Modelling the effects of thermal plumes on the coastal area. The case of Sines power plant, Portugal.

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Abstract

The thermoelectric power plant established at the Sines complex, in the Portuguese west coast, intakes a yearly average of 40 m^3/s of ocean water, due to cooling requirements for electricity production. This cooling water is discharged on its original environment, the Atlantic Ocean, creating a thermal plume that mixes and disperses according to the existing environmental conditions. The environmental license states that, within a distance of 30 meters, the temperature increase must not be greater than 3ºC.

The present work aims at studying, through mathematical modeling, the hydrodynamics of the thermal plume during different hydrodynamic conditions. The most relevant factors for mixing are identified and the conformity with the legal limits is analyzed. The modelling efforts were conducted using a downscaling methodology for configuring the MOHID numerical model.

The results show that the main effect of discharging the effluent on ocean waters is a thermal stratification, being mostly defined by dominant wind conditions. None of the simulated scenarios have shown compliance with legal limits, as temperatures were always above the 3ºC clearance relative to the natural environment.

Key words: Coastal Hydrodynamic; Thermal plume; Numerical modelling, MOHID

Introduction

Thermal power plants require significant amounts of water for cooling purposes (Langford 1990). If the power plant is located near a water source, the cooling process can be performed by flowing water through a condenser system and discharging it back to the original environment, with an increase in temperature relatively to the intake.

Thermal effluent discharges creates a thermal plume whose mix and dispersion depend on the effluent characteristics, discharge conditions and the nature of the receiving environment (Environment Canada 2014).The effluent characteristics that mostly influence initial mix and dispersion are density and velocity, when compared to those of the receiving waters. Effluent density, which is related with temperature, influences the rate of rise and position of the plume in water column. Velocity determines the intensity of shear stresses and mixing that occurs when the effluent is discharged. The discharge configuration determines if thermal effluent spreads as a layer or a jet. The first situation occurs when the discharges is done through channel and the second occurs when the discharge is done through submersed pipes (Subtil 2012). If the receiving environment is a coastal area, the main factors that affects the plume dispersion are wind, tides, water column stratification and bathymetry.

The divergence between effluent and source water properties can dangerously affect the marine environment (Agarwal 2005). Understanding the phenomena involved in the dispersion and mixing processes is vital when trying to understand the role of the effluent in the marine environment and numerical modelling provides a useful platform for such purpose.

The present work aimed at studying, through mathematical modeling, the hydrodynamics of the thermal plume streaming from the power plant at Sines during different atmospheric and tidal conditions. By employing a reference scenario without the referred discharge, the main effects of the discharge on the natural hydrodynamics and thermal structure were quantified. The most relevant factors for mixing were identified and the conformity with the legal limits is analyzed.

Case study

The thermal power plant produces electricity and is located in Sines, on the west Portuguese coast, next to São Torpes beach, as shown in Figure 1. On yearly average, 40 m^3/s of cooling water go through the intake structure (Direcção de Produção Térmica da EDP 2012) and, after flowing through a condenser system inside the power plant, are discharged back to the ocean through two open channels. The discharge structure is located 400 m to the south of the water intake. The environmental license in use for the operation of the power plant imposes that, within a distance of 30 meters downstream of the discharge, the temperature increase must not be greater than 3ºC (Agência Portuguesa do Ambiente 2009).

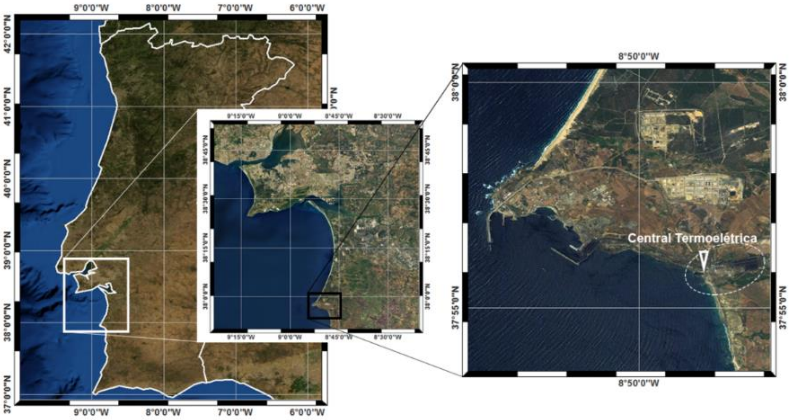


Figure 1: Location of Sines thermal power plant.

