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Report on Turbulence and Mixing in Geophysical Flows II

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Abstract. We describe the presentations at the international meeting/workshop on Mixing in Geophysical Flows that took place at Vilanova i la Geltru, near Barcelona during the 20, 21 and 22nd of March 1997. There were more than 100 participants from 20 countries with 66 oral and poster presentations covering experimental and theoretical aspects of rotating and stratified fluids as well as field observations. The main topics discussed at the workshop were stratified flows, rotating stratified flows, gravity waves, instabilities and mixing, convection, experiments and numerical simulations of Geophysical flows and turbulent mixing. The papers are summarised in this report giving a state-of-the-art overview of present research in geophysical turbulent mixing.

Key words: turbulent mixing, stratified flows, geophysical flows.

1. Introduction

Flows where both the velocity and density vary with height arise naturally. Understanding both the fundamental processes which trigger transition to turbulence and also the mixing properties of the ensuing turbulence itself is essential to the parameterization of the redistribution of important quantities such as moisture, heat, momentum and pollutants within geophysical flows.

The workshop addressed a wide range of geophysical mixing processes through 8 invited talks, 30 oral contributions and 28 posters. Approximately one third of the papers discussed experimental research, one quarter dealt with theoretical matters and a further quarter discussed numerical studies while the remainder of the contributions were related to geophysical observations. This mix of approaches provided a broad spectrum of mixing processes and a nice balance of the methods used to address the problems associated with them. Topics were discussed in contributed papers mainly falling under categories determined by an invited review paper.

The conference opened with a discussion of mixing processes in stably stratified fluids where the mixing is produced by some imposed turbulence. These processes occur when turbulence is generated, for example at the lower boundary of a stratified region and the turbulence interacts with the stratification. The discussion of mixing processes has recently become concerned with the efficiency of the mixing. This efficiency involves considerations of the energetics of the turbulence and the changes in the stratification as a result of increases in potential energy driven by the turbulence. Under certain circumstances it is known that smooth stratification develops a series of layers separated by relatively sharp interfaces. This layer formation process appears to be related to questions of mixing efficiency and discussion concentrated on this aspect. The presence of layers and sharp interfaces raises interesting issues concerning the role of molecular properties of the fluid and has relationships to layering in double-diffusive systems. This aspect was also a theme of the conference and was related to other mechanisms for layer formation.

Since geophysical flows are characterised by stable stratification they support waves, and internal gravity waves were the subject of a number of the papers discussed at the conference. Both numerical and theoretical work on internal gravity waves and their relation to observations, especially in the atmosphere, was a major theme of the meeting. The role of internal gravity waves in the energetics and the relationship to mixing efficiency was also discussed in the context of mixing in high Richardson number flows.

The generation of turbulent motion in geophysical systems is often thought to be a result of some local instability usually produced by shear. Shear instabilities depend crucially on the detailed velocity and density profiles in the region of high shear and, consequently, there is considerable interest in analysing the effects of these different profiles. Under certain circumstances when the overall Richardson number for a flow is large it is still possible to generate vigorous shear instability and a wide range of modes are unstable from Kelvin Helmholtz to Holmboe modes depending on the nature of the density profile. A major theme of these discussions was the way these modes arise and the energy they extract from the flow which again has implications for mixing efficiency in stratified fluids.

A further theme of the meeting was gravity driven flows. In convectively unstable flows interest now has begun to focus on the effects of local but distributed heating. These flows are relevant to deep convection in the ocean and to intense convective events in the atmosphere such as hurricanes. Analysis of these flows using dimensional and scaling arguments was a feature of a number of presentations and also some further developments in the theory of plumes was discussed. Other types of gravity-driven flows which were examined at the meeting were gravity currents which result from primarily horizontal variations in density and these may be thought of in some sense as analogous to convective plumes, particularly in regions of sloping topography. Further, the effects of convective flows produced by the presence of suspended particulate matter has seen significant developments recently. Some of these were discussed and their role in geophysical mixing evaluated.

Mixing at high Richardson numbers is an intermittent process and the effects of stratification is to produce vertical vorticity in the flow. These vortical motions can trap fluid and can lead to anomalous forms of horizontal dispersion. The interaction between these vortical modes on different density surfaces can lead to vertical mixing and this theme relates to the discussion about mixing efficiency and layer formation using a more mechanistic view of the way in which fluid is mixed by the forcing motions.

In the remainder of this paper we describe the individual contributions to the conference and outline the main results which were presented. These are divided into sections according to the main themes of the meeting as defined by the invited review lectures. The discussion of these contributions is our interpretation of the papers that are presented and do not necessarily reflect the views of the authors themselves. Further details of some of the contributed papers may be found in accompanying papers in this volume.

2. Stratified Flows

The first session was dedicated to stratified flows and the meeting started with an invited Lecture by J.H.S. Fernando on "Mixing in Stratified and Rotating Flows, Experiments of Some Geophysical Relevance" who reviewed different laboratory experiments which investigate important geophysical phenomena, such as the mixed-layer dynamics in the lower atmosphere and the upper ocean or deep convection occurring in both the atmosphere and oceans. He showed how the experiments were used to isolate and study the fundamental mechanisms taking place, to interpret field measurements and to validate predictive models.

J.L. Pelegri and P. Sangra presented work done at the Canary Islands on "Comparison between Two Different Mechanisms for Layer Formation in Stratified Flows". The Phillips–Posmentier mechanism, see [5], in which the vertical buoyancy flux is reduced in regions of high density gradient, has often been invoked to explain staircase type structures observed in the ocean. The role of the temporal scale of turbulence was investigated in a numerical model comparing both layering and shear induced instabilities. A temporal memory for turbulence was deemed critical in generating layering for Kelvin–Helmholtz instability.

