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VALIDATION OF OPERATIONAL OCEAN CIRCULATION FORECAST MODELS OF THE AEGEAN SEA

by

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As the nominated University supervisor of this M.Sc. project by Panourgias Siderakos, I confirm that I have had the opportunity to comment on earlier drafts of the report prior to submission of the dissertation for consideration of the award of M.Sc. Oceanography.

Signed:

Supervisor's name: Nikolaos Skliris

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ABSTRACT

From the ancient years till present, the Aegean Sea has always been a sea with major importance. From famous ancient ship battles to modern trading, it always played an essential role for the whole world. Nowadays, all the above combined with its unique oceanographic conditions and topography, the Aegean Sea has become the field of development for two operational, ocean circulation forecast models, the ALERMO model and the POSEIDON model. In this project, an effort for the validation of both models was originally targeted. However, due to lack of data from the POSEIDON model, the validation was performed only for the ALERMO model. Two months were initially chosen, one in winter and one in summer in order to compare their errors based on the different season. As a result, every forecast of the model was being examined in both resolutions of the model (1/30 □ and 1/60□) fo both months. Detailed figures of the forecasts are given, in both months and both resolutions in order for the reader to understand the differences that the model demonstrates in relation to the season. In addition, the Root Mean Square Error is calculated and given for each different case. Finally, from in-situ CTD measurements that took place in the Aegean Sea during 2014 and 2016 from an oceanographic ship of the Greek Navy, vertical temperature and salinity profiles were made in relation to depth in order to see the performance of the model in the water column generally. The most important conclusion of this research project is that the model performs very well with specific defects. Each season has its own defects and the model has permanent errors in specific areas in the Aegean. These areas are the mouth of the Dardanelles Strait and the waters adjacent to the coastline of Greece's mainland. A significant part of these errors happen probably because of the fact that ALERMO is one-way nested to a larger model that covers the whole Mediterranean Sea and has quite low resolution (1/16 □). Neverthele development of the model is continuous and the improvements are visible both in its function and its errors. A research with salinity data would be very useful and interesting in the future, as today the daily and monthly data for this region are very poor.

1. Introduction

1.1 General introduction

The Aegean Sea. The sea in which, according to the Greek mythology, the mythical king of Athens, Aegeus drowned himself after falsely believing that his beloved son, Theseus, died in war. After that accident, the ancient Athenians named this sea with his name in order to honor him.

In scientific terms, the Aegean Sea is the northeastern part of the Mediterranean Sea. A semi-enclosed sea surrounded by the Greek (from the west and north) and the Turkish (from the east) mainland. In the northeast, it is connected to the Marmara Sea and the Black Sea through the Dardanelles and the Bosphorus Strait. The area that it covers is approximately 240,000 square kilometers. It includes approximately 3,000 islands, islets and rocks in its waters, of which only around 200 are inhabited. An exact definition with specific coordinates of its boundaries is given by the International Hydrographic Organization (IHO, 1953). Moreover, the Aegean constitutes of three major basins: the North Aegean one, the Chios basin and the Cretan basin. The first one has maximum depths of 1,500 m, the second one 1,100 m and the last one, which is the deepest one, depths of 2,500 m. All these three basins communicate between them with channels of depth lower than 400 m (Georgiou et al., 2014). However, the exchange fluxes between these basins are not well known, especially at the intermediate and deep layers (Zervakis et al., 2003).

From the ancient times, the Aegean Sea has always been a sea with major importance, not only for the Greeks but for the whole world. Its geographical position stands as a crossroad between 3 continents, Europe, Africa and Asia. Throughout its waters, trade and communication between different civilizations has flourished during history. Moreover, the Aegean Sea has been in the past the site for naval battles that changed the fate and future of the whole world. It was in the Aegean Sea, in the island of Salamis where the Greeks conducted the famous naval battle of Salamis where they managed to repel the Persians that tried to conquer Greece. Modern historians support the view that if the Persians had won that battle, the development of ancient Greece would have been destroyed and seriously affected the evolution of the whole world.

Nowadays, the sea still remains the number one trading route globally, as the cost effectiveness through the sea cannot be beaten by any other modern way of transportation (Pinardi et al., 2002). The Aegean Sea is also widely accepted as one of the most beautiful sceneries in the world, with islands of incomparable beauty. In addition, in the last decades, motivated by recent research studies performed in the waters of the Aegean Sea, a more intensive interest from many important companies around the world has arisen because of the huge, potential deposits of oil and natural gas in the sea floor.

However, the most important is the fact that the Aegean Sea is a sea with very interesting oceanographic conditions. The amount of fresh water input from the northern part of the basin, by rivers and especially by the Black Sea Water outflow of considerably lower salinity, is massive and ranges between 5.000 and 15.000 m^3/sec according to Kourafalou et al., 2003. The Aegean Sea displays prominent hydrodynamic features involving all time/space scales such as strong baroclinic and topography-induced currents, mesoscale eddies, upwelling regions and frontal zones. Very important ocean processes have been observed throughout years of research and observation, such as the Eastern Mediterranean Transient (EMT) which is actually a transition of the major deep water formation site in the Eastern Mediterranean from the Adriatic Sea to the Aegean Sea (Amitai et al., 2016). More specifically, Adriatic Sea was always considered to be the main source of deep water (Nielsen, 1912; Wüst, 1961) with the Aegean Sea being only a sporadic source (Roether et al., 1991). Surprisingly, more recent studies proved that the Aegean Sea is a new and much stronger source of deep water (Roether et al., 1996), a fact that triggered multiple studies and gave possible scientific explanations (Lascaratos et al., 1999; Malanotte-Rizzoli et al., 1999; Theocharis et al., 2002; Josey, 2003).All the above are the reasons why for many years now, specific scientific groups have established, created and continuously been developing for the last decades, operational forecasting models of ocean circulation in the Greek Seas, the Ionian Sea, the Aegean Sea and the Sea of Levantine as well. Their true and honest ambition, and literally an everyday fact, is to predict main characteristics of the sea's circulation in order to monitor and predict oceanographic and climatological conditions that affect the general climate change that is being observed. All the above also have a huge impact on all aspects of life in the modern societies that inhabit the whole area of interest, for example severe storms, sea level rise and thermohaline circulation modification. Scientists are now in a position that can collect huge amounts of data provided by the models and assess the circulation and other dynamic processes as well as variability and trends (e.g. decadal, annual, seasonal).This is the reason why forecasting the ocean state in short, medium and long time scales is now well-timed more than ever (National Research Council, 2009).

Moreover, these models also help ordinary people. People from plain fishermen that wish for a descent fishery, professional mariners that demand a safe navigation in the wider area of the Eastern Mediterranean, to the navies of different countries that operate in these waters (e.g. with submarines) and try to detect the effect of the ocean circulation in their combat operations.

1.2 Objectives

In Greece, at this time as this project is being conducted, there are only two operational forecast systems that give forecasts for the ocean circulation. The first, in alphabetical order, is the ALERMO model. This model is being operated by the National and Kapodistrian University of Athens, in the center of Athens, and more specifically from the Division of Environmental Physics (Ocean Physics and Modelling Group). The second is the POSEIDON operational forecast system. A forecast model that is being operated by the Hellenic Center for Marine Research (HCMR) in Anavyssos, a coastal city of east Attiki. The main purpose of this project is to assess the performance of these two models. In particular assess the role of the models' spatial resolution and come to conclusions that will help the reader to understand their functionality, their technical evolution during the years, if there is any, and the existence of possible errors and deficiencies.

The methods of this validation will be described in full detail along with the datasets that were being used and also the models and their functionality. The author, despite the fact that significant difficulties that could not be overpassed came up, made efforts for the validation to be as more objective as possible, using independent datasets and completely unrelated to each other for unbiased results and conclusions.

2. Model description

The initial aim and desire of the author was to manage and validate both of the existing models that operate in Greece, ALERMO and POSEIDON. Unfortunately, after several efforts from the author to communicate and gain access to the forecasting data of the POSEIDON model, the official reply from the HCMR (through email) was that there are no forecasting data available from previous years. Automatically, this means that the analysis and further validation will be focused only on the ALERMO model. There will be no further reference or report to the POSEIDON model from now and on in this project.

As mentioned in the introduction, ALERMO is an operational ocean forecasting system operated by the University of Athens, from the Ocean Physics And Modelling (OPAM) group. ALERMO is the acronym for the Aegean and Levantine Eddy Resolving MOdel (Korres et al., 2003). In general, ALERMO provides ocean circulation forecast in the Eastern Mediterranean in high resolution. In addition, nested within the ALERMO and coupled with an oil-spill monitoring/forecasting application, runs another model of higher resolution for the North Aegean area only. ALERMO as a whole runs as a part of the Mediterranean Oceanography Network for the Global Ocean Observing System (MONGOOS). Although it is not in the area of interest of this project and won’t be analyzed, in order to highlight the importance of this model, it must be said that the model also gives plenty of other information. Firstly, it gives the opportunity to the user to gain access to a 60-hour wave forecast with a system called TRITON which includes a series of wave models with increasing resolution and goes from global scales to regional down to coastal, focusing on the Greek seas. Furthermore, another system is being operated named DIAVLOS which is an oil-spill forecasting system. This system is targeting the area around the terminal of the Bourgas-Alexandroupoli (North Aegean Sea only) oil pipe in case of an oil-spill accident. A very useful interactive forecasting tool including ocean circulation, wave and wind field predictions (http://www.oc.phys.uoa.gr).

More specifically, the ALERMO model consists of a high-resolution implementation of the Princeton Ocean Model-POM (Blumberg et al., 1987). It was developed within the framework of the Mediterranean Forecasting System Pilot Project – MFSPP (Pinardi et al., 2003). In MFSPP the ALERMO model had a 1/20º of horizontal resolution and it was one-way nested with a 1/8º$\times$1/8º global Mediterranean OGCM model (MOM). An upgraded version of the ALERMO model with a 1/30º of horizontal resolution was developed within the framework of MFSTEP (Mediterranean Forecasting System - Towards Environmental Predictions) and is recently upgraded to 1/50º horizontal resolution and assimilation of oceanic data in the framework of the ECOOP project. ALERMO is one-way nested to a global Mediterranean OGCM (MOM, $1/16^o \times 1/16^o$) running operationally on a daily basis. The system provides daily a 5-days forecast of the ocean characteristics and circulation in the Eastern Mediterranean. Furthermore, the forecasting system (1/50º) is validated daily with Sea Surface Temperatures from satellite data. The model for the North Aegean gives a 4-days forecast as it is nested in the bigger model. The one day difference between them stands because the bigger model needs to run for one day in order to give the smaller one the initial and boundary conditions to give the new forecast for the North Aegean.

Below, specific characteristics of the model are given concerning its functionality:

- Geographical area covered: $20^oE – 36.4^oE$ & $30.7^oN – 41.2^oN$
- Horizontal resolution: $1/30^o \times 1/30^o$, 1/50º× 1/50º, 1/60º×1/60º
- Vertical resolution: 25 sigma levels logarithmically distributed
- Advection of tracers: Smolarkiewicz upstream scheme with anti-diffusive velocities
- Open boundary conditions: One-way nesting with the $1/16^o \times 1/16^o$ MFSTEP Mediterranean OGCM model running operationally. The nesting scheme has been developed within MFSPP and is based on:

1) Flathers (1975) open boundary conditions for nesting of the barotropic velocities normal to the open boundaries

2) Volume conservation at the open boundaries

3) Direct specification of baroclinic velocities, free surface elevation and tangential barotropic velocities

4) Direct specification of tracers (T/S) in case of inflow and upstream advection in the case of outflow

- Dardanelles inflow/outflow: The present version of the model treats the Dardanelles as open boundary where the net volume inflow into the Aegean Sea, the interface depth and the salinity of the inflowing waters are specified. This vital change was initially motivated by the fact that the old way of parameterization was underestimating the freshwater input of the Black Sea into the Aegean.
- Atmospheric coupling: The model of ALERMO is operating in a one-way coupling with the SKIRON model. The SKIRON is a weather forecasting system that provides:
  1) Wind velocity at 10m above the sea surface
  2) Atmospheric pressure at sea level
  3) Precipitation rate
  4) Air temperature and relative humidity at 2m above the sea surface
  5) Net shortwave radiation at the sea surface
  6) Downward longwave radiation

Momentum fluxes, evaporative, upward longwave radiation and sensible heat fluxes are calculated through bulk formulae using the SST predicted by the ALERMO model (Kallos et al., 1997).Furthermore, the upgraded version of the ALERMO model provides the atmospheric pressure loading and optional inclusion of tidal forcing.

- Surface freshwater flux: Real freshwater flux instead of (virtual) salt flux is used for the sea surface boundary conditions.
- Variational Initialization: The ALERMO model is initialized from the MFSTEP OGCM on a weekly basis (operationally during the TOP

period) using the Variational Initialization (VI) method (Auclair et al. 2000).

– Data assimilation: An optimal interpolation scheme (O.I. MARK-II) will be implemented in the near future.

In figures 1(a), (b) and (c) a typical, daily, ocean circulation forecast from the model is being shown. The figures were chosen in a way to make the reader understand how many characteristics in different depths the model can predict. Figure 1 (c) is the daily validation that the model is performing for its own functionality, giving the RMSE for the SST for each forecast of the day.

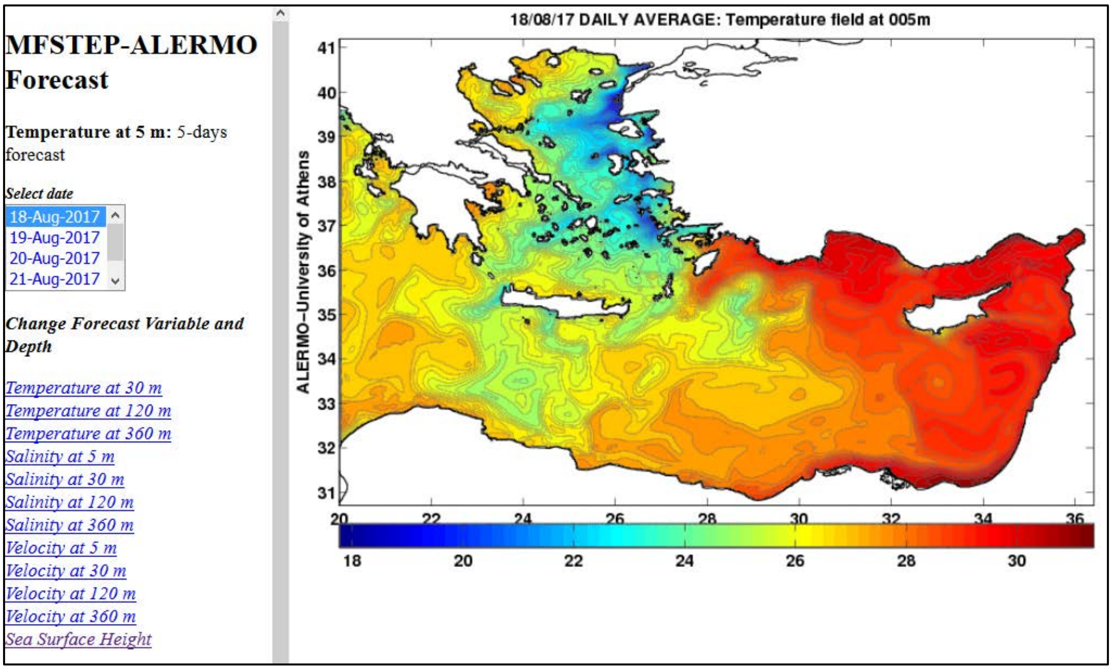


Figure 1(a): Sea Surface Temperature at 5m depth in the 1/30º resolution – 18th of August 2017 - 1st day of the 5-days forecast

(Ocean Physics and Modelling Group – University of Athens website)

The difference between the resolutions is obvious as figure 1 (c) shows the highest resolution of the model (1/60º), performing high details and aspects of the North Aegean Sea. In all resolutions, the model does not give data for the Black Sea. This is the reason why from the entrance of the Dardanelles and northeast, the color of the sea is white as the land.

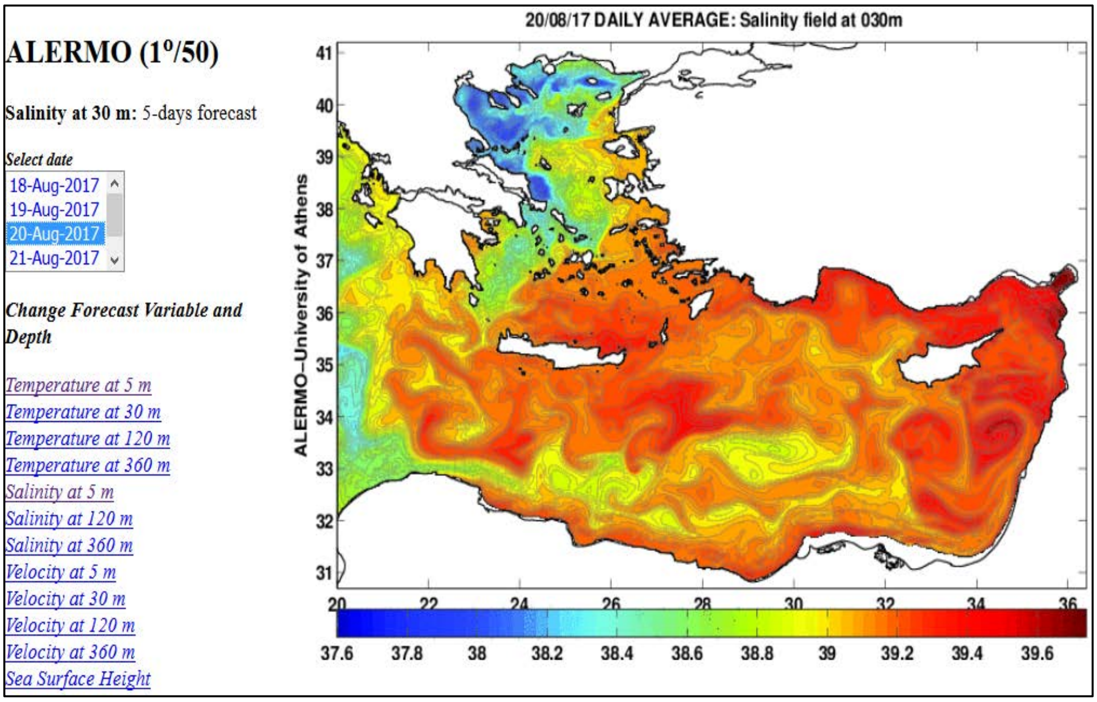


Figure 1(b): Salinity at 30m depth (1/50º resolution) –

20th of August – 3rd day of the 5-days forecast

(Ocean Physics and Modelling Group – University of Athens website)

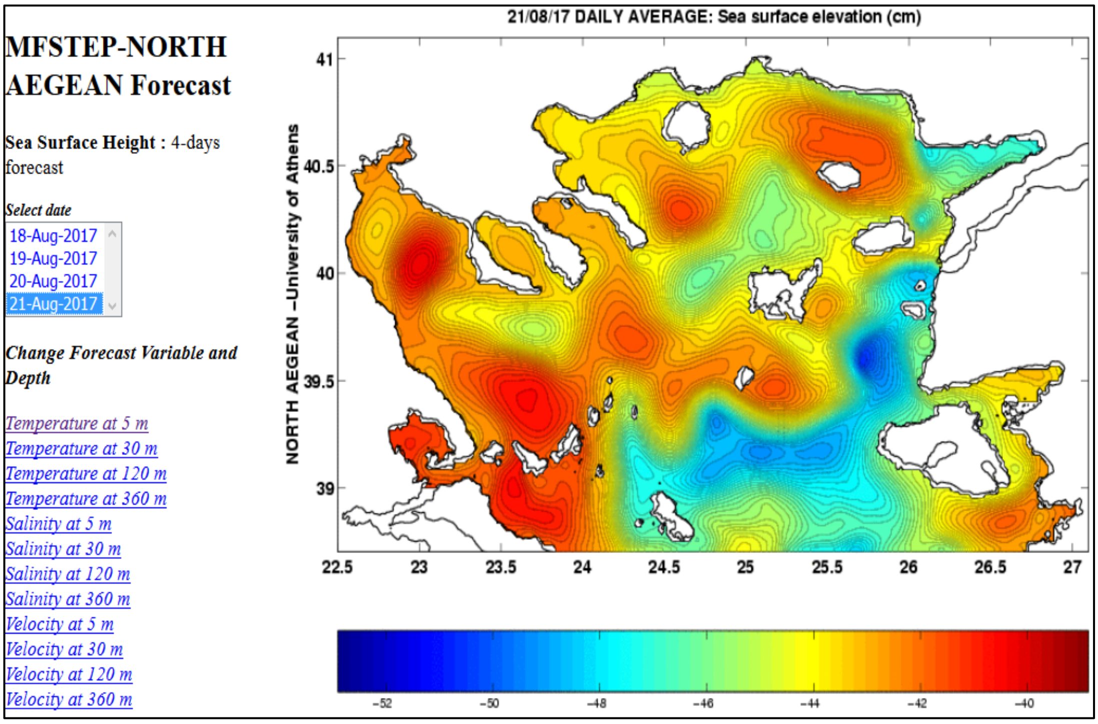


Figure 1(c): Sea Surface Elevation (1/60º resolution) – North Aegean –

21th of August-4th day of the 4-days forecast

(Ocean Physics and Modelling Group – University of Athens website)

