atmosphere

MDPI

Article

The Role of Weather during the Greek–Persian "Naval Battle of Salamis" in 480 B.C.

Christos Zerefos [1,2,3,4,*], Stavros Solomos [1], Dimitris Melas [5], John Kapsomenakis [1] and Christos Repapis [1,4]

1 Research Centre for Atmospheric Physics and Climatology, Academy of Athens, 106 80 Athens, Greece; ssolomos@academyofathens.gr (S.S.); jkaps@academyofathens.gr (J.K.); repapis@mariolopoulosfoundation.gr (C.R.)
2 Biomedical Research Foundation, Academy of Athens, 115 27 Athens, Greece
3 Navarino Environmental Observatory (N.E.O.), 24 001 Messinia, Greece
4 Mariolopoulos-Kanaginis Foundation for the Environmental Sciences, 106 75 Athens, Greece
5 Department of Applied and Environmental Physics, School of Physics, Faculty of Sciences, Aristotle University of Thessaloniki, 54 124 Thessaloniki, Greece; melas@auth.gr
* Correspondence: zerefos@geol.uoa.gr

Received: 14 July 2020; Accepted: 6 August 2020; Published: 8 August 2020

check for updates

Abstract: The Battle of Salamis in 480 B.C. is one of the most important naval battles of all times. This work examines in detail the climatically prevailing weather conditions during the Persian invasion in Greece. We perform a climatological analysis of the wind regime in the narrow straits of Salamis, where this historic battle took place, based on available station measurements, reanalysis and modeling simulations (ERA5, WRF) spanning through the period of 1960–2019. Our results are compared to ancient sources before and during the course of the conflict and can be summarized as follows: (i) Our climatological station measurements and model runs describing the prevailing winds in the area of interest are consistent with the eyewitness descriptions reported by ancient historians and (ii) The ancient Greeks and particularly Themistocles must have been aware of the local wind climatology since their strategic plan was carefully designed and implemented to take advantage of the diurnal wind variation. The combination of northwest wind during the night and early morning, converging with a south sea breeze after 10:00 A.M., formed a "pincer" that aided the Greeks at the beginning of the clash in the morning, while it brought turmoil to the Persian fleet and prevented them to escape to the open sea in the early afternoon hours.

Keywords: naval battle of Salamis; ancient Greece; Persians; sea breeze; Etesians; ERA5; WRF

1. Introduction

September 2020 marks the anniversary for the 2500 years that have passed since the famous naval battle of Salamis which took place in late September 480 B.C. That titanic naval battle historically represents the clash of two major civilizations, namely the Hellenic and the Babylonian-Persian. As will be seen in the following paragraphs, the knowledge of local climatology by the Greek admirals was used effectively in their strategic plans. The prevailing summer circulation in the Aegean Sea is defined by the combination between the monsoon thermal low, centered over the high plains of Iraq and the high pressure system that is established in the summer over the Balkans. This results in the establishment of a background system of northerly winds in the Aegean Sea called "Etesians", which in Greek means "annually recurring". The Etesian winds were well known for their annual recurrence and strength by ancient Greeks and other Eastern Mediterranean seafarers. Aristotle describes these winds, their timing (after the summer solstice) and their strength with great accuracy [1]. On a local scale, the summer wind regime in the Aegean Sea is determined by the relative strength between the Etesians and the local winds, such as the sea breezes. The ancient Greeks were aware of such local climatologies which, as will also be shown in the following sections, are remarkably similar even today, 25 centuries later.

Before studying the climatological conditions in the particular area of Salamis, it is worth presenting a brief historical background focusing on certain weather-related incidents that took place before the naval battle at Salamis. This description is based on all available ancient sources regarding the weather conditions during the Persian invasion in Greece. The spark that started the flame of the Persian invasion in Greece can be traced back to the Ionian Revolt in 499 B.C. when Greek colonies in Asia Minor rebelled against the Persian rule and both Athens and Eretria supported their uprising [2] (5, 35) (*The numbers inside the parentheses denote book chapter and lines*).

This action led the Persian king, Darius, father of Xerxes, to seek revenge from Greece. The first attempt which took place in 492 B.C. led by the Persian General Mardonius turned into a disaster, since almost all of his fleet sank in a severe storm off the shore of Mount Athos, in North Greece [2] (6,44) (Figure 1). The second attempt took place in 490 B.C. under the command of the Persian Admiral Datis and Persian General Artaphernes. Their defeat in the battle of Marathon in 490 B.C. is well known [2] (6, 102–105) and celebrated globally during the Olympic Games.

After their defeat in Marathon, the Persians postponed their preparations to invade Greece for almost nine years. This postponement was due to both the rebellion of Egypt and the need to expand the volume and power of the Persian forces. It was decided that the third attempt to invade Greece should take place inland, rather than at sea, by bridging Hellespont from Abydos to the opposite shore of Sestus in the spring of 481 B.C (Figure 1). The bridging failed on account of a storm, which destroyed whatever Xerxes' engineers had made [2] (7, 33). The storm, which dismantled the construction, must have been accompanied by gale-force winds. According to Herodotus, the solution was to place three hundred and sixty ships connected side-by-side so that they would make up a bridge, over which the Persian army finally managed to cross into Europe in the spring of 480 B.C. [2] (7, 36). Bearing in mind the destruction of the Persian fleet due to heavy seas in the area of Mt. Athos twelve years before (492 B.C.), Xerxes decided to set up an isthmus of approximately two kilometers at the Peninsula of Athos [2] (7, 24). The vestiges of that isthmus are still apparent even to this day in a region called Nea Roda (see Figure 1).

Subsequently, the Persian marine and land forces met at the Evros estuary (Figure 1) and Xerxes himself inspected the fleet [2] (7, 128). The triremes counted were one thousand two hundred and seven, while the total of the rest of the ships amounted to three thousand [2] (7, 21). The Persian fleet sailed in parallel to the advancing land troops, until they reached the Axios estuary at the Thermaic Gulf, where all Persian land forces gathered (Figure 1). The Greeks, in their attempt to intercept the Persian invasion, decided to occupy Thermopylae with their land forces and Artemisio (Figure 1) with their fleet [2] (7, 175). Eleven days after the Persian fleet had set sail from the Thermaic Gulf, it arrived at the coast of Magnesia (see Figure 1). The next day, gale-force northeast winds (i.e., Etesians) brought about very heavy seas which lasted for three days [2] (7, 188). It is estimated that three hundred triremes and dozens of smaller ships were lost, while larger vessels were carried away by the winds and the heavy seas to the coasts of Pelion. It is obvious that the disaster caught the Persians off guard and, in panic, those of them who survived set sail to the southeast end of Magnesia, where they anchored in the Pagasetic Gulf (Figure 1). The Greeks, who were informed by the day scouts about the Persian fleet damage, returned at the highest possible speed from Chalkis to Artemisio (Figure 1), so that they would arrive there earlier than the Persian ships. As a matter of fact, they also captured fifteen of them [2] (7, 8); [3]; [4] (8, 15). Another two hundred Persian ships attempting to circumnavigate Euboea were lamentably wrecked at Cape Kafireas (Figure 1). At the same time the Greek army was defeated at Thermopylae and the Greek fleet set sail south to protect the southern regions [4] (8, 21). The Persian fleet anchored in Artemisio and they stayed there for several days, during which their land troops were passing through Thermopylae, so that at the demand of King Xerxes the entire army would be able to see the fallen Greeks at Thermopylae on their way to Athens [4]. When the Persians arrived in the city of Athens, which was completely destroyed, their fleet must have numbered about one thousand ships, whereas the corresponding Greek fleet comprised around three hundred [5] (338–343).

