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Sea-Breeze Front Research Based on Remote Sensing Methods in Coastal Baltic Sea Climate: Case of Lithuania

Remigijus Dailidė [1,*], Greta Dailidė [1], Indrė Razbadauskaitė-Venskė [1,2], Ramūnas Povilanskas [1] and Inga Dailidienė [1]

[1] Marine Research Institute, Klaipeda University, LT-92294 Klaipeda, Lithuania
[2] International Business Department, LCC International University, LT-93100 Klaipėda, Lithuania
* Correspondence: remigijus.dailide@gmail.com; Tel.: +370-676-66275

Abstract: Sea breezes, as one of the most important local varieties of daily wind dynamics, are responsible for the formation of the climate by coasts of large bodies of water. In recent decades, due to climate change, the air temperature is rising, causing larger temperature gradients to form and the dynamics of the atmosphere to change globally and locally. This research investigated the spread of sea breezes in the years 2018–2019 during the warm period of the year (June, July, and August) to the mainland territory of the southeastern Baltic and coastal Lithuania by applying in situ and remote methods. The results of the study showed that sea-breeze fronts are better identified by the formation line of convective clouds in the continental part seen in remote images. During the first half of the day (until noon), the effect of sea breezes extends on average about 20–30 km from the coast of the sea. However, maximum extension of the breeze fronts can penetrate the continent much further than previously thought. During the summer, when the westward movement of air masses prevails, the band of cumulus (Cu) clouds formed by the sea breeze marks the front of the sea breeze, and at the time of the most extended spread (around 5 pm) in the continental part of Lithuania, the sea-breeze front is an average of around 60 km away from the seacoast. Until noon, the area covered by sea breezes in the western part of Lithuania extends over 1886.2 km^2. During the second half of the day, the spatial spread of the breeze impacts an average area of about 6445.2 km^2 by around 5 pm. Hence, the sea breeze affects not only the coastal climate region of Lithuania, as previously recognized, but it also affects the climate of part of the region of the Samogitian (Žemaitijos) Uplands of Lithuania. Remote-sensing methods helped to identify sea-breeze fronts and evaluate the limits of marine climate expansion along the seashore. The methods used in this work can play a role in answering the question of how climate change can affect the coastal climate.

Keywords: sea breezes; sea-breeze front; remote-sensing methods; climate change; Baltic Sea; Lithuania coast

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1. Introduction

Sea breezes are an important phenomenon contributing to the formation of the coastal climate. The study of sea breezes and their variation has essential practical and theoretical applications. The sea breeze may be analyzed as one indicator of how much an area is influenced by maritime air masses.

Sea breezes are usually classified as local winds. However, knowledge of sea breezes is important when assessing the renewable energy resources of seacoasts, the spread of heat waves and various pollutants, evaluating recreational resources, and planning people's economic and tourist activities across the shorelines. A changing climate manifests itself in different ways in different areas. Therefore, scientific research aims not only to record changes in climate change but also to forecast and explain possible changes and their impact in the future. It is important to provide answers to questions of public concern in a timely manner. Addressing these issues can help us both preserve natural diversity and to reorganize our activities for sustainable innovation.

The land–sea breeze system, driven by the thermal contrast between the land and the adjacent ocean, is a widely known atmospheric phenomenon that occurs in coastal regions globally [1,2]. The temperature difference between the land and sea drives the land–sea breeze system. Due to the greater temperature differences between the sea and land coasts, the wind changes its direction twice a day during the warm season, blowing from the cooler continent towards the sea at night and from the sea towards the warmer continent during the day. During the night, due to different thermal properties, the land cools down faster than the sea, and the pressure differences also change. This causes a wind called the land or onshore breeze to blow from the land to the sea. The incoming solar radiation during the day causes differential heating of the land because the specific heat capacity of the land is lower than that of the adjacent sea. Sea breezes are common along coasts after sunrise because the land warms up much faster than the water.

In coastal areas, one of the most obvious atmospheric demonstrations of the relationship between the maritime and terrestrial domains is the sea breeze [3]. Sea breezes are one of the most widely studied phenomena in scientific literature because sea breezes occur in many coastal regions of the world and significantly contribute to the formation of local marine climate conditions. The sea breeze phenomenon is defined by the World Meteorological Organization as "wind in coastal regions, blowing by day from a large water surface towards the land as a result of diurnal heating of the land surface" [4]. A sea breeze is a mesoscale meteorological phenomenon based on the thermal contrasts between the land and the sea, and it develops along coastal regions when the temperature difference between two adjacent surfaces is large enough and the geostrophic wind is weak [5].

The sea breeze is a surface manifestation of a thermally driven mesoscale circulation called the sea-breeze circulation, which often includes a weak return (land to sea) flow aloft. As a consequence of the resulting temperature and later pressure differences in the low atmospheric levels, the breeze from the sea begins to blow towards the land to a certain point: the front line (Figure 1). The sea-breeze front is often associated with sharp changes in temperature, moisture, and wind, and its approach often is marked by the development of fair-weather cumulus (Cu) clouds [1]. Sea breezes have a local characteristic. It is interesting that scientists also determine their wider specific impact on the dynamics and characteristics of air masses. For example, the details of a sea breeze's behavior along specific coastlines can be surprising when the leading edge of the sea breeze may separate from the feeder flow behind the front and move hundreds of kilometers inland as an independent entity [1].

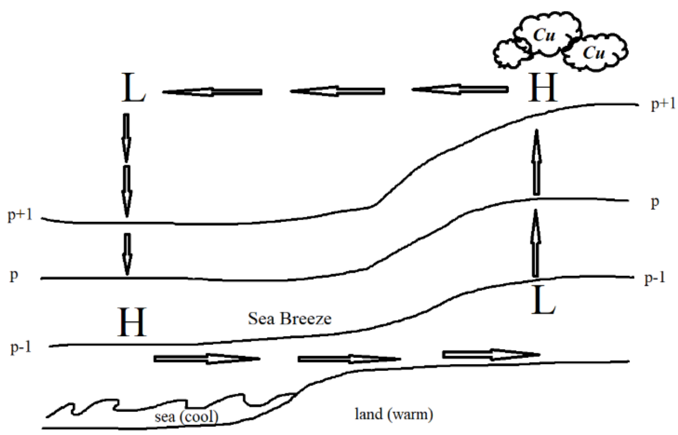

Figure 1. Sea breeze circulation.

