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Review article

Sea Breeze Circulation: Theory and Two-Dimensional Simulation (Review)

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Abstract
Purpose. Sea breeze circulation is a common mesoscale phenomenon near the coasts of water bodies. However, at the moment, a number of the published review papers on this topic remain small. Therefore, the purpose of the work is to complement the existing reviews on sea breezes by generalizing the available knowledge on the influence of air heating intensity near the land surface, atmosphere stratification, synoptic background wind and the Coriolis force upon the sea breeze circulation.
Methods and Results. An overview of the results of studies involving the theoretical research methods, namely linear theory and two-dimensional numerical simulation, is presented. At first, the sea breeze circulation is considered within the framework of linear theory. Further, a technical description of two-dimensional models and the breeze features obtained applying these models are presented. The published works having been reviewed made it possible to consider the influence of four main factors (heat flux, atmosphere stratification, background synoptic wind and the Coriolis force) upon the breeze circulation.
Conclusions. Within the framework of linear theory, the breeze circulation represents an internal inertial-gravity wave with a diurnal period. Depending on the uniformity of vertical profile of the background synoptic wind, its influence on the linear sea breeze circulation leads to the asymmetry of circulation relative to the coast and to limitation of the breeze height. In a nonlinear regime, the important feature of breeze circulation obtained by applying numerical simulation consists in formation of a gravity current propagating over the surface. The nonlinear regime implies a fairly clear dependence of the velocity of gravity current front propagation on its height. The main manifestation of the background wind influence upon the gravity current is the change in its height that results in formation of a stationary or rapidly spreading current. Due to the Coriolis force influence, both within the framework of linear theory and in the nonlinear regime, an along-coastal velocity component is formed that leads to a decrease of the velocity component perpendicular to the coastline.

Keywords: sea breeze circulation, linear theory, numerical simulation, internal gravity waves

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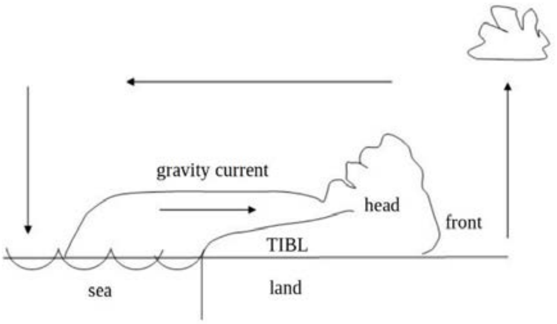
Introduction

Sea breeze circulation is a common mesoscale phenomenon near the coasts of water bodies. Sea breeze occurs under effect of a pressure gradient due to different heating of the air near the land surface and the water body surface.

Sea breeze develops in the lower layer of the atmosphere and affects boundary layer structures [1, 2] and the atmosphere above it [3, 4] as well as the formation of cumulus convection [5–7] and interacts with processes of various scales in the atmosphere and ocean [8–11]. Being formed in coastal regions, sea breeze affects the weather and climate of these areas. In addition, the relevance of sea breeze research is determined by its effect on pollution transport [12–14], especially in urbanized industrially developed coastal regions. The structure of sea breeze circulation (Fig. 1) includes gravity current, front, gravity current head, region of strong turbulent mixing behind the head, returned current, thermal internal boundary layer (TIBL) [15].

Sea breeze gravity current is a flow of cold sea air onto the land. The boundary between cold and warm air on the land (a sea breeze front) is usually characterized by large gradients of temperature, pressure and humidity. Directly behind the breeze front, the raised gravity current head is located which is formed due to the convergence of cold and warm air masses located above the water body and land, respectively. The head height is several times greater than the current main body one. Behind the head, a region of strong turbulent mixing is formed due to the instability of the Kelvin – Helmholtz waves which arise at the boundary between two layers of air with different densities and velocities. A returned current is directed in the opposite direction above the sea breeze gravity current. A thermal internal boundary layer is formed inside the body of the cold gravity current. It occurs when cold air moves onto the land and is gradually warmed by the land surface.



