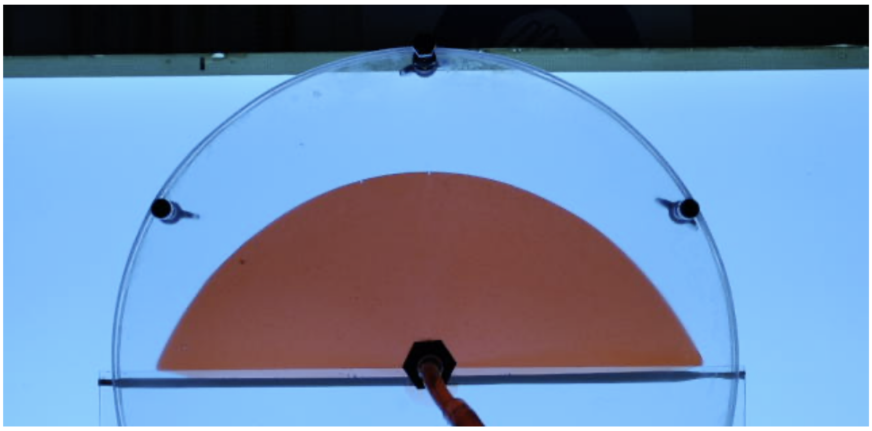
Studying CO_2 storage using a Hele-Shaw cell

Laboratory Experiments

Fluid Dynamics of Sustainability and the Environment



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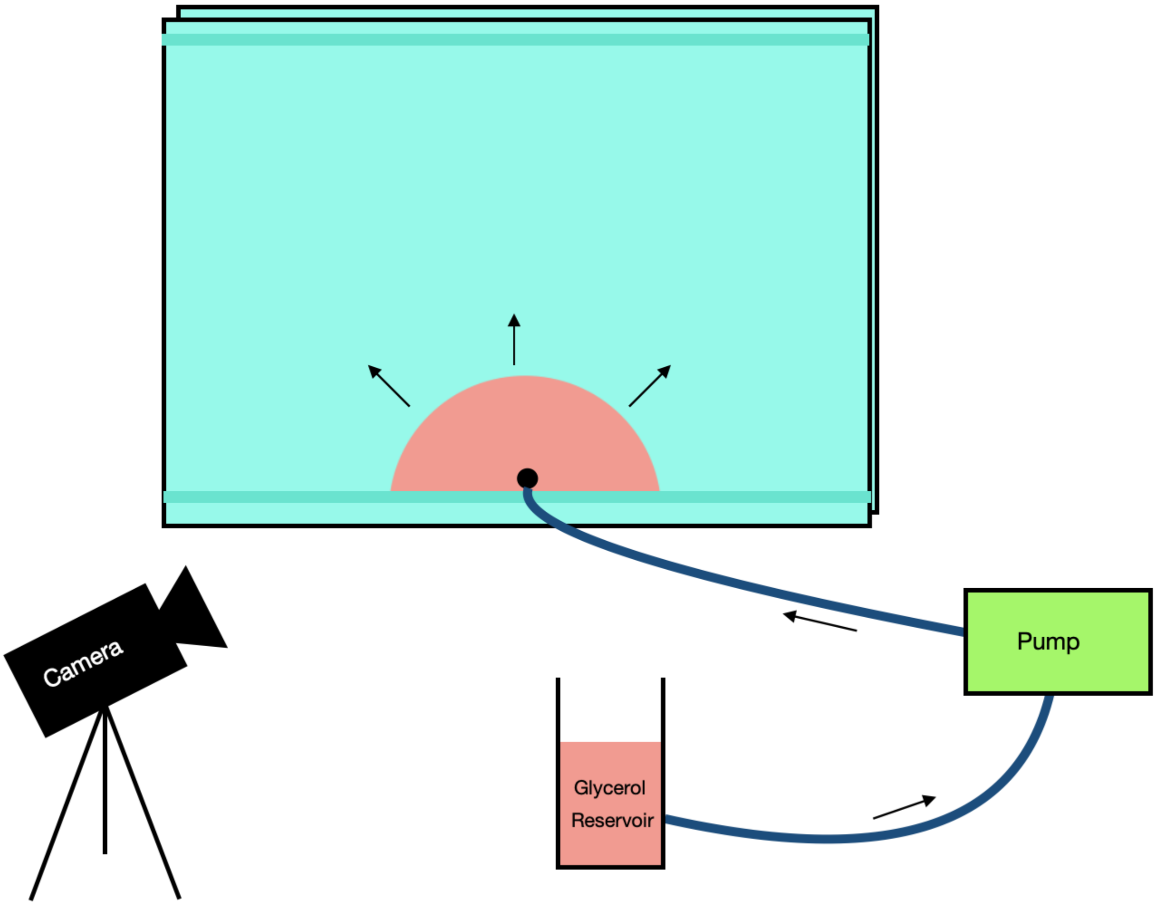
The overproduction of carbon dioxide emissions is one of biggest challenges facing humankind over the next century. As outlined in the Paris Agreement (2015), it is necessary to limit global warming to less than 2°C by the year 2100 to avoid the most dangerous consequences of climate change. To meet these temperature targets it is imperative to cut down our CO_2 emissions quickly, and by as much as possible.

