VALIDATION OF BOUNDARY LAYER SCHEMES

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1.INTRODUCTION

The general problem of validating a boundary-layer scheme is a very difficult one. More precisely, one can imagine different kinds of validation procedures, depending upon the type of modelling of the boundary-layer one is interested in. It is quite natural to concentrate on detailed time and space validation of mean parameters (e.g. temperature, wind and moisture) and turbulence quantities when one is dealing with high-resolution, sophisticated, bondary-layer models. On the other hand one will restrict validation to the basic processes, which describe the interaction between the boundary layer and the free atmosphere, when one is more particularly interested in implementing a boundary-layer parameterization scheme within a large-scale three-dimensional numerical weather prediction or climate model. It must be said here that only a small number of already proposed boundary-layer schemes have been adequately validated, with validation procedures adapted to the objectives of the particular model. Most of the time the computed surface fluxes and coarse vertical profiles of temperature and wind are simply compared to the corresponding values observed during a field experiment, which could lead to improper validation, as will be shown below.

We shall describe here the various validation techniques which have been, or could be, used, and give when possible one or two examples taken from recent literature. These various techniques can be classified under three broad types : those addressing the basic physical processes, those dealing with one-dimensional testing, and those related to three-dimensional implementation. We shall finally give some indication about prospects for future research in this field.

2. VALIDATING THE "SMALL-SCALE" PHYSICS

Under this general heading one can distinguish between different possibilities, ranging from a better calculation of various constants appearing in boundary-layer schemes, to the experimental or theoretical determination of closure functions, and finally to a critical appraisal of the possibility to use at the meso-scale laws which have been derived and tested at the micro-scale.

2.1. Validating the numerical constants

As the first example of such a validation technique, one can refer to the recent work by Högström (1985), who addressed the question of determining the best value of the Karman's constant. It has indeed been debated for a long time if the value was closer to 0.44 (e.g. Nikuradse, 1932), or to 0.4 (e.g. Dyer and Hicks, 1970), or to 0.35 (Businger et al., 1971). Field experiments have been conducted, where the friction velocity u_* , the wind profile $\bar{u}(z)$, and the Monin-Obukhov length L, have been simultaneously measured in order to determine the Karman's constant k defined as

$$k = \left(\frac{z}{u_*} \frac{\partial \bar{u}}{\partial z} \right)^{-1} \phi_u(z/L) \Big|_{z/L=0} \qquad (1)$$

Results show that the best choice for k is

$$k = 0.40 \pm 0.01 \qquad (2)$$

rather than the widely used value of .35 derived from the Kansas experiment (Businger et al., 1971). This also leads to a modification of the dimensionless universal stability correction for wind profile around neutrality, namely

$$\phi_u(z/L) = 1 + 4\ z/L, \qquad (3a)$$

instead of

$$\phi_u(z/L) = 1 + 4.7\ z/L \qquad (3b)$$

as for the Kansas experiment. After such careful experiments, the value of the Karman's constant should be considered as given, and should by no means be used as an adjustable parameter as it is sometimes done.

Another, but slightly different, example concerns the determination of the ratio A between the surface heat flux $\overline{w'\theta'}_{sfc}$ and the heat flux $\overline{w'\theta'}_i$ at the top of the boundary-layer or inversion level

$$A = -\overline{w'\theta'}_i \Big/ \overline{w'\theta'}_{sfc} \qquad (4)$$

This parameter is often used in bulk boundary-layer schemes (e.g. Driedonks, 1985). Its value does of course determine to some extent the precise depth of the boundary layer, which is one of the most important outputs of such bulk schemes. There is however no definitive evidence that this parameter A is really a well-defined constant, as for example experimental data exhibit a very large scatter with no clear trends (Artaz and André, 1980). Adjustement of bulk boundary-layer schemes, where the parameter A is varied in order to correctly describe the depth of the boundary-layer (e.g. Augstein and Wendel, 1980), cannot consequently be considered as definitive, as it is mostly a sensitivity study rather than a validation test.

2.2. Validating the closure functions

Among the unknown functions which have to be introduced in boundary-layer schemes in order to close the system, the "mixing", l_k , and "dissipative", l_ε , lengths are probably the most crucial ones. They are defined as

$$K = \ell_k \bar{e}^{1/2} \qquad (5)$$

and

$$\varepsilon = \bar{e}^{3/2} / \ell_{\varepsilon} \qquad (6)$$

where K is the eddy-diffusivity, $\bar{e}$ the eddy kinetic energy and ε the molecular dissipation rate of kinetic energy. In the recent years it became progressively clearer that l_K and l_{ε} could be different from each other, specially for the case of stable stratification (Therry and Lacarrère, 1983). Experimental determinations of l_{ε} in the case of convective flows are now available, e.g. from the laboratory work of Willis and Deardorff (1974), and become progressively available in the case of stable flow (Louis et al., 1983). These data should allow for a preliminary validation of formulations for l's which have been proposed earlier, like the ones by Mellor and Yamada (1974) in the neutral and unstable cases :