F i g. 1. Structure of breeze circulation (TIBL – thermal internal boundary layer)

The sea breeze development is influenced by a large number of factors [16]. The main factor determining the sea breeze occurrence is the heat flux at the land surface [17, 18], under effect of which a pressure difference over the land and sea surfaces is formed.

Other major factors affecting sea breezes include background synoptic wind [19−21], Earth's rotation [22, 23] and atmospheric stratification [24−26] which is different over the sea and the land and varies with the diurnal cycle. Secondary factors affecting sea breeze circulation include surface friction [1] [27], turbulent mixing [19, 28, 29], topography (height and slope) [30, 31], coastline shape [32, 10],

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[1] Malone, T.F., ed., 1951. *Compendium of Meteorology*. Boston, Massachusetts: American Meteorological Society, 1334 p.

basin [33, 34] and land scale [35−37] as well as air humidity [5, 38]. Although most of these factors affect sea breezes after they have formed, some can affect the balance of forces and support or prevent their development.

The history of sea breeze circulation research spans over a century. A fairly detailed description of the early stages is given in monograph [2] and reviews [39, 40, 15]. Various methods are applied to study sea breezes: theory, numerical simulation, experiments and *in situ* observations. Among the theoretical methods for studying sea breezes, the following are distinguished: linear theory [22, 41, 42], nonlinear theory for some exact solutions [43, 44] and similarity theory [25, 26, 45, 46].

Numerical simulation studies can be divided into two categories. The first category includes idealized two-dimensional models with simplified representation of physical processes [17, 18, 28, 47, 48]. The second category covers numerical simulation of sea breezes in specific geographic regions using three-dimensional mesoscale atmospheric models with high spatial resolution and detailed representation of physical processes [49−56]. The stages of development and comparison of two-dimensional and three-dimensional models are presented in works [3] [16].

Both laboratory [4] [57] and *in situ* [51, 58] experiments have been carried out. The behavior of gravity currents depending on the parameters of environment [59–61] is mainly studied in laboratory experiments. The largest number of works are devoted to *in situ* observations which include contact [50, 54, 62, 63] and remote observations from satellites in different spectral ranges [34, 64, 65] as well as meteorological radar data, to mention but a few.

This work is purposed at presenting the main results of the impact of surface heat flux, background wind, stratification and the Coriolis force on sea breeze circulation using analytical theory and ideal two-dimensional simulation.

Linear theory of sea breeze circulation

Sea breeze studies in the 19th century and in the first half of the 20th century were more qualitative. By the 1950s, the observations had revealed that sea breeze had the form of a circulation cell changing its direction during the day. Sea breeze is formed due to different heat capacity of the land and sea which results in a temperature gradient formation at the land-sea interface. This leads to the formation of a pressure gradient and, as a result, sea breeze circulation. Sea breeze is observed in calm weather or with a weak background wind. The nighttime sea breeze is less intense than the daytime one.

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[2] Simpson, J.E., 1994. Sea Breeze and Local Winds. Cambridge: Cambridge University Press, 234 p.

[3] Clark, I.W., 1986. *A Three-Dimensional Numerical Model of the Sea Breeze for the Plymouth Region: Thesis*. Devon, England: University of Plymouth, 259 p. https://doi.org/10.24382/1380

[4] Simpson, J.E., 1997. *Gravity Currents in the Environment and the Laboratory*. Cambridge, United Kingdom: Cambridge University Press, 244 p.

Experimental dependences of wind speed on temperature, distribution of meteorological parameters, breeze horizontal and vertical sizes, their dependence on season and latitude in individual geographic regions were obtained. For example, it is found that the daytime sea breeze extends to a distance of up to 50 km in middle latitudes and up to 150 km in the tropics. The nighttime sea breeze penetrates shorter distances than the daytime one.

The background wind can both strengthen and weaken the breeze or prevent its development. When the headwind is calm, the breeze manifests itself as a cold front. When the breeze develops, air moves at a right angle to the coastline, the breeze direction changes due to the Coriolis force [1].

Based on observational data, the authors of the first theoretical works considered the following questions: what forces should be taken into consideration for the correct description of the sea breeze, how to obtain the difference in time between its maximum intensity and temperature corresponding to observations [1]?

