N87-22350

PHYSICAL MECHANISMS OF HEAT, MOMENTUM, AND TURBULENCE FLUXES

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This paper discusses, in a qualitative way, the physical mechanisms which generate fluxes of heat, momentum, and turbulence in the atmosphere. This material is presented to acquaint those people in attendance at the workshop who normally are involved in the aviation aspects of turbulence with the Earth science aspects of turbulence as important processes in the atmosphere.

To attempt to describe turbulent fluxes of heat, momentum, and moisture in precise mathematical detail becomes an intractable problem. It is burdened by an eighth order set of equations involving more variables than equations. It is a closure problem which requires complicated assumptions that are not necessarily always satisfied, variable boundary conditions, and sparse observational data. Therefore, we must approach the problem in a simplified manner to obtain any kind of solution involving the variables of shear, stress, and heat, moisture, and momentum fluxes. In general, the planetary boundary layer is small in comparison to the total depth of the atmosphere. Thus, in models which attempt to describe the entire atmosphere (for example, general circulation models), the planetary boundary layer can be ignored entirely because it does exert a fairly small influence over a short time scale. However, after about 12 hours or more, the dissipation processes in the planetary boundary layer become noticeable and when the model is applied to longer and longer forecast time periods of up to a week or ten days (as is now being done in Europe), then these effects must be included. They become very important in models describing the long-term behavior of the atmosphere, especially climate models.

There are other problems, of course, in which the inclusion of the planetary boundary layer is extremely important. Air pollution studies, air-sea exchanges, mesoscale models, and so on, must account for the planetary layer in very specific terms. Some of the physical mechanisms that are involved in generating fluxes are described in the following.

Figure 1 illustrates the scales of size and motion that are important in the generation of fluxes in the atmosphere (after Brown [1]). The top part of the figure shows the depth of the entire tropopause to be on the order of 10 to 20 km and the mixed layer depth about 1 km. An expanded view of the lowest kilometer shows this to be the level of the typical inversion (at 1 to 1.5 km), or the layer below which there is complete mixing with more or less stratified flow above. The important dimensions here in terms of roughness are of the order of 10 m high, but examination of the microscale in that layer involves concerns about such things as the trees, bushes, etc. Again, examination of an even smaller scale, perhaps the lowest 10 cm, which would normally be called a smooth surface on the planetary boundary layer scale, has within it roughness elements as well. These are very fine in detail and the turbulence they generate is also very small. Fortunately, it is not necessary to describe the smallest scales in that succession to obtain some benefit from the processes of heat, momentum, and moisture exchange. It is now recognized that the biosphere has a very important role in exchanging moisture, heat, and momentum with the atmosphere.

Let us consider some of the physical mechanisms for this exchange. Figure 2 shows, conceptually, some of the mechanisms for the generation of atmospheric turbulence which effect the fluxes of heat, momentum, and moisture. Of course, one of the most obvious mechanisms is vertical wind shear, shown in Figure 2(a). When there is a shearing action of any kind, turbulence can occur if the shear is sufficiently strong. This is a means for converting the energy in the larger scale flow into turbulence kinetic energy, and it is a mechanism that can generate turbulence anywhere in the atmosphere. Frequently, it is near the ground because strong shears occur in flows near a fixed boundary.

Differential heating is also a very important turbulence generating mechanism. The surfaces of the Earth are not uniform. Forests absorb solar energy quite differently from the oceans, and the highly reflective areas in the desert have quite a different capability for absorbing solar energy. In terms of thermal properties, the ocean has great heat capacity and is relatively stable in surface temperature both day and night. The reason is that the energy is absorbed through a deeper layer. Also, the heat capacity of water is large and can be mixed to a depth which virtually guarantees that the temperature of the surface will not change very much during the diurnal heating cycle. On the other hand, particularly barren land surfaces have very little thermal capacity. They have very poor conduction to the subsurface layers, and so the surface temperature over land can vary enormously from day to night. As shown in Figure 2(b), such temperature differences can generate vertical motions, literally heating or boiling the air that is lying in contact with the hot surfaces to generate turbulence. Flying in an aircraft in the boundary layer on a bright, sunny day produces a choppy ride from this kind of effect.

