MT26F Atmospheric Analogues

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Rooms GU01, GL42/GL61

These practical classes provide hands-on experience of a series of laboratory fluid experiments. The experiments are intended to illustrate some key features of geophysical fluid flows, as well as providing experience in laboratory measurements and techniques. The experiments reinforce selected concepts from the MT24A course, Atmosphere and Ocean Dynamics.

The following notes provide a basic "manual" for the module. They include information about safety, organisational details, and the treatment of experimental errors; they also provide detailed instructions for each of the laboratory experiments.

All students should read these notes before carrying out any experiments

1 Safety

The fluids laboratory is a hazardous environment. However most accidents can be avoided through exercising care and common sense.

In particular:

- Do not make adjustments to mains-supplied instruments or attempt to modify any apparatus without consulting a demonstrator or technician.
- If you are unsure about the condition of any electrical plug, lead, or equipment, bring it to the attention of a technician **before** turning it on.
- The rotating tanks, by their nature, operate with some considerable angular momentum. It is important to remain aware of their motion while they are operating. Do not put your hands inside the safety frames and do not lean against the frames.
- Take particular care when moving tanks filled with water around the laboratory.
- Acquaint yourself with the fire notices and establish the best escape route before you begin each experiment. All exits must be kept clear of obstacles and bags at all times. Should the fire alarm sound, leave quickly via the ground floor corridor, past the electrical workshop and exit the building at the base of the stairs.
- Never work in the laboratory unless a member of the academic or technical staff is also present. If you wish to use the laboratory outside normal timetabled hours, then you must arrange this with a member of staff beforehand.
- You are not allowed to use the laboratory outside normal working hours, which are 0845-1300 and 1400-1715, Monday to Friday.
- Do not bring food and drink into the laboratory.
- **When in doubt please ask a demonstrator**.

2 Organisation

The module consists of a) a short introductory session, b) 5 three-hour practical sessions and c) a short test. You will be assigned a different laboratory experiment each session. Details will be posted on the notice-board outside the Sutcliffe lecture theatre.

2.1 Preparation

Find out which experiment you will be performing in advance and read the notes on that experiment—this can save a lot of time and confusion on the day. If any point in the notes is not clear, ask a demonstrator or member of staff **before** you attempt to carry out the experiments. Always familiarise yourself with the layout of the apparatus before beginning an experiment.

2.2 Structure of the experiments

The experiments are mainly of the "black-box" type in the sense that you do not have to carry out any major design or setting-up of apparatus beforehand. However in some experiments you will need to decide on the appropriate measurements to take, and to develop an appropriate strategy. You should aim to complete the experiment within two hours, using the remaining time to complete the analysis of data and to write up your conclusions.

2.3 Laboratory Notes

Be organised: you should acquire a folder or laboratory notebook to enter your observations, analysis and discussion for each experiment. Tabulate data wherever possible. When preparing tables, remember that you will often need extra columns for data analysis, and that the number of rows may be initially unknown. Therefore, it is good practice to dedicate most of a page to your skeleton table, with a generous space for extra columns if subsequently needed. A "comments" column is often useful for recording additional information such as "reading not steady", "voltmeter range changed", etc, which might help identify ambiguous results, or justify rejection of certain data points in a subsequent analysis.

Be objective when considering data (e.g. if there's a good physical reason to reject outliers before estimating fits, do so) and include full consideration of error analysis for a small number of data points. Errors bars on dependent and independent variables should be clearly indicated on graphs even when not explicitly requested in the notes.

2.4 Assessment

Assessment is by 3 reports (20 marks each) and an open book test (40 marks).

The experiments performed on the Thursday sessions will be assessed and should be submitted to Katherine Shaw in the School Undergraduate Office by midday Friday.

You should submit lab books, addressing each of the points described in the notes, based on the Thursday experiments. Do not include a detailed description of the background theory and experimental method—this is already available from the course notes. However, you should always begin each experiment with the title, date, and list of objectives. Each of the experiments has specific instructions and a numbered list of questions and instructions for graphing and analysis. The bulk of your report will be responses to these items. In most of the experiments, measurements are compared with a theoretical model. So the your report should end with a conclusions section that summarises the main findings, including a comment on how well the theory can explain your measurements and and explaining the physical reasons for any discrepancies. The report should typically be no more than four pages of text long, not including graphs. Reports and graphs should be hand-written.

Assessment is out of 20. 14 of the available marks are allocated based on your answers to the specific questions and your analysis. The remaining 6 of the available 20 marks are discretionary and are allocated based on good error analysis and well argued conclusions, although novel analyses will also be rewarded. An indication of the level expected by the marking scheme is given in Appendix D.