J. Holford and P.F. Linden discussed "A Mechanism for the Development of Layers in a Turbulent Stratified Fluid". This paper continued the theme of layer formation in stratified flows by describing a series of laboratory experiments in which a uniformly stratified fluid is stirred repeatedly by a rake of vertical bars. The paper concentrated on a new layering mechanism, see Figure 1, which occurs at intermediate Richardson numbers, Ri, in which the interfaces develop as a result of the divergence of the buoyancy flux due to the presence of impermeable horizontal boundaries. At these boundaries well-mixed boundary layers form as a result of the zero flux conditions at the top and bottom of the fluid. Interfaces form at the edges of these boundary layers which reduce the buoyancy flux locally and, consequently,

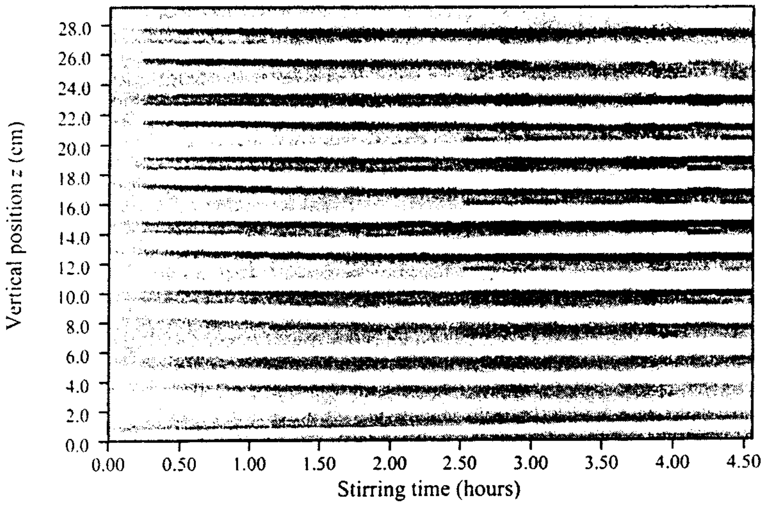

Figure 1. Layering produced by stirring in a linearly stratified flow at Ri $= 0.75$.

they act in an analogous manner to the impermeable boundaries. Subsequently, further layers grow inwards from the boundaries and once formed the interfaces strengthen as the stirring continues in a manner typical of high Richardson number flows. The explanation for this process can be given in terms of the divergence of the buoyancy flux associated with perturbations to the density field resulting from the boundary conditions. The experiments show clearly that the boundary grew as if controlled by a diffusive process and the turbulence within the mixed layers appears to be characterised by passive diffusivity scalings.

3. Rotating and Stratified Fluids

Y. Chashechkin presented his work on “The Impact of Boundary Conditions on the Onset of Diffusion Induced Boundary Current or Convective Driven Flow on a Sloping Wall in a Multicomponent Stratified Medium”, where he showed that the main feature of the multicomponent diffusion induced flow is a composite boundary layer with different scales of spatial variability for velocity, density and concentration of components. On a heated wall besides the boundary current, a front is formed, in which the boundary fluid propagates with a constant velocity perpendicular to heater surface.

The fine structure of convective cells flow near a sloping plane in a stably stratified brine was investigated using optical (different Schlieren and colour Schlieren methods, dye markers) and probe techniques. The time dependence of the velocity and temperature fields of the growing convective cells is determined for different values of the heat source inclination angle.

A. Stegner and V. Zeitlin presented their work on “Monopolar Solitary Vortices in Barotropic and Baroclinic Differentially Rotating Fluid and Their Transport

Properties", both theoretically and experimentally. They examined the dynamics of large scale monopolar vortices in differentially rotating fluid, by investigating several asymptotic regimes close to quasi-geostrophic balance. These regimes were identified depending on the mutual relations of the Rossby number, Burger number and the non-dimensional gradient of the Coriolis parameter in the shallow-water, multilayer and continuously stratified models. They showed that large scale solitary vortices exist with long lifetimes. These vortices were dynamically robust and are capable of significant transport of the fluid trapped within them. Theoretical predictions were validated in the laboratory by studying a shallow fluid layer in a rapidly rotating paraboloidal tank and using visual image analysis techniques.

A related study by G.S.L. Smith, "Entrainment by Vortices" described a point vortex in shear flow, using Lagrangian methods and dynamical system analysis to estimate residence times and entrainment rates. This study also showed that fluid has long residence times trapped in the vortices.

A.I. Ginzburg, A.G. Kostianoy, D.M. Soloviev and S.V. Stanichny discussed the role of "Transversal Filaments in Coastal Upwelling Satellite Images of the Black Sea". Temperature signatures were detected by means of Infrared sensors of the NOAA-11. The upwelling front was detected between 20 and 50 km from the coast showing transverse filaments of 4–14 km. These filaments have been identified as a significant process in the transport of material from the coastal zone to the interior of the Black Sea. The sizes of the observed filaments do not match analogous flows in the laboratory and their dynamical structure is still under investigation.

4. Gravity Waves and Stratification

This session started with an invited presentation by the first author in J.M. Rees, J.C.W Denholm-Price, P.S. Anderson and J.C. King, who discussed "Case Studies of Internal Gravity Waves in the Stably Stratified Atmospheric Boundary Layer".

The transport of energy and momentum by internal gravity waves in the stable atmospheric boundary layer is significant and hence it is of interest to investigate their properties and the conditions under which they occur. To date, few papers have been published which present a climatology of gravity wave activity, yet such information is needed for the evaluation of the statistical influence of gravity waves on boundary layer dynamics.

J.M. Rees analysed an extensive set of boundary layer observations collected by the British Antarctic Survey from Halley Station, Antarctica, during Phase II of their Stable Antarctic Boundary Layer Experiment (STABLE). Since gravity waves at the surface are most readily detected via pressure measurements, an array of six microbarographs was designed specifically to operate under the extreme climatological conditions prevalent in the Antarctic. Microbarograph observations were supplemented with measurements from an instrumented 32 m meterological mast and SODAR. The layout of the microbarograph array was chosen so as to be sensitive to typical wavelengths and phase speeds [1]. The importance of internal

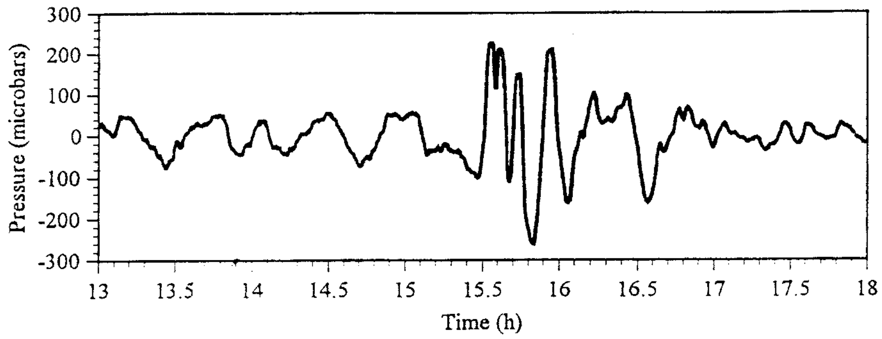

Figure 2. Time series of micro-barograph data detecting internal waves in the Antarctica.

waves was highlighted during the presentation and several sections of data analysed in detail as that shown in Figure 2.

C. Koudella and C. Staquet presented work on "Dynamics of Two- and Three-Dimensional Progressive Internal Waves", which described direct numerical simulations of internal waves propagating through a linearly stratified fluid. When white noise is added, the space time coherence is lost causing the waves to break and mix. For 2D waves three stages of evolution were defined during which secondary modes are selected by resonant wave interaction and the waves degrade and break to generate small scale turbulence. Finally, buoyancy causes the decay of this turbulence. The evolution of 3D waves is basically similar but the wave interactions induced more complex behaviour.