One of the few proposed technological solutions to this problem is carbon capture and storage (CCS) - that is, capturing CO_2 at source (e.g. power plants and factories) and injecting it into porous geological reservoirs to be sequestered (stored), either by dissolution or trapping in the rock pores and boundaries.

A key question in CO_2 sequestration is how to predict the long-term motion of the injected flow to ensure sustainable and safe storage. In this session we will study a simplified experiment which demonstrates some of the interesting and unexpected behaviours of the fluid motion resulting from the injection of CO_2, gaining insights into the control parameters and scaling laws used for field predictions.

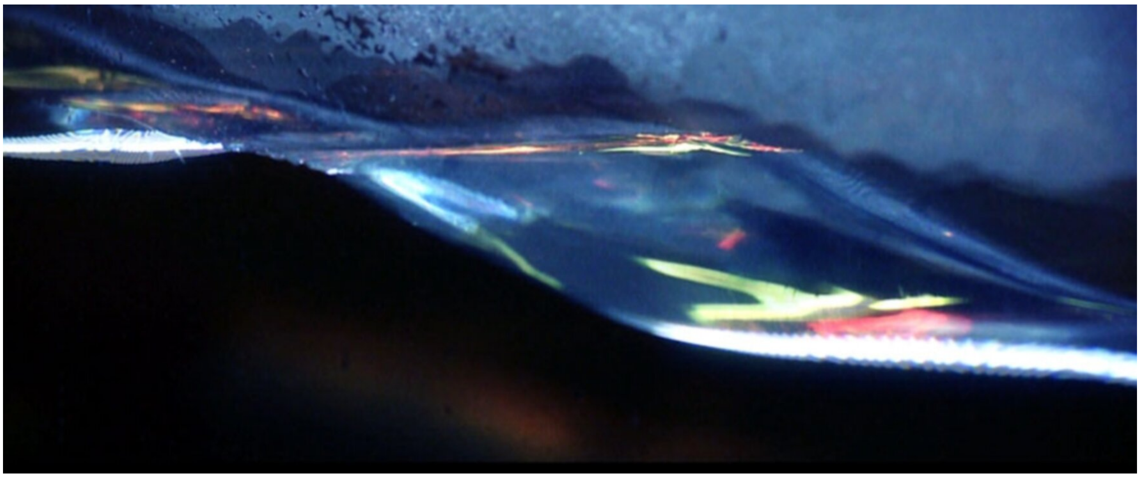


We will build an analogue experiment to interrogate the behaviour of an injected flow of CO_2 in a confined geological reservoir. Whilst CO_2 is injected into salty water in a reservoir, in our experiment we will use an analogous setup with glycerol injected into air between two narrowly spaced transparent plates, also known as a Hele-Shaw cell. We will record the evolution of the flow and analyse the growth rates of the glycerol current whilst varying different experimental parameters. Theoretical predictions will be developed to help understand the different flow regimes and interpret the experimental data. Finally we will discuss the implications of our results for CO_2 storage applications.

WORSHOP ARTs and SCIENCEs

Laboratory Experiments

Fluid Dynamics of Sustainability and the Environment



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The Workshop proposes, with students in art, design in internship at the Lab and science students from the summer school, to exchange reflections and research, to present and comment on chaire arts and sciences works, animated objects and installations that question the field of arts and sciences. In the Workshop, students, who will have the opportunity to work in groups as Art and Science students, carry out simple tests and manipulations around the question of water, mist, fog, vortices, movement, flow and light. These experiments will constitute a set of singular artistic proposals, in the field of an Art-Science movement based on this principle of duality, symmetry and a process where artists and scientists, together, by changing roles, have given way to letting go. Through this, the projects will share a kinship, through the place and freedom left to the eye, with the "Science Galeries" movement, which is trying to reinvent the uses and codes of scientific mediation. These actions, where the public-science exchange is symmetrical, where the public can dialogue with the work, make it possible to transmit knowledge into popular culture accessible to all, favouring the imagination. They also change the way scientists project their role and the public's perception of it, as the Art-Science duality has displaced the lines and cancelled the thresholds.

Sirta Observatory:
Monitoring the Atmospheric Boundary Layer

Laboratory Experiments

Fluid Dynamics of Sustainability and the Environment

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Monitoring the Atmospheric Boundary Layer (ABL).

Operational observations at SIRTA

1. Dynamics: Stability, radiative and heat fluxes, turbulence
2. Renewable Energies applications.

Imma Bastida (Labex IPSL), Jean-Charles Dupont (UPSaclay-SIRTA), Jordi Badosa (LMD-TrendX)

SIRTA
SITE INSTRUMENTAL DE RECHERCHE PAR TÉLÉDÉTECTION ATMOSPHÉRIQUE

Institut Pierre Simon Laplace

Welcome to SIRTA!

SIRTA (Site Instrumental de Recherche par Télédétection Atmosphérique) is a French national atmospheric observatory dedicated mainly to:

It is located in Palaiseau (49N, 2E), 20 km south of Paris (France) in a semi-urban environment.

The observatory gathers and operates a suite of state-of-the-art active and passive remote sensing instruments from a large community to document and monitor an ensemble of radiative and dynamic processes in the atmosphere. The detailed description of the state of the atmospheric column is archived and made accessible to the scientific community. The primary applications are to improve our understanding of atmospheric processes, to test the performance of atmospheric models, and to develop new remote sensing methods for future space-borne observations.