As sea breeze circulation plays an important role in moderating the temperature in coastal areas during the warm season, it can also contribute to the formation of various air pollutant transports and extreme events. The first environmental consequence of this phenomenon is climatic and specifically wind-related; in places where they blow very often and regularly, breezes are true 'wind clocks' and have a marked influence on the hourly, daily, and annual wind regime [3]. As climate change accelerates and the scale of urbanization expands, the circulation of breezes becomes an important factor determining wind energy resources and often results in more favorable coastal climatic conditions than in the inland part of the continents.

When conditions are favorable, the breeze circulation affects the formation of heat islands and mitigates the heat island effect, which reduces temperature indicators in cities, thus delaying their formation or pushing them to other areas [6,7]. The phenomenon of heat islands increases the thermal gradients, which creates more favorable conditions for the formation and strengthening of the sea breeze along the coasts during the day and the simultaneous weakening of the land breeze during the night [8]. Additionally, the pronounced action of breeze circulation in urbanized coastal areas disrupts convection processes and creates new thermal layers above urbanized centers [7].

Research on sea breezes can help specialists in various fields better understand climate change processes, sea-coast ecosystem sensitivities to climate change, changes in atmospheric dynamics, and irregularities of air pollution propagation. Research conducted in recent years shows that breeze circulation can lead to the transport of various pollutants and other particles dangerous to human health far inland on clear days. This is noticeable at especially industrialized coasts where anthropogenic activities are constantly carried out. During typical breeze formation days, several tens of percent higher concentrations of particles are recorded in the air near the coasts, and indicators of increased aerosols are recorded in the mainland, which coincide with the boundaries of the breeze fronts and occur in areas where there are no signs of intensive industrial or other anthropogenic activities [9–12]. The sea breeze can participate in the processes of litter dispersion in coastal stretches by facilitating the transfer of waste from the ocean or the beach to the dunes [13]. The consequences of this can be aesthetic, making the beach unattractive to vacationers, and can disturb the local ecosystems. Scientists also investigate how breeze circulation can affect wave formation and nearshore currents or contribute to shore erosion processes on coasts characterized by strong sea breeze development [14].

In recent decades, with the improvement of satellite platforms and the resolution of satellite photos (especially satellites in geostationary orbits), satellite data is increasingly being used to study local meteorological phenomena, including the formation of breezes. Satellite data in the visible spectrum (RGB) is often used to study cloud formation processes, as they allow observation and analysis of cloud shape, extent, and boundaries as well as the landward boundary of the sea-breeze front. The cumulus line of convective clouds that runs parallel to the seashore on the mainland helps to calculate how far the front line of the sea influence has shifted to the mainland [15–18]. The infrared (IR) channel of the satellite sensor helps to trace the front line of the breeze circulation. This channel monitors and analyzes sea and coastal land temperatures and allows comparison of the differences, thus enabling a trace of the boundaries of the breeze circulation front [19,20].

Most of the conducted scientific studies [18,19,21] show that the location of the sea-breeze front coincides with the line of cumulus-type convergent clouds. Therefore, similar remote-sensing methods have been applied to study the limits of the distribution of breezes on the continent based on the bands of cumulus clouds visible in satellite images [1,22]. Remote-sensing methods have been applied to breeze circulation studies in Western Europe [21] and along the northeast coast of Brazil [18,19]. Corpetti and Planchon [17] analyzed the formation and movement of breeze fronts along the coasts of Brazil and southern England by comparing the coastline with the cumulus cloud line.

Sea breezes are not uniform geographically on the different coasts of the Baltic Sea, so detailed information about its distribution is necessary to locally assess the impact on coastal regions. Breeze circulation studies on the Baltic Sea coast are usually carried out by analyzing specific regions and wind regimes [23,24]. In the warm season, especially in summer months when the cyclone activity in the Baltic region is the weakest, the most suitable conditions for the emergence of a sea breeze are created [25]. Until now, research on the circulation of breezes is mostly based on data from meteorological stations and analyzing changes in wind direction and speed, temperature, and pressure. However, the density of the meteorological station network is often not sufficient for more detailed studies of the circulation of breezes. Therefore, remote studies using satellite systems and their sensor data, as well as high-resolution space images, help to compensate for sparse meteorological station networks and are increasingly used for sea breeze research.

In this work, remote methods and in situ meteorological data are used to analyze and map a sea breeze and its spread in space and time on the coast of the southeastern Baltic Sea. The main aim is the application of satellite data and remote methods to determine the boundary of the sea-breeze front and, specifically, the limits of its expansion inward to the mainland of Lithuania. These studies on the spread of breeze circulation in the continental part of the Baltic Sea basin using remote methods can help determine how much sea-breeze fronts can penetrate the continent and the size of the area that is affected by the maritime climate.

2. Study Site, Materials, and Methods

The Baltic Sea region is located between maritime temperate and continental sub-Arctic climate zones, and the climate of the Baltic Sea region has large variability due to the opposing effects of moist and relatively mild marine airflows from the North Atlantic Ocean and the Eurasian continental climate [26]. The Baltic Sea has different climate zones due to its geographical location and great length from south to north. The southern and western parts of the Baltic Sea belong to the central European mild climate zone in the westerly circulation, while the northern part is located at the polar front [26].

The continental part of the southeast coast of the Baltic Sea in western Lithuania was selected for the study of the penetration of the sea breeze circulation into continental land (Figure 2). Lithuanian territory, like all European continent regions, lies in the area of influence of the Atlantic Ocean and westerly airflow of global atmospheric dynamics in the northern hemisphere. Lithuania is located in the northern part of the temperate climate zone, and the climate can be characterized as transitional between mild Western European and continental Eastern European climates [27].

