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Sensitivity Study of Nonlocal Turbulence Closure Scheme in Local Circulation

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ABSTRACT

In this paper, the Theory of Transient Turbulence (TTT) is applied to a 2–D local circulation model to parameterize the turbulent transport processes. Our purpose is to test the effciency of TTT in higher dimensional model and the sensitivity of simulated results to the TTT parameters. The results a show that under near–neutral and unstable situations the TTT is feasible, but the mean field and the turbulence field may have different sensitivities to the parameters. Some modification should be given to the magnitudes of parameters suggested Stull and Driedonks (1987) for different background fields and numerical grid spaces.

Key words: Nonlocal, Transilient, Scale–multiple

I. INTRODUCTION

Since the Theory of Transilient Turbulence was established (Stull, 1984), two parameterization schemes (Stull et al., 1984; Stull and Driedonks, 1987, hereafter SD87) have been developed to apply this theory to numerical modelling. Using 1–D PBL models, some studies have been done to compare the modelling results of these two schemes with that of other approaches (Chrobok, 1992), and observations (Zhang er al., 1991). Outstanding results have been brought out to prove that TTT is able to reproduce the general features of PBL, especially in the modelling of convective boundary layer (CBL). Even though there are some disagreements with the turbulent statistics concepts deduced from this theory and the kernel part of this theory–transilient matrix (Deardoff, 1985; Sawford, 1986), the advantage of TTT in numerical modelling is still attractive. Traditional numerical models use many hypotheses and parameters to parameterize the turbulent fluxes or higher–order moments for different vector fields and scalar fields. Some of these schemes are far from realistic levels to damp numerical noise. What is worse, all these models imply a fatal defect in the basic physical hypothesis, namely, local transfer hypothesis, which is based on the analogy between turbulence and molecular diffusion. However turbulence is intrinsicly nonlocal and scale–multiple, so more and more investigators are now returning to nonlocal closure methods which include the large–eddy, integral (Fiedler, 1984), spectral approaches (Berkowicz and Prahm, 1979) and the TTT. The TTT is one of the most attractive among them. This is due to its mathematical technique and its automatically responsive approach of physical parameterization (SD87). Results from different 1–D models with TTT also show good consistence with experimental data. It seems that the TTT superiority in simple 1–D model is undoubted till now. But the disadvantages of this theory are also obvious. Firstly, to carry out this theory, one should artificially divide the real physical process into two parts: external forces including dynamics, thermodynamics, boundary forcings, etc., destabilize the flow, then the transilient turbulence scheme relaxes the instability. As a consequence of this assumption, the turbulence structure will be changed with the same external forces but different finite–difference schemes (SD87). This is not very suitable for the study of turbulence statistics, especially the dispersion of air pollution particles. The other consequence is that different relaxed extent will bring out different turbulent mixing. Someone may say even the gradient theory, K–theory, is not able to describe the mixing exact turbulent extent either. That is true. But the difference is that K–theory relates turbulent processes of different physical quantities only to the individual and local mean field, and adjusts mean fields simultaneously. The error between the real turbulence and the parameterized one belongs to individual local fields. On the contrary, TTT incorporates all the individual turbulent processes into a universal turbulence field (physically it may be right), and mathematically makes it become one independent part, Consequently, any error from the mean fields including different finite–difference schemes and all the other possible errors should affect or even deform the whole turbulence field. As the same, errors from the universal turbulence field will influence all the mean fields. If we regard the error of K–theory as individual error, then the error of TTT is a cumulative one, which cumulates not only in space but also in time. Thus, more attentions should be paid to every aspects of modelling, not only the parameterization itself.

