# *DESCRIPTION OF THE DEPARTMENT*

## History

The history of meteorology at McGill dates back from the middle of the nineteenth century when the McGill Weather Observatory was established. It has made continuous measurements of meteorological variables for over a century. Following the Second World War, two active atmospheric sciences research groups emerged at McGill. Dr. J. Stewart Marshall led a radar meteorology group in the Physics Department, and Dr. F. Kenneth Hare directed an arctic meteorology program in Geography. These two groups united in 1959 to form the Department of Meteorology. Since its creation, the Department has been a Canadian and international leader in the training of many distinguished atmospheric scientists. McGill has awarded over 350 M.Sc. degrees and more than 150 Ph.D. degrees in this field.

The history of oceanographic research at McGill also dates from the 1850's, and was brought into focus in 1963 with the establishment of the Marine Sciences Centre (later the Institute of Oceanography). Under the directorship of Dr. Max J. Dunbar, the Institute offered M.Sc. and Ph.D. degree programs in the areas of physical, geological and biological oceanography. In 1987 the Institute was closed and a Graduate Program in Oceanography was established to coordinate teaching and research in the marine sciences carried out by faculty members in the Departments of Atmospheric and Oceanic Sciences, Earth and Planetary Sciences and Biology. In 1992, the Department of Meteorology became the Department of Atmospheric and Oceanic Sciences (AOS), to demonstrate the broad range of research activities in the atmospheric sciences, physical oceanography and climate studies.

## Mission

The Department of Atmospheric and Oceanic Sciences continues to strengthen its educational leadership in teaching, research, and service on the Canadian and international scene. Graduate students in the field move on to successful careers, such as environmental research and consulting, weather and climate forecasting and analysis, and teaching at the college and university level. Our research areas include:

- Atmospheric Chemistry
- Geophysical Fluid Dynamics
- Cloud Physics and Dynamics
- Atmospheric Radiation
- Mesoscale Meteorology
- Physical Meteorology
- Paleoclimate Dynamics
- Physical Oceanography and Biogeochemistry
- Stratospheric Dynamics and Chemistry
- Dynamical Meteorology and Climatology
- Global Climate Change and Variability
- Radar Meteorology
- Synoptic Meteorology

## Faculty Professors

**Parisa Ariya**
Professor, Ph.D. (York)
(Joint with Chemistry; William Dawson Scholar)

**Peter Bartello**
Professor, Ph.D. (McGill)
(Joint with Mathematics and Statistics)

**Frédéric Fabry**
Associate Professor, Ph.D. (McGill)
(Joint with McGill School of Environment; Director, J. Stewart Marshall Radar Observatory)

**John R. Gyakum**
Professor, Ph.D. (M.I.T.)
(Chair)

**Yi Huang**
Assistant Professor, Ph.D. (Princeton)

**Daniel Kirshbaum**
Assistant Professor, Ph.D. (U. Washington)
(Undergraduate Program Director)

**Timothy Merlis**
Assistant Professor, Ph.D. (Caltech)
(Canada Research Chair, Tier 2)

**Thomas Preston**
Assistant Professor, Ph.D. (U.B.C.)
(Joint with Chemistry)

**David N. Straub**
Associate Professor, Ph.D. (U. Washington)
(Graduate Program Director)

**Bruno Tremblay**
Associate Professor, Ph.D. (McGill)

**Man K. (Peter) Yau**
Professor, Ph.D. (M.I.T.)
(NSERC/Hydro-Quebec Industrial Research Chair)

**Andreas Zuend**
Assistant Professor, Ph.D. (ETH Zurich)

## Adjunct Professors

**Luc Fillion**
Adjunct Professor, Ph.D. (McGill)
(Research Scientist, Environment Canada)

**Pierre Gauthier**
Adjunct Professor, Ph.D. (McGill)
(University of Quebec at Montreal; Research Scientist, Meteorological Service of Canada)

**Charles Lin**
Adjunct Professor, Ph.D. (M.I.T.)
(Director General, Atmospheric Science and Technology Directorate (ASTD), Environment Canada)

