Virtually-enhanced fluid laboratories for teaching meteorology

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Abstract

The 'Weather in a Tank' project offers instructors a repertoire of rotating tank experiments and a curriculum in fluid dynamics to better assist students in learning how to move between phenomena in the real world and basic principles of rotating fluid dynamics which play a central role in determining the climate of the planet. Despite the increasing use of laboratory experiments in teaching meteorology, many teachers and students do not have access to suitable apparatus and so cannot benefit from them. This article describes a 'virtually-enhanced' laboratory that could be very effective in getting across a flavor of the experiments and bring them to a wider audience. In the pedagogical spirit of 'Weather in a Tank', the focus is on how simple underlying principles, illustrated through laboratory experiments, shape the observed structure of the large-scale atmospheric circulation.

Capsule Summary

A virtually-enhanced 'Weather in a Tank' laboratory illustrates how fundamental principles of rotating fluid dynamics shape the observed structure of atmospheric circulation.

1. Introduction

The general circulation of the atmosphere is extraordinarily complex comprising many interacting components. Yet it has an underlying beauty and order which reflects the controlling influence of Earth's rotation and differential heating. At MIT - and in collaboration with other universities (see Illari et al., 2009) - we have explored an approach to teaching meteorology which combines observations with key fundamental theoretical concepts, but which is enlivened and illuminated by carefully chosen rotating laboratory experiments. The importance of laboratory experiments in understanding atmospheric fluid dynamics has been long recognized - Hide (1966), Gill et al. (2010). Persson (2010) stresses how laboratory experiments can help in communicating the non-intuitive nature of geophysical fluids.

In 'Weather in a Tank' (Illari et al., 2009 and Mackin et al., 2012), the general circulation of the atmosphere emerges from the 'mix' of two key planetary 'ingredients':

1. differential heating of the atmosphere: cooling of polar latitudes relative to the equator
2. rotation of the earth.

The first ingredient is intuitively understood and part of common knowledge. However, the second is known to be important but often not well explained, or the details are glossed over. Teachers often believe that rotational effects can only be demonstrated by complex mathematics that are beyond the grasp of many students, particularly in introductory classes (see the discussion in Mackin et al., 2012).

In ‘Weather in a Tank’ the combined effect of rotation and differential heating is illustrated using simple laboratory experiments in which a can of ice in the middle of a rotating tank of water represents the Pole-Equator temperature difference and the rotating turntable the rotation of the earth (see Fig.1). A ‘three legged stool’ approach is followed in which fluid experiments are used together with real time observations and relevant theory (Fig. 1). Students are encouraged to explore the same phenomenon from a number of aspects and become accustomed to moving between observation, theory and laboratory abstraction. The simplification required to set up laboratory experiments demands that complicating details be removed to reveal the essence of the underlying processes at work. This is a truer analogue, we believe, of how research scientists work and, most importantly in the present context, is also very effective pedagogy. Experiments capture the interest of many, if not all students, irrespective of their background knowledge or sophistication in mathematics and physics. They are also great ‘fun’ and particularly useful in outreach to non-scientists and the public in informal educational settings such as museums and libraries.

This use of laboratory experiments combined with real world phenomena and relevant theory has proved very effective in teaching the non-intuitive nature of rotating fluids in undergraduate courses. Over the past several years many colleges have adopted the curriculum and the related equipment. A comprehensive guide to the ‘Weather in a Tank’ experiments and how to obtain the apparatus can be found in Illari and Marshall, (2006). For a quantitative assessment of the impact of the ‘Weather in a Tank’ curriculum on student learning see Mackin et al., 2012. Despite the increasing use of laboratory experiments in teaching meteorology we are acutely aware that many teachers and students do not have access to suitable apparatus and so cannot benefit from them. However, the digital world of online education provides the possibility of reaching out to a vast audience of ‘distance’ learners. How can we make a laboratory experience available to such an audience? Thus far virtual labs available to the educators in meteorology are mainly comprised of computational modules or educational games – see, for example, the virtual labs from UCAR listed in the references. Here, instead, we describe a ‘virtually-enhanced’ laboratory that is very effective in getting across a flavor of the experiments and bringing them to a wider audience. In the pedagogical spirit of ‘Weather in a Tank’ we focus on how simple underlying principles, illustrated through laboratory experiments, shape the observed structure of the large-scale atmospheric circulation.

Our paper is set out as follows. In Section 2 we describe the teaching method we advocate and the role that real and virtual laboratories can play in it. In Section 3 we present a particular example focusing on the Hadley regime of the tropical atmosphere. ‘Virtually-enhanced’ annulus experiments are presented, available through an accompanying website described in the Appendix, which renders digital recordings of laboratory experiments allowing features of the circulation to be viewed from different angles. Real world applications of the Hadley circulation are presented using advanced graphics (Integrated Data Viewer (IDV) by UNIDATA) to highlight connections to the laboratory experiment. In Section 4 we argue that the availability of virtually-enhanced experiments could allow students to benefit from a laboratory experience even though they may not have access to a real laboratory. Finally we outline some of our future plans.

2. Teaching Meteorology Using Virtual Laboratories

We begin by briefly describing three closely related fluid experiments used in our undergraduate courses at MIT to teach students about the general circulation of the atmosphere and the underlying dynamical principles that cause it. This will give the reader a flavor of the pedagogical approach advocated here and the central role that laboratory experiments play in it.

The set-up in the three experiments is the same and comprises a circular tank of water at the center of which is a can containing a mix of ice and water - Fig. 1. The melting ice extracts heat from the surrounding water at the center of the tank, inducing differential cooling and a circulation, the first ingredient mentioned in the introduction. The only difference between the three experiments is in the second ingredient, the rotation rate, Ω, of the turntable, on which the circular tank sits.

We carry out the following experiments in turn:

1. non-rotating, $\Omega = 0$: this is used as our control experiment;
2. low rotation, Ω = small (less than one revolution per minute, rpm), an analogue of the circulation of the tropical atmosphere, the Hadley circulation;
3. high rotation, Ω = large (order 6 rpm), an analogue of mid-latitude weather systems (see Section 3.5).

Experiments two and three involve the use of a rotating turntable with a co-rotating camera (see Fig. 1), which may not be available to the teacher. However, the first experiment can easily be carried out in any classroom on a solid bench using readily available equipment, including an ice can, water tank, colored dyes, etc. The ‘virtual lab’ could then be used to illustrate the two rotating experiments.

The sequence of three experiments can be presented in one (~ 1.5 to 2 hour) class. Even better, perhaps, they can be broken up in to extended activities spread over several classes with related discussions of the laboratory experiments, theory and study of observations.

We have found it to be very useful to introduce the experiments to the students through use of a matrix (Fig. 2) printed on a sheet of paper which lays out the experiment in a logical order. Before the experiment is carried our students are encouraged to sketch on the matrix what they think will happen, and share and discuss their predictions with the class. The experiment is then performed before returning to a discussion of student predictions in the context of what actually happened, and why. Relevant theory (for example the thermal wind relation, Ekman layers, conservation of angular momentum as described in Marshall and Plumb, 2008) is developed and/or reviewed to help constrain and inform speculations about what did and did not happen. Finally, meteorological observations are explored in a manner that makes the connection to the laboratory experiments clear.

3. Example of pedagogy: Hadley Circulation

3.1 Laboratory experiments

To give the reader a concrete example, we now describe laboratory experiments that pertain to the Hadley Circulation, real and virtual manifestations, associated theory and exploration of relevant meteorological observations.