Even when there is a uniform surface temperature, surface roughness can generate turbulent flow. Figure 2(c) illustrates a stratified, laminar flow encountering a rough underlying surface which generates turbulence. This is the same kind of mechanism that occurs when an aerodynamic surface with rivets or surface debris on it trips a laminar flow into a turbulent flow.

Professor Wurtele [2] mentioned waves in the atmosphere that are set up by obstacles to the flow. Certainly, gravity waves can be generated by a number of phenomena in the atmosphere. Such waves can reach a state where their amplitudes are sufficiently large and the shear and buoyancy forces acting on them are conducive to the generation of turbulence. Figure 2(d) shows that the wave can literally destroy itself in turbulence. Professor Wurtele showed an example of Kelvin-Helmhotz waves that do produce overturning in the atmosphere, thereby generating turbulence.

It has been known for a long time that when the horizontal gradient is sufficiently severe in jet streams, and particularly if there is curvature in the flow, vortices can be shed to one side of the jet as illustrated in Figure 2(e). Such a phenomena is one cause of clear-air turbulence.

Differential advection often occurs in the midwest and southwest in the springtime. In such a case, a low-level flow from the south, which is quite warm and moisture laden, is overrun by a dry flow from the west across the Rockies, as illustrated in Figure 2(f). This situation can literally produce sufficient vertical instability so that there is natural overturning. Of course, when that happens, very severe turbulence occurs and the conditions are very conducive to producing thunderstorms and tornadoes.

The downburst is a phenomenon that in recent years has received a lot of attention. One type of downburst is thought to occur when a moist layer aloft drops precipitation through a fairly dry layer below it. The precipitation evaporates and in so doing cools the dry layer considerably. As shown in Figure 2(g), the resulting cold air is very dense, causing it to plunge downward rapidly toward the surface in a relatively confined region. This downburst generates turbulence as it shears through the horizontal flow on the way down, and when the plunging column of air hits the ground, it generates additional turbulence as well.

We heard yesterday how precipitation generates turbulence. This mechanism operates on a smaller scale, but hydrometeors falling through the air very definitely generate turbulence and alter the flow patterns that would otherwise occur in the vicinity of non-precipitating clouds. Figure 2(h) shows schematically the turbulence generated by falling precipitation.

Tropopause folds are a phenomenon which have been recognized for some years, but until recently no one believed that they occur as frequently as they do, nor was their role in transporting potential vorticity into the troposphere well understood previously. These folds generate turbulence because of the instability established when more buoyant stratospheric air is forced below heavier tropospheric air as shown schematically in Figure 2(i). Here, the air with higher potential temperature (θ) penetrates into the dense air below it in the fold and is then cut off. The instability thus generated is restored to more stable flow by turbulent processes.

We have already heard about the role of fronts in generating turbulence. Figure 2(j) shows a cold dome of air that has a reasonably coherent surface advancing into warmer, lighter air and actually stirring it up. Ahead of the front, squall lines or thunderstorms often develop. Thus, fronts are a source of turbulence and, though it is a moving mass of air, it could just as well be considered a solid obstacle that is moving along the surface generating turbulence ahead of it.

Orography is another important mechanism for generating turbulence, particularly in the boundary layer. Figure 2(k) shows the turbulence generated when flow crosses an orographic barrier. In this case, air is flowing over mountains, and a wake that contains considerable turbulence is generated right in the boundary layer. Rotor flows are generated in the wake at the top of the boundary layer, stirring additional turbulence themselves. There are gravity waves and mountain waves; gravity waves propagating away from the mountain and mountain waves standing on the lee side of the mountain at higher levels. Graphic examples of such waves were given in Dr. Wurtele's paper [2].