**Hai Lin**
Adjunct Professor, Ph.D. (McGill)
(Research Scientist, Meteorological Service of Canada)

**Damon Matthews**
Adjunct Professor, Ph.D. (U. Vic.)
(Associate Professor, Concordia University)

**Jaime Palter**
Adjunct Professor, Ph.D. (Duke)
(Assistant Professor, University of Rhode Island)

**Seok-Woo Son**
Adjunct Professor, Ph.D. (Pennsylvania State)
(Associate Professor, Seoul National University)

## Emeritus Professors

**Jacques Derome**
Emeritus Professor, F.R.S.C., Ph.D. (Michigan)

**Henry G. Leighton**
Emeritus Professor, Ph.D. (Alberta)

**Lawrence A. Mysak**
Emeritus Professor, C.M., F.R.S.C., Ph.D. (Harvard)
(Canada Steamship Lines Professor)

**Isztar Zawadzki**
Emeritus Professor, F.R.S.C., Ph.D. (McGill)

## Administrative Staff

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| **Technical Staff** |
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## Admission Requirements

Applicants for the **M.Sc. program** must meet the general requirements of McGill's Graduate and Postdoctoral Studies (GPS) and hold a bachelor's degree, with high standing, in meteorology, physical oceanography, physics, mathematics, engineering, or other related subjects. According to GPS standards, academic achievement must be evidenced by a minimum standing equivalent to a Cumulative Grade Point Average (CGPA) of **3.0 out of a possible 4 or a Grade Point Average (GPA) of 3.2/4.0 for the last two full-time academic years**. Normally, the Department sets a higher level of CGPA for admission. As well, higher grades are expected in those courses considered to be preparatory for the Department's graduate program.

Students registered in the M.Sc. program who perform especially well may be considered for a transfer to the Ph.D. program before the completion of their M.Sc. program. The normal requirement for admission to the **Ph.D. program** is a Master's degree in atmospheric science, physical oceanography, or a related discipline, with **acceptably high standing**. In addition, a Faculty member in the Department must agree to supervise the thesis of an incoming Ph.D. student before an offer of admission is made. Other requirements may apply to Ph.D. and M.Sc. applicants, and are indicated in the next paragraph.

Non-Canadian applicants whose mother tongue is not English and who have not completed an undergraduate degree using the English language are required to submit documented proof of competency in oral and written English by **one** of the following appropriate exams:

- **TOEFL** Paper-Based Test (PBT): minimum score 567
- **TOEFL** Internet-Based Test (iBT): minimum overall score of 86 with each component score not less than 20
- **IELTS**: a band score of 6.5 or greater

Please refer to the following website for a comprehensive listing of accepted proof of English proficiency: **www.mcgill.ca/files/gps/EnglishProficiencyTestsFactsheet.pdf**

## Financial Support

The Department normally provides financial support to all graduate students in the form of a graduate assistantship. The value of assistantships varies according to the amount of external support received by the student and the fees that have to be paid. For example, out-of-province and international students who pay a higher tuition receive additional support from the Department to partially or fully offset this additional expense. Students with external funding (scholarships, etc.) receive a top-up to their scholarship, such that the total is above the typical stipend received by non-scholarship students. A limited number of small teaching assistantships are also available.

Student accepting employment outside the University while still receiving a graduate assistantship from the Department must immediately notify the Department's Chair, in writing,

as this could lead to a reduction or termination of Departmental financial support.
Canadians and Permanent Residents of Canada are strongly encouraged to apply for postgraduate fellowships offered by federal and provincial government agencies such as the Natural Sciences and Engineering Research Council (NSERC), the Meteorological Service of Canada (MSC) and Le Fonds Québécois de la Recherche sur la Nature et les Technologies (FQRNT). International students are also encouraged to apply for external support in the form of scholarships. For **further inquiries**, please address them to the **Administrative and Student Affairs Coordinator: info.aos@mcgill.ca**

## Departmental Fellowships and Awards

The **Stephen and Anastasia Mysak Graduate Fellowship** was established in 2006 by Professor Lawrence A. Mysak in honour of his father, Stephen Mysak (1906–2007), and in memory of his mother, Anastasia Mysak (1907–1978). The Fellowship's official launch came in a ceremony at McGill University, sponsored by the Dean of Science, and held at the Redpath Museum on November 23rd, 2006. The Fellowship is to be awarded by the Graduate and Postdoctoral Studies upon recommendation of the Department of Atmospheric and Oceanic Sciences, to a full-time graduate student in the Department of Atmospheric and Oceanic Sciences. The Fellowship will be awarded on the basis of academic excellence to students pursuing research in one or more fields of air-sea interaction, oceanography or climate. The estimated value of this fellowship is $15,000 per year, renewable once at the Master's level, and twice at the Doctoral level. The Mysak Fellowship may not be held in conjunction with other McGill or major granting agency awards.