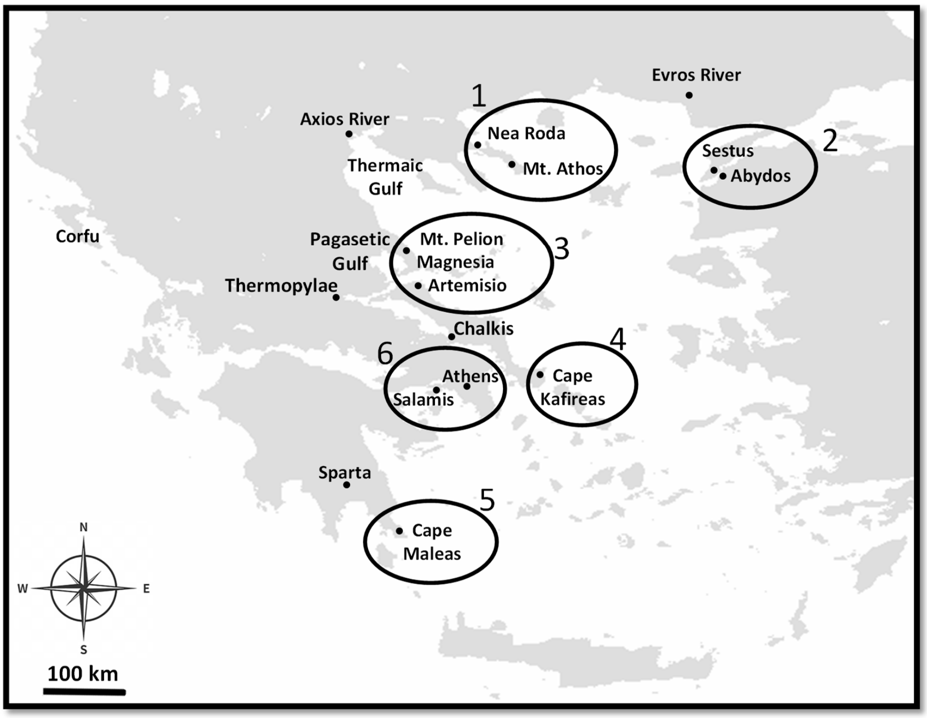

Figure 1. Weather related events during the Persian invasions in Greece. (1) Mardonius' fleet is completely destroyed by a storm at Mt. Athos in 492 B.C.; (2) storm and gale winds prevent Xerxes' army from crossing into Europe (481 B.C.); (3) gale-force northeast winds and heavy seas lasting for three days destroy three hundred triremes and dozens of other ships (480 B.C.); (4) two hundred Persian ships were wrecked by strong winds at Cape Kafireas in their attempt to approach Athens from the open sea (480 B.C.); (5) the Greeks from Corfu fail to join the allied Greek forces in Salamis due to strong winds at Cape Maleas (480 B.C.); (6) naval battle at Salamis.

The decisive clash between the Greek and the Persian forces took place in the straits between Attica and Salamis (Figure 1) and went down in history under the name "The Naval Battle of Salamis". This naval conflict is the focus of our study. More specifically, we examine how the Athenian leader Themistocles took advantage of the prevailing local climatological conditions to develop an ingenious strategic plan that led to a great victory against the far more numerous navy of the Persian king, Xerxes. Our main evidence on the weather conditions during the battle comes from Herodotus, who wrote his 'Enquiries' around 440–430 B.C., some 40–50 years after the second invasion of Persia in Greece. Moreover, the tragedian Aeschylus, who personally participated in the battle, in his 472 B.C. tragedy 'Persae' describes the space and time development of the naval battle. Additional information is available by some of the later ancient historians that dealt with the Greek–Persian wars such as Thucydides, Plutarch, Pausanias, Diodorus Siculus and Ctesias of Cnidus. In Section 2, we present the observations and modeling tools used in our study. Section 3 includes the analysis of the prevailing climatological conditions as observed, measured and modeled in the straits of Salamis, as well as their diurnal variability, taking into account the local and larger scale climatological forcing systems. Discussion and conclusions are presented in Section 4.

2. Methodology

Combined observational and modeling data are used to describe the wind climatology in the greater area of the Saronic Gulf and Salamis Straits. More details on the available measurements and model configurations follow below.

2.1. Observational Data

The observations used in the present study include wind speed and direction at 10 m from two coastal stations: (a) Elefsina (38.04° N, 23.54° E) during 1960–2010 and (b) Piraeus (37.93° N, 23.63° E) during 1960–2010. The stations of Elefsina and Piraeus belong to the Hellenic National Meteorological Service and these measurements are available at 3-h intervals.

2.2. Reanalysis and Modeling

In order to analyze the climatology of atmospheric dynamics and wind properties in the area of interest, we used the ERA5 dataset [6] that is available globally at 0.25 ° × 0.25 ° grid space. The ERA5 period 1979–2019 is used to extract the climatological properties of the mean sea level pressure over the greater area of southeast Europe and Asia Minor. For the reconstruction of wind properties inside the Saronic Gulf we used the WRF model [7] in a telescopic nesting configuration as seen in Figure 2. The outer model domain is at 12 × 12 km, the intermediate (d02) is at 3 × 3 km and the finest domain (d03) is at 1 × km grid space, respectively. Downscaling at this higher analysis is necessary to allow the model to reproduce the local wind flows (e.g., sea breeze) that cannot be described at the coarser ERA5 resolution. To obtain the average wind properties in the area, we performed ten separate runs with the WRF model. Each one of these runs is driven by the monthly average ERA5 atmospheric fields for the month of September of each particular year, from 2007 to 2016. The output of each run contains 24 hourly values (00:00–23:00 UTC) that are also averaged by hour to produce the hour–average wind maps for the period between 2007 and 2016, which are shown in the following sections.

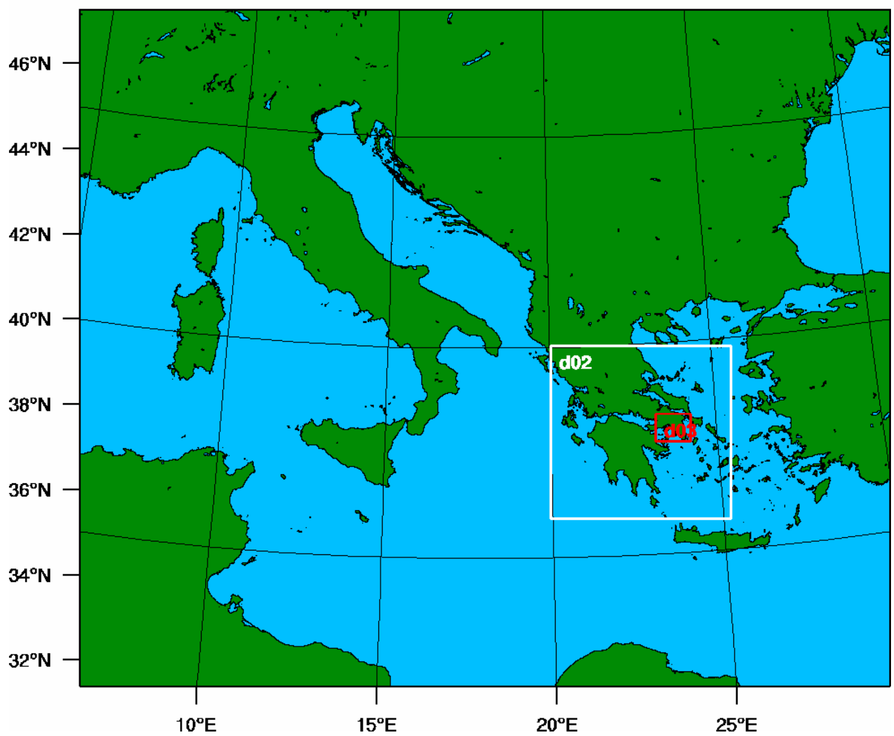

Figure 2. Nesting structure of the Weather Research and Forecasting (WRF) model setup: External domain (d01) at 12 × 12 km grid space; Intermediate domain (d02) at 3 × 3 km grid space; and inner domain (d03) at 1 × 1 km grid space.

3. Results

Our effort to simulate the meteorological conditions that prevailed during the sea battle of Salamis is based both on the historical texts and on today's knowledge regarding the prevailing meteorological conditions in the region of the Saronic Gulf. The analysis in this section is focused on the local wind features which, according to Plutarch, Themistocles was so well aware of Ref. [3].

