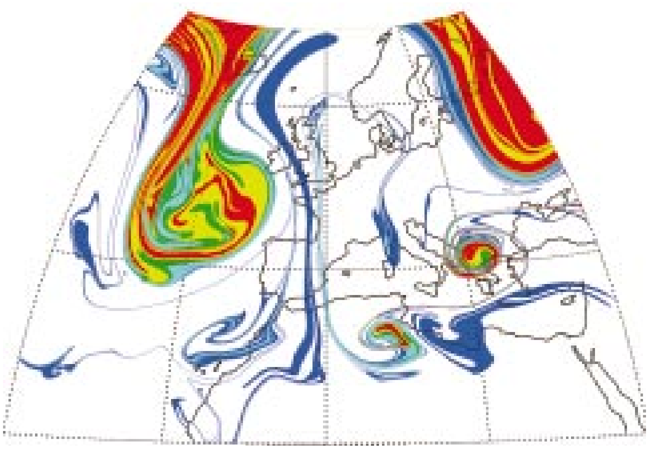
# Transport processes in the atmosphere and oceans (TAO)

**An ESF scientific programme**

*The complex phenomena associated with fluid transport define a fundamental physical problem with many important applications, particularly in the atmosphere and the ocean. These include high-profile environmental problems such as dispersal of chemical and radioactive components on scales of a few kilometres to chemical-climate change on a global scale. A better understanding of fluid transport will allow more effective scientific exploitation of observational data and will bring direct benefits for modelling and forecasting.*

*The aims of the ESF scientific programme on* Transport processes in the atmosphere and oceans *are two-fold. Firstly, it is stimulating research on atmospheric and oceanic applications, ranging from stratospheric ozone depletion to the role of mesoscale ocean eddies in water mass budgets, and encouraging such research to take account of the advances in fundamental theoretical understanding of fluid transport that have taken place over the last decade or so. Secondly, the programme is encouraging the fundamental research, placing particular emphasis on areas where recent theoretical advances potentially have direct applications. An overall priority is to encourage through greater interdisciplinary communication an integration of expertise and effort across the lively European community of researchers working in these areas. A number of new interdisciplinary collaborations have already been established as a result of the programme activity.*



The European Science Foundation acts as a catalyst for the development of science by bringing together leading scientists and funding agencies to debate, plan and implement pan-European initiatives.

## Introduction

Fluid transport lies at the heart of a number of key environmental issues such as the dispersal of chemical and radioactive components and chemical-climate change. The perceived importance of such issues has led over the last decade to the collection of large amounts of new data on the atmosphere and the ocean in observational campaigns such as EASOE and SESAME (lower stratospheric chemistry), MOZAIC (upper tropospheric and lower stratospheric ozone and water vapour), and WOCE (large-scale ocean circulation). These efforts will continue through such projects as STRATEOLE (lower stratospheric balloon measurements) and EUROFLOAT (float measurements in Eastern Atlantic).

Some of the data, e.g. that from the various campaigns to study lower stratospheric ozone depletion, is at very high spatial resolution, but only available for localised regions or time periods. Other data, e.g. from satellite instruments, has good spatial and temporal coverage, but may be of rather coarse spatial resolution or only give information on a limited set of quantities. Rapidly growing datasets from freely drifting ocean buoys and atmospheric balloons are making it possible to perform more detailed analyses based on Lagrangian methods, but lead to particular problems of interpretation. In all these cases there is the opportunity to use models of fluid transport as a basis for interpreting the data. It is also clear there is a need for better understanding of transport in the atmosphere and the ocean if current models for forecasting environmental impacts and environmental change are to be substantially improved. So with need and opportunity overlapping, a stronger focus on the fluid transport problem in its own right is extremely timely and potentially very rewarding.

The ultimate aim is a full scientific understanding of the complex phenomena associated with transport in the atmosphere and oceans. However this is a huge task, and far too ambitious for a single programme of limited duration. The ESF TAO programme therefore focusses on three issues that have immediate importance, either fundamental or practical, and that are most suitable for a four-year scientific programme.

These are:

**1** ■ *The dependence of tracer transport, dispersion and mixing on the flow structure.*
The aim here is to assess the impact of the Eulerian structure of geophysical flows on transport and mixing, taking account of strong spatial inhomogeneity such as local eddies and vortices.

**2** ■ *Relationship between Eulerian and Lagrangian statistics.*
The aim is to develop new theoretical, numerical and experimental ways of extrapolating from Lagrangian observations, such as the positions of balloons or floats, to establish a full picture of the flow. For example, a long-standing and

extremely difficult theoretical problem is to devise ways of using Lagrangian observations to deduce Eulerian velocity fields. More generally, there is a need for methods of using data on chemical and biological tracers in a systematic way to validate numerical models of dynamics and transport.

