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Practical considerations concerning the use of the planetary boundary layer top as a coordinate surface

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1. INTRODUCTION

The depth of the turbulent planetary boundary layer (PBL) is highly variable in space and time. It must be accurately determined in a general circulation model (GCM) because:

(a) The entrainment of mass at the PBL top imposes a very important upper boundary condition on the turbulent fluxes inside the PBL.

(b) The PBL top is frequently observed to coincide with the base of deep cumulus clouds, and imposes a lower boundary condition on the cumulus layer. The evolution of the PBL depth plays a key role in the coupling between the PBL and deep convection.

(c) In many cases the PBL top coincides with the top of a stratocumulus or shallow cumulus cloud layer. Strong radiative cooling is concentrated in a very thin layer near the cloud top. The fact that this cooling is highly concentrated has profound consequences for the PBL turbulence.

(d) The PBL top is often marked by extremely sharp features (hereafter, "jumps") in the temperature, moisture, and wind fields.

Typically the PBL depth evolves continuously in space and time, in response to diurnal, synoptic, and seasonal forcing.

Experience with higher-order closure models shows that in order to accurately represent the evolution of the PBL depth and the jumps near the PBL top it is necessary to use a vertical resolution on the order of 5 mb or even less. Most existing GCMs employ a vertical resolution on the order of 100 mb. In a few cases, higher resolution is provided in a few layers very near the earth's surface, but not throughout the entire PBL depth. The use of coarse resolution is dictated by two considerations:

(a) Higher resolution is computationally more expensive.

(b) In order to take advantage of high resolution, it is necessary to use very accurate turbulence parameterisations, which may not exist yet. In any case, the use of a highly detailed turbulence parameterisation is difficult to justify in view of the current serious deficiencies in other important parameterisations, such as the cumulus parameterisation.

Coarse vertical resolution makes it difficult to represent adequately the continuous and progressive evolution of the PBL depth, or to determine adequately the vertical structure in the immediate vicinity of the PBL top.

Deardorff (1972) proposed that these difficulties could be circumvented in a coarse-resolution model by including the PBL depth as an explicit prognostic variable. He envisioned a scheme in which the PBL top could migrate freely within the lowest layers of a GCM's vertical grid. The vertically integrated PBL potential temperature, mixing ratio, and wind vector would be determined by an interpolation, and the jumps at the PBL top would be found by an extrapolation. Randall (1976) proposed an elaboration of this approach, in which the jumps were prognostically determined, and were used to infer the bulk structure of the PBL below. This method was tested in the UCLA GCM, and is still being used in the U.S. Navy's operational forecast model (Rosmond, 1981) and in the GCM of the Japanese Meteorological Research Institute.

However, the method is complex and provides only a rather indirect coupling between the parameterised PBL and the other components of the GCM.

A simpler approach that provides a very direct coupling has recently been implemented in the UCLA GCM and published by Suarez et al. (1983). The same approach has been used in a mesoscale model by Deardorff et al. (1984). Some results from the UCLA GCM have been published by Randall et al. (1985). In this approach, the PBL top is made an internal coordinate surface of the GCM. The earth's surface below and a selected isobaric far above are also coordinate surfaces of the model; the vertical coordinate of the model can thus be described as a "generalised sigma coordinate". The PBL consists identically of the lowest GCM layer. In principle, more than one layer could be provided to resolve the internal structure of the PBL but this has not been attempted yet. As the PBL top moves up and down, the coordinate surfaces above the PBL top are squashed and stretched, like the bellows of an accordion.

At first sight, a large-scale dynamicist might view this scheme with alarm. He would envision that this writhing coordinate system inflicts havoc on the motion field. And he might suspect that implementation of the scheme would be very complex, requiring a complete rewrite of his gigantic model code. Experience has shown that these fears are groundless. The purpose of this note is to give a straightforward and practical account of the implementation, advantages, and disadvantages of the generalised sigma coordinate.

2. IMPLEMENTATION

2.1 Dynamics

As discussed by Suarez et al. (1983), the basic governing equations of the GCM as written in the generalised sigma coordinate system differ only slightly from the corresponding equations written in a conventional sigma coordinate system. To convert a sigma model to a generalised sigma model, essentially three changes have to be made.

