ADDING ENVIRONMENTAL PHYSICS INTO ADVANCED PHYSICS LABORATORIES

SUMMARY: This paper describes the development of teaching laboratory experiments related to atmospheric processes to provide undergraduate students with authentic research experiences and exposure to scientific instrumentation used by scientists. We focus on a senior-level course that gives students freedom to ask their own research questions and, with guidance, design and pursue investigations aligned with their own research interests. This approach fosters inquiry, scientific autonomy, and development of research skills.



By **A. M. HARLICK**[1] <ania.harlick@utoronto.ca>, **C. LEE**[1] <christop.lee@utoronto.ca>, **M. HOOPER**[2] <morgan.hooper@utoronto.ca>, **D. WUNCH**[1] <debra.wunch@utoronto.ca>, **P. BANWAIT**[1] <parveer.banwait@mail.utoronto.ca>, **J. CHEN**[3] <jkchen4@ualberta.ca>, **M. KOU**[4] <mk2217@cam.ac.uk>, **Q. XUE**[1] <qilin.xue@mail.utoronto.ca>, **C. ESPINAS**[2] <c.espinas@mail.utoronto.ca>, and **A. ZHANG**[5] <aiqi_zhang@berkeley.edu>

[1]Department of Physics, University of Toronto, Toronto, ON, M5S 1A7, Canada
[2]Faculty of Applied Science & Engineering, University of Toronto, Toronto, ON, M5S 2E4, Canada
[3]Faculty of Engineering – Electrical & Computer Engineering Department, University of Alberta, Edmonton, AB, T6G 1H9, Canada
[4]Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge, CB3 0WA, United Kingdom
[5]Department of Civil and Environmental Engineering, University of California, Berkeley, Berkeley, CA, 94720, United States of America

One of the crucial missions of higher education is to train responsible citizens and contribute to a sustainable future [1]. Exposing students to research on Earth's climate and its components, and introducing them to relevant experimental techniques, is a crucial learning tool. The primary outcome of the Advanced Physics Laboratory courses at the University of Toronto is for students to explore how to measure and model physical systems and to critically assess, connect, and communicate their results [2]. Experiments in the course range from classical to very modern, and they represent fields of study pursued in the department. They are designed to "form a bridge to current experimental research" [3] by employing techniques and equipment used in professional laboratories in all fields of physics. The experiments are constantly updated, both through collaboration with the Engineering Science senior undergraduate design course at our institution [4] and through engagement with faculty members. In recent years, growing enrollment, student feedback, and analysis of the offerings identified a gap in the experiments; experiments related to atmospheric and environmental

physics, a field pursued by about 20% of the faculty members, was underrepresented in the experiment offering. This discovery inspired a focused developmental effort to address this issue and provide opportunities for students to pursue their research interests. The work resulted in significant updates to an existing experiment (*Fourier Infrared Spectroscopy, FTIR)* and the creation of three new experiments: a data-analysis focused *Anthropogenic Climate Change (ACC), a* field work inspired *Ozone Measurement* (*O3M)*, and geophysical fluid dynamics experiment *Weather in a Tank (WTK)*. Additional experiments being integrated into junior labs help develop interest in these experiments earlier in the undergraduate program and present a framework for integrating environment and climate physics into advanced laboratory curricula using a combination of data-driven, field-measurements, and analogue experiments.

COURSE OVERVIEW

The Advanced Physics Laboratory course at the University of Toronto hosts senior physics and engineering science students completing their third- or fourth-year course requirements. The course is staffed by faculty members, who supervise and assess students' work, and teaching assistants whose main role is to aid with setting up the equipment and conducting the experiments. The variety of experiments, skills, and tools required, and the expertise of the supervising faculty, ensure that the students experience a vibrant learning environment in which no two experiences are the same. Students state their experiment preferences in a selection process, and while not all requests can be honoured, most will work on one of their top choices. Students complete three experiments during the term, typically working individually, and they spend approximately 18 hours in the lab with each experiment over three weeks. The instruction manuals provide suggested experiments but leave room for students to design their own inquiry to extend their exploration. The course is integrated with an Engineering Science Capstone Design course [4], in which students work in small teams to redesign and implement experiments suitable for undergraduate laboratories at various levels.