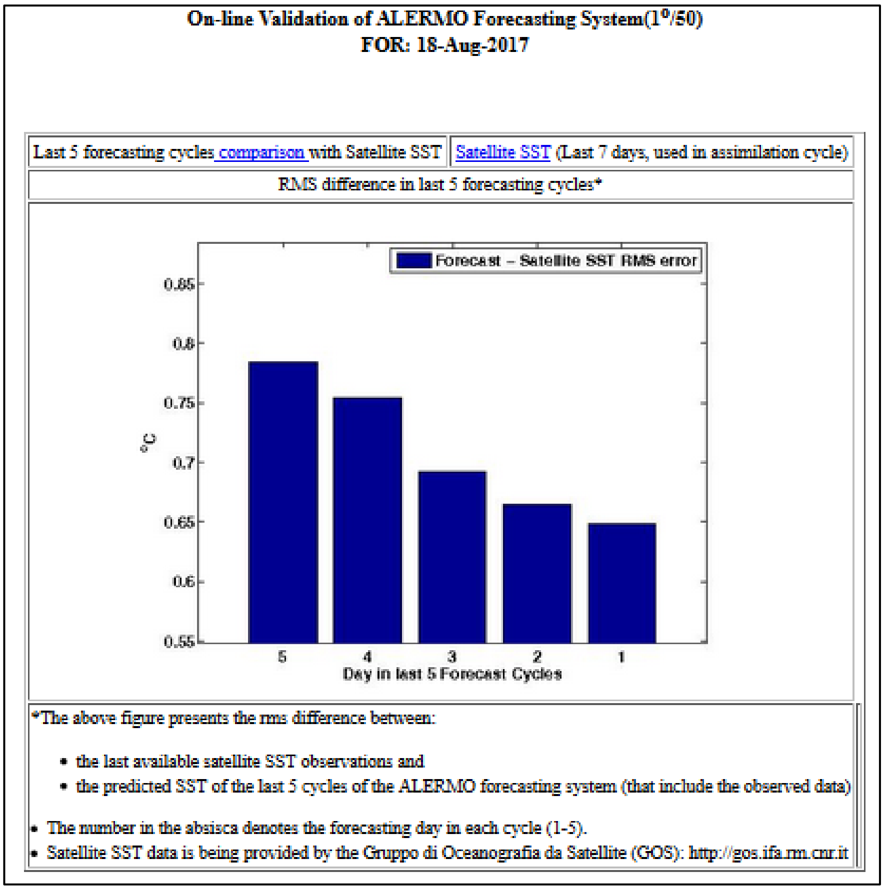


Figure 1(d): Daily validation (SST) of the system for the 5-days forecast – 18th of August 2017

(Ocean Physics and Modelling Group – University of Athens website)

3. Datasets

The datasets that were being used are divided into two different types. Firstly, data were used from satellites because of the great and free availability on the internet. There is a huge variety of resolutions and types of sensors that can match most of a researcher's needs. Secondly, an effort to use data from Argo floaters was made. Unfortunately, the Argo floaters that are drifting in the Aegean Sea are very few. In addition, for the time periods that were chosen for the model's validation, there were no data from the Argo system. Finally, due to the fact that the author of this project is a navy officer of the Hellenic Navy and sponsored by the Hellenic Hydrographic Service, access to classified, in-situ data was gained. More accurately, data (CTD measurements) from two boat trips of the oceanographic/hydrographic research ship, HS NAUTILUS, in the Aegean Sea were gathered. Further details are given below.

3.1 Satellite data

At the beginning of the project, appropriate satellite data for the statistical analysis were looked for. After visiting many websites with satellite data and comparing the available satellite data and the forecast data that the model gives, a conclusion was reached. The most suitable characteristics that should be examined were the Sea Surface Temperature (SST) and the Sea Surface Height (SSH). Although the initial target was to examine SST and Sea Surface Salinity (SSS), this couldn't happen because the existing satellites that give data for SSS are very few and their swaths have enormous data gaps, especially in the Mediterranean Sea. The final choice of the appropriate website to download all the data was that of the Physical Oceanography Distributed Active Archive Center (PODAAC) (http://www.podaac.jpl.nasa.gov). The time periods for the validation that were chosen were two months, February and August 2015. The reasons for this choice will be described in the analysis section.

A closer look to the data revealed another problem, the disadvantages of the different types of sensors that the satellites use in order to gather data for the SST. Passive sensors (infrared (IR), microwave (MW), using solar radiation etc.) have specific problems. Many of them are obstructed by clouds (e.g. IR) and suffer from errors due to absorption from the 'greenhouse' gases. Others (MW) are affected by ordinary weather conditions such as rain, have poor spatial resolution and don't seem to work near the coast (~100km) as energy 'leakage' from telecommunication bands is observed and errors in measurements occur.

Therefore, for the optimal results, a specific type of satellite data was chosen for the SST, the Optimally Interpolated Sea Surface Temperatures (OISSTs). More specifically, the Mediterranean Sea Ultra High Resolution SST L4 Analysis 0.001 deg resolution data were chosen. These data provide daily gap-free maps (Processing Level 4, which means 'blended') at 0.01 deg $\times$ 0.01 deg. horizontal resolution over the Mediterranean Sea. The data were obtained from IR measurements collected by satellite radiometers and statistical interpolation. The platforms/sensors used for all these data are: AQUA/MODIS, ENVISAT/AATSR, MetOp-A/AVHRR, MSG/SEVIRI, NOAA-18/AVHRR-3, TERRA/MODIS. Detailed description about the process and production of these OISSTs can be found in the project made by Buongiorno Nardelli et al., (2013).

On the other hand, for the validation of the SSH, another website for satellite data was used. The COPERNICUS MARINE ENVIRONMENT MONITORING SERVICE website was used ((http://www.marine.copernicus.eu) as it was the only website that provided data without gaps (Level 4). The resolution of the data was quite low at 0.125 deg x 0.125 deg.(1/8 □). Data from various altimeter missions were processed all together such as Jason-3, Sentinel-3A, HY-2A, Saral/AltiKa, Cryosat-2, Jason-2, Jason-1, T/P, ENVISAT, GFO, ERS1/2. However, the data were not exactly data for the SSH but for the SLA (Sea Level Anomaly). All the problems that were faced will be described in the analysis section.

3.2 In-situ data

In addition to the satellite data, in-situ data were also used. After the permission of the Hellenic Navy headquarters was given, access to CTD (Conductivity-Temperature-Density) measurements was granted. To be more accurate, the oceanographic department of the Hellenic Hydrographic Service performed oceanographic measurements in the wider area of the Aegean Sea in 2014 and 2016 in specific time periods. In these periods, multiple oceanographic stations took place were specific characteristics were measured with the use of the CTD device and special echo sounders.

Tables with exact coordinates of the stations were collected, along with all the information of the CTD measurements (depth. conductivity, temperature, density etc.) and the other information (seawater transparency, sound velocity etc.). Moreover, extra meteorological data were also collected from other sensors of the ship that helped the whole procedure and understanding of the general climate conditions of the area. These were dry and wet bulb temperatures, barometric pressure, wind direction with speed and intensity, wave direction and wave height, atmospheric visibility.

The two boat trips were made in two different time periods, from the 27th to the 31st May of 2014 and from the 25th to the 28th of May 2016. In figure 2 (a) and (b) the exact positions of the stations is being shown. The trip in 2014 focused mainly on the North Aegean whilst the one in 2016 focused on a wider area in the central and eastern Aegean.

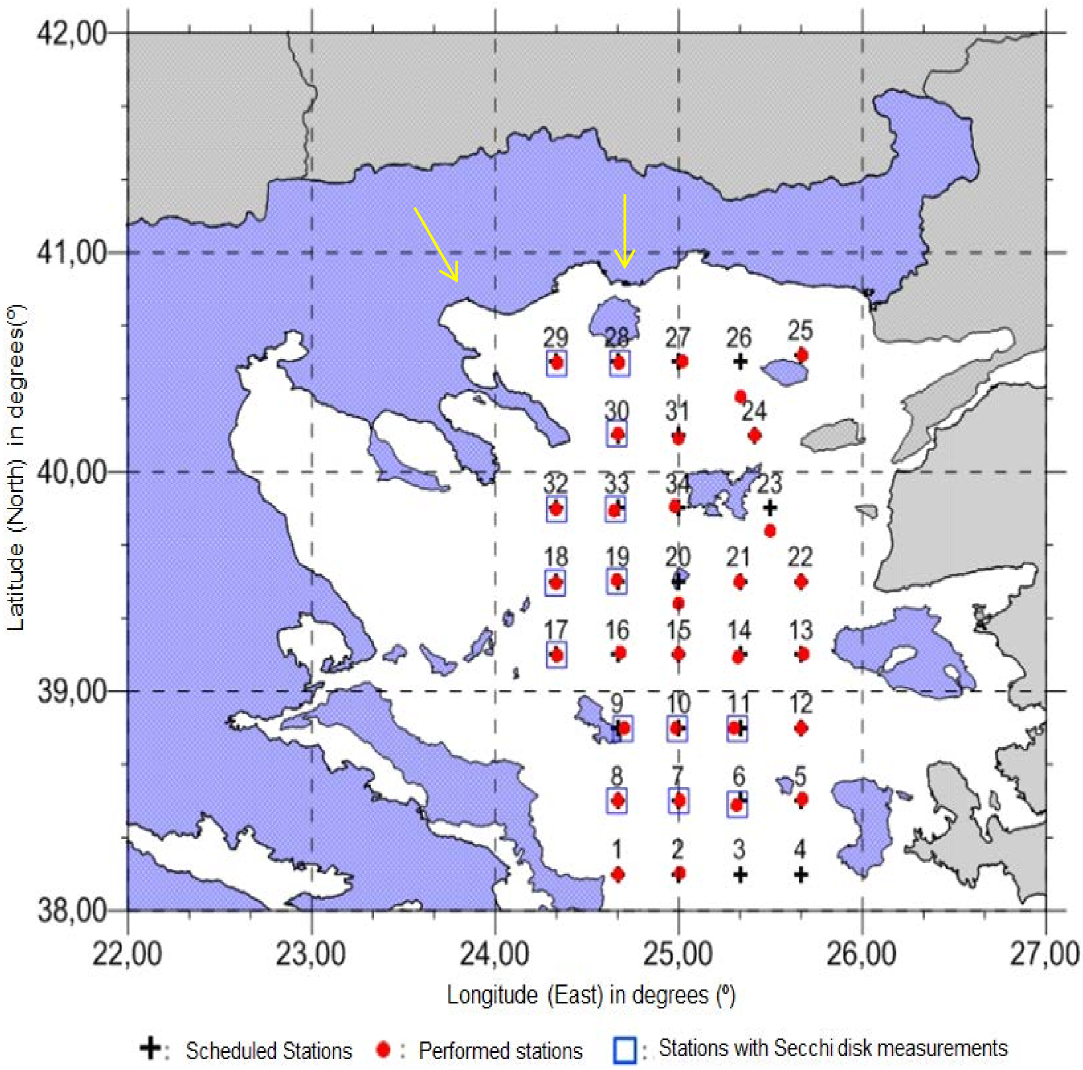


Figure 2 (a): All stations during the trip in May 2014

(North Aegean)

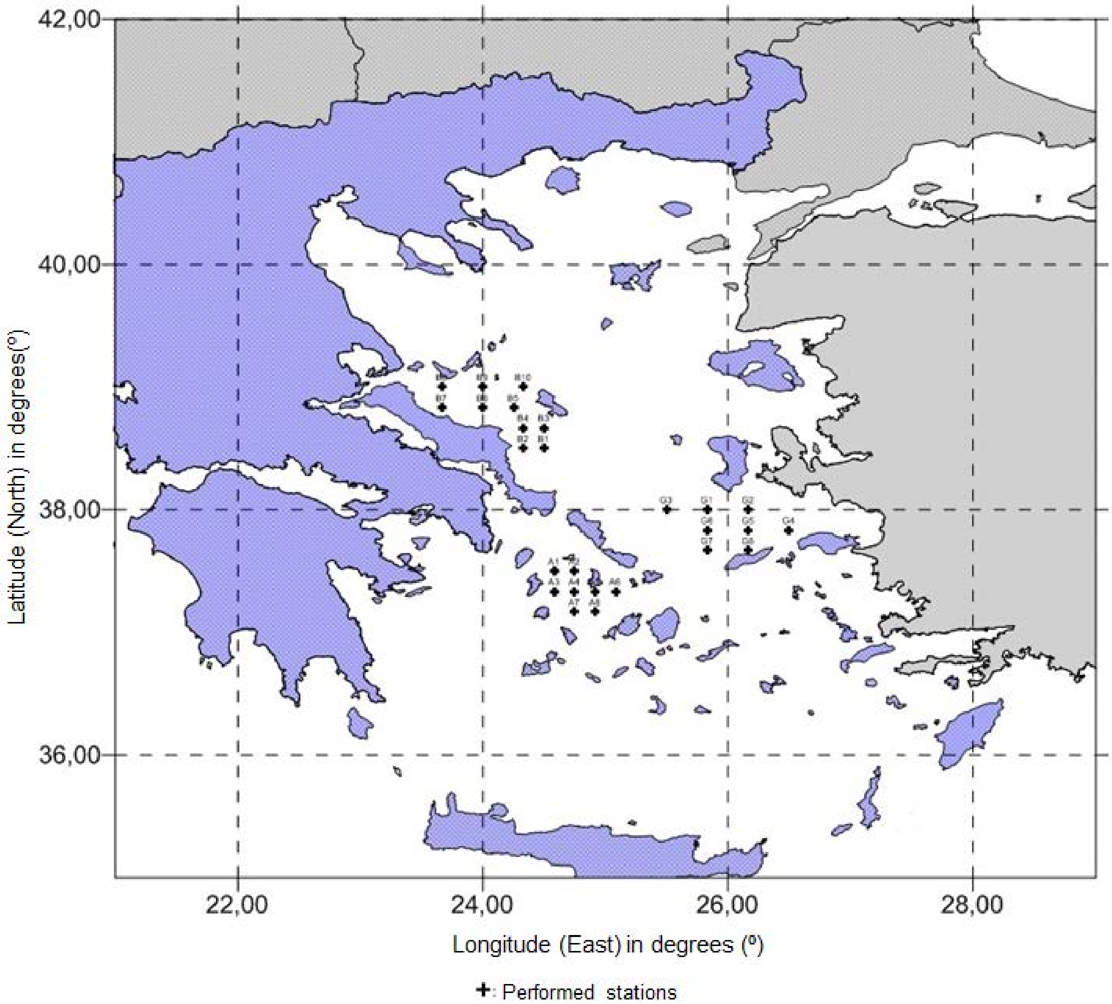


Figure 2 (b): All stations during the trip in May 2016

4. Methods

Before analyzing the methods that were used in the statistical analysis of all the data, it must be stated that the main book that the analysis was based on was “Data Analysis Methods in Physical Oceanography-Second edition” (Emery et. al., 2001). The analysis is divided into two sections, the first that concerns the satellite/model data and the second that concerns the in-situ/model data. The biggest part of the data (approximately 95%) was processed through Matlab (R2016b Version). The smallest part (approximately 5%) was processed through Microsoft Office Excel.

4.1 Satellite/model data analysis.

First of all, it was decided to evaluate model data from two completely different seasons, winter and summer. This selection was made with the primary intention of finding bigger errors and fluctuations as the weather conditions in both these seasons are quite extreme. On one hand there are strong atmospheric conditions (winter), such as wind and low temperatures, while on the other hand (summer) there are very high temperatures that can be escorted with strong seasonal winds and high humidity. The months that were chosen were February and August in 2015. The choice of the year was based on the quality and the quantity of the existing model data as it is a common fact that in few months throughout a year the model does not perform well due to external factors (e.g. lack of initial conditions from the one-way nesting to the Mediterranean Model).

In addition, the spatial resolution of the 1/50 was not act examined and evaluated. Unfortunately, the model data from the University of Athens did not include all the forecasts (only the 1st was included) of the 1/50 resolution, s resolutions would be meaningless.

4.1.1 Sea Surface Temperature (SST) data

All the satellite and model data were processed and analyzed through Matlab. For the SST validation, the first process was to transform and produce all the available data (both satellite and model) in the same resolution. This process was necessary as the initial resolutions of each dataset were completely different to each other. The spatial resolutions of the model's data were 1/30º, 1/50º and 1/60º. On the other side, the satellite data were having a resolution of 1/120 . So, in order to process the files that contained all the data between them, a common resolution was necessary. In order to avoid any mistakes in the matrices' process through Matlab, a higher resolution was chosen (1/240 so) as to make the difference in the resolution extremely small, almost zero, and to finally match the two different matrices with the data. After that, the matrices had the exact same spatial resolution. In order το increase the resolution of the existing data (both satellite and model) to the resolution of 1/240 □, a specific co

was based entirely on the linear interpolation in order to fill the data gaps with new values after the resolution increase. According to literature (Emergy et al., 2001), the most appropriate method of interpolation (for enclosed areas, like the Aegean) in order to fill the gaps in data matrices, is the linear one. Moreover, in order to compare results, other kinds of interpolation were also used but the results were almost identical as the differences between the temperatures or the heights were extremely small. However, the satellite data included the whole Mediterranean Sea. So, in order to make the two areas (satellite and model) with the exact same grid size, the satellite data were then cropped exactly at the area of the Aegean Sea (or the North Aegean area for the 1/60 □ resolution), where the model is focused.

Due to lack of forecasts in the 1/50 □ model, the va

focused only on the resolutions of 1/30 □ and 1/60□. A

give the reader an aspect of the massive process that took place, for the SST only, approximately 530 different forecasts (in both resolutions) were being analyzed and further processed (4-5 times each one of them) in order to get the final images and results. As a result, around 2,000 different processes were made only for the SST.

Finally, after all that process for the SST, the Root Mean Square Error was found for each resolution and each month, in order to compare the existing errors in the model's performance. The RMSE is the standard deviation of the residuals (forecasting errors). The residuals are kind of a way to measure of how far from the regression line data points are; RMSE is a measure of how spread out these residuals are. In more simple words, it tells how concentrated the data are around the line of best fit. RMSE is highly applicable and commonly used by the scientific society in climatology and forecasting in order to validate experimental results (Hyndman et al., 2006). The general formula that was used for the RMSE was:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} e_i^2}$$

(Chai et al., 2014)

Where e = f-o (forecast values – observed values)

n = samples of e

In order to use this formula on Matlab, a more specific and appropriate code was made and finally the monthly-averaged RMSE for each forecast and resolution was actually calculated individually.

4.1.2 Sea Surface Height (SSH)

Exactly the same procedure with the satellite and the model data was also followed for the analysis and validation of the SSH. Unfortunately, in the beginning two essential issues came up. At first, the best resolution for satellite data that could be found on the internet in the free databases of the satellites, was 1/8 °. A fact which automatically meant that the final output for the visual comparison would not have an accurate resolution which we will be able to observe in the figures that will follow in the results' section. Secondly and most important, all the available satellite data gave Sea Level Anomaly for the area of the Mediterranean Sea whereas the model gives Sea Surface Height (SSH). That happens because the lack of an accurate geoid still prevents precise computation of the ocean absolute dynamic topography (ADT) from satellite altimetry and only sea level anomalies (SLAs) can be accurately deduced (Rio et al., 2004). As a result, all satellite-altimeter devices nowadays produce SLAs. In order to have a better understanding, SLAs describe the difference between the actual sea surface height (SSH) and a mean sea surface height (MSSH). Moreover, these measurements are already corrected by the most actual geophysical corrections (e.g. tides and atmospheric delays).

In order to be able to compare the SSH and the SLA, a specific conversion was made. First of all, the relation between the SLA, the ADT and the MDT (Mean Dynamic Topography) of an area is given by the equation

ADT=SLA+MDT. The ADT was also given inside the satellite data. Therefore, in order to be able to compare one day's SSH from the model with the SLA from the satellite data, the mean ADT of that day was calculated by subtracting the average ADT of the whole month from the ADT of the day. Afterwards, the average SSH of the whole month was also calculated and then it was subtracted from a day's SSH in order to find the average SSH of that day. As a result, the final ADT (average of the day) and SSH (also average of the day) were comparable (Hernandez et al., 2001).