3.1. Climatology of Synoptic Scale Dynamics

As revealed by numerous studies, the wind regime in the area is very complicated [8,9]. During the warm period of the year, the wind regime is dominated by two distinctively different wind systems, namely the Etesians and the sea breeze. The Etesians are manifested as an annual summer strong northerly flow in the Aegean, while in the Greater Athens Area (GAA) they appear as northeasterly winds with moderate to strong speeds. They last from May until the beginning of October and they blow in the Aegean with significant intensity in some cases, reaching even that of a gale. The atmospheric circulation that creates these winds is of monsoon type and it is brought about by the combination of the high pressures prevailing during the summer period in the Balkans and Central Europe, with the extension of Iraq's extended thermal low up to the Middle East and Cyprus [10]. The weakening of the Etesians allows the development of local circulation systems, such as sea/land breezes along the axis of the basin (NE to SW). As seen by the 41-year (1979–2019) climatological analysis of the ERA5 mean sea level pressure (Figure 3), a weakening of the horizontal pressure gradient is evident in the Aegean Sea during September compared to the strong pressure gradient that prevails in July and August. This condition also results in a weakening of the geostrophic wind component that forms the north Etesian winds in this area.

3.2. The Course of Weather Conditions during the Battle

The local characteristics of Etesian winds in the Aegean, regarding their direction and intensity, are determined by topographic features such as islands, capes and mountains as well as by their interplay with other systems of local circulation. For example, the sea breeze system in the Saronic Gulf is always active, because it depends on the thermal gradient between the sea and land. Whether this southeast to southwest sea breeze cell will be allowed to fully develop and become dominant in the area depends on the strength of the counteracting Etesian winds blowing in the same area from northwest to northeast directions. Themistocles' and the Athenians' knowledge of local climatology must have played an important role in the selection of Salamis Straits for the confrontation with the Persian fleet. The obvious advantage offered by the narrow channel was that the Persian fleet would not be able to perform tactical maneuvers in order to circle the Greek ships. Moreover, Themistocles knew that in that particular time of the year (end of September) there were two possibilities for the wind properties in Salamis: (i) a prevailing north wind (Etesian) making the area unsuitable for sea-battle, especially since the Persians had only recently experienced severe casualties due to the Etesian winds or (ii) a rather moderate northwest wind early in the morning veering to a persisting southeast sea breeze channeling into the Straits of Salamis from about 10:00 local standard time (LST) until sunset. The course of weather conditions during the conflict is described in this section in parallel with the corresponding historical evidence. The results are presented in LST for easier comparison with the ancient sources.

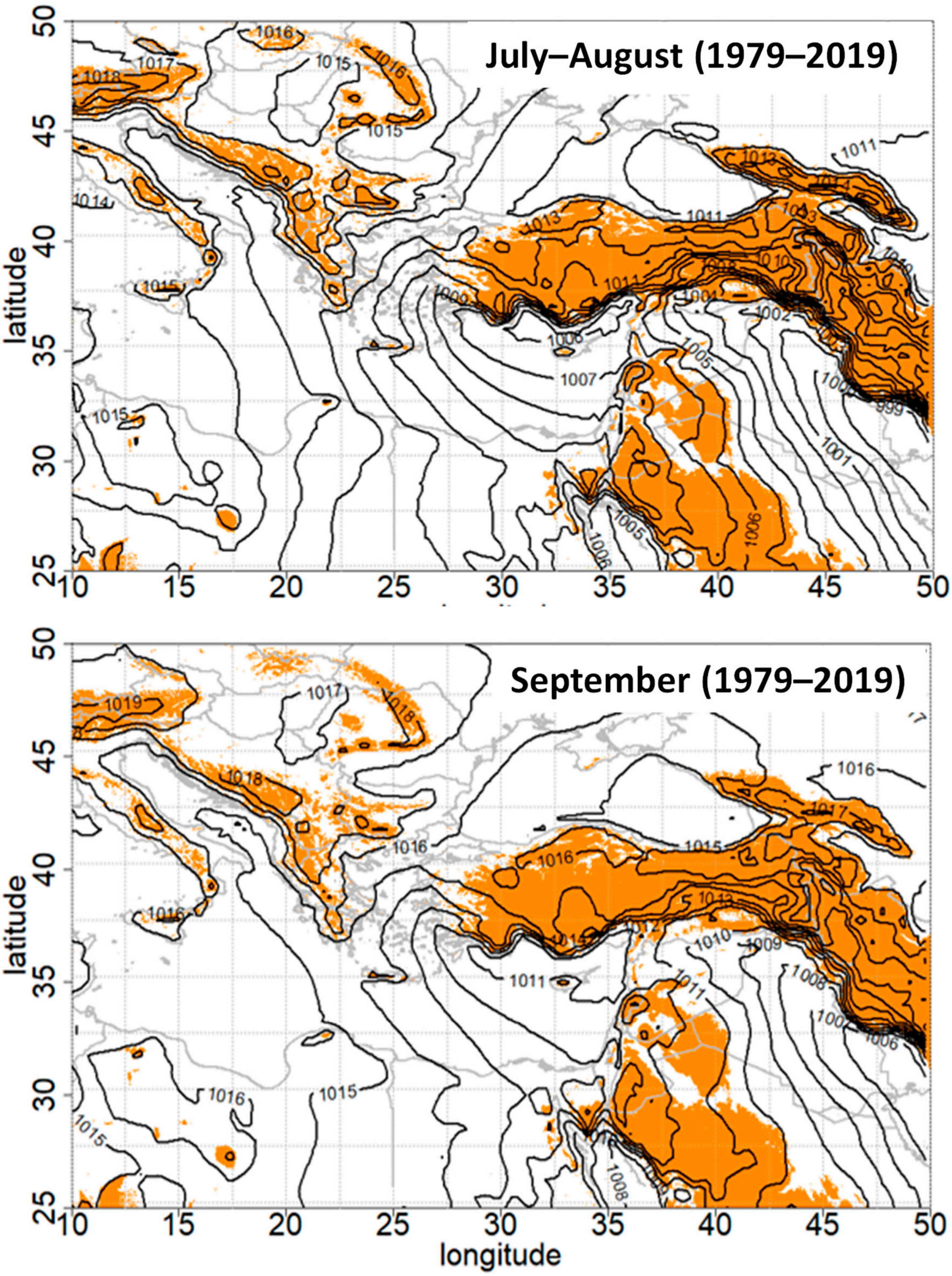

Figure 3. European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis (ERA5) average mean sea level pressure (mb) at 06:00 UTC for the period of 1979–2019 during (**top**) July–August and (**bottom**) September. Elevation higher than 700 m is shown by shaded areas. An almost double pressure gradient is evident over the Aegean Sea for July and August compared to September.

In the evening before the battle, the Greek fleet resides at the Straits of Salamis (see the map in Figure 6) while the Persian armada holds position at Phalerum Bay [4] (8.66–7). Although the exact number of ships for both sides differ depending on the source, it is safe to say that the number of the Persian ships was around four times greater than that of the Greek ones. The intention of the Greek commanders was to bring the conflict in the Salamis Channel because, according to Herodotus: "to fight in the narrows is to our advantage, but to fight in open waters is to their advantage" [4] (8.60). The advantages included the narrow front, the Greek hoplites on the shore that would cover their right flank, and the Persian fleet that would have to enter the relatively confined vestibule between Cape Cynosoura and Attica coast to the north [11]. To lure them into the narrows, Themistocles sent his messenger, Sicinnus, to deliver a misleading message to King Xerxes. Sicinnus reported that the Greeks were demoralized and considering flight and his words were taken by Xerxes to be true [4] (8.74–76); [5] (355–362). Upon this news and during the night hours, Xerxes sent a detachment to the deserted island of Psitalia [4] (8.76), a squadron to close the narrows between Salamis and Megara [5] (368); [4] (8.79) and finally, the main fleet to block the eastern exits. At dawn, he would attack what he considered to be the remaining Greek fleet.

Historians determine the date of the naval battle of Salamis between the 25th and 30th September, 480 B.C. As described previously, the most prevalent weather type during September in Salamis is either that of the sea breeze or a combination of the annual winds with the sea breeze. At the end of September, there is, of course, a slight probability of rainfall or even a chance of a summer storm during the early afternoon hours. However, Aeschylus mentions that there was sunshine on the morning of the sea battle, which leads us to the exclusion of any other type of weather except that with a sea breeze or/and with an annual wind, usually observed, as was mentioned above, when the sky is clear.