There is a class of stirring actions in the atmosphere that literally consists of convective instabilities. Here I am talking about air that might initially be stable but if slightly disturbed, it becomes unstable. In Figure 2(1), convergence is shown which lifts a parcel from near the surface to its original level. If the parcel contains enough moisture, the moisture starts to condense, releasing latent heat. Of course, that energy makes the parcel more buoyant, raising it further. This lifting mechanism can generate a great deal of turbulence. Once the process starts, it can accelerate, becoming less stable, and eventually generating thunderstorms with violent weather activity.

All of these mechanisms are somewhat localized in space and time. If you look at the atmosphere as a whole, you would probably say that the atmosphere is largely stratified, and it is. But these important turbulence generating mechanisms are exceptions to that stratification which really make the system what it is, and they cannot be neglected. Turbulence creates the fluxes of heat, momentum, and moisture which account for virtually all the interactions between the surface and the rest of the atmosphere.

There are a number of ways that people have attempted to handle all of these exchanges in models. Time does not permit me to talk about all of them, but I am going to mention one that is in current use today. It was developed in 1972 by Deardorff [3]. His method relies on a bulk parameterization scheme as follows:

1. Deardorff begins by estimating the mean values of wind velocity, potential temperature, and moisture in the boundary layer from the estimated height of the boundary layer and the lowest grid levels of the model.

2. Then he estimates the mean vertical fluxes of momentum, heat, and moisture from the bulk Richardson number (based upon the differences between the mean values of the boundary layer and the surface values).

3. Next, he estimates the direction of the surface wind using the surface pressure gradient to refine the mean wind velocity in the bulk Richardson number. If needed, these steps are iterated.

4. Finally, he obtains the height of the boundary layer as a function of x, y, $t + \Delta t$, given the height as a function of x, y, t (from the prognostic equation in unstable cases and a simple relationship in stable cases). This step uses model velocities and surface fluxes from step 2 above.

If you go through all the equations, you will find that it is still simple compared to a detailed description of the real processes that are involved.

This parameterization of the boundary layer is used in a number of models. Figure 3 is a schematic of the way it is used in the Goddard Laboratory for an atmosphere fourth-order, primitive equation, general circulation model. In this particular case, Deardorff's parameterization is used and the fluxes at the surface, indicated by F_s, are equated to the mean fluxes in the mixed layer, F_m. Inclusion of these fluxes actually makes a difference in the results of the model. It is a simplified accounting for all the processes described in Figure 2.

In Figure 4, a schematic diagram of a newer model called the global integrated biosphere model (by Sellers et al. [4]) is shown. This model has just recently been developed. The diagram shows how the fluxes develop from the surface, the ground cover, and the tree canopy, particularly the moisture and heat fluxes. The portion of Figure 4 outlined at the top of the page is the Deardorff parameterization, which describes the bulk flux parameterization between the surface and the atmosphere, but, in addition, there is a more elaborate system for describing the fluxes from the canopy and the ground cover and from the soil. The cavities represent the stomata of the plants. The symbolic resistances represent the resistance to the transport of moisture, in this case, through the biota. It is a complicated process which is empirically determined and accounts for both heat and moisture exchanges. Although it makes the model more complicated, it actually does produce visible results. From this approach, the surface stresses are computed in the model. The surface stress varies considerably according to the vegetation, soil type, roughness, etc.

Differences have been generated in the atmospheric portion of the model because soil moisture and vegetation do affect the behavior of the atmosphere. Precipitation is more realistically simulated because of the moisture mixing which is related to the vegetation. Soil moisture makes an enormous difference in how the model actually responds by producing precipitation which we hope will be realistic. It really does make a difference, particularly in climate models.

To summarize, although the atmospheric flow is basically stratified, there are a number of very important exceptions. In qualitative terms, these exceptions to that stratification make a significant difference in the way the atmosphere behaves. These exceptions enhance turbulent exchange processes and these turbulent exchange processes ultimately modify the behavior of the atmosphere over a wide range of spatial and temporal scales. Finally, the present methods for parameterizing turbulence and the fluxes they generate use bulk approximations. The question is: Are these adequate and can we improve them?

