Chapter 14

Representation of Clear and Cloudy Boundary Layers in Climate Models

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Abstract

The atmospheric general circulation models which are being used as components of climate models rely on their boundary layer parameterizations to produce realistic simulations of the surface turbulent fluxes of sensible heat, moisture, and momentum; of the boundary-layer depth over which these fluxes converge; of boundary-layer cloudiness; and of the interactions of the boundary layer with the deep convective clouds that grow upwards from it. Two current atmospheric general circulation models are used as examples to show how these requirements are being addressed; these are version 3 of the Community Climate Model, which has been developed at the U. S. National Center for Atmospheric Research, and the Colorado State University atmospheric general circulation model. The formulations and results of both models are discussed. Finally, areas for future research are suggested.

1 Introduction

From their origins around 1960 up through about the late 1980s, atmospheric général circulation models (AGCMs) were used mainly with fixed, prescribed sea surface temperatures. Although coupled global ocean-atmosphere models were developed in the late 1960s (Manabe and Bryan, 1969), they did not really come into their own until the late 1980s. Today, however, coupled ocean-atmosphere modeling is a very active field (e.g. Mechoso et al. 1995), particularly for climate simulation, and to some extent even in the arena of numerical weather prediction (e.g. Chen et al., 1997).

The first AGCMs were coupled with very crude representations of the land surface. This has now drastically changed; through the work of Dickinson (1983), Sellers et al. (1986), and others, relatively sophisticated land-surface parameterizations have been implemented in many modern AGCMs; see the review by Sellers et al. (1997).

The new coupled ocean-land surface-atmosphere models are making major new demands on the planetary boundary layer (PBL) parameterizations that are used in AGCMs, because the turbulence of the PBL is one of the most important modes of communication between the Earth's surface and the atmosphere. This increased importance and visibility of the parameterized PBL physics in climate models represents a major challenge to the PBL parameterization community: to bring forth a new generation of PBL parameterizations with improved physics and improved numerics, suitable for use with the new, very demanding, and rapidly evolving coupled models.

The purpose of this chapter is to discuss current approaches to PBL parameterization for climate models, and to suggest what directions may be followed in the future. Section 2 summarizes the main issues that arise in connection with the development of PBL parameterizations for climate models. Section 3 presents two examples of PBL parameterizations used in current AGCMs, including an outline of the formulation and a few results from each. The first model is version 3 of the Community Climate Model (CCM3) developed at the National Center for Atmospheric Research (NCAR), and the second is the Colorado State University (CSU) AGCM. Both CCM3 and the CSU-AGCM have been coupled with ocean models, and both have modern land-surface parameterizations; the results presented here are based on runs in which the sea surface temperatures are prescribed, however. Space limitations do not allow a comprehensive discussion, so just a few selected results from each model are shown. Section 4 outlines some current issues and possible directions for development of future PBL parameterizations, and gives the chapter's conclusions.

2 Physical and numerical issues

2.1 The surface fluxes

The most obvious "job" of a PBL parameterization is to determine the surface fluxes of sensible heat, moisture, and momentum, and in some models additional species such as CO_2 (e.g. Denning et al. 1996). In virtually all AGCMs, these surface fluxes are parameterized using a method that is consistent with if not explicitly based on surface-layer (i.e. Monin-Obukhov) similarity theory. Some models use surface-layer similarity theory directly, while others use it implicitly by tying the surface fluxes to the winds, temperature, etcetera in the "outer" part of the PBL. Examples of both approaches are given later.

2.2 Flux profiles, the PBL depth, and vertical discretization

The top of the PBL is, by definition, the upper limit of the turbulent fluxes, although there is some ambiguity; tradewind cumulus clouds, for example, might or might not be considered to reside within the PBL. The most obvious reason to want to know the PBL depth is that the turbulent fluxes vanish above the PBL top. Every AGCM determines the flux profiles in one way or another (although in some cases with very crude vertical resolution), so in this sense we can say that every AGCM determines the PBL depth, at least implicitly and semi-quantitatively. Some models determine the PBL depth explicitly and quantitatively; that is the case with both of the models discussed later in this paper.

A second reason for wanting to know the PBL depth is that, for given values of the surface fluxes, a deep PBL will experience slower (vertically averaged) tendencies than a shallow PBL, simply because in a deep PBL the surface fluxes have to exert their influence over more mass.

The PBL depth is known to be highly variable in space and time, but at present we do not have anything like an observationally based global climatology of this important quantity. There is some evidence that over the oceans the PBL tends to be particularly deep when cold air flows out over warm water, e.g. over the Gulf Stream in winter. There is also some evidence that the PBL is relatively shallow in regions of active oceanic deep convection (Menzies and Tratt, 1997). Over land, especially in the tropics and in midlatitudes in summer, the PBL depth typically undergoes a very strong diurnal cycle, with surface heating leading to rapid deepening during the day to afternoon depths which can be as large as several kilometers. Around sunset, as surface heating subsides, the PBL rapidly reorganizes itself into a much shallower turbulent layer near the surface. This layer gradually deepens during the night under the influence of shear-driven turbulence. This strong diurnal cycle of the PBL depth over land represents a particularly difficult challenge for large-scale numerical models, which typically have modest vertical resolution. Further discussion is given later.