After the above conversions, the same type of interpolation was also used as in the SST data and then the data matrices were cropped exactly in the same dimensions in order to proceed and find the RMS errors.

4.2 In-situ data analysis

As mentioned in section 3.2 above, in May 2014 and May 2016 two boat trips were made by a Greek hydrographic ship named Nautilus. Numerous stations took place and the data from the CTD measurements were collected and processed through Matlab. Finally, profiles of salinity and temperature in relation to depth were made for every one of them. The main objective for accomplishment was to find stations with coordinates that would exist in both of the sub-models of the model (1/30^0 and 1/60 □ resolution) in order to show the performance of the two models at the same time with the CTD measurements across the vertical profile of the water column.

Most of the work was made 'manually'. More specifically, the exact grid position of the coordinates of the station, both in the matrices of the salinity forecasts and the temperature forecasts of the model, were had to be found. After these exact two dimensions were found, a vertical profile in relation to depth for the salinity and temperature could be created for that specific point using the model data. These two profiles were made for both resolutions of the model (1/30□ and 1/60□) and CTD measurements to show the difference between the model and the observational data.

In addition, a more specific conversion had to be made in the sigma levels of the models' vertical distribution in order for a correlation with the actual depth of each station to exist. The exact bathymetry of each station's position was annually found inside the models' data and a specific code on Matlab was made in order to convert the 25 sigma levels of depth into actual depths measured in meters. More detailed information and figures are given below in the results-discussion section.

5. Results – Discussion

5.1 SST

In figures 3 (a), (b), (c), (d) and (e) a random day of February (18th February of 2015) with the model's error in SST is being shown, in the low resolution (1/30). All five forecasts are shown in order to understand how the model error evolves in time.

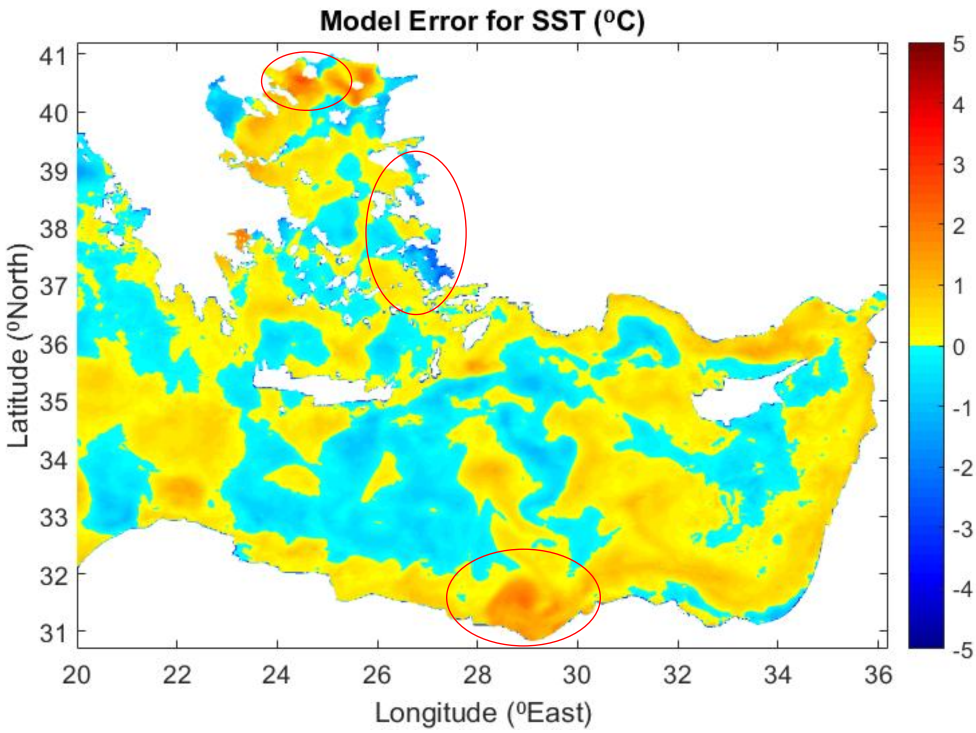


Figure 3 (a): Model's error (1/30) of SST for the 18th of February 2015 – 1st forecast

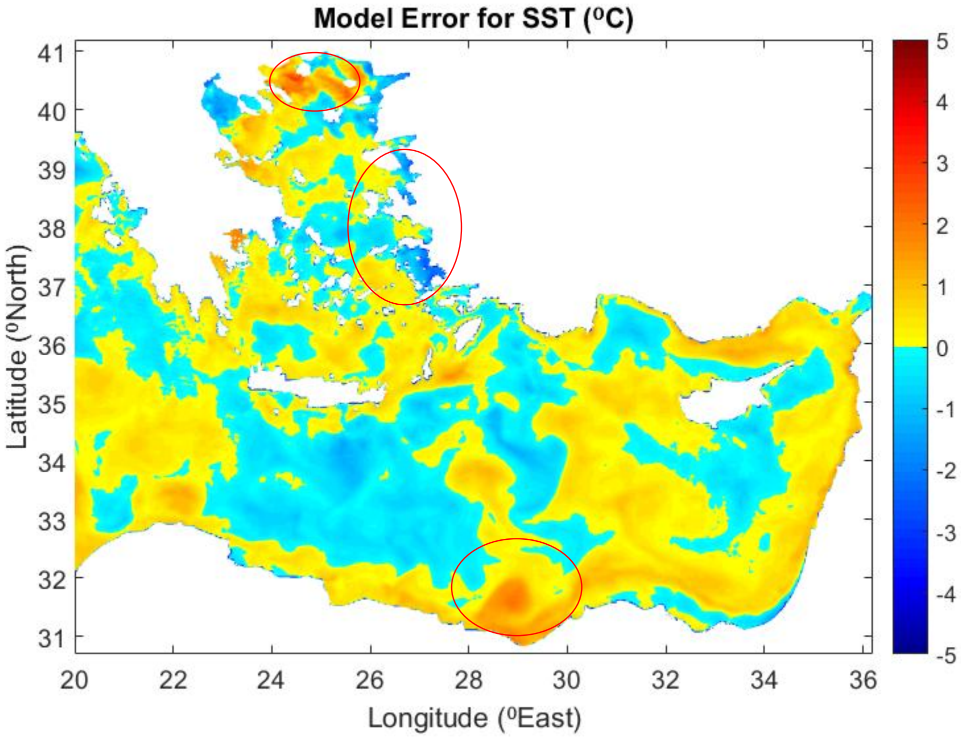


Figure 3 (b): Model's error (1/30th) of SST for the 15th of February 2018 – 2nd forecast

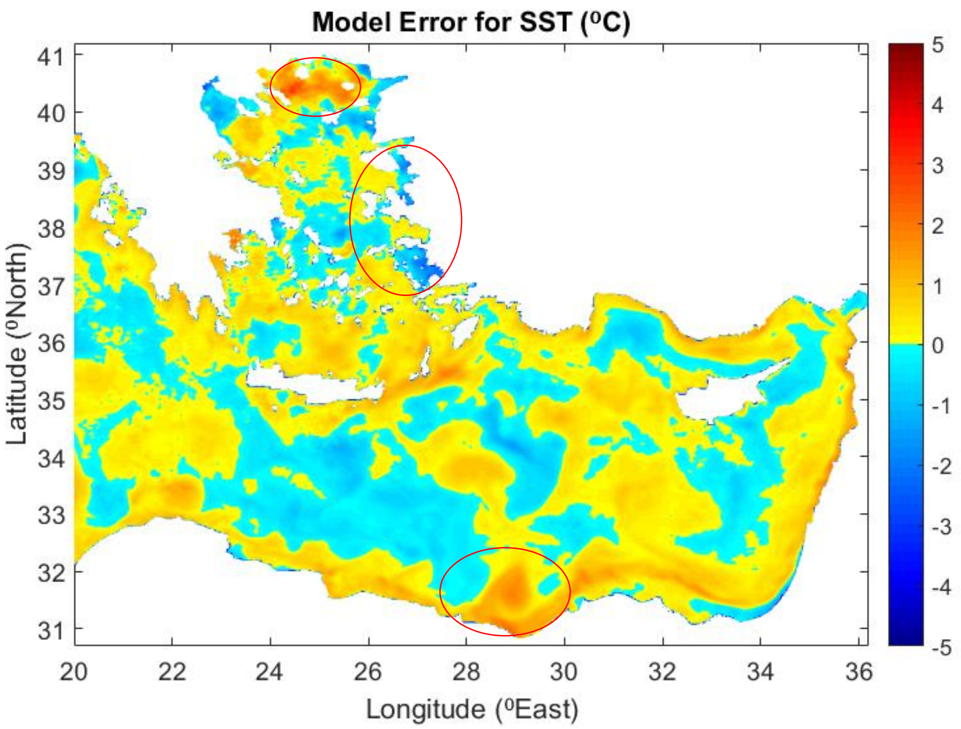


Figure 3 (c): Model's error (1/30th) of SST for the 15th of February 2018 – 3rd forecast

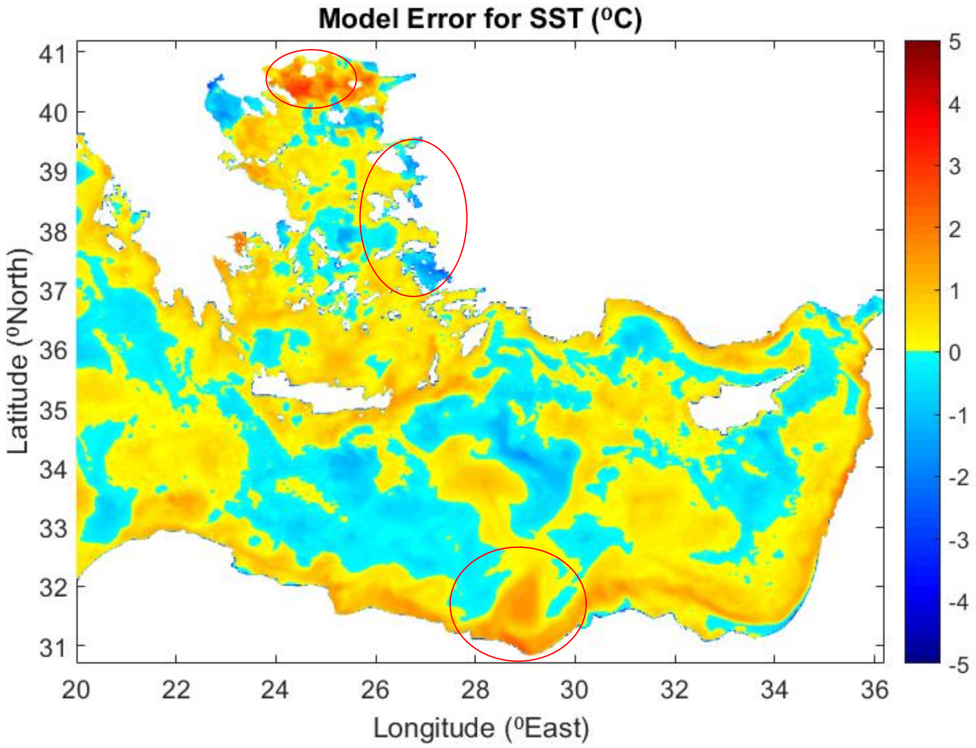


Figure 3 (d): Model's error ($1/30^{th}$) of SST for the 15th February 2018 –

4^{th} forecast

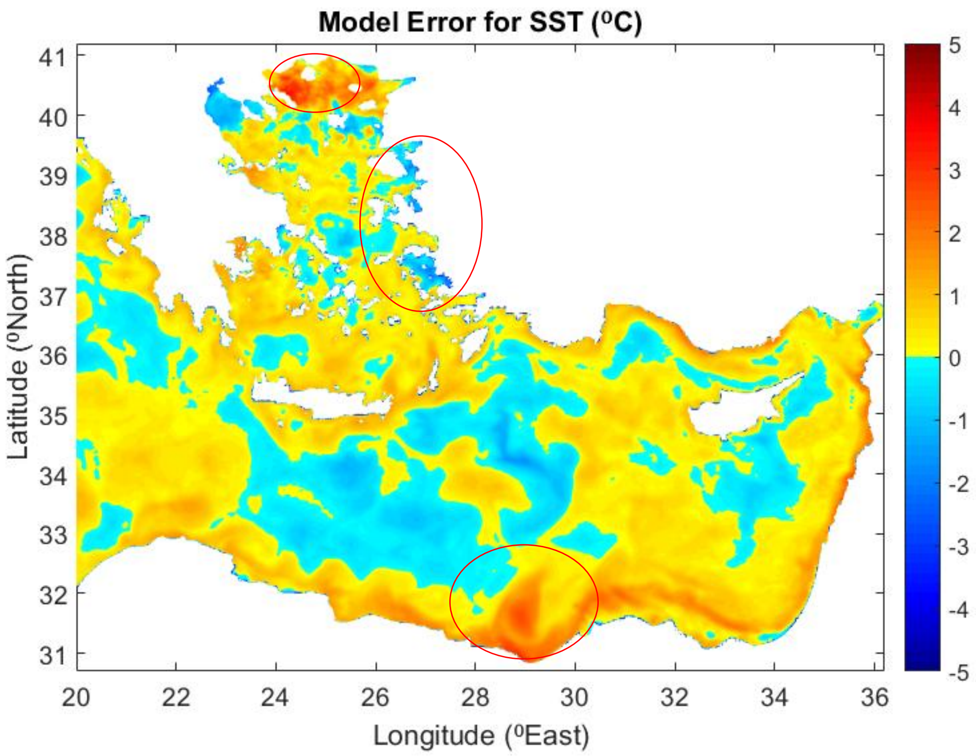


Figure 3 (e): Model's error ($1/30^{th}$) of SST for the 15th February 2018 –

5^{th} forecast

Generally, the model seems to perform quite well in the low resolution for the winter month. The errors are small in most of the parts of the Aegean Sea and the Levantine and they increase as days of the forecast go by. However, there are some errors that the model shows in specific places and in almost every forecast. Specifically, the model shows permanent errors (mainly positive ones around 2 to 4 □C) in the North coast line south of the Aegean. In addition, right next to Turkey's west coastline the model performs a negative error (manly negative ones around -2 to -3 □C) and also no Africa's coastline (mainly positive ones around 2 □C). Furthermore, the model does not perform any significant error in the mouth of the Dardanelles, as in winter the outflow is at its lowest rates (Kourafalou et al., 2003).

In figures 4 (a), (b), (c), (d) and (e) a random day of August (19th August of 2015) with the model's error in SST are being shown, in the low resolution (1/30 □).

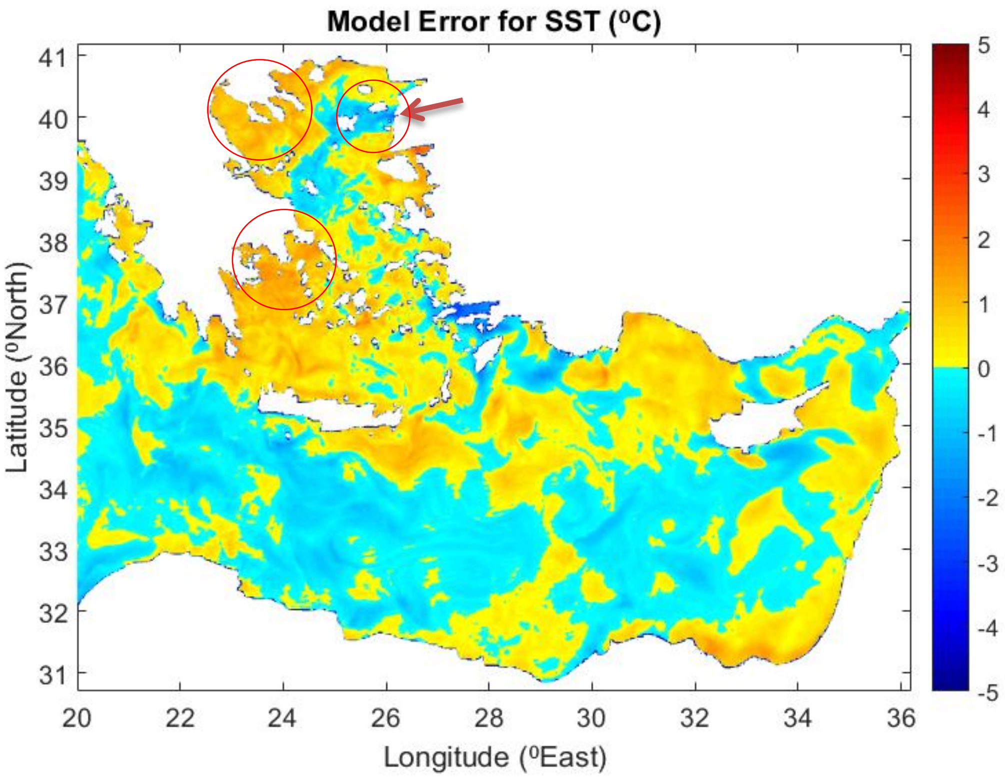


Figure 4 (a): Model's error (1/30 □) in SST for the 19th of August 2015 – 1st forecast

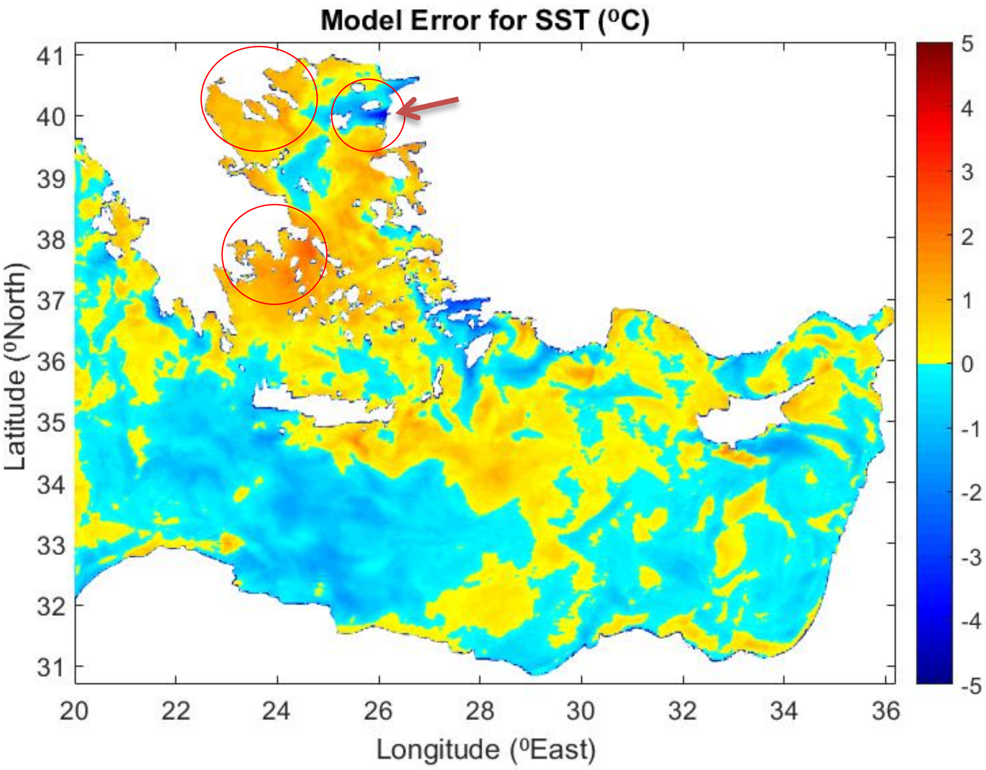


Figure 4 (b): Model's error (1/30 r) in the SST for 19th of August 2015 – 2nd forecast