Among the observed and derived quantities we obtain:

- Aerosols observations: profile from lidar observations; spectral Aerosol Optical Depth (AOD) from sun-photometer
- Cloud observations: Cloud base height (CBH), , cloud fraction (CF), liquid water path (LWP)
- Wind profile from sonic anemometers at different altitudes, sodar, wind lidars, radar UHF. radiosonde
- Air temperature, and relative humidity profiles from radiosondes and microwave radiometer
- Global, direct and diffuse downwelling irradiance from sun-tracker-based ground measurements
- Radiative shortwave and longwave budget from 10m mast measurements
- Visibility from several ground visibility meters
- Integrated water vapour, from sun-photometer
- Classic meteorological observations (2m Air temperature, relative humidity, pressure, precipitation, 10m wind)
- Turbulent parameters from sonic anemometers and wind lidars.

In this sessions we will **train** ourselves to observe and analyse different representations of data, gathered from different instruments from SIRTA's site.

The main goal will be to characterize the ABL stability state and its dynamics as well as its quality, through the study of specific **study cases** of relevant scientific/society interests.

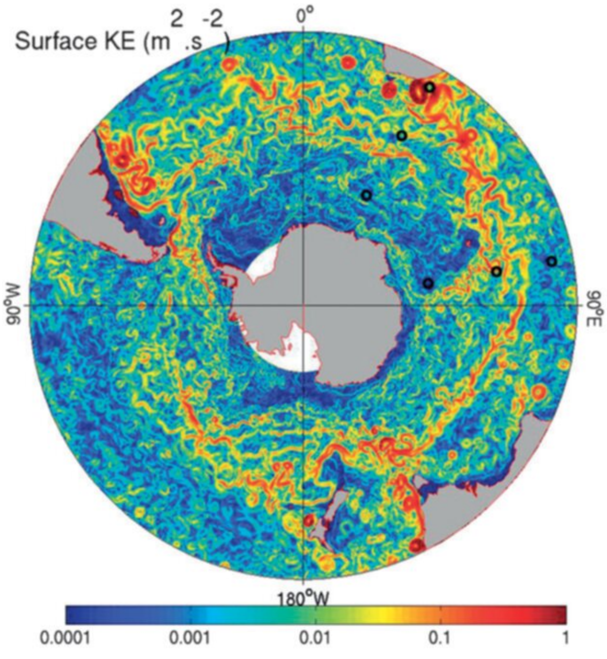
We will use SIRTA measurements to achieve the following **objectives**:

1) Characterise the ABL under clear-sky convective conditions
2) Analyse of radiative measurements to study the radiative budget and the relation to ABL height and turbulence.
3) ABL under different conditions
4) Applications: atmospheric sciences and renewable energies

ROTATING TANK:
Geostrophic currents and eddies

Laboratory Experiments

Fluid Dynamics of Sustainability and the Environment



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Two factors strongly impact the dynamics of the atmosphere and the oceans. First, the earth is spinning at a rate of one rotation per day. The rotating frame of reference is no longer Galilean and we must take into account the Coriolis and centrifugal forces to describe the dynamics of the flow. The second factor is that the earth receives short wave radiations from the sun. These radiations heat the upper layer of the ocean and maintains the ocean and the atmosphere in a stratified state.

During the FDSE summer school, we propose to build an experiment to study the effect of rotation and stratification on the dynamics of the flow. More precisely, we will try to understand how the atmospheric and oceanic jets (front page figure – from Venaille et al. (2011)) are sustained. We will study the dynamics of the jets with the main two balances of forces for fluids on earth: the hydrostatic balance, and the geostrophic balance. The goal of this experiment is to see how these two balances of forces combine to create a thermal wind equilibrium. We will observe the onset and the destabilization of this thermal wind (generation of baroclinic eddies).

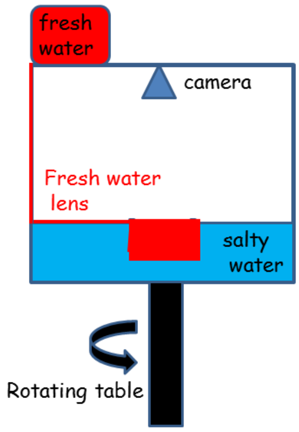

Figure 1: Side view of the experiment

In this experiment, the ocean is modeled by a salt water tank placed on a rotating table (Fig.). In the center of the tank, we inject fresh water into a cylinder. The experiment starts when we raise the inner cylinder and observe how the fresh water spreads into the salty water (e.g. https://pba.locean-ipsl.upmc.fr/TaTou.html, Bouruet-Aubertot et al. (2016)). The whole experiment is recorded using a camera placed in the rotating reference frame of the tank. We will perform several experiments for several values of the Rossby deformation radius and we will analyze the dynamics in the tank with two types of measurements:

– We will track the interface between the fresh water and the salty water: we will use dye in the fresh water part and measure the intensity of the light in the movie. The geostrophic velocity will then be inferred.
– The surface velocity of the fluid will be inferred from small paper parcel trajectories.