References

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4. Sellers, P. J.; Mintz, Y.; Sud, Y. C.; and Dalcher, A.: "A Simple Biosphere Model (SiB) for Use within General Circulation Models," *Journal of the Atmospheric Sciences*, 43(6):505-531, March 15, 1986.

QUESTION: Jack Ehernberger (NASA Ames). You've indicated the importance of turbulence processes to the atmosphere. Can you characterize or has it been examined to any extent, the degree which the interest from the atmospheric prediction standpoint in simulation depends on turbulence as the turbulence intensity increases. In other words, the aircraft audience probably begins to be interested in an RMS value of 0.5 m/s and generally everyone who flies is interested in 1 m/s. The extreme incidents and accidents probably happen at a range of 3 or 5 m/s RMS. That doesn't infer that the larger the RMS is the more important it is to the atmospheric circulation. Has a breakdown been made or might it be made? Does your interest increase with the severity of the turbulence?

ANSWER: I don't think I have come across any cases in which in large-scale modeling or climate modeling that is a consideration. Certainly, if people are trying to model mesoscale processes they might be very concerned with it, and there are local scale models and cloud scale models that might account for turbulence. I think, in general terms, that even the smaller processes which occur more frequently are of great importance because they occur on a very widespread basis. For example, by changing the roughness of the Saudia Arabian peninsula, we were able to show that the Indian monsoon flow could be considerably altered. There is a very small-scale process (we are talking about turbulent flows over sand). It is generally concluded that sand does not produce much in the way of turbulence, but alter the roughness in the model slightly and increased surface stress actually produces curvature in the flow that leaves Saudia Arabia, thus changing the very important monsoon that occurs over India. So, the answer to your question is: I think not. I would like to emphasize the areas of mutual interest and perhaps overlook the divergence of interests at this meeting. With that intent, we attempted to convene the two communities, aviation and earth sciences.

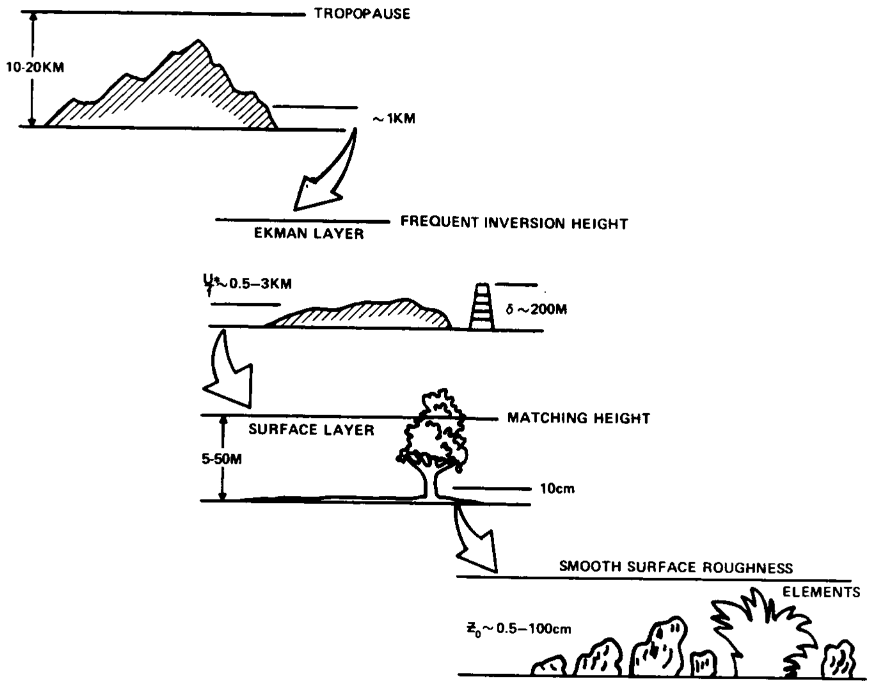


Figure 1. Turbulent scales of size and motion important to generation of fluxes (after Brown [1]).