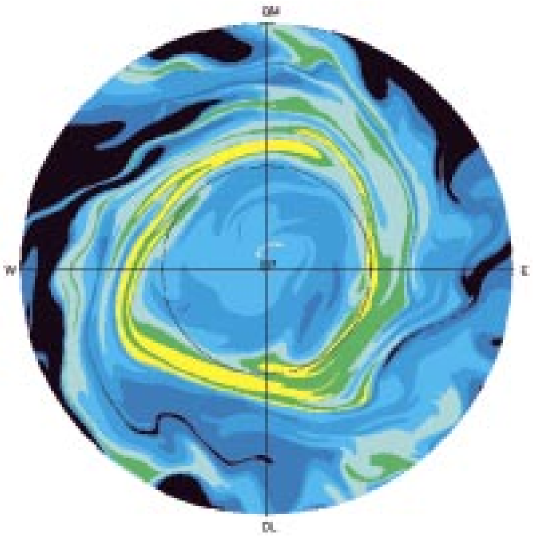
**3 ■** *Parameterisation of transport and mixing in geophysical flows.*
Most large-scale dynamical models of the ocean and atmosphere have relied on simplified parameterisations such as eddy diffusion coefficients, but these have proved inadequate for realistic flows. There is now the potential to achieve improved parameterisation of transport and mixing in complex environmental flows by exploiting recent theoretical advances, particularly in dynamical systems, but also in geophysical fluid dynamics.

## Scientific background

**F**low in the atmosphere and the ocean has a complex spatial and temporal structure and is in this sense 'turbulent'. Of course, the problem of turbulent flow remains one of the most difficult in theoretical physics, and it is only relatively recently that quantitative theoretical approaches to turbulence have moved beyond simplified statistical approaches that ignore coherent structures and local regions of concentrated vorticity. Laboratory and numerical experiments show that coherent structures such as vortices play a significant role in the overall dynamics of rotating and stratified flows and the importance of such structures in the real atmosphere and ocean is apparent from observations.

Over the last decade or so, as a result of progress in dynamical systems theory, the important new paradigm of 'chaotic advection' has been developed. The idea here is that flows with very simple spatial and temporal structure can have transport properties that are spatially complex and in particular, can lead to spatially complex structures in advected tracers such as chemicals or biological populations. Flow in the atmosphere and the ocean, as well as being in some senses 'turbulent', has much in common with the 'chaotic-advection' paradigm. This is because in rotating stratified flow there is no strong cascade of energy to small scales and the transport, stirring and mixing properties are largely determined by the large-scale flow, e.g. the flow at the scale of the coherent vortices.

One of the striking aspects of atmospheric and oceanic flows is their strong spatial heterogeneity, i.e. the variation in their properties over relatively short distances. This is particularly problematic for ocean modelling, where the relatively small scales of the eddies and of the mean currents puts strong demands on the spatial resolution of numerical models. In the atmosphere the scales of the active flow structures are larger, but there is striking spatial heterogeneity in the transport




Transport by the Southern hemisphere Polar Vortex. Reconstruction of ozone mixing ratios at the potential temperature of 510K, on August 8 1994, by the "Contour Advection with Surgery" high resolution method.

properties of such flows with important implications for ozone depletion and other aspects of chemical-climate change. The challenge ahead is to improve understanding, and hence predictive modelling, of atmospheric and oceanic flows and their transport properties, by exploiting the recent theoretical progress in the fields of turbulence and of chaotic advection.

## ESF programme

The aim of the ESF scientific programme on *Transport processes in the atmosphere and oceans* is to exploit the potential for important scientific advances in this area by bringing together those working on theoretical aspects of fluid transport and those working on atmospheric and oceanic problems. There is a lively European community of researchers in these areas, adopting a wide variety of approaches, and it is important to encourage this to continue. But it is also important to make sure that this work is as productive as possible by encouraging communication between different groups, particularly in areas requiring an interdisciplinary approach, where the most significant opportunities for scientific progress are often found. The activities of the programme have so far involved over 100 scientists, including meteorologists, oceanographers, fluid dynamicists and mathematicians, from all over Europe and also from Russia and North America.

The programme is tackling the issues outlined in the scientific background under three headings: (1) *Dynamical systems approach to transport and mixing*; (2) *Influence of coherent structures on transport*; and (3) *Key applications*. These three areas are, of course, closely inter-related, since coherent structures have a considerable influence on the whole structure of transport and also raise issues, such as the need for new data analysis methods, for the application of improved understanding of fundamentals.