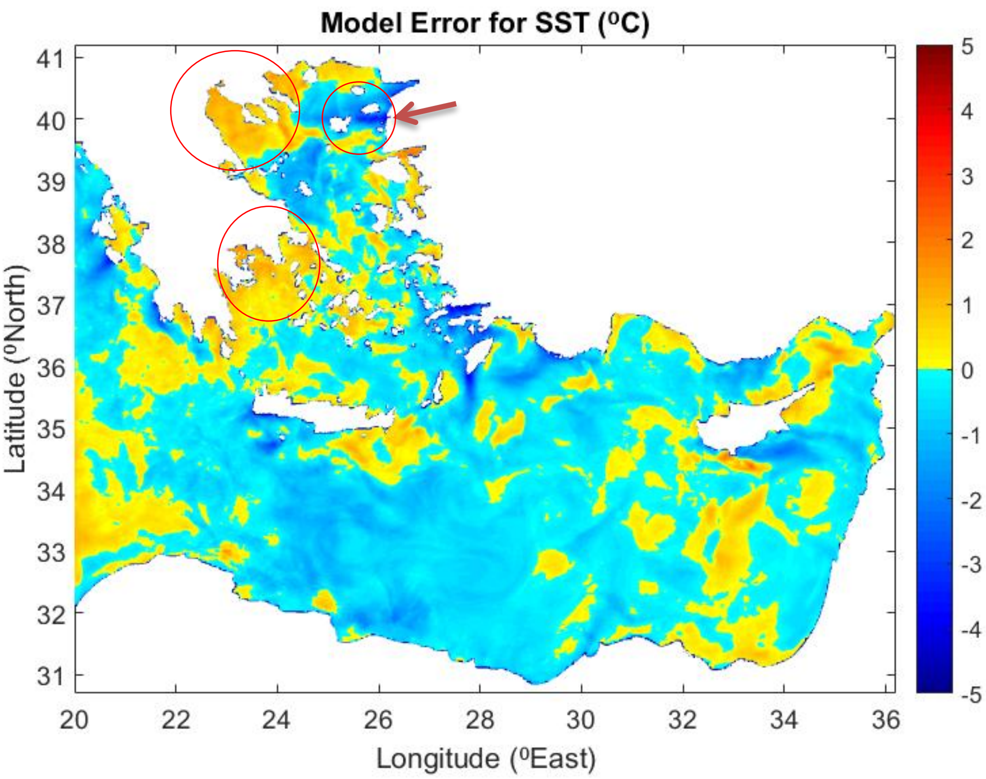


Figure 4 (c): Model's error (1/30 r) in the SST for 19th of August 2015 – 3rd forecast

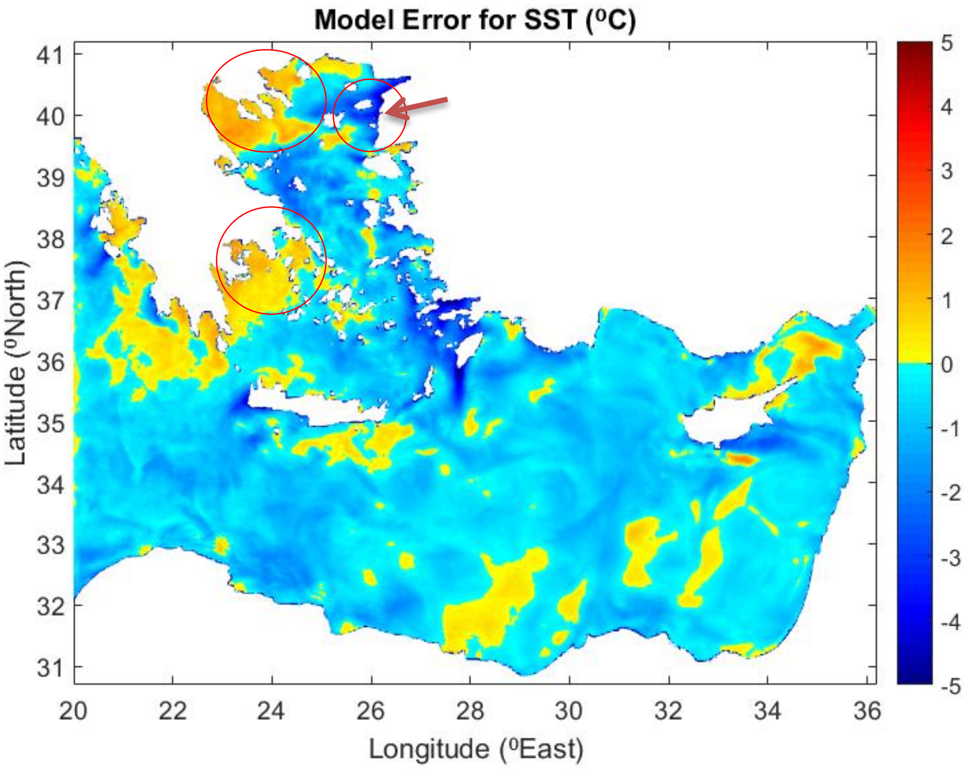


Figure 4 (d): Model's error (1/30°) in the SST for 19th August 2015 – 4th forecast

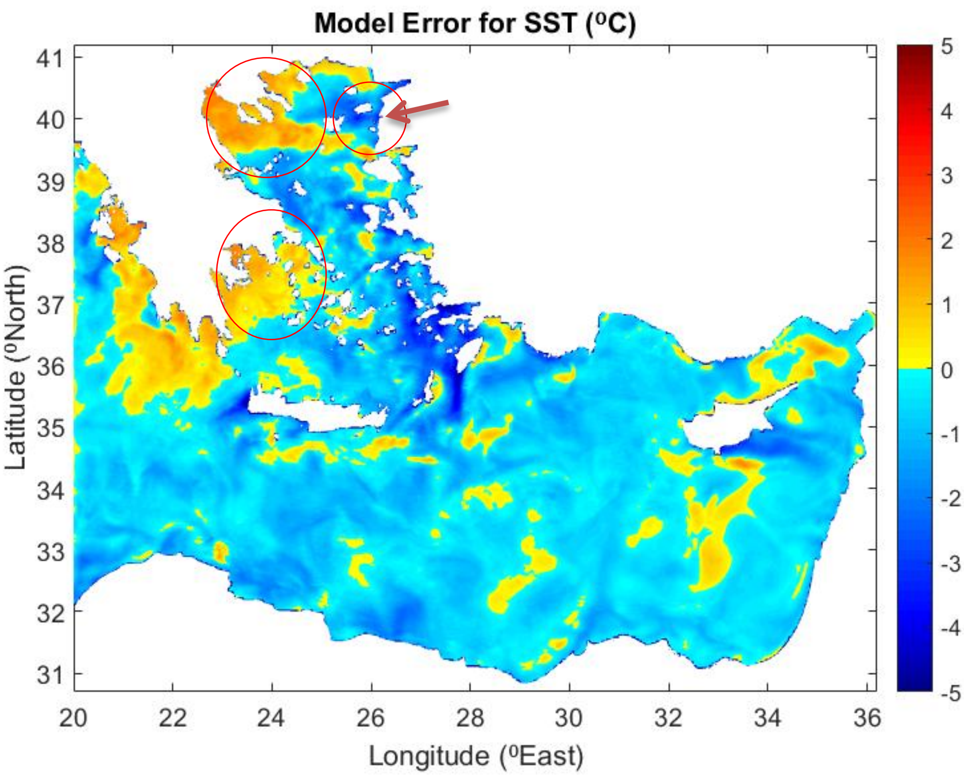


Figure 4 (e): Model's error (1/30°) in the SST for 19th August 2015 – 5th forecast

It is obvious that the model has a completely different performance in summer. Despite the fact that the model starts with a moderate error in the first forecast, the later forecasts keep giving larger and bigger errors. Furthermore, it is also clear that the difference in the model's error is bigger in summer than it was in the winter. The model still performs permanent errors in specific places although they are different from the winter ones. A significant error (always negative) always exists in the mouth of the Dardanelles Strait (indicated with red arrows). It is spotted in the northeast side of the Aegean Sea and it keeps decreasing to higher negative values as the day of forecast goes by. This fact can be easily explained as the input of the waters in the Dardanelles strait is something already proved and thoroughly studied. The waters coming out of the strait (waters of Black Sea origin, BSW) are cooler, less saline (24.0-35.0) and also have higher nutrient content (Theocharis et al., 1993). All the above, along with warmer, highly saline waters and oligotrophic waters of the Aegean Sea create strong fronts that can be easily identified in SST images from the satellites (Gerin et al., 2014). So, the model cannot easily predict the outflow of the strait (as it is treated as an open boundary) into the Aegean Sea and gives an error. This error is more evident in the summer due to the high temperature ranges that exist in the upper layer of the sea water. The model also performs some permanent errors near the coastline of Greece's mainland which are also indicated with red, ellipsoid lines on the forecasting maps.

In figures 5 (a), (b), (c), (d) and (e) a random day of February (20th February of 2015) with the model's error in SST is being shown, in the high resolution (1/60 □) Already mentioned, the high resolution model covers the North Aegean and it gives a 4-days forecast. The high resolution model performs really well too. The model's errors are reasonable and acceptable; however there are also permanent errors in specific places. The model gives errors (mainly positive around 3)□ east of Halkidiki, south of the north coastline of Greece's mainland. An error also exists, but not always, in the mouth of the Dardanelles strait but it remains very low as the temperature difference in the winter of the two different water masses is low. The permanent errors are also indicated by red ellipsoid lines on the forecasting maps.

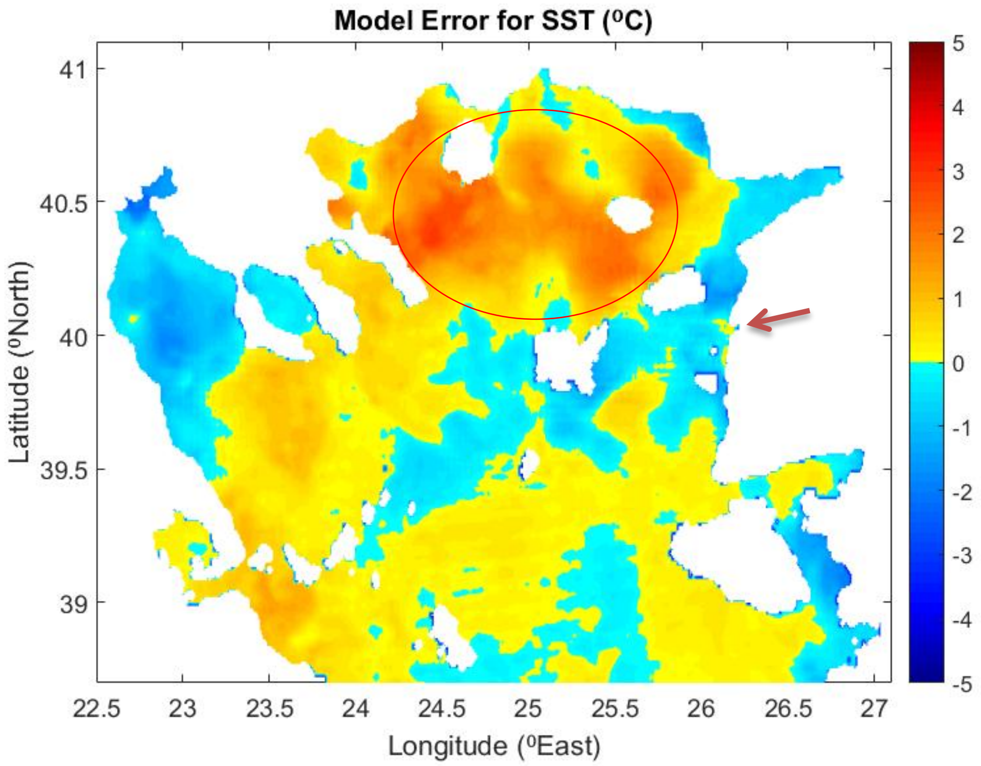


Figure 5 (a): Model's error (1/60 □) in SST the 28th of February 2015 – 1st forecast – North Aegean

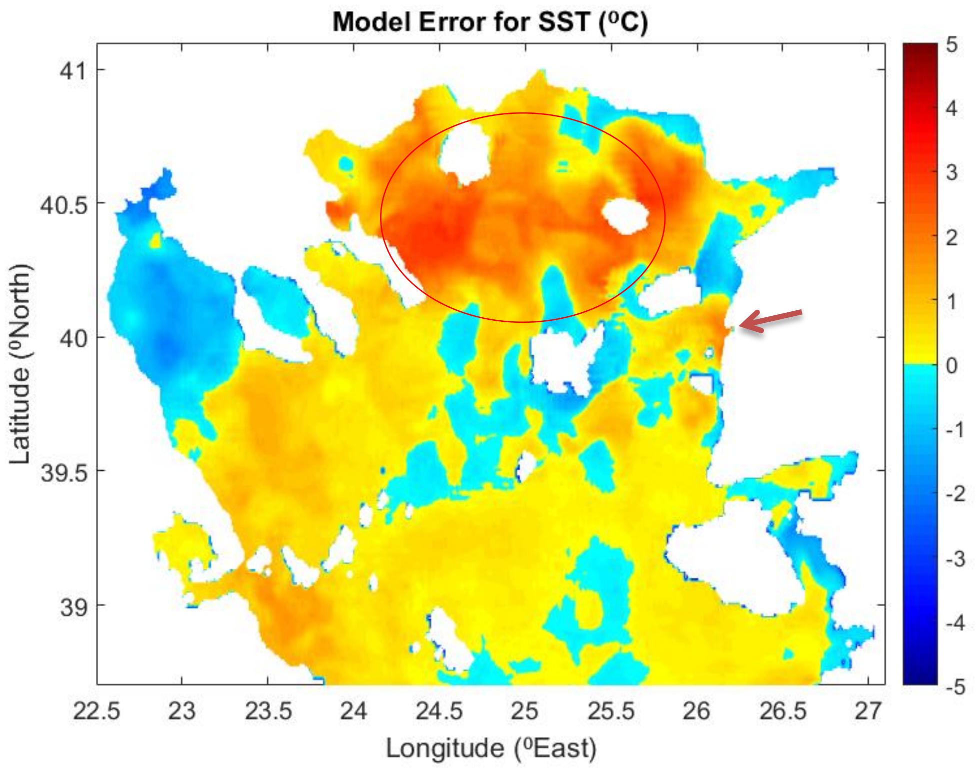


Figure 5 (b): Model's error (1/60 □) in SST the 28th of February 2015 – 2nd forecast – North Aegean

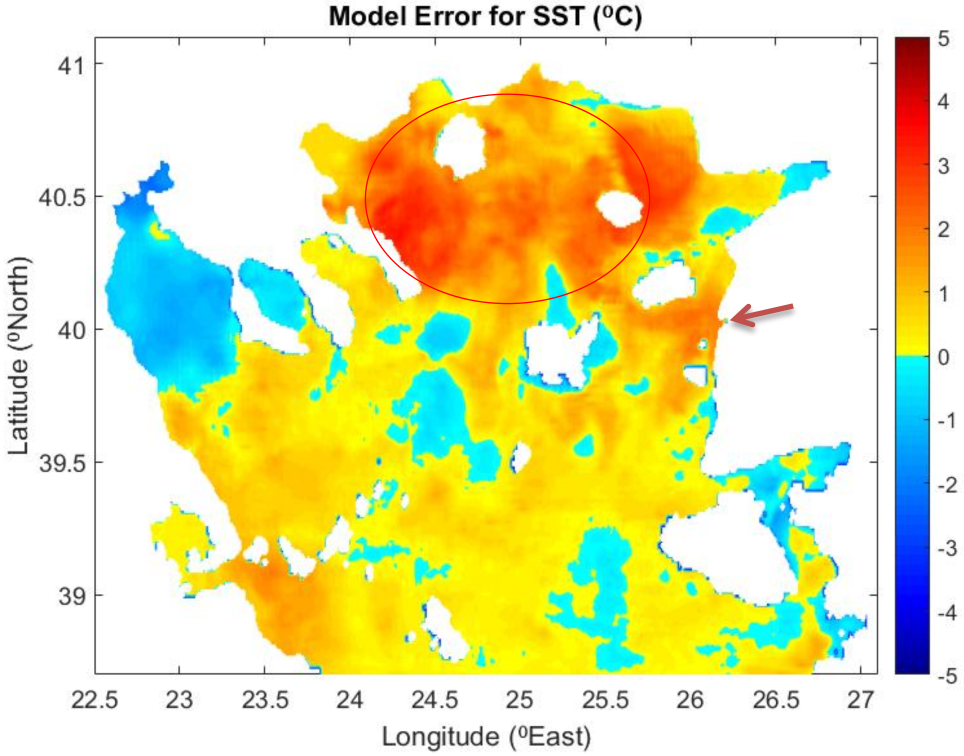


Figure 5 (c): Model's error (1/60 r) in the SST for 28th of February 2015 –
3rd forecast – North Aegean

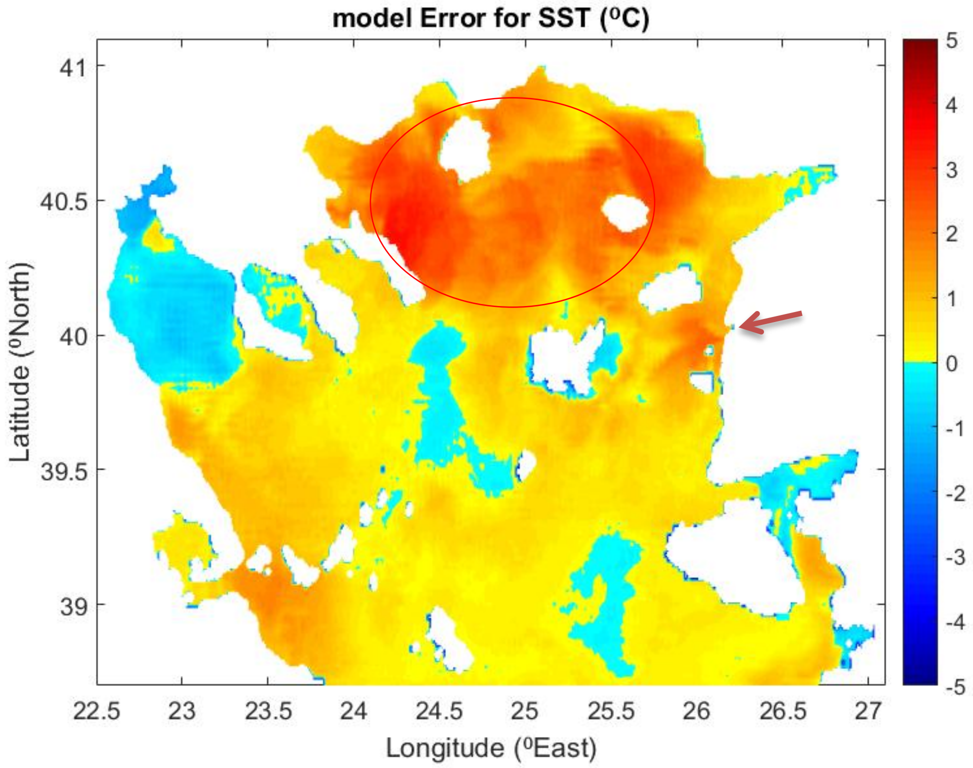


Figure 5 (d): Model's error (1/60 r) in the SST for 28th of February 2015 –
4th forecast – North Aegean

In figures 6 (a), (b), (c) and (d) a random day of August (4^{th} August of 2015) with the model's error in SST is being shown, in the high resolution (1/60). A complete resolution model giving completely different errors as it gave in the winter. The model's error in the mouth of the Dardanelles strait is obvious and always negative as in August, according to Kourafalou et al. (2003), the Dardanelles have a very high rate of outflow (approximately 12,500 m^3/sec). The exact position of the strait's mouth is also indicated with a red arrow in the figures. The error south of the north coastline remains and keeps increasing as days go by. Another error of the model, though not very high, is the error that exists because of the advection of the lower temperature from the water masses that outflow from the Dardanelles strait in a southwest direction. It is clear that the colder water masses affect the wider area of the North Aegean till the coastlines of the Sporades islands. This event is indicated with black arrows on the figures. This event was also observed and studied by Gerin et al., 2014. Data collected and studied suggested that the BSW can reach south to Crete Island passing along the western Aegean cast and finally enter the deeper Eastern Mediterranean basin.