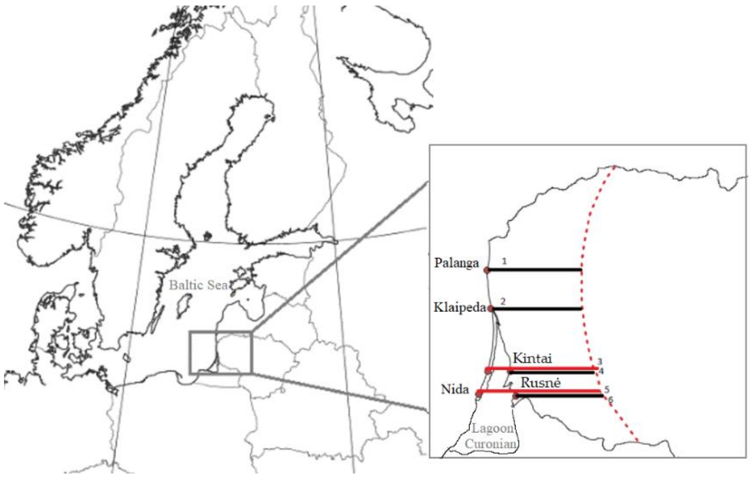

Figure 2. Research area: Baltic Sea, southeast coast, Lithuania.

The coastal lowlands extend 30–40 km along the coast of the Baltic Sea and the Curonian Lagoon, and they border the plateau of the Samogitian (Žemaiciai) highlands on the east. It is distinguished by its maritime climate. According to Lithuanian climate zoning [28], the coastal lowlands correspond to the Coastal (Pajūris) climatic region, and the Samogitian (Žemaičiai) highlands correspond to the Samogitian (Žemaiciai) climatic region. Between the Curonian Spit and the coastal lowlands, the Curonian Lagoon is the largest lagoon in the Baltic Sea, with an area of 1584 km^2 [29,30]. Therefore, the coastal climatic region is divided into three subregions: the Curonian Spit, the Sea coast, and the coastal lowlands.

In the territory of western Lithuania, the climate changes from maritime to continental. The Baltic Sea and western transport air masses coming from the Atlantic Ocean have the greatest influence on the climatic conditions in this territory of Lithuania. The number of sunny days per year is recorded on the coast and in the Curonian Spit (1900–1950 h yearly) in the areas directly affected by the sea [31]. Sunshine duration is the number of hours when the Sun shines and is not obscured by clouds [28]. It depends on the length of the day and the geographical latitude as well as on cloud formation processes, which are usually determined by the dynamics of air masses. In the coastal region of western Lithuania, around 770 mm of precipitation falls per year, and during the summer, circulation of sea-breeze winds and continental winds is observed [32]. The western Samogitian (Žemaičiai) Plateau holds the sea masses and is distinguished by a peculiar rainier climate, which is considered a conditional transitional boundary between the maritime and continental climates of Lithuania. The highest amount of precipitation (~850 mm) falls on the Samogitian highlands of Lithuania because, due to the prevailing westerly winds and the influence of the local altitude, moist sea air masses rise on the western slopes of the highlands. The Samogitian (Žemaičiai) Plateau consists of large and high hills. The average height of these hills is about 119 m, and the highest place is the 234 m Medvėgalis hill [33].

In this study, using meteorological stations and remote-sensing data, the propagation of wind circulations and their fronts in the southeastern Baltic region was determined. In situ data from the months of June-August 2018–2019 were used in this work. This assisted in identifying and selecting cases of sea breezes on the Baltic coast in the territory of Lithuania for the research. Meteorological stations and data were obtained from the Lithuanian Hydrometeorological Service (LHMS) under the Ministry of Environment.

In this research, the data of the Meteosat-10 satellite were selected based on resolution (1 km^2) and timeframe of pictures (every 5 min). The satellite is in geostationary orbit and is a part of the platform of Meteosat Second Generation (MSG) satellites belonging to the European Organization for the Exploitation of Meteorological Satellites (hereinafter—EUMETSAT). Meteosat-10 has a rapid scan SEVIRI sensor HRV that provides 1 km^2 resolution Rapid Scan High Rate SEVIRI Level 1.5 Image Data. The resolution of (1 km^2) and tight timeframe of 5 min of these satellite photos enabled the research to determine the circulation of southeast Baltic sea breezes and their fronts.

Satellite images were analyzed and selected for research in several stages. In the first stage, 1204 satellite images from 2018–2019 were reviewed during the summer period (June–August). Satellite images were reviewed at 2 h intervals each day. In the second stage, 786 photos were selected and assessed for use in case studies from the photos reviewed and days with obvious breeze circulation selected in the first stage. Each of these photos was checked against meteorological stations data. In the third stage, 456 photos were selected for study of the breeze front line. Eventually, all pictures that represented the best views of cumulus (Cu) and cumulonimbus (Cb) type cloud lines (Figure 1) and did not have a breeze-overwhelming condition were selected.

Using Meteosat-10 satellite images of the visible spectrum during the study period, it was found that about 74 days of cloud formation phenomena were observed, which helped to identify sea-breeze fronts in the continental part of the southeastern Baltic Sea coast. However, not all of those days were used for more detailed studies of breezes. Some were rejected during the selection due to lower resolution and more intensive changes in meteorological conditions (Figure 3). Only the days with the best illustration of the breeze phenomenon when the sea-breeze front is clearly visible from the satellite were selected (Figure 4). Of those, 6 days were selected for the detailed study and mapping of the sea breeze, which involved determining its movement in time and space and mapping it.