Non-rotating

An initially resting tank of water is differentially cooled by filling a can at its center with a mix of ice and water. The system is not rotating and thus represents our ‘control’ experiment. It is very simple yet encourages students to think about the effect of thermal contrast: where does the cold water in contact with the ice can move and what are the consequences for the ‘general circulation’ in the tank?

The resulting circulation can be easily visualized by using dye (food coloring) and permanganate crystals, as shown in the photograph in Fig. 2 (bottom-left). The permanganate is particularly useful in indicating flow at the bottom since it sinks in the water column, whereas dye is more nearly neutrally-buoyant and reveals flow interior to the fluid. Cold water sinks near the ice can, flows radially outwards (the pink streaks) inducing water on the periphery to rises at the edge of the tank. To conserve mass, surface waters must move towards the ice can, thus completing the overturning circulation. The resulting circulation is axi-symmetric with predominantly radial (inward and outward) flow. Students are generally 'comfortable' with this circulation and can readily rationalize what they see happening. But, now, what happens when we add rotation?

Slowly rotating

The set-up is exactly the same as the non-rotating case except that now the tank of water sits on a turntable which is rotating very slowly, here at only 1 rpm. The scene is viewed from above via a co-rotating camera, as indicated in Fig. 1. Even though the turntable completes only one rotation in a full 60 seconds, the circulation is strikingly different from the non-rotating experiment. Rotation imparts a 'winding effect' on the fluid as revealed by the beautiful corkscrew patterns of the green dye-streaks seen in Fig. 3. Flow at the top is cyclonic (in the same sense of rotation as the tank) but flow at the bottom is anti-cyclonic, as revealed by the pink permanganate streaks - Fig. 3 (top right).

This circulation pattern is a surprise to almost all students and few are able to predict it. Our mind has difficulty in visualizing and anticipating the effects of rotation. This is perhaps not surprising in view of the fact that Hadley himself did not fully appreciate the effect of rotation on atmospheric flows (see Lorenz, 1967; Marshall and Plumb, 2008).

In summarizing and reviewing student sketches and observed circulation patterns, we introduce angular momentum principles to rationalize the features of the corkscrew zonal circulation. As in the non-rotating experiment, water in the outer region of the tank is displaced by cold waters flowing outward along the bottom, away from the ice can at the center. It rises and subsequently moves inward at the surface. But now with rotation, contracting rings of fluid associated with inward flow conserve their angular momentum and thus speed up, generating upper-level zonal flow which has the same sense of rotation as the tank (i.e. cyclonic). This flow is analogous to the upper-level atmospheric westerlies, as will become apparent later when meteorological data is analyzed (see Section 3.4).

On reaching the ice can, the water is cooled, descends and moves outward along the bottom. Rings of fluid expand and begin to circulate in the opposite direction of the turntable, as expected from conservation of angular momentum. As can be seen from the pink streaks in Fig. 3 (top-right), flow at the bottom is anti-cyclonic (opposite to the sense of rotation of the tank). The bottom flow is directly analogous to the easterly (trade) winds of the low-latitude Hadley circulation. The accompanying video of the experiment, found on the project website, provides views from the camera above the tank and from another camera viewing the side of the tank.

In summary, the circulation of the low rotation experiment is not intuitive. Many students have difficulty in visualizing what it is going on and it is not easy to anticipate the impact that rotation has on the fluid.

3.2 Virtually-enhanced Hadley example

The experiments described above have been recorded, put through a process of virtual enhancement using animation software, and presented for viewing over the web. The capture process involves recording from different angles using top and side cameras in co-rotating and laboratory frames. By combining all of the views together using specialized programs such as 'Rhinoceros 3d', it is possible to reconstruct and enhance the 3-dimensional structure of the evolving dyes. The process used to produce the virtually-enhanced video is illustrated in Figs. 4 & 5.

As described in more detail in Appendix A, multi-view images of the experiment from two different cameras (top-view from the co-rotating camera above and side-views from camera in the lab) - Fig. 4 - are processed to produce line contours, turned into volumetric meshes and finally fully rendered surfaces as shown in Fig. 5. For more on the rendering process see Appendix A2. The fully rendered surface looks very realistic and can be viewed from different angles. Students can readily see what is going on in 3 dimensions thus gaining a more complete perspective of the effect of rotation on the fluid motion. The enhancement of the video, and the ability to view it over the web, gives students a vivid impression of the experiment, even though they may never have had the benefit of a first-hand experience. The experiment comes alive as in a PIXAR movie! See the fly-by animation from digitally-enhanced, merged video loops here: http://lab.rotating.co/#/10.

The accompanying website - see http://lab.rotating.co allows one not only to inspect pre-recorded experiments but is also designed to give one a feel for how and what it is like to carry out the experiment. Moreover data of flow speeds and temperatures are provided enabling one to quantitatively check dynamical balances that one expects to pertain, as we now go on to explain.

3.3 Associated theory

The Hadley experiment provides an excellent tutorial for exploring the ‘Thermal Wind’ relation, the theory leg of our stool. As described above, the radial temperature gradient (induced by the ice can and decreasing ‘poleward’) supports zonal motions in the tank, the nature of which depends, inter alia, on the rotation rate. When weakly rotating ($\Omega \lesssim 1$ rpm), we see the development of the thermal wind in the form of a strong ‘eastward’ (i.e., super-rotating) flow in the upper part of the fluid which can be revealed by paper dots floating on the surface. At these low rotation rates the flow is stable to baroclinic instability and laminar motion is observed, as seen in Fig. 5, for example. At higher rotation rates the flow breaks up in to eddying motions analogous to synoptic systems, as described in Section 3.5 below and discussed in detail in Section 7.3.1 of Marshall and Plumb (2008).

For an incompressible fluid in cylindrical geometry (with radius, r, increasing outwards), the thermal wind relation is:

$$\partial u/\partial z = - 1/(f\rho)(\partial \rho/\partial r). \qquad \text{Eq. (1).}$$

Where f is the Coriolis parameter, ρ is the density and u is the azimuthal speed of the current. Since ρ increases towards the center of the tank, because the water is cold there, ($\partial\rho/\partial r < 0$) then, for positive f, $\partial u/\partial z > 0$. Since u is constrained by friction to be weak at the bottom of the tank, we therefore expect to see $u > 0$ at the top, with the strongest flow at the radius of maximum density gradient. As we have seen, dye streaks clearly show the thermal wind shear - see Fig. 3 - especially near the cold can where the density gradient is strong.

On the web site that accompanies this article, data are presented of the flow speeds (by tracking particles) and temperature gradients (from thermistors deployed in the tank) existing in the Hadley experiment enabling the thermal wind relation, Eq. (1), to be quantitatively checked – see http://lab.rotating.co/#/31.

3.4 Connections to the observed Hadley circulation

Along with the laboratory experiment we have produced graphical displays using IDV (Integrated Data Viewer, by UNIDATA) that enable one to present meteorological observations in a manner which emphasizes connections to the fluid experiments. Students are encouraged to carry out exactly analogous calculations from meteorological data to check the thermal wind in action for atmospheric flows. Indeed the jet observed in the laboratory experiment is directly analogous to the creation of the subtropical jet by the Hadley circulation, as we now discuss.