(a) Quite obviously, the PBL depth must be included as a prognostic variable of the model. The PBL depth can change as a result of lateral mass convergence or divergence, turbulent entrainment, and the loss of PBL mass into cumulus towers. The first process is explicitly resolved by the model, while the second and third processes must be parameterised. In the absence of parameterised processes, the PBL top is a material surface. The effects of the generalised sigma coordinate on the parameterised processes are discussed in Sect. 2.2 below. For computational reasons it is necessary to impose maximum and minimum values on the PBL depth. We currently allow the depth to range between 180 mb and 10 mb.

(b) The vertical motion, "sigma dot", as seen in the generalised sigma system, involves terms representing the rate at which mass crosses the PBL top. For example, if there is no large-scale motion at all but the PBL is gradually deepening due to turbulent entrainment of mass, then the internal coordinate surfaces of the model gradually rise away from the earth's surface. The coordinate surfaces are moving upward relative to the air, and there is a positive sigma dot which decreases linearly with pressure both upward and downward away from the PBL top. This sigma dot field is of course used in the vertical advection terms of the governing equations. In this way, as a given model layer in the free atmosphere moves upward through the troposphere, its properties change to reflect the vertical structure of the sounding. We refer to this as "virtual advection". As explained by Suarez et al. (1983), virtual advection is included in the model by making a simple revision to the computation of sigma dot. The use of sigma dot in the model's vertical advection code is not changed, with one exception. Since jumps in the state variables can occur at the PBL top, the "layer-edge" values used for virtual advection across the PBL top should not be determined through the usual interpolation scheme. In the UCLA GCM, "upstream" values are used. To maintain computational stability, forward time differencing is used for virtual advection at the PBL top. Leapfrog time differencing is used elsewhere. Details are given by Suarez et al, (1983). A further discussion of virtual advection is given in Sect. 3.

(c) One additional term appears in the pressure-gradient force for layers within the PBL only. This addition term is proportional to the gradient of the pressure at the PBL top. Details are given by Suarez et.al (1983).

There are no other changes.

One further consideration is relevant for application in spectral models that use semi-implicit time differencing, however. Such models linearise about a reference state. Use of the generalised sigma coordinate may necessitate redefinition of the reference state. T. Rosmond (personal communication, 1985) has investigated this problem.

2.2 Physics

A GCM's physical parameterisations operate within a vertical column. The physics is presented with a stack of layers whose edges are known pressure surfaces, and whose temperatures, humidities, and winds are also known. To a large extent, therefore, the physics doesn't need to know that the model is using the generalised sigma coordinate; the radiation parameterisation, for example, doesn't care.

For boundary layer and convective processes, however, the generalised coordinate offers a number of important advantages; after all, it is these advantages that motivate the use of the coordinate.

First of all, because the PBL top is the upper boundary of the turbulent layer, all turbulent fluxes vanish above the top. The coordinate surface that marks the PBL top is assumed to lie slightly above the turbulence, so there is no turbulent exchange across this surface. Any sharp features in the sounding at the PBL top (e.g., inversions) are assumed to lie within the layer edge, and their effects on the turbulence are parameterised. This is useful, since anyway in practice it is not possible to resolve these features explicitly, because of inadequate vertical resolution.

The parameterisation of the surface fluxes and the entrainment rate are discussed by Suarez et al. (1983). A further discussion of entrainment is given by Randall (1984). The upper boundary conditions on the turbulent fluxes are determined by the entrainment rate and the properties of the entrained air. When the rate of production of turbulence kinetic energy becomes sufficiently weak relative to the rate of consumption due to surface cooling, the entrainment rate can become strongly negative. This means that the turbulence rapidly collapses, except for a shallow layer very near the earth's surface. During the collapse, the effective mass flux across the PBL top is upward, i.e. sigma dot is negative there.