The open-book test will cover material from **all** of the experiments, therefore make sure you have reached satisfactory conclusions for each one, and have a good record of data and error analysis. You should bring your lab notes and a calculator to the test.

2.5 Absences

Please indicate as soon as possible if you will be absent during any of the laboratory sessions. Alternative arrangements will be made on a case-by-case basis.

3 Analysis of Observational Errors

The following notes summarise the major aspects of elementary error analysis relevant to this module.

3.1 General

Any laboratory measurement is subject to error ϵ in the sense that if $\tilde{x}$ is the true value of the quantity being observed and x is the observed value, then

$$\epsilon = x - \tilde{x}$$

is generally non-zero. The total error can consist of *systematic* and *random* components. *Systematic* errors are difficult to detect, but care in setting up the apparatus, zero adjustment and calibration checks on measuring equipment can help to minimise them. In the following discussion, we will assume that ϵ is composed principally of its *random* component which would average out to zero given a large number of measurements.

3.2 A single measurement

In many experiments, the quantity being observed, $\tilde{x}$, changes between each measurement. In this case there is no way of estimating the typical magnitude of ϵ from the measurements themselves. Instead, we specify an *estimated error* $\hat{\epsilon}$ by considering the limitations of both the measuring device and our own ability to observe. A single reading would then be presented as

$$x \pm \hat{\epsilon}. \qquad (1)$$

For example, if a thermometer is marked in divisions of 0.2°C, we cannot expect to read the temperature to better than ±0.1°C. A more realistic estimate of $\hat{\epsilon}$ would be 0.2°C, allowing for calibration uncertainties in the thermometer. A quoted reading might thus be

$$T = (30.3 \pm 0.2)^\circ\mathrm{C}.$$

As a rough guide, we would expect there to be a better than 50% chance that $\tilde{T}$ lies between 30.1°C and 30.5°C.

For experiments involving measurements on dependent (y) and independent (x) variables, the range of estimated errors on each pair should be noted and represented as error bars on the graph of y versus x.

3.3 Multiple measurements

In a few experiments, several measurements, x_j, can be made when the quantity being observed, $\tilde{x}$, is known to be constant. In this case, the magnitude of ϵ can be estimated directly from the observations. Suppose we have n observations, x_j $(j = 1, 2, \ldots, n)$. The best estimate of $\tilde{x}$ is then

$$\overline{x} \pm \hat{\sigma}_m, \tag{2}$$

where

$$\overline{x} = \frac{1}{n}\sum_{j=1}^{n} x_j$$

is the arithmetic mean of the individual measurements, and

$$\hat{\sigma}_m = \left\{ \frac{1}{n(n-1)} \sum_{j=1}^{n} (x_j - \overline{x})^2 \right\}^{1/2}$$

is called the "*standard error*".

For $n > 20$, there is a 68% probability that $\tilde{x}$ lies between $\overline{x} \pm \hat{\sigma}_m$, a 95% probability that $\tilde{x}$ lies between $\overline{x} \pm 2\hat{\sigma}_m$, and a 99.8% probability that $\tilde{x}$ lies between $\overline{x} \pm 3\hat{\sigma}_m$. For smaller sample sizes, the data are not necessarily distributed normally and other probabilities will apply. For small n, it is therefore good practice to quote

$$\overline{x} \pm \hat{\sigma}_m \quad (n = 8).$$

Notice that the uncertainty in x decreases as the number of readings increases since $\hat{\sigma}_m$ varies as $1/\sqrt{n}$.

3.4 Combining errors

Suppose we wish to compute a quantity z which is a function of measured variables x and y, that is

$$z = z(x, y).$$

If the errors in x and y are δx and δy (and are independent of each other), then the most probable value, δz, of the error in z is given by

$$(\delta z)^2 = \left\{ \frac{\partial z}{\partial x} \right\}^2 (\delta x)^2 + \left\{ \frac{\partial z}{\partial y} \right\}^2 (\delta y)^2. \tag{3}$$

Two limiting cases occur most frequently:

- If $z(x,y) = x^m y^n$, then

$$\left(\frac{\delta z}{z}\right)^2 = \left(m\frac{\delta x}{x}\right)^2 + \left(n\frac{\delta y}{y}\right)^2.$$

- If $z(x,y) = \alpha x + \beta y$, then

$$(\delta z)^2 = (\alpha\,\delta x)^2 + (\beta\,\delta y)^2.$$

These rules are easily extended to cover cases where z is a function of three or more variables.