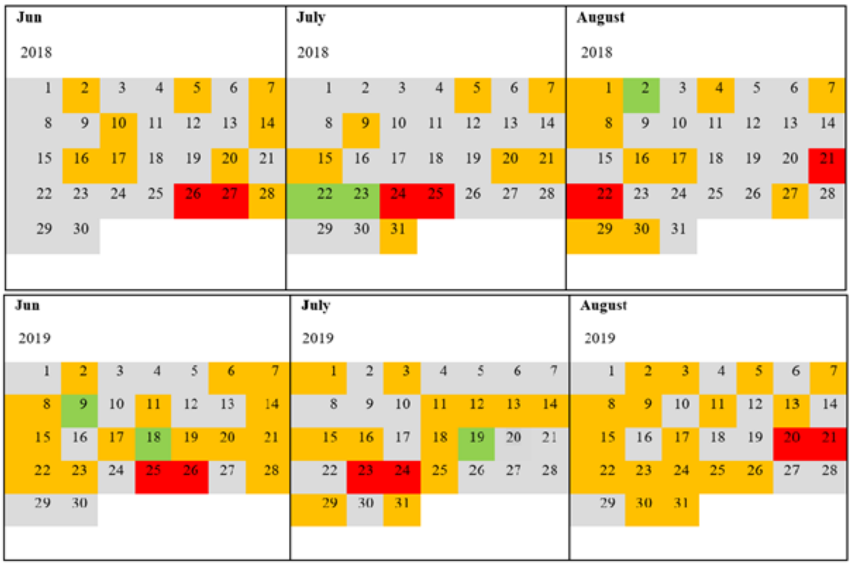

Figure 3. Eligibility for sea breeze research satellite images/days 2018–2019 June-August: green—the breeze front is visible from satellite; yellow—a clear influence of the sea on the cloud formation processes is visible, but the breeze front cannot be precisely identified because the meteorological conditions are changing; gray—the breeze front is not visible; red—the satellite did not work or was on maintenance.

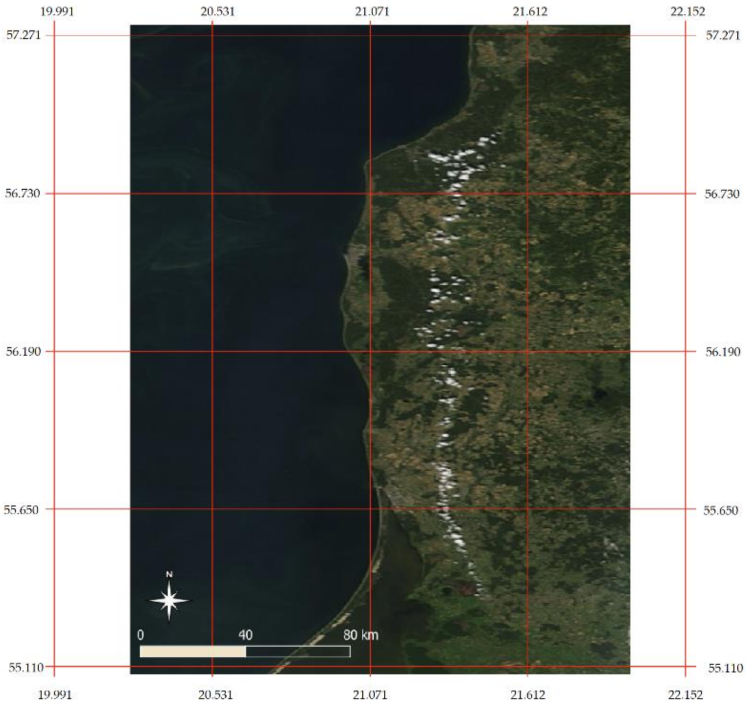

Figure 4. Meteosat-10 satellite images. 23 July 2018, 13:30 (GMT+2).

Days when the cumulus (Cu) and cumulonimbus (Cb) cloud belts were clearly formed and highly visible in remote photographs were suitable for more detailed studies of sea-breeze fronts. Although sea breezes blow mostly in conditions of clear skies, their distinctive feature is a line of clouds parallel to the shoreline which develops at the sea-breeze convergence zone [34]. This discontinuity represents a low-level convergence zone between sea breezes and offshore large-scale winds, which is known as a sea-breeze front [34]. Therefore, remote images where the Cu and Cb cloud lines were clearly visible were selected.

Convective clouds (Cu and Cb) can be observed inland along the sea-breeze convergence or sea-breeze front (prime location for convective initiation).

The main criterion for selecting imagery with clearly visible cloud lines is that they mark the boundary of air mass convection. Boundaries form due to the temperature difference between land and sea air masses. Cu clouds are the lower layer clouds in the troposphere that form up to a height of up to 2 km. The height of the breeze circulation in many cases corresponds to the height of the first-floor cloud formation. Hence, imagery with clear cloud lines visible that consisted of Cu clouds were used.

The maximum penetration of sea breezes into the territory of Lithuania and the area occupied by this phenomenon were calculated using the QGIS 3.10 software after defining the polygons and transects from the coast to the borders of the sea-breeze fronts. Satellite images were mapped to the WGS-84 geographic coordinates, and cumulus cloud lines were marked with vector lines using a QGIS-supplied package and later converted to the raster format by applying a 3 × 3 filter to smooth-out the convective cloud line markings. Transects that are vertical to the shore were selected reaching ground-based meteorological stations across the shoreline that were in range for the sea-breeze reach. On the path of these transects, cumulus cloud lines were followed on satellite imagery at a 5 min time window. After cloud lines reached meteorological stations, a change in temperature and wind direction was monitored using in situ measurements.

3. Results

3.1. Identification of Sea Breeze

In this research Meoteosat-10 and in situ data from meteorological stations were used to study the sea breeze, its cycle of formation, construction of its front, and movement inward to the continent from the southeastern Baltic Sea during the warm season (June, July, and August).

During the warmest months, favorable meteorological conditions for the formation of breeze circulation occur on the coast of the southeastern Baltic Sea. The different thermal properties of the sea surface and land causes favorable meteorological conditions for the formation of sea–land breeze circulation. Unequally warmed land and water affect the temperature of the subsurface air, which in turn affects the atmospheric pressure. During the day after sunrise, above the colder water, formations of higher pressure are dominant, and advective air mass movement from the coast to the continent gradually appears, which contributes to the local wind and the sea breeze. This colder, denser air travels along the ground like a wedge, pushing the warm air upward. The warm air cools as it rises, and when it reaches the point of condensation, it forms spherical cumulus (Cu) clouds in the lower troposphere (Figure 1). A line of these clouds formed on a clear day parallel to the mainland of the coast can be observed from satellite images.

