Numerical simulation of breeze circulation in Crimea using WRF-ARW model

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Abstract. Breeze circulation is an important atmospheric process that affects the weather and climate of coastal regions. Crimea is one of such regions. One of the methods of breeze research is numerical simulation, which has been quite successfully used to obtain information on breeze circulation in various geographical regions. The purpose of this work is to describe the regional features of sea breeze in Crimea, specifically, a breeze circulation near the Crimean Mountains. We use an array of satellite images and data of global operational analysis, NCEP GDAS, to choose a day with a pronounced breeze. A numerical experiment is performed for the day using a mesoscale model, WRF-ARW. Based on the results of the numerical simulation, the structure of the sea breeze circulation in Crimea is described. Some classical elements of the breeze characteristics of the flat part of Crimea are observed. A unique phenomenon of collision of breeze gravity currents has been revealed. It is a characteristic of the rather small land areas. Much attention is given to the features of breeze in the mountains associated with the complex topography.

1. Introduction
Sea breeze circulation is an important atmospheric process that affects the weather and climate of coastal regions [1, 2]. Weak background pressure gradients are needed for the development of breeze circulation, which is typical of the middle latitudes in summer.

Various methods are used to study the breeze circulation: analytical theory (linear and nonlinear), measurements (in situ and remote), laboratory experiments, and numerical simulation (ideal and realistic).

The breeze of weak intensity is described by a linear theory, in which breeze circulation is represented as a forced internal gravity wave localized near the coast. This wave is a reaction of the atmosphere to a heat source with a daily frequency [3, 4].

For a high intensity breeze, the lower branch of the breeze circulation cell is a propagating gravity current. It is a substantially nonlinear phenomenon that has been the subject of a number of studies [2, 5–7].

Breeze field observations include the data from standard weather stations, the results of specialized programs and expeditions [8–11], as well as numerous satellite data in different spectral ranges [12–13].

In laboratory experiments, the features of the breeze circulation and gravity currents are studied under controlled conditions, such as stratification, velocity profile, etc. [2, 14].
In the ideal numerical simulation, the problem is usually posed with maximum simplifications, such as a straight endless coast, constant buoyancy frequency, no complex topography, and simple parameterization of viscosity and thermal conductivity [7, 15, 16]. Ideal simulation makes it possible to determine and investigate the influence of each factor that is involved in the formation and modification of the breeze.

Realistic numerical simulation of the breeze in a particular region, taking into account real geography, mountain topography, etc., using mesoscale atmospheric models and reliable input data from global forecasts and analyses, makes it possible to describe in detail the real breeze circulation with high spatial resolution, taking into account all other processes, for example, synoptic ones.

Realistic numerical simulation together with the data from weather stations and satellite data has been successfully used to obtain reliable information on breeze circulation in various geographical areas with complex topography, such as Spain [8, 10], Greece [9], Mississippi area [11], etc.

To describe the breeze circulation of the Crimean Peninsula, a number of studies were performed using numerical simulation [17 – 18]. It was noted that the features of breeze in Crimea are explained by its limited size, a complex shape of the coastline, and the presence of mountains. A significant difference between the breeze in the flat terrain and in the mountains was also noted.

Two diagnostic methods can be used in realistic numerical simulation of the breeze:

1. Numerical simulation and subsequent averaging over some period (months, years) of time, in order to get an idea of the average characteristics of the breeze in a given area. In this case, background synoptic and large-scale processes should be taken into account and properly filtered [17 – 18].

2. Case study: diagnosing the structure of a breeze for one particular day makes it possible to investigate the development and dynamics of the breeze in a specific synoptic situation, to highlight the influence of geographical features of a territory.

Due to the influence of numerous atmospheric factors, such as the vertical profile of the synoptic wind, the vertical profile of the buoyancy frequency, the distribution of humidity, etc., the structure and dynamics of the breeze in a given area greatly vary from day to day. Therefore, the use of the averaging method can largely distort the picture and, therefore, it is preferable to consider the breeze circulation on a particular day when there is no such distortion.

In order to consider the breeze circulation in its pure form, it is necessary to choose the simplest state of the surrounding atmosphere characterized by the absence of strong synoptic processes, large-scale clouds, and enhanced cumulus convection. For this purpose, a day with a well pronounced breeze over the Crimean Peninsula was selected from the archived data of satellite images and global operational analysis data.

For the selected day, a numerical experiment was performed using the mesoscale atmospheric model WRF-ARW, and a detailed analysis of the breeze circulation was made.