3.5 Best straight line

In many experiments, we have an *a priori* model for the relation between dependent (y) and independent (x) variables. This model is often a linear model,

$$\tilde{y} = m\,\tilde{x} + c,$$

where $\tilde{x}$, $\tilde{y}$, represent the true values of the variables. If we replace $\tilde{y}$ and $\tilde{x}$ by observations y_j, x_j, for the jth point, then

$$y_j = mx_j + c + r_j$$

where r_j is the *residual* associated with errors of measurement in y_j and x_j. For the purposes of this module, we will use one main methods for estimating m and c:

By constructing a straight line "by eye" through plotted observations, taking account of estimated error bars. For this module it is sufficient to estimate the error on the line by adjusting this fit (to all relevent data points) to estimate the uncertainty.

A formal *least-squares regression* is not required, but may be attempted if time permits. This method involves calculation of estimates, $\hat{m}$ and $\hat{c}$, to minimise the sum of the squared residuals,

$$\hat{m} = \frac{\sum x_j y_j - n\overline{x}\,\overline{y}}{\sum x_j^2 - n\overline{x}^2}, \qquad \hat{c} = \frac{\overline{y}\sum x_j^2 - \overline{x}\sum x_j y_j}{\sum x_j^2 - n\overline{x}^2}.$$

Standard errors in $\hat{m}$ and $\hat{c}$ can also be calculated from the sum of squared residuals. A *weighted least-squares regression* is also possible if the errors in the measurements x_j and y_j are known.

Reference:

Squires, G.L. 1998: *Practical Physics*, C.U.P.

4 The Experiments

A: Density currents

B: Surface waves

C: Effects of rotation

D: Thermals

E: Rotating convection

Experiment A: Density currents

Aims

To observe and measure the properties of density currents as a function of density excess and water depth.

Background

A density current is formed when a dense fluid flows under a less dense fluid. Density currents occur in the atmosphere as sea breezes and cold air outflows from thunderstorms, and in the ocean as dense water outflows from marginal seas. Here we study an analogue of an atmospheric density current in which the characteristic time-scale is less than a day and rotational effects can be safely neglected.

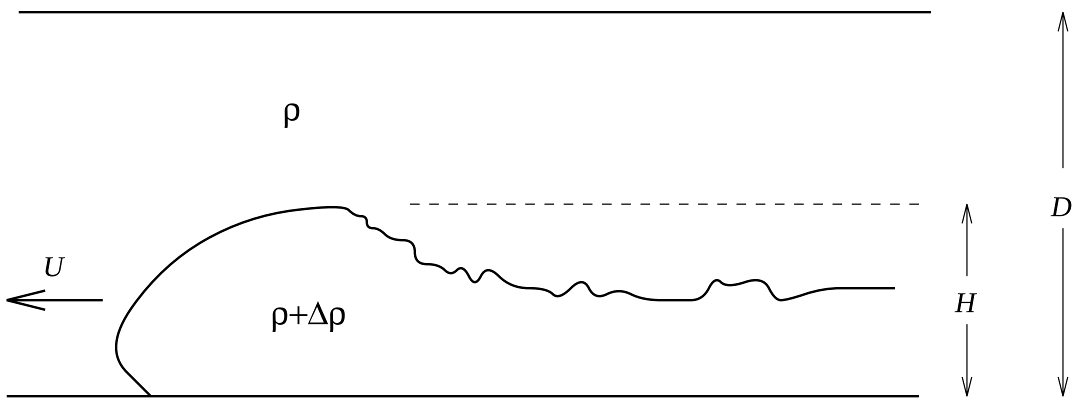
Theory predicts that the speed of a steady, energy-conserving density current is

$$U = \frac{1}{2}\left(gD\frac{\Delta\rho}{\rho}\right)^{1/2}, \tag{A1}$$

where ρ is the density of the less dense fluid, $\rho + \Delta\rho$ is the density of the denser fluid, g is the gravitational acceleration, and D the original depth of the less dense fluid. Theory also predicts that the height of the density current head is simply

$$H = \frac{D}{2} \tag{A2}$$

(see Turner 1979 for details).



Suggested procedure

In this experiment, a "lock exchange" method is used to generate the density current. Initially a vertical "lock gate" separates a volume of the denser fluid (salt water) at one end of the tank from the less dense fluid (fresh water) in the remainder of the tank. When the lock gate is removed, the denser fluid collapses and flows underneath the less dense fluid as a density current.