We can predict the PBL depth by using a mean (M) mass budget equation:

$$\frac{\partial}{\partial t}(\rho_M h) + \nabla \cdot [(\rho \mathbf{V})_M h] = E - M_B. \tag{1}$$

Here ρ is the density of the air; h is the PBL depth; $\mathbf{V}$ is the horizontal wind vector; E is the rate at which turbulence annexes mass from the free atmosphere, by entrainment across the PBL top; and M_B is the net rate at which cumulus convection removes mass from the PBL, which is the difference between the rate at which mass is lost into cumulus updrafts originating in the PBL and the rate at which mass is gained through cumulus downdrafts which penetrate the PBL from above. Because Eq. (1) is simply a mass budget, it is exact, and in principle the simulated PBL depth should satisfy (1) in any and all models.

Both E and M_B must be parameterized. In some models these parameters are parameterized very explicitly, while in others the time evolution of the PBL depth can be used to infer implicit values. The problem of parameterizing the entrainment rate is covered extensively elsewhere in this volume, and so will not be discussed here. We note, however, that entrainment is a "one-way" process in which mass is transferred from the free atmosphere into the PBL; it cannot be well represented by mixing.

In a numerical model with a vertically discrete structure, the turbulent fluxes of sensible heat, moisture, and momentum must be determined at the surface and also at any "layer edges" that happen to lie inside the PBL. One way to minimize the impact of this requirement is to make the lowest model layer deep enough so that all layer edges (except of course for the bottom of the lowest layer) lie above the PBL top. Such a strategy may appear not to be viable, however, because in order to determine the surface fluxes we need to know the mean state near the surface, and this becomes impossible if the lowest layer is excessively deep. As discussed later, this problem can be circumvented if the lowest vertically discrete model layer is identically the variable-depth PBL. At any rate, one way or another we must provide sufficient vertical resolution [1] to represent the flux profiles and mean state within the PBL itself. For this reason, the flux profiles, the PBL depth, and the vertical resolution of a model must be considered together in the formulation of the model's design, and this is why we are discussing these three items together in this section.

Going to the opposite extreme, then, a modeler could use very high vertical resolution near the surface, perhaps over the lowest two or three kilometers, so that the internal structure of the PBL would be represented by many layers. It would then be necessary to compute the turbulent fluxes across the edges of all those layers; if the fluxes could not be determined accurately, the additional layers would be wasted. In other words, high vertical resolution makes sense only if the flux profiles can be accurately determined. More generally, the vertical resolution adopted should not exceed that which the flux parameterization can make good use of.

At present, "high-resolution" AGCMs have on the order of 50 total layers, of which perhaps 30 or so reside in the troposphere. Current AGCMs with low to moderate vertical resolutions (on the order of 20 layers to rep-

[1] Of course, high vertical resolution is also desirable from many other points of view (e.g. Lindzen and Fox Rabinovitz, 1989).

resent the troposphere, with perhaps four or five layers in the lowest two or three kilometers) commonly use mixing-length theory, in some cases with a "counter-gradient" correction (e.g. Deardorff, 1966; Holtslag and Boville, 1993). An example is CCM3, discussed later. In a high-vertical-resolution AGCM, a relatively elaborate turbulence parameterization, such as third-order closure, could be used to determine the vertical profiles of the turbulent fluxes. Simpler high-order closure parameterizations are in fact being used in some AGCMs (e.g. Helfand and Labraga, 1988). In one-dimensional models, such closures are typically used with vertical grid spacings on the order of 10 to 50 meters, however, and such high vertical resolution will not be feasible in global models, and especially in global climate models, for the foreseeable future.

Why is such high vertical resolution needed? The reason is that the PBL top is often marked by extremely sharp, almost discontinuous changes in both the mean state and the turbulent fluxes. Away from the PBL top, both the mean state and the turbulent fluxes change smoothly with height, so that relatively coarse resolution would suffice. This suggests the possibility of using high resolution only near the PBL top. The problem with this approach, of course, is that because the depth of the PBL is highly variable in time and space, we have no way of knowing in advance where to provide the high resolution. Adaptive grid methods could be used, but this would be complicated and might generate more problems than it solved.

A possible solution, which was suggested by Deardorff (1972), is to introduce the depth of the PBL as an explicit parameter, either diagnostic or prognostic (Deardorff proposed prognostic), using information about both the turbulent fluxes and the profile of the mean state as represented on the AGCM's vertical grid. As already mentioned, both of the AGCMs discussed later in this paper determine the PBL depth explicitly.

In an AGCM with a standard Eulerian vertical grid, the top of the PBL can wander around inside the vertical grid. This approach is used with CCM3, and it was also tested in an early version of the UCLA (University of California, Los Angeles) AGCM by Randall (1976). A more radical approach is to explicitly tie the AGCM's vertical grid structure to the depth of the PBL, through the use of a stretched vertical coordinate. The stretched coordinate approach was implemented in the UCLA AGCM by Suarez et al. (1983), and is also being used in the CSU-AGCM, which is described in Section 5. With the stretched vertical coordinate, it would be feasible in principle to represent the smooth structure of the PBL's interior using just a few layers – perhaps 4 or 5. At present, however, both the UCLA and CSU-AGCMs allocate only one layer to the PBL, and this layer is assumed to be well mixed.