The sea breeze starts to blow from the sea towards the land a few hours after sunrise when there is a greater air temperature difference between the surface of the continent and the Baltic Sea. In the continental part of western Lithuania during the summer, the sea breeze starts from 06:00 h on average, when the shore breeze weakens and the wind changes direction and starts blowing from the sea to the coast (Figure 5). The beginning of the formation of this phenomenon and the sudden change of the wind direction from the sea to the continent is connected with a sudden jump in air temperature after sunrise when the air temperature rises by about 3–5 °C per hour. On the southeastern Baltic coast, the end of the sea breeze at the Klaipeda meteorological station is monitored around 19:00 h, where the sudden change in the direction of the dominant wind is observed (Figure 5). As the air temperature decreases (approximately from 16:00 h), the wind direction changes from land to sea after about 2–3 h.

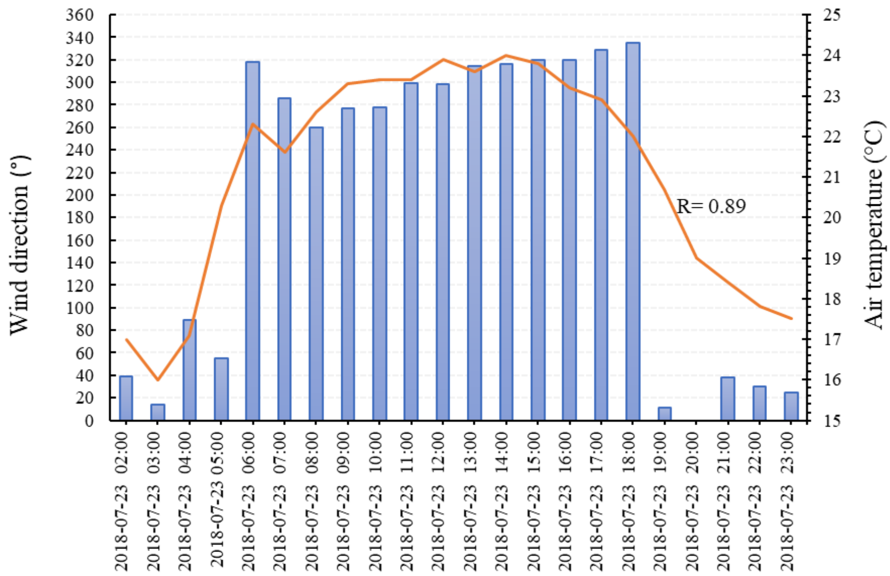

Figure 5. The predominance of the sea breeze at the southeastern Baltic Sea coast. Data from the coastal meteorological station, Klaipeda (23 July 2018). The beginning is fixed at 06:00 h, and the end of the phenomena is around 19:00 h. R (correlation coefficient) represents the relationship between the change in air temperature and wind direction during the day.

3.2. Sea-Breeze Fronts

The network of meteorological stations is too sparse and insufficient on the coast of the Lithuanian sea, especially when the aim is to determine the extent of sea breeze spread and the boundaries of the fronts with their movement in the territory of the continent.

The sea-breeze fronts were analyzed using Meteosat-10 photos and mapped in more detail based on the data of six days selected in the study (Figure 3): 22 July 2018; 23 July 2018; 02 August 2018; 09 June 2019; 18 June 2019; 19 July 2019. These days were selected after analyzing satellite images and comparing them with in situ data from meteorological stations. During the formation of the sea breeze, the visible band of clouds helped to define the frontal line that marks the boundary between the maritime and continental air masses.

Based on Meteosat-10 images and recording the time of cloud formation and disappearance, four periods can be distinguished: (a) no clouds visible although the wind direction changes from sea to land, 06:00–10:00 h; (b) the beginning of the formation of lower cumulus clouds, 10:00–11:00 h; (c) a clear band of cumulus clouds is visible to mark the propagation of the sea breeze to the mainland, 11:00–16:00 h; and (d) weakening of the sea breeze at 17:00 h when the cloud line is at its most extended but begins to become less pronounced as a "solid line".

Monitoring the spread of the sea breeze and the changes of fronts every hour in western Lithuania revealed that the maximum penetration of the fronts into the mainland took place around 17:00 h (Figure 6). After the midday hours, as the angle of incidence of the sun begins to decrease, the sea breeze begins to weaken and the clouds begin to disperse.

The penetration of the sea-breeze front into the continental part of western Lithuania changes during the day. Using the Meteosat-10 satellite data, it was determined that the clouds of the sea-breeze front in western Lithuania can travel an average of 41 km from the shore of the Baltic Sea throughout the day (Table 1). After the cumulus line formed around 11:00 h it reached an average of about 20 km, and when the front reaches its maximum extent (around 17:00 h) it penetrated the continent to an average of 59 km. With sea breezes, the cumulus cloud band became most clearly visible around 11:00 h. At that time, the average distance of the breeze front spread from the seashore perpendicular to the continent was from 10 km to 25 km (Table 1). This average extent of sea-breeze front penetration is typical of mid-latitude coastal areas [16].