The **Max Dunbar Award** was established in 1985 by former students of Professor M.J. Dunbar in recognition of his teaching and research career at McGill. Formerly administered by the Institute of Oceanography, the Dunbar Award is now awarded by the Departments of Atmospheric and Oceanic Sciences, Biology, and Earth and Planetary Sciences, upon recommendation of the departments' award committees to a graduate student in any marine field of study with an outstanding academic record. The award value varies.

## Student Rights and Responsibilities

Students have the responsibility of informing themselves of the university regulations, program requirements, fellowship opportunities and deadline dates. Useful sources of information are the Administrative and Student Affairs Coordinator, the Graduate Program Director, the Departmental website, and the Graduate and Postdoctoral Studies website (**www.mcgill.ca/gps**). The **Handbook of Student Rights and Responsibilities** is available on the web, via the link at: **www.mcgill.ca/secretariat/policies/students**

## Academic Integrity

McGill University values academic integrity, which is fundamental to achieving our mission of the advancement of learning. The web site, **www.mcgill.ca/integrity**, is a resource for faculty and students. Its purpose is to promote academic integrity at McGill by providing information about the meaning of integrity, about how to foster it, and about the consequences of breaching it. There is specific information about requirements for citing the work of others. These requirements refer to both print and electronic sources. Students have the responsibility of informing themselves about these matters.

## Academic Standing and Failure Policies

Students must obtain grades of **B- or better** in courses used to fulfil program requirements (See Graduate and Postdoctoral Studies Calendar, Section 6.9).

Students who have **failed one course** required by their department while registered as a graduate student may automatically write one **supplemental examination** or, with the permission of their supervisor and the Graduate Program Director, **retake that course** or **substitute an equivalent course**. A student with any further failures in that course, including the supplemental, or a failure in any other course, will be required to withdraw from the program. Students who fail more than one course (required or otherwise) will be asked to withdraw from the graduate program (See Graduate and Postdoctoral Studies Calendar, Section 6.14).

## Vacation Policy

Graduate students and postdocs should normally be entitled to vacation leave equivalent to university holidays and an additional total of fifteen (15) working days in the year. Funded students with fellowships and research grant stipends taking additional vacation leave may have their funding reduced accordingly. (See Graduate and Postdoctoral Studies Calendar, Section 10.3.)

## Leave of Absence Policy

All students are eligible to request a leave of absence from the Graduate and Postdoctoral Studies for maternity, parenting, or health reasons. Leaves must be requested on a term by term basis by writing to the Department's Chair, who will then forward the request to the GPS office. Please refer to Section 6.1.10 "Leave of Absence Status" for information regarding registration of graduate students and postdocs on such leaves.

## Master's Curriculum

Depending on their background, students must take from **9 to 21 course credits** normally chosen from courses offered by the Department at the 500 and 600 levels. Additionally, students would take between **24 to 36 thesis credits** (i.e., ATOC 691–699), such that the total (thesis plus non-thesis) satisfies the **M.Sc. degree requirement** of **45 credits**. Master's students with no previous background in atmospheric or oceanic sciences or related fields generally take 21 course credits spread over two semesters (September–December and January–April). Students with a suitable background may be given permission by the Graduate Program Director or Department Chair to take fewer course credits. For example, students who have a strong B.Sc. in atmospheric science, or a Diploma in Meteorology, may be allowed to take as few as 8 course credits. Sometimes, with the approval of the Graduate Program Director, a portion of the course credit requirements may be satisfied by taking one or more courses from other departments at the 500-level or higher. Most students choose the No Specialization option. For students with special interests, however, the Environment option may also be appropriate. (refer to pp. 10–11).

Thesis research normally begins in early May of the M.Sc. 1 year. The formal procedure for choosing a supervisor for M.Sc. thesis research generally begins in December, near the end of the first Fall term of the M.Sc. program. At this time, a set of research topics prepared by the faculty is circulated to all the M.Sc. 1 students. Normally, these topics will be related to the material presented by each professor in ATOC 550, which is taken in the fall term of the M.Sc. 1 year. However, in a given year, there may be some faculty who do not submit a research topic, because of funding limitations or other commitments. Prior to receiving this set of research topics in December, students are encouraged to speak with the professors about their research interests. Each student is asked to choose up to three topics (in ranked order) in which he or she would like to do research. The students should consult the professors about their choices. Then, in early January of the Winter term, each student is interviewed by a committee of two to three professors. At this interview, the student gives reasons for each of the three topics chosen, and states whether or not the professors associated with each topic are willing to supervise the student. Generally, the students receive their first choice as the topic for their research. However, in the case of a conflict between two students (e.g., two students choosing the same topic as their first choice), the interview committee determines which student will get his/her first choice; the other student in this conflict will normally get his/her second choice for a research topic. The interview committee's decision is based on various factors, including the academic performance of the student in the topics of their choice, and the work loads of faculty members. In some special cases, an entering M.Sc. student may already have an agreement to work with a particular supervisor on a topic of mutual interest. In this situation, the student would not participate in the interview process, and could begin research with his/her supervisor prior to May of the M.Sc. 1 year, providing their background is deemed appropriate.