Secondly, there are $n^2 - n$ degrees of freedom (just in one dimension). It is very difficult to parameterize practically without any theoretical guidance. If we want to decrease degrees of freedom, we should continue to make various hypotheses, say, exchange hypothesis (SD87). Large–eddy simulation has shown that not only the transilient matrix is not symmetric, but also the maximum values are not always on the diagonal of the matrix (Ebert et al., 1989). The venture to decrease the degrees of freedom is that if the reduced degrees are not so sufficient or the values of parameters are not so precise, the model must become very sensitive and difficult to be controlled. Raymond applied TTT to a mesoscale numerical modelling and used SD87 scheme for all the physical processes. The results turned out that TTT could improve forecast accuracy of some fields in the boundary layer while giving bad simulations of some other fields, such as precipitation, evaporation, etc.. They also found that the SD87 model became much more sensitive to the way that physical quantities were represented, for example, when evaporative cooling of rain and cloud water became extremely important. Atmospheric radiation, cloud radiation feedback process and topography were also shown to be significant. That is unavoidable. Just as argued above, the degrees of freedom used in that model were not enough to simulate all the physical variables fields when the model included more physical processes than SD87. Even though Raymond et al. used the feedback mechanism to modify the rainfall process, the results were still not as expected and other fields were affected.

One way that may lead to decrease or eliminate the randomness and unpreciseness is to modify TTT itself and its parameterization. Before all these attempts, some primary studies are still essential. One is to confirm whether TTT is able to reproduce the pronounced features due to basic external forces in two–or three–dimensional models. In spite of the successes in one–dimensional modelling, TTT and its parameterization may meet more problems mentioned above in higher dimension mixing. The other primary study is what will affect the parameterization and which are the main factors that parameters are most sensitive to. This will be a heavy and long-period work. But for a new theory, it is necessary and valuable. In the following study, we will try to employ SD87 in a 2-D hydrostatic model to simulate sea breeze. The following influences on the results are examined: 1) horizontal space 2) environmental stability 3) surface heating intensity. The sensitivity of results to the interior parameters are also tested here.

II. MODEL DESCRIPTION

1. *Model Equations*

The sea breeze(SB) is a well known meteorological phenomenon. There has been extensive studies on SB (e.g., Pielke, 1980; Yan and Anthes, 1988). Some investigators even gave out its linear theoretical results. All these studies have shown many universal recognitions on this phenomenon, which provide a substantial base for our new research. Now, we incorporate SD87 into a 2-D sea breeze model and try to reproduce these common features. The reason that we use sea breeze model here is that there have been fewer comparisons of different turbulence closure schemes in this area.

The 2-D model used here was originated by Pearson (1973, 1974). It is hydrostatic. There are no vapor water physics and other physical processes except sensible heating. Even though we have realized that all the other physical processes should affect or even change the parameterization of TTT, we are mainly concerned about the efficiency of SD87 scheme in turbulent mixing, and the effects of background fields and grid spaces on the parameters used in SD87. Other factors that may confuse or complicate our analysis woll be avoided as far as possible. The original model will serve as a reference model (RM). Both models have the same equations, boundary and initial conditions apart from different turbulence closure schemes. Results from them will be compared.

The governing equations of motions are:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+w\frac{\partial u}{\partial z}=-\frac{\partial p}{\partial x}+fv+TT_{(1)}\ , \tag{1}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial t}+w\frac{\partial v}{\partial z}=TT_{(2)}\ . \tag{2}$$

The thermodynamic equation is:

$$\frac{\partial \sigma}{\partial t}+u\frac{\partial \sigma}{\partial x}+w\frac{\partial \sigma}{\partial z}-N^2w=TT_{(3)}\ . \tag{3}$$

The contonuity equation is:

$$\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}=0\ . \tag{4}$$

The hydrostatic equation is:

$$\frac{\partial p}{\partial z}=-\sigma\ , \tag{5}$$

where u, v, w are components of velocity in x, y, z direction; p is the perturbation from the original hydrostatic presser divided by air density; N is Brunt-Vaisala frequency; σ is negative buoyancy