The work consists of four sections. The following section describes the area under study, the model, the input data, and the model options used for the calculation. The third section presents the simulation results, describes the structure and development of the breeze during the day in the flat and mountainous parts of Crimea. The last section is devoted to conclusions.

2. Numerical experiment

2.1. Description of the study area
The study area includes the Crimean Peninsula with the adjacent Black and Azov Seas. Most of the peninsula is flat terrain. In the south and southeast of the peninsula a mountain ridge stretches along the coast; its height does not exceed 1600 m. On all sides Crimea is surrounded by seas. In the north, the peninsula is connected with the continent by an isthmus. From the West and South of Crimea, the Black Sea is located, and in the north-east – the Sea of Azov.
2.2. Choice of the day for the study
The day for the study was selected using the data of the global operational analysis NCEP GDAS. We considered the wind speed field at levels from the surface to 850 mb and estimated the maximum wind speed and the general synoptic situation. Days with the lowest wind speed and the absence of cyclones and anticyclones in the vicinity of the Crimean Peninsula were selected.

We also used the data in the visible range from MODIS Terra and MODIS Aqua satellites, with a resolution of 250 m. The breeze indicator on the satellite imagery was characteristic cumulus clouds that formed in front of the breeze front. Since these satellites pass over the same point of the surface with an interval of 3 hours, this allows one to see the development of cumulus clouds during the day.

Days without strong displacement of the cumulus clouds of the breeze front by the synoptic wind were selected for numerical modeling. The days were also selected without deep convection and the formation of cumulonimbus clouds strongly influencing the development of the breeze.

Figure 1. MODIS Aqua satellite image, 29 July 2018.

Three summer seasons of 2016-2018 were analyzed and, as a result, the day of 29 July 2018 was chosen for the simulation. Figure 1 shows the distribution of clouds over the Crimean Peninsula according to the MODIS Aqua satellite data for this day.

An analysis of the GDAS global operational analysis data for the Crimean Peninsula for this day showed that in the lower part of the troposphere the wind speed, wind shift, and horizontal temperature gradients were small. At the lower levels, a weak northwest wind was observed with a speed of 2-3 m/s, and at the level of 500 hPa the wind speed was 5 m/s. In the upper part of the troposphere, above the level of 350 hPa, a southwestern flow was observed with a vertical wind shift of 24 m/s between the levels of 350 and 250 hPa, and the corresponding horizontal temperature gradient. However, the motion in the upper troposphere does not affect the breeze circulation.

2.3. Description of the model and input data
For the numerical simulation, the mesoscale model WRF-ARW of version 3.7 [19] was used, based on a system of nonhydrostatic equations written for a compressible atmosphere. The model vertical coordinate is a terrain-following eta coordinate, with stretching permitted by the vertical grid. The horizontal grid is presented by a staggered Arakawa C-grid. Time-split integration is performed using a 2-nd- or 3-rd-order Runge-Kutta scheme. For spatial discretization, 2-nd- to 6-th-order advection schemes in the horizontal and vertical directions are used.
The model has a wide range of options for describing subgrid processes, such as turbulence in the boundary planetary layer, radiation transfer, cloud microphysics, cumulus convection, heat and moisture transfer in the soil (Table 1).

Data from the global operational analysis NCEP GDAS / FNL 0.25 were taken for the numerical simulation of the breeze circulation as initial conditions in the internal area of both computational domains, and then in the process of calculating the boundary conditions at the boundary of the external domain. The data had a resolution of 0.25 degrees in space, 6 hours in time. Data on the topography were taken from the GEOG array with a spatial resolution of 30 seconds.

2.4. Numerical simulation
Table 1 provides information on the numerical experiment for the selected day and the model options used.

For the internal domain, a resolution of 2 km was chosen, which is enough to describe the features of the breeze structure.

32 vertical levels were selected to have a sufficiently high resolution in the lower troposphere, in which the breeze circulation develops.

The time step is determined by the spatial resolution.

The listed parameterizations are traditionally used in the numerical simulation of a breeze under conditions of complex topography [8, 9, 11, 17, 18].

Table 1. Details of the domain grids and options for physical parameterizations used in the numerical simulation.

| Domains | Domain 1 | Domain 2 |
|----------|----------|----------|
| Horizontal resolution | 6 km | 2 km |
| Domain coordinates | 41.028 — 49.433 N, 27.968 — 40.632 E | 44.132 — 46.939 N, 32.227 — 37.108 E |
| Time step | 36 s | 12 s |
| Vertical resolution | 32 levels |
| Simulation time | 1 day |

Physical parameterizations

| microphysics | WSM 3-class simple ice scheme |
| longwave radiation | RRTM scheme |
| shortwave radiation | Dudhia scheme |
| surface-layer | Revised MM5 Monin-Obukhov scheme |
| land-surface | thermal diffusion scheme |
| boundary-layer | YSU scheme |
| cumulus | Kain-Fritsch (new Eta) scheme |

3. Results
To analyze the breeze circulation, we used the results of numerical simulation in the internal domain with a resolution of 2 km.