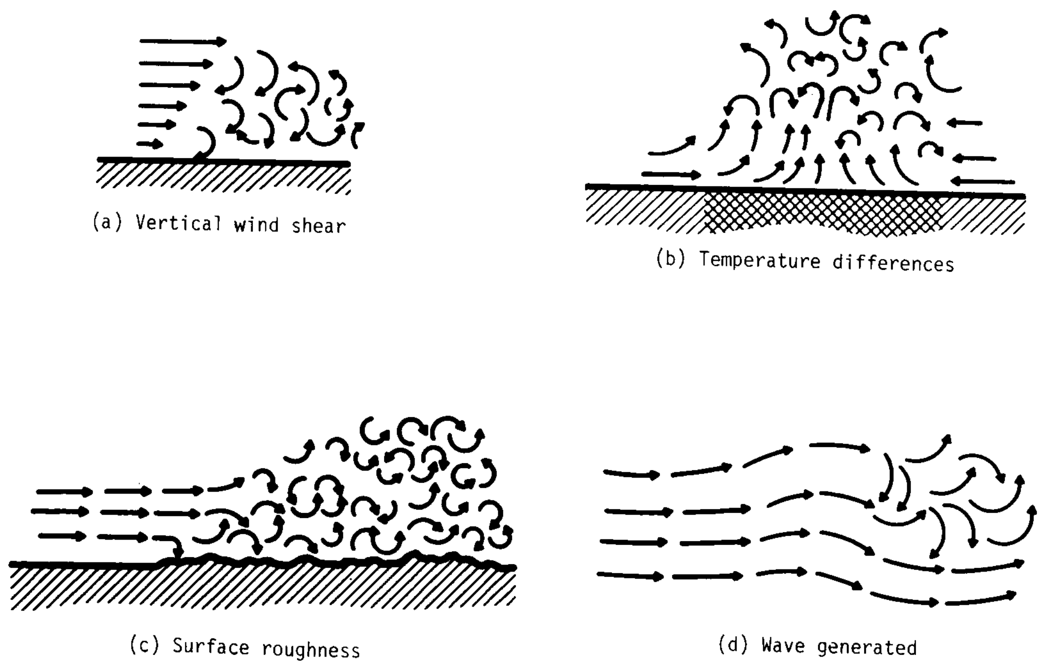


Figure 2. Conceptual illustration of mechanisms for generation of atmospheric turbulence.