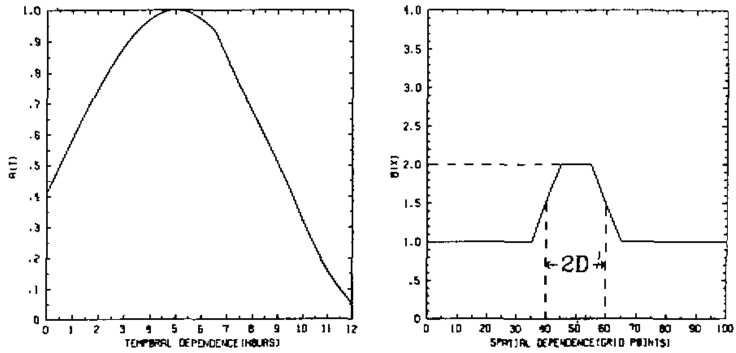

Fig. 1. Idealised function of sensible heat flux at surface (a) temporal dependence $A(t)$ (b) spatial dependence $B(x)$, dashed lines indicate amplitude and the central part of island.

$$\sigma = -g\frac{\theta'}{\theta_0} , \tag{6}$$

where θ_0 is mean potential temperature; θ' is the deviation from θ_0.

The $TT_{(\theta)}$ terms represent turbulent mixing effects. Different closure schemes result in different frameworks. The scheme used in this study is SD87 (see Section 2.2). The reference model adopted the scheme developed by Richiardone and Longhetto (1984).

Integration was performed using a 40 s time step on a staggered grid with 101 points in the horizontal and 21 in the vertical. Horizontal grid spacing varied from 1 km to 3 km in different runs, vertical grid spacing was uniform with 200 m increment in each run.

The lower surface was given a sea–land–sea shape along the X–coordinate (west–east direction). The land surface was assumed to be homogeneous and occupied 20 grid points in all the runs.

Idealized sensible heat flux at the ground was introduced as the following separated form:

$$H(x,t) = \sigma_0 A(t)B(x) , \tag{7}$$

where $A(t)$, $B(x)$ are temporal and spatial dependence of sensible heat flux respectively (Fig.1); σ_0 is a constant bearing the amplitude of sensible heat flux.

Constant Brunt–Vaisala frequency with height and zero geostrophic wind was used as the initial conditions. Different magnitudes of Brunt–Vaisala frequency were considersd.

2. *Turbulence Closure Scheme—TTT TKE Version* (SD87)

The Theory of Transilient Turbulence has been described by Stull et al. in their early papers (1984, 1987). To summarize here, this theory assumes that turbulence is advective, not diffusive. Turbulent mixing of fluid elements may occur across a range of distance. That is to say, any point in a turbulence field may be affected simultaneously by many points in the same field. Mathematically, Stull et al. expressed the net turbulent effects in the discrete and one–dimensional case as

$$\bar{S}_i(t+\Delta t)=\sum_{j=1}^{n} c_{ij}\bar{S}_j(t) \ , \tag{8}$$

where $\bar{S}_i$ denotes the state of scalar $\bar{S}$ at i–th destination point; $\bar{S}_j$ describes the state of scalar $\bar{S}$ at j–th source point, and c_{ij} gives the relative amount of mixture coming from that source. All the c_{ij} elements built up an $N \times N$ matrix C, called transilient matrix.

To do this, each time step should be split into two parts: one part where external forcings destabilize the flow, and the second part where turbulence reacts to the instabilities. To parameterize the transilient matrix C, SD87 suggested the following scheme:

$$\begin{aligned} c_{ij} &= \frac{Y_{ij}}{\|Y\|} \ , \qquad i \neq j \\ c_{ii} &= 1-\sum_{\substack{j=1 \\ j\neq i}}^{n} c_{ij} \ , \\ \|Y\| &= \max_i\left(\sum_{j=1}^{n} Y_{ij}\right) , \end{aligned} \tag{2.9}$$

where Y_{ij} is the elements of symmetric matrix Y, called "mixing potential". $\|\cdot\|$ denotes the matrix norm (see Stull et al., 1987). The "mixing potential" matrix Y relates the mean quantities of given fields with the intensity of mixing, and is derived from a simplified TKE equation as the following:

$$\begin{aligned} \hat{Y}_{ij} = T0\Delta t\Bigg[& \frac{1}{(z_i-z_j)^2}[(u_i-u_j)^2+(v_i-v_j)^2] \\ & -\frac{g}{R_c\left(\dfrac{\theta_i+\theta_j}{2}\right)}\left(\frac{\theta_i-\theta_j}{Z_i-Z_j}\right)\Bigg]-\frac{D}{T0}\Delta t \ , \qquad i\neq j \end{aligned} \tag{10}$$

where $T0$ is a time scale of turbulence; R_c is a dimensionless parameter analogous to a critical Richardson number, and D is a dimensionless dissipation factor.