The first work that provided a quantitative description of sea breeze circulation was devoted to the linear theory [22]. Assuming that locally, at a coastline point near the surface, the acceleration is determined by the pressure gradient created by the temperature contrast between the sea and land, the Coriolis force and linear Rayleigh friction, a correct elliptical shape of the velocity hodograph was obtained. The clockwise velocity vector rotation was also established. However, no spatial distribution of all three components of velocity, temperature and pressure was obtained since complete equations of hydrodynamics were not solved. It is demonstrated that the circulation source of breeze circulation cell is temperature (buoyancy) contrast between land and sea. It should be noted that application of linear friction made it possible to obtain a phase shift in the model between heating and the sea breeze circulation intensity close to observations.

At the same time, in [66], the author examines the atmosphere reaction to a given temperature distribution which was a periodic function of time and an exponentially decaying function of height. Theoretical result describing the dependence of the maximum wind speed on height in the daytime sea breeze agreed quite well with the experimental data at the equator. In the middle latitudes, the velocity dependence on height in both daytime and nighttime sea breezes is similar to that observed in the tropics. The difference is that velocity vector changes its direction during the day due to the Coriolis force.

In work [1], a linear solution for a horizontally periodic heat source was obtained, which provided the application of the Fourier transform. At the 45th parallell, this solution described the observed circulation quite completely. It was found that the height of both daytime and nighttime sea breezes was 400 m and increased with rising friction. The Coriolis force effect is manifested in the occurrence of an alongshore velocity component which is shifted in time by approximately 12 hours relative to the component normal to the shore. The maximum temperature difference at the land-sea boundary and the maximum sea breeze intensity differ in time by 4.7 hours. Consideration of friction and the Coriolis force reduces this shift. The height occupied by the returned current is 4–5 times greater than one of the current near the surface. The maximum velocity in the returned current is approximately 4 times lower than in the surface current. The upper boundary of sea breeze circulation increases with rising friction and decreases with the increasing Coriolis force.

An important study examining the background wind effect on breezes is [67]. It examines the response of a homogeneous stratified flow to a heat source (island) of finite horizontal size on the surface. Waves are formed in the atmosphere on the leeward side of the island, their horizontal wavelength depends on the island dimensions.

Work [47] demonstrates that the motion can be divided into two parts – the rotational part and the large-scale wave potential motion. The wave motion occupies a large horizontal scale of ~5000 km and transfers mass from land to sea with small velocity values of ~1 km/h.

In [68] the formation of breeze circulation forerunner is considered in a stably stratified atmosphere in the form of internal gravity waves generated near the coastline at the moment of heating activation and propagating quite quickly from the coast towards the sea and towards the land.

A certain stage was [24]. Due to consideration of turbulent viscosity and thermal conductivity, a sixth order equation for stream function was obtained, so it had to be solved numerically. It was found that large values of velocity gradients near the coast arose due to the absence of temperature advection. The returned current directed from the coast towards the sea is two times weaker than one directed towards the coast. Affected by the Coriolis force, the wind velocity vector rotates clockwise at all heights. The distance over which the sea breeze propagates increases with rising atmospheric stratification. The background wind from the coast makes the maximum of the coast-perpendicular velocity shift towards the sea and its value decreases with an increase in the background wind. A sharp front is formed at the coast at small values of the background wind speed.

In [69], thermal convection in a stratified fluid is studied using the Boussinesq approximation and constant values of viscosity and thermal conductivity. Convection is caused by heating or cooling of the lower surface. At an infinitely small amplitude of heating, temperature field is controlled by a single parameter proportional to the vertical temperature gradient, heated surface size, thermal expansion coefficient, gravitational acceleration and is inversely proportional to viscosity and thermal conductivity.

Work [70] notes that the rotation rate of wind velocity vector during a sea breeze varies within a day. A two-dimensional linear model was applied for the study. The specified velocity is determined by three terms: the Coriolis parameter, the vector product of horizontal mesoscale pressure gradient by the sea breeze velocity and the vector product of horizontal synoptic pressure gradient by the sea breeze velocity.