The region is defined by a moderate climate. The winter season has lower temperatures and higher precipitation levels, as opposed to the dry and warm summer season.

The temperature of the receiving environment depends on the air temperature and so the summer temperature is generally greater that in winter. However, the environment temperature also depends on wind conditions due to the upwelling phenomena. During a typical year, 80% of wind observations feature north winds. The resulting upwelling causes the cooler water from deeper layers to rise to the surface, causing lower temperatures during the summer season

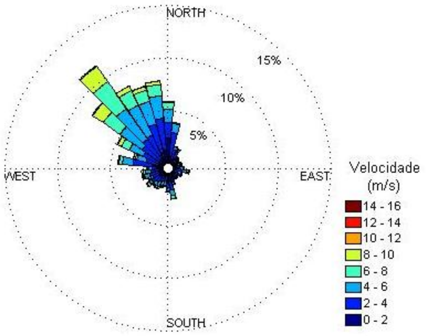


Figure 2 Wind direction and intensity for the time period between 2008 and 2013, recorded on Montes Chaos Sines synoptic station. Adapted from Citizen Weather Observer Program (2014).

Material and methods

The numerical model used in this study is the MOHID model (www.mohid.com). MOHID is a water modelling system developed at the Marine Environment Technology Center (MARETEC) at Instituto Superior Técnico (IST). MOHID solves the equations of advection–diffusion for temperature, salinity and horizontal momentum. It also solves the equation of continuity to determine the vertical velocity and the water elevation. The density is solved with the UNESCO state equation as a function of salinity, temperature and pressure (MARETEC 2014). This numerical model uses a finite volume approach to discretize the equations. In this approach, the discrete form of the governing equations is applied macroscopically to a cell control volume, which allows the use of a generic vertical coordinate (Martins et al. 2001).

For this study, the numerical model was implemented using a downscaling methodology. This method is used to interpolate boundary conditions to local models, with greater resolution, from regional models, with lower resolution (Ascione et al. 2014).

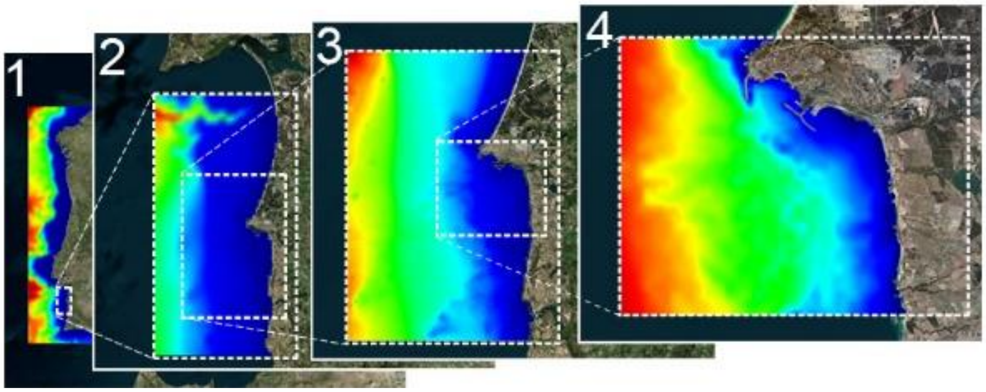


Figure 3 Model configuration.