3.2.1. Station Measurements

The climatological evidence of the Saronic Gulf sea-breeze is apparent at the coastal station of Piraeus (37.93° N, 23.63° E), which is located about 4 km east of the battlefield and at the coastal station of Elefsina (38.06° N, 23.56° E), which is located at the northwest side of the Salamis Channel at about 10 km distance from the battlefield. Wind measurements in Piraeus and Elefsina stations are available at three-hour intervals. Analysis of the 50 years (1960–2010) wind measurements in Elefsina (Figure 4 top), indicates how the sea breeze takes effect between 11:00–17:00 LST characterized by south winds of up to 4–6 m/s speed and how the north winds prevail during the night and early morning (02:00–08:00 LST and 21:00–23:00 LST). The north winds in Elefsina are associated either with synoptic north flow (Etesians) or with weaker downslope winds from the mountains at the north of the station. Similarly, the 50-year (1960–2010) wind measurements in Piraeus (Figure 4 bottom), indicate the existence of significant south and southeast sea breeze components up to 6 m s^{-1} during 11:00–21:00 LST, with north winds prevailing for the rest of the day. The percentage of calm conditions (0–2 m s^{-1}) during the night and early morning hours is also significant in Piraeus, reaching about 30%–35%. The north sector winds are in general stronger at both stations, reaching up to 10–12 m s^{-1} while the south sector winds, which are associated with the sea breeze, reach up to 6–8 m s^{-1}. A similar analysis for July and August 1960–2010 at Elefsis and Piraeus stations (not shown) results in higher frequencies of recorded north Etesian winds compared to September. In addition, an earlier initiation of the sea breeze circulation (11:00 LST) is evident for September compared to July–August, especially at the station of Piraeus that is closer to the open Saronic Gulf.

3.2.2. Model Simulations

In order to display the spatial distribution of the major meteorological features during the course of the conflict, we analyze the average wind derived from the ten WRF model runs. As described in Section 2, these runs are driven by the ERA5 monthly average fields for September 2007–2016. The modeling results are shown in the following paragraphs along with the related classical literature quotations. The average northeast Etesian wind from the intermediate model grid at 3 × 3 km grid space is evident in Figure 5 at 08:00 LST. Channeling effects accelerate the flow at Kafireas Straits and Cape Maleas and the 10-year average winds for September exceed 10 m s^{-1} and 6 m s^{-1} in these areas, respectively. Such wind conditions explain the Persian fleet losses in their way from Artemision towards Salamis along the east coast of Euboea (see also Figure 1) and the failure of Corfu fleet to join the Greek forces due to adverse weather south of Peloponnese at the channel between Cape Maleas and Cythera [2] (7.168). The possible evolution of weather conditions on the day of the battle is shown in Figure 6 from the 10-year average model runs at 1×1 km grid space.

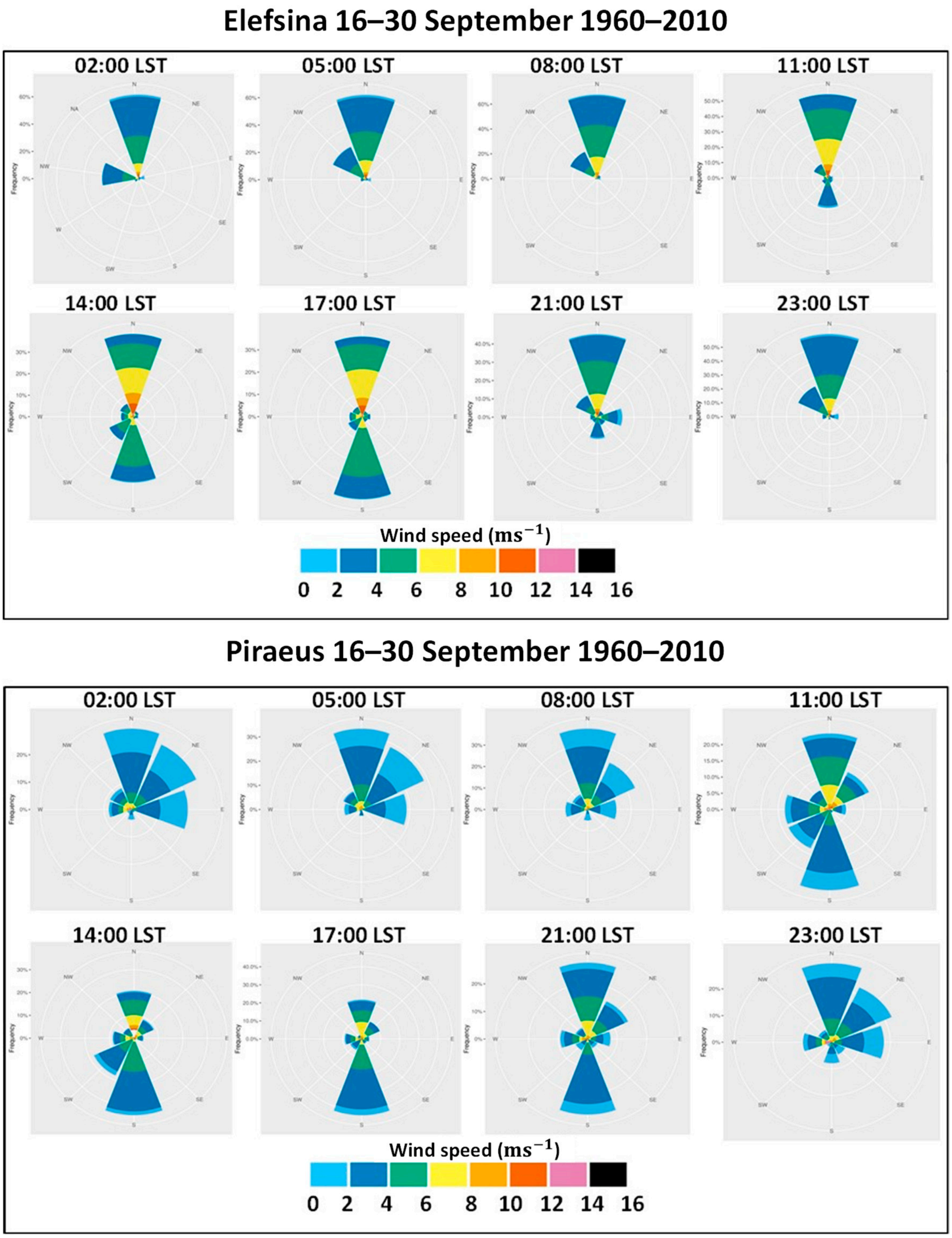

Figure 4. (**top**) Elefsina (38.04° N, 23.54° E) during 1960–2010 and (**bottom**) Piraeus (37.93° N, 23.63° E) during 1960–2010. Elefsina and Piraeus measurements are available at 3-h intervals.