P. Bouruet-Aubertot, C. Koudella, C. Staquet and K. Winters showed results on "Particle Dispersion and Mixing by Breaking Internal Gravity Waves". A numerical simulation of diapycnal mixing produced by breaking internal waves was used to evaluate the mixing produced by the different kinds of instability. This mixing was estimated by two different methods; first by the evaluation of the increase in potential energy and also from the vertical dispersion of a cloud of particles as shown in Figure 3. Good agreement was found between the two methods, and this comparison enable vertical dispersion rates to be related to the energetics of the mixing process.

5. Instabilities and Mixing

The session was opened by an invited lecture by C.P. Caulfield entitled "Sheared Stratified Flows". The lecture commenced with a review of the range of instabilities that may develop in an initially laminar stably stratified shear flow. Such flows may arise in a variety of geophysical situations. Flow instabilities may lead to the breakdown of laminar flow, triggering turbulent eddies which are responsible for the redistribution of important quantities such as heat, momentum and pollutants. Current research focusses on identifying and understanding the mechanisms which lead to transition to turbulence and the ensuing mixing processes. This work in-

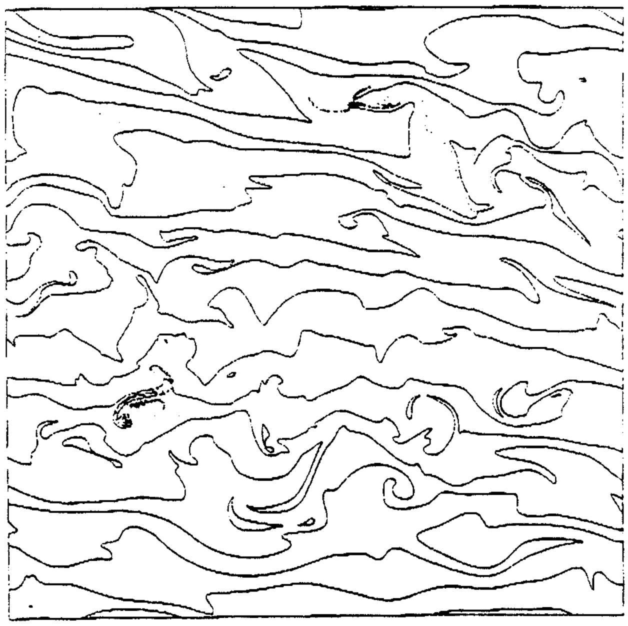

Figure 3. Dispersion of two initially compact particle clouds by progressive internal waves after 7 buoyancy periods.

volves understanding the effects of variation in stratification and the significance of length scales involved.

It is important to note that the evaluation of a bulk Richardson number is inadequate for characterising the stability of a flow, the presence of thin layers with small gradient Richardson number can destabilise a flow even if the bulk Richardson number is large. In a stratified shear flow transition to turbulence occurs in two stages: the onset of "primary" two-dimensional instabilities may be followed by the development of three-dimensional "secondary" perturbations of the primary vortical structures. The Kelvin–Helmholtz billow dominates when the length scales over which velocity and density vary are of the same order. If the density interface is sharp, then Holmboe instabilities (characterised by a cusped shape) may develop. In contrast to the Kelvin–Helmholtz billows, Holmboe instabilities are inefficient at mixing the background density distribution. Future work in this field will address the issues of three-dimensional merging and the effects of strain.

M.A. Bees addressed "Planktonic Interactions and Chaotic Advection in Langmuir Circulation". Langmuir circulations arise if there is a balance between a wind induced Stokes drift gradient (a stabilising influence) and a temperature driven, vertical density stratification (a destabilising effect). They are typically manifested as long roll structures of width between 1 and 100 m commonly identified from debris or windrows at regions of surface convergence.

Recent studies of plankton dynamics identify plankton patchiness as a significant cause of the discrepancy between predictions from bulk-averaged models and field measurements. Moreover, Langmuir circulation is thought to play a significant role in causing planktonic mixing and/or aggregations in the so-called Stommel retention zones.

A time-dependent numerical model for such a flow has been used to study the effects of unsteadiness and buoyancy on the distribution of plankton. Deterministic transport of scalars (in this case the plankton) may take place via chaotic advection, leading to a large effective diffusivity. Discussion ensued on whether predators should adopt a different strategy when looking for food in an unsteady flow (rather than a steady flow) in order to minimise their foraging time. It was concluded that the presence of chaotic regions within Langmuir circulations may benefit filter feeders but may be detrimental to active predators. Zooplankton can make use of chaotic regions to travel large distances in order to look for food. Future work in this area will examine the effects of turbulence on such flows.

A paper entitled "Mixing and Biological Effects of Internal Tides on the Shelf Break of Gran Canaria Island" was presented by P. Sanga, J.L. Pelegri, V. Favrel, J. Aristegui, G. Basterrechea and B. Jimenez. Over a two-week period in 1994, a CTD/acoustic current meter and chlorophyll distribution survey was made in the Gran Canaria shelf break in order to investigate internal tide mixing and associated biological effects. The time evolution of the pycnocline was studied. Couplings between pycnocline and barotropic tide oscillations were observed at semi-diurnal frequency, suggesting the presence of a baroclinic internal mode. Profiles of the gradient Richardson number suggested that intense mixing was mainly related to pycnocline troughs. Chlorophyll profiles indicated strong coupling with pycnocline motion and mixing. A bio-physical model was run to study the biological effects of internal tides. Simulations indicated the presence of a second maxima in the zooplankton annual cycle in October, which is in agreement with previous biological studies made off the coast of Gran Canaria.

The last paper in the session was on "Turbulent Buoyant Plumes in a Rotating Channel with Applications to Hydrothermal Systems", by J.W.M. Bush and A.W. Woods. Hydrothermal plumes at mid-ocean ridges play an important role in deep-ocean mixing and the chemical and thermal budget of the oceans. Mineral-laden hydrothermal effluent emerges from isolated chimneys in the form of turbulent buoyant plumes and rises approximately 200 m until it reaches its level of neutral buoyancy and spreads as a gravity current. The influence of rotation and channel geometry on the dispersal of hydrothermal effluent from axial valleys was considered in this paper. A theoretical model describing the influence of rotation on the plume was developed assuming that the gravity current is in geostrophic balance. In a rotating environment, plume motions are suppressed by the Taylor–Proudman constraint. Model results were compared with an experimental study of turbulent buoyant plumes in a rotating channel, designed to allow examination of the dependence of the mode of discharge on governing parameters and to characterise the influence of rotation on entrainment into the plume.

