J4.5 THE APPLICABILITY OF A NONLOCAL TURBULENCE PARAMETRIZATION AT CLOUD RESOLVING SCALES

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1. INTRODUCTION

Parameterizations in numerical weather prediction models are intended to represent sub-grid scale processes. Increased computing power has led to increased resolution in NWP models, and thus the parameterizations chosen must be re-examined for applicability to ensure that the processes the parameterizations represent are in fact still sub-grid scale. One of the parameterizations whose applicability is limited by horizontal resolution is nonlocal turbulence parameterization.

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. K-theory by itself, with the absence of a nonlocal transport term, will develop unrealistically deep superadiabatic layers in convective boundary layers with strong surface forcing.

Lake effect snow events occur when arctic air masses move over the relatively warm waters of the Great Lakes, and thus are driven by strong surface heating. Convective eddies of various sizes exist in boundary layer of lake effect events, and provide a condition in which nonlocal transport by eddies is occurring, and thus provide a situation in which nonlocal parameterization can be closely examined.

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. This convective boundary and the associated cloud field were modeled using the University of Wisconsin-Madison Nonhydrostatic Modeling System (UW-NMS). A nonlocal turbulence parameterization was tested in simulations where the cloud structure was both partially and fully resolvable.

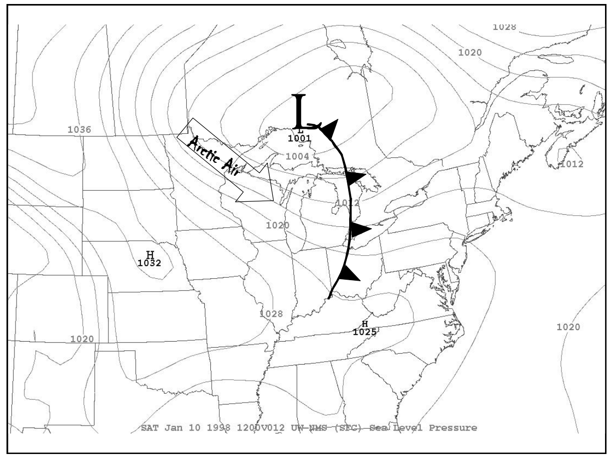

Figure 1: By 12z on 10 January 1998, the cold front was to the east of Lake Michigan allowing cold, arctic air to move over the warm waters of Lake Michigan. From 12hr forecast of 00z operational run of UW-NMS 10 January 1998.

2. UW-NMS

The UW-NMS (Tripoli, 1992) 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).

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial z}\left[\overline{w'C'}\right] = \frac{\partial}{\partial z}\left[-K_c\frac{\partial C}{\partial z}\right] \qquad (1)$$

This type of parameterization allows quantities to be transferred only from high values to low values. With K-theory, there is no turbulent 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,

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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:

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

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.

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

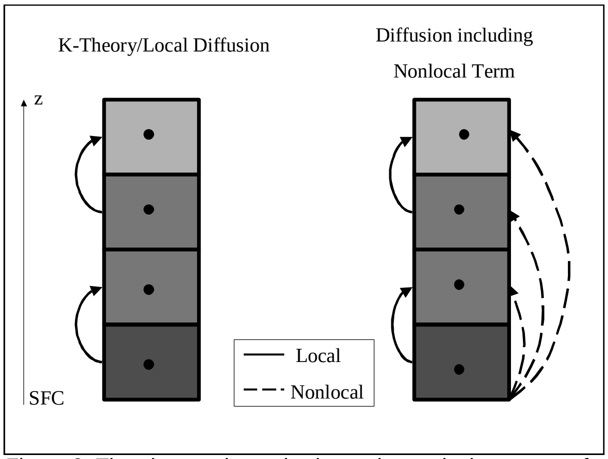

Figure 2: The above schematic shows the vertical transport of a variable by both K-Theory and the nonlocal correction term. The darker boxes represent a greater value of the transferred quantity (i.e. darker= warmer potential temperature). Notice that the K-Theory only transfers between adjacent grid 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.

b. Nonlocal turbulence closure

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

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial z}\left[\overline{w'C'}\right] = \frac{\partial}{\partial z}\left[-K_c\left(\frac{\partial C}{\partial z} - \gamma_c\right)\right] \qquad (4)$$

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

$$\gamma = 2\frac{w_*\left(\overline{w'\theta'}\right)_{SFC}}{\overline{w'^2}\;\; z_i} \qquad (5)$$

$$w_* = \left(\frac{g}{\theta_v(k1)} z_i \overline{w'\theta'}_{sfc}\right)^{1/3} \qquad (6)$$

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:

$$\frac{\overline{w'^2}}{w_*^2} = 1.8\left(\frac{z}{z_i}\right)^{2/3}\left(1 - 0.8\frac{z}{z_i}\right)^2 \qquad (7)$$

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).