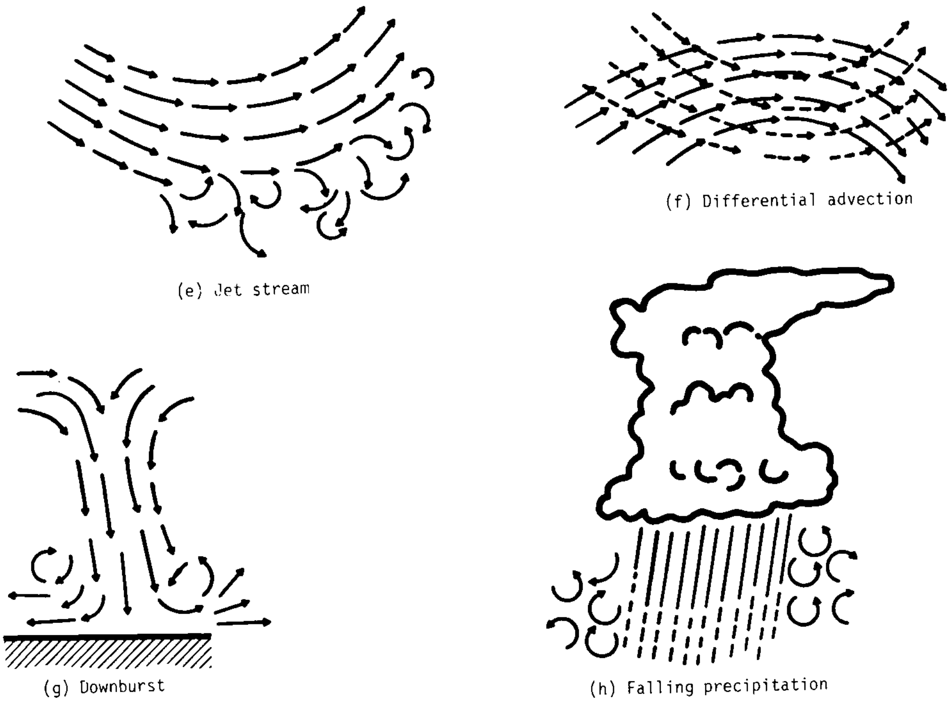
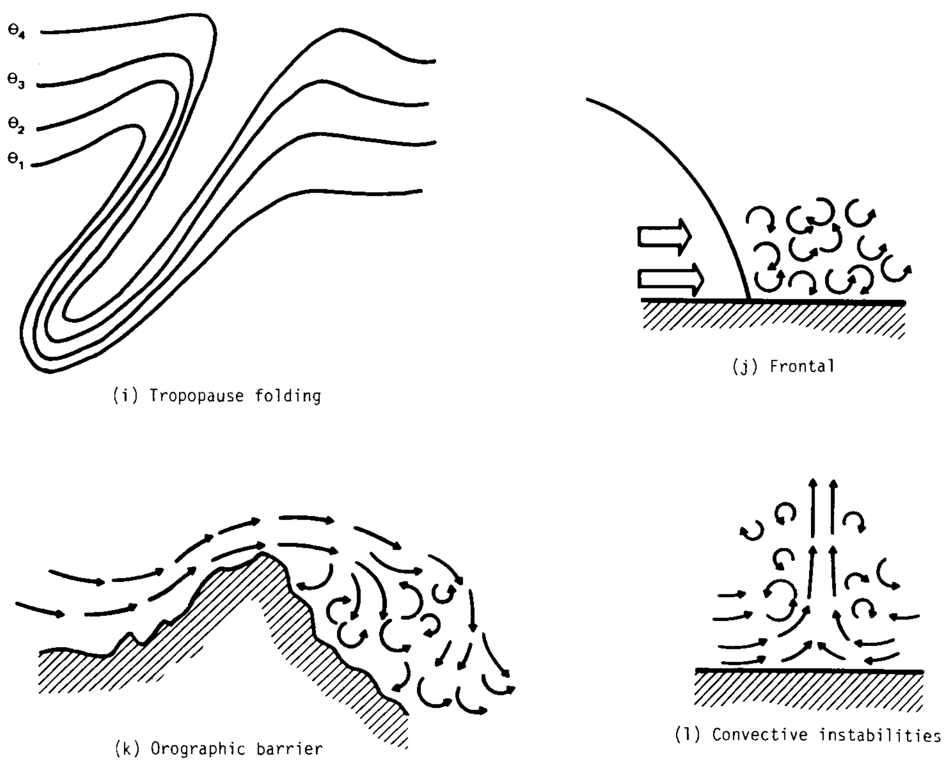


Figure 2. (continued).