In the present work, the model was configured using four nested grids, as shown in Figure 3. The outer grid is an acquisition window, pushing data from the PCOMS operational model (Operational Model for the Portuguese Coast) described by Mateus et al.(2012).PCOMS provides data regarding tide levels, velocity fields, density, temperature and salinity for the whole Portuguese coast. The first level has a spatial resolution of 6000 m, the second and third levels have 1200 m and 240 m, respectively, and the fourth and most refined level is discretized using a 50 meters grid. The intake and discharge structures are modelled on the fourth level, as well as the nearby port of Sines. For the water intake, a constant flow of 40 m^3/s is considered and modelled using a simple sink. The discharge is modelled differently, using a simple source of 30 m^3/s, for the downstream section of the open channels, and two linear discharges totaling 5 m^3/s each, simulating the crosswise flow that percolates through the breakwaters.

Results

Validation

Temperature data acquired during in situ monitoring campaigns and, disclosed by the power plant executive board, supported the validation of higher resolution domain, where the thermal effluent discharge is simulated. The temperature monitoring was conducted directly, by sampling the water column, in the vicinity of the discharge and in a reference area, away from the thermal plume. Figure

4 displays the temperature profiles obtained through monitoring actions on the 4th September 2012, as well as the results provided by the numerical model for the same area and time.

The Figure 4 shows that the numerical model can accurately recreate the monitored temperature along the water column. For both locations, a Pearson correlation coefficient of 0.97 was obtained, suggesting that the model exhibits a positive linear variation relative to field data. By computing the RMSE (Root Mean Square Error) one can infer that the model overestimates the temperature, in the discharge vicinity, by +1ºC and underestimates the temperature of the reference area by -0.4ºC. The wider difference between modeled and observed data may be related with some of the assumptions made for the discharge, namely the usage of a constant yearly average value, which does not specify any possible fluctuations for this particular period.

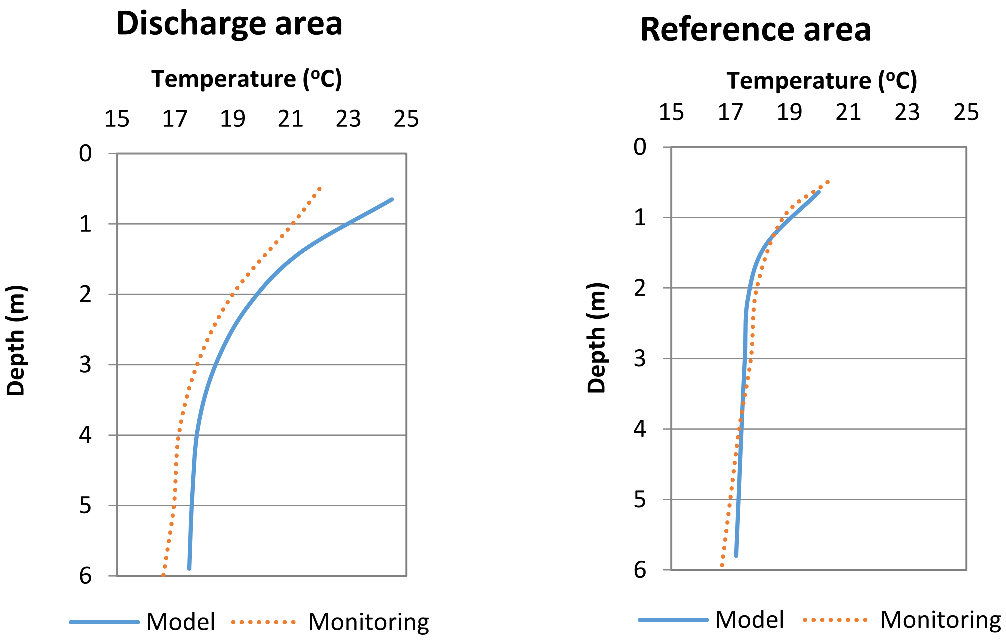


Figure 4 Model Validation on discharge area (on left) and on a reference area (on right).