3. SIMULATIONS

a. Experimental design

The set of experiments conducted tested the use of the nonlocal diffusion scheme against simulations with explicitly resolved convection. The nonlocal diffusion was also tested at a coarse resolution to see if it could produce the same vertical transport of entropy and moisture as the simulated resolved convection did.

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 (Figure 3). 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 presented in this text 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.

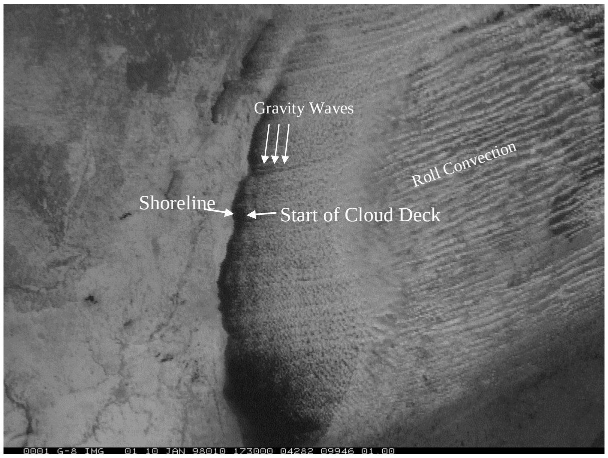

Figure 3: Cloud field at 1730UTC associated with the lake effect snow event of 10 January 1998.

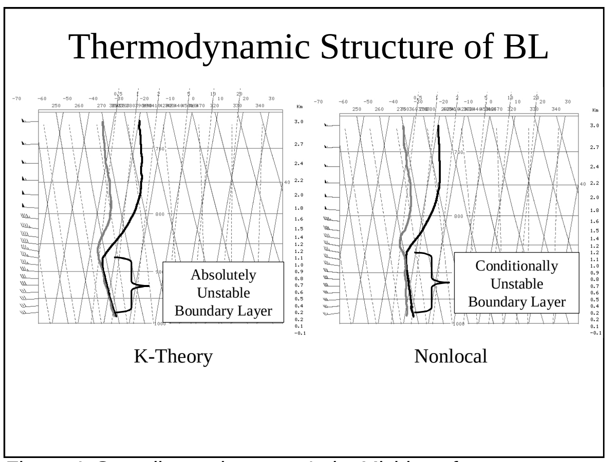

Figure 4: Soundings taken over Lake Michigan from a simulation utilizing standard K-Theory diffusion (left) and a simulation that adds a nonlocal correction term to the K-Theory diffusion (right). Both soundings are taken 3 hours into the simulation, allowing sufficient time for Lake Michigan to modify the boundary layer.

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 4). 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 was 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 air very close to the surface where friction is important. The boundary layer structure of the simulations with the nonlocal correction term applied to diffusion of entropy and moisture appear more consistent with what would occur in the real atmosphere (Figure 4). This result supports the need for a nonlocal parameterization in boundary layers driven by strong surface heating.

The ability of the nonlocal term to transport entropy and moisture through the depth of the boundary layer also improved the western extent of the simulated cloud cover by moving it closer to the western shore (Figure 5), 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.