For each experiment, either refill the tank with tap water to the required depth, or if you are reusing the water, mix it thoroughly to remove any pre-existing density gradients. Insert the lock gate vertically in the tank 15 cm from the end. To provide a density current with a known density excess $\Delta\rho$, calculate the volume of water behind the lock gate and the weight of salt required (see Appendix A). Weigh out the required amount and stir it into the water behind the lock gate. Add a small amount of food colouring as a tracer, and stir well. When the salt is dissolved and the solution is at rest, smoothly lift the lock gate vertically out of the tank and make your measurements.

For the first experiment, use a water depth of 10 cm and a density excess of 1%. Using the chart recorder/microswitch as an event recorder, measure the distance travelled by the density current as a function of time. Also estimate the height of the head.

Using the same water, repeat this experiment for a range of different density excesses (for example, 0.25%, 0.5%, 2.0%, 4%, ...). After 3-4 runs you may need to drain and refill the tank to revert back to fresh water.

1. For each experiment, plot a graph of distance against time and determine the speed of the density current.

2. Plot a graph of the measured speed of the density current against the value predicted by theory, equation (A1). After accounting for error bars, can you say whether or not the theory can explain the measurements? What factors might explain any disagreement you see between your measurements and the theory?

3. Compare the measured height of the gravity current with the theoretical formula give in equation (A2), and suggest explanations for any discrepancies.

4. The shear instability behind the head of the current adjusts so that the Richardson number is a constant value. Estimate this constant value and describe how the parameters of the mixing region vary to maintain this constant value.

References

Turner J.S. (1979) Buoyancy Effects in Fluids, Cambridge University Press.

Experiment B: Surface gravity waves

Aims

To measure the dispersion relation and group velocity of small-amplitude surface gravity waves.

Background

Small-amplitude surface gravity waves of angular frequency ω and wavenumber k propagate on a layer of water of mean depth h with a phase speed

$$c_p^2 = \frac{g}{k} \tanh{(kh)}, \tag{B1}$$

where g is the gravitational acceleration. Since $c_p = \omega/k$, the *dispersion relation* is

$$\omega^2 = gk \tanh{(kh)}. \tag{B2}$$

The waves are therefore generally dispersive, that is, different frequencies travel with different phase speeds.

Part 1: Particle motions

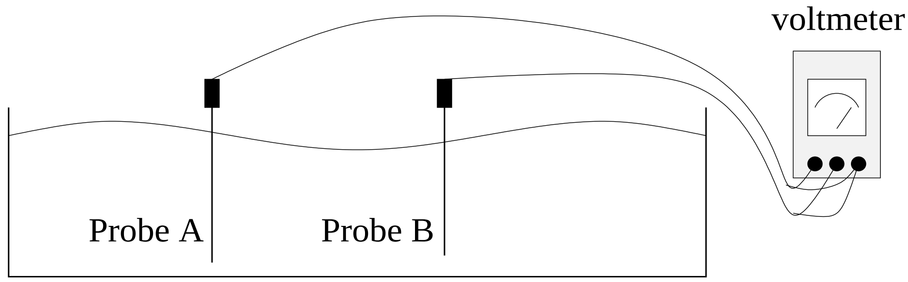
Start by obtaining a qualitative feel for the motion of fluid parcels at the surface of the wave tank. Turn on the wave generator-controller and record the period using the electronic timer (which is triggered once per revolution of the motor). Now place the small yellow ducks into the tank and qualitatively observe their motion.

1. Describe the characteristic motion within a single wave period, and the net displacement of the ducks over several wave periods. Explain the observed behaviour by thinking about parcel displacements in a propagating wave.

Part 2: Dispersion relation

The wave amplitude is measured using the wave monitor and a wave probe. Each probe consists of a pair of stainless steel wires dipping into the water. Each probe is connected to a "wave monitor" which measures the resistance between the pair of wires and converts this into an output voltage. Controls on the wave monitor are: TEST/OPERATE which should be in the "operate" position; SET DATUM which adds a fixed DC voltage to the output; SET OUTPUT which controls the sensitivity of the probes. The output voltage is taken from the socket marked OUTPUT.

Turn on the wave generator and record the period. Place two wave probes into the tank, and set up the voltmeter to measure the difference between their respective output voltages—you need to connect the positive output from probe A to the positive (red) terminal on the voltmeter, to connect the positive output from probe B to the negative (black) terminal on the voltmeter, and connect the negative outputs from *both* probes to the ground (green) terminal. The voltmeter should now give a measure of the difference in wave height between the two probes.



Increase the separation of the wave probes from zero until the amplitude of oscillation indicated on the voltmeter is a minimum.