In the theoretical model, the plume dynamics is not strongly influenced by rotation; consequently, the source conditions of the gravity current may be deduced from the scaling which describes classical turbulent plume theory.

The relative importance of rotation and buoyancy in the dynamics of the gravity current is prescribed by the ratio of the channel width to the Rossby deformation radius. Choosing parameter values relevant for hydrothermal plumes indicates that rotation plays a significant role in the discharge of hydrothermal effluent from axial valleys.

6. Field and Laboratory Measurements

T. Granata and M. Estrada presented their work on "Estimates of Mesoscale Vorticity Associated with Large Scale Variability of Chlorophyll-Fluorescence in Planktonic Phytoplankton" discussing the density front between the Catalan and Balearic currents. The front is often associated with high levels of phytoplankton production. From field measurements they found that the vorticity production across the front was correlated to biological production on scales comparable to the width of the front, showing a strong link between physical and biological aspects.

J. Salat presented "A Dynamic Method for Horizontal Distributions of Sea Water Properties" which was used to interpret recent campaigns in the Alboran sea. In an attempt to obtain synoptic data uncontaminated by time aliasing the extrapolation algorithm accounts for the relative movements of the water masses that took place during the ship cruise. These distributions are calibrated and optimised with satellite images of the region.

J.L. Aider presented work in collaboration with G. Stolovitzky, E. Gaudin and J.E. Wesfreid on "Coherent Structures and Conditional Statistics of a Passive Scalar". As has been described above, the presence of coherent structures have a strong influence on dispersion. This paper described the behaviour of an archetypal structure with a view to delineating the influence on a scalar field. The structures investigated were Gortler vortices arising from centrifugal instability in the boundary layer over a concave wall of a curved channel. They found the basic mushroom shape is advected and distorted in the turbulent flow without destroying it. The structure of the scalar tails was gaussian and the statistics of pdfs were explained.

O. Ben-Mahjoub and J.M. Redondo presented a paper on "Velocity Structure Functions and Higher Order Moments in Non-Homogeneous Turbulence" using a 3D sonic velocimeter to calculate the ratios of moments and structure functions of decaying grid turbulence. The ratios of moments allow an estimate the scaling exponents by means of extended self similarity. The higher the intermittency of the flow, the greater the discrepancy between Kolmogorov theory and the experimental data.

A.C. Marti, J.M. Sancho and F. Sagues presented their work on "Synthetic Turbulence: Generation Model and Applications" using a 2D kinematic simulation model based on a stream function. The statistics of the model was gaussian and it was used to investigate the dispersion of particles and the phase separation process under stirring.

R. Bresinski and M. Pocwierz discussed “A Model for Dust Spreading in the Turbulent Atmosphere” using the diffusion advection equation in order to predict dust concentration. The washout by precipitation was included defining the probability of particles in suspension being affected by rain, fog and snow. Several cases were discussed showing different spreading rates for diffusion dominated flows and advection dominated ones.

A. Montoto, A. Falques and D. Vila described the “Set Up Instabilities in the Nearshore Hydrodynamics” setting the conditions for instability driving nearshore processes in the absence of a longshore current, these disturbances may lead to rip currents and rhythmic bathometry. An important observation was the role that the wave breaking parameter has on the formation of secondary instabilities.

S.N. Dikarev presented work on “Laboratory Models of Deep Ocean Convection” identifying two different mechanisms either for shelf convection or open ocean deep convection. This latter takes place in the center of cyclonic gyres during winter cooling. From a model of overturning formed by a buoyant jet in a rotating tank, it was observed that the rotation enhanced the efficiency of local overturning.

J.J. Martinez-Benjamin showed “SAR Images in the Western Mediterranean Sea” including the detection of internal waves, the characterisation of coherent structures and the extent of coastal features. A comparison between Scan SAR Narrow from Radarsat and SAR images from ERS-1 and ERS-2 was made discussing the advantages of both. Examples such as the one shown in Figure 4, from the Clean Sea European project were discussed. The complex structure of interacting eddies is revealed by SAR due to changes in the surface tension of the sea.

A. Rodriguez-Santana, P. Sangra and J.L. Pelegri presented their work on “Dyapicnal Mixing in Frontal Systems” considering that the Jacobian of the function between depth and density is determined by vertical mixing. The diapycnal velocity $D\rho/Dt$ was expressed in terms of the eddy diffusivity and the geostrophic gradient Richardson number. The layer formation in the frontal areas was studied with the help of a numerical model that reproduces the layering features often found in such regions.

Several posters presented at the meeting will be discussed briefly: A.G. Zatsepin, S.N. Dikarev, S.G. Poyarkov and N.A. Sheremet presented the results of a “Laboratory Experiment on Stirring of Stratified Fluid by the System of Oscillating Vertical Rods” showing the formation of layers after continuous stirring for some parameters. The number of layers decreased in time due to merging of the layers until a two layer system was formed.

M. Alarcon from UPC at Vilanova presented “A Lagrangian Model for Long-Range Atmospheric Transport Simulation” called TRACOMIX that takes into account complex orography and applied it to the NW Mediterranean coastal area.

Figure 4. SAR image revealing a complex structure of interacting vortices.

D. Abdeslam, on behalf of I. Mercader and J.M. Massaguer presented their work on “Instabilities of Tollmien–Schlichting Waves in a Finite Periodic” showing the conditions for bifurcations in the solution of Poiseauille flow.

M.O. Bezerra, C. Medeiros and I. Freitas from Pernambuco University in Brazil showed some field work on the “Effects of Wave Height, Winds and Tidal Currents on Coastal Diffusion” using image analysis of dye dispersion in the ocean to calculate eddy diffusivity coefficients, they showed the dependence with wave height and wind stress. A similar technique was used by A. Rodriguez, A. Sanchez-Arcilla, E. Bahia, J.M. Redondo and M. Diaz from UPC for data obtained at the Ebro Delta with aerial camera views presenting a “Study of Surf-Zone Mixing Using Video Images”, see Figure 5 for a view on the dye blob structure.

M.A. Sanchez presented some “Experimental Techniques in Zero-Mean-Flow Stirring” applied to the lift off of sediments by means of grid stirred turbulence generated by an oscillating grid.