Since the scheme restricts the mixing potential to non–negative values to avoid meaningless negative mixing potentials, so the off–diagonal elements of Y are then defined as

$$Y_{ij} = \max(0, \hat{Y}_{ij}) \ . \tag{2.11}$$

In order to prevent convective overturning, values of Y elements have been assumed to increase monotonically from the value of the upper right–most element toward the values on the main diagonal, finally, the diagonal elements are chosen to be

$$Y_{ii} = \max(Y_{i,i-1}, Y_{i,i+1}) + Y_{\mathrm{ref}} \ , \tag{2.12}$$

where Y_{ref} is reference potential, accounting for the potential for subgrid–scale internal mixing within box i.

The approach summarized above reduced the degrees of freedom from (n^2-n) to 4, where the four parameters are $T0$, R_c, D, Y_{ref}. SD87 recommended a best combination of these parameters values

$$R_c = 0.21, \qquad T0 = 100 \text{ s}, \qquad Y_{\mathrm{ref}} = 1000, \qquad D = 1 \ ,$$

however our studies show that they will be changed under different background fields and grid spaces.

Horizontal mixing suggested by Raymond (1990) will be used when it is necessary.

III. NUMERICAL RESULTS AND DISCUSSION

Numerical experiments with different values of horizontal space Δx, Brunt–Vaisala frequency N, surface heating intensity σ_0, and the four parameters used in SD87 scheme have been performed to reproduce the general features of SB and test the sensitivity of SD87 parameters under different background fields and grid spaces. Best combinations of T_0, R_c, Y_{ref}, D have been chosen so that the sea breeze circulation could be formed and its intensity could reach that of RM as nearly as possible. The integration for all the experiments was 10 hours, within which the diurnal variation of the SB could be simulated. The summary of the model design and characteristics is given in Table 1. All the time used here is integration time.

Table 1. Summary of Experiments

Experiment	Δx (Km)	N (S^{-1})	σ_0 (WM^{-2})	T_0 Y_{ref} R_c D
GS1	1.0	0.0115	255.0	1000,100,0.21,1
GS2	2.0			500, 200, 0.21, 1
GS3	3.0			500, 500, 0.21, 1
BV1	2.0	0.0115	255.0	500, 200, 0.21, 1
BV2		0.0180		500, 200, 0.21, 1
HI1	3.0	0.0115	255.0	500, 200, 0.21, 1
HI2			155.0	500, 200, 0.21, 1

1. *General Results*

It is very important for a new scheme to reproduce the general characteristics of some phenomenon. If the scheme can do, qualitatively, it is available in practice; On the contrary, it may have some fatal flaw in itself. With suitable magnitudes of parameters, we find that the model is able to generate the SB circulation and simulate its changing with different background and grid space in each experiment. A typical example of sea–land–sea pattern circulation with its two closed cells is shown in Fig. 2. For each experiment, the symmetric SB generally formed after 2 hours of model simulation along both sides of the land. Then the two SB cells moved inland and merged over the centre of the island. Even though the turbulenec field was determined only by the velocity field and potential temperature field, the results of stream function and vorticity field also turned out to be reasonable using the same transilient turbulence matrix. This means that the transilient turbulence matrix was universal to some extent for all the quantities. But one must keep in mind that we include only the sensible heat process in our model. Any more general conclusion should be made after deeper theoretical study and sophisticated modelling.