2. Why are the probes now one wavelength apart? Measure the wavelength and estimate its accuracy. Are you able to improve on this accuracy by taking further measurements?.

3. Repeat the above at 4 different wave periods chosen to ensure a coverage of parameter space. For each measured wavelength verify that $\tanh kh \approx 1$ and state the physical meaning of this regime. Plot a graph of ω^2 against gk to investigate the validity of the dispersion relation (B2), accounting for experimental error.

Part 2: Group velocity

Adjust the wave period to lie between 0.3 s and 0.5 s. Switch the wave generator to PULSE to generate a wave group, and observe its passage through the tank. You should be able to see wave crests entering the wave group from behind with small amplitude, increasing their amplitude to a maximum, and leaving the group with small amplitude at the front as they overtake it.

Connect the outputs of the two wave probes to two channels on the chart recorder, which should be run at $60\,\mathrm{cm\,min^{-1}}$. With the two probes separated by about 1 m, observe the passage of the wave group using the chart recorder.

4. Estimate the group speed, c_g. Using a simplified version of (B2) with $\tanh kh \approx 1$, calculate the theoretical group speed $c_g = d\omega/dk$ as a function of frequency. Repeat the measurement for two further wave periods and plot the measured group speed against the theoretical value, showing error bars. Comment on the comparison.

Experiment C: Effects of rotation

Aims

To observe the nature of the centrifugal and Coriolis accelerations, and the gross effects of rotation on fluid flows.

Background

The kinematic equation describing the motion of an object in a rotating frame of reference is

$$\frac{d\mathbf{v}}{dt} = \mathbf{g} - \boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \mathbf{R}) - 2\boldsymbol{\Omega} \times \mathbf{v}, \tag{C1}$$

where the terms on the right hand side represent the gravitational acceleration, centrifugal acceleration and Coriolis acceleration respectively. Here $\boldsymbol{\Omega}$ is the angular velocity, $\mathbf{R}$ is distance from the rotation axis, and $\mathbf{v}$ is velocity.

Part 1: The geoid

Because the centrifugal acceleration is independent of velocity, it is typically combined with the gravitational acceleration to form an "effective gravity",

$$\tilde{\mathbf{g}} = \mathbf{g} - \boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \mathbf{R}). \tag{C2}$$

On a rotating turntable in the laboratory, we can write a potential for the effective gravity,

$$\tilde{\phi} = gz - \frac{\Omega^2 R^2}{2}. \tag{C3}$$

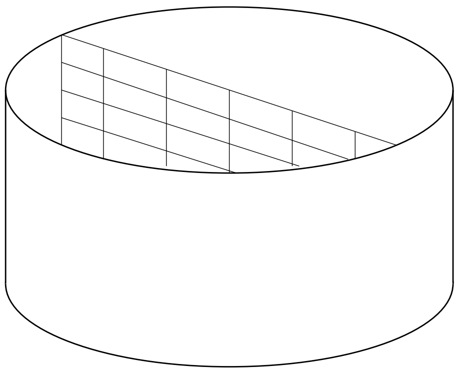
A surface of constant potential therefore takes the form of a parabola,

$$z = z_0 + \frac{\Omega^2 R^2}{2g}. \tag{C4}$$

The free surface of a resting fluid corresponds to a surface of constant $\tilde{\phi}$ and is known as the "geoid". Along this surface, the gravitational and centrifugal accelerations exactly compensate and an object feels no net acceleration.

To test the validity of (C4), fill the circular tank to a depth of about 5cm and place on the rotating table. Now insert the perspex sheet into the centre of the tank, as sketched below. Set the tank rotating with a rotation period of roughly 1 second. (**Important: Watch the free surface carefully as the tank spins up to ensure the water does not rise above the walls of the tank.**) Once the water comes into solid body rotation, estimate the height of the free surface, z, at 0cm, 5cm, 10cm, and 14cm from the centre of the tank.

1. Plot a graph of z against R^2 to compare your results with the theory. Accounting for error bars comment on the comparison. Sketch the shape of the geoid on the Earth.



Part 2: Inertial oscillations

Objects moving in the rotating frame of reference additionally experience the Coriolis acceleration. Since the Coriolis force acts perpendicular to the motion, an object subject only to the Coriolis force will describe circular orbits, known as "inertial oscillations" or "inertia circles". We can determine the angular frequency, ω, of these inertial oscillations as follows. The acceleration required to maintain a circular orbit of radius r is $\omega^2 r$, and its orbital velocity is ωr. Equating the former to the Coriolis acceleration and the latter to the velocity gives

$$\begin{aligned} \omega^2 r &= 2\Omega v, \\ \omega r &= v, \end{aligned}$$

and thus

$$\omega = 2\Omega. \tag{C5}$$

The period of an inertial oscillation is therefore exactly one half the period of rotation of the reference frame.