Below we consider the structure of the breeze over the Crimean Peninsula and provide an interpretation of its features.
3.1. Sea breeze over Crimea

A detailed analysis of the results of the numerical simulation showed that the breeze circulation over Crimea has standard characteristics inherent in classical concepts. These include: 1) formation of the daytime convective boundary layer; 2) development and propagation of breeze gravity currents from the coast; 3) formation of the breeze front, head, and tail of the breeze gravity current; 4) intense vertical lift in front of the gravity current; 5) reverse branch of the breeze circulation cell.

To highlight these characteristics for different moments in time, maps were constructed at different levels and various vertical sections of the horizontal and vertical components of wind velocity, temperature and potential temperature, humidity, the planetary boundary layer height, cloudiness, etc.

Due to a limited volume of this article, of all these maps only a map of direction and module of the horizontal velocity component is shown in Figure 2. This figure clearly depicts the spread of gravity currents.

In addition to these classical characteristics, the breeze circulation in Crimea has its own features. One of them is the propagation of several gravity currents from different shores to the center of the peninsula and subsequent collision of these currents, which can lead to the development of deep convection. The Crimean Mountains also have a significant impact on the breeze, especially on the southern slope.

Consider the horizontal and vertical structure of the breeze over Crimea (Figure 2). To obtain information about the vertical structure, consider two vertical sections marked in Figure 2 as black straight lines.

![Figure 2. Wind speed (color) (m/s) and direction (streamlines) at 15:00 local time (LT) (UTC + 3) at 2.5-d eta level (73.5 m) for velocity. 1 – cross section along which the vertical structure of sea breeze in the flat part of Crimea is considered. 2 – cross section along which the vertical structure of sea breeze in the Crimean Mountains is studied.](image-url)
3.2. Sea breeze on the plain
Consider the sea breeze circulation over the central plain part of Crimea. In the morning, a convective atmospheric boundary layer is formed over most of the peninsula, in which there is a uniform vertical profile of potential temperature. A heated convective boundary layer over land is necessary for the intrusion of cold sea air to the land, the formation of breeze gravity currents, and their subsequent propagation from the coast to the land.

The Crimean Peninsula is surrounded by seas on all sides, but breeze does not develop on each side. Only two fronts are clearly visible in Figure 2: from the west (Black Sea) and from the east (the Sea of Azov).

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The third breeze front from the northwest, from the Karkinitsky Bay, is absent on the study day. This is because on this day there was a weak northwest synoptic wind over the entire territory of Crimea; it prevented the development of a breeze on the north-western coast of Crimea.

The fourth front from the side of the Southern Coast of Crimea is being formed, but the Crimean Mountains prevent its propagation. Its features are described in more detail in the next section.

A more detailed analysis of the breeze gravity currents at different moments shows that during the day, as their structure develops, the feature elements of sea breeze form: the front, the head of the current (with a height of about 600-800 m), and the tail (with a height of about 300-500 m). In front of and above the fronts of breeze gravity currents, intense vertical movements (about 0.5-0.7 m/s) occur in rather narrow areas (about 10 km), which leads to enhanced cumulus convection seen in satellite images (Figure 1). When advancing further on land, the fronts of gravity currents follow the shorelines of the coasts where they formed.

Above the near-surface currents, the wind direction changes to the opposite one, and reverse branches of the sea breeze circulation cells form.

The time of occurrence and the distance that the breeze fronts cover during the day differ at different shores. On the west coast, a breeze front occurs at 10:00 LT and on the east coast, at 12:00 LT. During the day the western front covers a distance of about 100 km, and the eastern front, of about 80 km.

In the evening at 19:00 – 20:00 LT there is a collision of breeze currents. Figure 3 shows a vertical section of the longitudinal component of wind velocity at the time before the collision at 15:00 LT. The direct and reverse branches of the circulation of both fronts, their heads, and tails are clearly visible. After the collision, the current extending from the Sea of Azov propagates above the current from the Black Sea, which continues to spread on the surface. This is due to the fact that the Black Sea breeze front is stronger (it has a greater thickness and propagation speed) than the Azov one.