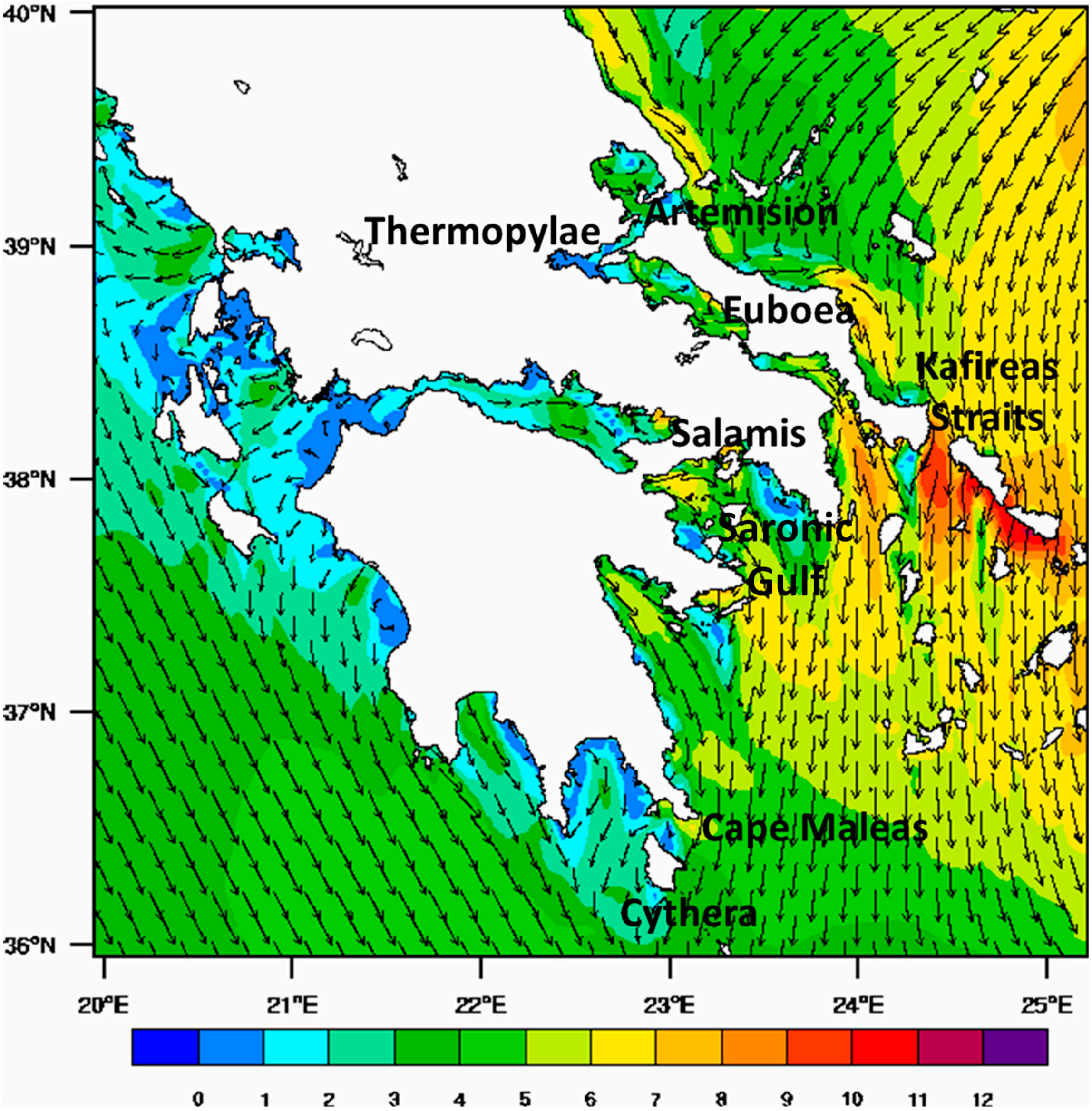

Figure 5. Wind speed in m s^{-1} (color scale) and direction (vectors), at 10-m height, 08:00 local standard time (LST). Ten-year average (2007–2016), from WRF intermediate grid at 3 × 3 km grid space driven by the ERA5 monthly average fields for September.

Before the Battle

The local sunrise at the end of September is at about 07:00–07:10 LST. Herodotus [4] (8.83) and Aeschylus stated that the battle had commenced at dawn. Although maneuvers may have begun at dawn, the actual battle did not, due to the time needed for ship preparations, the gathering of the troops, the admiral and commander speeches and the embarkation of the crew on the ships [12]. Hammond [11] estimated the approximate timing of the battle and reached the conclusion that at least two and a half hours were needed for the Persians and two hours for the Greeks to deploy and reach their battle positions. During the early morning hours, the prevailing wind blows off shore, and comes down the Salamis Channel as a north-westerly or westerly flow, raising no sea. This is also supported by Hammond [11], who indicated that the sea was calm enough in the Channel of Salamis for the Persian fleet to advance under oar and for the Greeks to muster and advance under oar and sails. This is the time when the Greek paean marks the beginning of the Greek attack. As seen in Figure 6a, moderate north–west winds prevail during the early morning hours (07:00 LST) throughout the Saronic

Gulf, reaching up to 6 m s^{-1} in the region of the battle. The northwest winds continue blowing with gradually less strength until 10:00 LST. Map details and topographic names are also given in Figure 6a.

During the Battle

The Persian fleet moved on against the Greek fleet which at that time was ordered to roar astern yet always keeping the prow towards the Persian fleet. Themistocles' tactics was on one hand, to attract the Persian fleet in the narrower place and to impel them to fight there and second, to gain time for the wind to rise, as Themistocles had been anticipating from the local wind climatology. This operation would require an additional half an hour or more. Taking into account that the local dawn at this time of the year is at ~07:00 LST, we come to the conclusion that the commencement of the battle could not have started earlier than ~10:00 LST. This is the time when, according to Plutarch, Themistocles "made sure that he would not send his triremes bow on against the Persian vessels until the hour of the day had come which always brought the breeze fresh from the sea". Indeed, at around 10:00 LST the change in wind pattern is evident and the southerly sea-breeze starts affecting the Salamis Channel (Figure 6b). Convergence between the existing northwest wind and the incoming southeast sea breeze occurs inside the battlefield as shown by the dashed red line in Figure 6b. The sea breeze intensifies during the day reaching up to 5–6 m s^{-1} (Figure 6c at 15:00) and it also brings waves into the channel due to the large fetch from the Saronic Gulf and the Aegean Sea.

The Greeks were aware and in anticipation of these changes in the local wind conditions. As described by Plutarch, the sea breeze had minor effects on the smaller Greek ships due to their shorter bows and sterns. In contrast, the taller Persian ships were severely affected by the increasing winds since these could not easily steer and thus became more vulnerable to being rammed by the Greek ships [3]. Herodotus writes that according to the accounts of the Athenians, on the morning of the sea battle, the Corinthians, panicking at the sight of the enemy, set sail and left hastily [2] (7, 94). He also adds that the Corinthians did not only refute the Athenians' accusation, but on the contrary they claimed that their move was made to cover the rear of the Greek fleet in case of a counterattack by the Persian squadron, which had already cut off the retreat path of the Greek fleet. Anyway, setting sail towards the northwest exit of the channel would have been possible only with a southeast sea-breeze flow. As seen from the zoom plots in Figure 6, the complex topography of the battlefield also played an important role during the course of the battle. For example, the Cape of Kinosoura must have been strategically selected by the Greek fleet for their formation since it protects the west part of Salamis Channel from the incoming sea breeze waves.

It is also interesting to present the vertical structure of the sea-breeze inside the battlefield, as shown in Figure 7 by the cross-section plots of wind direction from the monthly average WRF model runs. As seen in these plots, the prevailing winds in the free troposphere (above 1.0 km) come from the north sector (0°–90° and 270°–360°) throughout the day. The returning current of the local sea breeze appears as a rather shallow southern flow (90°–270°) at 10:00 LST developing to a maximum depth of about 1 km inside the planetary boundary layer (PBL) until 15:00 LST. After sunset, the sea breeze retreats towards the open sea and by 23:00 LST the wind in the domain turns back to north from the surface up to 3 km.