Thermal plume dynamics

A reference scenario without the effluent discharge, similar in every other way to the remaining scenarios, was used in order to acknowledge the effects of the discharge of the cooling water in the receiving environment. The two most representative scenarios are presented, namely the months of August and October 2013 featuring dominant North and South winds, respectively. The determining factors for the mixing and dispersion of the thermal plumes are also characterized.

The results obtained with North wind scenario are presented in Figure 5, showing slight differences in the hydrodynamics near the power plant if the discharge is present, where an increase of 0.1 m/s in the vicinity of the discharge is noticeable. Surface temperature distribution exhibits a thermal plume (line b), with a temperature increase of approximately 8ºC relative to the baseline simulation, in the vicinity of the discharge.

This increase in temperature leads to a thermal stratification, noticeable in the C line of Figure 5. In the baseline, a well-mixed water column is visible with colder waters flowing upward, as opposed to the discharge simulations where an increase in temperature is visible over the whole water column. Further downstream the mixture of the effluent is less evident, with a temperature decrease and warmer water flowing towards the surface.

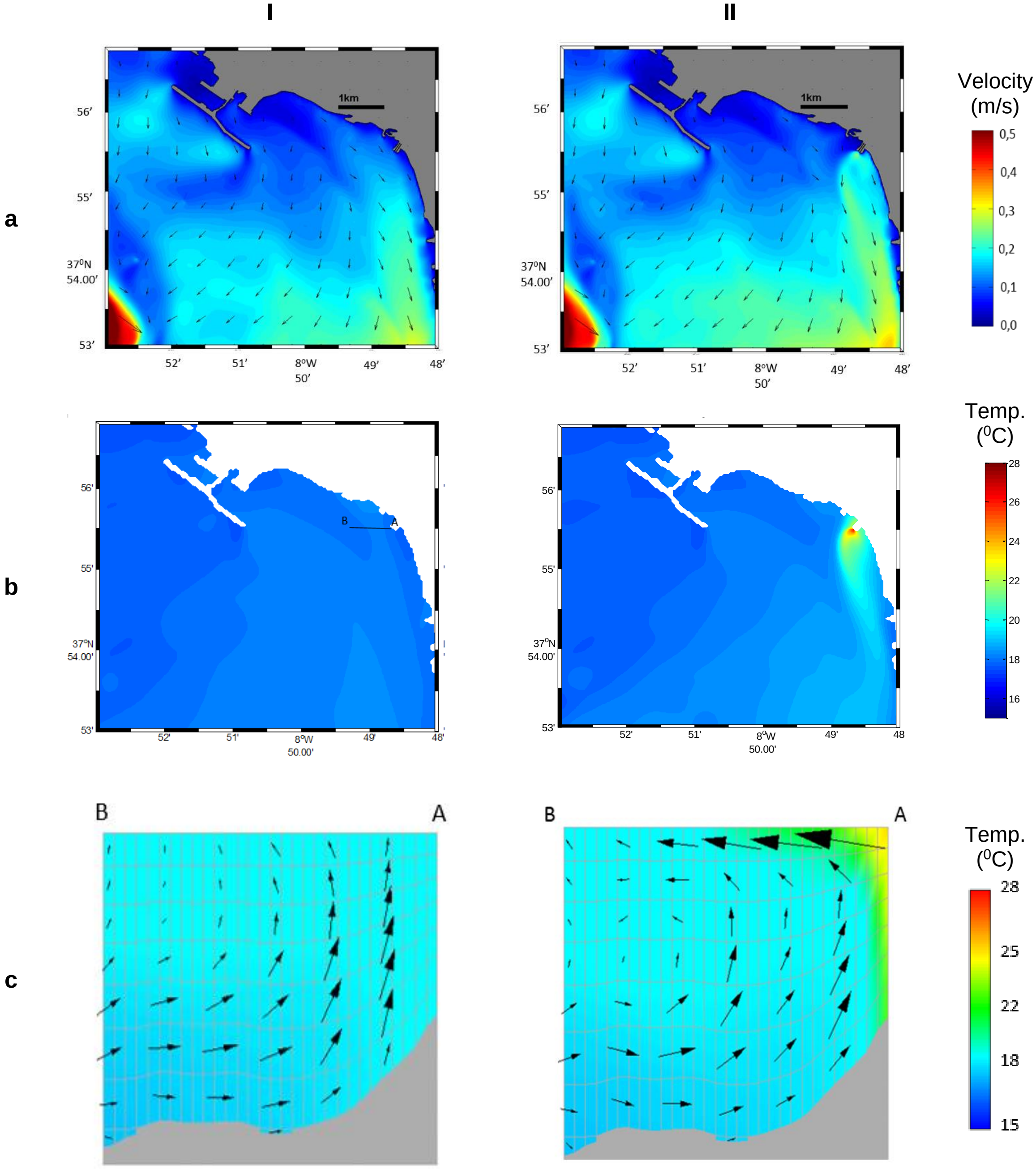
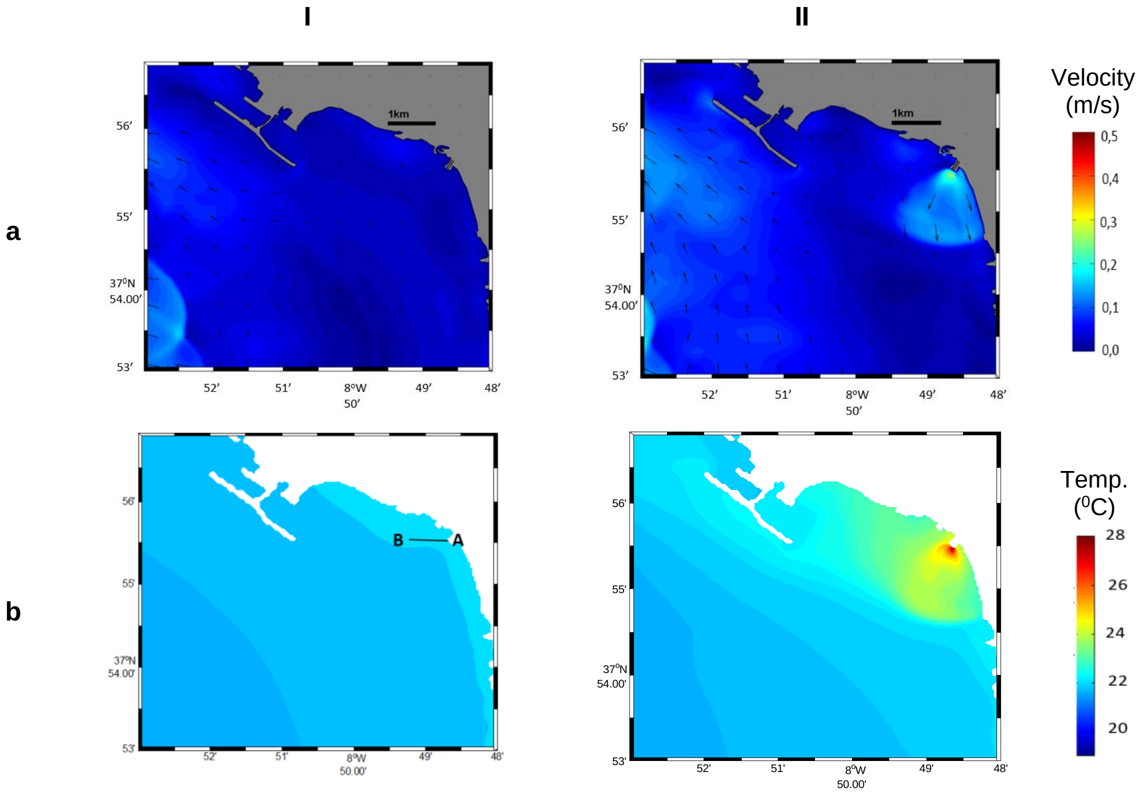


Figure 5 Results for north wind scenario.