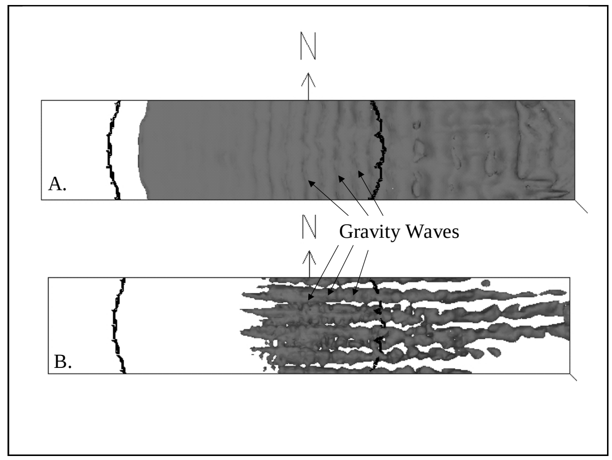

Figure 5: Cloud structure produced for fine resolution ($\Delta x = \Delta y = 400m$) simulations with the nonlocal term (A) and with only K-Theory diffusion (B). Valid 6 hours into simulation. Notice that the nonlocal term allows the model to develop a cloud much closer to the western shore of Lake 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 6d). The presence of a deep superadiabatic layer in this simulation, though eventually eliminated by explicit convection, demonstrates that until the explicit convection occurred, the large convective eddies were not being adequately parameterized by the K-theory closure. When the nonlocal term was used at cloud resolving horizontal spacing, superadiabatic lapse rates were present in only the lowest 300 meters (Figure 6c). The use of the nonlocal term at cloud resolving scales, while reducing the depth of the superadiabatic layer, introduced a drastic change to the simulated cloud field (Figure 5). The roll convection that characterized this type of lake effect event was unable to develop in the cloud resolving simulation that used the nonlocal transport. It is hypothesized that the inability to resolve the roll convection when applying the nonlocal term is due to a double accounting problem; the explicit convection can partially resolve the large eddies that the turbulence parameterization is representing. 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 6a). Lidar observations from Lake-ICE (Figure 7) on 10 January 1998, show the approximate scale of the large convective eddies. At course resolution it is easy to see that the eddies would not be resolvable, and thus must be parameterized. At the cloud resolving scale of 400m, while the structure of every single eddy is not resolvable, the largest of the eddies should be adequately resolved.

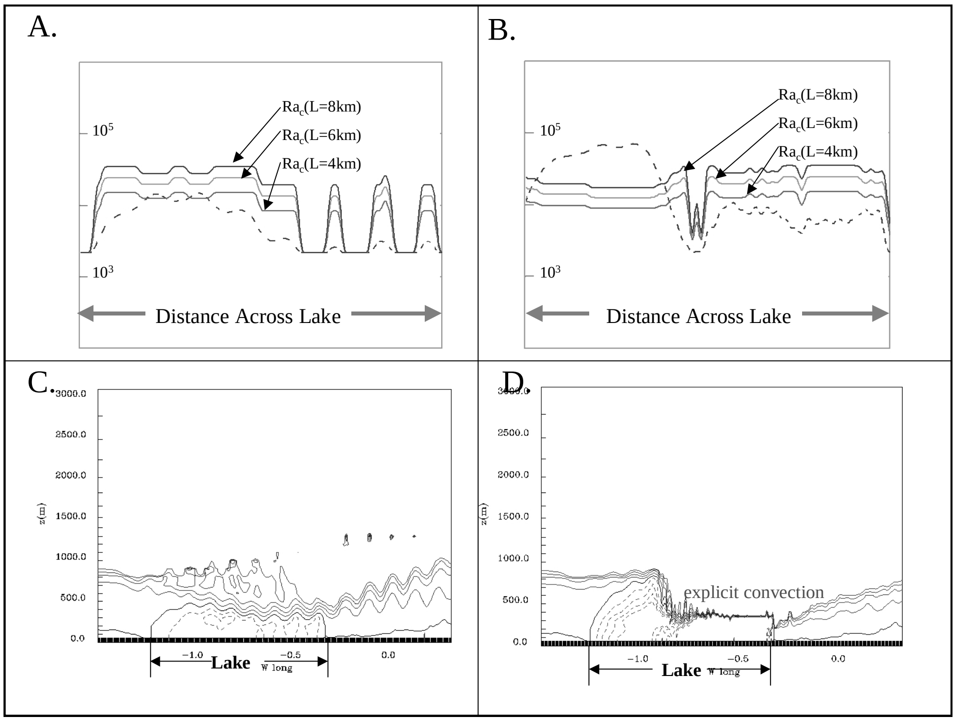

Figure 6: Dashed line represents the Dry Rayleigh Number computed across the lake (90km) for fine resolution simulations ($\Delta x = \Delta y = 400m$) that include the nonlocal correction term(A) and only standard K-Theory diffusion (B) at the final time (6hr). Solid lines represent different wavelengths 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 superadiabatic lapse rates to a shallower layer than the K-Theory simulation (D). The K-Theory simulation has stable Richardson

4. CONCLUSIONS

The simulation of the transition from small unresolved circulations to resolved circulations is proving to be a significant challenge. The simulations conducted show that nonlocal turbulence parameterizations, by representing the moist thermal transport accomplished by large convective eddies adequately simulate the mean thermal structure of the convective boundary layer without explicitly representing individual convective plumes. However, when the nonlocal term was added to a high resolution simulation that resolved the largest convective plumes but not the smallest, the largest convective circulations were lost (when compared to a simulation not employing non local closure) and as with the coarse resolution application, were represented only statistically. Hence it appears that the described non-local turbulence scheme will not allow one to realistically simulate both resolved and parameterized unresolved convective circulations simultaneously.

