# 1.4 MODELLING THE SMALL-SCALE IMPACT OF LEADS ON THE POLAR ATMOSPHERIC BOUNDARY LAYER USING A NEW NONLOCAL TURBULENCE CLOSURE

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## 1. INTRODUCTION

The polar sea ice cover is always smaller than 100 %, since even during winter inhomogeneous forcing by wind and ocean currents is generating leads which are either free of ice or covered by thin new ice. From autumn to spring the large differences in the temperatures between the surface of leads and the cold advected air cause strong atmospheric convection. Until now its impact on the atmospheric boundary layer (ABL) is not fully understood. This is caused e.g., by the difficulties in obtaining observations over the leads. So, most of the available data (e.g., Paulson and Smith, 1974; Andreas et al., 1979; Alam and Curry, 1997; Persson et al., 1997; Andreas and Cash, 1999) were obtained from stations downstream of leads and not in the center of the convective plumes. There are also only few studies using high resolution models as those by Glendening and Burk (1992), Zulauf and Krueger (2003), Weinbrecht and Raasch (2001) and most recently of Esau (2007). Such studies require large computational costs which is due to high resolution required to resolve the processes over leads, whose widths range between meters (cracks) and sometimes a few kilometers.

The goal of the present study was to investigate the physics of air ice interaction in the presence of leads using different modeling strategies as explained below. It is demonstrated that especially during winter leads may have a strong impact on the surface energy budget and near-surface air temperature. Furthermore, our studies show that the application of traditional turbulence closures in climate models may cause deficiencies in the turbulent fluxes of heat and momentum over a domain with leads. Our studies initiated in Lüpkes et al. (2008a,b) are carried out with the nonhydrostatic atmospheric mesoscale model METRAS (Schlünzen, 1990; Lüpkes and Schlünzen, 1996) and are partly based on the analysis of data obtained from the Large Eddy Simulation model PALM (Raasch and Schröter, 2001).

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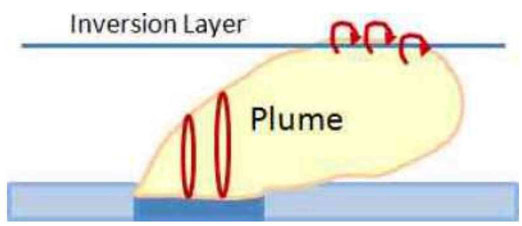


Figure 1: *Convection over leads (schematic)*

## 2. MODELING STRATEGIES

The impact of convective processes over leads on the atmospheric boundary layer and its interaction with sea ice can be investigated with different modeling strategies. The most complex one is the use of Large Eddy Simulation (LES) with grid sizes small enough to resolve individual thermals developing over the leads. We know from such investigations (e.g. Weinbrecht and Raasch, 2001) that these thermals generate an internal boundary layer, whose thickness $\delta$ is increasing until the capping inversion is reached and entrainment fluxes can develop. The warm air which is transported downstream in a convective plume is warming the ice surface in the environment of leads, since over ice the near-surface heat fluxes are directed downward.

There is a large discrepancy between the detailed modeling using LES and the modeling of the lead impact in a climate or weather forecast model which cannnot resolve the small scale processes over leads. In the best case such models have a flux averaging scheme at the surface so that at least the lead and ice fraction can be prescribed and different fluxes occur over both surface types. Above the first grid level, however, horizontal gradients in one grid box are zero so that climate models implicitely apply instantaneous horizontal mixing of all variables. This approach is similar as if a 1D model were used. The effect of leads as obtained in a climate model can be investigated therefore using a 1D model, which is done in the next section.

Due to the large discrepancy between LES and the treatment in non-eddy resolving models an intermediate method has been developed by Lüpkes et al. (2008b), which uses a model with grid sizes small enough to resolve the plume region (Figure 1), but not the individual thermals like LES. So, such a model which will be called a microscale model needs its own turbulence parametrization, since strong horizontal gradients are present which cannot be treated by traditional tubulence parametrizations. Its advantage compared with LES is that it needs much less cpu-time, its disadvantage is that up to now only simple lead geometries are possible. The development of the turbulence parametrization for such a model contributes to a deeper understanding of the convective processes over leads, since the driving parameters and reasons for the small scale ABL structure have to be identified to obtain finally a physically well-grounded parametrization.

## 3. RESULTS

In the following we discuss results which were obtained with the modeling strategies obtained above. This includes also the description of the turbulence parametrization developed for the microscale model which is based on results of the Large Eddy Simulation model PALM (Raasch and Schröder, 2001).