2.3 PBL clouds

The PBL physics community has long appreciated the importance of boundary-layer clouds and their interactions with the PBL turbulence (e.g. Lilly, 1968). The coupled ocean-atmosphere modeling community now recognizes that a realistic simulation of marine stratocumulus clouds is a necessary condition for realistic simulations of the sea surface temperature distribution (e.g. Li and Philander, 1996; Ma et al., 1996). At present, many AGCMs still fail to produce realistic distributions of marine stratocumulus clouds.

The trade-wind cumulus cloud regime, which covers about 30% of the Earth's surface, is also of great importance for climate, both because of the role of the trade cumuli in producing vertical transports below the trade inversion, and because of the radiative effects of these clouds. The tradewind regime is characterized by cloud amounts on the order of 20 to 30%, which is considerably less than the cloudiness of the stratocumulus regime, but still high enough to be of great radiative importance. Because the tradewind regime is so wide-spread, its accurate simulation is very important for coupled ocean-atmosphere modeling. Unfortunately, physically based parameterizations of tradewind cumulus clouds, designed for use in AGCMs, are currently at a very primitive stage.

2.4 Interactions with deep convection

Deep cumulus and cumulonimbus clouds typically grow upwards from the PBL. (Exceptions are discussed by Ding and Randall (1998).) As already mentioned in connection with Eq. (1), convective updrafts drain mass from the PBL and so tend to reduce its depth (Arakawa and Schubert, 1974); this tendency can be opposed by, for example, turbulent entrainment and low-level convergence, yielding an equilibrium on time-averaged PBL depth which is partly determined by the level of convective activity.

Betts (1976) pointed out that the mean thermodynamic structure of the PBL is radically transformed by the downdrafts associated with deep convection. Jabouille et al. (1996) have recently reported observations of enhanced surface fluxes associated with deep convection during TOGA COARE. A few current AGCMs include parameterizations of convective downdrafts (e.g. Cheng and Arakawa, 1997), but up to now these parameterizations have stressed the effects of downdrafts on the convective heating and moistening in the free atmosphere, rather than their effects on the PBL. The effects of cumulus downdrafts on the PBL is an important area for future research.

3 Two examples of current PBL parameterizations

3.1 Model formulations

In this section, we outline the formulations of the PBL parameterizations and present some results from CCM3 and from the Colorado State University AGCM. An extensive analysis of a PBL simulation with a much earlier version of the CSU-AGCM was published by Randall et al. (1985). A discussion of the recent evolution of the CSU-AGCM's formulation is given by Randall et al. (1995). As discussed below, both CCM3 and CSU-AGCM make use of an explicit PBL depth variable.

In CCM3, the surface fluxes of heat, moisture and momentum are parameterized using bulk exchange formulae based on Monin-Obukhov similarity theory, following Louis et al. (1982). The surface transfer coefficients depend on the surface-layer stability and the surface roughness lengths. Separate surface roughness lengths are defined for momentum, heat, and moisture. These vary with surface conditions and with surface type.

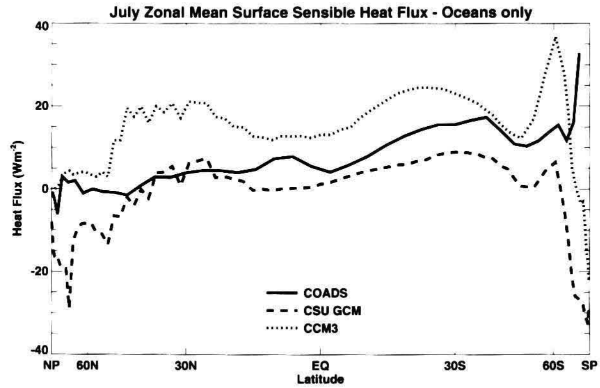
The CSU-AGCM currently uses the surface flux parameterization proposed by Deardorff (1972), in which the bulk aerodynamic formulae relate the surface fluxes to the differences between surface properties and the vertically averaged properties of the PBL. A similar approach has recently been advocated by Stull (1994). The surface roughness varies with surface type in the model, but the variation of roughness with wind speed over the ocean is neglected. Deardorff's (1972) parameterization does not distinguish among the roughness lengths for momentum, sensible heat, and moisture; all are assumed to be equal to the roughness length for momentum. Clearly it is time to replace the 25-year old Deardorff parameterization, and some ideas on how to proceed are discussed, briefly, later in this paper.

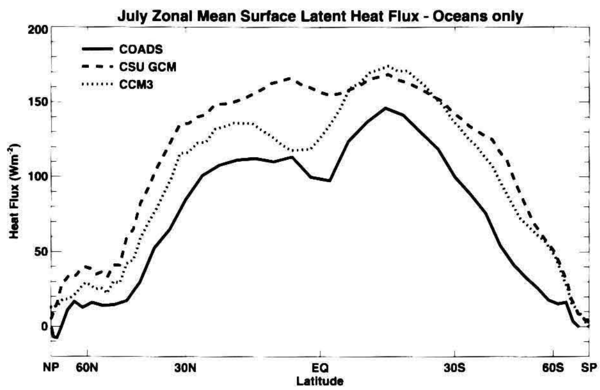
In CCM3, the flux profiles are parameterized using a non-local vertical diffusion scheme for potential temperature and moisture (Holtslag and Moeng, 1991), and a local diffusion scheme for momentum. The diffusion coefficients are cubic polynomials in height (Troen and Mahrt, 1986; Holtslag et al., 1990).