The collision of sea breeze gravity currents in the center of the Crimean Peninsula is a unique phenomenon associated with the small size of the peninsula. The breeze fronts manage to travel distances (approximately 100 km) from the coast to the center of the peninsula within a few hours (8 hours) with a characteristic speed of about 5 m/s.
3.3. Sea breeze in the mountains

The wind in the mountains occurs due to the breeze circulation and the anabatic slope wind, caused by one reason — the daytime heating of the (inclined) land surface. On the northern slope, there is a slope wind, a northwest background wind which coincides in direction with the slope wind, and breezes from the western and eastern shores of Crimea. Pure breeze is not observed on the northern slope, but it occurs on the southern slope of the mountains.

Consider the sea breeze circulation on the southern slope of the Crimean Mountains, where the picture of motion is less complex than on the northern slope.

On the southern coast of Crimea, the breeze from the adjacent Black Sea propagates up the slope of the whole chain of the Crimean Mountains.

In this part of the peninsula, the circulation develops earlier (at about 8 am local time) compared with the other shores of Crimea (at about 10:00 – 12:00 LT).

The breeze covers the entire southern coast from Foros to Feodosiya (Figure 2), and represents a narrow band with a wind of the southern direction, at a speed of up to 4 m/s.

During the day, the width of the area occupied by breeze changes from 2 – 4 km at 11:00 LT to 20 km during the maximum breeze development at 15:00 LT, and then decreases by 19:00 LT, that is, by the end of the sea breeze circulation.

The visible difference in the distribution of the breeze in the western and eastern parts of the mountains (Figure 2) is due to different heights of the mountains and different steepness of the slopes. The western part of the Crimean Mountains is higher than the eastern part, and has steeper southern slopes, which significantly affects the characteristics of the sea breeze. First, the coastal band width on the Southern Coast covered with the sea breeze circulation in the west (5 km) is less than in the east (15 - 20 km). Second, the intensity of the breeze circulation in the west is less (3 m/s) than in the east (5 m/s). Third, the duration of the sea breeze in the east (11:00 – 20:00 LT) is longer than in the west (11:00 – 18:00 LT).

In particular places of the Southern Coast of Crimea, along the mountain passes, large values of the horizontal velocity are observed during the day.

Consider now the vertical structure of the breeze in the mountains. To do this, we choose a cross-section that runs perpendicular to the ridge of the Crimean Mountains, and consider the distribution of the velocity component perpendicular to the ridge (Figure 4).
Figure 4. Velocity component (m/s) along cross-section 2 at 15:00 LT. The position of cross-section 2 is shown in Figure 2.

The breeze structure in the mountains also has characteristic elements of a classical breeze, in particular, the lower branch of the breeze circulation, which after the breeze commences (at about 8:00 LT) propagates up the slope. Its advance is accompanied by an intense vertical motion.

The breeze front extends only to the top of the ridge, and after 14:00 LT it is observed along the southern slope of the mountain, not moving further north. The current cannot pass further due to a northwestern synoptic headwind on the northern slope of the mountain ridge, which flows on the breeze gravity current from above. Due to the collision of the breeze and the background wind, convergence areas are observed along the entire chain of the Crimean Mountains.

After 20:00 LT, the breeze structure collapses. Maximum speeds in the surface gravity current were observed during the day (from 12:00 to 15:00 LT) and reached 3 m/s.

4. Conclusions
Based on the results of a numerical simulation, the structure of a sea breeze circulation in Crimea has been described. Some classical elements of the sea breeze of the flat part of Crimea were observed. A unique phenomenon of collision of breeze gravity currents has been revealed. It is a characteristic of small-size peninsulas and islands (see, for example, [20]).

Much attention was given to the features of the breeze associated with the influence of the mountains. On the Southern Coast of Crimea, in the daytime, two mesoscale atmospheric phenomena occur simultaneously — a breeze circulation and an anabatic slope wind caused by daytime heating of the (inclined) land surface.

The numerical modeling allowed us to describe in detail the sea breeze circulation of the southern coast of the peninsula. Here the sea breeze develops earlier compared to the other shores. The breeze of the southern coast is a narrow band with a southern wind, and during the day the width of this band changes greatly. There is a difference in the propagation of the breeze in the western and eastern parts of the mountains, due to the difference in height between the mountains and the steepness of the slopes.

Some elements typical of a classical breeze have been observed in the vertical structure of the breeze in the mountains, specifically, a gravity current near the surface, which propagates up the southern slope of the mountain.
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