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The influence of background wind on aspect ratios of convective cells during cold air outbreaks - Studies with a large eddy simulation model

H. Jansen (1), M. Schröter (1), S. Raasch (1) and I.-S. Kang (2)

(1) Institut für Meteorologie und Klimatologie, Universität Hannover, Germany,
(2) Yonsei University, Department of Atmospheric Sciences, Soul, Korea

Introduction

During so called cold-air outbreaks (CAOB) initially cloud free and stably stratified air is advected from land or from an ice surface over a warmer sea surface. Subsequent heating and moistening from below causes the development of a convective boundary layer, in which a typical sequence of convection patterns can be observed: As soon as the cold air encounters the warm sea surface, roll-like secondary flow patterns develop, appearing in satellite images as so called cloud-streets [2,7]. Further downstream the roll pattern gradually changes to a hexagonal cellular convection pattern that can contain either open or closed cells. Open cells consist of broad central areas of descending air, enclosed by relatively narrow rings of updrafts, whereas closed cells are characterized by a reversed circulation. Near the ice-edge or coast the convection pattern define aspect ratios ranging from 1 to 3 gradually increasing up to the scale of MCC reaching typical values for the aspect ratios of 10 to 30. The frequent occurrence of so called mesoscale cellular convection patterns (MCC) over vast regions of the oceans has been revealed by satellite imaging and its properties have been reviewed in detail by various authors [1,2,7]. Within the last decade both CAOBs and MCCs have been studied intensively using numerical simulation [6,8,9,10,13,16]. Most of these studies yielded diabatic processes to be an essential prerequisite for cell broadening and thus large aspect ratios, defined as the quotient of cell diameter and boundary layer height, as observed in nature. However, the underlying physical mechanisms remain unclear

[5]. To the authors knowledge, the influence of background wind on the scale growth in MCC has not yet been investigated.

Simulation setup and initial conditions

The LES-model PALM (**Pa**rallelized **L**ES **M**odel) applied in the present study is specially designed for use on massively parallel computers. It is described in detail in [15] and has been applied successfully to the atmospheric and oceanic boundary layer [e.g. 11,12,14,16,17].

We consider a CAOB situation observed during the ARKTIS 1991 experiment [3,4]. The initialization parameters for the simulations performed here can be described as follows: At a latitude of 72° N an initially dry and stably stratified air mass is advected by an easterly geostrophic wind of $13\,\mathrm{m\,s^{-1}}$ from the packice across the relatively warm water of ice-free ocean. The model domain covers an area of $102.5\,\mathrm{km} \times 102.5\,\mathrm{km}$ and rises approximately $5.5\,\mathrm{km}$ in the vertical direction. We have used a grid spacing of $100\,\mathrm{m}$ in the horizontal and $50\,\mathrm{m}$ in the vertical direction (for $z > 4\,\mathrm{km}$ the vertical grid spacing is smoothly stretched), resulting in $1024 \times 1024 \times 96 \approx 10^8$ grid points. Based on these initial conditions we have performed three model runs. All model simulations include moist processes like cloud formation and radiation processes. The background wind has been varied, resulting in three runs with $v_g = 0,\ 11$ and $22\,\mathrm{m\,s^{-1}}$, respectively. The moisture flux was set to $0.05\,\mathrm{g\,kg^{-1}\,m\,s^{-1}}$ initially and was increased linearly further on according to observations during ARKTIS 1991 ($6.67 \cdot 10^{-8}\,\mathrm{g\,kg^{-1}\,m\,s^{-1}}$). The surface heat flux has been set to $0.175\,\mathrm{K\,m\,s^{-1}}$ independently of background wind, in order to specifically focus on the influence of the wind on the development of cloud cells. All simulations performed for this study cover a period of 15 hours. The model runs are refered to as CA22, CA11 and CA0 for $v_g = 22,\ 11$ and $0\,\mathrm{m\,s^{-1}}$, respectively.

Results

Throughout the 15 hour simulation, the boundary layer height increases in the well known $\sqrt{\mathrm{t}}$ fashion from initially $\sim$ 650 m up to $\sim$ 2800 m. The boundary layer temperature increases throughout the simulation. The liquid water content, representing the cloud layer, is both increasing in magnitude and in height. The inversion height, defined here at the minimum of the sensible heat flux, is growing in height, reflecting the growth of the boundary layer depth. Latent heat fluxes are seen to be maximal at the bottom of the cloud layer. In all three model runs, MCC of type closed cells are developing. We have calculated the aspect ratios of the liquid water path (LWP), vertical velocity and potential temperature, respectively, i.e. the quotient of the dominant scale with the boundary layer height, where the dominant scale is given by the largest peak in the spectral representation of the specific variable. These scales increase throughout time in all simulations. This is in line with our previous results, showing that diabatic processes are a necessary prerequisite for scale growth and that any convective cells did not grow in comparable dry simulations [16].

Model results show that the magnitude of background wind is positively correlated with the size of developed MCC during cold air outbreaks. In the case of $22\,\mathrm{m\,s^{-1}}$ background wind, compared to the no-wind situation, aspect ratios of LWP, vertical velocity and potential temperature structures are on average 93%, 59% and 163% larger, respectively. Following [5], we have calculated flux ratios of the relevant scalar variables. However, these flux ratios are seen to be widely independent of background wind, so the observed increase in scale growth cannot be explained by a change in the relevant flux ratios.

We have derived horizontal transfer coefficients from our simulation data using passive particle advection to study whether diabatic heat sources are causing a stronger horizontal mixing. We released horizontally homogeneously distributed particles within the model domain, which are advected by the velocity field. The effective diffusivities increase with increasing wind. However, it remains unclear whether this fact is the cause or the result of increasing scale growth. The influence of the background wind may be explained by different vertical wind shear production. The stronger the horizontal wind, the more vertical wind shear is developed, leading to increased eddy turbulence production. [18] found an influence of wind shear on both the heating rate at the cloud bottom and the cooling rate at cloud top, and thus on the magnitude of convective cell development.

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