We will compare these two sets of measurements and assess the validity of the geostrophic balance. We will then compare the results of this experiments to theoretical results of the geostrophic adjustment and the baroclinic instability (Stegner et al. (2004), Vallis (2006)).

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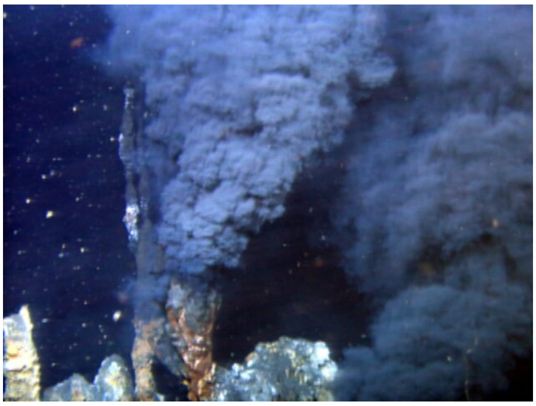
Turbulent jets and plumes in nature

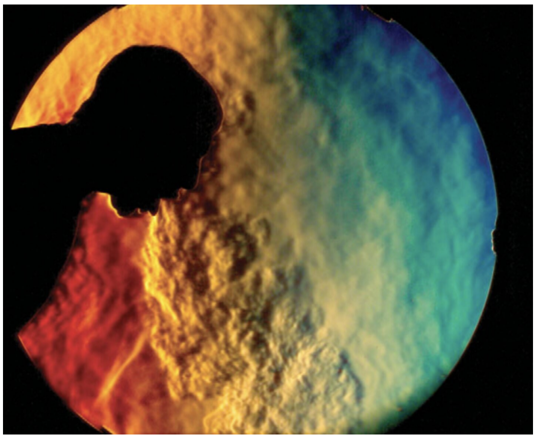
Laboratory Experiments

Fluid Dynamics of Sustainability and the Environment

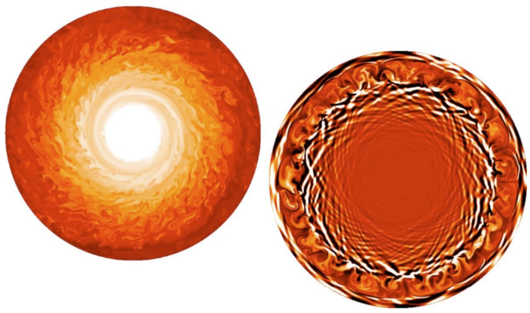
(a) Volcanic eruption of the Mount St Helens, H. Huppert, DAMTP



(b) High-temperature black smoker vent, NOAA PMEL Earth-Ocean Interactions Program



(c) Turbulent jet of a human cough visualized by schlieren photography, J. W. Tang et al. (2009)



(d) Convective plumes sheared by differential rotation in an equatorial plane of a giant planet, G. A. Glatzmaier et al. (2008)

Figure 1: Turbulent jets and plumes in nature

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Turbulent jets and plumes are ubiquitious in Nature, ranging over orders of magnitude in size (see e.g. cover pictures figure 1). Exemples include seafloor hydrothermal vents, explosive volcanic eruptions, giant planet convective plumes, animal respiratory flow, etc. In all cases, turbulent jets and plumes strongly influence the dynamics of the considered system, in particular through the associated mixing with the ambient fluid and through their interactions with the adjacent fluid layers (e.g. troposphere and stratosphere, convective and radiative zone of stars). A global understanding of their short and long-term behaviour is thus of fundamental interest for a wide range of applications, from weather forecast to stellar evolution.

The details of the turbulent patterns and entrainement processes associated to jets and plumes are obviously very complex. However, the seminal studies of G.I. Taylor [1] and collaborators in the 50's have shown that the overall behaviour of these flows is largely controlled by large-scale balances and conservation of fundamental quantities (buoyancy, momentum, mass): jets and plumes are thus canonical examples of the concepts of scaling laws and dimensional analysis [2]. As humans, turbulent jets are an integral part of our daily lives, when exhaling through the nose or mouth [3].

The purpose of this experimental session is to address in a model experiment some key aspects of the dynamics of jets and plumes and of their interactions with their environment. Three complementary studies will be performed (see figure 2 for the two last experiences), each occupying about 1/3 of the session time. We will successively address (1) the universal self-similar shape of a turbulent jet; (2) the penetration and spreading of a jet at a density interface; (3) the mixing by an impacting jet at a density interface. In all studies, water will be used as a working fluid, with various amount of salt to control the density, and a micro-pump will generate the jet in a large-scale tank. Visualizations will be performed using fluorescent dye and measurements will be performed by video analyzing using the free software ImageJ. Systematic changes in the flow rate and/or density constrat will allow exploring the different regimes and discovering the scaling laws that control the flow dynamics, in direct connection with simple analytical models.

This session will allow a rapid overview of the existing knowledge on turbulent jets and plumes. It will also allow tackling some actual research problems and unresolved questions, as for instance the efficiency of turbulent mixing through a density interface.

