12.4 THE IMPACT OF A NONLOCAL TURBULENCE PARAMETERIZATION ON THE CONVECTIVE BOUNDARY LAYER AND CLOUD RESOLVING SIMULATIONS

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1. INTRODUCTION

The varying size of eddies within the convective boundary layer makes their parameterization difficult. The effect of the smaller eddies can be represented by simple K-Theory which employs the use of the local gradient of the transported variable. Large convective eddies can transport quantities through the depth of the boundary layer, often counter to the local gradient, and thus a nonlocal turbulence closure is needed.

During the 1997/1998 winter season the Lake-Induced Convective Experiment (Lake-ICE) was conducted over Lake Michigan in order to gain better observations and understanding of the convective boundary layer associated with lake effect snow events. During Lake-ICE several intensive observation periods were conducted. The IOP of 10 January 1998 resulted from a 9 January 1998 frontal passage (Figure 1) that brought chilly arctic air into the Great Lakes. The arctic air mass, characterized by surface temperatures around -18^{o}C, moved over a warm Lake Michigan (lake surface temperatures were approximately 5^{o}C), creating an unstable situation and thus a convectively robust boundary layer.

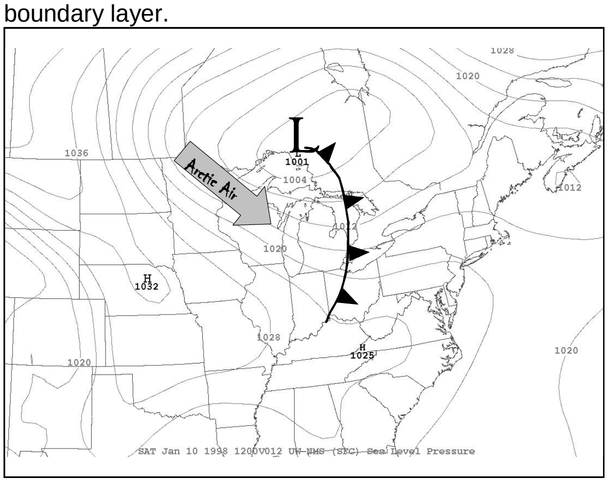

Figure 1: By 12z on 10 January 1998, the cold front was to the east of Lake Michigan allowing cold, arctic air to move over the warm waters of Lake Michigan. From 12hr forecast of 00z operational run of UW-NMS 10 January 1998.

Efforts to model the convective boundary layer structure and cloud bands over Lake Michigan on 10 January 1998 led to the implementation of a nonlocal turbulence parameterization in the UW-NMS (University of Wisconsin-Nonhydrostatic Modeling System). This new parameterization was tested in simulations where the cloud structure was both partially and fully resolvable.

2. UW-NMS

The UW-NMS is a fully scalable, three dimensional, quasi-compressible, nonhydrostatic, enstrophy conserving model formulated in the non-Boussinesq framework. A variably stepped topography is used, which allows the UW-NMS to account for topography changes as small as one meter. The surface fluxes are calculated using the Louis (1979) surface layer scheme. The thermodynamics are based on the prediction of ice-liquid water potential temperature (θ_{il}). The effect of sub-grid scale turbulence is handled by diffusion, and is described in the below sections.

a. Local turbulence closure

Diffusion in the UW-NMS is based on the turbulent kinetic energy (TKE). The local turbulence closure employs standard K-Theory, where the vertical flux of a given variable (C) is assumed to be dependent on the vertical gradient of that quantity and eddy diffusivity (K).

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial z}\left[\overline{w'C'}\right] = \frac{\partial}{\partial z}\left[-K_c \frac{\partial C}{\partial z}\right] \qquad (0.1)$$

This type of parameterization allows quantities to be transferred only from high values to low values. With K-Theory, there is no heat transfer between adjacent grid boxes if they have the same potential temperature. This implies that in order to transfer heat up from the surface a superadiabatic layer must exist, where potential temperature decreases with height (Figure 2).