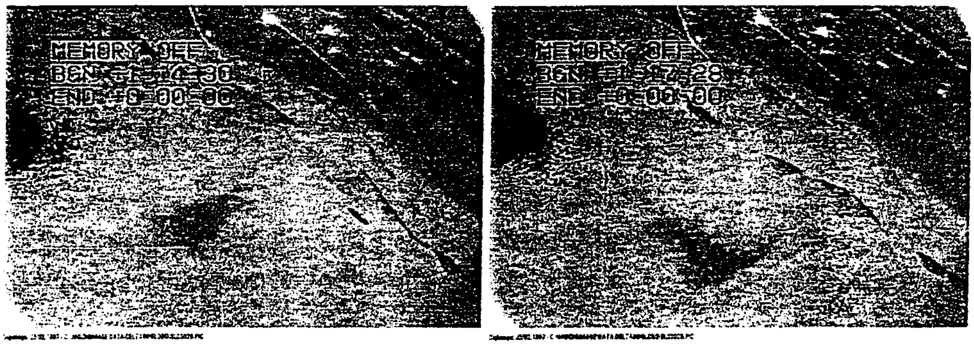

Figure 5. Dispersion of a blob of dye in the surf zone due to wave induced mixing and longshore instabilities.

I.R. Cantalapiedra, C. Benitez and J.M. Redondo discussed “Velocity Measurements and LES of Bubble Induced Circulation” comparing experiments on non-homogeneous turbulence generated by a linear air bubble plume with Large Eddy Simulation of the same flow. Velocity measurements were made by ultrasonic velocimetry and the overall patterns were simulated by the LES with a Smagorinski type of eddy viscosity.

R. Castilla presented a “Kinematic Simulation on Homogeneous and Isotropic Turbulence” comparing the free fall in a turbulent flow of sediments of different sizes there is a complex relationship between the turbulence characteristics such as the Kolmogorov and Integral scales and the slowing or accelerating of the sediments.

7. Geophysical Flows Driven by Convection

The session devoted to convective flows started with the invited lecture by B.M. Bouvnov on “Vortex Mixing in Convection from Local Heating in Rotating Fluids”. He showed that convection arising from localised heating is the usual source of convective motions in geophysics. Consideration of convection from a heated disk showed several different mechanisms: a laminar thermal layer above a disk, turbulent motions at some distance above a disk, motions from the edge to the center of the disk and flows far from the disk. Background rotation changes motions in all of these regions in different ways.

The non-dimensional parameters are: aspect ratio, A, Rayleigh and Taylor numbers. A Rossby number Ro can be introduced by using a convection velocity, which depends on the heat flux.

When $A > 1$ and the height of the layer is large different regimes develop with an increase in background rotation: for $\mathrm{Ro} > 10$, there is an anticyclonic turbulent plume above the disk. Periodical tornado-like vortex occurs for $10 > \mathrm{Ro} > 1$ and a system of vortices above the disk appears for Ro less than one 1.

When the aspect ratio is of order unity additional interactions between the vortex motions with the upper boundaries takes place. In this case an intensive quasi-laminar cylindrical vortex transforms into a turbulent toroidal vortex.

R. Verzicco and R. Camussi presented a paper on "Transitional Regimes of Low-Prandtl Thermal Convection in a Cylindrical Cell" showing numerical results on the onset of convection for mercury which takes place at a Rayleigh number of Ra = 3750. When Ra is increased, several transitions take place leading to turbulent convection. The Nusselt *versus* Rayleigh number curve was also presented with a power law behaviour.

A.W. Woods and C.P. Caulfield presented their work on "Similarity Solutions for Turbulent Buoyant Plumes" in both non-uniform environments and with non-localised sources of buoyancy. This work has application in a number of environmental and geophysical situations, where the background stratification is non-uniform, e.g., the thermal stratification within buildings and the stratification in the upper few hundred metres of the ocean. (In the building ventilation context, turbulent buoyant plumes often develop from heating or cooling units, and the motion of these plumes also depends critically on the the geometry of the source.)

A family of similarity solutions for turbulent buoyant plumes in non-uniform environments were modelled with power-law density profiles, and they identified the critical power-law stratification for which buoyant plumes are just able to ascend indefinitely even in a stably stratified fluid. These provide new estimates of the filling box mixing in a non-uniformly stratified buildings, and the related applications to natural ventilation.

W.B. Zimmerman discussed the "Formation of Stable Stratification in a Driven Cavity Flow" where he showed that in stratified situations, the equation of state determines the mixing in terms of the density as a function of solution concentration. Several types of equations of state were considered in hydrostatic equilibrium leading to multilayer systems. In the presence of convective mixing the equation of state ceases to play an important role.

8. Geophysical Fluid Dynamics Experiments

The invited lecture by T. Maxworthy was devoted to the "Laboratory Modelling of Stratified and Rotating Flows". He reviewed experiments on the decay of stratified turbulence generated by a grid. By constructing a "time-line", Maxworthy showed that the stratification acts over several time scales. Initially, on a time scale of N^{-1}, buoyancy forces suppress vertical velocities and the turbulence becomes strongly anisotropic. Internal gravity waves are generated. On longer time scales, the flow develops strong vortical motions confined to different vertical layers within the fluid. Energy cascades to these large scale coherent structures which have long life times. Their decay is caused by dissipation resulting from the vertical shear of the horizontal velocities. Similar behaviour has been observed in numerical calculations (e.g., [2]).

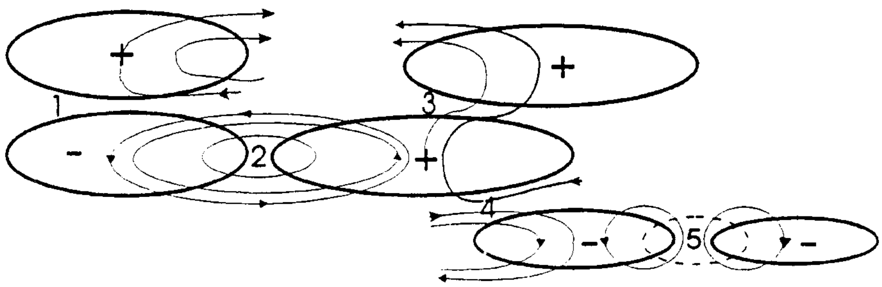

Figure 6. Cross section of the possible connections between turbulent vortical structures in a stratified fluid.

The underlining mechanism seen in a series of careful experiments on the structure of wake generated turbulence in a stratified layer was that internal waves provide some exchange mechanism to couple different stratified well mixed lenses "Blini" at different heights in the decaying stratified fluid [4]. See in Figure 6 an example of the possible structure and links between these patches.

A.G. Zatsepin, V.L. Didkovskii and A.V. Semenov presented a series of laboratory experiments on "Gravity Currents on the Sloping Bottom in the Rotating Fluid" in order to model the spreading and sinking of dense water in an inclined oceanic bottom or platform area as this is an important process in deep water recirculation. Dense fluid was injected on the side of a submerged cone in a rotating tank showing different types of flows and instabilities depending on the governing parameters. A striking feature of these experiments was the production of coherent, isolated vortices even though the source of dense fluid is constant in time.

