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TRANSPORT MODELS FOR NUMERICAL FORECAST

Stephen D. Burk
Naval Environmental Prediction Research Facility
Monterey, California

The explosive growth of computing power, coupled with scientific and technological emphasis on the national scale, has led to significant major advances in operational numerical weather prediction (NWP) during the last two decades. There are about half a dozen major centers around the world running global NWP models operationally. Many more countries have operational hemispheric or limited-area models which provide weather forecasts. The global models typically have several hundred kilometer resolution, while the limited-area models usually have horizontal spacing of 50 to 100 km. Given the pace of burgeoning growth in this area, it seems warranted to occasionally take an overview of aspects of the field common to all modelers. In this note I take a brief look at the nature of subgrid scale turbulence transport parameterization, and some of the difficulties pertaining thereto, with particular emphasis on operational NWP models.

The Navier-Stokes equations describe the physics of atmospheric flow, and one might expect that it would be possible to numerically solve these equations in such a way as to yield near perfect depiction of all details of the flow, and hence, near perfect forecasts. It would be simply a matter of resolving all elements of the flow which have a significant impact on its evolution. While such direct simulations are possible for low Reynolds number flows, it can be demonstrated [1] that because of the wide range of scales of turbulent motion that are coupled nonlinearly, it would take roughly 10^{20} grid points to directly compute the flow over a region 10 km on a side. This is clearly beyond the capability of any dimly envisioned future computer.

Instead of trying to resolve all important eddy scales, one necessarily must address a less ambitious goal of forecasting the evolution of averaged values of the meteorological relevant quantities. Typically in operational NWP models, this means forecasting the value of a variable within a grid volume that may be 100 km on a side horizontally, and 50 to 100 mb thick vertically. Clearly, this grid will not have sufficient resolution to describe many interesting phenomena. A powerful thunderstorm having a horizontal scale of 10 km will not be resolved by this grid, nor will the details of a sea breeze, or clear-air turbulence, etc. But if the model cannot resolve these phenomena, and if we are only attempting to define averages on quite a large scale, do we really have to concern ourselves with such subgrid scale processes? The answer is a definite yes. These features of the turbulent flow, even though they be subgrid to our model, still interact in a complex, nonlinear manner with flow on the resolved scale. Thus we are led to the problem of parameterization, which in essence is the science (and to some degree, art) of properly representing subgrid scale influences on the model's resolvable scale variables.

There exists considerable diversity in the techniques used for parameterizing transport processes within NWP models. The earliest form of transport parameterization used in NWP models involved eddy-coefficient or K-theory. In K-theory the subgrid fluxes which one wishes to parameterize are assumed to be proportional to the local gradient of the relevant mean quantity. The proportionality factor is the eddy coefficient, K. The problem thus shifts from one of specifying unknown subgrid scale fluxes to that of defining "proper" eddy coefficients for the flow. In early treatments, the eddy coefficients generally were selected *a priori* according to some analytical function. Thus, to some extent one was determining the answer before beginning the integration. Current K-theory models often use eddy coefficients which depend in some manner on the stability of the flow (through deformation and buoyancy, or a bulk Richardson number, for example). Thus, the magnitude of K varies in time and space in a manner dependent on the evolution of the flow variables--a very desirable feature. Some weaknesses in K-theory, however, have led to the development of alternative approaches to transport modeling. For example, in convective situations where large eddies fill the atmospheric boundary layer (ABL) and are responsible for a significant fraction of the transport, the fluxes are not strongly related to the immediate local gradient. In fact, these eddies may transport heat counter to the local temperature gradient, which would imply nonphysical, negative eddy coefficients.