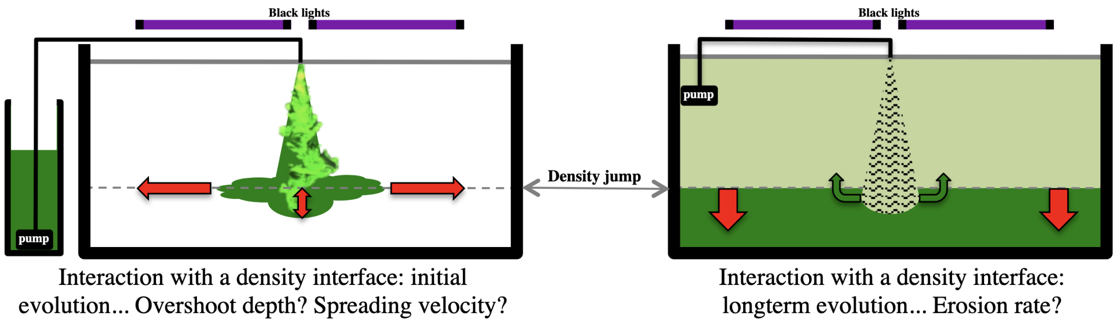

Figure 2: Diagram of the experimental set-up.

References

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[2] G. N. Abramovich. *The Theory of Turbulent Jets.* MIT, ISBN: 9780262010085, 1963.

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Gravity currents:
From dust storms to volcano eruptions

Laboratory Experiments

Fluid Dynamics of Sustainability and the Environment

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1 Introduction

Who has never chilled because of doorway flows? Who has never felt on his face the freezing air flowing down the hallways of the métro in Paris (the tube in London)? These are two examples of gravity currents that you encounter daily. Gravity currents are flows between two fluids of different density driven by gravity. They are highly common in Nature: snow avalanches, submarine rock slides, dust storms, explosive volcano eruption, lava flows, mud flows (see (1)). Since these flows are harmful for humans, they have been highly studied (2; 3; 4). The purpose of the experiments is to get insights on the variation of the flow as a function of the parameters involved in the fluid dynamics. This experimental study focuses on two types of gravity currents. The first experiment is a model for classic forms of gravity currents (avalanches, lava flows, mud flows or dust storms) (80% of the time). You will have to discover what are the scaling laws which control the flow dynamics. To this aim, you will realize different experiments varying some of the parameters. Thanks to Guillaume Roullet, you will have also the possibility to perform numerical simulations of a similar flow during the numerical sessions. Hence, you will be able to compare experimental and numerical results.

The second experiment models the strait of Gibraltar (20% of the time). Here the work is to understand some of the characteristics of a gravity current flowing over a topography.

2 Experiment

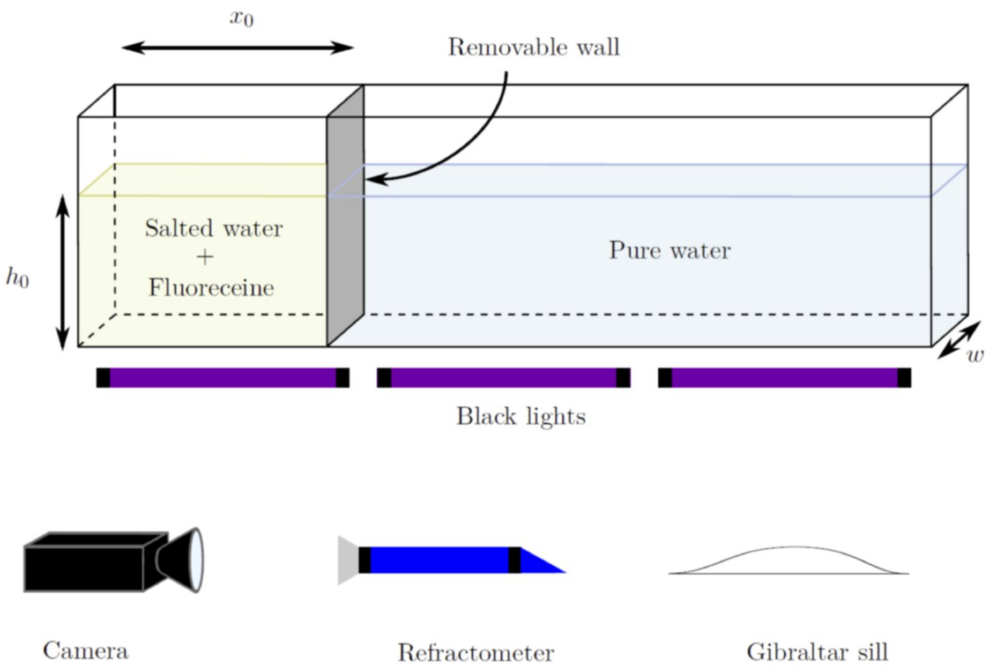

Figure 1: Sketch of the experimental apparatus and materials

References

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[2] John E. Simpson, *Gravity currents: In the environment and the laboratory, Cambridge University Press, 1999*

[3] Shin J. O.& S.B. Dalziel & P. F. Linden,*Gravity currents produced by lock exchange, Journal of Fluid Mechanics, (2004), vol. 521, p. 1-34*