To observe the Coriolis force and inertial oscillations in the laboratory, we study the motion of a metal ball on a rotating parabolic dish. Place the parabolic dish (an old satellite dish) on the rotating table. Set the table rotating and release the ball from the upper end of the metal chute. **You must not place your hands inside the safety frame while the table is rotating.**

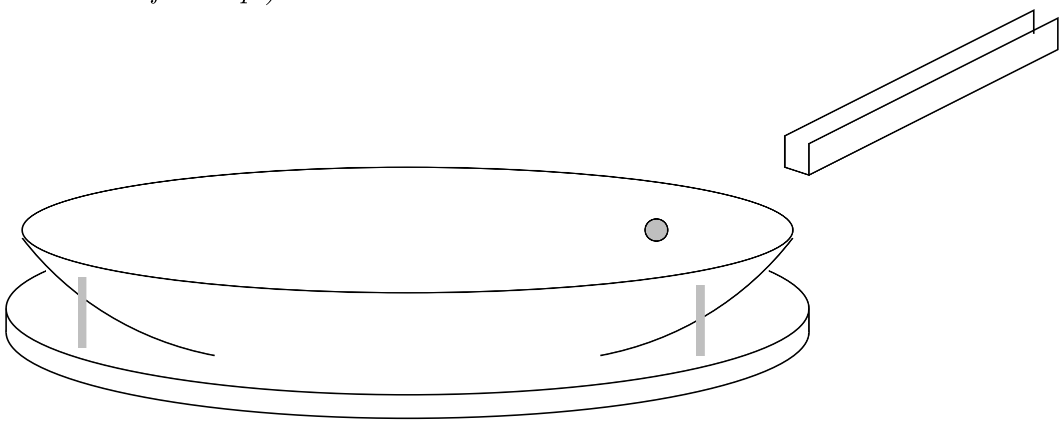
Vary the rotation rate until the dish is the geoid, so that, in the rotating frame of reference, the ball is stationary or moves in a circular motion.

2. Sketch the motion of the ball at rotation rates higher than and lower than the rotation rate for the geoid and comment on the force balance in each case.

3. What is the rotation period and hence rotation rate at which the surface of the dish corresponds to the geoid?

4. Measure the period of the inertial oscillations and compare with the theoretical value. Can you suggest a reason for any discrepancy?

(Note: The video camera mounted on the table can also be connected to a particle visualisation system "DigImage" which displays particle streaks. This system is used primarily for Experiment F, but it should be possible to borrow the system for a few minutes—ask a demonstrator for help.)



References

Pedlosky, J.(1987) Geophysical Fluid Dynamics, 2nd Ed., Springer-Verlag.

Experiment D: Thermals

Aims To study the characteristics of thermals as they rise through their environment, and to illustrate the use of standard error analysis.

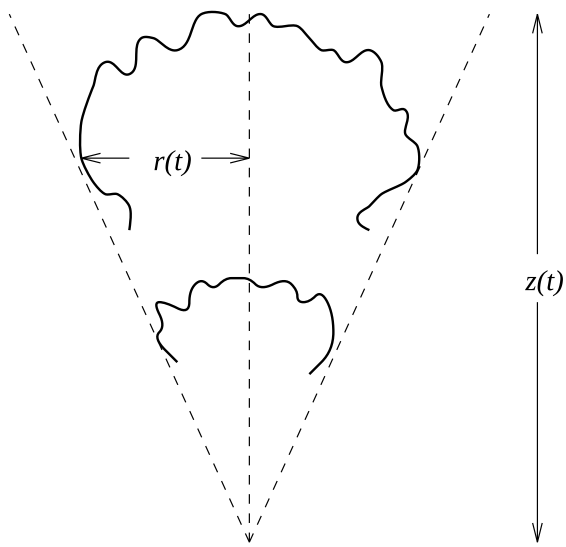
Background

A thermal is a buoyant mass of fluid, released instantaneously and with no initial momentum, which rises through and mixes with its environment. The mixing occurs mainly over the front cap of the thermal, with some at its rear. As the thermal rises, it expands roughly within a cone of half-angle between 10° and 20°, and its ascent rate decreases with time.