In Fig. 6 (top) NCEP re-analysis climatological winter-mean (DJF) data are used to map the main features of the Hadley circulation and strengthen the connection between the real world and the tank experiment. IDV is a powerful graphical package giving us the tools to go beyond the usual horizontal and vertical sections and explore the 3d structure of the atmosphere. The cyan picks out the tubular surface corresponding to westerly winds aloft. The pink tube highlights easterly winds near the surface. The Arctic ice cap is clearly visible at the surface over the pole. Superimposed is the Northern Hemisphere wintertime Hadley Circulation with the meridional and vertical components of the wind indicated by the arrows. The rendering of the data in this way, Fig. 6 (top), makes the connection with the laboratory experiment, Fig. 6 (bottom), much more immediate and compelling.

To further emphasize the main features of the observed meridional circulation, zonally averaged fields, as shown in the section in Fig. 6, are plotted separately in Fig. 7. Fig. 7 (bottom) shows the potential temperature (θ in K) and zonal wind (u in m/s) in January. In the troposphere maximum warmth is found south of the equator, consistent with the winter radiative forcing. The north-south potential temperature gradient is small in the tropical region, whereas it is large in middle latitudes - this is the Polar front, marking the edge of the dome of cold polar air. By thermal wind arguments there are strong westerlies at upper levels (in middle latitudes), with weaker easterlies in the lower troposphere (at low latitudes). Fig. 7 (top) shows the vertical and meridional winds. Vertical velocities are large in the tropical band with air rising where it is warm (south of the Equator) and sinking where it is colder in the Northern Hemisphere (around 30°N). Meridional winds are directed poleward at upper levels and equatorward at low levels, consistent with rising close to the equator and in the subtropics. Arrows mark the sense of the overturning circulation in the tropical regions. Meridional winds tend to be large in the tropical band and small everywhere else – a clear signal of the Hadley circulation confined to the tropical belt.

Figs. 6 and 7 together give a summary of the general circulation and illustrate the main features of the Hadley cell in the tropics. The connection between the laboratory flows and the observed Hadley circulation is clearly evident.

3.5 Baroclinic instability of the thermal wind: the weather regime

Following our matrix of experiments shown in Fig. 2, students are encouraged to compare and contrast the low rotation Hadley experiment with exactly the same laboratory set-up but now rotating much more rapidly, Ω large, as shown in Fig. 8 (top). This illustrates dynamics typical of the middle-latitudes. The difference is striking: at a higher rotation rate the axi-symmetric circulation of the Hadley regime breaks down. The flow becomes turbulent and more chaotic; tongues of cold and warm fluids intermingle, sliding one on top of one-another – see Fig. 8 (middle). The analogy to the mid-latitude weather systems is very evident by visually comparing with Fig. 8 (bottom), showing the 850 mb temperature over the northern hemisphere for a typical wintertime day. Tongues of warm air move north towards the pole, while cold air vice-versa is moving south towards the equator, equilibrating the Pole-Equator temperature gradient. A video of the high rotation experiment together with observed temperature field can be found at http://lab.rotating.co/#/eddies.

The contrast between the low and high rotation experiments helps one grasp the importance of rotation in shaping weather regimes. Students are amazed to see that the complexity of weather systems can readily be captured by such a transparent rotating fluid experiment with an ice can in the middle and an appropriate rotation rate. Indeed, experiments such as these, known as ‘annulus’ experiments, were fundamental to our understanding of the general circulation of the atmosphere: see Hide (1966) for a comprehensive discussion of relevant laboratory experiments and Lorenz’s (1967) classic review of the general circulation of the atmosphere.

4. Discussion and Future plans

As demonstrated in the ‘Weather in a Tank’ approach to teaching weather and climate (Illari et al., 2009; Mackin et al., 2012), we believe that student learning is enhanced by being exposed to simple rotating fluid analogues of meteorological (and oceanographic) phenomena. However, we are aware that not everyone has access to rotating turntables, hence the emphasis here on virtually-enhanced experiments which can provide a flavor of the true laboratory. Indeed, we have noted in teaching that the availability of a virtually-enhanced laboratory can deepen understanding by helping students to gain a 3d perspective of the phenomenon studied. This is very clear when studying the general circulation of the atmosphere, whose regimes are rather complex and difficult to unravel. The availability of virtually-enhanced movies and snapshots can help the students appreciate the essence of the phenomena. The ‘virtual lab’ can also be used in conjunction with ‘live’ experiments enabling students to replay and explore again both in and out of class. It is also a valuable and highly effective means to reach larger audiences.

In conclusion, we would like to contrast the approach presented here to other explorations of digital learning in meteorology. Often the ‘virtual laboratory’ is presented in a gaming context (typically in introductory courses) or a set of computational simulations (in more advanced courses). Indeed the UCAR list of virtual labs (scied.ucar.edu) is dominated by games or simple computational exercises. For example there are several virtual tornadoes:

- the early work of Gallus et al (2006) developing a Virtual Tornadic Thunderstorm, combining data collection and analysis;
- the more recent and very realistic experience provided by the CUBE theater/lab where one steps in to a virtual recreation of the tornado that hit Oklahoma in 2013, Carstensen (2015);
- the GEOPod game (Yalda et al., 2012), designed to give a 3d virtual experience to meteorology majors. GEOPod makes use of IDV graphics fly-simulation capabilities and encouraged students to 'dive in' and analyze a variety of atmospheric data. Evaluation of student learning showed that the technology was not only visually compelling, but also helped students deepen their understanding of meteorological concepts.

Such examples demonstrate that technology can indeed give exciting experiences to students. The approach presented here is perhaps a little more conservative, rooted as it is in the 'tradition' of the laboratory exploration of simplified systems in the spirit of geophysical fluid dynamics. Nevertheless, the artful use of laboratory visualization together with the use of 3d graphics of the real phenomena, as made possible by IDV software, can perhaps give new life to these classic experiments and enthuse a new generation of online students helping them understand the world around them at a deeper level.

Acknowledgments

This study was made possible in part by NSF support through AGS-1338814, ‘FESD Type 1: ‘The impact of the ozone hole on the climate of the Southern Hemisphere’.

Appendix

The rotating fluid experiment presents a 360-degree rolling view to laboratory observers with each complete rotation of the system. This driving action shapes the dynamic forms of 'Weather in a Tank' as well as making them opportune subjects for digital capture and virtualization. Here we outline the processes used to create an enhanced animation from video recordings of the Hadley Cell experiment for a virtual laboratory setting as described in Section 3.2.

A1. Building a Viewing Tool

Footage of the experiment from multiple cameras is combined into a synchronized multi-view video. Imagery for a selected tank angle is cued into a 3d modeling environment to create a viewing tool for photogrammetric reconstruction of the fluid forms.

Camera Set

Set-up of cameras for recording rotating fluid experiments is illustrated in Fig. A1.1:

'A' is the camera on-axis overhead, co-rotating with the turntable.

'B' is the camera on a tripod in the fixed frame of the lab, capturing the vertical structure of the whole system as it turns.

'C' is an additional camera affixed to the turntable, providing a single viewpoint which can be used to check the consistency in camera B's capture.

Synchronized Imagery

Viewing frames from the various cameras are aligned and scaled to be consistent with one-another, as illustrated in Fig. A1.2. The experiment is sampled at a rate of 12 frames per rotation.

Fluid zoetropes

The views from around the system over the course of one period can be used to create a virtual co-rotating viewing tool, similar to the cylindrical image sequence inside a zoetrope – see Fig. A1.3.

[Software used: AfterFX » Max MSP / Jitter » Rhinoceros 3d]

A2. Animation Tools

Information about the evolution of dye streaks in the co-rotating frame is analyzed with selected view-angle observations from the lab frame to build up a 3d animation of the fluid flows.

