

TRANSPORT AND MIXING IN THE ATMOSPHERE

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Summary Transport and mixing processes in the atmosphere operate on scales from millimeters to thousands of kilometers. In certain parts of the atmosphere the large-scale ‘layerwise two-dimensional’ flow appears to play the dominant role in transport and in the stirring process that leads ultimately to true (molecular) mixing at very small scales. There is therefore much in common with fluid dynamical topics such as ‘chaotic advection’ or ‘Batchelor-regime turbulence’. My talk will describe how, with appropriate modification, some of the theoretical tools developed in these contexts can be used, in conjunction with observational data on large-scale velocity fields or on chemical species, to quantify different aspects of transport and mixing in the atmosphere.

MOTIVATION

On sufficiently large scales in the atmosphere, e.g. larger than a few tens of kilometers, rotation and buoyancy stratification both tend to inhibit strong three-dimensionality of the flow. The flow is quasi-horizontal, with air parcel trajectories along weakly sloping surfaces, so that horizontal displacements are generally much larger than vertical displacements. These flows have a dual character, with some aspects of their behaviour appearing organised and wave-like and other aspects exhibiting considerable nonlinearity and randomness. In the latter respect these flows might therefore be regarded as a kind of turbulence, analogous to the two-dimensional turbulence studied in idealised numerical simulations and laboratory experiments. However, the strong difference of these flows from three-dimensional turbulence is that strong vortex stretching is inhibited and therefore the cascade of energy to small scales is inhibited. The velocity field has a finite spatial scale and hence there is no strong increase of velocity gradients as scale shrinks.

It is now realised that flows with a relatively simple structure in space and time may be highly effective at stirring and mixing through the phenomenon now widely known as ‘chaotic advection’. Velocity fields with a very simple structure in space and time may lead to complex and irregular, i.e. chaotic, particle trajectories, with, for example, the distance between initially nearby particles, increasing exponentially in time. This separation of nearby particles implies that the fields of advected quantities, such as chemical species, rapidly become complex, with variations on scales much smaller than that of the advecting flow. Chaotic advection has often been studied in the context of time-periodic flows. But what essentially distinguishes chaotic advection from, say transport and mixing in three-dimensional turbulence, is that in the latter the small-scale velocity field plays an active role in stirring. Thus the term chaotic advection may be usefully applied to any flow with a finite spatial scale that naturally leads to spatial structure in advected chemical species on a much smaller scale. In this sense the atmospheric flow is a chaotic advection flow.

USE OF OBSERVATIONAL VELOCITY FIELDS IN TRANSPORT STUDIES

Global datasets of atmospheric dynamical quantities including velocity fields are now routinely produced as part of the weather forecasting process. These datasets are typically at a horizontal resolution of 100km or so. The datasets include a subtle blend of information direct from observations and information from the numerical models used to generate forecasts. The velocity datasets are now widely used as input to transport models. These might be Lagrangian models, which advect large numbers of particles (or sometimes finite parcels containing reacting chemical species), or Eulerian models, which represent global fields of different chemical species. Such models have been used with great success for many different scientific purposes, e.g to interpret high-resolution one-dimensional sections of chemical species measured in observational campaigns or to predict chemical ozone destruction in the stratosphere (e.g. Waugh et al., 1994, Methven et al., 2003). Of course, this whole approach depends on the chaotic advection idea that the large-scale flow dominates, otherwise the fact that information from spatial scales below the resolution of the datasets is not included would be a serious limitation.

TRANSPORT AND STIRRING

Simple chaotic advection models and analogous dynamical systems show that transport and stirring is often highly inhomogeneous, with regions of strong stirring (i.e. strong stretching) separated by barrier regions in which stirring is weak and across which there is no, or relatively little, transport. In time periodic and quasiperiodic flows the barriers are usually perfect (they are composed of invariant tori) for some ranges of values of the parameters defining the flow.

In the real atmosphere observations and models show similarly inhomogeneous transport and stirring. In the stratosphere, for example, the edge of the winter polar vortex seems to form a transport barrier which is not perfect, but across which transport is very weak. Outside the vortex, in mid-latitudes, and to a lesser extent inside the vortex, there are regions of strong stirring. Lower in the atmosphere the subtropical jet seems to form a similar, if less effective, barrier to quasi-horizontal transport which separates the upper troposphere and the lowest part of the stratosphere. Once again, poleward and equatorward of the subtropical jet there are regions of strong stirring. This sort of spatial structure, with transport barriers and stirring regions, is found in a wide class of geophysical flows and depends on the strong relation, provided by

the potential vorticity field, between transport and stirring on the one hand and dynamics on the other.

The relation between the dynamical transport barriers in the geophysical flows and the invariant tori of the simple time-periodic flows is not very clear at all. Nonetheless the various mathematical tools originating in dynamical systems theory that have been applied to simple chaotic advection flows are potentially of interest in considering realistic atmospheric flows and several have been carefully studied in this context (e.g. Koh and Plumb 2000, Joseph and Legras 2002). Other tools such as ‘effective diffusivity’ calculated from an advected test tracer look promising (e.g. Haynes and Shuckburgh 2000). Such tools are needed to compare effectively the transport and stirring structure of velocity fields in different observational datasets or generated by different numerical models.

STIRRING AND MIXING

The reduction in spatial scale of fields of advected chemical species by stirring ultimately terminates in true mixing by molecular diffusion. This could be achieved in laminar flow, but in practice in the real atmosphere the effects of molecular diffusion are likely to be enhanced through intermittent encounters of air parcels with three-dimensional turbulence. This enhancement might be substantial in the troposphere, where convection is relatively common, is likely to be much weaker in the lower stratosphere and then to increase again in the upper stratosphere and mesosphere, where three-dimensional turbulence associated with the breaking of gravity waves is more widespread. To some approximation the mixing effects of encounters with turbulence may be represented as an enhanced molecular diffusion and the stirring and mixing process is therefore one in which the stirring (i.e. stretching) effects of the large-scale flow interact with diffusion.

This is a classical problem in fluid dynamics, often studied in the context of the ‘Batchelor regime’ of turbulence, where the diffusivity of the advected quantity is assumed to be much less than the momentum diffusivity, so that there is a sort of chaotic advection at scales smaller than the Kolmogorov scale. A promising theoretical approach to this problem has been to consider the interaction between stretching and diffusion in a flow that is a random function of time and a linear function of space. This theory has undergone significant developments recently (e.g. Balkovsky and Fouxon 1999, Falkovich et al 2001). Whilst it has apparent limitations in the initial-value problem (i.e. free decay from a specified initial field for the chemical concentration) these limitations do not seem to extend to the forced problem (where the chemical concentration is maintained by some source/sink distribution) and potentially it offers a quantitative theory for the chemical concentration field that arises from a specified combination of large-scale flow and small-scale mixing processes. The standard theories need some extension to be applied to the atmosphere. Firstly the atmospheric flow is layerwise two-dimensional and therefore strongly isotropic. This extension is relatively straightforward (Haynes and Anglade 1997). Secondly the spatial and temporal organisation of atmospheric flows (the persistent stratospheric polar vortex, for example) mean that the standard randomness assumptions do not apply. This extension is not straightforward at all.

References

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