Sodar observation of the breeze return currents over the coastal zone of the Black Sea

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Abstract. The breeze circulation was studied with the help of sodars in 2 short-term expeditions on the northern coast of the Black Sea. The measurements were carried out at a stationary oceanographic platform located 400 m from the coast. The main attention was paid to the vertical structure of breeze flows with the accompanying return currents aloft. The existence of turbulent exchange between the near-sea breeze flow and the return current at an altitude of several hundred meters is shown. Hence, the return current must be taken into account when determining the height of the mixing layer above the sea surface in the offshore zone.

1. Introduction

The physical mechanism for the formation of an “ideal” breeze is well known. However, in real conditions, there are many factors impacting breezes, and in each specific place the breeze circulation has its own characteristics [1]. Breezes significantly affect the weather, as well as air quality and the wind energy resource of coastal regions, where 40 to 60% of humanity live according to various sources. Therefore, a huge number of scientific publications have been devoted to the study of breezes over the past century. At the same time, experimental studies of the vertical structure of breezes are few in number, since they are very laborious. Such studies are possible using aircrafts [2] or remote sensing techniques such as sodars [3], lidars [4] and radars [5]. Sometimes (but not often) these tools are able to register not only main breeze flows, but also return currents above [5]. Knowledge of the vertical structure of the breezes, including return currents, is necessary to advancement of the mixing layer height $H_{mix}$ determination over water areas. The mixing layer height is generally understood to mean the height of the layer adjacent to the ground over which any contamination emitted into this layer become vertically dispersed due to convection or mechanical turbulence. The $H_{mix}$ value is a key parameter for air pollution models, and is also important for the marine ABL parameterization in weather and climate models (see, e.g. [6]). The $H_{mix}$ is not measured by standard meteorological practices and its estimation is often not straightforward.

This work is devoted to sodar studies of the vertical structure of breeze flows with a return currents above. The main task was to study the turbulent exchange between the surface breeze flow and the return current and estimate the height of the mixing layer $H_{mix}$ under such conditions. Due to the large temporal variability of the breeze circulation, in order to fully understand its characteristics in a specific place, year-round long-term measurements at stationary points are desirable. Such approach is implemented, for example, in the works [7, 8]. As a palliative, multiple short-term measurements at
the same site are possible. During this study the measurements were carried out for 1–2 weeks in the summer of 2015 and in autumn of 2016.

2. Measurements site and equipment
The measurements were carried out on a stationary oceanographic platform located 400 meters from the coast on the shelf slope of the southern coast of the Crimean Peninsula (figure 1(a)). The wind regime in this area is largely determined by the proximity of the mountain plateau, which blocks the southerly wind directions and leads to the occurrence of slope winds that enhance the night breeze [9]. The main wind directions in the near-sea layer are west and east in the daytime and north - at night.

Figure 1. Black Sea expedition, October 2016. (a) Coastline topography near the platform. (b) Minisodar LATAN-3M installed on the upper deck of the oceanographic platform.

Remote sensing of the ABL parameters was carried out using a three-antenna Doppler minisodar LATAN-3m (Institute of Atmospheric Physics: Moscow, Russia [10]) and a meteorological temperature profiler MTP-5 (Attex: Dolgoprudny, Russia [11]). The minisodar was operated in a synchronous mode (simultaneous sounding with three antennas) with an altitude resolution of 10 m and a temporal resolution of 6 s in 2015 and 3 s in 2016. The altitude range of sounding was from 30 to 400 meters above sea level, taking into account the “dead” zone of sounding and the height of the sodar location. The study used instantaneous echo and radial velocity profiles as well as average wind speed and direction profiles. A photograph of the minisodar installed on the upper deck of the platform is shown in figure 1(b). The vertical temperature profiles up to 600 m were measured by the temperature profiler MTP-5 placed at 15 m above sea level (a.s.l.) and facing the open sea. The MTP-5 provided data on the vertical temperature distribution with a height resolution of 50 m and a 5 min measurement cycle.

The accompanying standard meteorological measurements were provided by the WXT536 weather transmitter (Vaisala: Helsinki, Finland), monitoring of the radiation balance and measuring the temperature of the water surface were carried out using radiometers (Kipp & Zonen: Delft, The Netherlands).