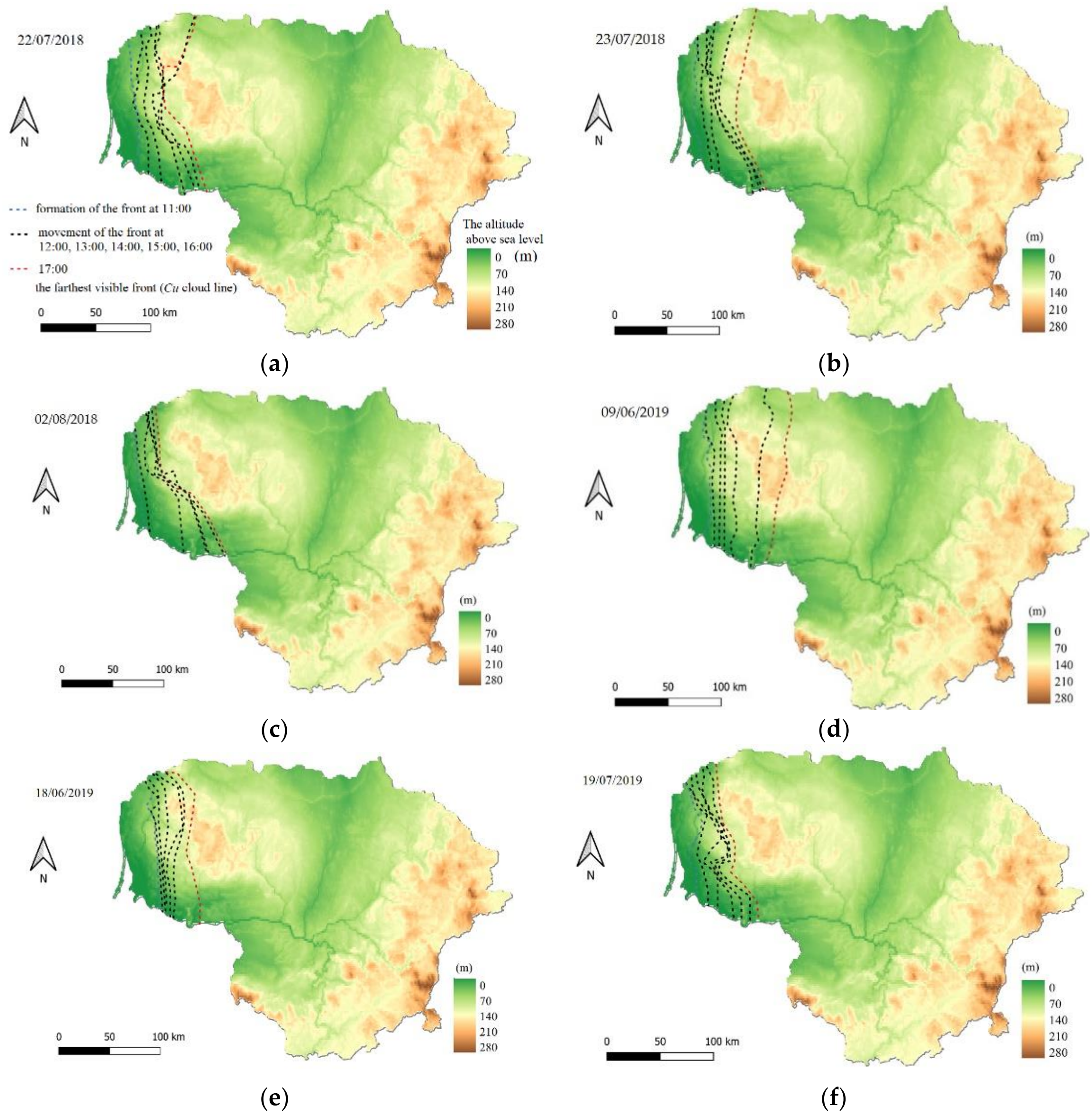

Figure 6. Spread of sea breeze and change of fronts every hour (11:00; 12:00; 13:00; 14:00; 15:00; 16:00; and 17:00 h) in the territory of Lithuania: (**a**) 22 July 2018; (**b**) 23 July 2018; (**c**) 02 August 2018; (**d**) 09 June 2019; (**e**) 18 June 2019; (**f**) 19 July 2019.

Table 1. The average distance of the breeze front spreading from the coast perpendicular to the continent (km) in the territory of Lithuania on the southeastern Baltic Sea coast (June—August, 2018–2019). STD—standard deviation; BS—Baltic Sea; CL—Curonian Lagoon.

Time	**Palanga (km)**	**Klaipeda (km)**	**Kintai BS Coast (km)**	**Kintai CL Coast (km)**	**Rusne BS Coast (km)**	**Rusne CL Coast (km)**	**Mean (km)**
11:00	22	21	25	13	30	10	20
12:00	27	23	31	19	37	17	26
13:00	32	33	41	29	47	27	35
14:00	39	39	50	38	60	40	44
15:00	43	40	54	41	66	45	48
16:00	50	47	60	47	71	51	54
17:00	53	53	66	54	73	53	59
Vid.	38	37	47	34	55	35	41
STD	12	12	15	15	17	17	14

The movement of sea-breeze fronts on the mainland can be enhanced by westerly winds. Westerly winds prevail in summer on the southeastern coast of the Baltic Sea (Figure 7). On the other hand, the terrain can also slow down the movement of the breeze front in the continental part after the front rests on the plateau of the Samogitian (Žemaičai) highlands. The Curonian Lagoon can also have a significant influence on the direction and coverage of sea breezes.

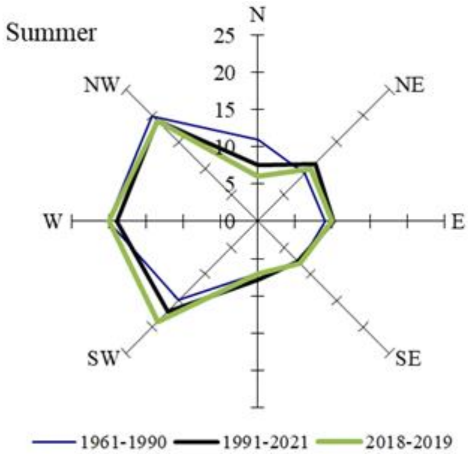

Figure 7. Dominant winds during the summer on the southeastern coast of the Baltic Sea (in situ data from the coastal meteorological station, Klaipeda).