Mapping evolving dye plumes

We use a modeling technique similar to ‘rotoscoping’, in which live footage is traced over to produce a realistic animation. The overhead features of the dye, Fig. A2.1, are traced into a closed 2d contour. This creates an initial curve matching the observed extent of the dye form, which is then traced back in time until the dye returns to the initial droplet.

The edges of the stretching 2d dye contour are given depth using elevation data from the tripod camera. A top view together with a pair of perpendicular side views allows us to triangulate the vertical structure of the evolving dye plume.

Surface volume mesh

In this phase we move from animated line contours to surfaces: the 3d contours in Fig.A2.1 are surfaced, thickened and turned into a closed mesh as shown in Fig. A2.2. This mesh provides the basis for rendering other properties.

Photo realistic rendering

The geometric surfaces created by the multi-angle modeling in Fig. A2.2 can be rendered to resemble real dye surfaces. In our case, the turntable, tank, fluid media, dye tracer, and can of ice are rendered separately and overlaid into co-axially nested systems. Some materials' parameters may be modified to reduce effects of refraction which usually distort the image. The final product can be seen as a continuous form without obstruction from the original tank vessel, as shown in Fig. A2.3. The layer-based animation and rendering can then be staged using dynamic views: in the lab, co-rotating with the tank, or even in the flow, moving in sync with a prominent fluid feature, for example, the super-rotating jet at the free surface. The enhancement allows points of views that would otherwise only be available through complex camera set-ups. For example see following movie: http://lab.rotating.co/#/10.

[Software used: Max MSP « » Rhinoceros 3d + Bongo + V-ray]

A3. Website

Real movie, virtual movies and observations of the Hadley cell are organized in a coherent story in the project website – see http://lab.rotating.co/

Utilizing the Virtual Lab

The website provides a 'public view' into the lab and can be used in various contexts:

- Web-based presentations for large classes or audiences at meetings - the scripted animations can be used instead of the real experiment, when the use of a turntable is not practical.
- Classroom environment – students can export the virtual models to a specified coordinate system for analysis and interrelation with world observations or their own run of the experiments.
- Stand-alone - the virtual rendering of the experiment can be replayed, skipped back, and studied at great length to 'research' the real behaviors of the fluid.

The website brings together the rotating fluid experiment and the real world with a comprehensive discussion of the climatology of the Hadley Cell, visualized with IDV (Integrated Data Viewer by Unidata) - see http://lab.rotating.co/#/world. Three dimensional plots of the Hadley Cell from climatological data (NCEP reanalysis I) show close analogies to the low rotation tank experiment.

Navigation of the website

Visitors to the virtual laboratory will arrive with differing intents, time constraints, and levels of familiarity with the material or laboratory methods. In consideration of this, we have devised a streamlined experience for 'Weather in a Tank' watchers along the top-level (progressing by right arrow / left swipe), while elaborations on a subject are folded-in below (discoverable through a downward arrow / upward swipe). We recommend a first pass through the main stream at the top before making a second pass to review and explore in-depth. Jumps across sections are possible on-click of the progress bar which us always present at the bottom, or by revealing the ‘guide’ with the menu icon just above.

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Figure captions

Fig. 1. The ‘three-legged-stool’ approach to teaching the fundamentals of atmospheric dynamics at the heart of the ‘Weather in a Tank’ project.

Fig. 2. Matrix used in teaching the general circulation. Three experiments are carried out in which a radial temperature gradient is induced through use of an ice can, placed at the center of a cylindrical tank of water. The only difference between them is that the rotation rate, **Ω**, of the tank is different (Ω = 0, small, large).

Fig. 3. The low rotation ‘Hadley’ experiment: (top) Overhead view shows the evolving azimuthal circulation at early (left) and later (right) times. The pink plume on the right emanates outward from crystals of permanganate dissolving at the bottom of the tank. They indicate the sense of the flow near the bottom. (bottom) Side views show the green dye streaks being tilted over into a corkscrew pattern early (left) and later (right) in the experiment.

Fig. 4. Views from three mutually perpendicular camera angles provide a spatial fix on the dye plume as it evolves and deforms with the fluid flow. Overhead lineaments are coordinated with side-views of tracer extents, enabling the 3d structure of the plumes to be reconstructed.

Fig. 5. Rendered (virtual) view of the Hadley Experiment showing the ‘winding up’ of green dye plumes by the cyclonic (anticlockwise viewed from above) flow in thermal wind balance with the radial temperature gradient. The evolution of the anti-cyclonic (clockwise) flow at the bottom is revealed by the pink plume. The geometric surfaces created by the multi-angle views of Fig. 4

have been given visual-perceptual properties, which resemble real dye surfaces. The final image is continuous without obstruction of the tank used in the experiment.

Fig.6. (top) Climatological winter mean circulation, showing upper level westerlies (cyan isosurface of u = 30 m/s) and low level easterlies (pink isosurface of u = -10m/s). The meridional section on the left hand side shows the zonally averaged overturning circulation at low latitudes - vertical and meridional wind directions are marked by white arrows. (All fields are plotted using IDV software). (bottom) A schematic diagram of the laboratory Hadley circulation, showing similar features to the observed climatology: the green streak of 'westerlies' and the pink plume of surface 'easterlies'. (cf Fig. 5.)

Fig. 7. The observed mean meridional circulation during January (from NCEP/NCAR Reanalysis I). (top) Zonally averaged meridional wind (scale on top) and vertical wind (scale on side) are contoured (and colored) and the sense of the flow indicated by arrows. (bottom) Zonally averaged potential temperature (scale on left hand side) and zonal wind (scale on top). Westerly winds are blue-green: easterlies are red-pink. All fields are plotted using IDV software.

Fig. 8. The high rotation experiment showing baroclinic instability: (top) view from the co-rotating camera showing turbulent eddies transfer fluid from the warm (red) edge of the tank to the cold (green) inner can with ice; (middle) sections across the whole tank, showing the colder green water sliding under the warmer red water and mixing laterally and vertically; (bottom) 850 mb temperature on a typical winter day over the North America sector, showing a burst of cold

arctic air being advected south over Canada and the US, while a tongue of warm tropical air is advected north.

Fig. A1. Variable-angle video from a turntable experiment in the lab (1.1) is sampled at a regular frequency subdividing the rotation period (1.2) and mapped to frames linked to time-points of view in the animation environment (1.3).

Fig. A2. Projections of extracted features from overhead & side-views combine to map the volume of fluid containing dye (2.1). The interpolated contour bounding the evolving dye plume is surfaced (2.2), to produce a visualization of the circulation pattern (2.3).