The turbulent kinetic energy plays a role in the diffusion through the eddy diffusivity. The eddy diffusivity for momentum (K_m) is diagnosed from predicted turbulent kinetic energy and given by:

$$K_m = c_1 l e^{1/2} \qquad (0.2)$$

where $c_1 = 0.21$, l is the scale length set to the vertical grid scale, and e is the turbulent kinetic energy. The eddy diffusivity for heat is proportional to the eddy diffusivity for momentum.

$$K_h = 3K_m \qquad (0.3)$$

b. Nonlocal turbulence closure

The ability of large convective eddies to transport quantities regardless of the local gradient requires the addition of nonlocal correction term (γ_c) to standard K-Theory formulation:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial z}\left[\overline{w'C'}\right] = \frac{\partial}{\partial z}\left[-K_c\left(\frac{\partial C}{\partial z} - \gamma_c\right)\right] \qquad (0.4)$$

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The nonlocal term used in the UW-NMS follows that of Holtslag and Moeng (1991):

$$\gamma = 2\frac{w_*\left(\overline{w'\theta'}\right)_{SFC}}{\overline{w'^2}\quad z_i} \qquad (0.5)$$

$$w_* = \left(\frac{g}{\theta_v(k1)} z_i \overline{w'\theta'}_{sfc}\right)^{1/3} \qquad (0.6)$$

The strength of the nonlocal term is dependant on the surface flux, depth of the boundary layer, the velocity variance, and the convective scale length. A velocity variance profile based on similarity theory (Stull, 1988) was applied:

$$\frac{\overline{w'^2}}{w_*^2} = 1.8\left(\frac{z}{z_i}\right)^{2/3}\left(1-0.8\frac{z}{z_i}\right)^2 \qquad (0.7)$$

The nonlocal term is applied throughout the depth of the boundary layer (refer to Adams, 2003, to see how the depth of the boundary layer was determined), even in areas where it opposes the transport done by the local gradient. The nonlocal term formulation and application results in transport from the surface (bottom edge of the lowest grid box) to the predicted variable location in the middle of the grid box (Figure 2).

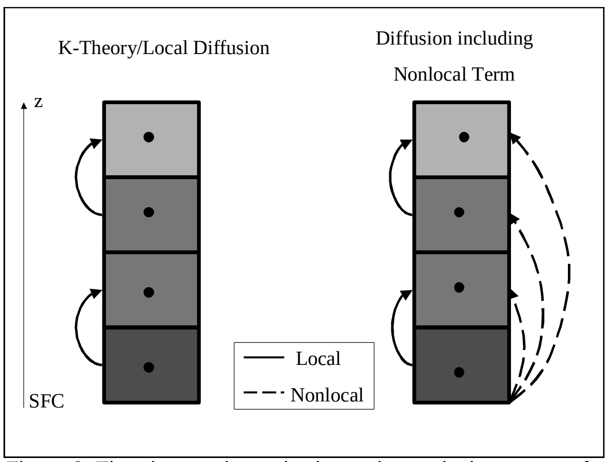

Figure 2: The above schematic shows the vertical transport of a variable by both K-Theory and the nonlocal correction term. The darker boxes represent a greater value of the transfered quantity (i.e. darker= warmer potential temperature). Notice that the K-Theory only transfers between adjacent grid boxes, where the nonlocal term transfers through the depth of the boundary layer. Dots in the center of boxes represent the location of predicted variables of θ_{il} and mixing ratio.

3. SIMULATIONS

a. Experimental design

The set of experiments conducted were designed to test the use of the nonlocal diffusion scheme against simulations with explicitly resolved convection. The nonlocal diffusion was tested at a coarse resolution to see if it could produce the same effect as explicitly resolved convection in terms of vertically transporting entropy and moisture.

Table 1: Summary of Fine and Coarse Resolution Simulations

	Fine Resolution	Coarse Resolution
Horizontal Resolution	400m	2000m
Number of Points in X-direction	500	100
Number of Points in Y-direction	97 *	25 *
Timestep	5 seconds	10 seconds
Number of Points in Absorbing Layer on Western Edge of Domain	50	10

* 7 of the points are used for the cyclic boundary condition

An idealized cloud resolving simulation ($\Delta x = \Delta y = 400m$), of the lake-effect snow event of 10 January 1998 performed by Tripoli (2003), produced a banded cloud structure similar to what was observed by satellite (not shown). The cloud resolving simulation of Tripoli was able to resolve the 6 km wind parallel cloud bands and the 12km shore parallel gravity waves. In order to use the cloud resolving simulation of Tripoli as a "truth" to the convective structure of 10 January 1998, simulations at coarser resolution ($\Delta x = \Delta y = 2000m$) were set up in the same manner. This special experimental design included a western absorbing layer, and a cyclic boundary condition; for a full explanation of the experimental design refer to Tripoli 2003.