When the horizontal dimension of the land area increased(experiments GS1–3) more time was required before the two cells merged. The maximum magnitude of vertical velocity, associated with horizontal convergence of the two SB cells, always appeared during the period of the cells–merging. Furthermore, the maximum magnitude of vertical velocity and the circulation height of SB also varied with the land size (Fig. 3). Generally, when the size of land increased within 20 km—100 km (occupying the same grid points but different grid spaces), the turbulence field could have more time to develop well over land, and therefore, the vertical

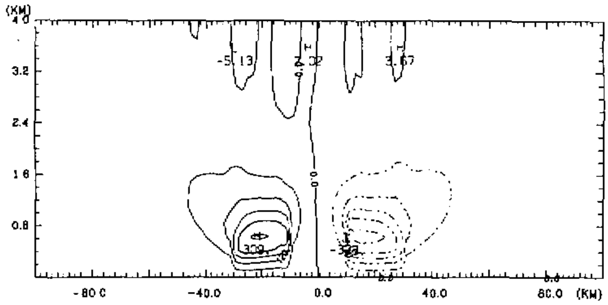

Fig. 2. Contour of stream function for experiment GS2 after 2.00 hour.

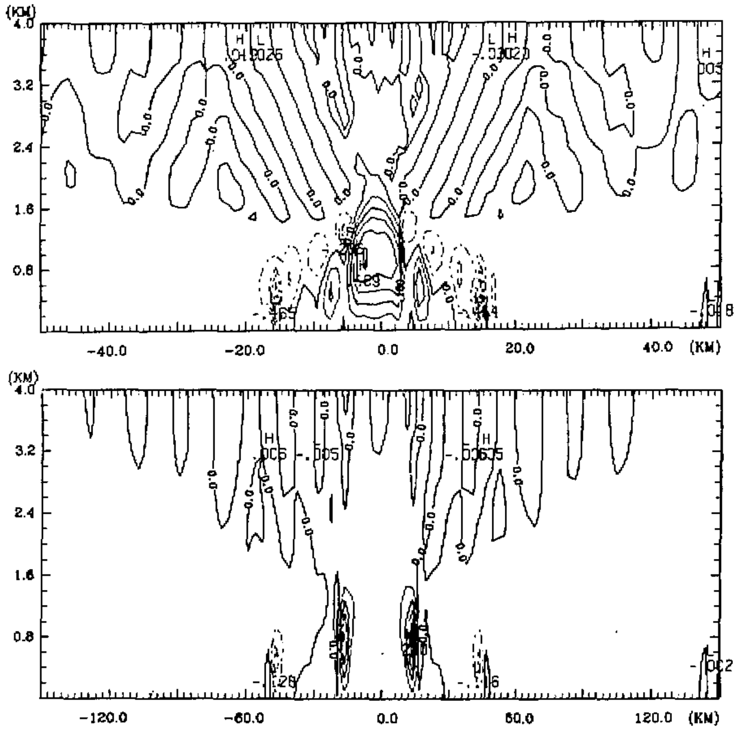

Fig. 3. Vertical velocity field after 4.00 hour for experiments. (a) GS1 with $\Delta x = 1$ km (b) GS3 with $\Delta x = 3$ km.

velocities would be maximized and deeper mixed–layer would be reached before the SB cells merged. These results agree well with Yan and Anthes (1988), Xian And Pielke (1991). In their numerical model simulation study, they found that the heated land with the size of 100 *km—150 km can produce the strongest SB vertical motion, where the two SB cells from both* coasts merge at the very time of maximum boundary–layer heating. Those with the land sizes larger or smaller than the above size will have weaker maximum vertical motions.