The PBL depth is diagnosed in CCM3, following Vogelezang and Holtslag (1996), by requiring that a bulk Richardson number be equal to a specified critical value:

$$\frac{g\left[\theta_v(h)-\theta_{sL}\right](h-z_s)}{\theta_{sL}\left[u(h)-u_{sL}\right]^2\left[v(h)-v_{sL}\right]^2+Bu_*^2}=R_{i_{cr}}. \tag{2}$$

Here $R_{i_{cr}}=0.3$ is the critical bulk Richardson number; z_s is the height above the surface of the lowest model level, where the wind components u_{sL}, v_{sL} and the virtual potential temperature θ_{sL} are defined; and h is the PBL-top height, where the wind components $u(h)$, $v(h)$ and the virtual potential temperature





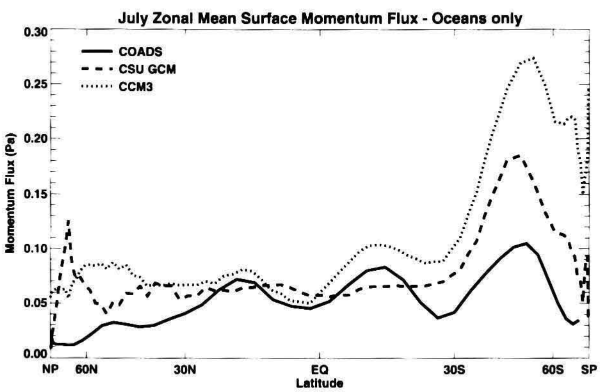


Fig. 1. The zonally averaged July surface sensible heat flux, surface latent heat flux, and the surface momentum flux (magnitude), as given by the COADS dataset, and as simulated by CCM3 and the CSU-AGCM.

$\theta_v(h)$ are defined. The constant $B = 100$, and u_* is the surface friction velocity. Note that h appears both explicitly and implicitly in (2), which must, therefore, be solved iteratively. CCM3 does not include an explicit parameterization of PBL-top entrainment. The model does include the effects of entrainment implicitly, through the action of the non-local diffusion parameterization. The cumulus mass flux and low-level convergence fields can also alter the PBL depth in CCM3, although it is not clear how to interpret the tendency of the simulated PBL depth in terms of Eq. (1). This question could be investigated by differentiating (2) to obtain an expression for the time-rate-of-change of h, but the analysis would be rather complicated.

The CSU-AGCM uses the stretched vertical coordinate developed by Suarez et al. (1983) to attach the PBL top to the AGCM's vertical coordinate system, so that the PBL top is a layer edge. At present, only one layer of the AGCM is allocated within the PBL, i.e. the PBL is identified with the lowest model layer; it is assumed to be vertically well mixed in suitably defined conservative thermodynamic variables, and in momentum. The CSU-AGCM uses Eq. (1) to prognose the depth of the PBL. The entrainment parameterization of the model will not be described in detail here, because an extended discussion would be needed to explain it. We note, however, that the parameterized entrainment rate is proportional to the square root of the prognostically determined TKE, and becomes slower as the PBL-capping inversion becomes sharper. The entrainment rate is modified in the presence of clouds by the cloud-top radiative cooling and by cloud-top evaporative cooling. Both radiative and evaporative cooling tend to reduce the positive buoyancy of newly entrained air as it sinks through the inversion base. The parameterization used is broadly consistent with the ideas of Moeng et al. (1998). Because, as mentioned above, the PBL is identified with the lowest layer of the AGCM, it is not necessary to determine the turbulent fluxes at layer edges inside the PBL; no such layer edges exist. The flux profiles are needed to predict the vertically averaged TKE, however, and the mixed-layer assumption is used to determine them.

The parameterized PBL clouds included in CCM3 include frontal and tropical low clouds, as well as the marine stratus clouds associated with low-level inversions mainly in the subtropics. The cloud formation schemes are empirical, involving the relative humidity and large-scale subsidence for frontal and tropical low clouds, and the relative humidity, inversion strength and PBL depth for subtropical stratus clouds. In CCM3, PBL clouds do not directly affect any parameterized turbulent process. For example, cloud formation does not directly affect the diagnosed PBL depth. Clouds, however, can indirectly affect the PBL depth by altering the thermodynamic profiles of the mean state. It should be possible to modify Eq. (2) so as to take the effects of PBL clouds into account.

The CSU-AGCM detects the presence of stratocumulus clouds when the relative humidity at the PBL top exceeds saturation, as determined through the mixed-layer assumption. Partial cloudiness is not allowed. The cloud base is assumed to reside where the relative humidity is exactly 100%; the mixed-layer assumption is used again here. The effects of PBL clouds on entrainment have already been discussed, above. In general, PBL clouds tend to increase the depth of the PBL.