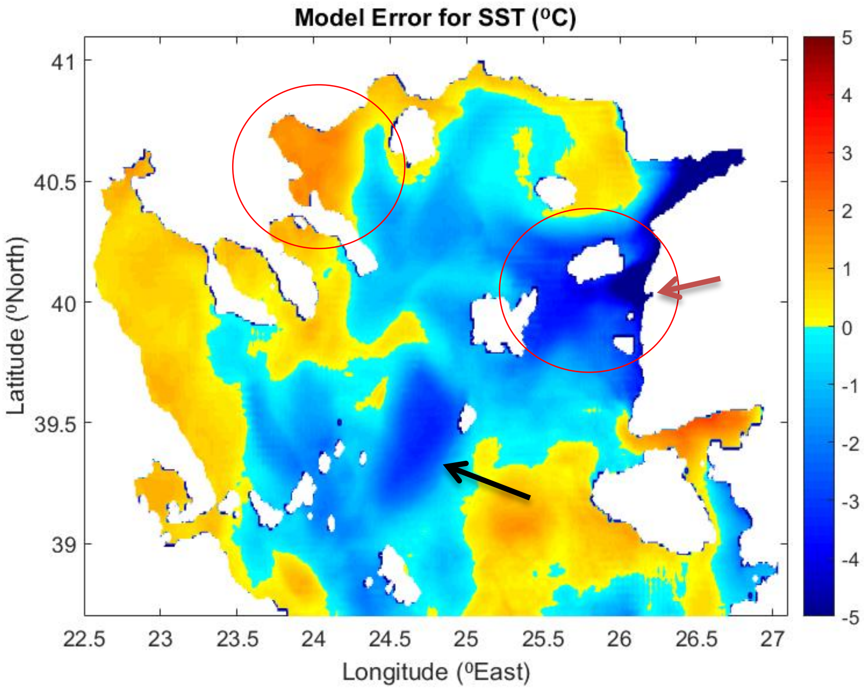


Figure 6 (a): Model's error (1/60) in SST for 4^{th} of August 2015 – 1^{st} forecast – North Aegean

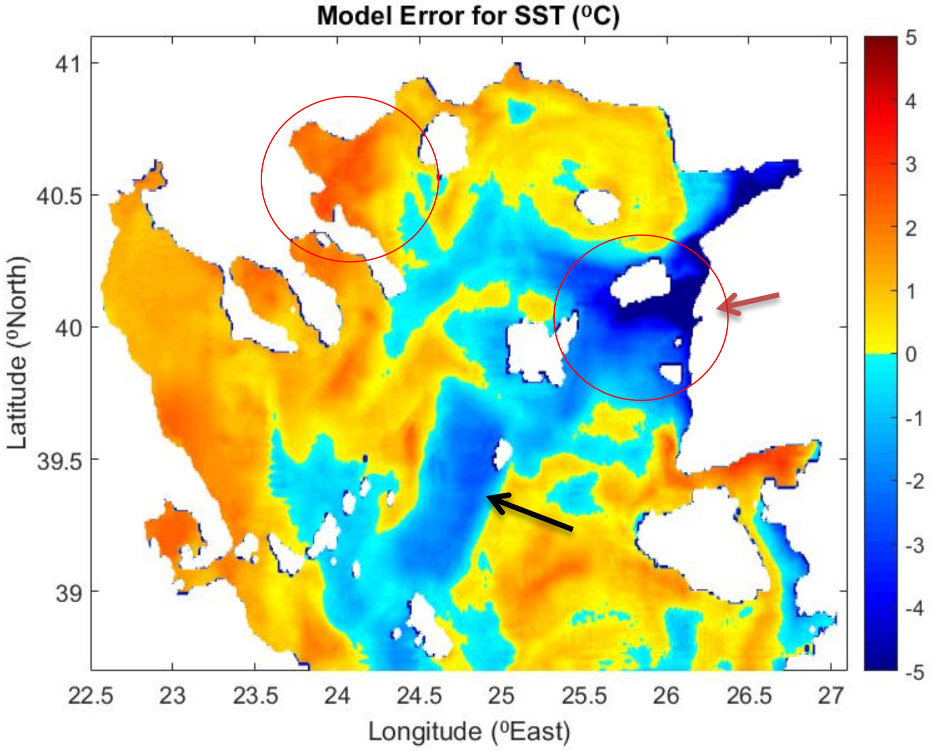


Figure 6 (b): Model's error (1/60 □) in SST for the 4th of August 2015 – 2nd forecast – North Aegean

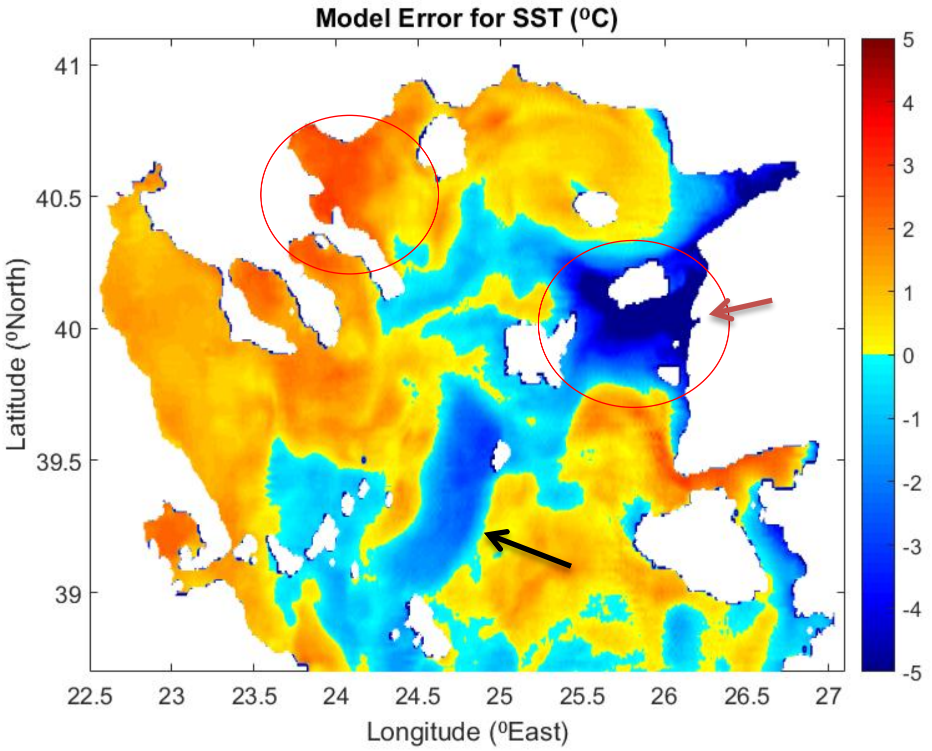


Figure 6 (c): Model's error (1/60 □) in SST for the 4th of August 2015 – 3rd forecast – North Aegean

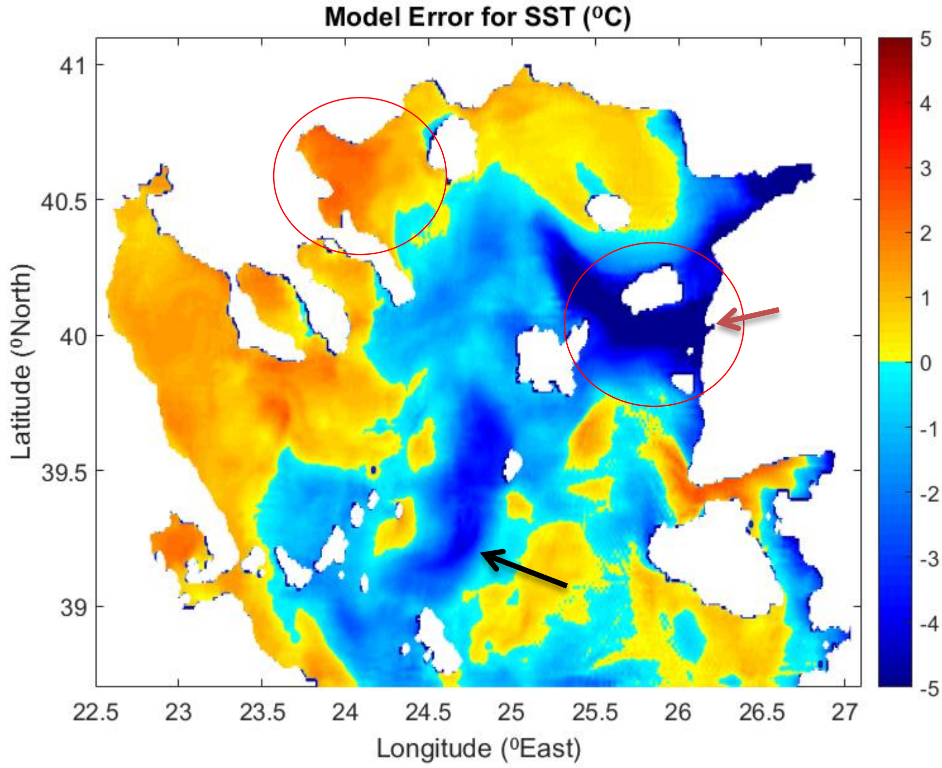
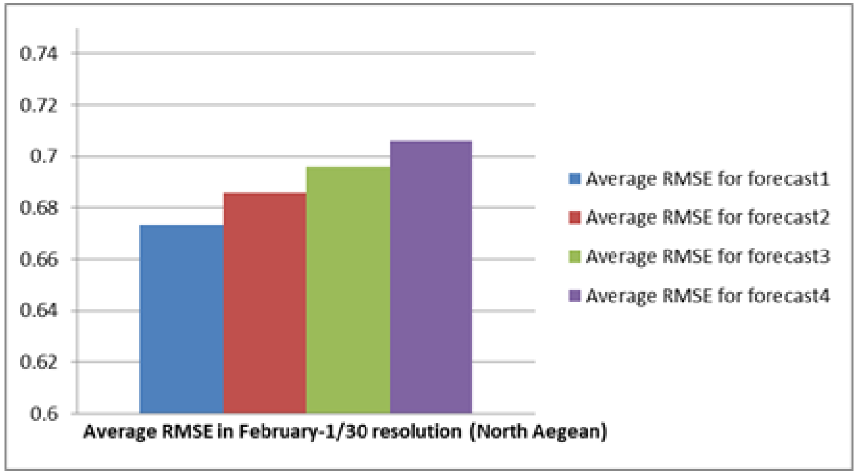
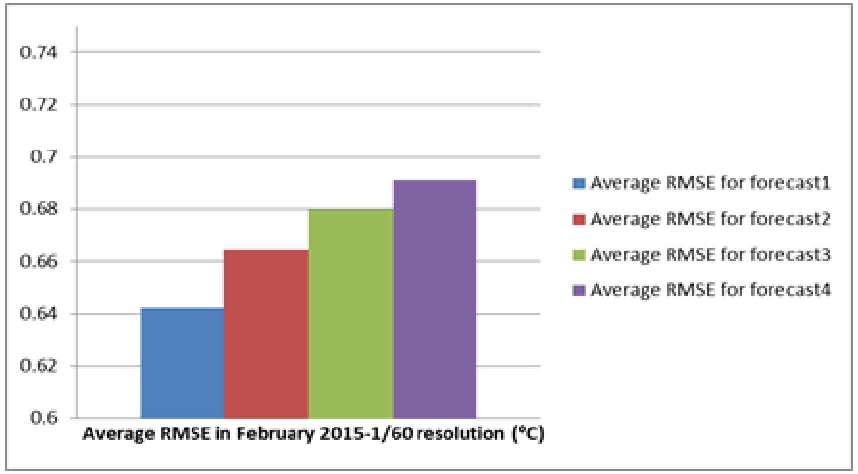


Figure 6 (d): Model's error (1/60°) in SST for the 4th of August 2015 –
4th forecast – North Aegean

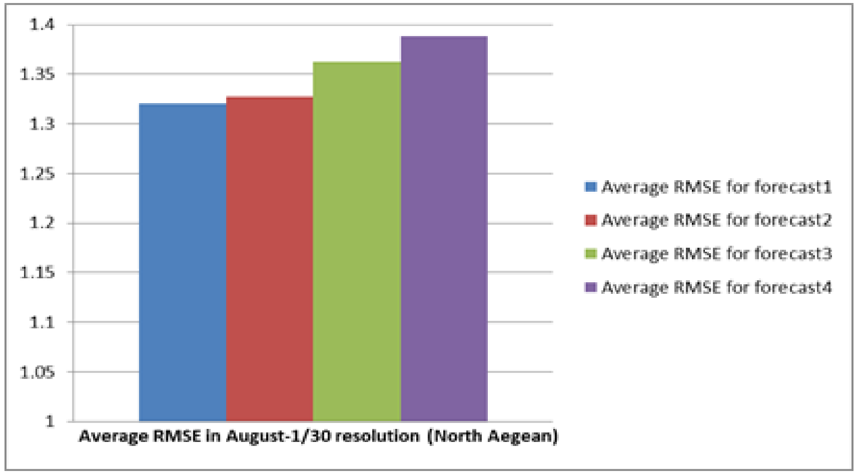
In order to see the statistical difference, the average Root Mean Square Error (RMSE) for every forecast, for each month and resolution was found. In figures 7 (a), (b), (c) and (d) the differences are obvious. Firstly, as the days of the forecast go by, the average RMS error increases, in all cases. This trend is actually expected and reasonable. Secondly, summer shows higher errors in relation to winter due to much higher variations in the upper layer of the sea. Finally, an increase in the model's spatial resolution results in decreased forecast errors. Generally, the RMS errors remain in low levels. Specifically, in August it varies from 1.32 to 1.39 °C (1/30°) and 1.25 7 °C (1/60°). In additi (1/30 °C) and from 0.642 to 0.691 °C (1/60°). It must also be mentioned that for every comparison between the 1/30° and the 1/60° RMSE evaluation, only the North Aegean values were taken into consideration because any other comparison (e.g. between the whole Aegean Sea and the North Aegean) would be wrong and invalid.



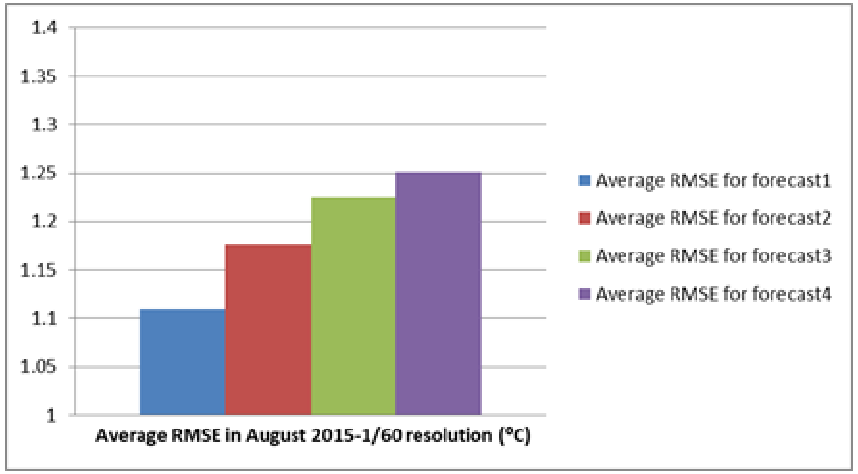
(a)



(b)



(c)



(d)

Figure 7 – Average RMSE for SST in ^{0} C (a): February 2015 - 1/30^{0} , (b): February 2015 - 1/60^{0} (c): August 2015 - 1/30^{0} , (d): August 2015 – 1/60^{0}

5.2 Normalised SSH

In figures 8 (a), (b), (c), (d) and (e) a random day of February (24th February of 2015) with the model's error in normalized SSH are being shown, in the low resolution (1/30°). It is obvious that the images have a coarser view from the ones shown before in the SST errors. This happens because the initial resolution (as already mentioned) of the satellite data was very low, only 1/8°. Despite the interpolation of the data and the final increase of the resolution to 1/240°, the coastlines remained coarser.

The first forecast starts with small, negative errors in the whole Aegean Sea and some positive errors in the Levantine Sea. The model seems to perform quite well. However, as the days of forecast go by, the errors become negative and they keep decreasing in the covering the whole map. The errors in the 5th forecast reach up to almost -25 cm whereas the area with the highest ones is north of the coastline of Africa.

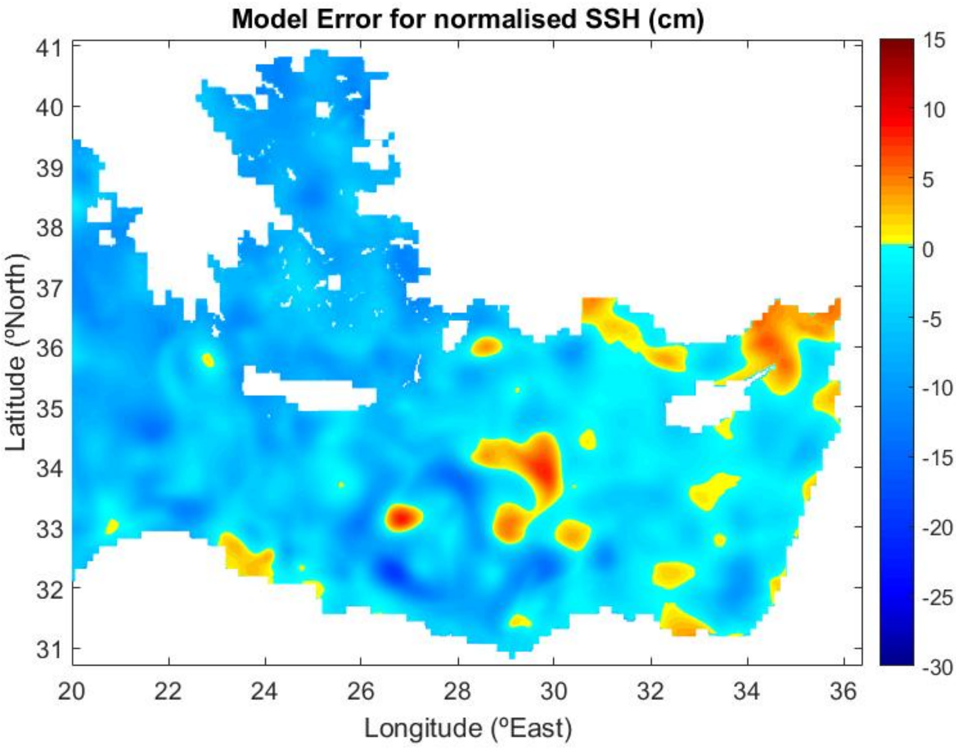


Figure 8 (a): Model's error (1/30°) in normalised SSH for the 24th of February 2015 –1st forecast

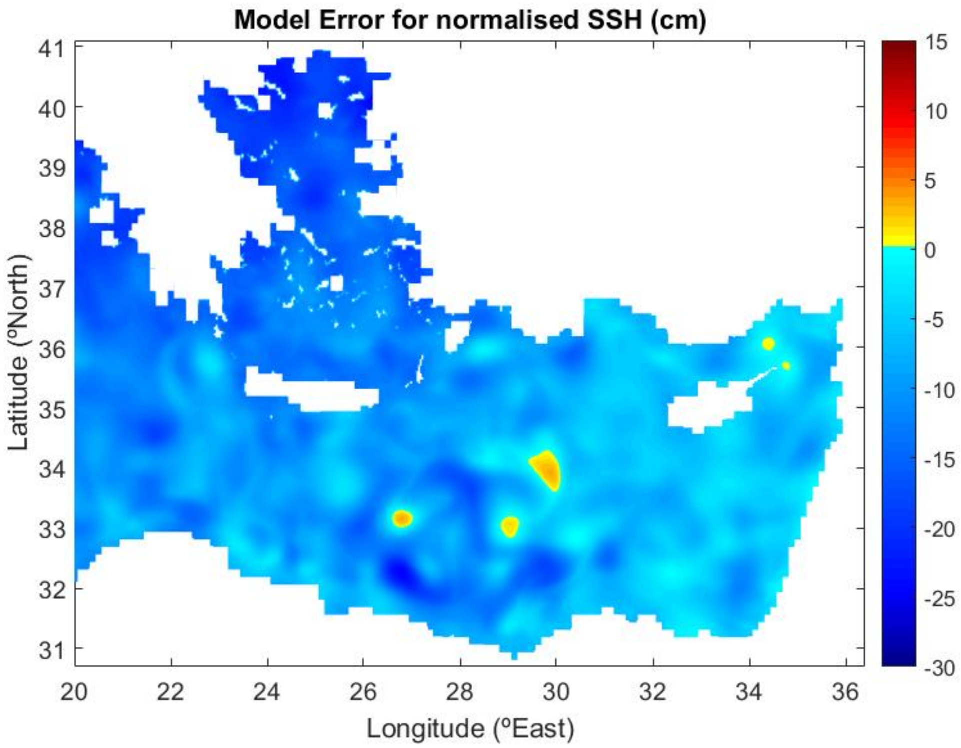


Figure 8 (b): Model's error (1/30°) normalised SSH for the 24th of February 2015 –2nd forecast