In [25], the reaction of a stratified atmosphere to periodic heating was considered with the application of linearized equations in the Boussinesq approximation with regard to viscosity and thermal conductivity. The solution structure can be characterized by a single parameter which is proportional to the heating frequency, the horizontal dimension of the heated surface and inversely proportional to the buoyancy frequency and viscosity coefficient. After perturbation of the basic state, three regimes can be observed: a thermal wave propagating upward (in which no air movement is observed), convection (in which the temperature perturbation is accompanied by air movement in the form of circulation, without vertical propagation) and an internal wave propagating downward.

A significant theoretical achievement in the linear theory of sea breezes became [41]. Unlike [24], viscosity and thermal conductivity were absent there and spatial distribution of heating was specified explicitly. This lowered the equation order for the stream function to the second one and significantly simplified the solution analysis. It was indicated that sea breeze circulation could be considered as an internal inertial-gravity wave of diurnal period generated on the surface by a buoyancy source. Qualitative difference is emphasized between the middle latitudes where this wave is captured near the surface and the tropics where it is radiated upward from the coastline. In the tropics, there is a time shift of 12 hours between circulation and heating. In the middle latitudes, under effect of the Coriolis force, this is not observed. The dissipation inclusion in the form of Rayleigh friction reduces the differences in the breeze structure in the tropics and middle latitudes. The effect of buoyancy and Coriolis force on the sea breeze circulation intensity was analyzed using Bjerknes circulation theorem. It is indicated that the circulation is predominantly affected by the Coriolis force, rather than the buoyancy force.

In [42], the horizontal scale of a sea breeze circulation cell is considered under the linear theory taking into account turbulent mixing with constant viscosity and thermal conductivity coefficients. The resulting horizontal scale of a sea breeze cell is a function of latitude and is proportional to the ratio of buoyancy frequency to the diurnal frequency and the vertical scale determined by thermal conductivity. The function describing the dependence on latitude takes a constant value for latitudes less than 30 degrees and decreases on drawing near the poles. In addition, it was found that the velocity component perpendicular to the shore decreased with distance from it as the Coriolis parameter increases.

In [27], based on the ideas from [41], it is shown that rotation and friction affect the sea breeze intensity, but they are not important at the initial stage of development. The authors analyzed transient processes at the initial stage of sea breeze development in the morning hours with sudden and gradual heating activation. Complete diurnal cycle was also analyzed. The characteristic sea breeze time scale is a combination of the inertial period and the attenuation time due to friction. For the time exceeding this scale, the distance over which the sea breeze propagates is limited by the Rossby radius of deformation with regard to friction. At the equator, friction is the limiting parameter for the intensity and propagation range.

A series of studies devoted to the effect of a uniform background synoptic wind on sea breeze circulation within the framework of the linear theory was resumed with the appearance of [71] which did not take into account the Coriolis force effect, i.e. considered the sea breeze at the equator. The main physical result is that the sets of internal gravity waves emitted from the surface from the coastline are subject to a Doppler shift, which manifests itself in the asymmetry of the waves relative to the coastline and wave dispersion on the leeward side. In addition to this effect, another additional feature arises – a set of stationary internal waves above the coastline similar to internal gravity waves arising when a stratified uniform wind flows around mountainous terrain. The solution corresponding to the stationary set becomes predominant with an increase in the background wind speed.

Further, in [7, 72], the Coriolis force effect was already taken into account, i.e. the problem of synoptic wind effect on the sea breeze in the middle latitudes was considered. It is shown that here, as well as at the equator, a set of stationary internal waves arises.

The wind profile is rarely vertically uniform in real synoptic situations. As a rule, a vertical wind speed shift takes place. In [73], the effect of thermal wind directed along the coastline on the sea breeze was considered. It is indicated that the sea breeze circulation cell becomes asymmetrical relative to the coastline leaning towards the sea.

It is known that the presence of a vertical velocity shift in a stratified fluid leads to the formation of critical levels at certain heights where the frequency of the internal inertial-gravity wave becomes zero considering the Doppler shift [74−77]. The problem of the effect of shore-perpendicular background wind shift on the sea breeze circulation at the equator has been considered relatively recently [48]. The main result is that critical layers are formed at certain heights absorbing internal waves and thus limiting the height of the sea breeze circulation ray propagating along the flow.

