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Baroclinic low-level jets in Arctic marine cold-air outbreaks

D G Chechin1,2, C Lüpkes1
1 Alfred-Wegener-Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany
2 A.M. Obukhov Institute of Atmospheric Physics of the Russian Academy of Sciences, Moscow, Russia
E-mail: chechin@ifaran.ru

Abstract. An analytical model describing the evolution of a convective atmospheric boundary layer in marine cold-air outbreaks in the Arctic is presented. The novelty of the model is a detailed description of the baroclinicity associated with the boundary-layer growth and heating. Ekman friction is also taken into account. Thereby, the model describes the evolution of mixed-layer wind components over the ocean. It is shown theoretically that baroclinicity leads either to deceleration or to acceleration of the flow over the ocean, which depends on the direction of the large-scale flow relative to the orientation of the ice edge. Acceleration of the flow leads to a formation of a low-level jet strongly affecting the surface fluxes of heat and momentum. Baroclinicity and the magnitude of the low-level jet are strongest close to the ice edge being proportional to the ocean-ice temperature difference and decays further downwind. Horizontal decay of the low-level jet strength is governed by the airmass transformation length scale which is estimated to be in the order of 500-1000 km for typical cold-air outbreaks. The model solutions are shown to be in good agreement with aircraft observations over the Fram Strait and results of a numerical nonhydrostatic model.

1. Introduction

Cold-air outbreaks (CAOs) represent the advection of a cold Arctic airmass over a relatively warm open ocean. The key feature of CAOs is a large heat loss of the ocean due to an extremely high surface turbulent heat flux. This shapes their role in the climate system. Namely, CAOs strongly influence i) the water-mass modification and ii) the meridional heat exchange in the atmosphere.

The magnitude of the surface heat flux in CAOs is primarily governed by a large temperature difference between the cold airmass and the ocean, but is also modulated by wind speed. Especially intense during CAOs can be mesoscale circulations such as polar mesocyclones, low-level fronts, orographic and baroclinic jets. The latter are in the focus of this study.

Earlier studies [1, 2, 3] hypothesized that the atmospheric boundary-layer heating during CAOs can lead to acceleration of the flow and formation of low-level jets. A systematic study of this phenomena has been carried out in [4, 5] and [6]. In the latter paper, we proposed a simple mixed-layer model describing the atmospheric boundary-layer evolution during CAOs, associated baroclinicity and its impact on wind speed. The model was evaluated by comparison with aircraft observations over the Fram Strait in the Arctic and with results of a more complete
three-dimensional nonhydrostatic model NH3D. Here, we summarize the results of [6] and also use simple schematics to better illustrate the effect of baroclinicity on wind speed in CAOs.

2. Analytical model

The analytical model is based on an idealized mixed-layer representation of the vertical profiles of potential temperature and horizontal wind components in the convective atmospheric boundary layer (ABL) over the ocean downwind the ice edge (Fig. 1a). The steady-state assumption is used. The model consists of prognostic equations for the mixed-layer potential temperature $\theta_m$, temperature jump at the boundary layer top $\Delta \theta$ and the mixed-layer height $z_i$, as well as of the diagnostic equations for the mixed-layer horizontal wind components $u_m$ and $v_m$. The latter equations represent a so-called geotriptic (or Ekman) balance, i.e. the balance between the horizontal pressure gradient force, Coriolis force and friction.

As discussed in Chechin et al. [6], it is possible to solve the prognostic equations for $\theta_m$, $z_i$ and $\Delta \theta$ independently from the momentum equations. The solution closely follows the one presented by Venkatram [7]. As a result, one obtains a prognostic equation for the normalized mixed-layer potential temperature $\bar{\theta}_m$ as function of the normalized distance from the ice edge $\bar{y}$, namely

$$\ln(1 - \bar{\theta}_m) + \bar{\theta}_m = -C_1 \bar{y} + C_2 ,$$

(1)

where $C_1$ and $C_2$ are constants consisting of external parameters. The normalized ABL height $\bar{z}_i$ and temperature jump $\Delta \bar{\theta}$ are linearly related to $\bar{\theta}_m$.

The solution, given by Eq. 1, is further used to obtain relations describing baroclinic components of the geostrophic wind in the ABL as functions of distance from the ice edge. After that, the known geostrophic wind speed and $z_i$ are used in the Ekman balance equations to find $u_m$ and $v_m$.

3. Mixed-layer geostrophic wind

One of the key parts of the model is a representation of the along-ice mixed-layer geostrophic wind component $u_{gm}$ as a sum

$$u_{gm} = U_g + U_{gt} + U_{gi} + U_g + U_{g+} ,$$

(2)
In this section, analytical solutions are compared to aircraft observations over the Fram Strait performed by the Alfred Wegener Institute, Bremerhaven (Germany). The observations from six cases of cold-air outbreaks are used. Figure 3 shows the normalized mixed-layer potential temperature, height and the baroclinic component $U_{gt}$ as functions of normalized distance from the ice edge together with analytical solutions. It can be seen, that the ABL temperature and height collapse quite well and closely follow the analytical solution. However, the ABL temperature is underestimated by the analytical solution probably due to neglect of condensation. The values of $U_{gt}$ demonstrate larger scatter around the analytical curve, but nevertheless, the agreement is reasonable.
cases are not shown in Fig. 4 because the large-scale flow was quite strong (15-17 ms−1). The large-scale flow was from north-west and deceleration of the flow was observed. Two more flow over the Fram Strait was from the north-east crossing the ice edge oriented in the west-east. Acceleration of the flow was observed and the model also produced acceleration. On those days the line). It can be seen that in three cases (14.10.1991, 04.03.1993 and 10.03.1993) where the shows the observed mixed-layer wind speed and the large-scale geostrophic wind (black dashed line) as functions of distance from the ice edge; blue dashed lines represent the analytical solutions. The figure is adopted from [6].

The model also predicts well the acceleration and deceleration of the flow in the ABL. Figure 4 shows the observed mixed-layer wind speed and the large-scale geostrophic wind (black dashed line). It can be seen that in three cases (14.10.1991, 04.03.1993 and 10.03.1993) where the acceleration of the flow was observed the model also produced acceleration. On those days the flow over the Fram Strait was from the north-west and deceleration of the flow was observed. On two more cases are not shown in Fig. 4 because the large-scale flow was quite strong (15-17 ms−1) and the relative effect of baroclinicity could not be identified both in the observations and was also very small in the analytical solutions. Finally, Fig. 3-4 show that baroclinicity and its
effect on wind speed decrease downwind the ice edge. As shown analytically in [6] the decay of baroclinicity with distance from the ice edge is governed by the airmass transformation scale. An analytical expression was obtained for the latter scale. It shows that this scale is proportional to the temperature difference between ocean and sea ice and varies in the range 500-1000 km for typical Arctic CAOs.

To conclude, the proposed model shows good qualitative and quantitative agreement with observations. It highlights the effect of baroclinicity on wind speed leading to the presence or absence of a low-level jet. The model describes the sensitivity of the low-level jet strength and horizontal extent to the external parameters, such as the ocean-ice temperature difference, direction of the large-scale flow, temperature lapse rate above the ABL. The model can be used as an analytical tool to interpret observations and results of numerical simulations.

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