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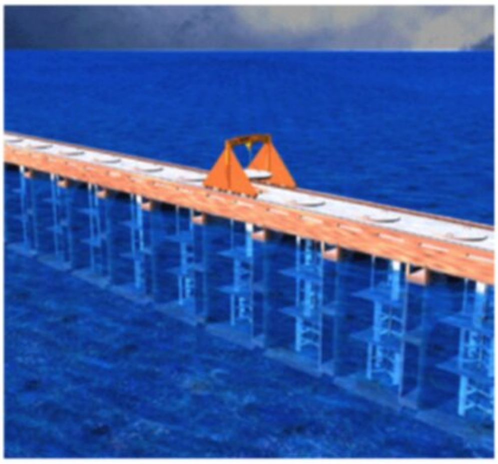
Harvesting fluvial and tidal energy: Turbulent dissipation at the bottom or useful energy

Laboratory Experiments

Fluid Dynamics of Sustainability and the Environment

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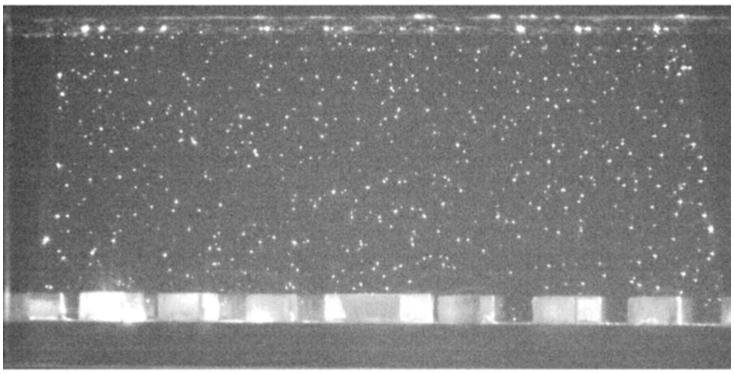
Hydroelectricity is the most widely used form of renewable energy, accounting for more than 16.6% of the world electricity production [1]. On one hand, traditional hydropower use intrusive and expensive dams. The environmental and social impacts of these hydropower dams are ongoing debate. It includes potential impacts on hydrological regimes, sediment transport, water quality, biological diversity, and land-use change, as well as the resettlement of people. On the other hand, a wide variety of hydrokinetic turbines are proposed to harvest the energy of rivers of tidal flows. With a lower efficiency than classical dams, the turbines, isolated or regularly spaced, intend to minimize the visual and the environmental impact of the energy production system.

The purpose of this experimental session is to understand and quantify the dynamical impact of few hydropower systems (run of river dam, river fence or isolated turbine) on a river or a tidal flow. We will first study the nature and the characteristics of the turbulent dissipation, generally induced by a rough bottom, in free surface flows [2]. Hydropower systems could be seen as an additional and organized dissipation (i.e. local energy extraction) in the natural system. Hence, in a second step, we will study how a local or a global change in the bottom dissipation affects the free surface? How the upstream and the downstream flow could be modified by the presence of various hydropower systems? What is the amount of energy and power available in comparison to the amount of the bottom dissipation ?

To do so, we will use an uniform and rectangular open channel 1.3 meter long, and measure free surface deviations, flow rate for various systems: artifical bottom roughness, small hydrolelectric dam or an idealized tidal turbine model. The vertical profile of the mean turbulent velocity will be also analysed and compared with standard profiles (Poiseuille, log, power law, . . .).



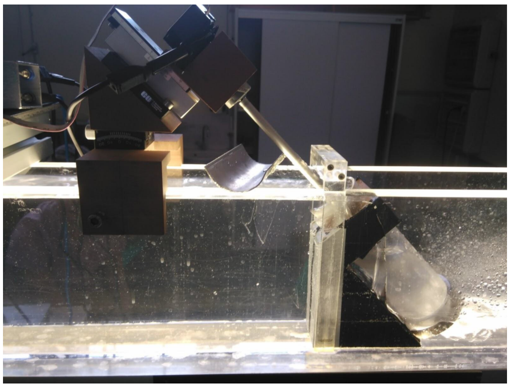


Figure 1: (Left) Side view of the free surface channel with bottom roughness. (Right) Small hydroelectric dam in the channel.

References

[1] REN21's Renewables Global Status Report, 2018 (http://www.ren21.net/status-of- renewables/global-status-report/)