## Seminar Participation

All Master's students are encouraged to attend the Departmental Research Seminars, normally held on **Monday afternoons**. All M.Sc. 2 students are also required to attend one of the seminar series, ATOC 751 or ATOC 752, even though they are not registered for these seminar courses. It is **by giving a seminar** in one of these that they **satisfy the seminar component of ATOC 694 (Master's Thesis Progress Report and Seminar)**.

## M.Sc. Curriculum – No Specialization (45 credits)

*Note: This is the default option chosen by the majority of students entering the program.*

| REQUIRED COURSES | | |
|---|---|---|
| ***Thesis Component (24 credits)*** | | |
| **ATOC 691** | Master's Thesis Literature Review | 3 cr. |
| **ATOC 692** | Master's Thesis Research 1 | 6 cr. |
| **ATOC 694** | Master's Thesis Progress Report and Seminar | 3 cr. |
| **ATOC 699** | Master's Thesis | 12 cr. |

| COMPLEMENTARY COURSES | | |
|---|---|---|
| ***Departmental Component (21 credits, chosen from)*** | | |
| **ATOC 512** | Atmospheric and Oceanic Dynamics | 3 cr. |
| **ATOC 513** | Waves and Stability | 3 cr. |
| **ATOC 515** | Turbulence in the Atmosphere and Oceans | 3 cr. |
| **ATOC 519** | Advances in Chemistry of Atmosphere | 3 cr. |
| **ATOC 521** | Cloud Physics | 3 cr. |
| **ATOC 525** | Atmospheric Radiation | 3 cr. |
| **ATOC 530** | Paleoclimate Dynamics | 3 cr. |
| **ATOC 531** | Dynamics of Current Climates | 3 cr. |
| **ATOC 540** | Synoptic Meteorology 1 | 3 cr. |
| **ATOC 541** | Synoptic Meteorology 2 | 3 cr. |
| **ATOC 568** | Ocean Physics | 3 cr. |
| **ATOC 626** | Atmospheric / Oceanic Remote Sensing | 3 cr. |
| **ATOC 646** | Mesoscale Meteorology | 3 cr. |

- Or other courses at the 500 level or higher recommended by the Department's Graduate Program Director.
- Students with a strong background in atmospheric or oceanic science, or a Diploma in Meteorology, will take at least the 7-credit minimum. Students with no previous background in atmospheric or oceanic science must take the 20-credit maximum.

## M.Sc. Curriculum – Environment Option (48 credits)

*Note: Students following the Environment option must first be accepted by the Department of Atmospheric and Oceanic Sciences, and then by the McGill School of Environment (MSE) before an offer of admission will be made by the University. Environment Option students require either a single supervisor with a joint appointment in Atmospheric and Oceanic Sciences and the MSE, or co-supervisors, one each in Atmospheric and Oceanic Sciences and the MSE. <u>This option will likely be retired in the near future</u>.*

| **REQUIRED COURSES** | | |
|---|---|---|
| ***Graduate-level Courses (6 credits)*** | | |
| **ENVR 610** | Foundations of Environmental Policy | 3 cr. |
| **ENVR 650** | Environmental Seminar 1 | 1 cr. |
| **ENVR 651** | Environmental Seminar 2 | 1 cr. |
| **ENVR 652** | Environmental Seminar 3 | 1 cr. |

| | | |
|---|---|---|
| ***Thesis Component (24 credits)*** | | |
| **ATOC 691** | Master's Thesis Literature Review | 3 cr. |
| **ATOC 692** | Master's Thesis Research 1 | 6 cr. |
| **ATOC 694** | Master's Thesis Progress Report and Seminar | 3 cr. |
| **ATOC 699** | Master's Thesis | 12 cr. |