Figure 6 depicts the obtained results for a South wind scenario, namely October 2013. Again, a baseline scenario is shown as a reference for the simulation featuring the discharge.

Figure 6 evidences that, similarly to the previous simulation, the discharge induces a velocity increase of roughly 0.1 m/s in the discharge vicinity.

This scenario also shows a thermal plume forming on the sea surface. However, when one compares the surface temperature distribution in South wind conditions (Figure 6, Column II, Line B) with those in North wind conditions (Figure 5, Column II, Line B), it becomes noticeable that the later situation forms a heavier mixed and elongated thermal plume. Higher temperatures spread along wider areas under South wind dominance due to several factors. In a South wind scenario the thermal plume is pushed northward, where the intake structure is located. This way, the water used in the cooling process is continuously drawn at increasing temperatures and, consequently, so is the discharged effluent. The coastal configuration also contributes to this continuous heating effect, since the water flow is conditioned by the coastal morphology.



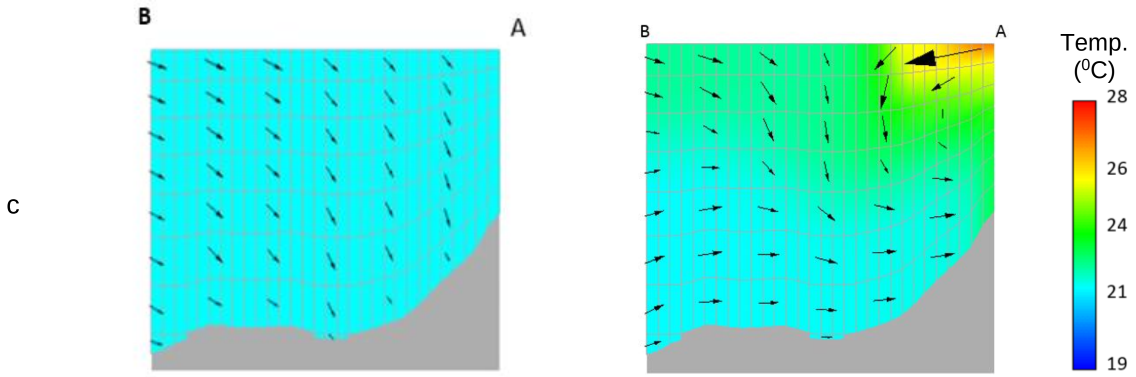


Figure 6 Results for south wind scenario.

As for the vertical thermal structure, the effluent discharge during North wind conditions induces a greater initial mixing, when compared to the south wind scenario. This could be explained by the fact that wind intensity is greater in a north wind situation and also leads to upwelling. In both scenarios the thermal plume develops along the direction of the dominant wind incidence.

The worst case scenario, regarding the thermal plume extents, is the South condition. This carries major efficiency losses for the operation of the power plant, as the water from the intake is constantly warming. On the other hand, south incidence is relatively rare as shown is Figure 2.

The tide is also a major factor in the near-field mixing of the thermal plume. Figure 7 displays the time series for temperature and water level in the vicinity of the discharge.

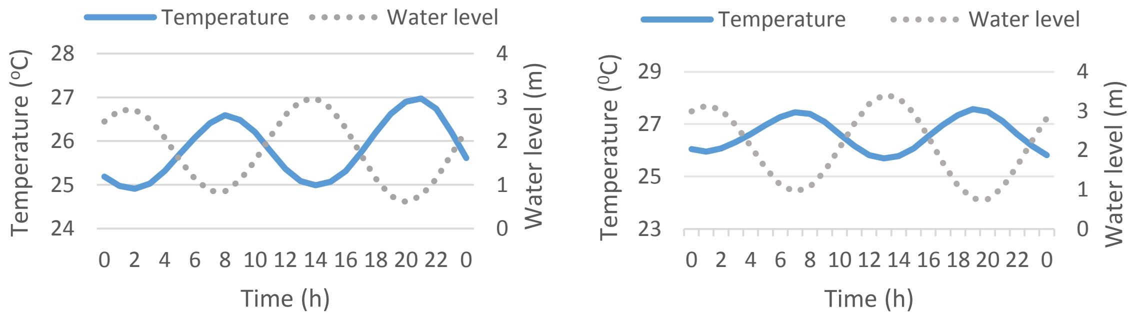


Figure 7 Tidal influence on temperature discharge, on North wind scenario (left) and on South wind scenario (right).