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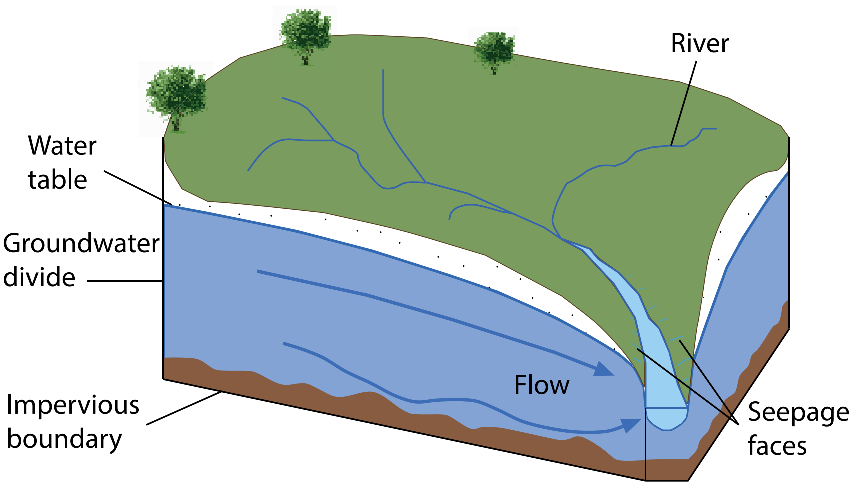
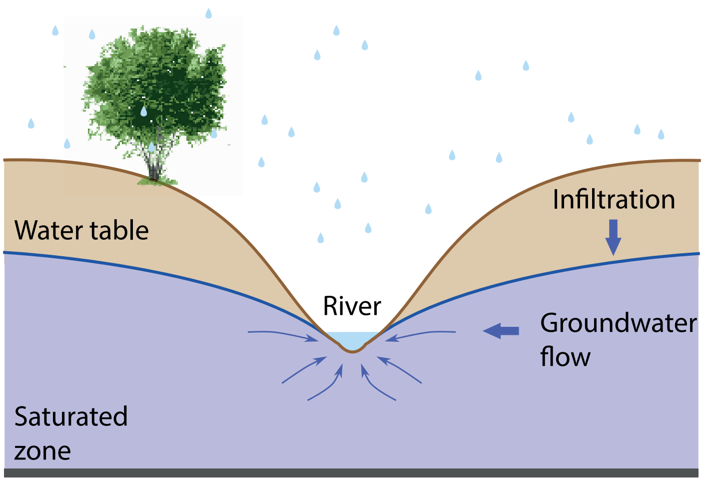
WATER FLOW IN AN AQUIFER AFTER RAINFALL

Laboratory Experiments

Fluid Dynamics of Sustainability and the Environment





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During a rain event, some of the rainwater flows over the landscape as surface run-off, while the rest of it infiltrates into the porous ground. Drained by gravity, the infiltrating water eventually joins a groundwater reservoir. As groundwater can react rapidly to rainfall events, the groundwater surface can rise almost instantly at the beginning of rainfall. Within this reservoir, the resulting pressure increases and induces a flow towards the drainage network. This dynamics suggests that, even during rainstorms, groundwater contributes significantly to the river discharge. Furthermore, through its ability to store water, the aquifer also acts as a filter between the rainfall signal and the water output to the drainage network. A visible consequence of this filtering is that a river still flows long after the rain has stopped. This drought flow has attracted much attention due to its obvious implications for water resource management, and because it provides information about the groundwater flow.

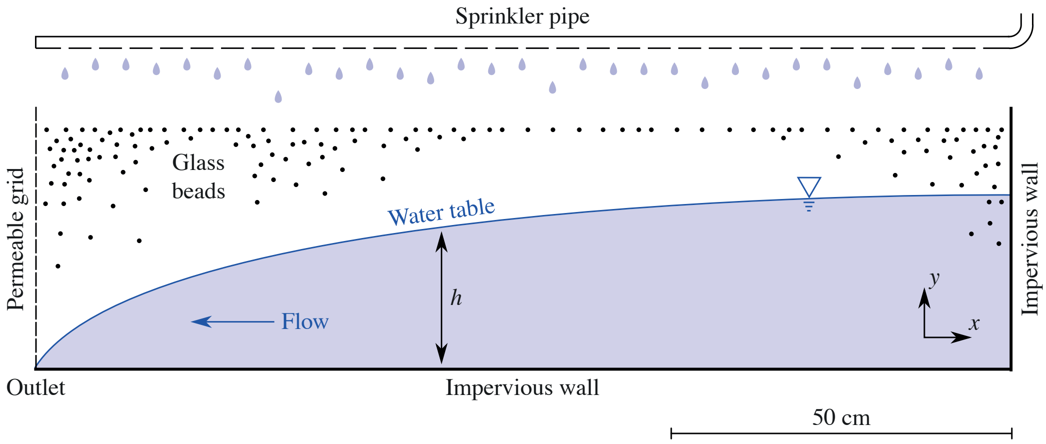

Figure 1: Experimental aquifer. The water table (blue line) is submitted to atmospheric pressure. The aspect ratio is preserved.

The purpose of this experimental session is to investigate the response of a laboratory aquifer submitted to artificial rainfall (see Fig. 1). In our almost two-dimensional experiment, the infiltrating rainwater, coming from the sprinkler pipe, forms a groundwater reservoir which rises vertically and exits the aquifer through one side (left on fig. 1). We will see that the resulting outflow resembles a typical stream hydrograph: the water discharge increases rapidly during rainfall and decays slowly after the rain has stopped. This two regimes following a rainfall will be experimentally characterized.

Theoretically, Darcy's law provides a natural representation of the groundwater flow. As most natural aquifers are far more extended horizontally than vertically, we will use the shallow-water approximation that provides a convenient simplification of the problem, referred to as the Dupuit-Boussinesq theory. Using this theory, we will see how the elevation of the groundwater surface in unconfined aquifers controls the horizontal pressure gradient that drives the flow. We will then compare the predictions of the model with our experimental water discharge measurement and show that the Dupuit-Boussinesq theory quantifies satisfyingly our two asymptotic regimes.

Through this experimental project you will gain basic knowledge on fluid flow through porous media and nonlinear dynamics of an aquifer. You will discover and practice how coupling experimental and theoretical modelling is a powerful tool for improving our understanding of a complex environmental flow. You will also address some actual problems and open questions on aquifer dynamics and flow in porous media.