| **COMPLEMENTARY COURSES** | | |
|---|---|---|
| ***Environment Component (3 credits, chosen from)*** | | |
| **ENVR 519** | Global Environmental Politics | 3 cr. |
| **ENVR 544** | Environmental Measurement and Modelling | 3 cr. |
| **ENVR 580** | Topics in Environment 3 | 3 cr. |
| **ENVR 611** | Economy of Nature | 3 cr. |
| **ENVR 620** | Environment and Health of Species | 3 cr. |
| **ENVR 622** | Sustainable Landscapes | 3 cr. |
| **ENVR 630** | Civilization and Environment 1 | 3 cr. |
| **ENVR 680** | Topics in Environment 4 | 3 cr. |
| ▪ Or substitute for another course at the 500-level or higher recommended by the advisory committee and approved by the Environment Option committee. | | |
| | | |
| ***Departmental Component (15 credits, chosen from)*** | | |
| **ATOC 512** | Atmospheric and Oceanic Dynamics | 3 cr. |
| **ATOC 513** | Waves and Stability | 3 cr. |
| **ATOC 515** | Turbulence in the Atmosphere and Oceans | 3 cr. |
| **ATOC 521** | Cloud Physics | 3 cr. |
| **ATOC 525** | Atmospheric Radiation | 3 cr. |
| **ATOC 530** | Paleoclimate Dynamics | 3 cr. |
| **ATOC 531** | Dynamics of Current Climates | 3 cr. |
| **ATOC 540** | Synoptic Meteorology 1 | 3 cr. |

| | | |
|---|---|---|
| **ATOC 541** | Synoptic Meteorology 2 | 3 cr. |
| **ATOC 568** | Ocean Physics | 3 cr. |
| **ATOC 619** | Atmospheric Chemistry | 3 cr. |
| **ATOC 626** | Atmospheric / Oceanic Remote Sensing | 3 cr. |
| **ATOC 646** | Mesoscale Meteorology | 3 cr. |
| **ATOC 666** | Topics in Ocean Circulation | 3 cr. |

## Guidelines on the Completion of the M.Sc. Thesis

*Refer to Section 4.1 of the Graduate and Postdoctoral Studies General Information, Faculty Regulations and Research Guidelines Calendar.*

**Purpose of the Thesis**

- The purpose of the M.Sc. thesis is to demonstrate that the student is able to carry out a meaningful research project and present the results according to academic standards.

**Scope**

- Since the amount of time devoted to research and thesis preparation is normally about one year, the project should be formulated and the thesis judged accordingly. The thesis should be of scope to demonstrate a thorough understanding of the subject matter. It should define the problem clearly, give an adequate summary of previous work, explain the methods used, and present the results. Details should be sufficient to enable a researcher outside the particular area of specialization to comprehend the approach and the significance of the work. Except in rare cases, a thesis is not equivalent to a manuscript submitted for journal publication. Theses typically are longer than the average journal paper because they contain more background material and explanatory details, but they should not normally exceed 100 pages.

**Originality**

- Although it is not required that M.Sc. theses contain a great deal of original scholarship, some originality is expected. This might consist of extending the application of an existing method or theory, of comparing several such methods or theories, or of giving a new interpretation to concepts already established. While it is not a degree requirement that the thesis be of publishable quality, it is very much in the student’s and the supervisor’s interest to strive, after the thesis is submitted, to prepare a paper based on the thesis for submission to a refereed journal.

**Research Schedule**

- For students who have completed their course requirements, the total time devoted to the thesis work should be about 12 to 14 months, two or three of which are needed to write the thesis and have it read and commented on by the supervisor. For example, students completing the course requirements at the end of April of the M.Sc. 1 year, and starting their research in early May, should submit their theses preferably by the end of April, and no later than the end of June of the following year. Students who start their research during their M.Sc. 1 year while taking some courses should adjust the above schedule in consultation with their supervisor.

**Tracking Research Progress**

- Once a student is at the stage where s/he is expected to be actively involved in thesis research, the student must **subsequently meet** with his/her supervisor(s) on a **12-month** basis **until the completion of the thesis**.

- McGill requires annual tracking of doctoral students' progress toward the degree. The Graduate Student Research Progress Tracking Form is to be used during face-to-face meetings between the doctoral student, supervisor, and at least one other departmental representative. Having written agreed-upon expectations and clearly defined requirements aids in reduced times to completion and leads to fewer supervisor-supervisee misunderstandings.

- All the other meetings following will be scheduled every 12 months, with **all 3 forms** completed and submitted accordingly (see above).