$$\ell_{MY} = 0.1 \frac{\int_0^{\infty} z\, \bar{e}^{1/2} dz}{\int_0^{\infty} \bar{e}^{1/2} dz} \qquad , (7)$$

by Deardorff (1976) in the stable case :

$$l_D = \left(\bar{e} \Big/ \beta \frac{\partial \bar{\theta}}{\partial z} \right)^{1/2} \qquad ,(8)$$

and by e.g. Yu (1977), Bodin (1979) or Therry and Lacarrère (1983) in the general case, where one has to consider a vertical distribution of stable, neutral and unstable layers. Such preliminary validations have been already undertaken (Louis et al., 1983 ; Therry and Lacarrère, 1983). They show that the mixing and dissipative lengths cannot be considered anymore as arbitrary closure functions which can be tuned at one's will in order to reproduce a given situation.

2.3 .Validating physical laws at the meso-scale

It sometime happens that one uses at the scale of a GCM grid square physical laws which have been derived and tested at the local, micrometeorological, scale. Although such laws are thought to be well tested and validated, their use at the mesoscale may lead to improper parameterization of the boundary layer. The most well-known example concerns the Monin-Obukhov similarity theory (see e.g. André,1985), whose validity at the micrometeorological scale has been demonstrated by the results from many field experiments. When one uses such a law to retrieve the effective surface fluxes, averaged over the three-dimensional grid square, from the vertical gradients of wind, temperature and humidity close to the ground, one has to deal with an underlying surface whose properties may strongly vary from place to place within the grid square. This leads for example to a juxtaposition within that grid square of stable, neutrally, and unstable surface layer flows. In such a case it may very well happen that the large positive temperature gradients which exist in stable regions will dominate the much smaller negative temperature gradients which occur in unstable regions, giving rise to a small, but positive, stable area-averaged temperature gradient. On the other hand, the heat flux itself is dominated by the large upward positive fluxes which characterize unstable zones, as compared to the much smaller negative fluxes occuring in stable regions. As a consequence it is to be expected that counter-gradient heat fluxes develop at the scale of a GCM, or numerical weather prediction model, grid square.

A somewhat similar problem arises when averaging in time is applied instead of spatial averaging. This simpler problem has been addressed by Mahrt et al. (1985), who studied the flux-gradient relationship for 24-hour averages. They found that the effective, 24-hour average, surface heat flux $\langle \overline{w'\theta'}_{sfc} \rangle$ is upward, while the effective temperature gradient $\langle (\partial\bar{\theta}/\partial z)_{sfc} \rangle \sim \langle\bar{\theta}\rangle - \langle\bar{\theta}\rangle_{sfc}$ is stable, leading to a countergradient relationship of the form

$$\langle \overline{w'\theta'}_{sfc} \rangle = c_\theta \langle \bar{V} \rangle \left\{ \langle \bar{\theta}_{sfc} \rangle - \langle \bar{\theta} \rangle + \Delta\theta_{cg} \right\} ,\quad (9)$$

where the counter-gradient $\Delta\theta_{cg}$ is shown to be Richardson-number dependant :

$$\Delta\theta_{cg} = 0.188 + 10.52 \; R_i \qquad (10)$$

Such an example indicates that using at the scale of the model grid square, and/or time step, physical laws whose validity has been shown only at the micrometeorological scale, may lead to fairly large, qualitative and quantitative, errors.

3. ONE DIMENSIONAL VALIDATION

This mode of validation, the so-called column mode, is probably the most popular amoung boundary-layer physicists. One must distinguish here between validation against experimental data and validation against other, most of the time more sophisticated, models.

3.1. Validation against experimental data

One-dimensional validation of boundary-layer schemes against results from field experiments may be of very little significance if limited to mean parameters: wind, temperature, boundary layer depth,.. It has been noted that the boundary-layer depth may be directly varied by simply tuning some parameters (see 2.1.). Almost the same can be said for the validation of boundary-layer mean temperature, as it is mostly determined by the magnitude of surface fluxes and not by internal dynamics, at least for the case of unstable regimes. Wind profiles are similarly very sensitive to surface friction, so that for example the height of the nocturnal jet may be adjusted by simply changing the roughness length (André et al., 1978). Despite this rather important limitations, a very large number of boundary-layer schemes have only been validated by comparing their predictions to the vertical mean profiles issued from field experiments, like the famous Wangara experiment (see Hess et al., 1981) used for example by Yamada and Mellor (1975), André et al. (1978), Mailhot and Benoit (1982),...

A more significant validation may be done when turbulence data are available. This is unfortunately not very often the case, but it has been attempted in a few cases. André and Lacarrère (1980) and Therry and Lacarrère (1983) were for example able to compare predictions from their models to experimental data concerning not only mean wind, temperature and humidity, but also heat fluxes and dissipation rates. This is of course a more severe test although restricted up to now to a small number of experimental cases.