Simulations of the 10 January 1998 case were run on a domain centered on Lake Michigan at two different horizontal resolutions (denoted as *coarse* and *fine*), and with and without the nonlocal correction term. All simulations used a vertical resolution of 100m for the first 1.2 km, above which the resolution was slowly stretched to 750m. A comparison of the *coarse* and *fine* resolution set-up can be seen in Table 1.

b. Results

Soundings produced over Lake Michigan from UW-NMS coarse resolution simulations show that a different boundary layer structure forms when using the nonlocal correction term (Figure 3). The profile produced through K-Theory diffusion is absolutely unstable and saturated through the depth of the boundary layer. While the superadiabatic lapse rates were consistent with how local K-Theory diffusion is able to transport entropy (θ), it was inconsistent with a realistic atmosphere. In the atmosphere, the instability associated with an absolutely unstable layer would result in spontaneous overturning. This instant mixing prevents absolutely unstable layers from existing, with the exception of close to the surface in the presence of large heat fluxes. The boundary layer structure of the simulations with the nonlocal correction term applied to diffusion of entropy and moisture is more consistent with what would occur in the real atmosphere (Figure 3).

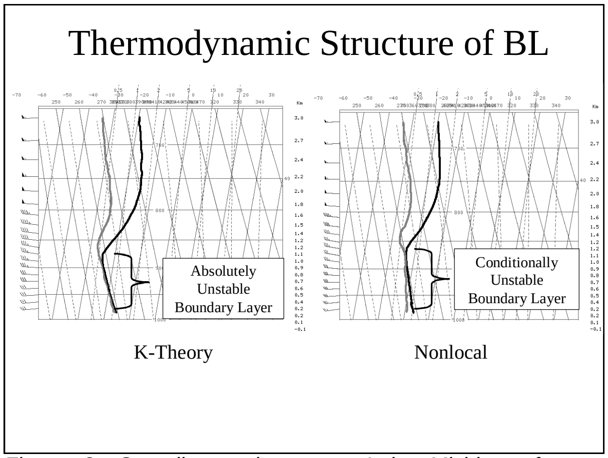

Figure 3: Soundings taken over Lake Michigan from a simulation utilizing standard K-Theory diffusion (left) and a simulation that adds a nonlocal correction term to the K-Theory diffusion (right). Both soundings are taken 3 hours into the simulation, allowing sufficient time for Lake Michigan to modify the boundary layer.

The ability of the nonlocal term to transport entropy and moisture through the depth of the boundary layer also improved the cloud cover extent moving it closer to the western shore (Figure 4), in better agreement with satellite imagery. There was also an improvement to how quickly the model was able to develop a cloud. This was the case at both cloud resolving (fine resolution) and the coarser resolution.

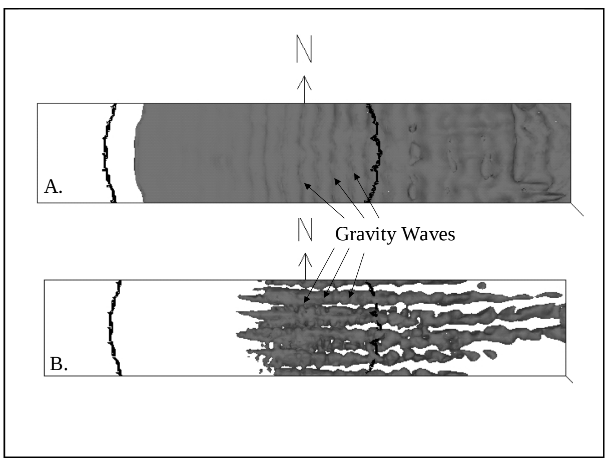

Figure 4: Cloud structure produced for fine resolution ($\Delta x = \Delta y = 400m$) simulations with the nonlocal term (A) and with only K-Theory diffusion (B). Valid 6 hours into simulation. Notice that the nonlocal term allows the model to develop a cloud much closer to the western shore of Lake Michigan (black lines indicate shore location). Both simulations produce the 12 km gravity waves, but the simulation with nonlocal diffusion (A), is unable to produce a banded cloud structure.

Cloud resolving simulations of 10 January 1998 (Tripoli, 2003), showed that when the banded cloud structure was resolved through explicit modeling of the convection, a superadiabatic layer existed until the convection overturned the boundary layer (Figure 5d). When the nonlocal term was used at cloud resolving horizontal spacing, super adiabatic lapse rates were present in only the lowest 300 meters(Figure 5c). However, without the growth of a deep superadiabatic layer, the Rayleigh-Bernard instability was weakened, and the boundary layer was stable relative to roll convection (Figure 5a). This implies that the nonlocal correction term is only applicable for certain resolutions.