One of the alternate approaches to modeling transport processes within the atmospheric boundary layer takes advantage of the observation that often under convective situations the wind, potential temperature, and specific humidity are nearly constant with height from near the surface to near the boundary layer top--that is, these quantities are <u>well-mixed</u> within the convective ABL. Given such conditions, it is unnecessary to have many grid points in the vertical resolving the profiles, since their values within the mixed-layer can be defined by single mean values. It is, however, necessary to carefully define the fluxes at the top and base of the mixed-layer since these fluxes will determine how the mean values within the mixed-layer change with time. Since one does not have multiple grid points near the top of the ABL to help compute the entrainment flux in this type of complex, this is particularly true when the boundary layer contains clouds, because the presence of clouds has a major impact on turbulence, hence entrainment at ABL top. Thus, although initially attractive because of their apparent simplicity, the mixed-layer formulations can become complex and require considerable ingenuity to define entrainment fluxes in situations more complicated than the clear, convective ABL.

In R&D applications, second-order closure modeling has been widely used for parameterizing the transports due to turbulence. Second-order models, like K-theory models, require numerous grid points for their computations--making no *a priori* assumptions concerning the degree to which the ABL is well mixed. Unlike K-theory models, however, the fluxes are not assumed directly proportional to local mean gradients. Instead, dynamic equations for the fluxes are developed and added to the collection of model equations to be numerically integrated. A multiplicity of terms requiring closure arises from these new equations, and fundamental work in this area centers on improving and generalizing the closure expressions.

While the second-order models often permit greater realism in their description of ABL processes, a significant price must be paid in model complexity and computer time. (In a recent third-order closure calculation, Bougeault [2] was required to integrate 50 differential equations--this being feasible only because it was a one-dimensional model.) Currently, only substantial simplification will permit second-order modeling techniques to be incorporated into operational NWP models. It is possible, for example, to include a length scale equation and the turbulent kinetic energy equation in a NWP model to help in defining a generalized eddy coefficient, without carrying all of the second-moment differential equations.

Thus, the necessity for an operational NWP model to represent the atmosphere on a horizontal scale of many hundreds or even thousands of kilometers means that resolution of turbulence transport with the same detail as practiced is current R&D boundary layer models is impractical. However, transport parameterization in these NWP models, while necessarily somewhat crude, is still of great importance to the success of their forecasts. The important question here then becomes this:

> How do we take the advances being made in turbulence modeling research with high-resolution models, and with observation programs that focus on the details of local ABL turbulence, and use them to the best advantage in developing the physical parameterizations required in coarser-scale NWP models?

It clearly requires more than "scaling-up" the closure assumptions used on the fine scale to the larger scale. For example, a transport parameterization used for describing turbulent fluxes in a detiled cloud model cannot be expected to also represent the situation when towering cumulus, embedded in an otherwise nearly laminar troposphere above the ABL, become entirely subgrid to the model. And, indeed, entirely different phenomenological approaches have been developed for representing cumulus effects in synoptic scale models. But where are the bounds defining the types of transport scheme appropriate to a given model simulation? Or, to pose the problem slightly differently, if we begin with a fine-resolution three-dimensional model and gradually increase the grid spacing in successive simulations of the same situation, how should we gradually alter the parameterization algorithms so as to continuously represent the flow in a realistic manner at each scale? The demand for increased skill in sub-synoptic and mesoscale NWP models requires that such questions be addressed in a serious, extensive manner.

References

1. Wyngaard, J.: Boundary-Layer Modeling in *Atmospheric Turbulence and Air Pollution Modeling* (Nieuwstadt, F. T. M.; and Van Dop, H., eds.), pp. 69-107, 1982.

2. Bougeault, P.: The Diurnal Cycle of the Marine Stratocumulus Layer: A Higher-Order Model Study, *Journal of the Atmospheric Sciences*, 42:2826-2843, 1986.

QUESTION: Warren Campbell (BDM Corporation). How do you calibrate the models that you use? Ordinarily when you start doing model equations you end up with a group of parameters and then you have to come up with solutions to those parameters. How do you go about actually making comparison with what's going on in the atmosphere in making those calibrations?

ANSWER: As far as the second-order closure models, most of that kind of thing is done first by using model calculations of laboratory flows to set the model constants. I have been working with the various versions of the Mellor and Yamada formulation, and they have a hierarchy of different order closure models. If you look at how they got the closure constants that are used, it traces back to laboratory flow simulations. So you don't have to change them for every new meteorological condition you are dealing with, which is a nice feature.