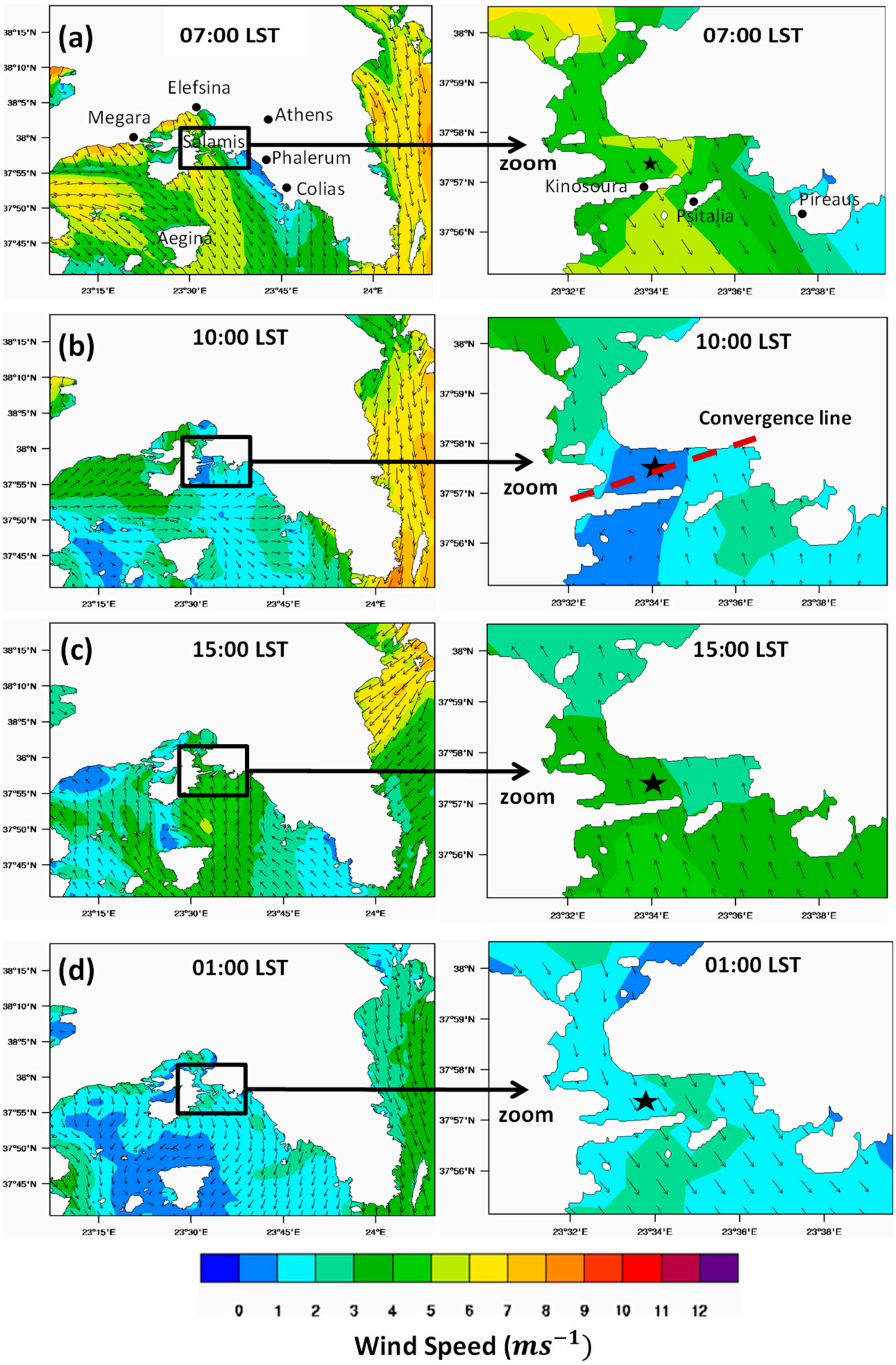

Figure 6. Wind speed (color scale) and direction (vectors) at 10 m (in ms^{-1}) at: (**a**) 07:00 LST, (**b**) 10:00 LST, (**c**) 15:00 LST and (**d**) 01:00 LST. Ten-year average (2007–2016) from WRF inner grid at 1×1 km grid space driven by the ERA5 monthly average fields for September. Black star in the zoom plots denotes the location of the diurnal wind course that is shown in Figure 8. Red dashes at 10:00 LST indicate the convergence line between the NW and SE flows.

After the Battle

As can be seen from Figure 6d, during the night the wind turns again to northwest. This could explain how the Persians managed to hoist sails and leave towards the east and also how the battle wreckage was transferred eastwards by the waves towards Cape Colias. Aeschylus and Herodotus [5] (480); [4] (8,96), mention that the westerly wind "Zephyrus" came to assist the exodus of the Persian ships at the closing hours of the battle. Moreover, according to the ancient writers [5] (418); [4] (8,96), the ship wrecks from the battle floated downwind past Phalerum, reaching even Cape Colias where "the women used Persian oars for cooking".

A summary of the weather–related references during the day of the battle is given in Table 1 along with the climatological evidence from our analysis. The original text in ancient Greek is also given along with the English translation for certain sources.

Table 1. Weather conditions and related course of events on the day of Salamis Battle.

Hour (LST)	Climatological Wind Regimes	Ancient Source
00:00–07:00	NW winds up to 3–4 ms^{-1} possibly assist the Persians to take battle positions during the night without being noticed by the Greeks. In addition, Aristides manages to pass unnoticed through the Persian ships and join the Greek fleet	*[4] (Hdt. 70.) (… So when they passed the word to put out to sea, they brought their ships out to Salamis and quietly ranged themselves along the shore in their several positions …)* *[4] (Hdt. 76.) (… These things they did in silence, so that the enemy might not take any notice of them … .)* *[4] (Hdt. 81.) (… .Aristides accordingly came forward and told them that he had come from Aegina and had escaped with difficulty without being perceived by those who were blockading them … .)*
07:00–09:00	Preparations and speeches delay the beginning of the battle by 1–2 h. At the time between sunrise (~07:15 LST) and embarkation, another trireme covers the 10-mile distance from Aegina towards Salamis (a trip of about 1–1.5 h, bearing in mind an average trireme speed of 8–10 miles per hour).	*[4] (Hdt.83.) (… .at the break of dawn, they made an assembly of those who fought on board the ships and addressed them, Themistocles made a speech which was the most eloquent of all; [… .] and thus having wound up his speech, he ordered them to board their ships. These then proceeded to embark, and in the meantime, the trireme which had gone away to bring the sons of Aiacos came from Aegina … .)*
09:00–10:00	At first light, the Greek ships, instead of trying to escape (as the Persians would have expected), appear in perfect battle formation and their war paean echoes on the rocks of Salamis The Greeks delay their counterattack by backing towards the shore. This was most probably part of their strategic plan to lure the Persians further into the narrow channel while also waiting for the sea breeze to take effect	*[5] (Aeschylus, Persae 386) (… .Advance, ye sons of Greece, free your country, free your wives, your children, the temples of your gods and the sacred tombs of your ancestors; now the fight is for all of them … .)* "Ὦ παῖδες Ἑλλήνων ἴτε, ἐλευθεροῦτε πατρίδ', ἐλευθεροῦτε δὲ παῖδας, γυναῖκας, θεῶν τέ πατρῴων ἕδη, θήκας τε προγόνων· νῦν ὑπὲρ πάντων ἀγών." *[4] (Hdt. 84.) (… Then the Hellenes put out all their ships, and while they were putting out from shore, the Barbarians attacked them immediately. Now the other Hellenes began backing their ships and were about to run them aground […] It is also reported that an apparition of a woman was seen by them, and that when she appeared, she encouraged them to the fight so that the whole of the army of the Hellenes heard it, while she reproached them in these words: "Madmen, how far will you still back your ships?" … .)* "Ὦ δαιμόνιοι, μέχρι κόσου ἔτι πρύμνην ἀνακρούεσθε;"
~10:00	The Greeks counterattack at the same time as the wind changes from NW to SE	*[3] (Plut. Them. 14.) (… Themistocles made sure that the Greek ships were lined up opposite the Persian ones at the specific time when a strong wind blew from the sea bringing waves to the straits …)* "ἣ τὴν εἰωθυῖαν ὥραν παραγενέσθαι, τὸ πνεῦμα λαμπρὸν ἐκ πελάγους ἀεὶ καὶ κῦμα διὰ τῶν στενῶν κατάγουσαν"

Table 1. *Cont.*

Hour (LST)	Climatological Wind Regimes	Ancient Source
10:00–11:00	At the beginning of the sea-battle the Corinthians are accused of putting up sails towards Elefsis. This would only be possible under a southeast sea breeze.	*[4] (Hdt. 94.) (. . . As regards Adeimantos, the commander of the Corinthians, the Athenians say that right at the beginning when the ships were engaging in the fight, being struck with panic and terror he put up his sails and fled away; and when the Corinthians saw the admiral's ship fleeing, they departed likewise . . . .)*
11:00–19:00	The battle takes place under sea breeze conditions. The incoming southeast wind flow into Salamis Straits possibly contributes to the disorganization of the Persian fleet by steering the higher Persian ships perpendicularly to the rams of the Greek triremes. The strengthening southeast sea breeze does not allow the Persians to hoist sails for a fast retreat towards the open Saronic Gulf. They are not able to reform and counterattack or to transfer the conflict to the open sea. The turmoil in the narrow straits increases and the Persian fleet is trapped in a "pincer" created by the Greek fleet with the aid of the local winds.	*[4] (Hdt. 86.) (. . . because the Hellenes fought in order and ranged in their places, while the Barbarians were no longer ranged in order nor did anything with design . . .)* *[3] (Pl. Them. 14) (. . . The wind falling on the higher Persian decks steered them and offered their sides to the attacking Greek ships . . .)* *" καὶ τοῖς καταστρώμασιν ὑψορόφους καὶ βαρείας ἐπιφερομένας ἔσφαλλε προςπίπτον, καὶ παρεδίδου πλαγίας τοῖς Ἕλλησιν ὀξέως προςφερομένοις "*
19:00 until the next morning	After sunset (~19:15 LST) the battle wrecks are taken by the west wind "Zephyrus" towards the coasts of Attica	*[4] (Hdt.96.) (. . . . many of the wrecks were taken by Zephyrus and brought to that strand in Attica which is called Colias . . .)* *"τῶν δὲ ναυηγίων πολλὰ ὑπολαβὼν ἄνεμος ζέφυρος ἔφερε τῆς Ἀττικῆς ἐπὶ τὴν ἠιόνα τὴν καλεομένην Κωλιάδα"*