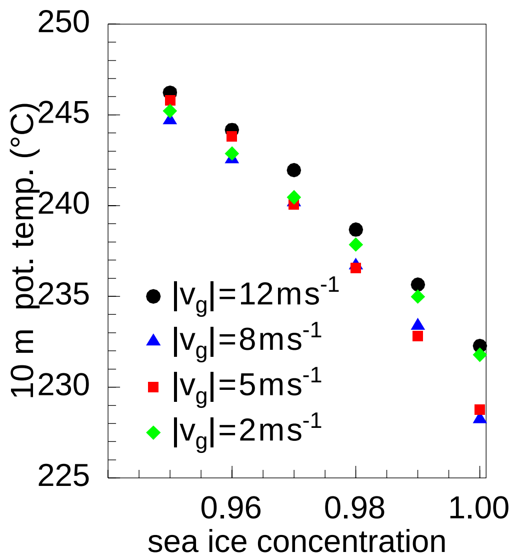


Figure 2: *10 m-potential temperature as a function of prescribed sea ice concentration and geostrophic wind after 2 days of simulation obatained with a 1D version of the coupled air-ice/snow model METRAS.*

### *3.1 1D-Modeling*

As concerns the impact of leads on the polar climate, one of the most important questions is, if leads have an impact on the ABL temperature. We show here a result, discussed by Lüpkes at al. (2008a), who used a 1D-version of the mesoscale model METRAS (15 layers below 300 m) which was coupled with a high resolution snow/sea ice model (1 cm grid size). The model was initiated with a temperature profile being typical for a late winter situation with a cloud topped boundary layer. A sea ice and lead fraction was prescribed as well as the geostrophic wind and clear-sky during polar night was assumed during the simulation time. So, the atmospheric temperature and wind evolution was considered under the impact of radiative cooling and convective heating over the lead fraction as well as cooling over the sea ice fraction. After about two days of simulation a quasi-stationary temperature profile developed.

An example of results is shown in Figure 2 with the 10-m temperature as a function of the prescribed sea ice concentration. According to this figure leads can have a strong impact on the ABL temperature, since only one percent change

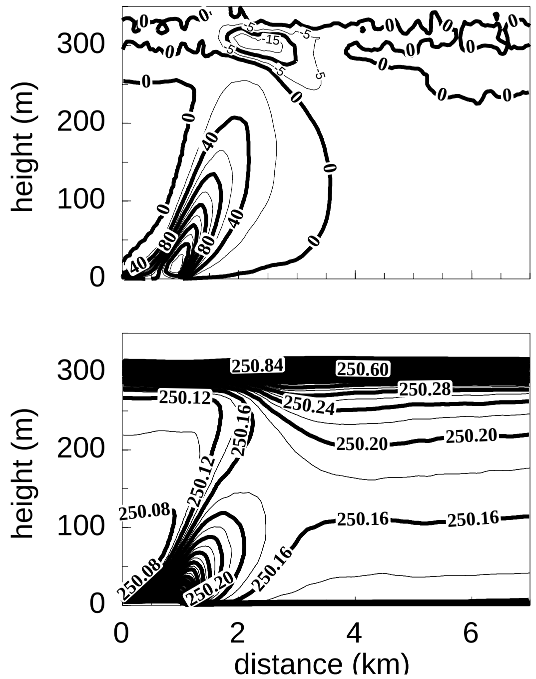


Figure 3: *Fluxes of sensible heat (W m$^{-2}$) (top) and potential temperature (K) (bottom) as a function of distance to a lead of 1 km width. Result of the LES model PALM discussed in Lüpkes et al. (2008b).*

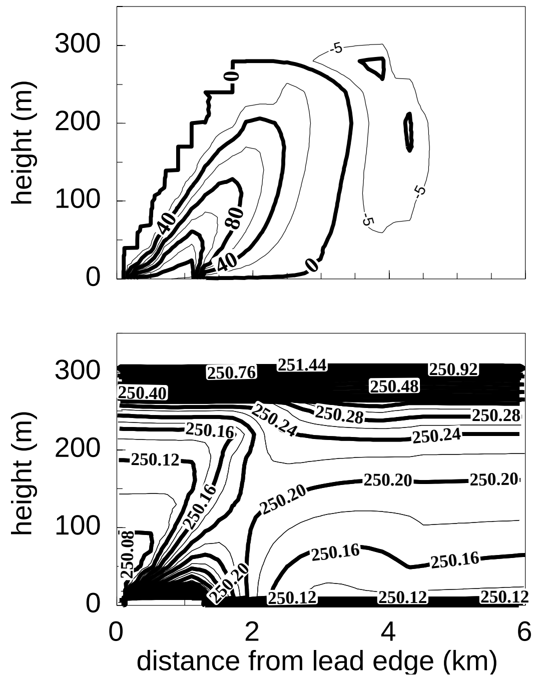


Figure 4: *Same as Figure 3, but results were obtained with the microscale model METRAS using the new closure.*

of the sea ice fraction can result in up to 4 K change of the 10m-temperature. Although one can expect that clouds would have a damping effect this result shows that the lead impact should be considered in more detail in the future due to its large potential to affect the ABL and surface energy budget. Previous investigations could not find a similar effect (e.g. Ebert and Curry, 1993), since the atmospheric conditions were prescribed from observations already containing the lead impact so that the atmosphere ice system could not freely develop.

