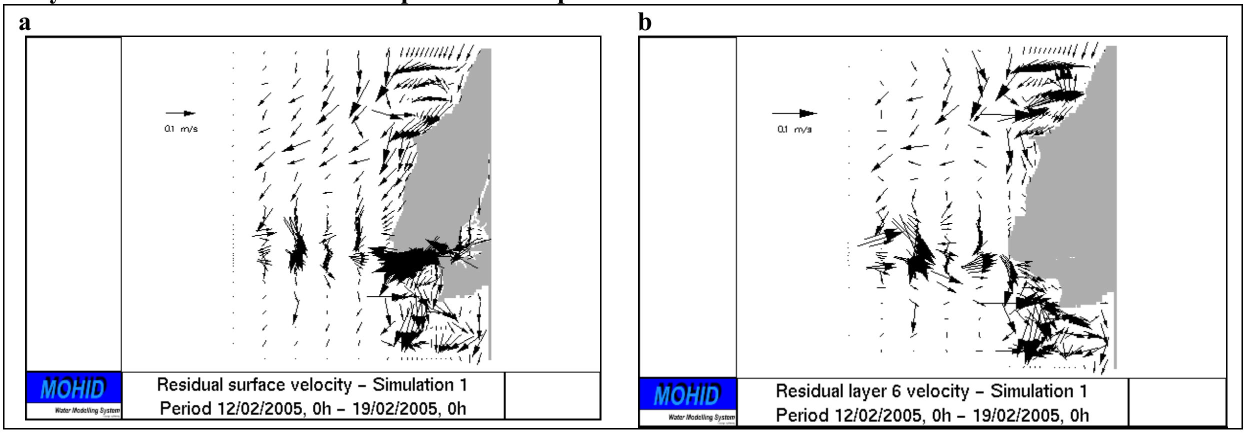


Figure IV-11: SST fields from MODIS (Level 2) satellite images (a, b) and existent (c, d) and alternative (e, f) 3D domain 2 MOHID Tagus Estuary simulation results for 18/02/2005 14h21 – 14h and 19/02/2005 13h25 – 13h. Model simulation results are presented for the nearest time instant.



The mass of colder water in the north boundary in the existent configuration is considered to be due to cooling from meteorological forcing as no other cooling mechanism exists in the model. This cooling happens only at this area apparently due to the velocity patterns originated from meteorological forcing. In Figure IV-12 are presented the residual horizontal velocities at surface and between 35 and 55m depths in the current configuration results of the three weeks which include the SST presented results. From these residual velocity fields is possible to observe that, both at surface and in depth, this is the only area of the domain to be continuously crossed by flow from boundary to other domain areas. Due to the null gradient boundary condition this causes possibly that the surface water temperature in this area in this configuration is very sensible to meteorological forcing.

Figure IV-12: Residual horizontal velocities for surface and layer 6 in existent 3D domain 2 MOHID Tagus Estuary configuration results calculated for period 12/02/2005 0h – 19/02/2005 0h, (a) and (b). Layer 6 of model extends from depth 35m to depth 55 m.



The wind shear stress interaction with stratified conditions seems also to justify the noticeable river plume exiting the estuary in the alternative configuration: this is expected to be colder water than the one in the coast as the temperature of the Tagus River discharge is approximately 12ºC and the surface temperature of climatology is 15ºC (see Appendix IV). This plume appears thus more visible than in the existent configuration results, where no stratification is assumed. It should be noted that the plume shape is very similar in both configurations (which is particularly evident in images for 17/02/2005 and 19/02/2005).

At the borders, north and south, of the Estremadura Promontory it is found in the alternative configuration results masses of water with temperature very similar to some areas of the Promontory-facing continental shelf. This pattern of spatial distribution of temperature is not visible, even in qualitative terms, in the MODIS images. Due to the internal waves presence in these locations in this model configuration this pattern seems to be the result of the internal waves induced mixing of the water column. The fact that it is not detectable in the MODIS images suggests that the climatology stratification may be unrealistic in these areas.

In what refers to time variability of SST, clearly presented in MODIS images, the performance of both model configurations is not adequate. This is more evident in the existent configuration due to the smaller spatial variability but even in the alternative configuration results this seems to be the case. In fact, the coastal areas with smaller SST in the alternative configuration results seem to be either too cold (in days 16/02/2005 and 18/02/2005) or too warm (in the other days) relative to the MODIS images since this spatial variability changes very little with time. However, it should be considered that the representation of time variability may be limited by the vertical resolution of the model (both configurations): since the surface layer of the model should have at least 1m deep due to the tidal motion, the SST provided by the model does not represents the surface conditions but instead the average in this water column of minimum 1m depth and maximum 4m depth according with the tidal range, appearing therefore quantitatively unadjusted with MODIS images time variability; this should be more noticeable in the alternative configuration than in the existent configuration due to the presence of climatology stratification.

While the existent configuration of the model apparently describes better the spatial distribution of SST in MODIS images of days 16/02/2005 and 18/02/2005 and the alternative configuration the other two days images, the discussion made in the previous paragraphs reveals that this representation should probably be only apparent and dependent of the initial and boundary conditions of thermal stratification. Accordingly, neither of the configurations can be considered robust in the representation of the real system SST variability.

Additionally, the constraint imposed by the newtonian relaxation to climatology in the alternative configuration domain boundary SST representation is evident, suggesting that larger decay times should be used. The results obtained without newtonian relaxation in the (north and south) boundaries of the continental shelf suggest that the strict null gradient boundary condition for temperature further offshore to adequately represent the spatial and time variability of SST. Since the climatology stratification in the boundary seems incorrect, at least near the surface, there is evidence that the some of the energy conveyed in the detected internal waves signal can be unrealistic.

Together these results suggest that the alternative 3D domain 2 MOHID Tagus Estuary configuration provides considerable improvements of the stratification representation in the Guia wastewater outfall area, an area where MOHID Tagus Estuary stratification forecast is very important. This improvement seems particularly connected to the use of the initial stratification condition and the spatially variable wind forcing but could also due in a smaller extent to the improved advection scheme. However, these results suggest that a considerable variability error still exists and that it is connected with the lack of variability associated to the use of climatology to provide the stratification, especially near the estuary mouth, and the representation deficiencies of the meteorological forcing. Apart from the Guia wastewater outfall area, the thermal climatology stratification seems to be inadequate near surface, particularly at the continental shelf and in the domain boundaries, and cause a lack of temperature time variability reproduction in the model. There is also evidence that the vertical resolution of model grid can limit the reproduction of this variability. Nevertheless, these results obtained provide support for the research Hypothesis 3 in the Tagus Estuary mouth area.