FOURIER TRANSFORM INFRARED SPECTROSCOPY

Fourier Transform Infrared Spectroscopy (FTIR) is a technique commonly used to identify a wide range of materials, including atmospheric trace gases [5]. Bacsik *et al.* [6] reviewed the frequent and significant applications of FTIR in air monitoring studies in both environmental and industrial settings. The spectrometer, shown in Fig. 1, allows students to study gaseous and solid samples [7]. The laboratory provides a selection of gases, but students are encouraged to suggest and source their own samples. The primary goal of the experiment is to study the spectra and line-shapes of a variety of atmospheric gases at different pressures and temperatures and develop an understanding of how these spectra can be used in a simple retrieval to infer gas concentrations [7]. There is less ability to adjust the equipment in this experiment, but students have more freedom to explore other parameters, like the gas they choose, its temperature and pressure, and how they develop a simple retrieval algorithm.

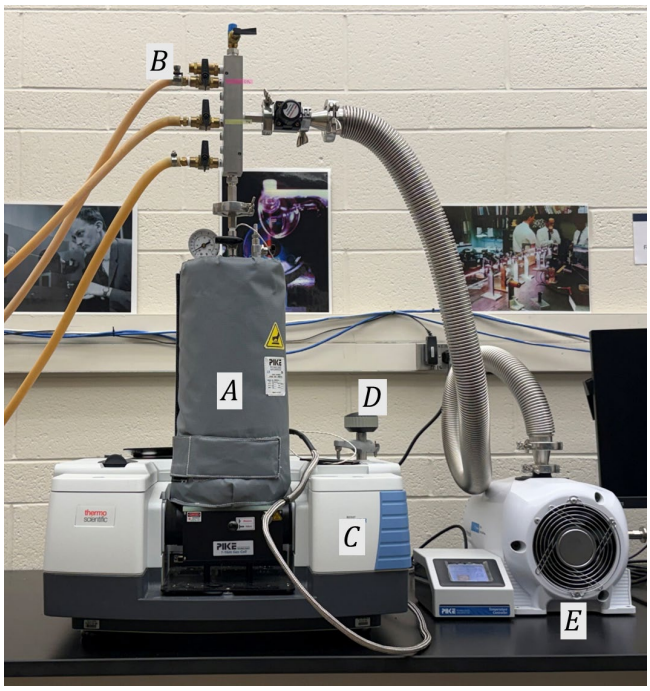


Figure 1. Multirange Nicolet iS50 spectrometer. A —gas sample compartment, B —entry points for gaseous samples, C —sample module, D —iS50 ATR module for investigation of solid and powder samples, E —pump.

ANTHROPOGENIC CLIMATE CHANGE

This experiment focuses on the analysis of large-scale climate datasets collected by researchers in the field. Students work with historical records of atmospheric composition, carbon dioxide emissions, temperature, and population data to investigate relationships between climate variables and develop their own research questions.

Students are provided with recommended sources for historical climate data [8] but are encouraged to find other suitable sources. Through guided preliminary experiments, students examine trends, consider data quality, and learn about future climate predictions and their societal relevance. In an open-ended exploration, students are asked to identify a suitable climate question from a selection of suggested topics, to identify relevant data, and to use that data to attempt to answer the question.

This experiment allows students to explore how complex environmental systems are studied using distributed datasets and to develop data analysis skills relevant to modern collaborative fields such as climate science, astrophysics, and particle physics. The experiment strongly emphasizes developing research questions and encourages students to connect environmental phenomena to the underlying physics. Both supervising professors and the TA supporting ACC highlight the importance and challenge of identifying research questions, encouraging the students to follow their curiosity.

OZONE MEASUREMENT

This experiment uses a portable instrument to measure solar radiation in narrow bands in the UV and near-IR bands to determine atmospheric composition. Students calibrate the instrument using nearby operational equipment and collect field measurements to determine the total ozone column and the concentration of water vapour in the atmosphere. The laboratory uses the Solar Light Microtops II Ozonometer [12], shown in Fig. 2. The instrument measures sunlight in three ultraviolet bands sensitive to light absorbed by Ozone and Oxygen (305 nm, 312.5 nm, and 320.5 nm), and two bands sensitive to light absorbed by water and aerosols (936 nm and 1029 nm). The device allows for dependable measurement of total ozone column per standard World Meteorological Organization configuration.