Consider a thermal with a density excess $\Delta\rho$. We assume that the mean motion in and around the thermal is similar at all stages of growth, such that ratios between length scales in different directions are preserved. If z is the height of the thermal above its release point, and r is the mean radius of the cap at that height, then

$$\frac{r}{z} = n, \tag{D1}$$

where $n = \tan\theta$ is a constant for a particular thermal.



The total mass within the thermal must also be preserved. Assuming that the volume of the thermal is $V = mr^3$ where m is a constant, we have

$$mr^3\,\Delta\rho = V_0\Delta\rho_0, \tag{D2}$$

where the initial volume is V_0 and the initial density excess is $\Delta\rho_0$.

The vertical velocity of the thermal, w, is determined only by its reduced gravity, $g' = g\,\Delta\rho/\rho_0$ (the buoyancy force per unit mass), and by its radius r which governs the drag force. Dimensional analysis suggests that $w = a(g'r)^{1/2}$, where a is a nondimensional constant. Putting the above together, we find

$$w = \frac{dz}{dt} = \frac{a}{n}\left(\frac{g\,\Delta\rho_0}{\rho_0}\frac{V_0}{m}\right)^{1/2}\frac{1}{z},$$

giving

$$z^2 = \frac{k}{n}\left(V_0\frac{\Delta\rho_0}{\rho_0}\right)^{1/2} t, \qquad \text{(D3)}$$

where $k = 2a(g/m)^{1/2}$ is an unknown constant.

Suggested procedure

The thermals are produced in a tank of water by rapidly inverting a small bucket of salt water at the top of the tank. They are observed using a shadowgraph optical system which detects small refractive index (and therefore salinity) changes in the water. The shadow is projected onto a screen.

Start with a density excess of $\Delta\rho_0/\rho_0 = 1.0\%$. Move the pivoted container to its upright position, making sure that it is empty. Using the syringe, carefully place a measured volume of salt solution (e.g. 2cm^3) into the bucket. With the light turned on, invert the pivoted bucket quickly. Use the chart recorder to record the times when the thermal crosses horizontal lines on the screen (say spaced every 4cm). Estimate a mean value of the cone angle, θ, and hence estimate n. Repeat these measurements for 4 or 5 thermals. **Hint: A well designed table will help you with the data processing in this experiment!**

1. Calculate the average values of $z(t)$ and n. Estimate the errors on the averaged results by calculating the standard errors. Comment on how the error on the averaged results reduces compared to the error on individual realisations.

2. Plot a graph of z^2 against t to determine the validity of (D3).

Perform experiments with each of the remaining solutions ($\Delta\rho_0/\rho_0 = 0.5\%$, 2.0%, 4.0%).

3. Analyse the results as above and for each value of the density plot a graph of z^2 against t, and determine in each case the slope of the best fit straight line.

4. Plot the measured values of these slopes against $(\Delta\rho/\rho_0)^{\frac{1}{2}}$ and compare with the theoretical formula (D3). Accounting for error bars, what can you say about how well the theory explains your data?

Experiment E: Rotating convection

Aims

To observe the impact of rotation on the circulation of a stratified fluid and to observe the process of baroclinic instability.

Background

An important length-scale in a rotating, stratified fluid is the *Rossby deformation radius.* Consider introducing a volume of dense water, density excess $\Delta\rho$, into a resting fluid of density ρ_0. For this problem the deformation radius is

$$L_D = \frac{\sqrt{g' D}}{f}, \tag{E1}$$

where $g' = g\,\Delta\rho/\rho_0$ is the reduced gravity, g is the gravitational acceleration, D is a vertical scale, and f is the Coriolis parameter. The deformation radius is the scale at which buoyant and rotational effects are of equal importance.

- If the extent of the dense fluid is much smaller than the deformation radius, then the dense fluid sinks as a non-rotating density current.
- If the extent of the dense fluid is larger than the deformation radius, then Coriolis forces prevent the dense water from sinking and spreading outward. A geostrophic current is generated around the density anomaly. In practice these currents are often *baroclinically unstable*, and baroclinic eddies are able to grow by extracting potential energy from the background state. These eddies have a length scale of the order the Rossby deformation radius.

The deformation radius is typically O(10 km) in the ocean, compared with O(1000 km) in the atmosphere. Thus, while rotation effects are generally negligible in atmospheric convection, rotation plays an important role in defining the characteristic scales of convection in the ocean.

Part 1: Non-rotating convection

We study rotating convection in this experiment by floating a frozen disk of potassium permanganate in the centre of a circular tank. As the ice melts, it extracts heat from the underlying water which thus cools and convects downward.