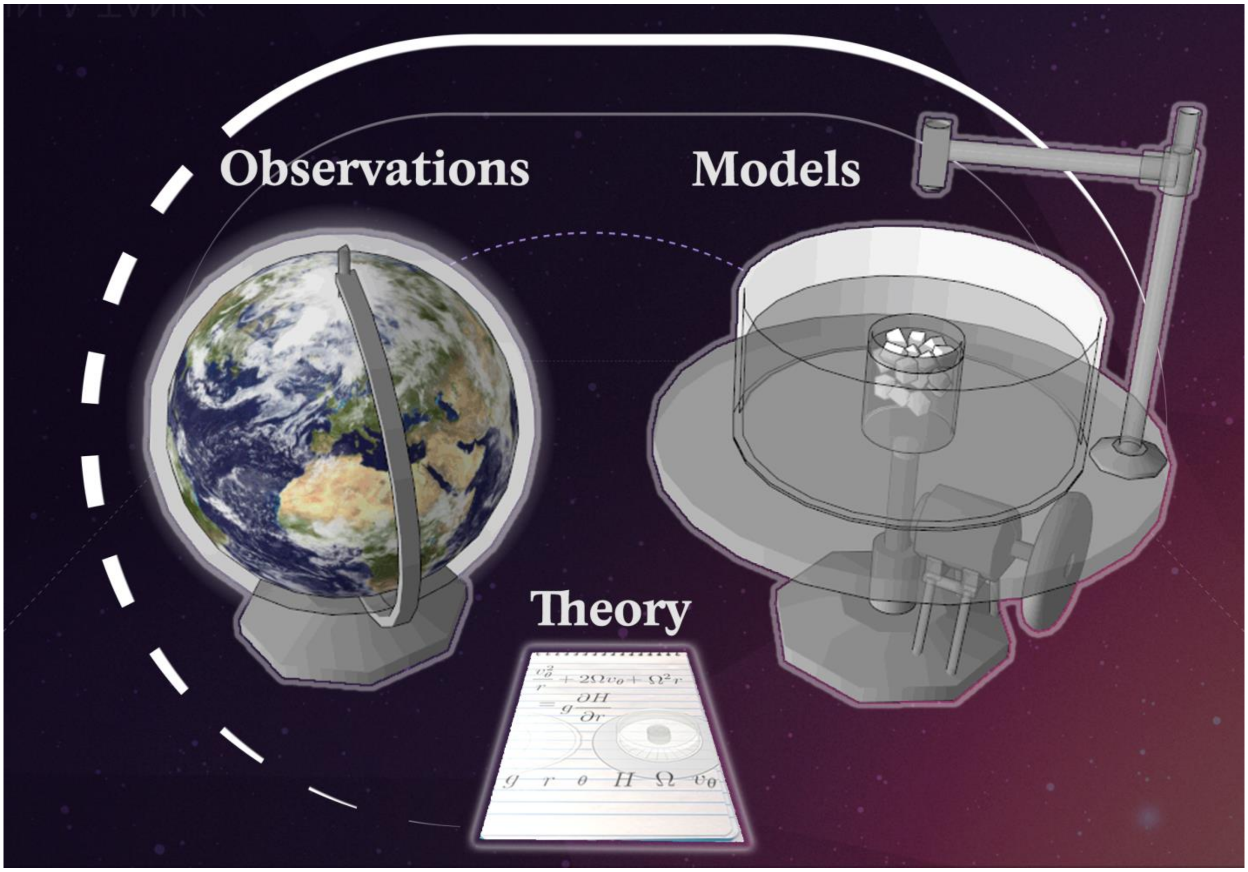


Fig. 1. The ‘three-legged-stool’ approach to teaching the fundamentals of atmospheric dynamics at the heart of the ‘Weather in a Tank’ project.

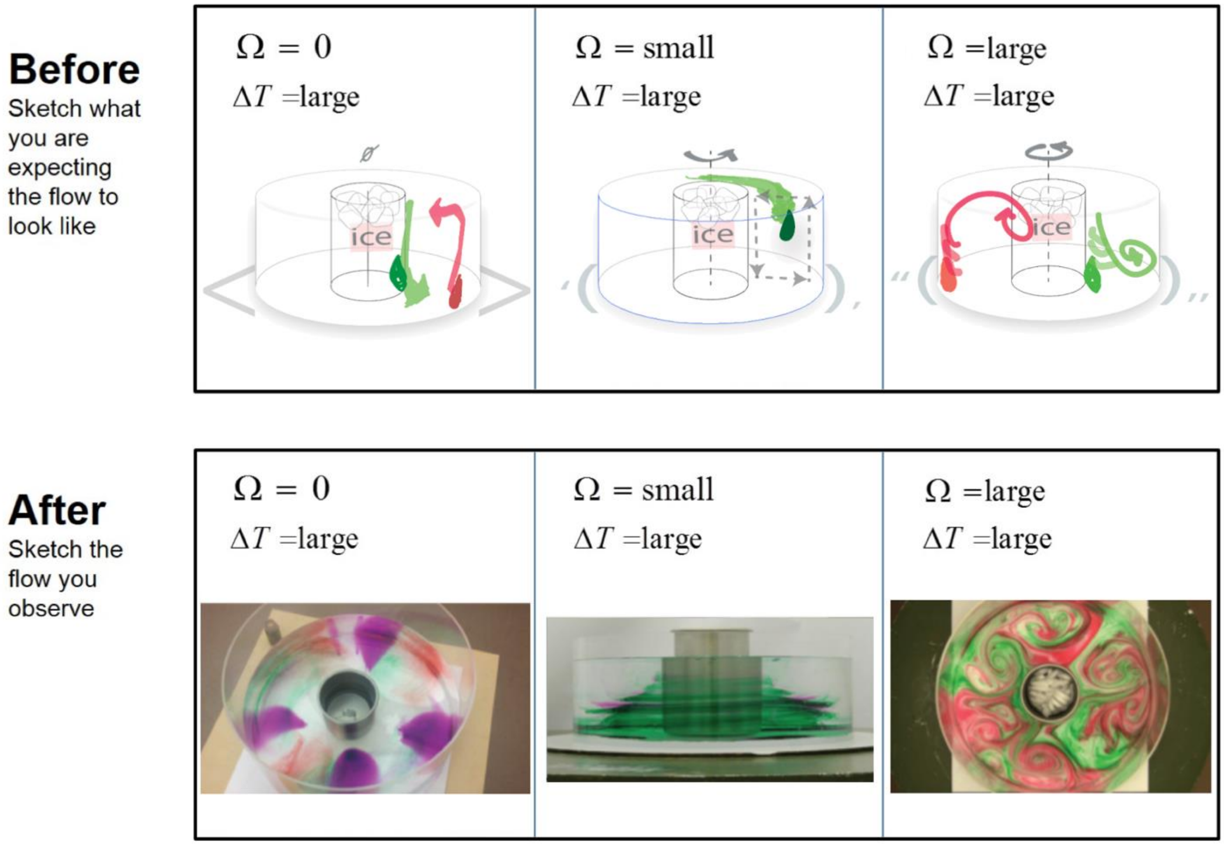


Fig. 2. Matrix used in teaching the general circulation. Three experiments are carried out in which a radial temperature gradient is induced through use of an ice can, placed at the center of a cylindrical tank of water. The only difference between them is that the rotation rate, **Ω**, of the tank is different (Ω = 0, small, large).