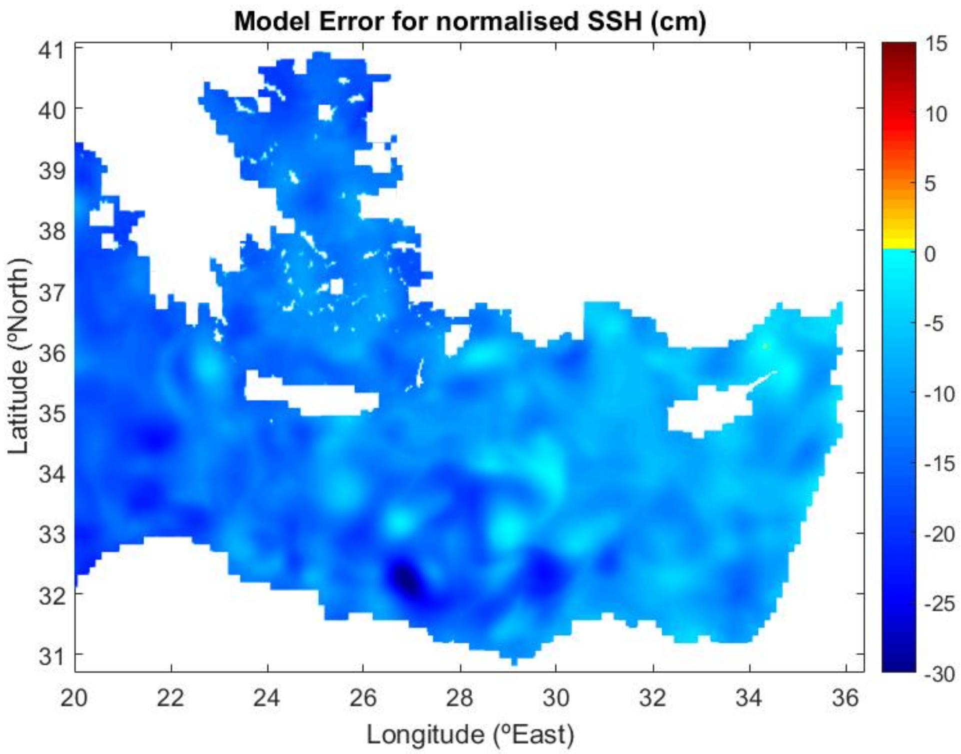


Figure 8 (c): Model's error (1/30°) normalised SSH for the 24th of February 2015 –3rd forecast

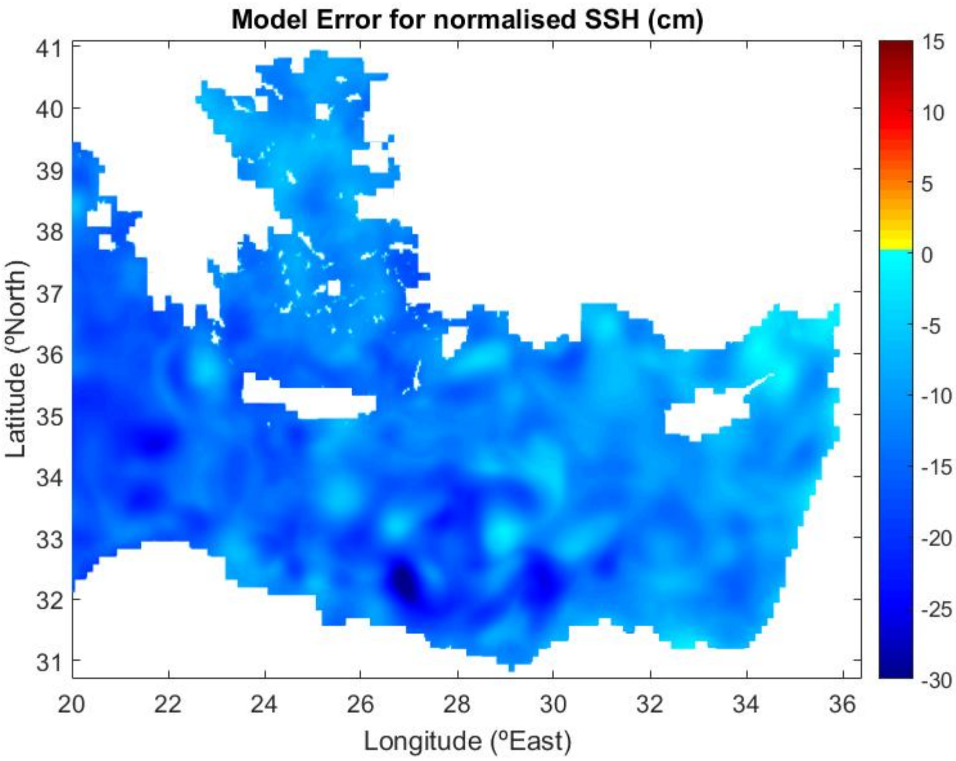


Figure 8 (d): Model's error (1/30) in normalised SSH for the 24th of February 2015 –4th forecast

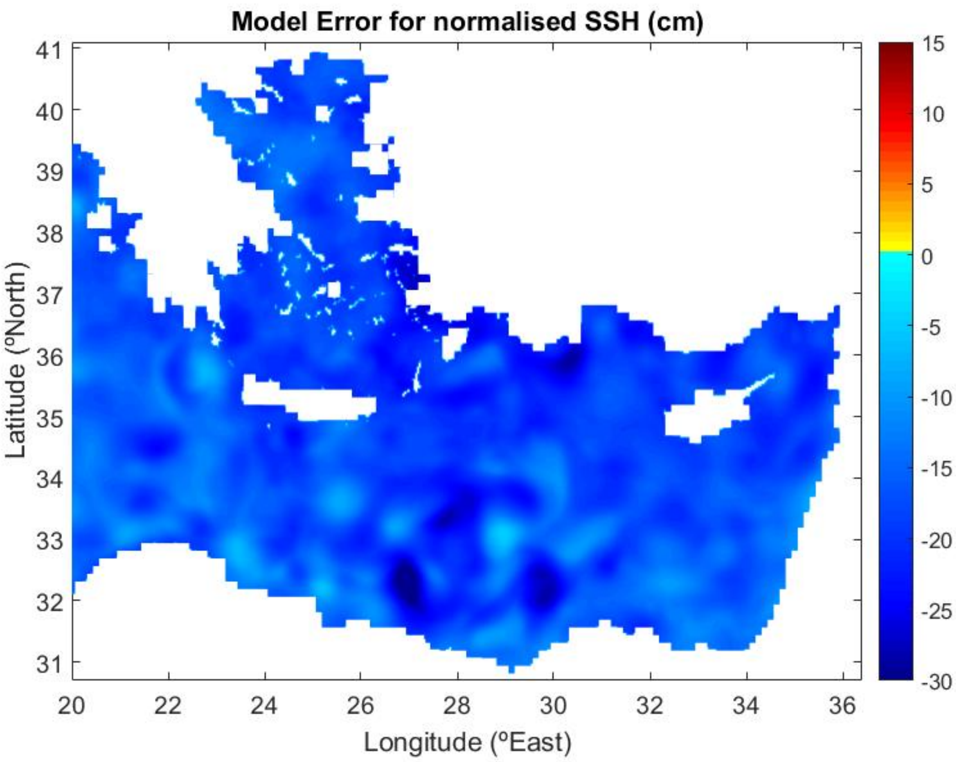


Figure 8 (e): Model's error (1/30) in normalised SSH for the 24th of February 2015 –5th forecast

In figures 9 (a), (b), (c), (d) and (e) a random day of August (12th August of 2015) with the model's error in normalized SSH are being shown, in the low resolution (1/30). The differences with the model's errors in February are obvious. The errors in summer appear to be much smaller. In the first forecast, a complex image of both positive and negative errors is being shown. The errors are small however. As the days of the forecast go by, the negative errors seem to prevail. The 4th and 5th forecasts have only negative errors which they don't seem to overpass the value of -10 or -15 cm at maximum.

This fact can be easily explained. It is proved that two of the main factors (besides the ocean circulation) that affect the SSH on a daily basis, are the tidal forces and the atmospheric pressure. However, in summer, the differences in the atmospheric pressure are milder and smaller ones as they are in the winter. That is the reason why the errors in the model are lower in summer than they are in winter.

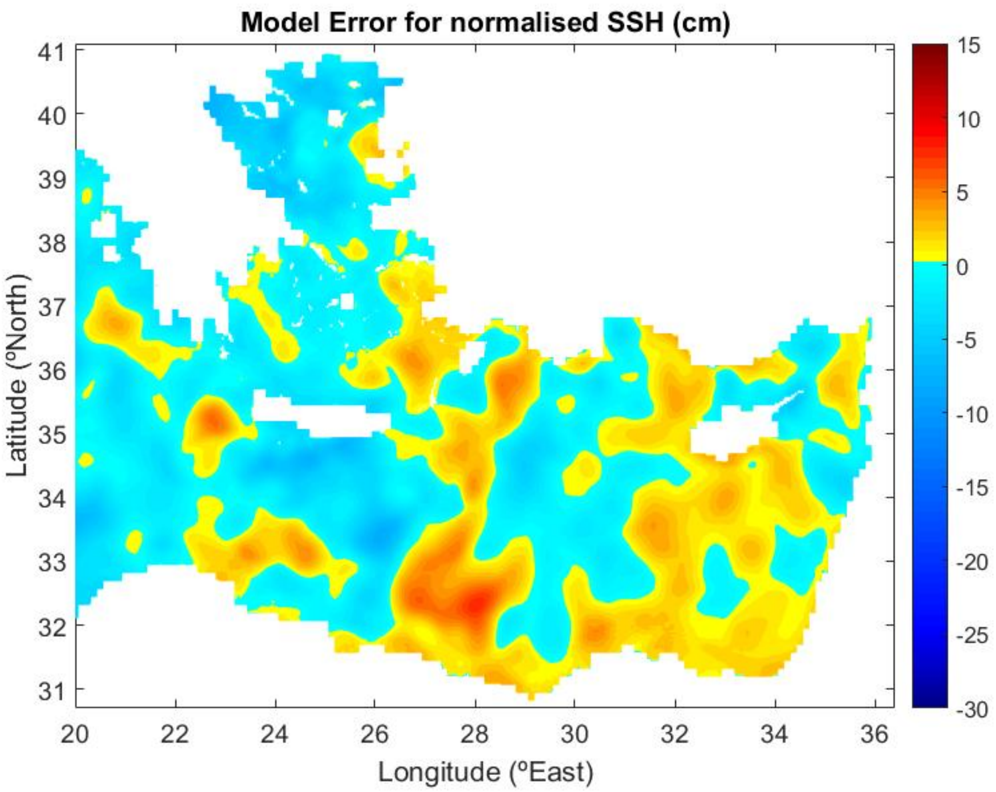


Figure 9 (a): Model's error (1/30) in normalised SSH for the 12th of August 2015 –1st forecast

On the other hand, one of the characteristics of the Aegean Sea and the Levantine is that the tidal forces created by the Moon and the Sun are quite weak. Therefore, a tide in the Aegean barely exceeds 10 cm and has an insignificant effect on the Sea Surface Height and the general circulation of the Aegean Sea (Tsimplis, 1994; Poulain, 2013). The only exception is the strait of Euripus (between Evoia Island and the continental Greece) which is affected by strong tidal currents. Unfortunately, this strait is not covered by the model's forecasts or the satellite data so as to get a view of what is actually happening in these very confined waters.

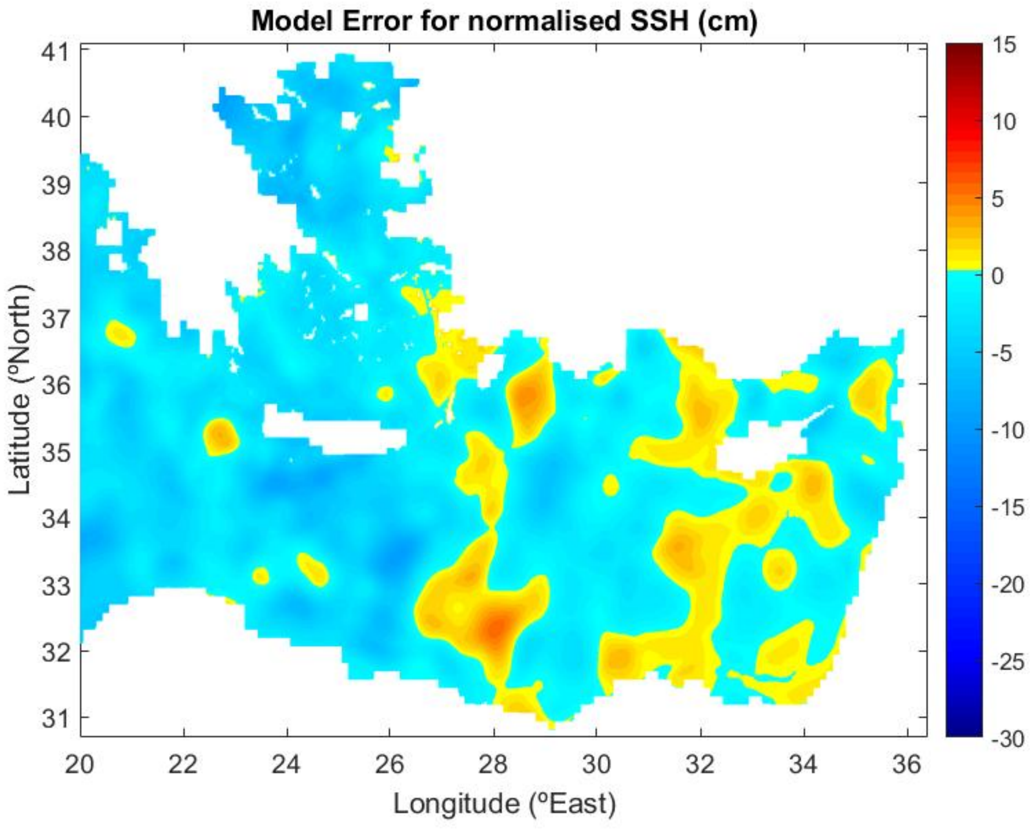


Figure 9 (b): Model's error (1/30°) in normalised SSH for the 12th of August 2015 –2nd forecast

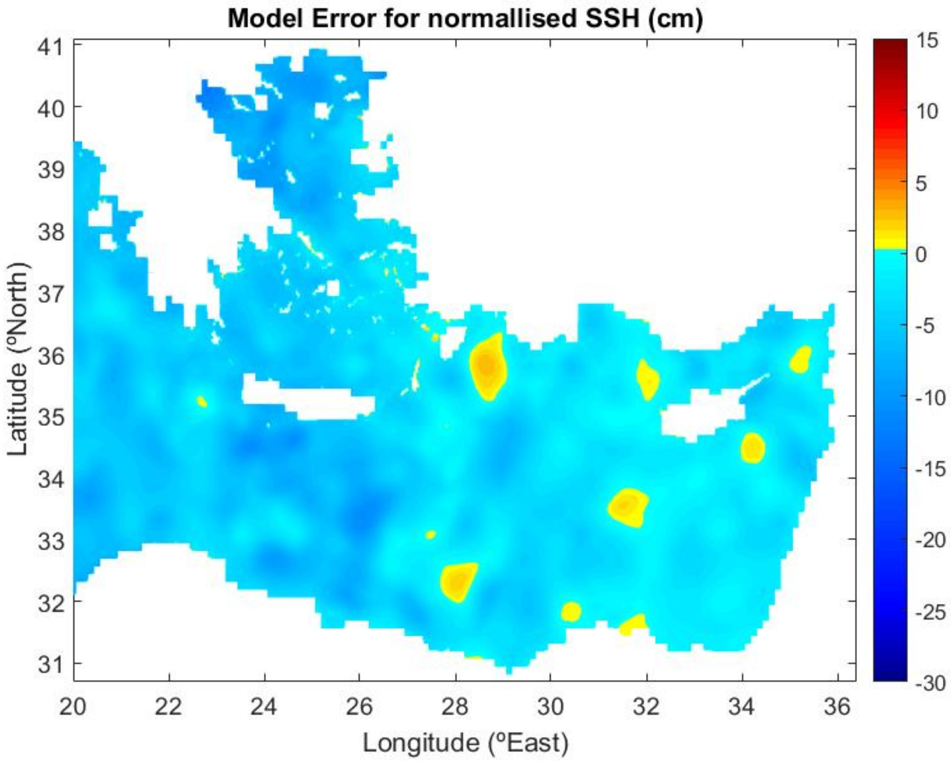


Figure 9 (c): Model's error (1/30) normalised SSH for the 12th of August 2015 –3rd forecast

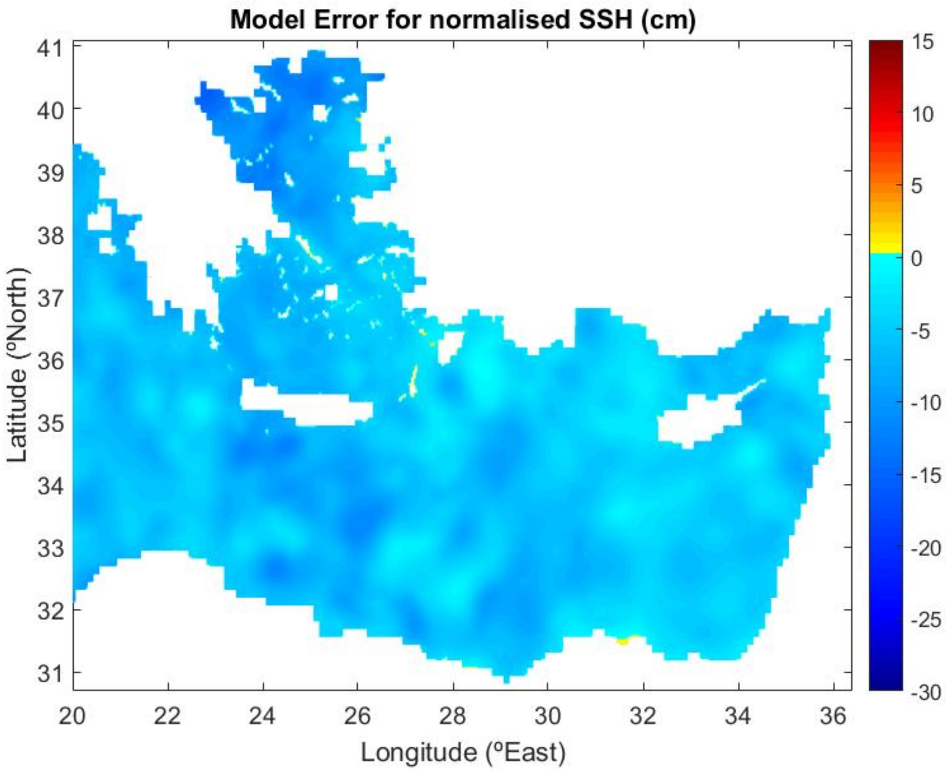


Figure 9 (d): Model's error (1/30) normalised SSH for the 12th of August 2015 –4th forecast

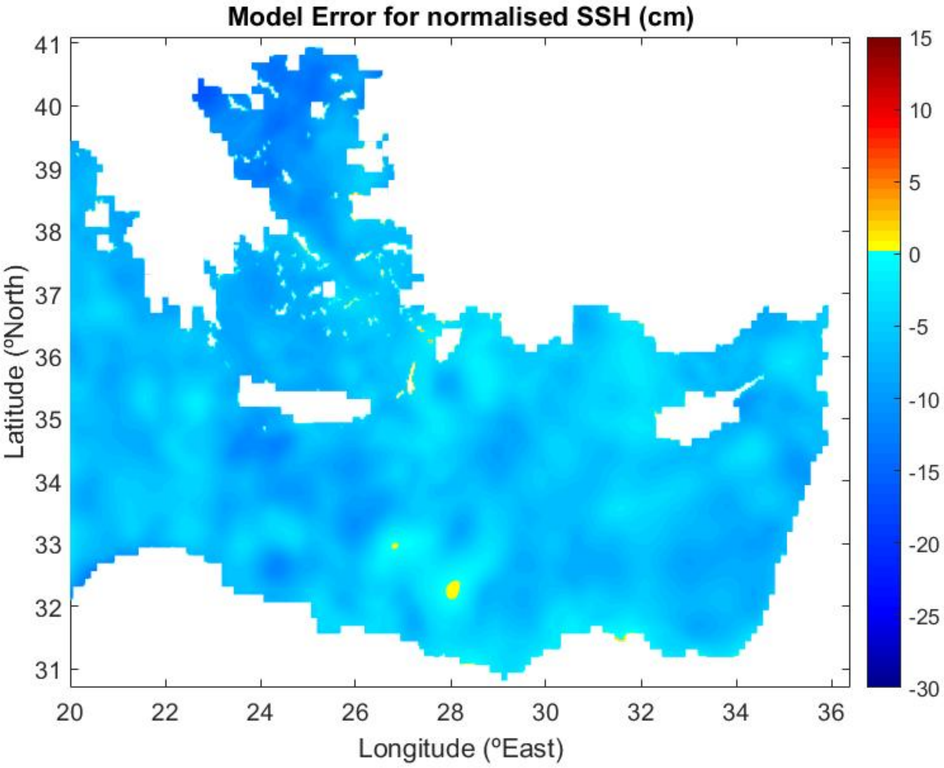


Figure 9 (e): Model's error (1/30) in normalised SSH for the 12th of August 2015 –5th forecast

Furthermore, instead of showing the differences between the model's errors of the normalised SSH in 1/60 resolution for February and August, some figures that are more interesting from another point of view will be given. In figures 10 (a) the monthly average SSH (not the error!) of the model (for the 1st forecast only) is given for February in the 1/30 . In addition, in figure 10 (b) the monthly average ADT from the satellite data is given for February as well. Despite the fact that these variables cannot be straightly compared, they can both show phenomena that appear in the wider area during the whole month. In figure 10 (b), there are several eddies (either cyclonic or anti-cyclonic) shown from the satellite data that are also forecasted by the model itself. For example, in the figures three eddies (two cyclonic and two anti-cyclonic) are indicated by black circles in both the model's and satellite's data.