The CSU-AGCM uses a modified Arakawa-Schubert (1974) cumulus parameterization, in which the cumulus kinetic energy is prognostic (Randall and Pan, 1993; Pan and Randall, 1998), and cumulus cloud bases are permitted to exist at any and all model levels (except for the top level) simultaneously (Ding and Randall, 1998). This cumulus parameterization is based on the concept of a cumulus mass flux. The closure assures that the cumuli maintain a near-neutral stratification, with respect to the parameterized moist convection. The net cumulus mass flux at the PBL top tends to reduce the PBL depth, as required by Eq. (1). At present, cumulus downdrafts are not included in the model, so the net cumulus mass flux is due to updrafts only. The cumulus updrafts are assumed to start with the mean properties of the PBL air, so that they have no effect on the vertically averaged PBL properties other than the PBL depth.

Penetrative convection originating near the surface is parameterized in CCM3 using the Zhang-McFarlane deep convection scheme (Zhang and McFarlane, 1995), with Hack's (1994) moist convective scheme included for shallow convection and also for convective clouds originating aloft. Like the Arakawa-Schubert parameterization, the Zhang-McFarlane and Hack parameterizations are based on the concept of a cumulus mass flux, and use buoyancy closures. As already mentioned CCM3 does not provide any explicit way for either low-level convergence or cumulus convection to influence the depth of the PBL.

Neither AGCM includes a parameterization of the effects of deep convection on the surface fluxes.

3.2 Results

The model results presented below are based on a July simulation using CCM3 using T42 (i.e. moderate) horizontal resolution, with 18 layers, and a July simulation using the CSU-AGCM, with a horizontal resolution of 5 degrees of longitude by 4 degrees of latitude, and 17 levels.

Fig. 1 shows the global distributions of the surface sensible and latent heat fluxes and the magnitude of the surface wind stress. CCM3 generally over-predicts the surface sensible heat flux, compared with COADS (Da Silva et al. 1994), while the CSU-AGCM generally under-predicts it. Both models over-predict the surface latent heat flux compared with COADS, although the CSU-AGCM's error is larger. The magnitude of the subtropical wind stress is underpredicted by the CSU model, and is much more successfully simulated by the CCM. The CCM predicts wind stresses over the "Southern Ocean"

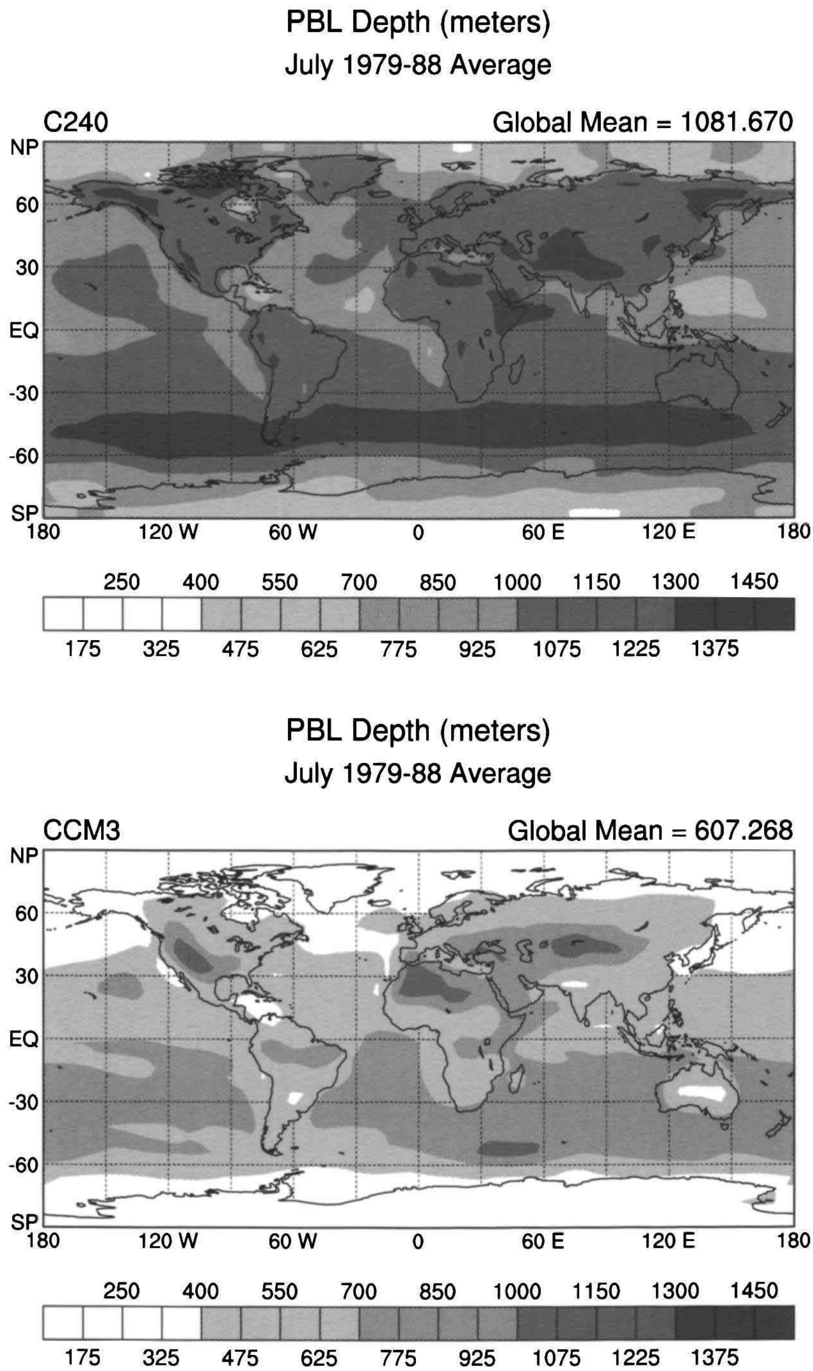


Fig. 2. Maps of July-mean PBL depth as simulated by CCM3 and the CSU-AGCM.