Surface gravity waves: From wave fundamentals to plastic drift in the ocean

Laboratory Experiments

Fluid Dynamics of Sustainability and the Environment

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Waves are omnipresent at the surface of the ocean. We indeed routinely observe small waves, big waves, capillarity waves, swell, etc. Waves are almost always generated by the wind. Waves can either be locally generated (local wind) or remotely generated. In the latter case, waves are advected at the surface of the ocean from their formation site to the observation site. But how does a disturbance generated at the surface of the ocean propagate? What are the physical ingredients that govern wave dynamics?

In this lab session, you will study the propagation of disturbances at the surface of water. You will use a water tank equipped with a wave generator (Fig. 1), you will show that such surface waves are dispersive, meaning that different wavelengths travel at different speeds down the tank. You will study the interferences occurring when such waves cross paths, as well as what happens when we depart from the most frequently studied linear regime of small amplitude disturbances. This will also be the opportunity to review wave dynamics fundamentals: dispersion relation, phase speed, group speed, WKB approximation.

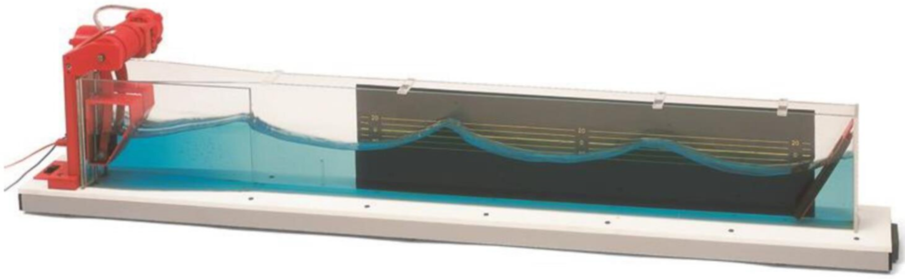

Figure 1: Wave tank aparatus

In the second part of the lab session, we will focus on the drift of debris when they are at the surface of the ocean. In the open ocean, these debris are primarily advected by winds and currents. However, when surface waves are present, these debris will feel an additional drift also known as Stokes drift. We will characterize the Stokes drift as a function of the wave characteristics. We will then measure the real drift for objects of various shapes. Last, we will propose a method to scale these results obtained in the lab to the real ocean.

Figure 2: Plastic bag in the ocean (istock picture)

Finally, it is worth emphasizing that waves are only partially represented in climate models even if recent observational and modeling works suggest these surface waves could significantly reduce model biases and uncertainties. Waves can indeed impact air-sea exchanges, modify the marine atmospheric and oceanic boundary layers with potential large-scale repercussions in the tropics, at high latitudes and in regions of strong oceanic eddy activity.

Wind Turbine:
The role of blade flexibility in the enhancement of energy production

Laboratory Experiments

Fluid Dynamics of Sustainability and the Environment

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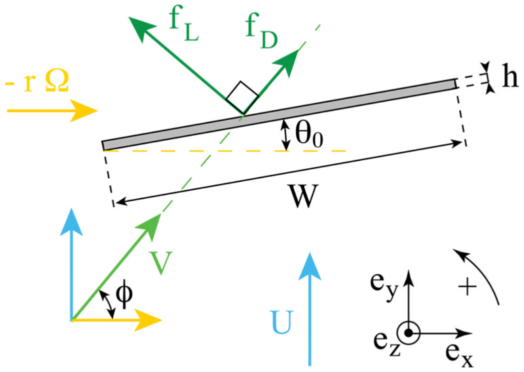
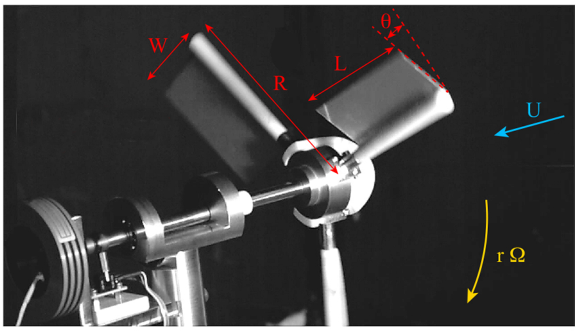
Wind energy is becoming a significant alternative solution for future energy production. Modern turbines now benefit from engineering expertise, and a large variety of different models exists, depending on the context and needs. However, classical wind turbines are designed to operate within a narrow zone centred around their optimal working point.





This limitation prevents the use of sites with variable wind to harvest energy, involving significant energetic and economic losses. The goal of this work is to study a new type of bio-inspired wind turbine using elastic blades, which passively deform through the air loading and centrifugal effects. The experimental study is inspired from recent studies on insect flight and plant reconfiguration, which show the ability of elastic wings or leaves to adapt to the wind conditions and thereby to optimize performance.

Based on an oversimplified model of wind turbine with rigid blades, we will first analyse the most efficient working regime of this type of harvester as a function of the two key parameters: the wind speed and the pitch angle. Then we will study the same model of turbine with flexible blades and will show how the reconfiguration of the elastic blades significantly extends the range of operating regimes using only passive, non-consuming mechanisms. The versatility of the new turbine model leads to a large increase of the converted energy rate, up to 35%.