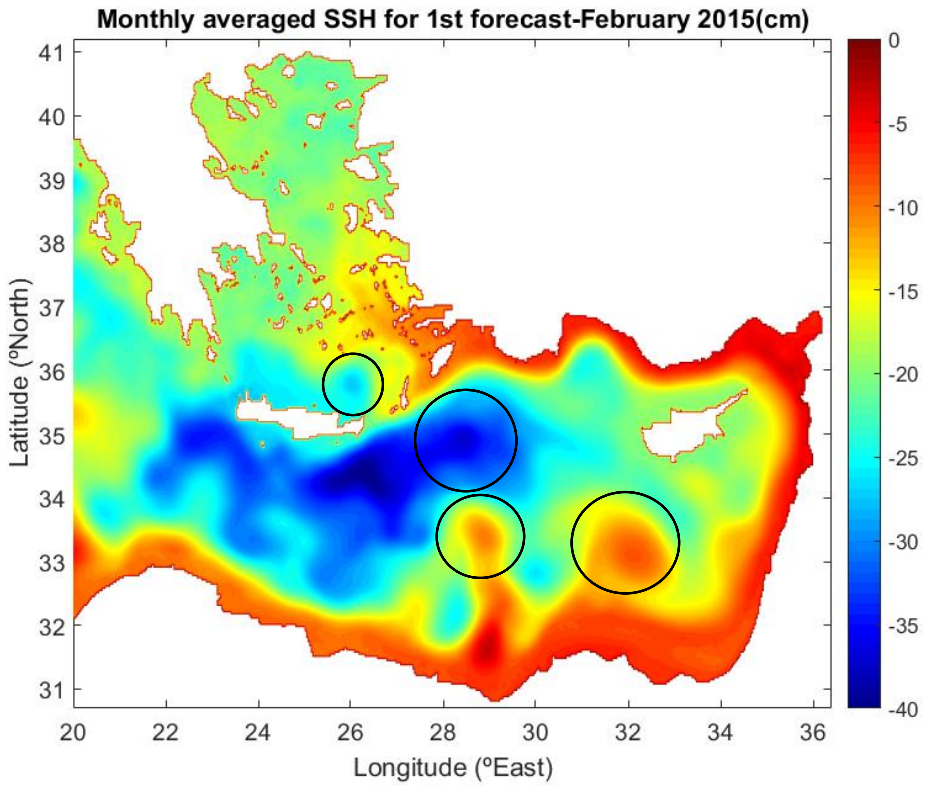


Figure 10 (a): Model's averaged SSH for February 2015–1st forecast (1/30 □)

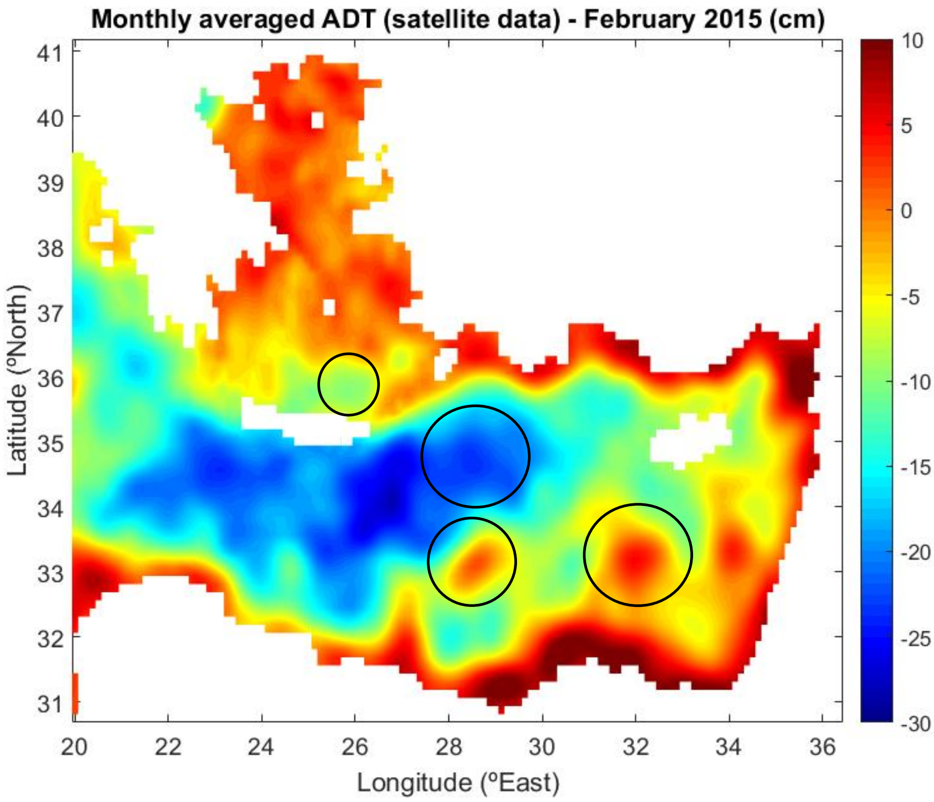


Figure 10 (b): Monthly averaged ADT for February 2015–satellite data

In figures 11 (a) the average SSH for the first forecast of the high resolution model (North Aegean) is shown. Moreover, in figure 11 (b) the monthly average ADT from satellite data for February 2015 is also shown.

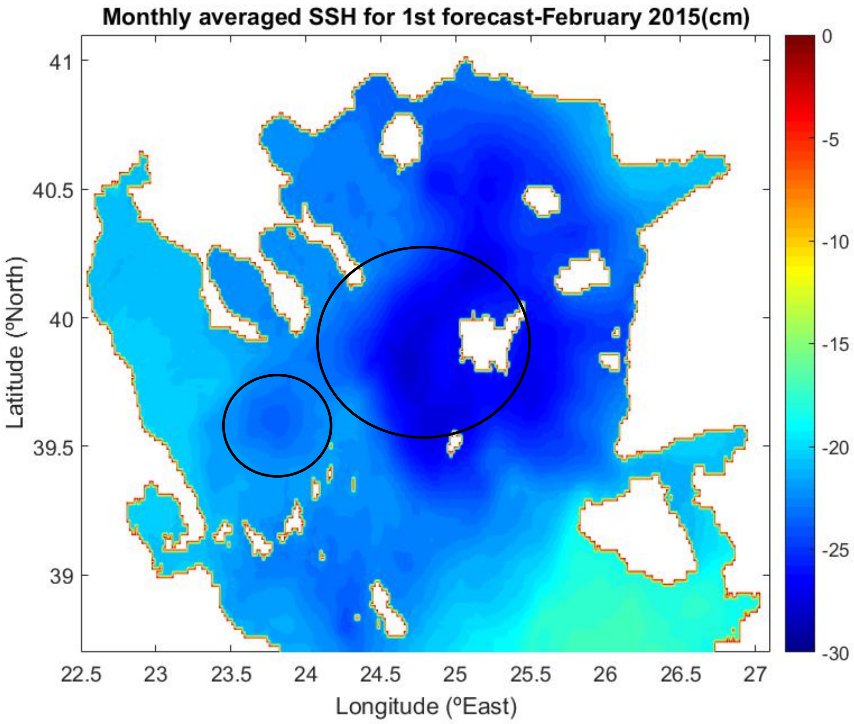


Figure 11 (a): Model's averaged SSH for February 2015–1st forecast (1/60 □)

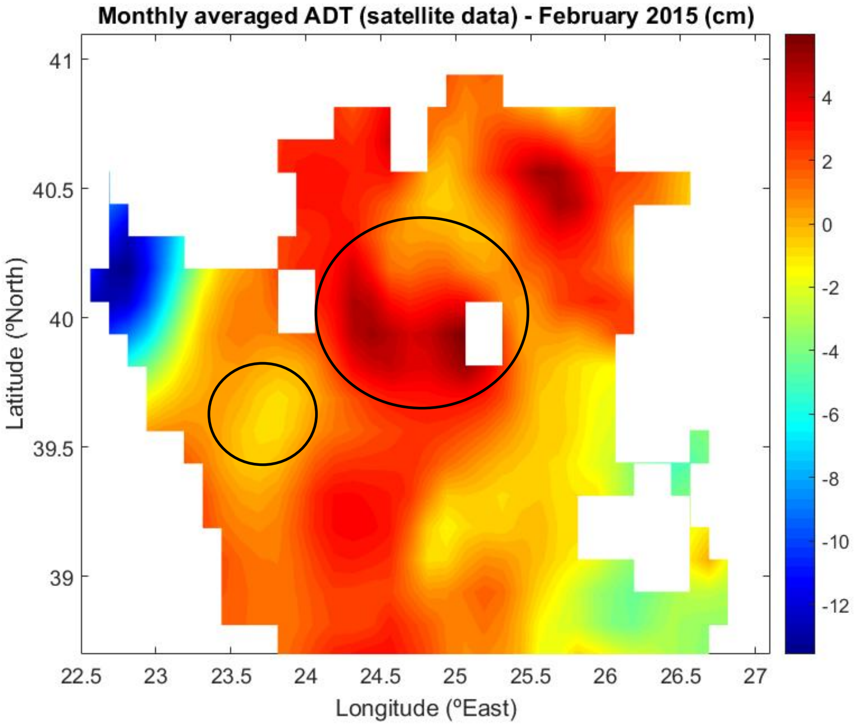


Figure 11 (b): Monthly averaged ADT for February 2015–satellite data

It is obvious that the two values cannot be directly compared. However, there are indications that the model performs well as it can forecast eddies that exist in reality, as the satellite data show. The eddies are indicated with black circles.

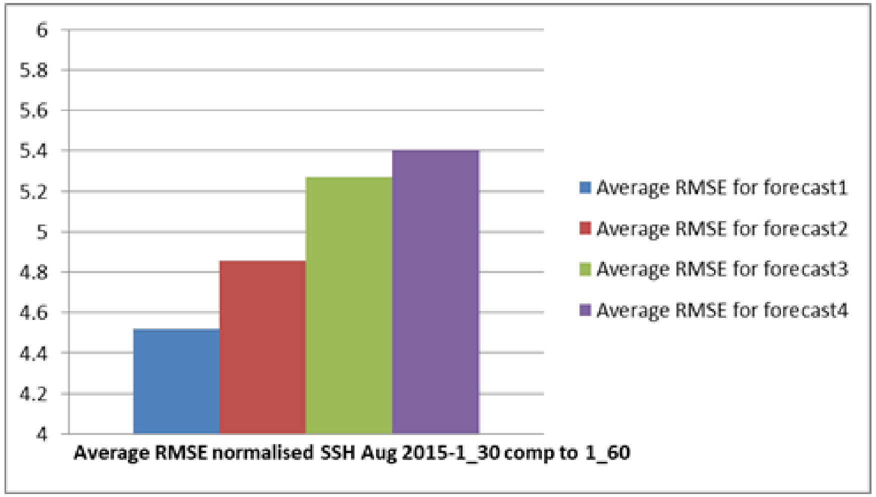
In order to see the statistical difference, the average Root Mean Square Error (RMSE) for every forecast, for each month and resolution was found for the normalised SSH. In figures 12 (a), (b), (c) and (d) the differences are obvious. Firstly, in August, as the days of the forecast go by, the average RMS errors increase. This trend is actually expected and reasonable. Secondly, winter shows much higher errors in relation to summer due to much higher variations of atmospheric pressure and barotropic environment. However, the way February's RMSEs follow is not actually the RMSE and then it keeps decreasing (in both resolutions). This can actually be interpreted because the model itself is nested to the wider model of the whole Mediterranean, which has a low resolution of 1/16 □ as already m

before. As a result, for this month particularly, the Mediterranean model could have demonstrated a significant error which was passed along to the ALERMO model. Obviously, the error was so big that the model itself managed to decrease it as days passed by. Furthermore, it would be very interesting to see the later evolution of the model if we could actually had the opportunity of more forecasts. For example, if the model gave out 8 forecasts, how would the model's RMSE would then evolve after the 5th forecast (if it would increase again)

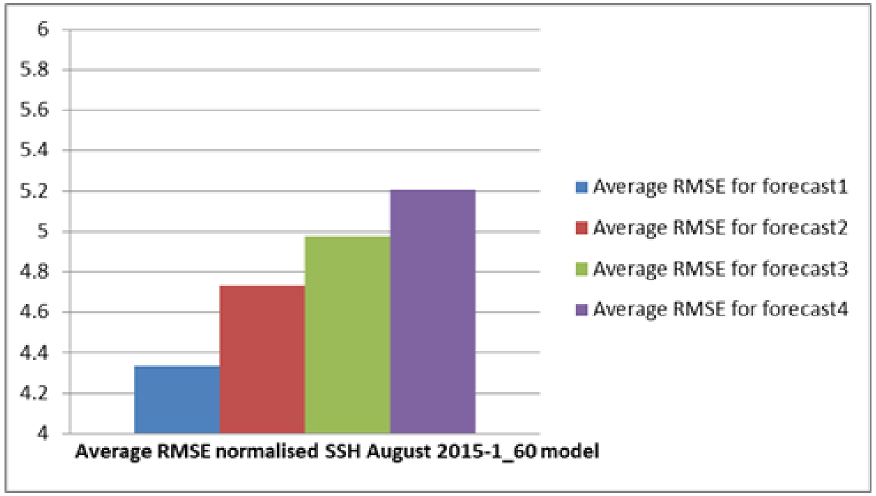
Finally, an increase in the model's spatial resolution results in decreased forecast errors and the RMS errors in August remain in much lower levels than in February. More accurately, in August it varies from 4.52 to 5.41 cm (1/30 □) and from 4.33 to 5.20 cm (1/60 □). In contrast, February gives much higher values and varies from 10.85 to 9.63 cm (1/30 □) and from 10.51 to 10.39 cm (1/60 □). It must als

comparison between the 1/30 □ and the 1/60

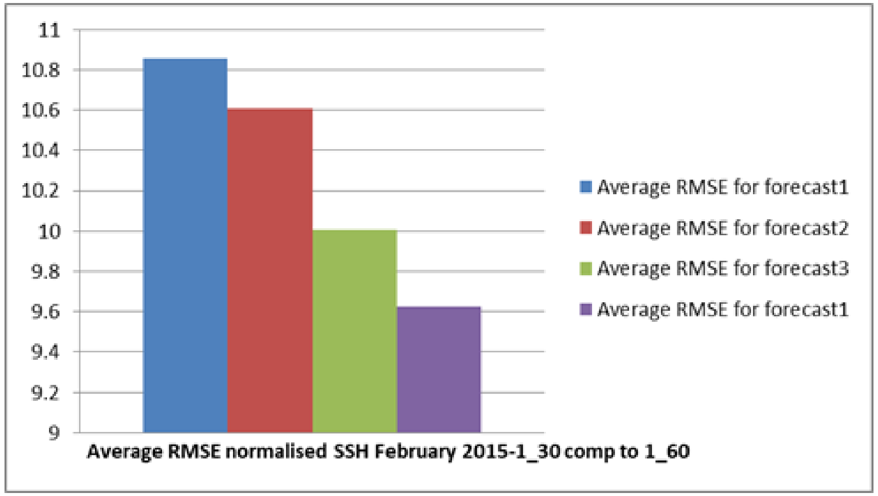
evaluation, only the North Aegean values were taken into consideration because any other comparison (e.g. between the whole Aegean Sea and the North Aegean) would be wrong and invalid.



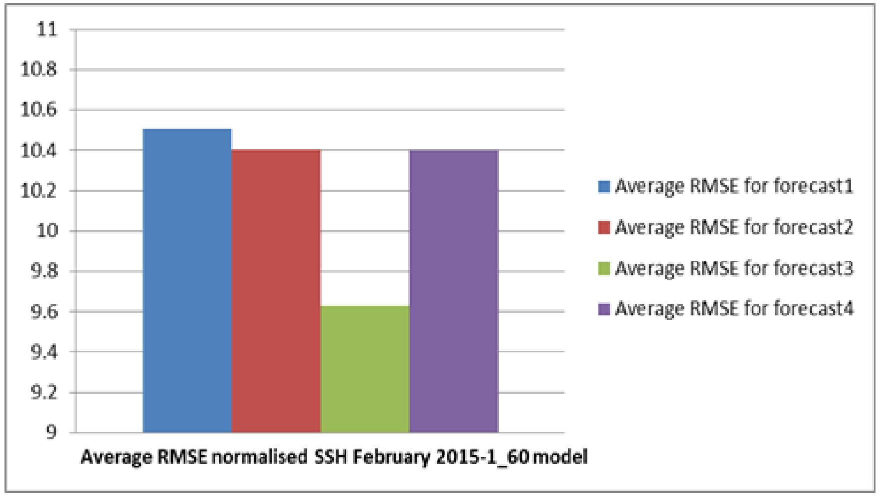
(a)



(b)



(c)



(d)

Figure 12– Average RMSE for normalised SSH in cm (a): August 2015 - 1/30^0 , (b): August 2015 – 1/60^0
(c): February 2015 - 1/30^0 , (d): February 2015 - 1/60^0

5.3 In-situ measurements

As already mentioned, in 2014 and 2016 many stations with CTD measurements took place in several areas in the Aegean by an oceanographic ship of the Greek Navy. Below, vertical profiles for salinity and temperature (in relation to depth) are shown. In the profiles, both models appear (1/30° and 1/60° resolution), if possible, and the data from the CTD measurements as well. Two different stations were chosen, one in the North Aegean Sea and one in the central Aegean Sea.