There is a direct influence of the tide on sea surface temperature, with oscillations of roughly 2ºC as the tide rises or falls. A higher tide provides a greater water mass for diluting the effluent, which is why the temperature and the tide exhibit an antiphase behavior.

Legal mandatory limits

To assess the compliance with the limits imposed in the environmental license, the temperature time series obtained 50 meters downstream of the discharge are compared with those of a reference area which was not under the influence of the thermal plume. The results are presented in Figure 8. The distance of 50m corresponds to the next cell downstream of the discharge. The Tref+3^{0}C parameter is the reference temperature offset by +3ºC, representing the instantaneous legal mandatory limit.

The results have shown that in all scenarios, simulated by the model, the legal clearance limit is exceeded. These figures show that over the discharge area the temperatures exceed the legal clearance by 1 to 5ºC, depending if the tide is high or low, respectively. At 50m downstream this difference is damped to an average of 2ºC.

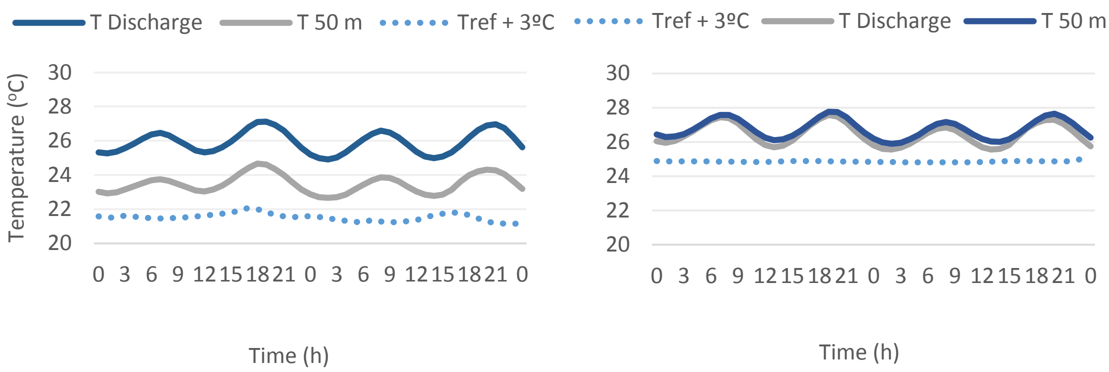


Figure 8 Legal mandatory limits, on North wind scenario (left) and on South wind scenario (right).

Conclusions

The simulations performed with the MOHID numerical model enabled a good understanding of the effects caused by the thermal effluent discharge on the coastal environment, namely what factors are determinant for the mixing and dispersion processes. Considering all the possibilities that would otherwise be unfeasible, such as the establishment of a baseline, numerical modeling was evidenced as a valuable tool for environmental management.

The main effects of the discharge of the cooling water is the formation of a thermal plume and consequent vertical stratification of the temperature. The hydrodynamic field is also slightly affected due to the momentum imparted to ocean waters from the discharge.

Wind was identified as the main drive force for the behavior of the thermal plume. It defines the surface currents that carried these thermal plumes, with a well-mixed, elongated and south developing plume during north wind dominance, as opposed to a more constrained and wider plume during south wind conditions. The tide also influences the mixing process, particularly in the near-field, mainly due to the significant variations of water mass available for initial dilution. Temperature and tide level exhibit an anti-phase variation over time.

The compliance with the legal mandatory limits established in the environmental license for the operation of the Sines thermal power plant was not observed in any of the simulated scenarios.

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