3. Breeze activity in different seasons
The expeditions were carried out in early summer and autumn. This work uses data from two expeditions: June 12–21, 2015 and October 3-10, 2016. In June, the water surface temperature was below air temperature at 15 m a.s.l., stratification was mostly stable, convection was observed less than 10 percent of the measurement time, mainly with wind from the coast. There was a pronounced diurnal cycle of wind speed and direction in the near-sea level, with dominant direction from the north for night hours
(from 19:00 to 7:00 local time) and from the west (along the coast) for the daytime (from 7:00 to 19:00). The mean wind speed time course had two maxima: about 6 m s\(^{-1}\) at around 03:00 and about 2.5 m s\(^{-1}\) at around 15:00; and two minima: at 08:00 and at around midnight. Breeze flows were observed mainly at night (land breeze), sea breezes were observed rarely and for a short time. In the autumn season, the water surface temperature most of the time exceeded the air temperature, convection was observed by sodar for 60% of the time, including at night. In the autumn season, episodes of a steady breeze, both sea and land, were observed; however, the short duration of measurements and bad weather do not allow judging the regularity of the breeze circulation in autumn (the expedition was interrupted by the start of the storm season). In the wind field for the autumn season, a greater contribution from the eastern wind directions was observed compared to the summer.

The return currents were determined by the characteristic shape of the vertical profiles of wind speed and direction: the presence of a minimum in the speed profile, accompanied by a change in direction by 90–180 degrees at the same height. The directions of the main breeze flows and the return currents, as a rule, did not correspond to the situation of the classical breeze circulation [9]. Return breeze currents within the sounding range of the sodar (up to 400 m) were observed regularly during the summer season (about one episode per day), but they were characterized by instability of direction and short duration (as a rule, no longer than an hour). All episodes were observed with a stable stratification; the total duration of the episodes was about 5% of the total observation time.

4. Vertical structure of the ABL in breeze currents with a return flow

Figures 2–4 present data on the vertical structure of the ABL from the remote sensing for three cases of observing the return current with a 180 degree wind direction turn. The duration of each episode was 30 minutes, which approximately corresponds to the characteristic time of the change in the ABL structure (the shape of vertical profiles of meteorological quantities and turbulent structures on the echograms) under the observed conditions. The profiles of wind speed and direction with a characteristic turn at heights from 100 to 200 m are shown in figures 2–4(a). The wind speed at the maximum of the jets reached 4 m s\(^{-1}\), which corresponds to the typical values for the breeze flows in the given area. Figures 2–4(b) show the vertical profiles of the temperature structure parameter \(C_T^2\) and vertical velocity variance \(\sigma_w^2\). The \(C_T^2\) parameter derived from sodar echo-signal intensity is directly related to the temperature fluctuations and its profile can be used to determine the mixing layer height \(H_{mix}\). The \(\sigma_w^2\) profile can be used to estimate the intensity of vertical turbulent exchange. Sodar echograms are shown in figures 2–4(c). In the field of the scattered signal, in most cases, two turbulized layers located at heights with maximum wind shear were observed. Sometimes a layer of the local minimum of the echo signal was seen at the height of the minimum of the wind speed. In the turbulized layers, Kelvin-Helmholtz billows (KHBs) were regularly observed, with an inclination to the right in the lower layer and an inclination to the left in the return current. In the presented cases, stable stratification with temperature inversion was observed (vertical temperature profiles are shown in figures 2–4(d)). A bulk Richardson number \(Ri\) vertical profile calculated from the wind speed and potential temperature gradients is shown in figures 2–4(e). The \(Ri\) profiles for all episodes had two minima at the heights of the maximum wind speed gradient and a local minimum at the height of the direction change. The dotted line marks the value \(Ri_{cr} = 0.25\), which is a critical value for the occurrence of the Kelvin-Helmholtz instability in the layer. Corresponding fields of vertical velocity obtained by the sodar are presented in figures 2–4(f).