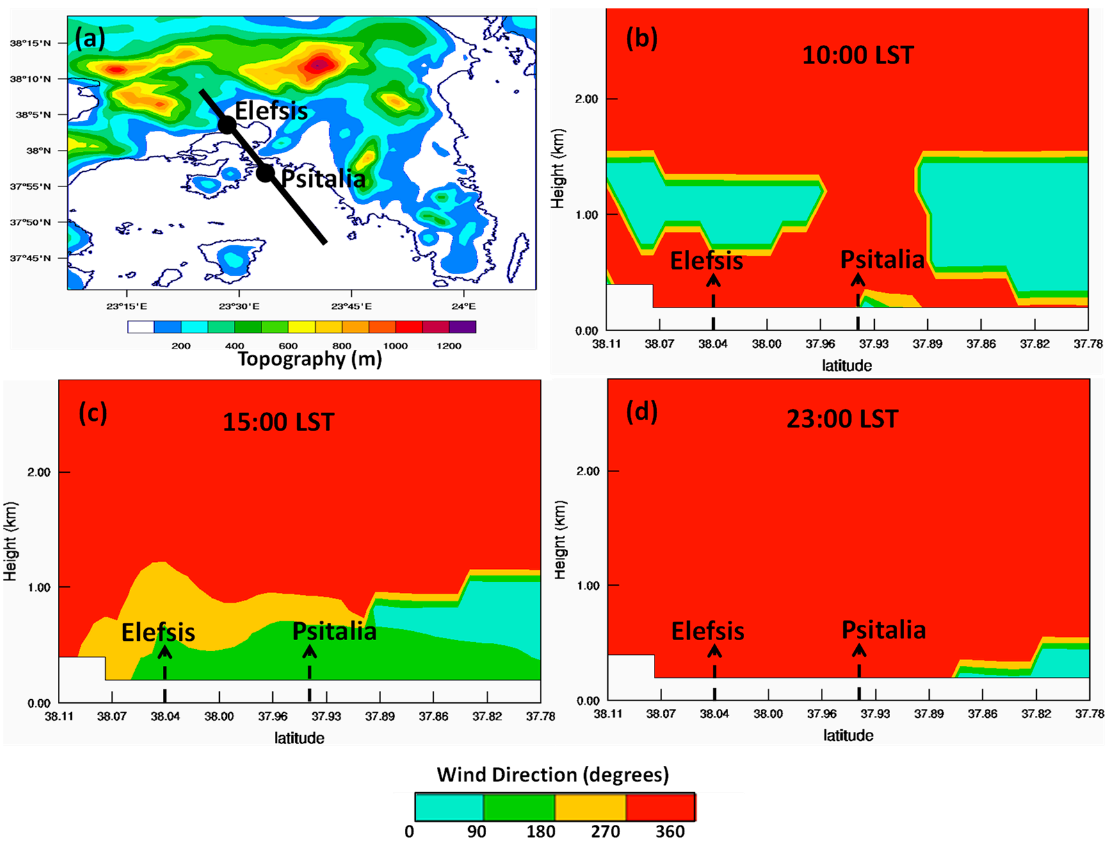

Figure 7. (**a**) Map of modeled topography (m). The black line shows the location of the cross section. Two-dimensional cross sections of wind direction (in degrees) on a vertical plane running from NW to SE in parallel to the straits of Salamis at: (**b**) 10:00 LST, (**c**) 15:00 LST, (**d**) 23:00 LST. Ten-year average (2007–2016) from WRF inner grid at 1 × 1 km grid space driven by the ERA5 monthly average fields for September. The vertical dashed lines indicate the locations of Elefsis and Psitalia.

4. Conclusions and Discussion

The summer wind regime in the Saronic Gulf is mainly determined by the interaction between the climatological northerly wind background (Etesian winds) and the local sea breeze. The direction of the resultant wind depends on the hour of the day and on the strength of the synoptic and sea breeze systems which compete. Both atmospheric mechanisms (Etesians and sea breeze) are in principle driven by the heating of the sea and land caused by the sun. The Etesians are related to the combination of the South Asian Summer Monsoon, the formation of the Anatolian thermal low and the high pressures over the Balkans [10,13–17]. As denoted by their name the Etesians are annually recurrent winds similar to the annually recurrent monsoons. The local sea breeze depends on the different solar heating rates between the Saronic Gulf and the land of Attica [8,9]. Therefore, it is no surprise that these mechanisms have been operating in the area in summer and early fall for thousands of years.

The ancient Greeks were aware of these climatological wind patterns, which last from May to September. According to Aristotle [1], the precursors of the Etesians, "prodromoi", start in May while the late Etesians, "metoporoi", last until the end of September. The end of September, when the sea-battle of Salamis took place, is a borderline period when the Etesians start weakening (Figure 2) but the sea breeze still continues to develop in the Saronic Gulf due to the high thermal gradients between land and sea. In September, the sea breeze starts as early as 10:00 LST and continues strengthening up to six meters per second until sunset, when it is replaced by the west-northwest winds of the Etesian regime at nighttime. Themistocles took advantage of the local winds which favored the Greek fleet, while in the course of the day the Persian fleet was trapped by the change of the wind inside the narrow channels of Salamis Straits. Our findings are in concurrence with the accounts by ancient writers. The situation, hour-by-hour, can be described as follows:

The sea-battle in Salamis most probably started about two hours after sunrise. The Persian fleet took battle formations under full daylight and they were taken by surprise at the sound of the Greek war song (paean), the trumpet and the leading Greek vessels [5] (386). Themistocles then ordered the Greek ships in the right wing and right center to reverse their course [4] (8.84) triggering the Persian ships to invade by entering further into the narrow straits of Salamis. The Greek ships started moving backwards, rowing in retrograde while they maintained their prows steadily facing the enemy. In this way, the encounter of the two fleets in the middle of the straits was averted and valuable time was gained until the change of the wind expected to turn to southerly directions took place at around after 10.00 LST. According to Plutarch, "Themistocles was well aware of the local wind climatology at Salamis, so this was the reason why he made sure that the Greek ships were lined up opposite the Persian ones at the specific time when a strong wind blew from the sea (i.e., southerly) bringing waves to the straits". He continues by saying that "while this wind would not harm the Greek ships which were low and did not protrude much from the sea, it would afflict the Persian ships that had upright sterns and high decks and it would turn them sideways to the Greek ships, thus rendering the former more vulnerable to ramming" [3]. The Persian ships were unaware of the phenomenon and they were caught off-guard, whereas the Greeks got an important operational advantage. Ramming and destruction continued to result in great damage to the Persian fleet which was trapped by the breeze. The breeze continued strengthening towards the noon and afternoon hours, inhibiting the Persian ships from setting sail and escaping towards the open sea. Instead, the Persian fleet was pushed into the narrow straits of Salamis where it was almost completely destroyed by the Greek ships in the early evening hours.

The outcome of the sea battle is known: a large part of the Persian fleet was lost, while the remaining ships abandoned the conflict area and fled to Phalerum Bay. During the afternoon hours, the winds completed their daily cycle and turned again into northwest. In all likelihood, it must have been the "Zephyrus" wind which, according to Herodotus, caused the wreckage of the Persian fleet to drift towards the east– southeast, as it was stranded on Cape Colias [4] (96). The described wind conditions are confirmed by the findings of our study and can be summarized by the modeled diurnal wind course inside the battlefield as shown in Figure 8. As seen in this plot, the north-northwest winds that are evident between 00:00 LST and 07:00 LST are replaced by a south-southwest to south-southeast sea breeze reaching its maximum between 11:00 LST and 16:00 LST. At night (20:00–23:00 LST) the winds veer again to north-northwest directions with light strength. It is worth mentioning here that these results are produced from the downscaling of the ERA5 monthly averaged fields at the 1×1 km WRF resolution, therefore the actual diurnal gradients on a specific day are expected to be even sharper.