### *3.2 3D-LES and 2D-microscale modeling*

The above results motivate a more detailed investigation of processes over leads. We consider in the following cases with a flow orthogonal to a small scale lead. Figure 3 shows a result obtained with the LES model PALM which was discussed in Lüpkes at al. (2008b). Results are presented as averages parallel to the lead orientation and orthogonal to the surface wind direction. An inclined plume indicating an internal boundary layer can be clearly identified by considering the fluxes of sensible heat. Comparing the upward flux field for this typical winter time flow with the field of potential temperature, it becomes clear that outside a core region of the convective plume (see Lüpkes et al., 2008b) fluxes can be considered as of nonlocal nature. They are related to thermals, whose size is in the order of the internal boundary layer height, rather than to small scale eddies. This feature formed the basic idea for the development of a closure for the microscale resolving the convective plume.

The most simple possibility accounting for nonlocal heat fluxes is to add a countergradient transport term in the equation for the heat flux so that

$$\overline{w'\Theta'} = -K_h \left( \frac{\partial \overline{\Theta}}{\partial z} - \Gamma \right) \qquad (1)$$

where $K_h$ is the eddy diffusivity for heat and $\Gamma$ is the countergradient term. Both $K_h$ and $\Gamma$ depend in homogeneous conditions on the surface buoyancy flux $B$ and on the mixed layer height

$z_i$. The latter form the convective velocity scale $w_\star = (Bz_i)^{1/3}$. Lüpkes at al. (2008b) transferred this concept to the nonhomogeneous case with the convection over leads. Now, $K_h$ and $\Gamma$ depend on the internal boundary layer height $\delta$ and on the surface bouyancy flux over the lead $B_{lead}$. A new vertical velocity scale is given then by

$$w_l(y) = c\,(B_{lead}\,\delta)^{1/3}\,exp[-(y/D)]\,. \qquad (2)$$

The exponential decay function with decay length scale $D$ is assumed, since turbulence is decaying with increasing distance $y$ on the downstrean side of the lead. $\delta$ can be derived as

$$\delta(y) = z_i\,[1 - \exp(-y/D)]^{3/2} \qquad (3)$$

with the assumption that the change of $\delta$ with distance is proportional to $w_l/U$, where $U$ is the characteristic horizontal wind speed upstream of the lead and is influencing the plume inclination. It can be shown that $D$ follows as

$$D = \frac{3}{2a}\left(\frac{U^3}{B_{lead}}\right)^{1/3} z_i^{2/3}\,. \qquad (4)$$

The factor $U^3/B_{lead}$ arises in $D$ which is similar to the Monin Obukhov length, while $U$ occurs here instead of $u_\star$. It should be stressed that the above scale does not depend on the lead width, since we considered up to now only small leads. In a more general formulation $D$ depends also on the lead width $L$, but the principal structure of $D$ remains unchanged.

Figure 4 shows results obtained with the above closure using the model METRAS with microscale resolution (horizontal grid size of 200 m). Although there are certain differences between the LES results of Figure 3 and the METRAS result in Figure 4 the general structure with the potential temperature increasing with height in most of the shown region is reproduced. Such a structure could only be obtained with a new nonlocal closure based on equations (1)-(4). Any attempts with a local traditional or nonmodified nonlocal closure failed to reproduce this detailed structure. Thus the simulations give at least a hint that the new scaling captures the basic physics of the involved processes.

With the new model it becomes possible to perform a large number of simulations over populations of leads and comparing high resolution runs with results of models using much larger grid sizes. Such a first test has been carried out. The microscale model with 200 m grid size was applied to the flow over an ensemble of leads in a domain of 120 km width. The same domain width with the same domain averaged sea ice concentration was then presecribed, but a version of METRAS was used with 35 km horizontal grid size which is similar to the resolution of a regional climate model. The domain averaged flux profiles differed strongly from each other. Compared to the microscale version the climate version underestimated the fluxes of sensible heat by roughly 50 %, while momentum fluxes were overestimated by 40 % near the surface. The latter effect is caused by a strong deceleration of the flow over the ice regions in the microscale solution.

## 4. CONCLUSIONS

Our results showed that leads may have a strong impact on the near-surface temperature. This forms a challenge for climate modeling for two reasons. The first is that the present day coupled air-ice-ocean (climate) models cannot reproduce the sea ice concentration with the required accuracy which is according to the present study in the order of 1 %. The second reason is that according to the present results even the geometry of the open water areas is important. The assumption of leads generates a different kind of heterogeneous convection than the assumption of a continuous open water fraction.

It was shown that the convective processes over leads are of nonlocal nature. A new scaling generalizing Deardorff scaling to nonhomogeneous conditions works well in a microscale model using grid sizes allowing to resolve convective plumes over leads.

## ACKNOWLEDGEMENTS

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