## Aims and objectives

### Dynamical systems approach to transport and mixing

The ‘chaotic advection’ paradigm shows that flows with simple velocity fields, such as 2D time-periodic flows or 3D steady flows, lead to complex (indeed, chaotic) particle trajectories and to complex structure in tracer fields. Important advances in the mathematical theory of dynamical systems have led to powerful techniques for analysing such flows and suggested general strategies for quantifying transport and mixing, e.g. identifying fractality or self-similarity in spatial structure. Many of these techniques have been developed after making simplifying assumptions, e.g. time periodicity, that are not precisely relevant to atmospheric and oceanic flows. It is important to establish what aspects of the behaviour are robust to relaxing such assumptions and to encourage further theoretical progress on questions that have a wider relevance for real atmosphere and ocean.

Three high-priority topics under this heading are:

■ *Anomalous dispersion*
The programme is studying the characteristic features of anomalous particle dispersion, not described by the Brownian law, in atmospheric and oceanic flows. This anomalous dispersion is often associated with the presence of coherent structures in the advecting flow.

■ *Transport in 3D quasi-geostrophic flows*
Studies of chaotic advection and particle-trapping are needed for realistic three-dimensional flows where transport properties can vary strongly with height.

■ *Dynamics of non-neutrally buoyant, finite-size passive particles*
Better understanding of the dynamics of such particles is needed to interpret correctly data collected by surface ocean drifters, subsurface floats and free atmospheric balloons.

**Influence of coherent structures on turbulent transport**
Turbulent transport has until recently been studied largely on a statistical basis treating the fluid system as a homogenous whole, ignoring the impact of significant coherent structures and regions of concentrated vorticity. Yet numerical experiments on two-dimensional and quasi-geostrophic turbulence and Lagrangian observations in the ocean and atmosphere have shown that coherent vortices have a strong effect on tracer transport and dispersion. These effects may result from persistent, large-scale vortices, such as that in the winter stratosphere, or from the many small-scale vortices found in the ocean thermocline. The edges of such coherent vortices are strongly impermeable, allowing the long-term trapping of particles inside the vortices or, alternatively in the region outside. Such trapping may, for example, lead to anomalous dispersion, at least over intermediate times and to other transport properties that are contrary to the predictions of traditional turbulent transport theories.

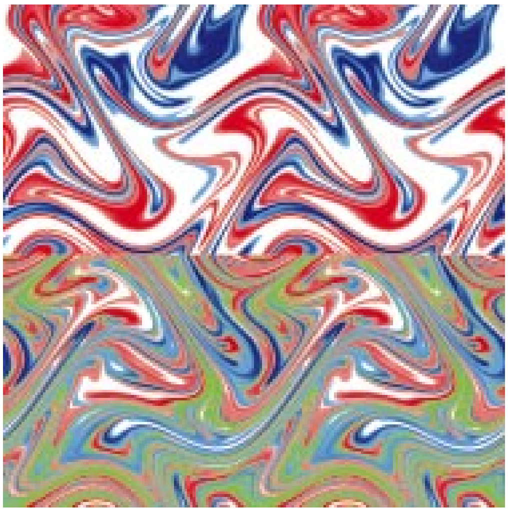
A number of individual topics are being studied under this heading:

■ *Trapping/Detrapping of passive tracers in coherent structures*
Given the apparent strong impermeability of vortex boundaries, it is crucial to understand the mechanisms for tracer leakage across such boundaries, perhaps in occasional events such as strong vortex interactions, perhaps through persistent weak transport associated with weak interactions or dissipative effects.

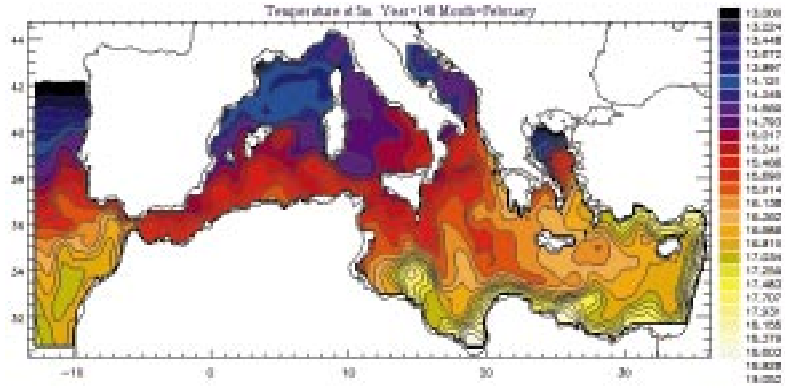
■ *Dispersion in a turbulent flow characterised by the presence of vortices*
Motivated by considerations of the role of mesoscale eddies in the ocean circulations, the objective is to study particle dispersion and tracer evolution, with the specific aim of understanding the deviations from the predictions of classical turbulence theories.