Figure 2 shows the episode of the daytime breeze on June 18, 2015. The echogram shows two turbulized layers corresponding to the main and return currents. The \(C_T^2\) profile does not have a sharp step and smoothly decreases with height. KHBs are observed in both layers, which corresponds to the two minima in the \(Ri\) profile. Ascending and descending motions with a vertical length of up to 150 m are observed in the vertical velocity field (figure 2(f)), penetrating both layers, which may indicate the presence of mixing between the direct and return currents. This hypothesis is also indirectly confirmed by the monotonicity of the \(\sigma_w^2\) profile (figure 2(b)). The height of the mixing layer \(H_{mix}\) can be estimated as 300 m.
Figure 2. Vertical ABL structure in the presence of a return current, June 18, 2015. The case represents strong turbulent exchange between two turbulized layers with KHBs. (a) Vertical profiles of wind speed and direction. The values from the weather station are marked with diamonds. (b) Vertical profiles of the vertical velocity variance $\sigma_w^2$, and the logarithm of the structure parameter $C_T^2$, proportional to the intensity of the sodar echosignal. (c) Sodar return signal in height–time coordinates (echogram). (d) Temperature profile according to the temperature profiler data. (e) Vertical profile of the bulk Richardson number calculated from the sodar and temperature profiler data, dotted line marks the critical value $Ri_{cr} = 0.25$. (f) Vertical velocity field obtained by the sodar. The averaging time for all profiles is 30 min.

Figure 3 shows the episode of the daytime breeze on June 17, 2015. The KHBs are observed only in the upper layer, which corresponds to the Richardson number profile, and the $C_T^2$ increases to the height of the return current core. The wave-like movements corresponding to the KHBs are also observed in the vertical velocity field (figure 3(f)). According to the echo signal intensity, the height of the mixing layer can be estimated as 200 m. However, this value is most likely greatly overestimated, since figure 3(c) shows a layer with a minimum of the echo signal in the lower part of the sounding range (at the height of the maximum of the lower jet or below), which indicates the absence of turbulent mixing between the near-surface layer and the raised turbulent layer. In this case, it is most likely that the mixing layer has a height of less than 30 m and lies below the sodar sounding range.

Figure 4 shows the episode of the night breeze on October 4, 2016, in which clear KHBs are observed only in the lower layer, and the height of the mixing layer approximately corresponds to the height of the minimum wind speed between the direct and return flows – about 100 m.

5. Conclusions
Sodar sounding of the ABL in a coastal zone makes it possible to study the vertical structure of breeze cells, including the return currents. Return breeze currents at altitudes of 200-300 meters were observed in summer and autumn seasons under stable conditions for the sea and land breezes in the form of short-term and unstable episodes. The observed monotonous profiles of the vertical velocity variance
Figure 3. Vertical ABL structure in the presence of a return current, June 17, 2015. The case represents strong KHBs in the return current. All notations are the same as in figure 2.

Figure 4. Vertical ABL structure in the presence of a return current, October 4, 2016. The case represents strong KHBs in the lower layer and a low level of the signal scattered in the return current. All notations are the same as in figure 2.

$\sigma_w^2$ and the temperature structure parameter $C_T^2$ indicate the presence of turbulent exchange between the direct and return flows in breezes and the need to take into account the return flow when determining
$H_{\text{mix}}$. However, the question remains as to how much the values of $\sigma_w^2$ and $C_T^2$ measured by sodar are determined by turbulent motions, and whether there is a contribution of wave motions that do not lead to vertical mixing of air masses (see [12]).

In general, in the case of breeze circulation, the height of the mixing layer $H_{\text{mix}}$ is determined ambiguously and in various cases can approximately correspond to either the height of the near-surface breeze current core, or the height of the minimum wind speed between the direct and return flows, or the height of the return current core. In addition, it is important to note that under these conditions it is difficult to accurately determine the height of the core of the near-surface current from the sodar sounding data, since its lower part (below the maximum of the wind speed) is below the minimum sounding height of the sodar in all the cases described. Long-term experimental studies of the ABL by means of remote sensing and local methods in the near-surface layer are required to solve the problem of parametrization of the mixing layer in the coastal zone taking into account the return currents.

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