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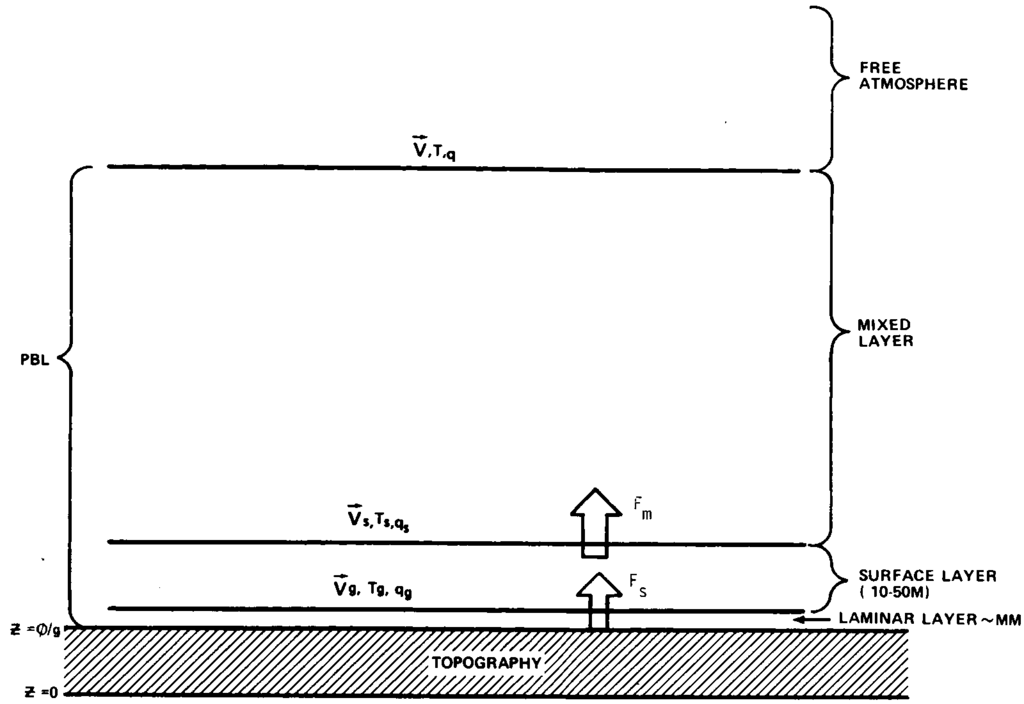

Figure 3. Schematic of parameterization model used by the Goddard Laboratory for Atmosphere.

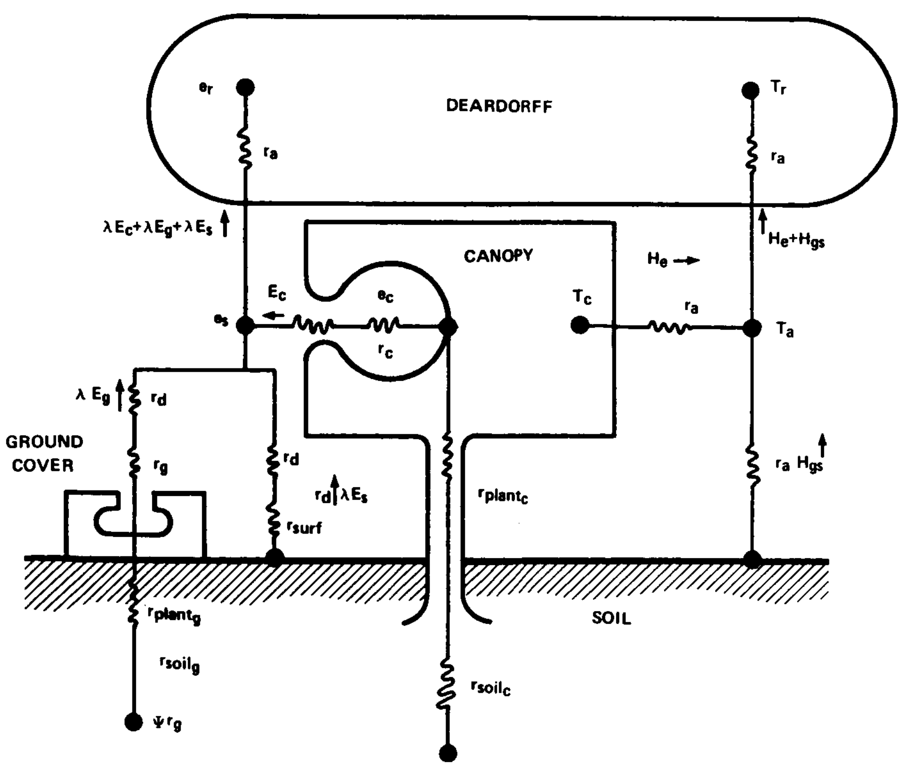

Figure 4. Global integrated biosphere model (by Sellars et al. [4]).