The first station that will be studied is station No 14 (referring to figure 2 (a)). It took place on the 29th of May 2014 and its exact coordinates were 39.17° North and 25.31° East. This station was chosen because its position is included in both models and it is very close to the Dardanelles' mouth so a possible effect from the BSW hopefully will be shown. In figures 13 (a) and (b) we have the salinity and the temperature vertical profiles respectively

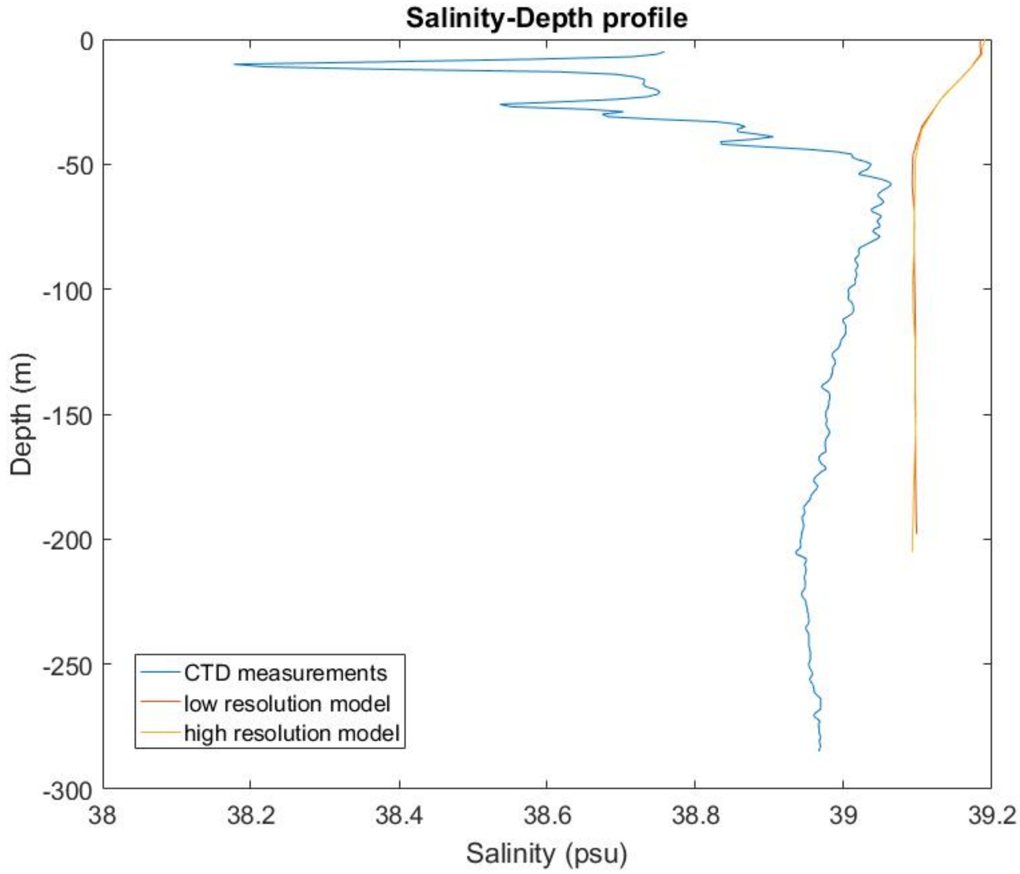


Figure 13 (a): Salinity vertical profile including both models' 1st forecast and CTD data

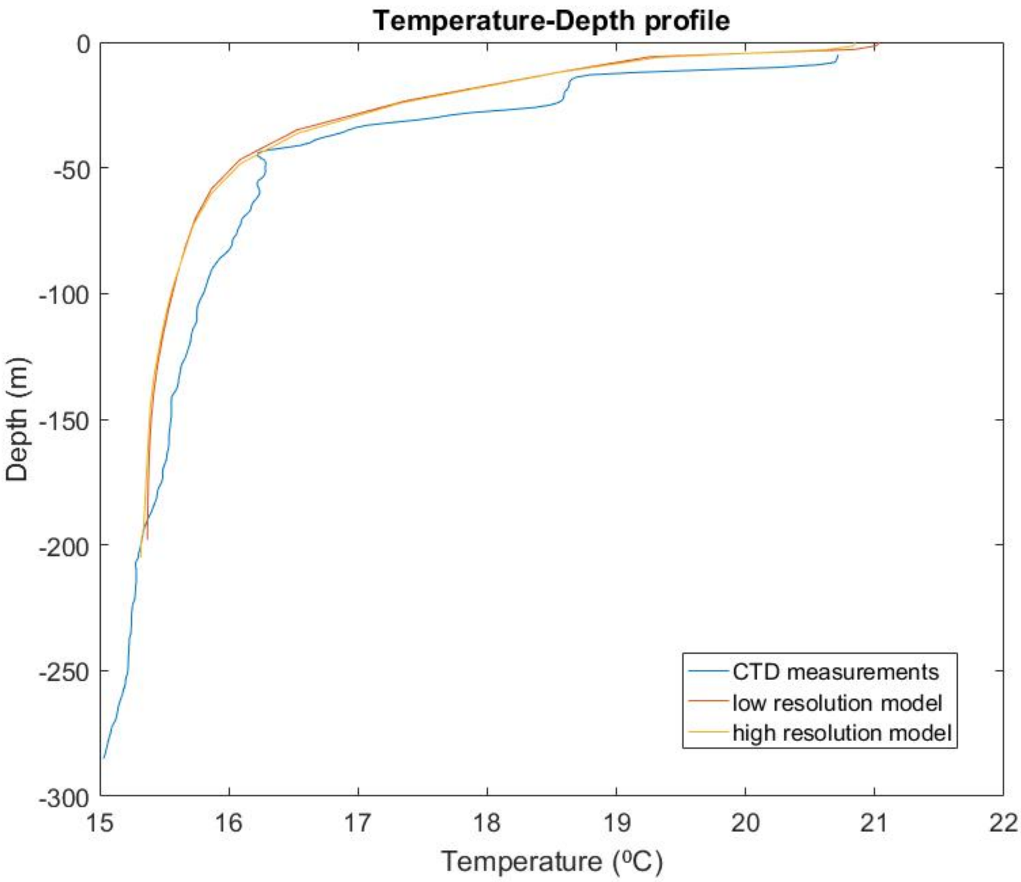


Figure 13 (b): Temperature vertical profile including both models' 1st forecast and CTD data

The model, in both resolutions performs quite well. Especially in the temperature profile, both models follow the curve of the thermocline amazingly well, with some small errors less than 0.3 □C in some dep 30m, 75m). The difference in the surface is around 0.3 □C which is als satisfying. However, a big difference would be expected in a "warmer" month like July, where the heating from the atmosphere is intense. In the salinity profile a difference in the surface layer is profound. Although it still remains small (approximately 0.5 psu) it indicates the fresher (less saline) waters that are coming out of the Dardanelles strait (BSW). As the models performed with almost zero differentiations in each forecast, the images from the 4th forecasts of the 26th of May showed no difference and there was no meaning in putting them in the project too.

The time period that these stations took place (May 2014-May 2016) were transitional periods (end of spring-beginning of summer). More accurately, these periods are characterized by the rise in atmospheric temperatures and the weakening of the winds. Facts that affect the temperature of the upper layer of the sea due to heating from the atmosphere and the reduction of the mixing. However, due to this transitional nature of May, the heating of the surface waters has not contributed to the creation of a deep surface layer. That is the reason why we observe in the temperature profile that the depth of the surface layer does not even exceed the range of 10 meters. The thermocline appears to be very intense (6-7 □C) and almost in every station it extends approximately to 50 meters depth. Below that depth, the water masses retain their "winter" characteristics and displaying temperatures around 15-16 □C.

Another interesting station is station No 28 (figure 2 (a)). Its exact coordinates were 40.5 □ North and 24. on the 30th of May 2014. However, looking the figures 14 (a) and (b) below, there is something that needs further interpretation.

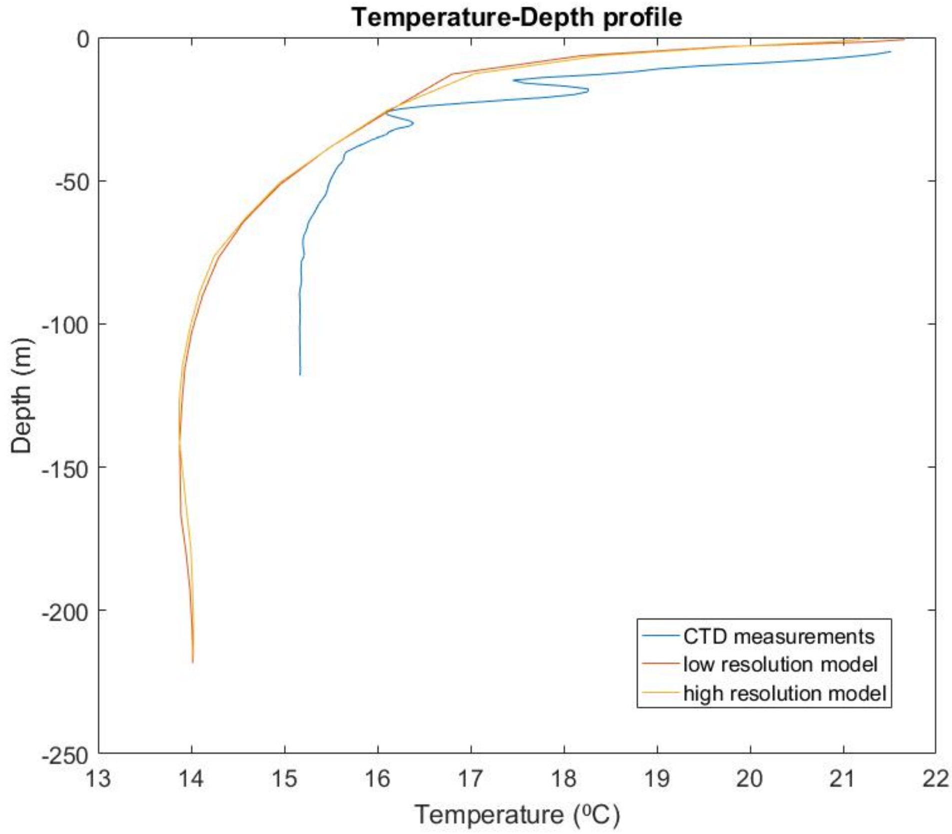


Figure 14 (a): Temperature vertical profile including both models' 1st forecast and CTD data

The temperature profile (Fig 14 (a)) seems to be quite reasonable and the models (in both resolutions) perform very well till the depth of 50 meters. After that depth, a slight difference is observed of around 1.2 □C. Generally, t curve of the thermocline is followed very well by the models

On the other hand, in figure 14 (b) the salinity profile from the CTD data indicates something very interesting. The salinity values of the surface layer are very low in relation to all the other values faced in the other stations. Furthermore, the station is quite far away from the mouth of the Dardanelles.

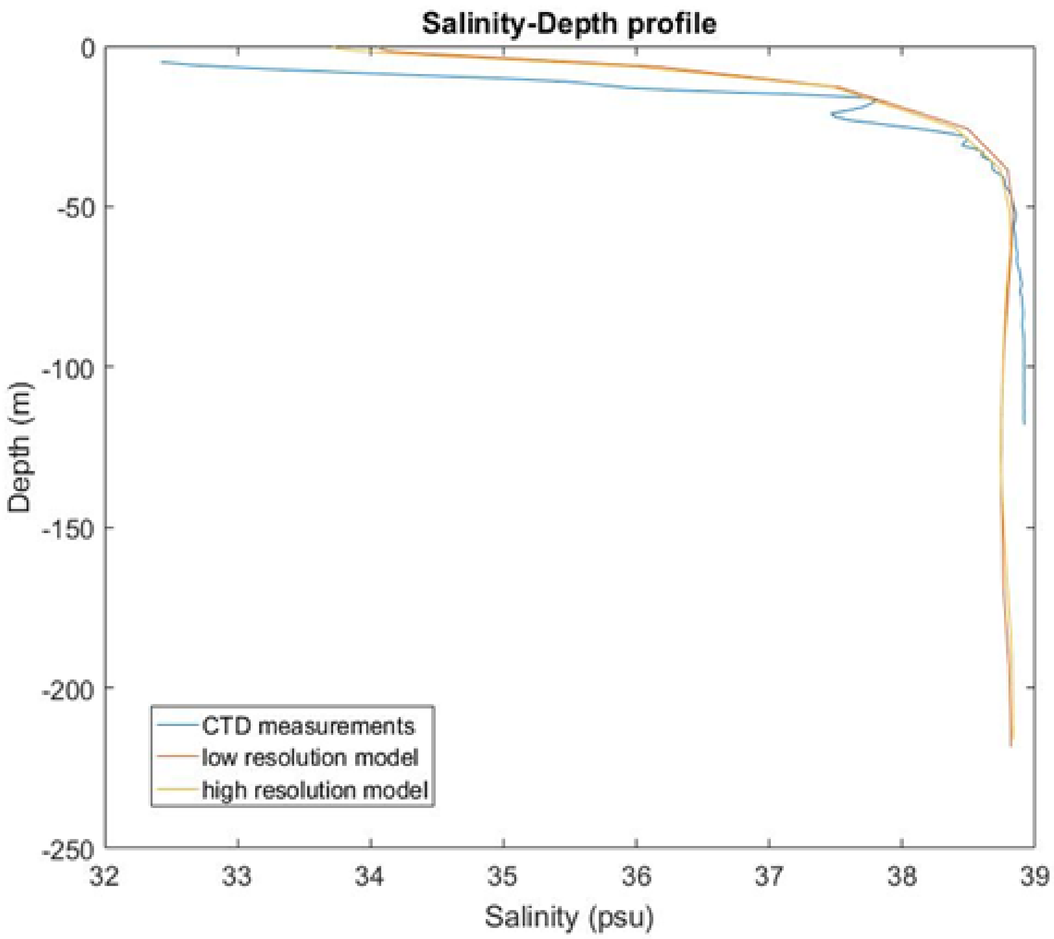


Figure 14 (b): Salinity vertical profile including both models' 1st forecast and CTD data

The reason lies upon the existence of big rivers that flow into the Aegean Sea very close to that specific station as already mentioned in the beginning of the this project. More specifically, the yellow arrows in figure 2 (a) show the mouths of two of Greece's biggest rivers, Strimonas and Nestos. Strimonas comes all the way from Bulgaria and has an average discharge rate of 100 m^3/sec of water into the Aegean Sea while Nestos has a rate of 50 m^3/sec (Kourafalou et al., 2003). A major output as a whole that is obviously affecting the nearby waters and is pretty obvious in the CTD data and already studied by Kourafalou et al., 2003. The surface has values of less than 33 psu and there is a salinity difference with the models of around 1.5 psu. The upper layer with the fresher (less saline) waters extend till the depth of 30-40 meters. After that depth, the usual expected values are present.

Finally, the last profiles shown in figures 15 (a) and (b) belong to station G3 which took place on the 27th of May 2016. It is in the central Aegean Sea and is included only by the low resolution model. The exact coordinates were 37.997□ North and 25.498□ East.

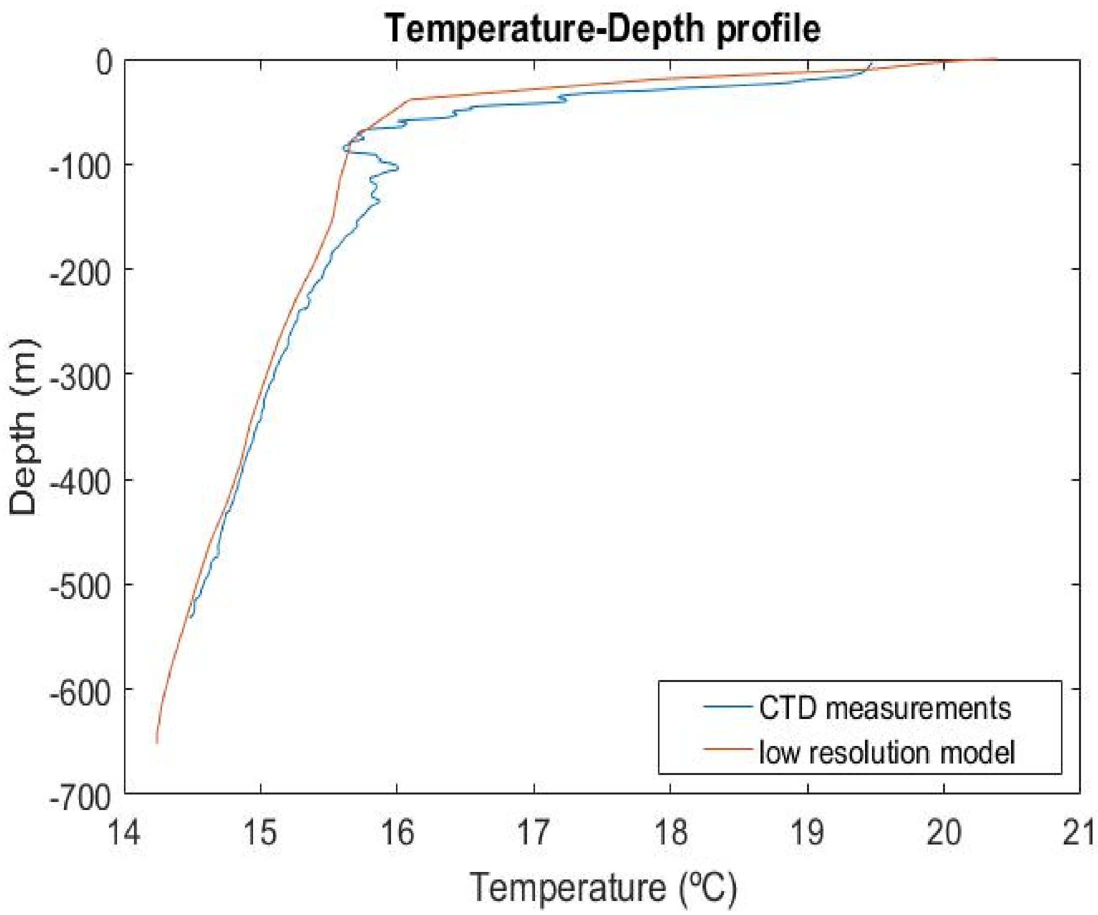


Figure 15 (a): Temperature vertical profile including model's 1st forecast and CTD data

The model (1/30 □) seems to pe

forecast with a small difference of approximately 0.5 □C in the surface. It keeps an impressively good track of the thermocline with a small difference in the depth around 120 meters.

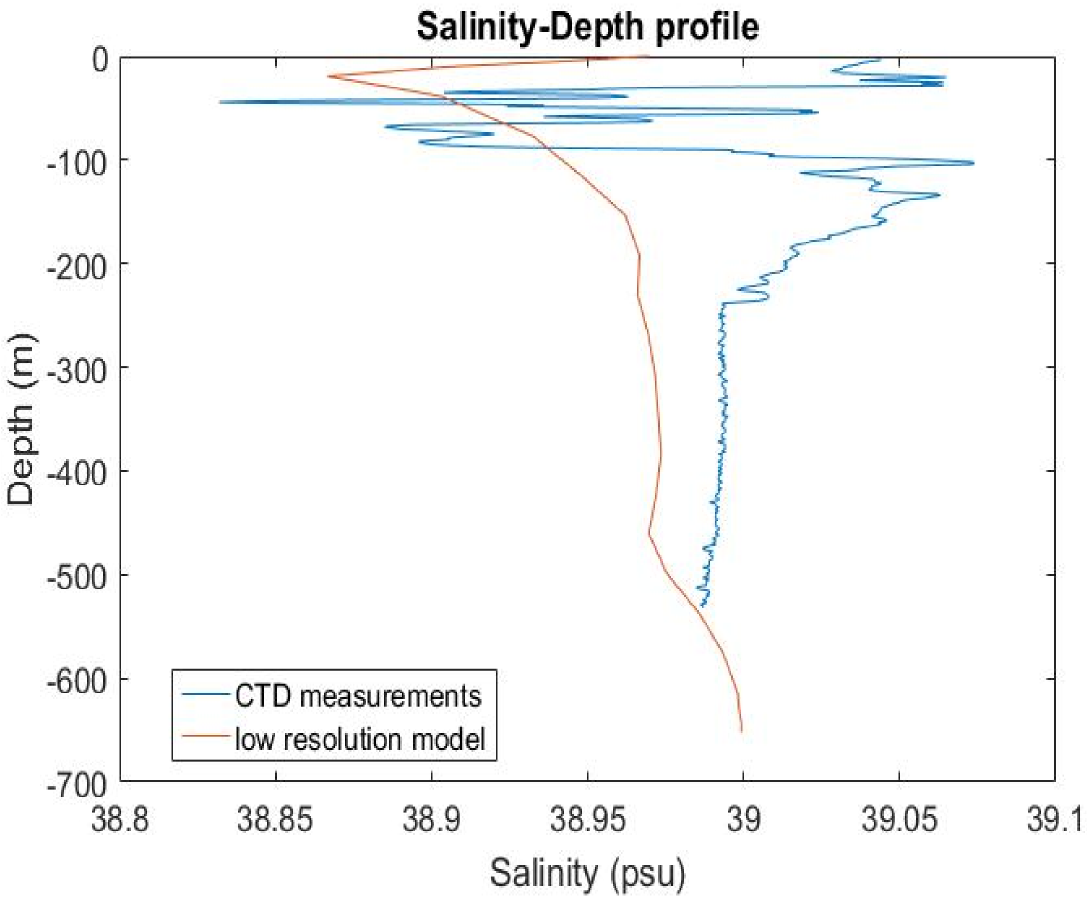


Figure 15 (b): Salinity vertical profile including model's 1st forecast and CTD data

Additionally, the salinity profiles are very good also. Despite the fact that they look very different, they are also misleading. The difference between the CTD profile and the model is insignificant. Even in the depth of 20 meters where it takes the highest value, it still remains less than 0.2 psu. As a result, it is quite clear that the model performs pretty well in the central Aegean Sea, far away from all the water inputs.

6. Conclusion

In conclusion, the ALERMO model performs very well. As proved, the errors' range varies in relation to the season (winter or summer) but they still remain with low values. The RMS errors that were computationally calculated were also quite low with an exception of winter in 2015. At that time period, the values of the normalised SSH were significantly high and probably this was actually the result of the nesting that exists between the ALERMO model and the wider, low-resolution model of the whole Mediterranean model operated by Italy (1/16 □). The initial co ALERMO had obviously a very high average error, which evidently the ALERMO (in both resolutions) managed to decrease throughout the forecasts, as shown in figures 12 (c) and (d).

The model seems to perform errors near the coastline of Greece's mainland and in the mouth of the Dardanelles Strait. In the first case a possible explanation is the outflow of many rivers in the Aegean Sea with cooler and less saline waters. In the second case the error can be attributed to the major rate of the outflow that the Dardanelles have throughout the year and especially in summer when the rate reaches its maximum and the errors as well.

Furthermore, the profiles from the CTD data showed that the model also performs very well in the water column vertically as well. In the central Aegean the errors remain very low. As expected, higher errors appear in the surface in the salinity profiles near the coastline of north Greece's mainland where major rivers flow out in the Aegean Sea. However, a detailed validation with salinity data has never been made before which would make that research very interesting and helpful if daily and monthly salinity data will be available in the future.

Taking into consideration the small time period that the ALERMO model is in operation, it must be stated that a huge progress has been made. The improvements are continuous and the actual results are very encouraging and promising at the same time.

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