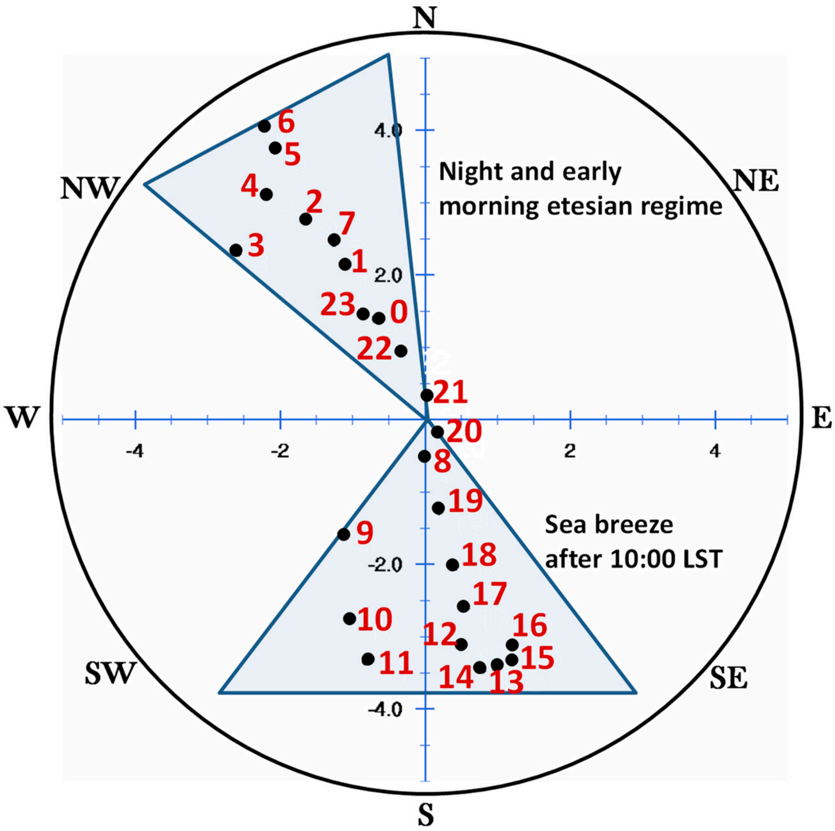

Figure 8. Modeled diurnal variation of the wind inside the battlefield (37.95° N, 23.57° E) from the WRF inner grid (1×1 km). Average from the modeling simulations driven by the ERA5 monthly fields for September 2007–2016. Red numbers correspond to local standard time (LST) and the position of the black dots shows the wind speed and direction (e.g., at 06:00 LST the direction is NNW and the speed is computed from u and v wind components as: $\sqrt{(-2)^2 + 4^2} \approx 4.5\ m\ s^{-1}$).

Our findings indicate that the climatological patterns of Etesian winds and sea breeze described by the ancient writers are still operating at the greater area of the Saronic Gulf 2500 years later. Moreover, our study indicates that Themistocles was aware of the prevailing wind patterns on the day of the battle. In the war council that took place before the battle and during an ongoing dispute regarding the following strategic moves of the Greeks, he said the famous phrase to the Spartan admiral Evriviades: "*πάταξον μέν, ἄκουσον δέ*" [3] (11.1–11.6). The broad meaning of this phrase is "hit me, but first listen to me" and it shows Themistocles' determination to battle against the Persian fleet at that particular location following the previously described strategic plan. Of course, there were a number of political reasons affecting Themistocles' decision to stay at Salamis, such as the proximity of Salamis to Athens and the existence of Athenian refugees and troops on the island. However, his knowledge of the local wind climatology in combination with the narrow straits must have been the critical argument that tilted the balance in the Greek council of admirals towards confronting the Persian fleet in the straits of Salamis. To summarize, we can describe the diurnal variation of the wind in the Saronic Gulf as an "invisible pincer" of air blowing from west-northwest at night and early in the morning being replaced by a southeast wind after 10.00 A.M. and through early evening. The formation of this local "pincer trapped the Persian fleet in Salamis and led to one of the greatest victories in history.

Author Contributions: Conceptualization, C.Z., S.S., D.M. and C.R.; Data curation, J.K.; Formal analysis, S.S., D.M. and J.K.; Funding acquisition, C.Z.; Investigation, C.Z., S.S., D.M., J.K. and C.R.; Methodology, C.Z., S.S., D.M. and J.K.; Software, S.S. and J.K.; Visualization, S.S. and J.K.; Writing—original draft, C.Z., S.S. and D.M.; Writing—review & editing, C.Z., S.S. and D.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Mariolopoulos-Kanaginis Foundation for the Environmental Sciences.

Acknowledgments: The authors acknowledge the Hellenic National Meteorological Service for providing the Piraeus and Elefsis station data and Copernicus Climate Change Service (C3S) for the use of ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate. This study is dedicated to the memory of Stelios Ginis.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Tsonis, A.; Zerefos, C. "Aristotle's Μετεωρολογικά: Meteorology Then and Now. Available online: http://www.archaeopress.com/ArchaeopressShop/Public/download.asp?id=\protect\T1\textbraceleftF42484FB-B6EB-405C-9E66-4D982C45E746\protect\T1\textbraceright) (accessed on 10 July 2020).
2. Godley, A.D. *Herodotus Histories, Books V-VII*; Harvard University Press: Cambridge, MA, USA, 1922.
3. Perrin, B. *Plutarch's Lives*; Harvard University Press: Cambridge, MA, USA, 1914.
4. Godley, A.D. *Herodotus Books VIII-IX*; Harvard University Press: Cambridge, MA, USA, 1922.
5. *Aeschylus, The Persae*; Cambridge University Press: Cambridge, UK, 1960.
6. Hersbach, H.; Bell, B.; Berrisford, P.; Hirahara, S.; Horányi, A.; Muñoz-Sabater, J.; Nicolas, J.; Peubey, C.; Radu, R.; Schepers, D.; et al. The ERA5 global reanalysis. *Q. J. R. Meteorol. Soc.* **2020**, *146*, 1999–2049. [CrossRef]
7. Skamarock, W.C.; Klemp, J.B.; Dudhia, J.; Gill, D.O.; Barker, D.M.; Duda, M.G.; Huang, X.Y.; Wang, W.; Powers, J.G. A Description of the Advanced Research WRF Version 3. Available online: https://opensky.ucar.edu/islandora/object/technotes%3A500/datastream/PDF/view (accessed on 10 July 2020).
8. Melas, D.; Ziomas, I.; Klemm, O.; Zerefos, C. Anatomy of the sea-breeze circulation in Athens area under weak large-scale ambient winds. *Atmos. Environ.* **1998**, *32*, 2223–2237. [CrossRef]
9. Melas, D.; Ziomas, I.; Klemm, O.; Zerefos, C. Flow dynamics in Athens area under moderate large-scale winds. *Atmos. Environ.* **1998**, *32*, 2209–2222. [CrossRef]
10. Repapis, C.; Zerefos, C.S.; Tritakis, B. On the Etesians over the Aegean. *Proc. Acad. Athens* **1977**, *52*, 572–606.
11. Hammond, N.G.L. The Battle of Salamis. *J. Hell. Stud.* **1956**, *76*, 32–54. [CrossRef]
12. Morton, J. *The Role of the Physical Environment in Ancient Greek Seafaring*; Brill: Leiden, The Netherlands, 2001.
13. Maheras, P. Le probleme des Etesiens. *Mediterranee* **1980**, *40*, 57–66. [CrossRef]
14. Kallos, G.; Kassomenos, P.; Pielke, R.A. Synoptic and mesoscale weather conditions during air pollution episodes in Athens, Greece. *Bound. Layer Meteorol.* **1993**, *63*, 163–184. [CrossRef]
15. Poupkou, A.; Zanis, P.; Nastos, P.; Papanastasiou, D.; Melas, D.; Tourpali, K.; Zerefos, C. Present climate trend analysis of the Etesian winds in the Aegean Sea. *Theor. Appl. Climatol.* **2011**, *106*, 459–472. [CrossRef]
16. Tyrlis, E.; Lelieveld, J. Climatology and dynamics of the summer Etesian winds over the eastern Mediterranean. *J. Atmos. Sci.* **2013**, *70*, 3374–3396. [CrossRef]
17. Dafka, S.; Xoplaki, E.; Toreti, A.; Zanis, P.; Tyrlis, E.; Zerefos, C.; Luterbacher, J. The Etesians: From observations to reanalysis. *Clim. Dyn.* **2016**, *47*, 1569–1585. [CrossRef]