The limit of the maximum spread of the sea breeze (km) in western Lithuania was determined in transects based on the band of the cumulus (Cu) and cumulonimbus (Cb) clouds recorded farthest from the seashore as read from remote data (photos). When the circulation of the local sea breeze started to weaken (around 17:00 h), the average distance of the penetration of the sea-breeze fronts into the continental part of western Lithuania from the coast reached from 53 km to 73 km (Table 1). The farthest sea-breeze front from the coast to the continent, as much as 89 km (Table 2), was recorded on 2 August 2018 at 17:00 h (Figure 6c). However, the largest territory was covered by the marine climate on 09 June 2019, (Figure 6d), which covered 10,765.4 km^2 of the studied territory of Lithuania (Table 3). This could be due to stronger westerly winds prevailing in the second half of the day coinciding with the direction of the sea breeze and thus strengthening the penetration of the breeze and the movement of the front into the continental part of Lithuania.

Table 2. Limit of maximum spread of sea breeze (km) perpendicular to the sea coastline in Lithuania) on the southeast Baltic coast (in case of maximum spread, at 17:00 h).

Date	Palanga (km)	Klaipeda (km)	Kintai BS Coast (km)	Kintai CL Coast (km)	Rusne BS Coast (km)	Rusne CL Coast (km)	Mean (km)
22 July 2018	48	46	70	58	78	57	60
23 July 2018	49	49	57	46	64	47	52
02 August 2018	34	36	77	64	89	68	61
09 June 2019	86	80	76	64	80	60	74
18 June 2019	60	57	65	51	62	42	56
19 July 2019	42	49	50	39	66	46	49
Mean	53	53	66	54	73	53	59
Max	86	80	77	64	89	68	77
Min	34	36	50	39	62	42	34
STD	18	15	11	10	11	10	14

Table 3. The area (km^2) of sea breeze penetration from the coast of the southeast Baltic Sea to the mainland of western Lithuania at the time of clear formation (11:00 h) and maximum spread (17:00 h) of the sea breeze.

Date	11:00 (km^2)	17:00 (km^2)
2018 July 22	2261.9	6926.7
2018 July 23	1520.1	6860.2
2018 August 02	1272.9	4027.8
2019 June 09	2524.5	10,765.4
2019 June 18	3314.4	6981.8
2019 July 19	1935.7	5120.8
Mean	2138.3	6780.0
Min	1272.9	4027.8
Max	3314.4	10,765.4
STD	737.5	2292.6

Breeze circulation research on the coast of the southeastern Baltic Sea, using remote sensing and in situ data, confirmed that the sea breeze phenomenon occurs quite often on the coast of the Baltic Sea in warm weather with clear days and that it has a prevailing wind speed of 3–5 m/s. The band of spherical clouds formed over the southeastern part of the Baltic Sea, marking the front line of the breeze, had an average speed of 4.8 m/s (minimum of 4.4 m/s and maximum of 10.3 m/s). The overall average westerly wind speed on the days of the breeze study at the meteorological stations was 2.8 m/s.

4. Discussion

Breeze circulation is one of the essential components contributing to coastal climate formation. Sea breezes, which result from temperature and pressure differences between land and sea, are one of the main components of coastal climate [22]. Wind circulation studies help to assess the impact of climate change on the mesoscale dynamics of the atmosphere. Future research should consider the variation of wind and atmospheric circulation when studying the climate of the Baltic Sea coasts.

Research on sea breezes of the southeastern Baltic coast using remote methods has shown that when sea breezes blow, their effects are felt on average about 40 km away from the sea in the territory of western Lithuania, but their maximum fronts can penetrate further, on average, even up to ~60 km when westerly winds prevail on the mainland. These results are consistent with previous studies of midlatitude breezes. The Universal Lithuanian Encyclopedia states that sea breezes cover an air layer approximately several hundred meters thick and several tens of kilometers wide [31]. In middle latitudes, sea breezes usually travel from 5 to 50 km inland but sometimes travel even further [35]. The same source declares that if we consider that only a fraction of all the sea breezes that develop near the coast travel 40 km inland, we must conclude that probably fewer than five percent of all sea breezes travel more than 100 km inland at latitudes of about 50°. Therefore, very deep inland penetration of sea breezes (100 km or more) is possible, but it seems rather unlikely [35]. The research results of this work show that the sea breeze circulation can penetrate into the continental area of the southeast Baltic Sea region further from the coast than was previously thought. The maximum distance of sea-breeze fronts from the seacoast to the deep mainland reached 89 km. Only six cases of sea breeze dominance were analyzed in detailed, but they do confirm that very deep inland penetration of sea breezes is possible. Therefore, further studies utilizing a longer study period are needed to determine the distribution and potential probability of the maximum extent of sea breezes.

The circulation of sea breezes in western Lithuania may lead to a higher number of sunny days in the Curonian Spit and the Baltic coast but higher cloudiness on the windward slopes of the Samogitian (Žemaicai) highlands. The sea breeze studies from this paper using remote methods confirm that with the persistence of the dominant transport of western winds and the increase in atmospheric pressure and air temperature gradients, more frequent and deeper expansions of maritime air masses to the continent are possible. The sunniest days each year are recorded at the seaside and the Curonian Spit [31]. The research shows that the sun shines ~30 h longer in summer (in July) than in the eastern part of Lithuania [28]. This may be partly related to more frequent cases of breeze circulation, which is determined by the warming summer air temperature and more frequent heat waves [36]. In the summer, sea breezes are important in coastal cities for reducing heat stress, which affects heat stress and air quality [37]. During the day, sea breezes can reduce the effects of heat waves in coastal settlements. However, a change in circulation from land to sea during the night can increase the warmth of nighttime air. The number of tropical nights on the coast of the southeastern Baltic Sea may increase due to this phenomenon.

Tropical nights are when the nighttime air temperature is higher than 20 °C. In the future, more detailed research is needed on how the circulation of sea breezes affects daytime heat waves in the territory of Lithuania. Moreover, how the wind blowing from the continent towards the sea can affect the air temperature at night near the seacoast in urbanized coastal areas should also be investigated. Future research should also consider how this phenomenon can change the day–night breeze system of local winds and influence the formation of tropical nights and their number per annum in mainland Lithuania. As the climate changes, an increase in the air and sea surface maximum temperatures of the warm season has been observed in the southeastern Baltic Sea [36]. The Baltic Sea region is warming, and this is almost certain to continue throughout the twenty-first century [26]. Regional warming is almost certain to have a variety of effects, including effects on sea–land breeze circulations.