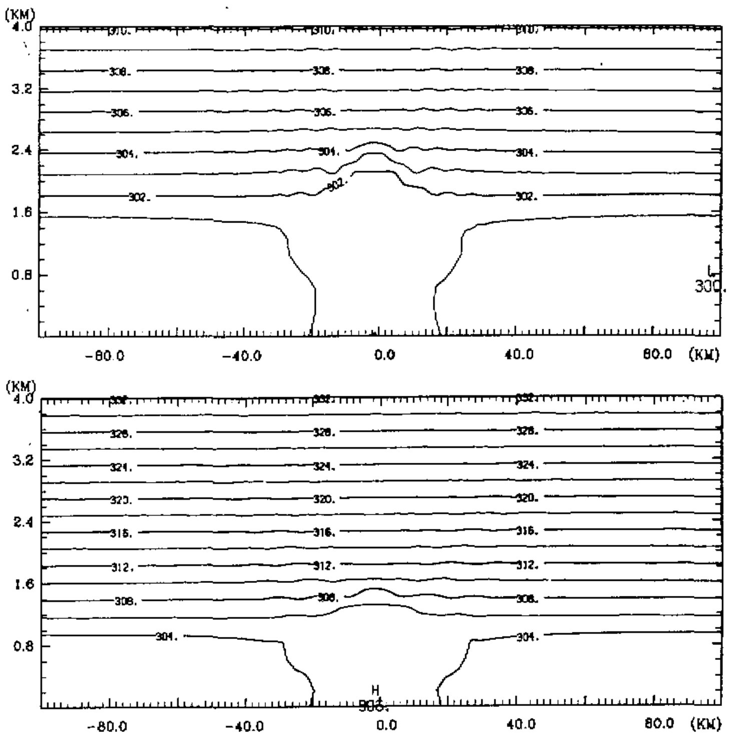

Fig. 4. Potential temperature field after 6.00 hour for experiments. (a) BV1 with Brunt–vaisala frequency $N = 0.0115$ s^{-1} (b) BV2 with $N = 0.0180$ s^{-1}.

A factor that is of significance to the development of SB system is the environmental stability. Many other studies have shown that more stable atmosphere will act as a strong damping mechanism on the vertical and horizontal circulation of SB. In experiments BV1 and BV2, we set the initial static stability with different constant Brunt–Vaisala frequency, 0.0115 and 0.018 respectively. Fig. 4 is their potential temperature fields. It is obvious that the air with weaker stratification provided more favourable environmental conditions for the sea breeze to develop. When the stability increased, the circulation height and intensity decreased correspondingly.

Since our SB system developed entirely due to differential heating in the lower atmosphere, the intensity of surface heating would obviously influence the system development. We changed the amplitude of surface heat flux from 255 in experiment HI1 to 155 in experiment HI2, and compared their results in Fig. 5. Just as expected, the change of surface heating indeed caused a substantial change in system intensity. As far as we know from above, the SD87 scheme is able to adjust successfully the turbulence field under different backgrounds and heating scales.

2. *Comparison with the Reference Model (RM)*

To evaluate physical parameterization scheme of a numerical model, it is always useful to compare its results with that of other models or with that of the same model but different