Recent paper [78] reveals that in the tropics, the sea breeze inertial-gravity wave of the diurnal period passes two critical levels and the attenuation region located between them. In the middle latitudes, the sea breeze inertial-gravity wave in the atmosphere without background wind attenuates with height. Therefore, the critical level effect will be observed under the following condition: the critical level height is less than the sea breeze circulation height. Based on a comparison of vertical flux of angular momentum at different latitudes, it is found that its greatest attenuation at the critical level occurs at the 15th degree, the least one – at the 45th.

Two-dimensional numerical models of sea breeze circulation

Application of linear models has significantly expanded the understanding of sea breeze circulation at a qualitative level. However, linear theory cannot provide a description of areas in the structure of sea breeze circulation with intense vertical and horizontal movements.

The first nonlinear numerical models of sea breeze circulation appeared with the advent of the first computers [19, 28, 47, 79]. With a straight coast, the problem of sea breeze circulation is essentially two-dimensional – all components of the velocity, temperature and pressure distribution do not depend on the coordinate directed along the coast. Thus, the formulation of the problem consists of solving hydrodynamics equations taking into account the Coriolis force in a vertical plane perpendicular to the coastline. In terms of calculations, two-dimensional models use significantly fewer computer resources than three-dimensional ones.

The first stages included the solution of the motion equations of incompressible fluid in the Boussinesq and hydrostatic approximations due to the lack of computing resources. The need to use the hydrostatic approximation and the limits of its applicability were assessed in detail in later works: in [80], the size of the heating source for which the hydrostatic approximation would be valid was discussed; the results of [81] revealed that for intense sea breezes, the non-hydrostatic approximation yielded a weaker sea breeze compared to the calculation using the hydrostatic approximation. For weak sea breezes, the differences between two approximations are small.

Over time, as the power of computers increased, approximations were gradually abandoned. In particular, a non-hydrostatic system of motion equations was applied for the simulation of sea breeze gravity currents taking into account compressibility in the so-called inelastic form and complete consideration of compressibility took place.

Initially, the breeze structure was considered in its simplest formulation without taking into account external factors. Then the influence of individual factors and their various combinations was added to the consideration. The task was to determine at what combination of factors certain features of sea breeze circulation can arise.

Below is an overview of two-dimensional numerical models of sea breeze circulation. First, the features of the numerical models are considered and then the main physical results obtained with their help are discussed.

One of the earliest works on numerical simulation [47] considered a two-dimensional numerical model of a sea breeze in a vertical plane perpendicular to the coastline. The velocity field was decomposed into divergent and rotational components. The rotational component was determined from a numerical solution of the vorticity equation by the finite-difference method.

In the next paper [79], a numerical model of the sea breeze was constructed using the hydrostatic approximation. The turbulent viscosity and thermal conductivity coefficients were functions of height. The temperature above the land surface with a diurnal variation was specified as the boundary conditions on the surface. The temperature above the sea surface did not change. The vorticity equation and the heat transfer equation were solved numerically.

In [28, 19], a numerical model in primitive equations was used. For turbulent viscosity and thermal conductivity, parameterizations were used to describe the atmospheric boundary layer. In [19], the influence of synoptic wind on sea breeze circulation was studied.

The ready-made models and their modifications were successfully used in a number of subsequent works: for example, a model was constructed in [82] based on the model from [28, 19]; a two-dimensional mesoscale model from [83] was used in [84].

In [17], a system of equations taking into account the Coriolis force and ignoring viscosity and friction as well as the hydrostatic approximation was used for the calculation. An arbitrary heat flux was specified as the boundary conditions on the surface.

In the nonlinear part of [24], a system of equations in the Boussinesq approximation was used taking into account rotation, viscosity and thermal conductivity. Atmospheric stratification was also taken into account. A boundary condition for the surface temperature was used to create initial disturbance.