M. Bonnier, P. Bonneton and M. Perrier presented their work on the "Far Wake of a Sphere in a Stably Stratified Fluid. Characterization and Behaviour of Vortex Structures" where the collapse of a wake was discussed and the far and near wake vortical structures were compared. They showed that the vertical propagation of vorticity is dominated by viscous transport and proposed a model of an idealised vortex to explain the observations of a tilt on the vortex dominated wake.

J. Colomer and X. Casamitjana in their paper on "Sediment Turbulent Entrainment in Karst Basins" presented a series of experiments modelling the resuspension of a sediment bed due to jets emerging from the bottom layer, see Figure 7. The results to the Lake Banyolas, which has a hydrothermal feeding system that creates lutoclines at a certain depth.

T. Serra and X. Casamitjana also presented "A Model to Describe the Aggregation and Break Up of Particles in a Turbulent Flow". The basis for aggregation came from the probability of two smaller particles meeting and aggregate. Losses due to both the break up of large aggregates due to shear and due to collisions.

T. Granata and C.M. Duarte presented some field work on the evaluation of the "Turbulent Kinetic Energy in and around Shallow Seagrass Canopies Measured Using Acoustic Doppler Velocimetry". Vertical velocity profiles were measured in

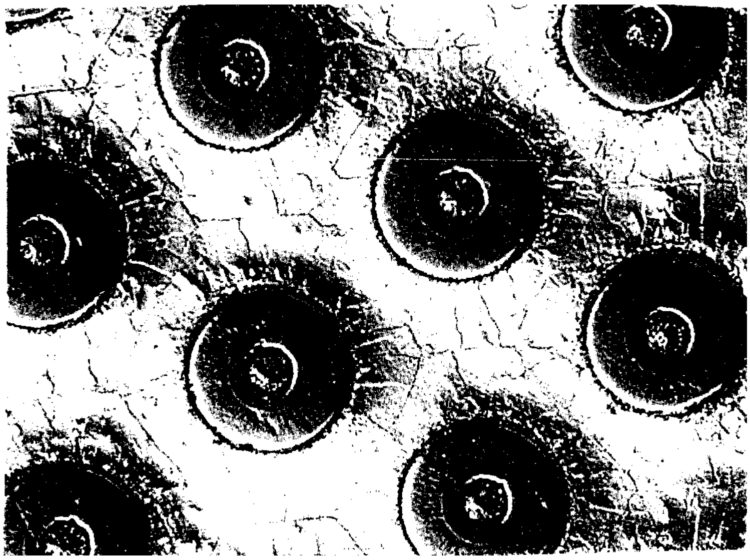

Figure 7. A top view of a jet induced erosion on a sediment bed.

situ a depth of about 5 m with a sonic 3D velocimeter. Significant differences in the vertical shear were measured within and outside the canopy region of *posidonia* spp. There were also large differences in diffusivity.

A.I. Gizburg, A.G. Kostianoy, N.A. Sheremet and A.G. Zatsepin discussed the effect of “Mesoscale Eddies and Relative Mixing in the Black Sea”. Satellite images were used to detect and study the evolution of two anticyclonic eddies and one cyclone with a life time of four months. The integral lengthscales associated to the eddies were described showing interactions between them which produced secondary vortices, throughout the lifetime of these long-lived vortices they changed their relative positions. The direction of the random displacements of the system are thought to be due to the wind.

F. Dupont, R.I. McLachan and V. Zeitlin presented work on “Anomalous Diffusion by Resonant Triads of Gravity Waves and Rossby Waves” where passive scalar advection by resonant triads of gravity waves and Rossby waves was investigated by integrating Lagrangian equations of particle motion in the plane with a velocity field provided by a resonant wave triad, they found that a phenomenon of ballistic advection of the tracer takes place, i.e., while for majority of initial positions of tracer particles a slow diffusion takes place, there are regions of positive measure in the phase-space where tracer particles experience a rapid ballistic motion in a direction determined by internal geometry of a triad.

A. Alonso and M. Net showed the stability analysis of an “Ekman Boundary Layers in a Rotating Annulus with Radial Heating” as a model of planetary convection in the equatorial regions. The role of the boundary conditions at the ends of the cylinder on the Eckman boundary layer was described.

9. Numerical Simulations of Geophysical Mixing

The session on numerical simulations was concerned with the application of a wide variety of numerical methodologies in an attempt to model the fundamental problem of turbulence in stably stratified turbulence. A broad spectrum of innovative techniques were presented, and substantial progress towards improved understanding of stably stratified turbulence was demonstrated. It is clear that numerical modelling has a vital part to play in the advancement of knowledge of mixing in stratified flows, and the presentations in this session demonstrated how numerical studies are complementary to theoretical, experimental and observational work presented elsewhere within the meeting.

The invited lecture of this session was presented by C. Staquet. The talk was entitled "Statistical Modelling and Direct Numerical Simulations of Stably-Stratified Homogeneous Decaying Turbulence". The first part of this talk was devoted to a detailed comparison of direct numerical simulations (DNS), results from a numerical calculation using the eddy damped quasi-normal Markovian approximation (EDQNM) model, and wind-tunnel experiments in the literature. EDQNM model utilises an anisotropic two-point closure, and allows a natural subdivision of flow quantities into "wave-like" and "vortex-like" components, a subdivision which has a very useful physical meaning in the limit of low Froude number.

The results of the EDQNM model calculations were validated both by comparison with DNS, and also by comparison with experiment in circumstances where alternative techniques (in particular Rapid Distortion Theory or RDT) are likely to have difficulties. Flows with strong nonlinearities were considered, and hence there is a significant amount of potential energy available at the beginning of the simulation. Typically, the initial potential energy was chosen to be equal to half the initial kinetic energy. Principal results of this comparison were very encouraging, with such important quantities as the Taylor microscale, Kolmogorov scale and total energy of the flow well predicted by the EDQNM model. For the particular initial conditions studied, RDT proved to be very poor at modelling the energy of the flow.

The various simulations also yielded interesting and significant information about the evolution of the energy field, over a longer period (normalised by the buoyancy period $2\pi/N$, where N is the buoyancy frequency) than the duration of the wind-tunnel experiments. Over the first buoyancy period, the dynamics are strongly influenced by the significant amounts of initial potential energy available within the flow, and the transfer of potential energy to small scales is very marked, so much so that there is a down gradient heat flux at large scales and an up gradient heat flux at small scales. There is a qualitative agreement with experiment, although since there is no potential energy within the experiments immediately behind the grid, care must be taken in comparison between experiment and simulation.