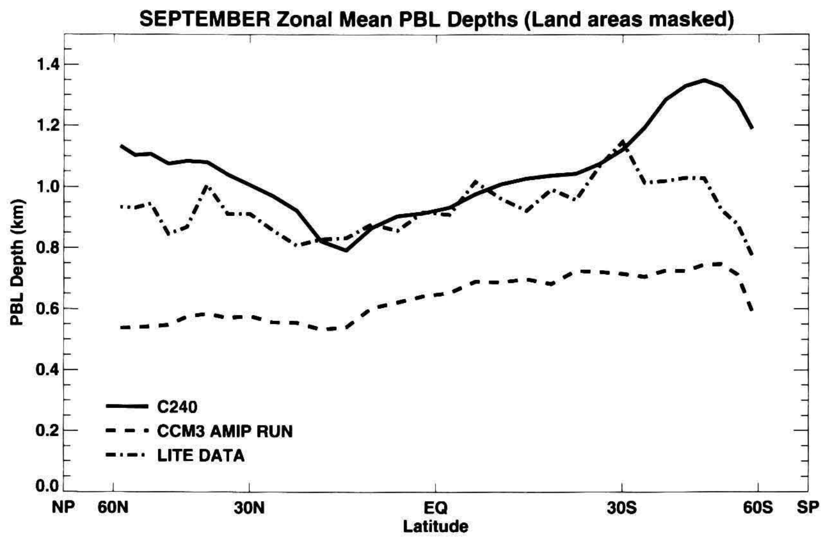


Fig. 3. The zonally averaged simulated and observed PBL depth, for ocean regions only. LITE (dash-dot), CSU-AGCM (solid) and CCM3 (dashed).

(north of Antarctica) which are well in excess of those given in the COADS dataset. We know, however, that the COADS data for the Southern Ocean must be viewed with suspicion, due to insufficient sampling, and more recent scatterometer data (not shown) suggest that the CCM wind stresses for the Southern Ocean may in fact be realistic, in which case the CSU model is underpredicting the wind stress in this region as well.

Fig. 2 shows maps of the July-mean PBL depth from CCM3 and the CSU-AGCM. Overall, the CSU-GCM produces a much deeper PBL than does CCM3. Nevertheless there are some striking similarities. For example, both models produce relatively shallow boundary layers over the eastern subtropical oceans, and both produce relatively deep boundary layers over the desert regions of Africa, Asia, and North America. The top of the PBL in the CSU-AGCM, over the subtropical oceans, appears to correspond to the height of the tradewind inversion, rather than the top of the subcloud layer.

It is quite difficult to obtain observations for comparison with these model results, but some progress is being made. In September 1994, a downward-pointing lidar was flown in the payload bay of the space shuttle Discovery, which was traveling in an orbit with an inclination of 57 °. This Lidar In-space Technology Experiment (LITE) made use of a three-wavelength lidar developed by NASA's Langley Research Center. Over a period of 9 days, the instrument collected a large number of data profiles that show the vertical structure of the clouds and aerosols from the Earth's surface up through the middle stratosphere. McCormick et al. (1993) and Winker et al. (1996) give detailed discussions of the LITE instrument and data. Analysis of the lidar backscatter profiles reveals, in many cases, a sharp aerosol gradient at the top of the PBL, allowing determination of the PBL depth.

Although the LITE dataset is too small to establish anything like a climatology of the PBL depth, there are so few measurements available that we have worked to compare the data with the simulated September-mean PBL depth climatologies produced by CCM3 and the CSU-AGCM. Fig. 3 is a plot of the zonally averaged PBL depth over the oceans only, as observed and as simulated by the CSU-AGCM and CCM3. Overall, CCM3 produces a shallower PBL than observed, while the results from the CSU-AGCM are in fair agreement with the observations. Remember that the boundary-layer formulation in CCM3 does not include the effect of clouds on the boundary-layer depth. The observations exhibit a minimum in the tropics between roughly 0°N and 25°N, and maxima in the subtropics just poleward of 30° in each hemisphere. A tropical minimum also appeared in results from NASA's Global Backscatter Experiment (GLOBE), which collected lidar measurements from aircraft over the Pacific Ocean in 1989-90 (Menzies and Tratt, 1997). This minimum may be a result of the moist convective activity associated with the ITCZ; certainly this is the case in the CSU-AGCM. The CSU model tends to produce excessively deep boundary layers over the Southern Hemisphere's storm track region and to some extent also in the Northern Hemisphere storm tracks.

The PBL depth can affect the PBL-top relative humidity, and thus it can affect the PBL cloudiness. All other things being equal, a deeper PBL is more likely to be cloudy. Fig. 4 shows the low cloud amounts from surface observations (Warren et al. 1988), as simulated by CCM3, and as simulated by the CSU-AGCM. Both models under-predict the stratocumulus cloud amount in the subtropics, but produce more realistic low cloudiness in higher latitudes.