Fill the tank with approximately 8cm of water and place above a sheet of graph paper, which helps in making a measurement. **Using disposable gloves (warning—potassium permanganate is an oxidising agent)**, take an ice disk from the freezer in the Instruments Laboratory. By pouring a small amount of hot water over the base of the dish, remove the ice disk, then remove the pole and carefully float the disk at the centre of the tank of water.

1. Describe qualitatively, with the aid of sketch diagrams, how this experiment evolves through three stages, describing the important physical processes in each stage.

Part 2: Rotating convection

Now do the experiment with the turntable rotating. Repeat a 2 or 3 times over a range of rotation rates, begining with periods of 2-4s. In each case wait for a few minutes for the fluid to come into solid body rotation before starting the experiment **(warning: watch the free surface carefully as the tank spins up to ensure the water does not rise above the walls of the tank)**.

2. Sketch the formation of the sinking plumes that form in the early stage of the motion and their variation with rotation rate. Can you say how the *net* vertical descent of dense fluid under the ice disk compares with the non-rotating case? By discussing the dynamics of a Taylor column, explain the difference between the rotating and non-rotating cases.

In a second stage of the motion, the plumes mix the fluid column and create a homogenised 'chimney' of dense fluid beneath the ice disk.

3. Explain qualitatively why the horizontal density gradient at the perimeter of the chimney creates a 'rim current' through thermal wind balance, namely

$$\frac{\partial \mathbf{u}}{\partial z} = -\frac{g}{\rho f} \mathbf{k} \times \nabla \rho. \tag{E2}$$

In the third stage of the motion, this rim current undergoes baroclinic instability.

4. Sketch the formation of the baroclinic eddies and record the number of waves, n, around the rim during the initial instability. Describe the evolution and vertical structure of the eddies.

5. Plot n^{-1} against the period of rotation of the turntable, T, for your experiments. How do your measurements relate to the theoretical prediction that the length of the eddies scales on the Rossby deformation radius (E1)?

6. Describe the evolution of the dye very close to the bottom of the tank. State the special force that acts there and hence explain qualitatively the different motion there.

5 Appendices

(A) Density of a salt solution

Density excess $\Delta\rho/\rho_0$	0.25%	0.5%	1.0%	2.0%	4.0%
Required salt C_s / g l^{-1}	3.6	7.0	14.1	28.5	58.0

(B) Rebooting DigImage

To reboot the system, press the "reset button" on the front of the PC. After about a minute, a menu appears offering a choice of software options. Select "7 Annulus experiment", followed by "1" at the "Main menu". The "threshold" will need to be raised to near its maximum value using the arrow keys. If in doubt, ask a demonstrator.

(C) Physical constants

molecular viscosity

$$\nu = 10^{-6}\mathrm{m}^2\mathrm{s}^{-1}$$

thermal expansion coefficient of water

$$\alpha = 1.5 \times 10^{-4}\mathrm{K}^{-1}$$

specific heat capacity of water at constant pressure

$$c_p \approx 4.2 \times 10^3 J\,K^{-1}kg^{-1}$$

(D) Marking scheme

0 marks	**Experiment not attempted** 5 marks are awarded for turning up and handing in a laboratory book.
5–7 marks	**Poor experimental work or report** Lacking understanding of the experiment and background material. The analysis will be marred by serious errors. Will most likely contain no analysis of experimental errors.
8–9 marks	**Barely adequate experimental work or report** Showing limited understanding of the experiment and background material. The analysis will generally contain errors. Containing no more than a basic attempt at estimating experimental errors.
10–11 marks	**Competent experimental work or report** Showing reasonable understanding of the experiment, and a basic grasp of the background material. A competent attempt at the experiment, including an attempt to estimate experimental errors. The analysis may contain some errors; alternatively a good report let down by significant errors.
12–13 marks	**Good experimental work or report** Showing a sound understanding of the experiment and background material. A good attempt at the experiment, with a systematic analysis of experimental errors. Probably lacking insight and/or originality. Generally correct, but may contain occasional errors; alternatively work at a higher level let down by a significant error.
14–16 marks	**Excellent experimental work or report in most respects** Showing good understanding of the experiment and associated material. Exhibits insight and possibly originality, combined with very good ability to analyse and synthesise the results, including a thorough analysis of experimental errors.
17–18 marks	**Outstanding experimental work or report, excellent in virtually all respects** Showing a deep understanding of the experiment and associated material. Exhibits a high level of insight and possibly originality.
19–20 marks	**Outstanding experimental work/report, excellent in every respect** Showing a deep understanding of the experiment and associated material. Exhibits a very high level of insight and significant originality.