- It is the graduate **student's responsibility** to properly **complete these forms** throughout the duration of his/her M.Sc. degree. Every time a form is completed, **submit** it to the **Administrative and Student Affairs Coordinator (Burnside Hall, room 945).** Original copies of all the tracking forms are kept in the student's file in the departmental office. Ideally, copies of these forms should also be retained by the student and her/his supervisor.

    - These forms are available on-line at: **http://www.mcgill.ca/gps/files/gps/gps_graduate_student_research_progress_tracking_report_2016.pdf**

- The objectives of these forms are to evaluate the progress of a student. A student deemed to have made **unsatisfactory progress** must **subsequently meet** with his/her supervisor(s) on a **6-month** basis **until the completion of the thesis**. On the occasion of a second unsatisfactory progress report, the student may be asked to withdraw from the M.Sc. program.

*Students with a Master's degree or equivalent in Atmospheric Science (Meteorology) or Physical Oceanography normally register at the Ph.D. 2 level when entering the program. The minimum course requirements are given below.*

| **REQUIRED COURSES (1 credit)** | | |
|---|---|---|
| **ATOC 700** | Ph.D. Proposal Seminar | 1 cr. |
| **ATOC 701** | Ph.D. Comprehensive (General) | 0 cr. |
| ▪ Ph.D. students are required to give **one seminar** in the registered seminar series of his/her choice, ATOC 751 or ATOC 752. | | |
| ▪ **Thesis proposal** may be **presented** at one of the registered seminar series in order to satisfy the requirements of ATOC 700 (Refer to Ph.D. guidelines which follow). | | |
| ▪ Students without a Master's degree in Atmospheric Science (Meteorology) or Physical Oceanography register at the Ph.D. 1 level when entering the program. The first year is then devoted mainly to course work and is usually similar to the M.Sc. 1 year (refer to M.Sc. 1 curriculum, p. 8). The selection of courses is made in consultation with the Ph.D. research supervisor, and is subject to the approval of the GPD. | | |

| **COMPLEMENTARY COURSES (7 credits)** | | |
|---|---|---|
| **ATOC 751 D1/D2** | Seminar: Physical Meteorology | 1 cr. |
| **OR** | | |
| **ATOC 752 D1/D2** | Atmospheric, Oceanic & Climate Dynamics Seminar | 1 cr. |
| ▪ **The remaining 6 credits** are chosen from the Department of Atmospheric and Oceanic Sciences, at the 500 or 600 level, as approved by the research supervisor and the Graduate Program Director (GPD). This **requirement may be waived** by the GPD for students whose prior experience or achievements give clear evidence that the additional courses are unnecessary. | | |

## Ph.D. Comprehensive (General) and Thesis Proposal Examination

*Refer to Section 10.4, Ph.D. Comprehensives Policy, of the Graduate and Postdoctoral Studies General Information, Regulations, and Research Guidelines Calendar. Both ATOC 701 and ATOC 700 fall under this comprehensive policy.*

Ph.D. candidates are required to take **two examinations**, **ATOC 701** (Ph.D. Comprehensive (General)) and **ATOC 700** (Ph.D. Proposal Seminar), usually during their Ph.D. 2 year.

### ATOC 701 – Ph.D. Comprehensive (General)

- ATOC 701 is an **oral examination** conducted by a committee ordinarily consisting of three examiners, one of which is the student's supervisor. This examination is intended to determine whether the candidate has a sufficiently broad understanding of topics in atmospheric sciences, climate dynamics and/or physical oceanography to proceed in the Ph.D. program. The level of knowledge should be sufficient, for example, to allow the candidate to teach at the undergraduate level. The candidate will be **examined on three topics** of atmospheric and oceanic sciences:

| Topics | Associated Courses |
|---|---|
| Geophysical Fluid Dynamics | ATOC 512 and ATOC 513 |
| Synoptic or Mesoscale Meteorology | ATOC 540 or ATOC 646 |
| Atmospheric Chemistry | ATOC/CHEM 619 |
| Turbulence or Numerical Methods or Data Analysis | ATOC 515 or ATOC 558 |
| Climate Dynamics and/or Physical Oceanography | ATOC 531 and, ATOC 530 or ATOC 568 |
| Physical Meteorology | ATOC 521 and, ATOC 525 or ATOC 626 |
| Other: In special cases and with the approval of the Graduate Program Director or Chair, another topic of direct relevance to atmospheric and oceanic sciences may be substituted for one of the above. | |