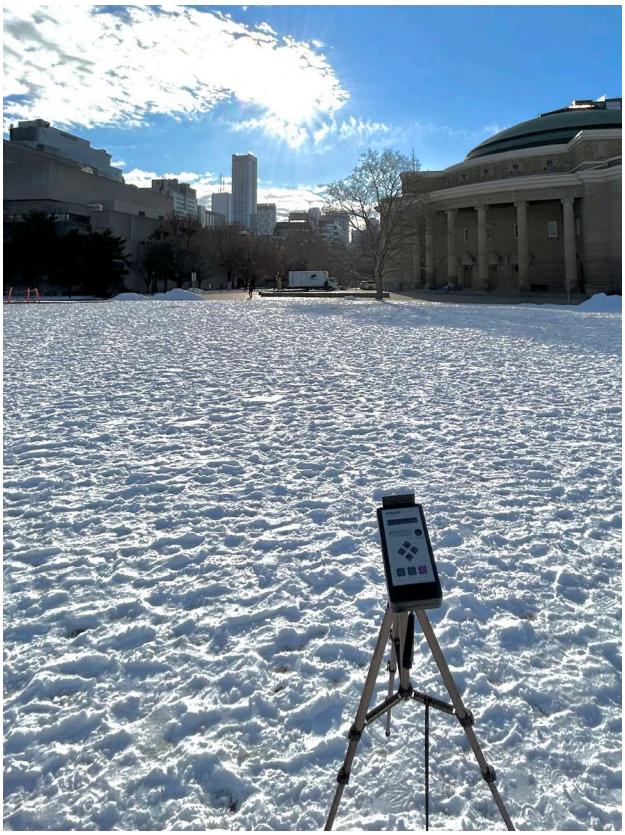


Figure 2. Solar Light's Model 520 Microtops II® Ozonometer [12], used in the *Ozone Measurement* experiment, set up on a sunny day (pointing at the Sun) during data collection in Winter 2025 at University of Toronto's St. George Campus.

The experiment emphasizes experimental design and planning in real-world conditions. The data acquisition takes place outside and depends on weather, time of day, and seasonal constraints.

Students must monitor weather conditions to identify suitable measurement windows, highlighting the challenges and uncertainties inherent in field-based research. After collecting their own measurements, students compare their localized measurements with the regional and global measurements of ozone from satellites and ground-based instruments.

WEATHER IN A TANK

This experiment uses a rotating tank of water as an analogue for Earth's atmosphere, allowing students to explore how large-scale flow patterns arise from the interplay of rotation and heating. By varying the rotation rate and imposing a temperature gradient, students observe how these fundamental drivers produce structured, weather-like circulation patterns. This design mimics larger-scale tanks [13] that are used as analogues of the Earth system.

In the experimental setup (Fig. 3), flow patterns are visualized using neutrally buoyant tracer particles illuminated by a laser sheet and recorded with a camera. The students then reconstruct the flow and analyze the fluid behaviour using Particle Image Velocimetry (PIV) software. The experiment emphasizes conceptual understanding through direct observations, connecting theoretical fluid dynamics to measurable phenomena.

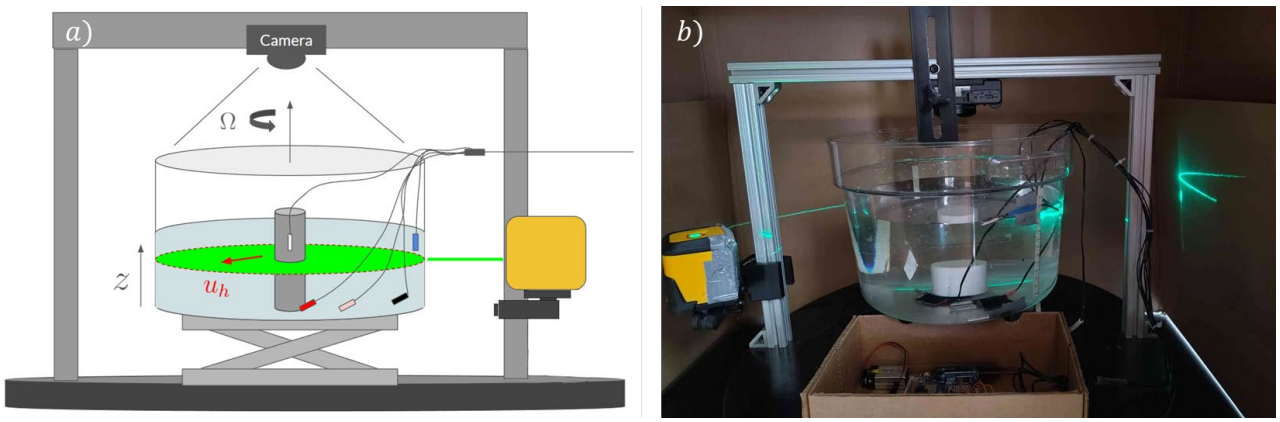


Figure 3. Experimental set up for the *Weather in a Tank* experiment. $a)$ The diagram of the set up viewed from the side, with z indicating the vertical direction, u_h indicating the radial component of of particle velocity, and Ω the angular velocity of the entire system. $b)$ The photograph of the set up enclosed in a box to minimize the external light.