3.2. Validation against other models

Due to the above difficulties in finding adequate and complete data sets against which it would be possible to fully test and validate boundary-layer schemes, it is attractive to turn towards multi-level, higher-order planetary boundary-layer models to generate numerical results relative to turbulence dynamics.One should of course be careful in choosing the "reference" model, which should be itself very detailed and fully tested against, for example, laboratory data. Such an approach has been used in some occasions, for example by Beniston and Sommeria (1981) and Bougeault (1981), who tested one-dimensional parameterization schemes of the cloudy processes against three-dimensional data generated by the large eddy simulation model of Sommeria (1976).

More recently, Therry and Lacarrère (1983) were able to propose and test their one-dimensional scheme for the parameterization of eddy kinetic energy fluxes $\overline{w'e}$. From the model of André et al. (1978), where a rather general form of the equation for $\overline{w'e}$ is solved

$$\frac{\partial \overline{w'e}}{\partial t} = -\overline{w'^2}\,\frac{\partial\left(\bar{e}+\overline{w'^2}\right)}{\partial z} - \overline{u'w'}\,\frac{\partial \overline{u'w'}}{\partial z} - c'\,\frac{\bar{e}^{1/2}}{\ell}\,\overline{w'e} \tag{11}$$
$$-(1-c)\left\{\overline{u'w'^2}\,\frac{\partial \bar{u}}{\partial z} + \beta\left(\overline{e\theta'} + \overline{w'^2\theta'}\right)\right\},$$

they looked at the order of magnitude of the various terms in the right-hand side, and proposed a much simpler expression

$$\overline{w'e} = -0.65\,\ell\,\bar{e}^{1/2}\left\{\frac{\partial \bar{e}}{\partial z} + \frac{1}{2}\,\beta w_{*}\,\overline{w'\theta'} + 0.83\,\overline{u'w'}\,\frac{\partial \bar{u}}{\partial z}\right\} \tag{12}$$

involving only second-order quantities and allowing for a precise description of counter-gradient energy fluxes (see also André and Lacarrère, 1985).

4. THREE-DIMENSIONAL VALIDATION

Three-dimensional validation would of course be the ultimate and definitive way to test boundary layer schemes.

4.1. Three-dimensional validation against experimental data

They have been a number of three-dimensional field experiments over the last fifteen years, e.g. the BOMEX (Holland and Rasmusson, 1973 ; Nitta and Esbensen, 1974), ATEX (Augstein et al., 1973), GATE (Nicholls et al., 1982), or JASIN (Taylor et al., 1983) experiments among many others. Unfortunately, the three-dimensional data collected during these field programmes have not been used for three-dimensional validation, but instead have been averaged over horizontal planes in order to provide with one-dimensional turbulent correlations and variances and various heat and energy budgets (see e.g. Augstein and Wendel, 1980 ; Nicholls et al., 1982 ; Nicholls et al., 1983).

4.2. Three-dimensional implementation within larger-scale models

In the absence of direct testing against three-dimensional data, boundary-layer schemes have been implemented within numerical weather prediction and general circulation models. The results of such tests are generally of qualitative nature, as for example the early results of Delsol et al. (1971), who showed that a distinction between friction over land and over sea is crucial for a good description of atmospheric circulation, or the more recent study of Tiedtke (1981), who could diagnose a poor description of shallow convection from the examination of surface heat fluxes over the trade-wind regions. Quantitative tests of this type are not possible presently due to the lack of adequate surface and boundary-layer data at the global scale (see e.g. Carson, 1981). It should nevertheless be possible to improve this situation by taking more advantage of the surface and low-level data which are exchanged on a routine basis through the global telecommunication system.

5. PROSPECTS FOR FUTURE RESEARCH

As we have seen above, the main difficulty regarding validation of boundary-layer schemes is the lack of adequate three-dimensional data at the proper scale, i.e. at the meso-scale. Due to the fact that such data will not be available on a global basis within the next few years, one should look for alternative solutions.

As already mentioned, a first possibility is to pay more attention to the surface and low-level data which are collected operationally : temperature and humidity at screen-height, wind at 10 m, boundary-layer depth possibly retrieved from radiosoundings in some favourable cases,...

The second avenue for possible research in this field is to use meso-scale models as an alternative way to generate small-scale data, which can then be spatially averaged and consequently provide with data adequate for parameterization at the scale of a model grid square. Such a procedure has been advocated by Eagleson (1981) and already used by Wipperman (1978). More recently André and Blondin (1985) followed that approach and proposed the parameterization of effective roughness length from the knowledge of the small scale distribution of roughness elements.

Finally, and probably most promising, boundary-layer physicists should organize field experiments at the meso-scale, where the variability of surface and atmospheric parameters would be fully documented. Such preliminary , or pilot, studies are already proposed, for example in the case of the water budget over land surfaces (André et al., 1985).

In the meantime there will still remain some ambiguity about the validity of various boundary-layer schemes. Each author will probably continue to test his own model against particular, possibly partially inadequate, sets of data, so that he will be entirely bona fide when asserting his model is fully tested and of great skill!

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