4. CONCLUSIONS

The simulations conducted showed that adding a nonlocal term to standard K-Theory diffusion allows a coarse resolution simulation to produce comparable results to a cloud resolving simulation with only K-Theory diffusion. Nonlocal transport eliminated many of the problems that simple K-Theory produced at coarse resolutions. Simulations employing the new diffusion scheme showed improvements in the boundary layer profiles of moisture and potential temperature. The new diffusion scheme eliminated the unrealistic superadiabatic lapse rates that coarse resolution simulations employing K-Theory allowed to build through the depth of the boundary layer.

At resolutions where the large convective eddies can be partially resolved, both the nonlocal term and explicit mixing are trying to represent the same eddies. Thus, at cloud resolving resolutions, the addition of the nonlocal term prevents the formation of roll convection, while standard K-Theory is able to initiate the roll convection through the build up of unrealistic deep superadiabatic layers. Whether the diffusion scheme with nonlocal transport or the standard K-Theory diffusion should be employed at small horizontal scales depends on whether the goal of the simulation is to produce a realistic thermal structure in the boundary layer or correct cloud structure.

5. FUTURE WORK

Future work plans to look at the influence that a nonlocal turbulence parameterization can have on other convective boundary layers. The dependence of the nonlocal term on the surface flux suggests that improvements to the surface fluxes could also help improve boundary layer structure. A soil and vegetation model has been coupled to run with the UW-NMS. Future work will look at how the improved surface fluxes, and nonlocal diffusion can improve the modeled structure of a summer time convective boundary layer. Future work will also look at the nonlocal transport of momentum.

6. ACKNOWLEDGEMENTS:

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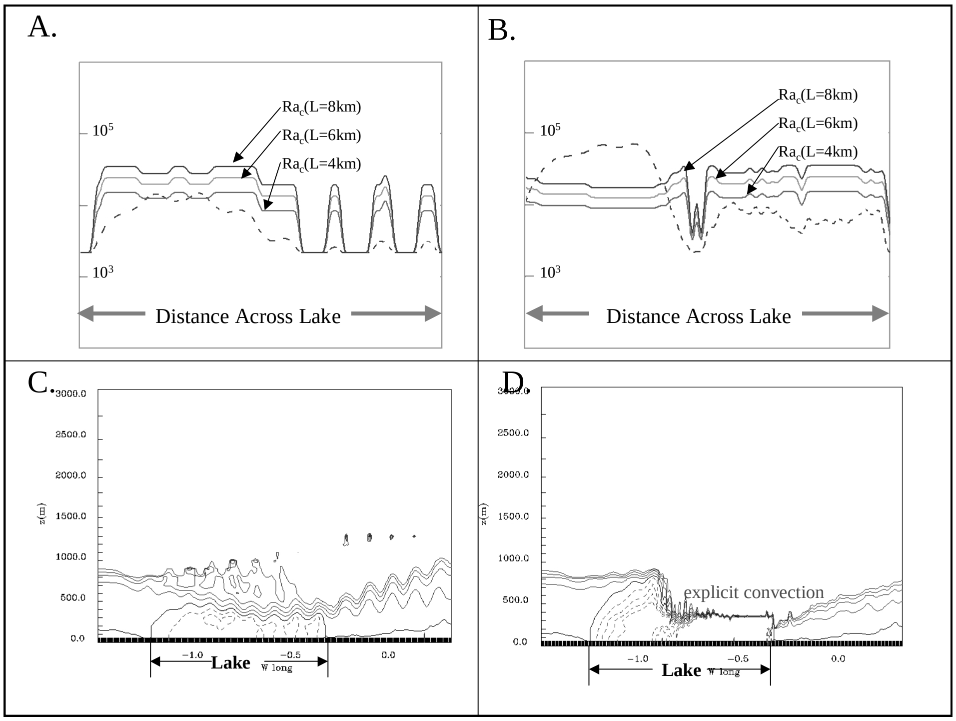

Figure 5: Dashed line represents the Dry Rayleigh Number computed across the lake (90km) for fine resolution simulations ($\Delta x = \Delta y = 400m$) that include the nonlocal correction term(A) and only standard K-Theory diffusion (B) at the final time (6hr). Solid lines represent different wavelengths of overturning. The scale on the left is from 10^2 to 10^6. Note that for the simulation with the nonlocal term the Rayleigh number remains stable. Also depicted (C and D) is the Richardson number on a west-east cross section across the model domain (.25 contour interval) for the same simulations shown in A and B. The dashed contours represent negative Richardson numbers, indicative of superadiabatic lapse rates. The simulation with the nonlocal term (C), keeps the superadaibatic lapse rates to a shallower layer than the K-Theory simulation (D). The K-Theory simulation has stable Richardson numbers in the region of explicit convection.

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