Paper [29] is devoted to studying the differences between daytime and nighttime breezes, so special attention was paid to the turbulence parameterization in the day and night atmospheric boundary layer over land.

In [1, 23], a two-dimensional version of a three-dimensional model [85] developed for describing atmospheric processes of various scales was used to study the sea breeze. Horizontal viscosity was described by harmonic and biharmonic operators. A boundary layer, in which the coefficients of vertical viscosity and thermal conductivity were functions of the local Richardson number, was especially distinguished.

In [86], a hydrostatic model [17] was used. The heat flux was specified on the surface and varied linearly with the height in the boundary layer. This height was determined by the buoyancy value on the surface.

In [87], the equations are written taking into account the geostrophic constant wind in the hydrostatic approximation. Prognostic equations for potential temperature, specific humidity and turbulent kinetic energy were used. The potential temperature profile for the standard atmosphere (3.3 K/km) was used to initialize the model; the relative humidity was 40% and remained constant vertically. The sea surface temperature did not change and the soil temperature and humidity were calculated using the energy budget.

In the non-hydrostatic model in [88], the equations are written taking into account the Earth’s rotation and turbulent mixing. The potential temperature on the sea surface was assumed to be constant and the temperature on the land surface varied with time proportionally to the sine.

In the theoretical part of [21], a two-dimensional version of the three-dimensional model was used. The model included primitive equations in the approximations of hydrostatics and incompressibility. Separation by spatial scales into mesoscale and synoptic processes was implemented. The short-wave and long-wave radiation transfer equations were solved, the energy budget on the surface was calculated, a multilayer soil model was included and a level 2.5 scheme was used to parameterize turbulence.

In [4], a two-dimensional hydrostatic model was used. The pressure was divided into two parts – a large-scale part and a part created by differential heating. The vertical component of the velocity was calculated from the continuity equation. A non-local diffusion scheme was used to parameterize the turbulent heat flux, and a local scheme with calculation of the turbulent viscosity coefficient was used to describe the turbulent momentum fluxes.

In [63], a two-dimensional model was used for a real geographic region since the coastline on the west coast of the Netherlands is almost straight. Real wind and temperature profiles obtained from observations were used to set the initial state of the atmosphere in the simulation.

In [26, 89], a mesoscale model of topographic vorticity was used. The predictive variables of the model include potential temperature, turbulent kinetic energy, and two horizontal components of vorticity. A dry (unsaturated) atmosphere was considered, a constant geostrophic wind was specified and the soil was described by a separate model. Filtering of high-frequency processes was carried out using a scheme with numerical viscosity. Non-hydrostatic and inelastic approximations were used and a closure scheme of order 1.5 was used to describe turbulent mixing.

Recently, two-dimensional idealized versions of full three-dimensional models with descriptions of all physical processes have been increasingly used. For example, a two-dimensional version of the mesoscale atmospheric model [90] was used in [18] for studying sea breeze gravity currents and in [7, 48] devoted to the linear theory taking into account the background wind.

Summarizing the review of two-dimensional numerical models of sea breeze circulation, note that the differences in the models consisted both in the approximations of the hydrodynamic equations used and in the methods of physical processes parameterization including turbulence in the boundary layer, radiation transfer, microphysics of clouds and precipitation and processes in the soil.

Now let us move on to the consideration of the main physical results obtained using two-dimensional numerical models of breeze circulation.

Work [47] resulted in a sea breeze gravity current near the surface which corresponded to the rotational part of the solution. The vorticity is formed in the area of the horizontal temperature gradient, which occupies ~100 km. The maximum vorticity is located in the area of the maximum horizontal temperature gradient near the coast. The velocity in the sea breeze gravity current is 2.8 m/s, which corresponds to the actually observed sea breeze.

In [79], the time-dependence of the sea breeze structure was described. The time, distance and height, the maximum values of velocity were observed at, were determined. Presence of a returned current, temperature gradient transfer and, as a consequence, the maximum velocity onto the land were noted. The obtained structure was compared with the observational data. The maximum values of velocity in the model were lower than the observed ones which could be associated with the background wind that existed during the observations and was not taken into account in the model.