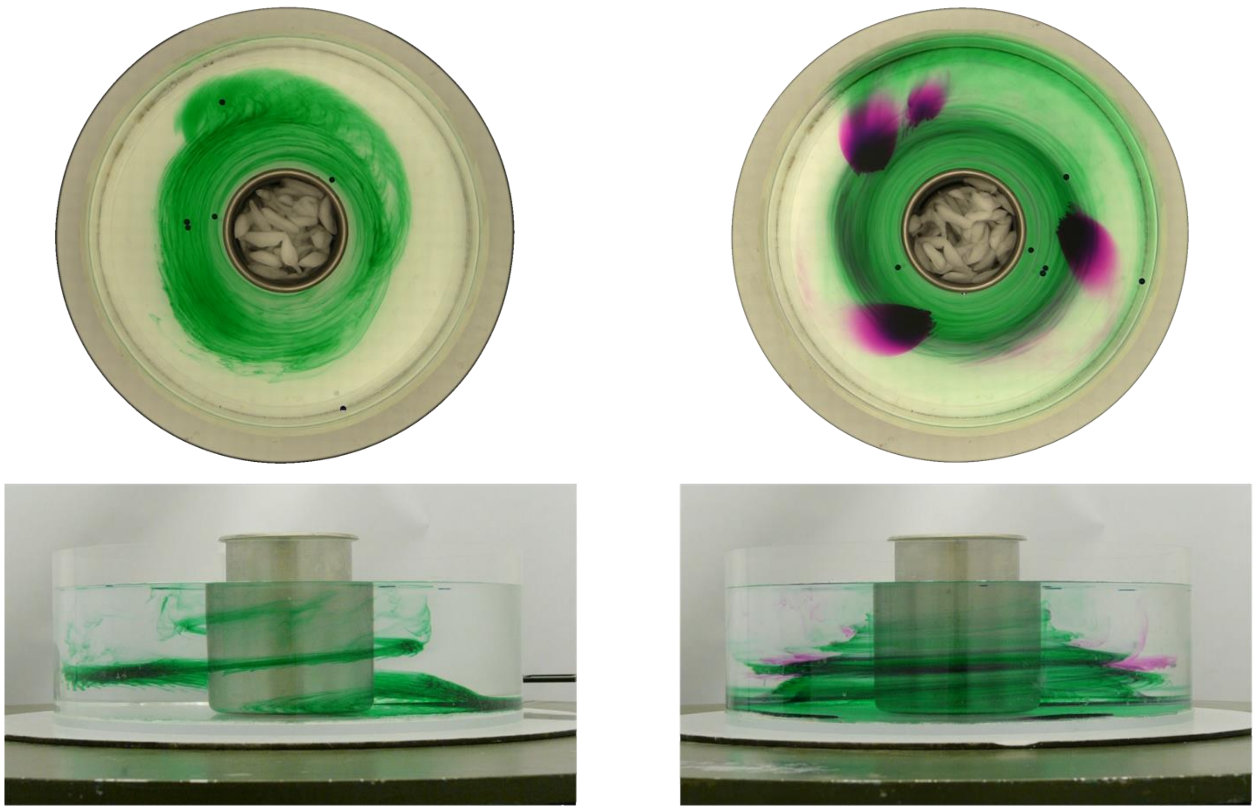


Fig. 3. The low rotation ‘Hadley’ experiment: (top) Overhead view shows the evolving azimuthal circulation at early (left) and later (right) times. The pink plume on the right emanates outward from crystals of permanganate dissolving at the bottom of the tank. They indicate the sense of the flow near the bottom. (bottom) Side views show the green dye streaks being tilted over into a corkscrew pattern early (left) and later (right) in the experiment.

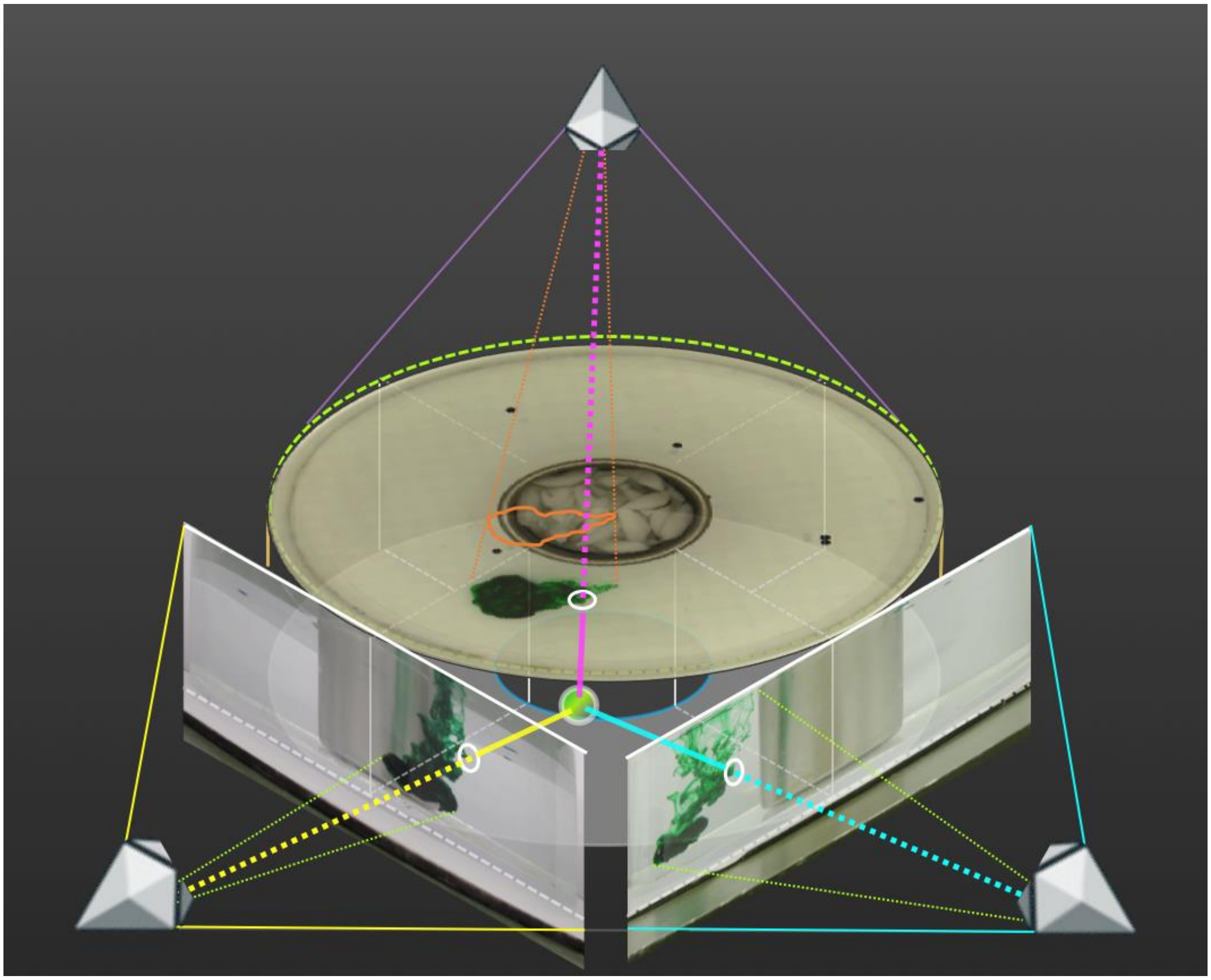


Fig. 4. Views from three mutually perpendicular camera angles provide a spatial fix on the dye plume as it evolves and deforms with the fluid flow. Overhead lineaments are coordinated with side-views of tracer extents, enabling the 3d structure of the plumes to be reconstructed.