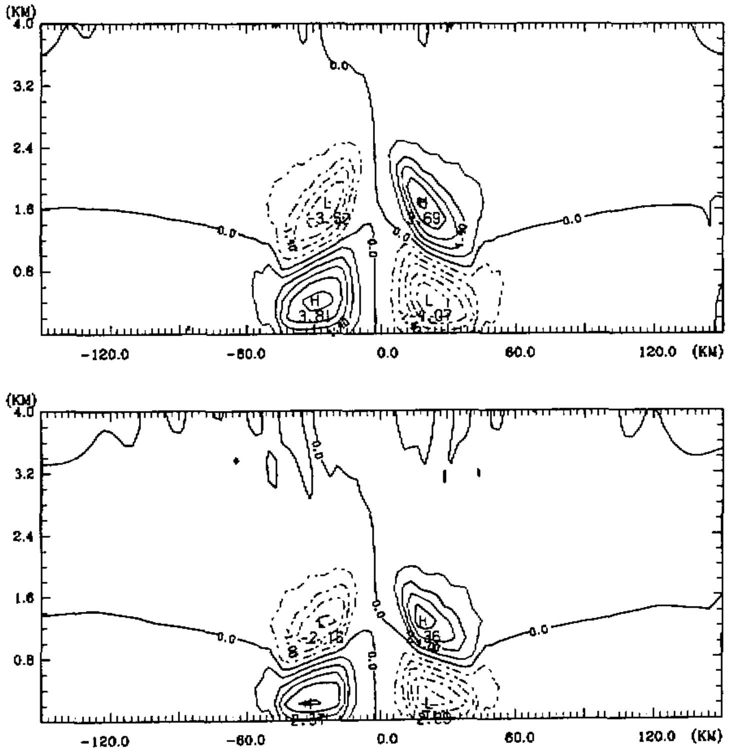

Fig. 5. Horizontal velocity (U) field after 6.00 hour for experiments. (a) HI1 with σ_0 = 255 wm^{-2} (b) HI2 with σ_0 = 155 wm^{-2}.

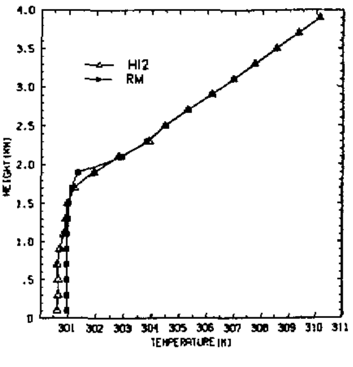

Fig. 6. Vertical profile of potential temperature for experiment HI2 and RM at horizontal grid point 45 after 8.00 hour.

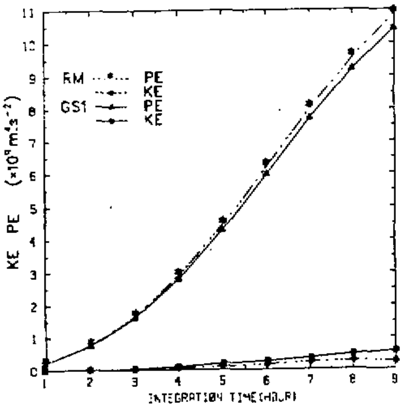

Fig. 7. Kinetic and potential energy (KE, PE) of system for experiment GS1 and RM.

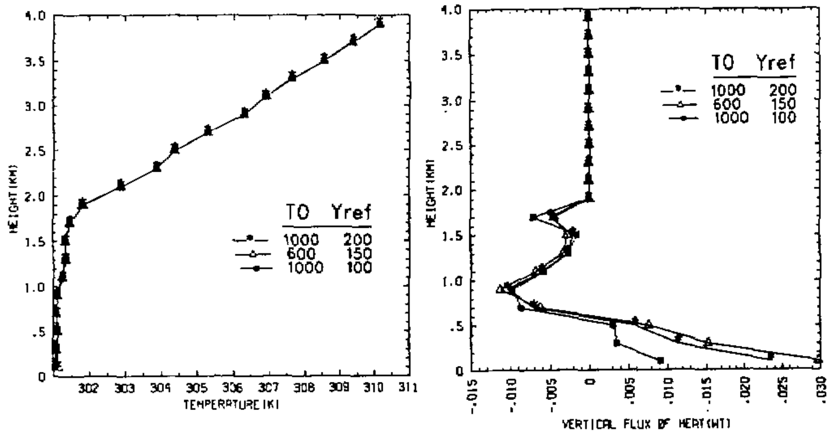

Fig. 8. Vertical profiles of potential temperature and heat flux for experiment GR1 at horizontal grid point 55 after 6.00 hour.

parameterization scheme. In our study, the scheme developed by Richardone and Longhetto (1984) was used as the counterpart of SD87. Results can be summarized as follows:

Generally, both were comparable in dynamic and thermodynamic field, but there was bigger difference in dynamic field. Since the boundary heating was the only source term in thermodynamic equation, the maximum difference always appeared when heating was near its highest value. The temperature of SD87 in all our experiments was lower than that of RM at almost all the grid points, but the biggest difference never exceeded 0.5 K (Fig. 6). In contrast to thermodynamic field, the dynamic field did not coincide with each other very well. Table 2 gives out the time history of maximum values of each wind components. We can find out that the horizontal components of SD87 are stronger that of RM during all the period of integration, but the vertical velocity is exactly opposite in later integration. Kinetic and potential energy of the system also show this kind of difference (Fig. 7). Since the finite–difference scheme first integrated stream function (Ψ) and then derived U from Ψ using the equation:

Table 2. Time History of Maximum Value of Experiment GS1

Time (hour)	U (m / s)		V (m / s)		W (m / s)	
	SD87	RM	SD87	RM	SD87	RM
1.00	0.244	0.205	0.019	0.009	0.039	0.026
2.00	1.100	0.750	0.180	0.059	0.235	0.095
3.00	2.360	1.640	0.552	0.185	0.262	0.209
4.00	3.310	2.780	0.970	0.390	0.477	0.428
5.00	3.900	3.460	1.390	0.592	1.360	0.875
6.00	4.230	3.920	1.980	0.747	1.430	2.000
7.00	4.460	4.120	2.090	0.904	1.580	2.980
8.00	4.490	4.100	2.450	1.040	1.960	3.670
9.00	4.430	3.620	2.720	1.150	1.530	2.270

$U=\frac{\partial\Psi}{\partial Z}$, the results aforesaid may tell the truth: the SD87 scheme could mix the fields of stream function and negative buoyancy, but never sufficiently. Hence, in some sense, we cannot say that TTT is universal.

3. *Sensitivity Test of SD87 Parameters*

In each experiment, we changed the magnitude of each SD87 parameters and re–grouped them such that the two SB cells could be formed. We found that a value more than 0.25 for R_c could never enable the results reach the order of magnitude of RM. Changing of D from 1 to 5 caused very little difference. That is to say, R_c is the most sensitive factor and D is the most insensitive in this scheme. The best and reasonable value for R_c seems to be 0.21, and D 1. Similar conclusion was also drawn out in SD87 and has been adopted by other 1–D modeller. Therefore, we chose $R_c=0.21$ and $D=1$ in all our experiments. Unlike the best combination suggestes by SD87, we discovered that when $Y_{ref}=1000$, the sea breeze could never be simulated out in smaller horizontal grid spaces, such as 1 Km and 2 Km. As $T_0=100$ s, Y_{ref} was required not to be more bigger than 100 for $x=1$ Km, 500 for 2 Km, and 1000 for 3 Km. When grid space decreased and background stability enhanced, T_0 should be set bigger value, say, 500, to get comparable results with that of RM. Onec the magnitudes of parameters dropped in the range that individual experiment allowed, the mean fields appeared insensitive to the changing of parameter values, but case appeared different in turbulence field (Fig. 8). In fact, it was not its absolute error but its relative that was big, and this phenomenon existed in all the experiments. Thus, as we put emphasis on turbulent fields, e.g., pollutant dispersion, more attention should be paid to the value–choosing of SD87 parameters.

IV. CONCLUSION

In order to test the efficiency of TTT in higher dimensional model and the effects of SD87 scheme on mean and turbulence fields, a set of SB numerical experiments have been performed under different background and grid space. As far as we know, TTT is able to implement the turbulent transfer and reproduce some pronounced features of SB with suitable parameter value. For each special case (specific initial and boundary conditions), there seems to be an upper limit for Y_{ref} and lower limit for $T0$ so that the SB can be produced. Within the limits, the average fields are insensitive to parameters, but the turbulence fields are susceptible to the change of parameter values. One reason of this disparity is the difference of the order of magnitude between the mean and turbulence field, which makes different relative errors. The other reason is the artificial split of real physical process, which creates the so–called cumulative error. The exchange hypotheses in transilient matrix here are not very suitable either. Therefore, the explicit values or functions of parameters with respect to background fields and time should be explored so that the turbulence field be represented adequately. We are also sure that the TTT will face to more challenge in the models with more complex physical processes, such as the problem of sufficient degrees of freedom and so on. This will resort to more theoretical and experimental research in the future.

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