■ *Study of the relationships between Eulerian and Lagrangian statistics in the presence of coherent structures*
New statistical models for relating Eulerian and Lagrangian data need to be developed for flows with strong spatial inhomogeneity.

■ *Analysis of laboratory experiments on transport in rotating and stratified flows*
Laboratory experiments are still an important tool for investigating aspects of atmospheric and oceanic fluid flows, particularly in assessing effects of strong stratification and of full three-dimensionality, such as in convection or in mixing events.



A simulation of chemical reaction taking place in a chaotic advection flow generated by simple two-dimensional map. Two different chemical species, indicated by red and blue regions, are initially separated, but are brought together by the flow, mix and react to give a chemical product, indicated by the green regions. In the early stages of the evolution, the region occupied by the product has a complex spatial structure, corresponding to fluid that has experienced the largest stretching by the flow.



A numerical simulation of Mediterranean circulation using the numerical primitive equation model (MOM). The figure shows the temperature field at 5 metres after 140 years of integration, showing the boundary current along the coast of Africa, relevant mesoscale activity either in the overall eastern part of the basin or in the Gulf of Lion in the western part.

**Key applications**

Three key areas where application of new theoretical ideas is encouraged by the programme are as follows.

■ *Lagrangian observations*

The main emphasis here is on developing and testing new data analysis methods for Lagrangian observations taken typically from neutrally buoyant floats or balloons, and also on identifying relevant statistical parameters for describing the Lagrangian transport process. There is an urgent need for such work given that observational campaigns such as EUROFLOAT and STRATEOLE are under way or in advanced stages of planning.

■ *Chemical and biological implications of transport and mixing*

Effects of transport and mixing are particularly relevant to important problems in atmospheric chemistry, e.g. ozone depletion, understanding the chemical balance of the free troposphere and in considering effects of urban and industrial pollution. In the ocean, the structure of the flow has a strong effect on biological populations, from the scales of individual fronts and eddies up to the basin scale. Even in spatially homogeneous systems, reacting chemicals, or biological populations and nutrients, obey highly nonlinear evolution equations. In fluid flow the evolution of spatially varying chemical or biological components is likely to be strongly affected by transport and mixing. The ESF programme is stimulating new theoretical investigations to study such problems in as much generality as possible and to develop relevant quantitative models and diagnostic techniques.

■ *Transport in specific atmospheric and oceanic contexts*

The Mediterranean Sea is a particular focus of ocean modelling studies, partly because it serves as a good test-case for ocean models. It is relatively small in size, but encompasses most of the processes, e.g. for water mass formation, that are present in larger oceans. Studies of Lagrangian dispersion using Mediterranean ocean models will naturally complement the theoretical part of the programme and are potentially useful in tracing the different water masses in the Mediterranean general circulation. Moving to the atmosphere, tracer and particle studies have already been used with much success in the study of stratospheric transport. Attention is now gradually shifting downwards to the upper troposphere/lower stratosphere region, because of its importance for climate, as well as for ozone. New theoretical insight is needed to understand the role of different circulation features in transport and mixing in this region, e.g. in exchange between troposphere and stratosphere.

## TAO work programme

The four-year programme, ending 1999, is designed to encourage the circulation of ideas and expertise via an intensive exchange of researchers, embracing all relevant European research groups, including those from eastern Europe. There is therefore strong emphasis on promotion of exchange visits of up to six months duration, for research and training purposes. In common with other ESF programmes, a particular objective is to encourage young researchers in the field to gain a more complete multi-disciplinary scientific background, and this is being accomplished through support of summer schools organised by various European institutions. A Workshop is being held each year, in which about 50-60 scientists spend four to five days discussing and debating recent ideas emerging from various parts of the programme. In 1997 a set of smaller working group meetings were held to focus on key questions that were identified during the first year or so of the programme. Towards the end of the programme it is intended to hold an extended study centre, lasting about one month, to ensure that some of the new ideas generated during the programme come to fruition.

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Cover picture:
Passive tracer on 320K isentropic surface, estimated from observed winds, using a high-precision Lagrangian tracer advection algorithm. The tracer contours were initialised 4 days earlier to coincide with contours of a dynamical tracer, potential vorticity, that can be estimated from meteorological observations. The contours were chosen to lie in the region of the tropopause, the notional boundary between troposphere and stratosphere, which intersects this isentropic surface. The figure illustrates the filamentation process by which air is exchanged from stratosphere to troposphere (and vice versa). (Figure supplied by Dr W.A. Norton, University of Oxford.)


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