Importantly, a fundamental ratio, which exhibits the same scaling properties in DNS, EDQNM modelling and experiment is the ratio of the two sinks of kinetic energy, namely vertical heat flux and dissipation rate of kinetic energy. In circumstances where these quantities can be identified independently, and calculated throughout time, this ratio may be referred to as an *instantaneous* mixing efficiency. It measures the relative significance (at any one instant) of the amount of kinetic energy within the flow which is redistributing fluid parcels in such a way as to increase the potential energy of the system (and thus in some sense "mix") to the kinetic energy of the flow which is being lost directly to turbulence. It is very important to note that at any particular instant this quantity may be greater than one, a point which though initially counter-intuitive, may be interpreted physically. For example, a large scale motion (with an attendant small amount of turbulent dissipation) may lead to a very large increase in potential energy at a particular time. Only at later times, when the motions contributing most to mixing are at a small enough scale so as to undergo substantial turbulent dissipation will this instantaneous "mixing efficiency" correspond closely to the more conventional "flux Richardson number" type definition of mixing efficiency, which of course is strictly bounded to be less than one. This qualitative change in behaviour was observed numerically to occur after about 1.5 buoyancy periods.

Since this instantaneous ratio of losses of kinetic energy appears to be a fundamental quantity, a recently developed formalism due to Winters and D'Asaro [3] was applied in detail to the results of a two-dimensional numerical simulation of a stratified shear layer, with Reynolds number 2000, and bulk Richardson number 0.167. The aim was to quantify, in a self-consistent and sensible manner, the processes of mixing, their "efficiency" and their relative importance. Fundamental to this concept of efficiency is the observation that (kinetic) energy must be converted into potential energy for mixing to take place. Furthermore, at any particular instant in time, the potential energy of the system can be divided into two parts. One part corresponds to reversible redistribution of fluid parcels of different density, the so-called "available potential energy". The other, irreversible part is the potential energy of a sorted, rearranged density profile, which represents the minimum potential energy of the system at equilibrium. This potential energy cannot be accessed by the fluid motions. It can be verified that the sorted minimised density profile has a step-like structure, consistent with experimental observations of decaying stratified turbulence. It was found that the mixing efficiency in this sense was indeed maximal at the stage in the evolution of the shear flow when the Kelvin–Helmholtz billow had maximal amplitude, and secondary instabilities were enhancing the mixing within the flow. Eventually, the value of the mixing efficiency relaxed back towards 0.2, as smaller scale motions started to dominate the process, consistent with experiments and observations.

The first of the lectures, entitled "Stochastic Models of Dispersion and Mixing in Stably Stratified Turbulence" was given by B.M.O. Heppe. In this talk, he considered the vertical dispersion of fluid particles in a homogeneous, stably stratified flow, principally considering the evolution of vertical velocity and temperature fluctuations about a constant mean gradient of moderate to strong stratification, using Lagrangian stochastic models. Fundamentally, to include the important effects of large, but finite Reynolds number, a Lagrangian time microscale was introduced, which mathematically corresponds to a non-Markovian “memory” term in the equation for the vertical velocity perturbations. Furthermore, molecular diffusion was simply modelled through a linear drift term in the temperature evolution equation. Good agreement, particularly in the velocity correlations, was found between this simple, but elegant model and direct numerical simulations of particle dispersion in a turbulent box.

The second of the contributed lectures was called “Direct Numerical Simulation of Turbulence in a Stably Stratified Fluid”, in which M. Galmiche discussed his joint work with P. Bonneton and O. Thual. Galmiche et al. conducted a series of direct numerical simulations of Boussinesq, stratified decaying turbulence in triply periodic three-dimensional domains. They used a poloidal-toroidal-mean shear decomposition. This is a highly useful way to decompose the velocity field, as each of the components can be associated with particular types of motion. The poloidal component of velocity is associated with flows with no vertical vorticity, the toroidal component of velocity has no vertical velocity, and the mean shear component is associated with horizontal mean flow. Understanding how the kinetic energy associated with each of these components evolves allows interpretation of the evolution and “collapse” of stratified turbulence.

Galmiche et al. found that the poloidal component of the kinetic energy and the potential energy interacted strongly through oscillations with period of approximately half the buoyancy period, in accordance with previous numerical and theoretical studies. Such oscillations can be described using RDT. Furthermore, if the initial conditions were chosen so that the energy in the mean shear velocity components was initially appreciably smaller than the energy in the poloidal and toroidal velocity components, they found that the energy in the mean shear velocity components increased rapidly. This implies that at later stages in the turbulent decay the flow is dominated by horizontal motions. In simulations where the energy in mean shear was of the same order initially as the other two parts (for example, in a turbulent wake, which also has significant amounts of vorticity initially) the mean shear energy still increased, and ultimately, irrespective of initial condition, the energy in the mean shear dominated the evolution of the flow.

The final lecture of the session was called “Kinematic Simulation for Stratified Flows and 2D Turbulence”, in which F. Nicolleau presented his joint work with J.C. Vassilicos and J.C.H. Fung. F. Nicolleau presented the argument that stochastic models of turbulent flow based around the concept of the random walk rely on the assumption that particle paths are Brownian motion paths. However, experimental observations imply that particle paths within turbulent flow are actually smooth, non-Markovian trajectories. This fundamental observational aspect of turbulent flow is mimicked by Kinematic Simulations (KS), which are Lagrangian models of dispersion that incorporate turbulent-like flow structure in every realisation of the Eulerian velocity field. The over-riding principle behind the use of KS is that the dominant property of turbulent flow is the smooth geometry of particle trajectories, and all other aspects of turbulent flow (e.g., departures from Gaussianity, solution of the Navier–Stokes equations, etc.) are secondary.

Mathematically in an unstratified flow, a KS flow field consists of a random, truncated Fourier representation in space and time, subject to constraints associated with incompressibility, and a prescribed initial energy spectrum. For stratified calculations, two further constraints are imposed, associated with the internal wave field in stratified flows, and the tendency of density variations to suppress vertical motion. With these model modifications, good agreement is found between KS and DNS with regard to the confinement in the vertical direction characteristic of stratified turbulence. Since stratified flows exhibit this vertical confinement, KS in strictly two dimensions was considered as a first step to understanding dispersion within a stratified flow. The properties of ensemble averages of the separation between two particles in a 2D turbulent flow were considered, and the KS approach was found to give highly satisfactory answers, with good comparison to experiment. In Figure 8 a vertical section of the velocity field at the initial conditions and after 5 turnover times is shown.

10. Mixing Details in Geophysical Flows

J. Cuxart described a "Large Eddy Simulation Model of a Convective Boundary Layer" and investigated the effects of sensitivity to resolution and parameterization. A turbulence scheme appropriate for use in a single column mode inside mesoscale models and in subgrid scale mode in very high resolution simulations was presented. It computes variable turbulent Prandtl numbers using a mixing length to close the system.