Works [28, 19] consider the breeze circulation structure at different values of velocity, background wind direction and stratification profiles. It is noted that the most intense breeze is observed in cases without background wind, with wind from the coast and wind parallel to the coast with a low-pressure area over the sea. The background wind affects the propagation of the breeze onto the land: with wind from the coast, the breeze spreads less inland compared to the case without wind. In all experiments, a decrease in temperature over the sea far from the coast is observed.

In [82], the first numerical simulation of the full diurnal cycle of sea breeze circulation was carried out, both daytime and nighttime breezes were considered. During the development of the daytime breeze, a current front was observed, near which an intensive vertical movement (~ 0.1 m/s) took place at a height of 600–850 m. A clockwise turn of the wind was observed during the day. A nighttime breeze was obtained – the spread of cold air from the land leading to the rise of warm air over the sea. A temperature inversion was observed over the land at night.

Important paper [17] shows that the velocity of the sea breeze gravity current front depends only on the total amount of heat supplied to the convective boundary layer over land and does not depend on the heat profile shape in the heated layer. In fact, the front velocity is determined by the integral height-wise buoyancy deficit at the head of the gravity current which is consistent with the general theory of gravity currents. It is also shown that the Coriolis force leads to a decrease in the velocity of front propagation and an increase in the alongshore velocity component.

According to [24], the total heat flux determines the kinetic energy of the sea breeze circulation cell. The cell asymmetry is also shown, namely: the upper return branch of the circulation is thicker than the lower one and the velocities in the return branch are lower than near the surface.

The most important result was the explanation of the causes of the asymmetry between the daytime and nighttime breezes [29]. Even with the same absolute values of heat fluxes on the surface during the day and night, the asymmetry between the daytime and nighttime breezes is due to the difference in stratification and the intensity of turbulent mixing over land.

Study [23] demonstrates the dependence of sea breeze circulation on latitude emphasizing the influence of the Coriolis force. In particular, at the equator, the daytime breeze (directed from the sea onto the land) is observed throughout the day, while at other latitudes a nighttime breeze is also formed. The breeze of maximum intensity is observed at different times of the day depending on the latitude – the closer to the equator, the later the maximum of the nighttime breeze is reached.

An important question addressed in [86] is what fraction of the potential energy generated by daytime heating is converted into kinetic energy of sea breeze circulation. As convective mixing increases, less potential energy can be available for convective scale and the potential energy available for breeze circulation increases.

In [84], the dependence of breeze circulation over a small lake on synoptic wind speed and water temperature is considered. The effect of water temperature is not important for narrow, elongated water bodies with a weak synoptic wind since the cooling of the stably stratified surface layer is insignificant compared to the air heating above the land surface. However, the apparent heat flux from the water surface increases with a strong synoptic wind, thus leading to sea breeze intensification. A sufficiently strong synoptic wind carries the entire breeze cell downstream.

The influence of background wind on breeze is studied in [87]. Particle trajectories are used as a diagnostic tool which can be used to draw conclusions about the sea breeze intensity. The sea breeze is most intense at a headwind speed of 5 m/s which coincides with the sea breeze propagation velocity while the circulation remains stationary relative to the shore. A stronger wind carries away the circulation towards the sea.

In [88], the breeze dependence on two dimensionless parameters characterizing the nonlinearity and hydrostaticity degree is considered. When using the linear model, the results coincide with the results of the linear theory: the maximum breeze velocity is observed near the shore and the breeze is almost symmetrical relative to it. When using the nonlinear model, a breeze front takes place, the maximum breeze is observed over land, the maximum horizontal velocity increases proportionally to the square of the nonlinearity parameter. The difference between the hydrostatic and non-hydrostatic cases is small in most experiments. Sea breeze circulation and vertical air lift are more intense in the non-hydrostatic case compared to the hydrostatic one.

Work [21] shows that if sea breeze and background wind directions coincide, the breeze is a weak disturbance for the background flow. At moderate values of the background headwind, the breeze is most intense. At even greater values of this wind, the breeze cell is carried away towards the sea and becomes weaker than in the case without background wind.