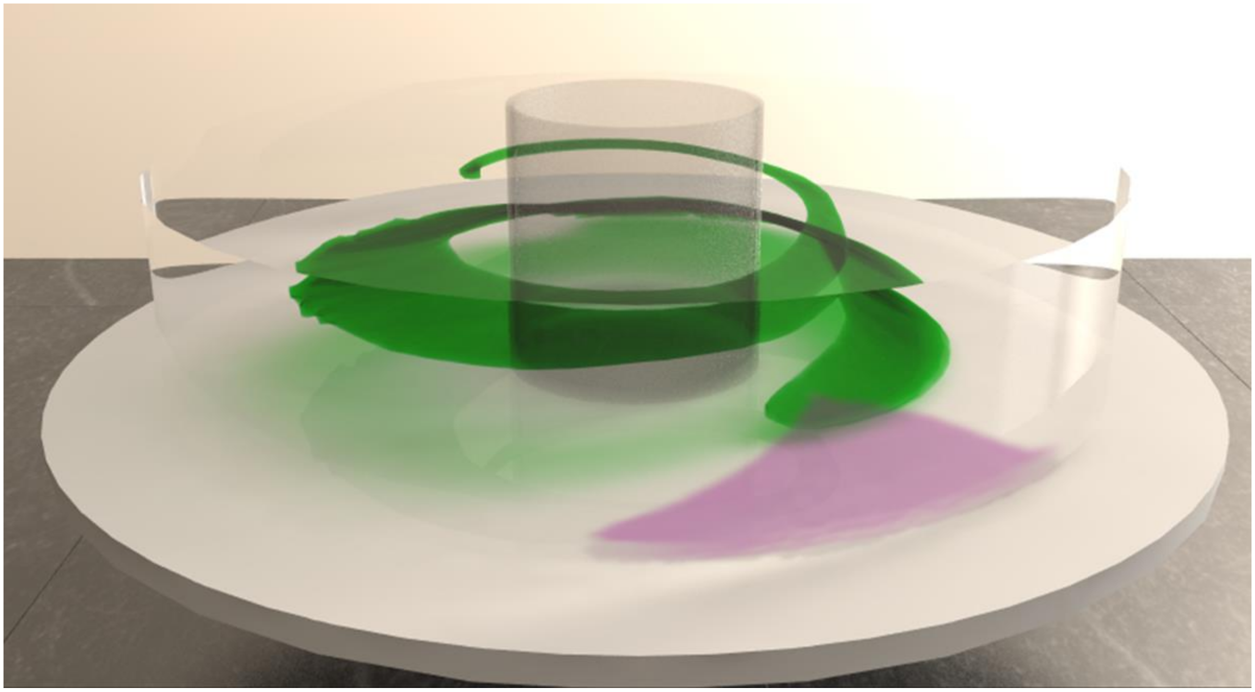
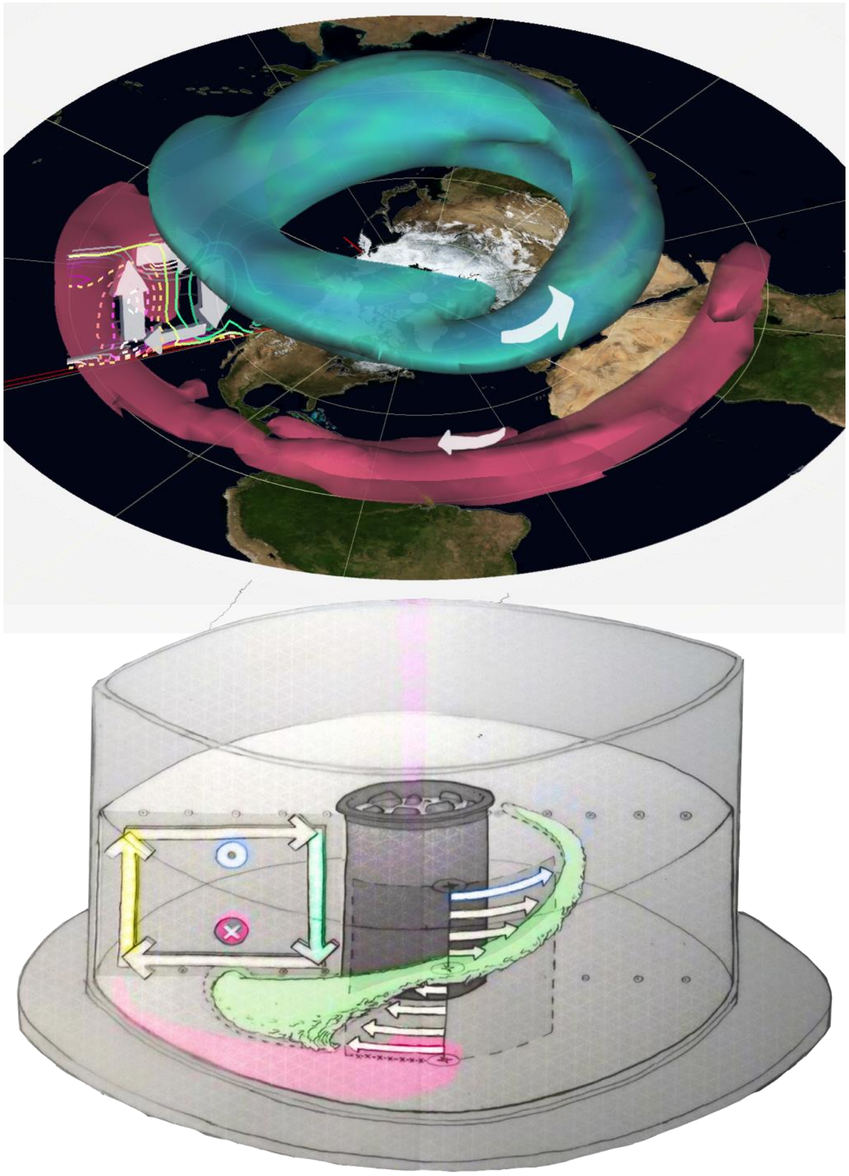


Fig. 5. Rendered (virtual) view of the Hadley Experiment showing the ‘winding up’ of green dye plumes by the cyclonic (anticlockwise viewed from above) flow in thermal wind balance with the radial temperature gradient. The evolution of the anti-cyclonic (clockwise) flow at the bottom is revealed by the pink plume. The geometric surfaces created by the multi-angle views of Fig. 4 have been given visual-perceptual properties, which resemble real dye surfaces. The final image is continuous without obstruction of the tank used in the experiment.