- The selection of the three topics is made by the student, subject to the approval of his/her Ph.D. supervisor. Within five days of being informed by the departmental Chair of the approximate date of the examination, the student must inform the departmental Chair of the three selected topics so that an appropriate examining committee can be appointed. The student is encouraged to then consult the committee members for advice as to how best to prepare for the examination. **The examination will normally take place within the first nine months of the Ph.D. 2 year**. Questions will not only test knowledge of the material in a particular book or books but will also test the candidate's ability to reason and to synthesize ideas from different areas. Prior to the commencement of the exam, the candidate will be invited to introduce himself/herself and say a few words about his/her academic background and research interests. If the candidate **fails the examination**, a grade of **HH (continuing)** is assigned and s/he may **take** the Comprehensive (General) examination **a second time**, normally after a period of two to three months. In the case of either a pass or a failure of this examination, a completed **ATOC 701 Feedback Form** will be given to the candidate by his or her supervisor. **A second failure, however, requires withdrawal from the Ph.D. program.**

**ATOC 700 – Ph.D. Proposal Seminar**

- ATOC 700 consists of a **written proposal and an oral presentation** followed by an examination before a committee made up of the three members of the student's supervisory committee, plus a fourth examiner designated by the Department's Chair. This examination is intended to assess the candidate's preparedness for undertaking original research in a particular subject area and it should be **taken 6 to 12 months after passing ATOC 701**. The student is required to **make a presentation** (approximately **30 minutes in length**) detailing his/her thesis proposal in order to meet part of the requirements for ATOC 700. This presentation may be part of the ATOC 751 or 752 seminar series, or it may be given at a specially scheduled seminar open to the students and faculty of AOS. **Prior to the presentation**, the student is required to prepare a **written thesis proposal** of about **20 pages** (type-written, double spaced) and to submit it to the ATOC 700 examination committee at least one week before the date of the oral presentation. The proposal should define the problem to be discussed, demonstrate that the candidate is familiar with the literature, describe the methodology to be used, present some preliminary results, and outline future work. After this presentation, the candidate will address questions from the audience (students and faculty). The audience will then be asked to leave and the candidate will be questioned further by the examination committee (the Supervisory Committee, plus a fourth faculty member), which will explore the depth of knowledge and understanding of the candidate in the area of the proposed research and in related areas. If the committee is satisfied that the candidate is adequately prepared to undertake the proposed research, a grade of **Passed** is reported to the Graduate and Postdoctoral Studies office. Otherwise, the candidate **fails** and a grade of **HH (continuing)** is assigned. In this case, after receiving appropriate feedback from the examination committee, the candidate is allowed to take the thesis proposal examination a second time in the presence of the same committee, normally after a period of two to three months. **A second failure of ATOC 700, however, requires the candidate to withdraw from the Ph.D. program.**

## Ph.D. Supervisory Committee

### Purpose

- The role of the Supervisory Committee is to assist the Ph.D. student in the advancement of his/her research and thesis, and to evaluate and report on progress.

- The primary responsibility for carrying out the research project rests with the student.

- The responsibility for day-to-day evaluation of work, providing suggestions and constructive criticism, and the overall guidance of the research belongs to the supervisor. Additional perspective provided by other members of the committee can be helpful to both student and supervisor. The committee may consider issues such as the validity of the approach, technical problems, the significance of results, directions to be taken in the future, and complementary course work. The Supervisory Committee participates actively in the setting of research goals and evaluating progress as detailed below.

### Appointment of Members

- A Supervisory Committee will be selected after the Ph.D. Comprehensive (General) examination, usually on the basis of consultations between the student, the supervisor, prospective members of the committee and the Department Chair.

- This Committee should consist of a minimum of three faculty members (including the supervisor, typically professors in the Atmospheric and Oceanic Sciences. However, professors in other McGill departments may also be appropriate in some cases), two of which are full-time at McGill.

- Normally, this Committee and one additional professor will comprise the examination committee for the Ph.D. Thesis Proposal examination. The additional professor is normally selected by the Chair. In case of conflict, however, the GPD will make this selection.

**Tracking Progress**

- Shortly after the student first registers in the program, the supervisor will discuss the degree requirements, including which courses are to be taken (refer to Ph.D. curriculum, p. 13).

- Once the student has **passed** the **ATOC 701** Ph.D. Comprehensive (General) examination within the first nine months of the **Ph.D. 2 year**, the Department requires that each Ph.D. student **meet** formally with his/her Supervisory Committee on a **12-month** basis up **until the completion of the thesis** in which the responsibility for scheduling meetings belongs to the supervisor(s). Note that informal meetings in addition to these formal ones are also encouraged.