A more detailed study in the future should consider how the height of the planetary boundary layer might affect the day–night circulation of land and sea breezes. The planetary boundary layer (PBL) is the lower troposphere in contact with the earth's surface [38]. The main variable of the PBL is its upper height dominated by its strong diurnal cycle; it is generally shallow (<500 m) at night as the surface layer becomes stable due to infrared radiative cooling. However, it grows deep (penetrating a few kilometers) in the daytime when solar heating causes convective unstable conditions [39]. The planetary boundary layer height (PBLH) values increase during the daytime and decrease during the night. Studies of the structure of the planet's land–sea boundary layer help identify seasonal variations. For example, studies at the Bohau Sea found that the duration of the sea breeze was ~10 h in the summer and only 3 h in the winter and that it extended inland ~50 km and up to 920 m vertically [40].

Continuous monitoring of breezes still requires irreplaceable data from in situ observations. The sea breeze is best indicated by wind direction and its change during the day. However, the network of meteorological stations should be optimized and reorganized in order to determine the spread of this phenomenon, the boundary of the front, and its movement in the territory of the southeastern Baltic Sea coast and western Lithuania. In situ observations, as in other Baltic Sea countries, allow direct analysis of winds. However, in situ measurements, especially over land, are often locally influenced, and inhomogeneities make the straightforward use of such data difficult [26]. Therefore, satellite data provides advantages when analyzing the spread of breeze circulation to the continent; it is possible to better observe the physical specifics of sea breeze phenomena, their change over time, and their spread in geographical latitudes.

High-resolution Meteosat—10 Rapid Scan High Rate SEVIRI Level 1.5 Image Data satellite photos of the HRV 1 km^2 rapid scan SEVIRI sensor can be used for recording and analyzing the processes of the circulation of sea breezes and the formation of their fronts in the Baltic region. It can help recognize and identify the boundaries of the sea-breeze front based on the cloud formation fronts represented by cumulus (Cu) and cumulonimbus (Cb) clouds. In this work, using Meteosat-10 satellite data in the period of 2018–2019 from June to August, six typical cases of sea breezes were recorded, during which the sea-breeze front was clearly visible and identifiable in the mainland of western Lithuania. These cases were assessed based on the period of formation and spread of Cu clouds and the change of wind direction and temperature during the day. The results of this study show that the location of the breeze front coincides with the line of cumulus-type convergent clouds, which mimics results obtained in similar studies [18,21] that applied similar remote sensing and research methods. During the formation of a sea breeze, the visible band of clouds helps to identify the frontal line that marks the boundary between the maritime and continental air masses.

The results obtained in this work show that it is possible to use the limits of the domination spread of sea breeze to determine the areas of maritime climate influence on oceans and seacoasts. When the sea breeze pushes the colder front towards the continent, it forms a belt of Cu clouds about 40 km away from the seashore on average. Based on the method of assessing the strength of the relationship between solar radiation and air temperature, similar limits of marine climate expansion were determined in the Baltic Sea region [41]. The maritime climate in the continental part extends from the seashore perpendicular to the land for an average of ~37 km in the southeast Baltic [41], including in the territory of Lithuania. The obtained similar results confirm that the sea-breeze fronts determined by remote-sensing methods can help to assess the limits of marine climate expansion and their changes in coastal areas.

Breeze circulation may change in the future as a result of climate change, as many future climate scenarios capture future changes in atmospheric dynamics. Climate continentality or maritimeness is one of the main characteristics of the local climatic conditions, and it varies with global and regional climate change [42]. The atmospheric circulation over Europe varies substantially from year to year, which leads to variations in temperature, precipitation, windiness, and other aspects of the surface climate [43].

Based on the investigation of continental and oceanic changes in the middle and high latitudes of the northern hemisphere, it is very likely that continentality will change in the future, and its changes may be amplified in the following decades [42].

Atmospheric circulation in the European/Atlantic sector plays an important role in the regional climate of the Baltic Sea basin [44]. The same research indicates that in projections of future anthropogenic climate change, summer air pressure and atmospheric circulation will change in the Atlantic and in the Baltic Sea region. Coastal breezes are one of the essential components that contribute to the formation of coastal climates. The sea breeze, which forms because of temperature and pressure differences between land and the sea, is one of the major components that contributes to coastal climates [22]. Breeze circulation studies help assess the impact of climate change on atmospheric mesoscale dynamics. The variability in land–sea breeze and its impact on weather are studied and to improve the quality of local short-range weather forecasting [45]. For future research, breeze and atmospheric circulation variation should be considered while studying the coastal climate of the Baltic Sea. Due to climate change, the different exposures of seacoast and continental orography, and the growth of urbanized areas, further detailed studies of the dynamics of sea breezes and possible changes are required.

5. Conclusions

1. The appearance of the sea breeze in the southeast Baltic coast during the warm period of the year is fixed at 06:00 h and diminishes around 19:00 h, as determined by the sudden change in the direction of the dominant wind observed by ground-based meteorological stations.
2. The front of the sea breeze in the territory of western Lithuania travels about 40 km from the Baltic Sea coast on average, and it occasionally penetrates the continent even further (up to 60 km).
3. The sea breeze affects not only the coastal climate region of Lithuania, as previously thought, but it also affects the climate of part of the region of the Samogitian (Žemaitijos) Uplands of Lithuania.
4. The largest territory covered by the sea breeze extending the marine climate occurred on 09 Jun 2019, (17:00 h), and it extended to an area of 10,765.4 km^2 of the studied territory of Lithuania.

5. Remote methods help to assess the dynamics of sea breeze winds and their fronts in more detail. The network of meteorological stations is not dense enough to sufficiently describe the distribution of sea breeze fronts in the territory of Lithuania.
6. The fronts (Cu and Cb cloud bands) marking the limits of the maximum spread of the sea breeze can help determine the limits of the transition between the maritime climate to the continental climate and map the areas of influence of maritime air masses on the coasts of the oceans and seas.

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