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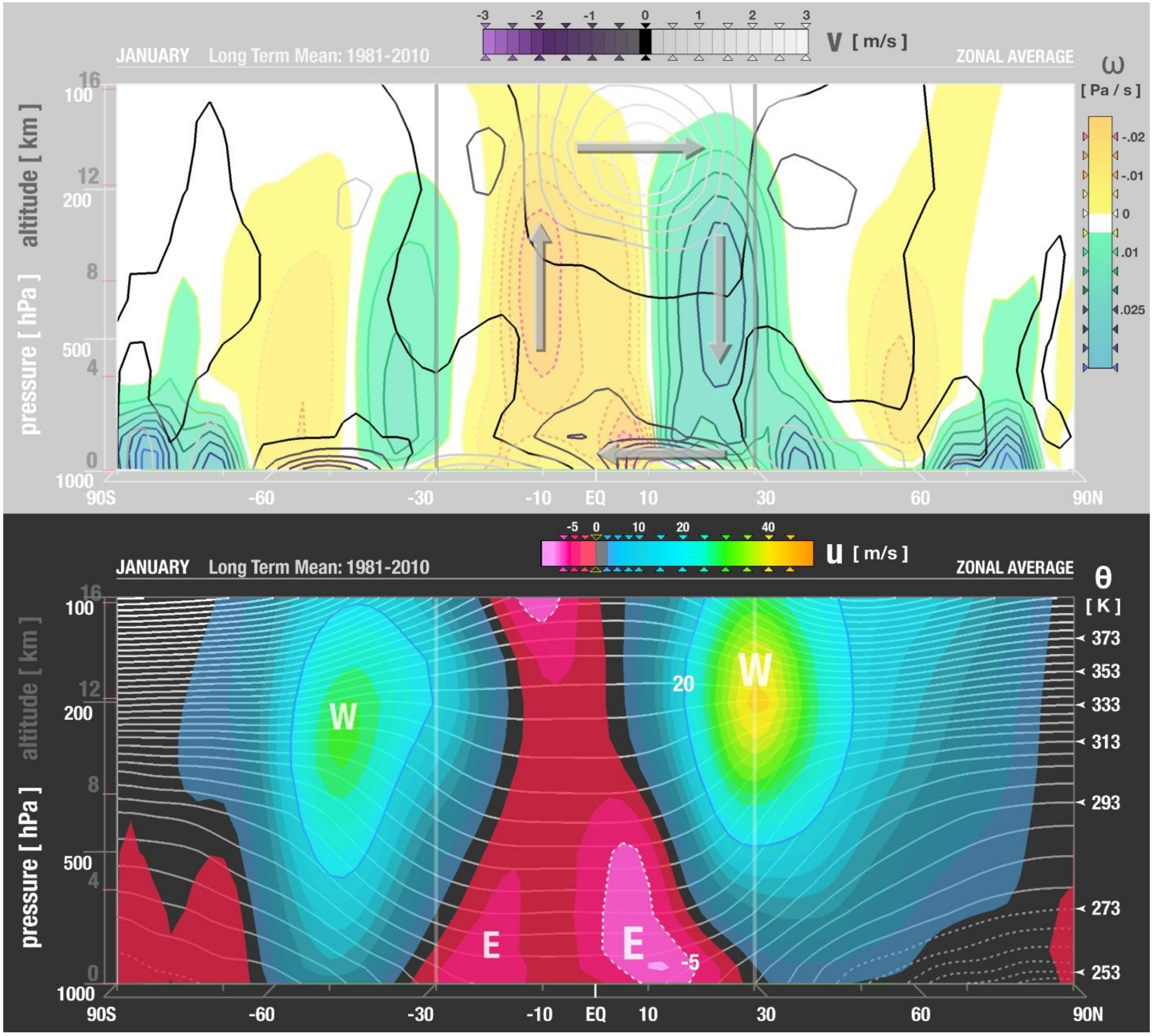

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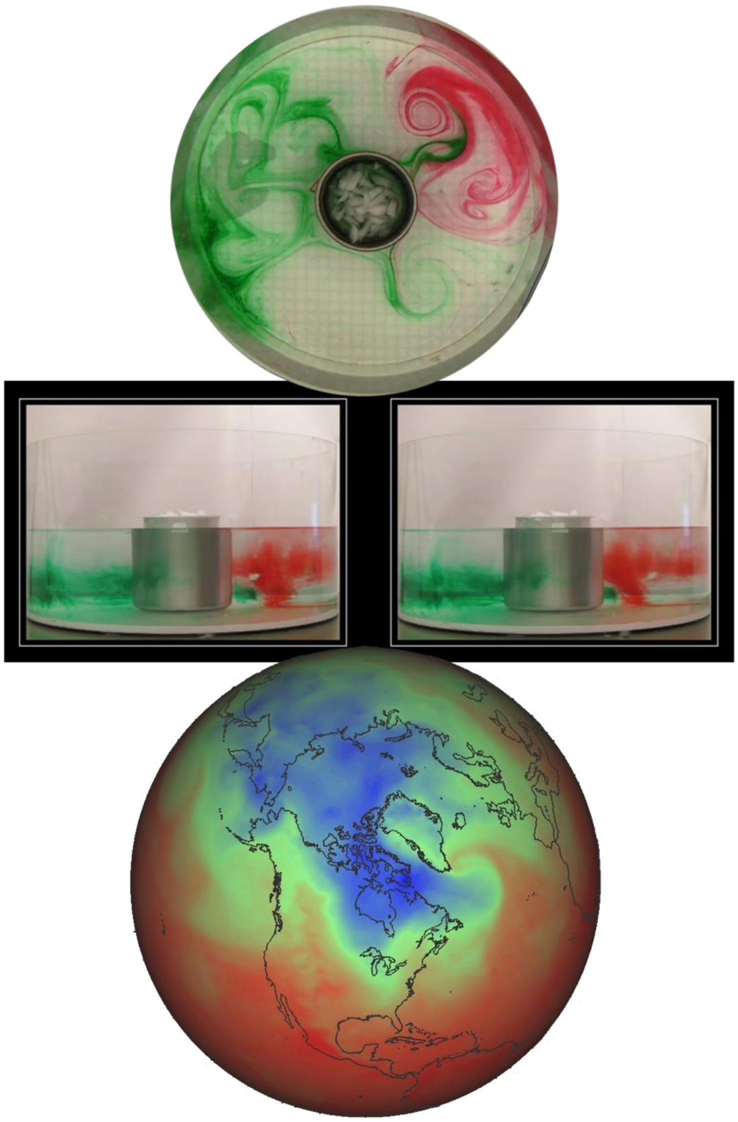

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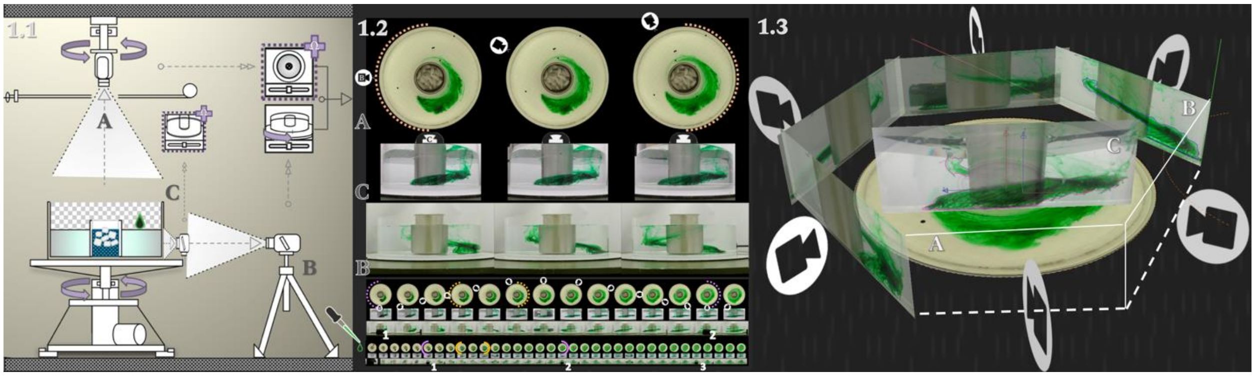

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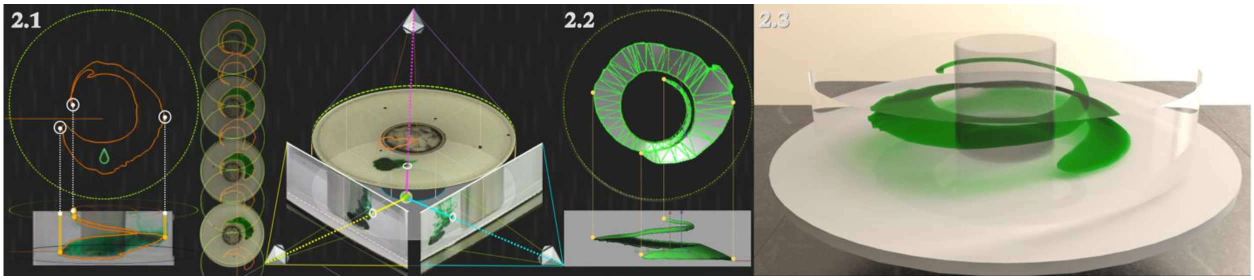

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