It is important that AGCMs be able to simulate not only the climatological distribution of marine stratocumulus clouds, but also the interannual variations of these clouds that are associated with the interannual variability of sea surface temperature and the atmospheric general circulation, e.g. during El Niño events. With this in mind, we have examined the interannual variations of the simulated and observed marine subtropical stratocumulus clouds for a region off western South America. The CSU-AGCM results are taken from an AMIP simulation (Gates, 1992) with prescribed sea surface temperatures for the years 1979-1988. The observations used are from ISCCP (the International Satellite Cloud Climatology Project; Rossow and Schiffer, 1991), which began producing data in 1983. The results, shown in Fig. 5, indicate that the CSU-AGCM is capable of reproducing some of the observed interannual variability of PBL cloudiness, as forced by sea surface temperature variations.

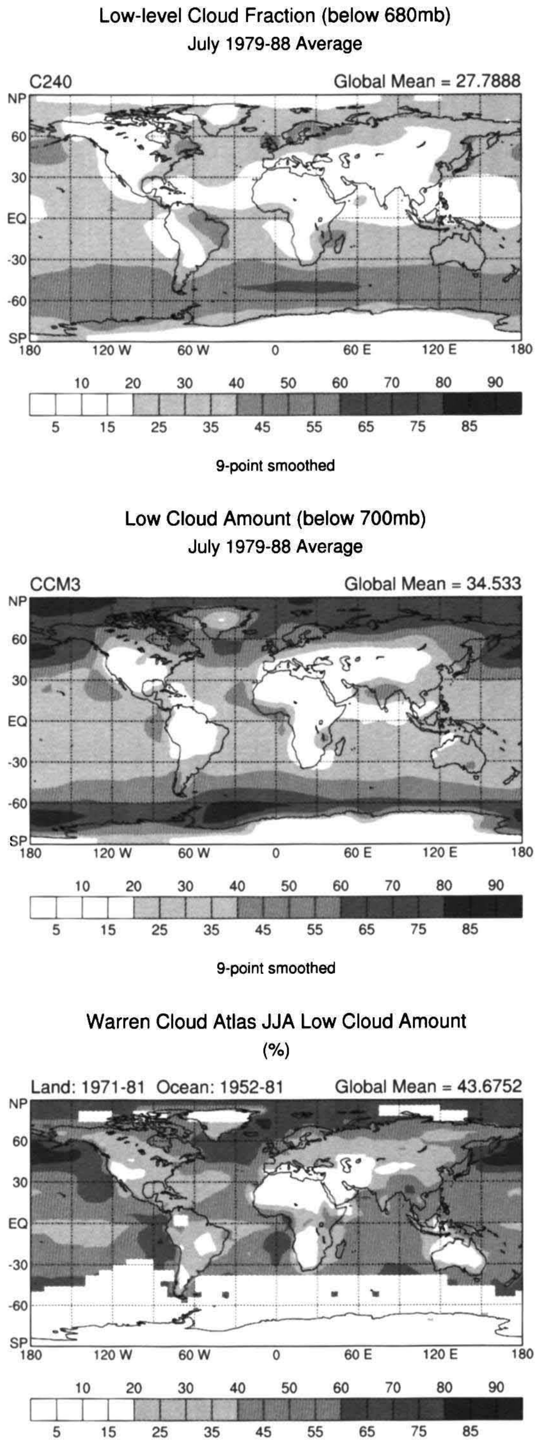


Fig. 4. Maps of July-mean low cloud amount as obtained from surface observations (Warren et al., 1988), and as simulated by the CCM3 and the CSU-AGCM

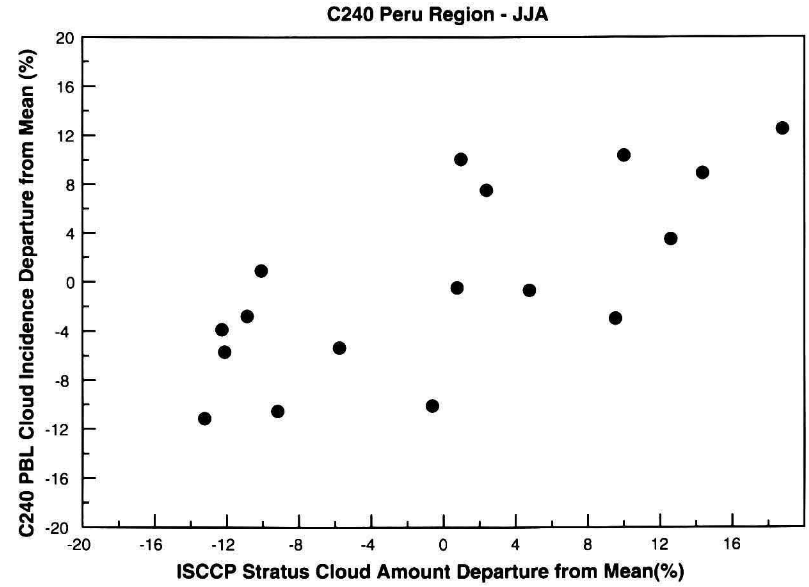


Fig. 5. The simulated and observed interannual variations of the June-July-August marine subtropical for a region off western South America. The observations are from ISCCP, and the simulation was performed with the CSU-AGCM, using observed interannually varying sea surface temperatures.