The vertical structure of the sea breeze on the coast of the Netherlands was considered in [4]. Three cases with a sea breeze were analyzed. The mass flux in the returned branch of the current depends on the large-scale flux and on the potential temperature gradients in the boundary layer and above the inversion. In this case, it is greater than in the lower branch when the vertical gradient of the potential temperature above the boundary layer is greater than the initial vertical gradient of the potential temperature above the inversion.

In [63] motivated by observations of the deep inland penetration of sea breezes in the Netherlands (up to 100 km from the coast), the most important factors influencing the penetration of sea breezes onto the land are identified based on the results of numerical simulation: the background counter synoptic wind and the heat flux on the surface. The values of these quantities determine the temporal and spatial scales of the sea breeze propagation onto the land.

In [26], the results of two-dimensional numerical simulation were used to verify the similarity theory previously constructed on the basis of *in situ* measurements [91]. The analysis showed that the sea breeze velocity depended only on the total heat flux on the surface and its height depended on the atmosphere stratification.

In [89], based on the results of two-dimensional numerical simulation, the similarity theory from [26] was generalized and a dimensionless index that characterizes the sea breeze propagation onto the land in the presence of a headwind in the atmosphere was introduced. The analysis showed that, depending on the background wind speed, two regimes were observed: the sea breeze propagation onto the land and its velocity decrease without such propagation.

Paper [18] is devoted to the study of the influence of stratification and the effect of different types of heating on the gravity current. If the full amount of heat enters the region at the initial moment of time, the gravity current reaches quickly the regime with a constant propagation velocity which is determined by the density gradient at the current front and the current height. The dependence of the front propagation velocity on the total amount of heat turns out to be valid for a wide range of atmospheric stability values. If a more realistic heating depending on time is considered, then a density and vorticity gradient is formed inside the cold current which leads to intensification of the internal circulation, weakening of the density gradient at the front and, as a result, to its slowdown.

To summarize the review of physical results obtained using two-dimensional nonlinear models, it can be concluded that the structure and dynamics of the sea breeze have been described and interpreted using these models which is confirmed by numerous observations.

Conclusions

The paper examines the principal features of sea breeze circulation obtained using linear theory and two-dimensional numerical simulation. Of the variety of factors affecting sea breeze circulation, only a few are considered. They are heating intensity, atmospheric stratification, synoptic wind and the Coriolis force

Sea breeze circulation can be considered under the linear theory as an internal inertial-gravity wave of the diurnal period radiated from the surface as a result of daytime heating and nighttime cooling of the atmospheric boundary layer over the land. The Coriolis force effect leads to the identification of two sea breeze circulation regimes. The circulation has the form of a wave propagating upward and from the coast in the latitude range from the equator to the 30th degree and it has the form of a cell limited in height and horizontally in the latitude range from the 30th degree to the pole.

When taking into account the uniform background wind at all latitudes, the breeze wave becomes asymmetrical relative to the coastline and a set of stationary high-frequency internal waves appears above the coastline. The presence of a background wind shift leads to the formation of critical levels that limit the height of sea breeze circulation.

Linear theory is applicable only for small values of heating amplitude as a nonlinear phenomenon, gravity current, is formed in the breeze structure when the amplitude increases. Two-dimensional simulation is used for theoretical description of sea breeze in nonlinear mode. It is shown that the presence of uniform background wind leads to a change in the height of the gravity current head which affects its propagation velocity.

Wind with shift changes the height of the current head and leads to the formation of an intense vertical elevation in front of the front when the angle of the gravity current front to the horizontal changes. Both uniform wind and wind with shift can prevent the current propagation and, conversely, increase its velocity.

Taking into account the nonlinearity, the Coriolis force effect leads to a decrease in the front propagation velocity and an increase in the alongshore velocity component.

The present paper summarizes the available results obtained using several theoretical research methods that describe the influence of selected environmental factors on the dynamics of sea breeze circulation formation and development, while this summary cannot provide a complete description of the phenomenon.

The reviewed works demonstrate consistent development of the breeze circulation theory, however, recent studies devoted, for example, to the linear theory, show that still there are some unresolved issues.

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