Nonlocal closure schemes presently cannot capture the scale interactions or momentum transports that explicit simulation can. Moreover, the resolvable coherent convective structures can be quite large, possibly deterministic in some cases and the precursors for deep organized convection under certain circumstances. Hence explicit simulation of the largest structures may offer important advantages that are lost when nonlocal closure is employed. This dilemma is similar to that which we face with cumulus parameterization on the mesoscale when resolutions are achieved that partially resolve deep convective storms.

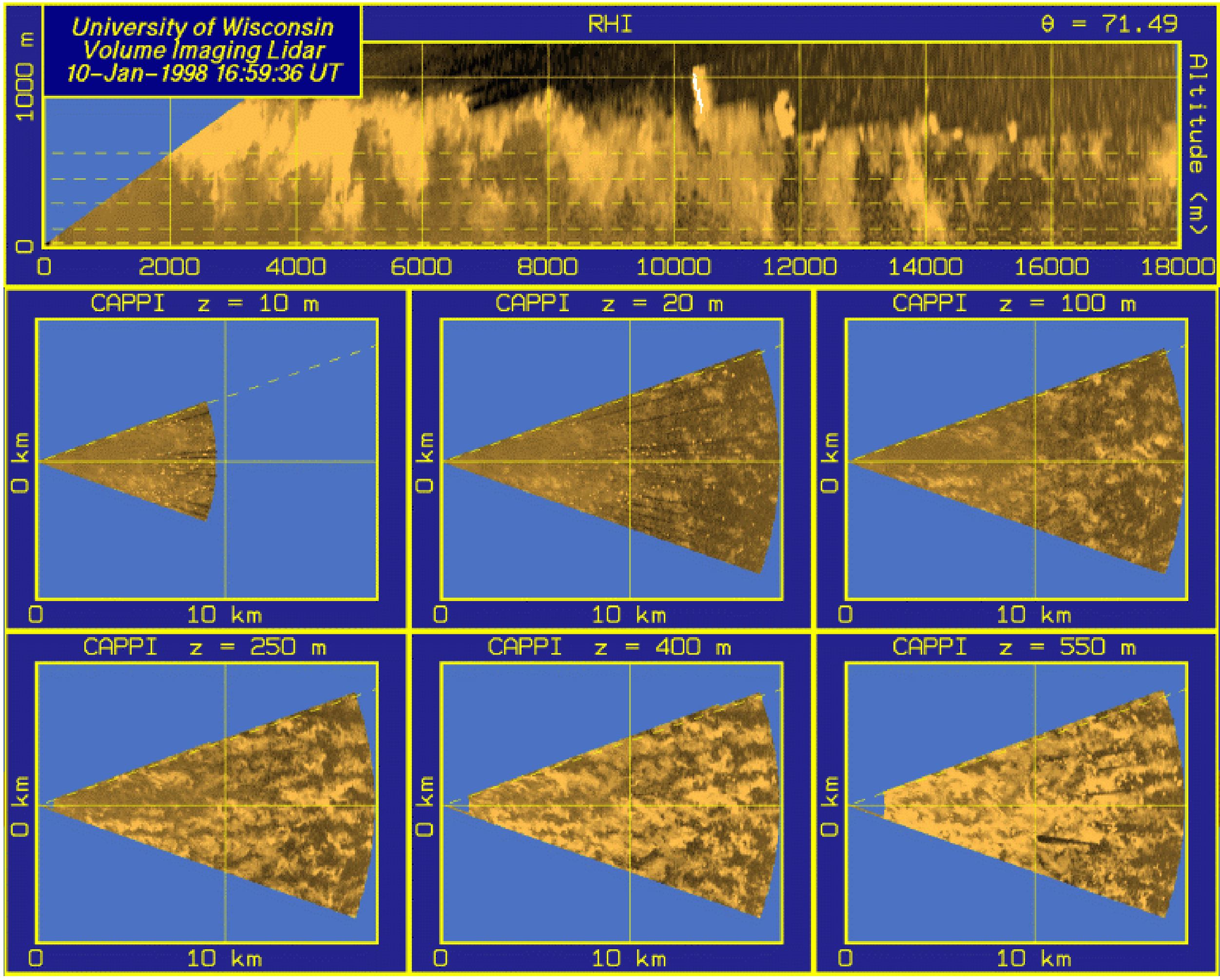

Figure 7: Lidar RHI volume scans from 16:59-18:05 UTC 10 January 1998. The large convective eddies are shown to be traveling through the depth of the boundary layer. The horizontal scale of these structures is not resolvable at 2000m, but can partially be resolved at 400m resolution.

5. ACKNOWLEDGEMENTS:

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