4 Concluding discussion

4.1 Summary

We have emphasized four key issues in formulating a PBL parameterization for use in the AGCM component of a climate model: surface flux parameterization, determination of the PBL depth and the vertical profiles of the fluxes and the mean state within the PBL, simulation of the effects of PBL clouds, and parameterization of the interactions of the PBL with deep convection.

CCM3 and the CSU-AGCM both attempt to simulate the same list of important boundary-layer processes, but they do so by very different means. CCM3 diagnoses the PBL depth, while the CSU-AGCM prognoses it. Nevertheless it is worth noting that both of these models make explicit use of a PBL depth parameter; the benefits of this approach were discussed earlier.

CCM3 can crudely represent the internal vertical structure of the PBL using its nonlocal flux parameterization, while the CSU-AGCM makes use of an idealized mixed-layer assumption. Both models produce PBL clouds, but their interactions with the PBL turbulence are neglected in CCM3 and included in the CSU-AGCM. Both models allow deep convection to originate in the PBL, but the effects of this process on the PBL depth are neglected in CCM3 and included in the CSU-AGCM.

Our analysis suggests that interactions of the surface fluxes, PBL dynamics, clouds, and convection are closely coupled in an AGCM. Their interaction has to be considered in an integrated PBL parameterization for use in climate models.

4.2 New directions and recommendations

We need new approaches to the parameterization of the profiles of the turbulent fluxes and the mean state within the PBL. For example, Zhang et al. (1996) presented a surface flux parameterization in which the square root of the turbulence kinetic energy is used as a velocity scale in the bulk aerodynamic formula, in place of the mean wind. The surface potential temperature flux is determined using

$$(\overline{w\prime\theta\prime})_S = e_M^{1/2} \cdot C_T \cdot (\theta_S - \theta_M), \qquad (3)$$

where e_M is the vertically averaged turbulence kinetic energy, C_T is a transfer coefficient, θ_S is the effective potential temperature of the Earth's surface, and θ_M is the vertically averaged potential temperature of the PBL. Relative to more conventional bulk aerodynamic formulae, Eq. (5) has the advantage that it ties the turbulent fluxes directly to the turbulence, rather than to the mean wind; for this reason, it behaves well in the limit of very weak mean winds. It also allows the cloud-strengthened turbulence of a cloud-topped PBL to affect the surface fluxes, through a larger value of e_M; whether or not this is realistic is an interesting question worth pursuing.

A "mass flux" approach to turbulent flux parameterization, similar to that used in cumulus parameterizations, was advocated by Penc and Albrecht (1986) and Chatfield and Brost (1987). Randall et al. (1992) have shown how the convective mass flux formalism can be combined with higher-order closure to yield a new nonlocal flux parameterization. This "second-order bulk model" can produce either downgradient or countergradient fluxes, depending on the turbulence regime. It can be implemented in the framework of the stretched vertical coordinate (Suarez et al. 1983), perhaps incorporating some of the ideas of Otte and Wyngaard (1996). Further work is currently under way to test the second-order bulk model against several datasets.

Over the past several years, there has been renewed interest in the use of isentropic coordinates in large-scale models (e.g. Bleck, 1973; Johnson and Uccellini, 1983; Hsu, and Arakawa, 1990; Bleck and Benjamin, 1993; Zapotocny et al., 1994; Heikes and Randall, 1996). Models that use isentropic vertical coordinates have accommodated the fact that the PBL is often well mixed in potential temperature. Bleck et al. (1989), working with an ocean model based on an isopycnal coordinate, introduced an explicit ocean mixed layer depth, and allowed the isopycnal layers to become "massless" along the base of the mixed layer. A similar approach can be used in an atmospheric model. This would be an interesting direction in which to take the "stretched" coordinate approach.

There are many difficult unsolved problems involving the parameterization of PBL clouds; here we mention only two.

First, we need a better understanding of the effects of evaporative cooling on PBL-top entrainment. It is clear that evaporative cooling of the entrained air can increase the entrainment rate, but the mechanisms are not well understood. It is difficult to test proposed entrainment parameterizations against data because the entrainment rate is very difficult to measure accurately. Large-eddy simulations can be used as substitutes for the real atmosphere, but caution is needed because in many studies involving entrainment different LES models give different results.

The parameterization of the effects of fractional PBL cloudiness is another long-standing problem (e.g. Randall, 1987; Ricard and Royer, 1993). The importance of cloudiness in coupled ocean-land surface-atmosphere models argues for a new urgency in our quest for a solution to this problem.

We need a way to simulate the convection-enhanced surface fluxes reported by Jabouille et al. (1996). This might be accomplished by generalizing (3) to take into account the stronger TKE associated with downdraft outflows from deep convection. Of course, it will also be necessary to take into account the downdraft-enhanced variability of the temperature and humidity in the PBL.

We also need to provide more realistic lower boundary conditions for deep convection parameterizations. Recently, Lin (1997) has used a cloud-resolving model to show that the air removed from the PBL by deep convection has properties significantly different from the average properties of the PBL; this implies that the convective updrafts can directly influence the mean thermodynamic state of the PBL. Further work is needed to establish the importance of this effect for the climate system.

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