Through this analogue system, students investigate how simplified physical models describe complex real-world phenomena. Although fluid motion is governed by the non-linear Navier-Stokes equations, the rotating tank configuration can be interpreted using simplified models, such as shallow-water approximations, that are commonly used to describe mid-latitude atmospheric dynamics. Students relate the phenomena in the tank to real atmospheric conditions using non-dimensional parameters that combine the rotation rate and fluid properties.

CONCLUSION

The integration of environmental and atmospheric physics experiments into the Advanced Physics Laboratory has expanded the range of experiences available to students. Together, these experiments demonstrate a framework for incorporating atmospheric physics into advanced laboratory curricula by combining data-driven analysis, field measurements, and analogue experiments. They are in demand – during the previous academic year approximately half of the students requested at least one of them among their top ten choices when stating preferences. Professors who conduct research related to environmental and atmospheric physics reported students looking for research projects reaching out to them quoting their experience in the lab as a factor in choosing the field.

The current implementation focuses on experiments that reflect departmental strengths, but there are opportunities to develop experiments that explore a broader range of topics in environmental and atmospheric physics. In the junior laboratories, climate datasets [CO_2] are being used to introduce model fitting and forecasting, and a new experiment on the "Greenhouse effect" [14] is being developed, in which students will use a broadband heat source and detector to measure the IR absorption of gaseous carbon dioxide. Once incorporated into the junior laboratories, this experiment will serve as a precursor for FTIR and ACC projects in APL.

REFERENCES

1. UNESCO, World Declaration on Higher Education for the Twenty-first Century: Vision and Action, in *World Conference on Higher Education in the Twenty First Century: Vision and Action.*, Paris, 1998 (published 2005).
2. Faculty of Arts and Science, University of Toronto, Academic Calendar - PHY424H1, [Online]. Available: https://artsci.calendar.utoronto.ca/course/phy424h1. [Accessed 05 April 2026].
3. Department of Physics, University of Toronto, Department of Physics, Undergraduate Program, 2025. [Online]. Available: https://www.physics.utoronto.ca/undergraduate/. [Accessed 08 April 2026].
4. Faculty of Applied Science and Engineering, Univerisity of Toronto, ESC471H1: Engineering Capstone Design, 2026. [Online]. Available: https://engineering.calendar.utoronto.ca/course/esc471h1.
5. Z. Bacsik, J. Mink and G. Keresztury, FTIR Spectroscopy of the Atmosphere. I. Principles and Methods, *Appl. Spectrosc. Rev.* **39**(3), 295-363 (2004).
6. Z. Bacsik, J. Mink and G. Keresztury, FTIR Spectroscopy of the Atmosphere Part 2. Application, *Appl. Spectrosc. Rev.* **40** (4), 327-390 (2005).
7. Thermo Fisher Scientific Inc., Nicolet iS50 Spectrometer User Guide, Madison, WI, USA, 2015.
8. P. Friedlingstein, *et al.*, Global Carbon Budget 2021, *Earth Syst. Sci. Data* **14**(4), 1917-2005 (2022).
9. P. Friedlingstein, *et al.*, Global Carbon Budget 2022, *Earth Syst. Sci. Data* **14**(11), 4811-4900 (2022).

10. H. Wan, A. C. Spassiani and L. A. Vincent, Canada's Fourth Generation of Homogeneized Surface Air Temperatre and its Trends for 1948-2023, *Atmosphere-Ocean* **63**(4), 223-240 (2023).
11. ECCC Data Catalogue/ ECCC Catalogue de donnees, Canadian Homogenized Surface Air Temperature, October 2025. [Online]. Available: https://catalogue.ec.gc.ca/geonetwork/srv/eng/catalog.search#/metadata/542b90f7-ab39-452c-be5c-2afebdc4724c. [Accessed April 2026].
12. Solar Light, Model 521 Microtops II (R) Ozonometer, Solar Light, 2026. [Online]. Available: https://www.solarlight.com/product/model-521-microtops-ii-ozonometer. [Accessed 15 April 2026].
13. M. Mabrouk and C. Mercier, Un manège pour la science, CNRS, 23 10 2017. [Online]. Available: https://lejournal.cnrs.fr/diaporamas/un-manege-pour-la-science. [Accessed 28 September 2026].
14. G. K. Vallis, *Atmospheric and Oceanic Fluid Dynamics: Fundamentals and Large-Scale Circulation., 2nd ed.* (Cambridgge, Cambridge University Press, 2017), pp. 3 - 52.