The UCLA GCM uses the cumulus parameterisation of Arakawa and Schubert (1974). The cumulus clouds are assumed to have their bases at the PBL top, and the air which rises into the clouds starts with the predicted bulk properties of the PBL, i.e., the lowest GCM layer. In this way, the generalised coordinate provides a natural lower boundary condition for the cumulus convection.

The Arakawa-Schubert parameterisation is implemented by adjusting the tropospheric sounding so that the cloud work function does not become appreciably positive for any cloud type. A positive cumulus mass flux tends to reduce the PBL depth, and so it tends to make sigma dot negative at the PBL top. Within the generalised sigma system, virtual advection therefore occurs. This virtual advection must be taken into account in determining the cloud work function of the adjusted state. This has been done in the version of the Arakawa-Schubert code that is used in the UCLA GCM.

Further details of the physical parameterisations and their use with the generalised sigma coordinate are given by Suarez et al. (1983).

3. FURTHER DISCUSSION

3.1 Pseudo-mountains

On a given time step, the PBL depth has a rich geographical structure. With the generalised sigma coordinate, the coordinate surfaces of the model are pushed up where the PBL is deep and pulled down where it is shallow. The effects of the spatial variability of the PBL depth on the generalised sigma coordinate surfaces are thus analogous to the effects of mountains on conventional sigma surfaces. As is well known, computational problems can arise in determining the pressure-gradient force in the vicinity of steep mountains, when using the conventional sigma coordinate. Analogous problems can occur when the PBL depth is highly variable and the generalised sigma coordinate is used. Three comments are in order:

(a) A carefully designed vertical differencing scheme can minimise these problems.

(b) In simulations with the UCLA GCM, we have not noticed any difficulties that are attributable to such problems.

(c) Over real mountains, the PBL top pressure tends to be less variable than the surface pressure (Deardorff et al, 1984). Therefore, use of the generalised sigma coordinate can actually improve the accuracy of the pressure gradient calculation over mountainous regions.

3.2 More about virtual advection

To gain a better understanding of the effects of virtual advection on the dynamics, it is useful to consider some special cases.

No mass flux across the PBL top

If the PBL top is a material surface, changes in the PBL depth are due solely to lateral convergence or divergence of mass. There is no virtual advection at any level. If convergence causes the PBL to deepen (say), the coordinate surfaces above the PBL are pushed up, so the geopotential height of each surface increases and the pressure on each surface decreases. True vertical motion occurs. The coordinate surfaces nearest the PBL top move almost as material surfaces, which those furthest away are nearly isobaric. In principle the circulation can be adiabatic and frictionless.

Positive entrainment

Turbulent deepening of the PBL also causes the coordinate surfaces to move upward, so again the geopotential height of each surface increases and the pressure of each surface decreases. However, in this case the movement of the coordinate surfaces is caused by a non-adiabatic, frictional process, namely turbulent entrainment. The entrainment tends to decrease the kinetic energy of the mean flow, and to increase the potential energy.

Negative entrainment

As discussed in Sect. 2.2, negative entrainment is due to the collapse of the turbulent layer; motions which have been turbulent become laminar. This is not an essentially nonadiabatic or frictional process.

Cumulus mass flux with positive entrainment

Both cumulus activity and positive entrainment cause virtual advection. However, these two mass fluxes across the PBL top are in opposing directions. Because of the existence of jumps at the PBL top, the cumulus clouds remove air with PBL properties, while entrainment adds air with the properties of the free atmosphere. Therefore, the two virtual advections should be treated separately at the PBL top. Both should be "upstream", but in opposing directions. At levels above the PBL top, no "jumps" occur, so the two types of virtual advection transport air with the same layer-edge properties, and they can be treated as one.

4. CONCLUDING REMARKS

Use of the generalised sigma coordinate allows a boundary layer parameterisation to take full advantage of current understanding of entrainment and the effects of cloud layers in the PBL. It also allows a simple and direct coupling between the PBL and cumulus parameterisations. It does not greatly alter the basic governing equations of the GCM, nor does it entail sweeping changes to the computer codes used to solve those equations. Actual experience with the UCLA GCM has shown that use of the coordinate does not trigger any serious numerical problems.

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