A convective boundary layer case was run at three different horizontal resolutions (50, 160, 300 m) and the computed statistics and the spectral diagnostics are intercompared. The aim is to inspect the ranges of applicability of the LES approach. The three simulations are able to represent the mean characteristics of a CBL. However, many differences exist concerning the boundary layer height, the entrainment flux and other averaged quantities. The distribution of updraughts and downdraughts changes with the resolution. The mixed layer is closer to neutral stratification for the highest resolution (HR) run.

The effects of the SGS turbulence model are very important in the entrainment zone, where the ability of the parameterization to compute the proper account of mixing is a key factor for the lower resolution simulation to give acceptable results. The lower the resolution is, the higher the CBL grows. Spectral analysis allows to identify a full inertial subrange only for the HR simulation. Superposition of the other simulation spectra on the HR gives the ranges of physical validity of each simulation. The extraction of the more energetic wavelength at each computation level is a new proposed diagnostic tool to interpret LES.

J. Prat presented the joint work with J.M. Massaguer and I. Mercader on "Nonlinear Interaction of Multi-Roll Solutions in the Rayleigh–Benard Problem", the

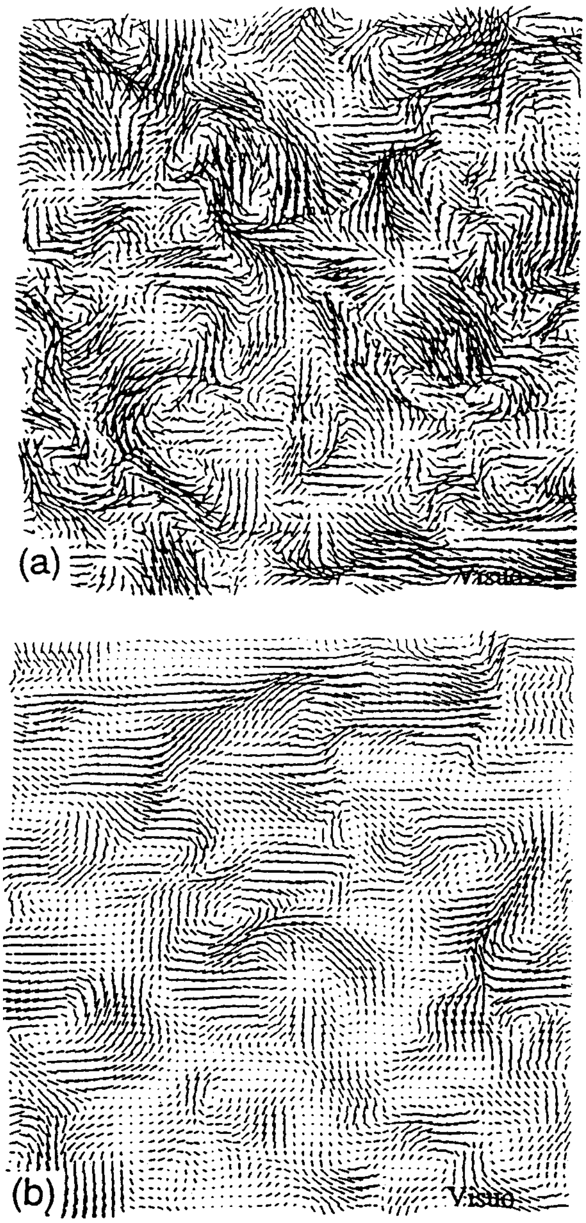

Figure 8. Vertical section of a velocity field: (a) initial condition, (b) after 5 eddy turnover time scales.

stability of convective rolls with respect to 2D perturbations and several resonances leading to the possibility of large scale flows were discussed.

J. Vila-Guerau, S. Galmarini, P.G. Duynkerke and C. Beets used LES to investigate “Entrainment and Mixing of Chemical Species in the Atmospheric Boundary Layer”. Differences between the convective and the stable boundary layers were shown to be functions of the Damkohler number (ratio of the characteristic time scales of the turbulence and chemical reactions) and the chemical species flux ratio.

J.M. Redondo discussed “Mixing and Stirring in Turbulent Flows” where a comparison between experiments where mixing is produced uniformly and those where mixing is localised and there are sideways intrusions is performed with the same apparatus with either a stepwise sharp density interface or a linear stratification, with constant N. The experiments covered the range $N = 0.01$ rad s^{-1} to $N = 1$ rad s^{-1}. The turbulence in the tank was produced by oscillating laterally an array of vertical bars. The region stirred was varied as a fraction of the base of the tank. Other methods of stirring, such as a vertically oscillating grid [4], grid dropping [5], bubble injection [6] or wave breaking [7], were compared showing different mixing efficiencies for the different systems.

Several laboratory experiments were presented in order to study the vertical structure and mixing across sharp and linear density interfaces. It was also shown that there is some difference in the amount of internal wave generation between the vertically and the horizontally oscillated grids.

O. Piro presented his work on “Dynamics of Neutral Particles in Cellular and Turbulent Flows” showing a Lagrangian dispersion model in the case of cell formation. The particles were shown to be trapped in the cell cores and suddenly cross cell transport takes place, leaving KAM regions where it is rare to find particles. The coherent structures produce anomalous dispersion like in atmosphere or ocean geophysical large scale flows.

E.P. Aniosimova, A.A Speranskaya and S.N. Dikarev presented their work on “The Usefulness of Free Turbulent Convection Models” showing the importance of the evaporation at small scale surface studies in the ocean, in order to combine different physical factors it is necessary to have a background model. A fresh water body subjected to cooling via surface evaporation has been used to study both the effect of rotation and of salinity.

11. Conclusions

The workshop described a wide range of mixing processes that occur in the environment [8]. These mixing processes are the key mechanisms for mass and momentum transfer in the oceans and atmosphere and as such play a crucial role in determining the environmental conditions in which mankind lives and operates. The approach almost universally adopted has been to isolate one or two particular processes and study these in detail using a combination of theoretical, numerical, experimental and observational techniques. This combination has proved very successful in delineating the physics of these processes and based upon this physical understanding it has been possible to develop simple formulae (parameterizations) which enable the effects of these processes to be represented in a simple way. It is clear from the presentations at this workshop that the physical processes are often subtle and involve time-dependent, three-dimensional turbulent flow. As such they are impossible to compute directly except in some very special circumstances and the rôle of this research is to provide parameterizations which capture in a faithful and defendable way the effects of these complex processes. It is clear from this workshop that there have been some significant advances in this direction and that there remain many challenges ahead. The third workshop on "Mixing in Geophysical Turbulence" will be held in April 2000 and we anticipate that further developments will be reported at that meeting.

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