- In the **1st meeting**, the Supervisory Committee and student will *jointly* complete the **Graduate Student Research Objectives Report Form** (Form 1) detailing his/her objectives for the next 12 months.

- In the **2nd meeting (12 months after the previous one)**, the student must bring to the meeting a *completed* **Graduate Student Research Progress Record Form** (Form 2). The objective of this meeting is to allow the Committee to discuss the student's progress and future plans, by doing so, another **Graduate Student Research Objectives Report Form** (Form 1) will be completed *jointly* by the student and supervisor(s). At the end of the meeting, the supervisor(s) is expected to complete the **Graduate Student Research Progress Report Form** (Form 3).

- The **next meeting** will be scheduled once the student has **passed ATOC 700**. After this examination, it is appropriate for the examining committee to provide feedback to the student. In this regard, the student may wish to make a list of special issues that s/he would like to have addressed.

- In the **3rd meeting (12 months after the previous one)**, **all 3 forms** must be completed and submitted accordingly similar to the previous meeting.

- If a student deemed to have made **unsatisfactory progress**, the Supervisory Committee will meet with the student on a **6-month** basis to review progress and if appropriate, set new objectives. On the occasion of a **second unsatisfactory progress report**, **the student may be asked to withdraw from the Ph.D. program.**

- It is the graduate **student's responsibility** to properly **complete these forms** throughout the duration of his/her Ph.D. degree. Every time a form is completed, **submit** it to the **Administrative and Student Affairs Coordinator in the departmental office (Burnside Hall, room 945).** Original copies of all the tracking forms are kept in the student's file in the departmental office. Ideally, copies of these forms should also be retained by the student and her/his supervisor.

    - These forms are available on-line at: **http://www.mcgill.ca/gps/students/research-tracking**

**Graduate Course Descriptions**

**ATOC 512 Atmospheric and Oceanic Dynamics** (3 credits)
Introduction to the fluid dynamics of large-scale flows of the atmosphere and oceans. Stratification of atmosphere and oceans. Equations of state, thermodynamics and momentum. Kinematics, circulation, and vorticity. Hydrostatic and quasi-geostrophic flows. Brief introduction to wave motions, flow over topography, Ekman boundary layers, turbulence.

**ATOC 513 Waves and Stability** (3 credits)
Linear theory of waves in rotating and stratified media. Geostrophic adjustment and model initialization. Wave propagation in slowly varying media. Mountain waves; waves in shear flows. Barotropic, baroclinic, symmetric, and Kelvin-Helmholtz instability. Wave-mean flow interaction. Equatorially trapped waves.

**ATOC 515 Turbulence in the Atmosphere and Oceans** (3 credits)
Application of statistical and semi-empirical methods to the study of geophysical turbulence. Reynolds' equations, dimensional analysis, and similarity. The surface and planetary boundary layers. Oceanic mixed layer. Theories of isotropic two- and three-dimensional turbulence: energy and enstrophy inertial ranges. Beta turbulence.

**ATOC 519 Advanced Atmospheric Chemistry** (4 credits)
The recent cutting-edge areas of planetary atmospheric chemistry from field and laboratory to theoretical modelling are examined. Photochemistry, kinetics (gas and surface) of organic and inorganic pollutants in atmosphere and atmospheric surfaces (clouds and aerosols). Satellite remote sensing of atmospheric chemical species, and issues related to chemical global change.

**ATOC 521 Cloud Physics** (3 credits)
Review of dry and moist atmospheric thermodynamics concepts. Atmospheric aerosols, nucleation of water and ice. Formation and growth of cloud droplets and ice crystals. Initiation of precipitation. Severe storms and hail. Weather modification. Numerical cloud models.

**ATOC 525 Atmospheric Radiation** (3 credits)
Solar and terrestrial radiation. Interactions of molecules, aerosols, clouds, and precipitation with radiation of various wavelengths. Radiative transfer through the clear and cloudy atmosphere. Radiation budgets. Satellite and ground-based measurements. Climate implications.

**ATOC 530 Paleoclimate Dynamics** (3 credits)
Introduction to the components of the climate system. Review of paleoclimates. Physical processes and models of climate and climate change.

**ATOC 531 Dynamics of Current Climates** (3 credits)
The general circulation of the atmosphere and oceans. Atmospheric and oceanic general circulation models. Observations and models of the El Niño and Southern Oscillation phenomena.

**ATOC 540 Synoptic Meteorology 1** (3 credits)
Analysis of current meteorological data. Description of a geostrophic, hydrostatic atmosphere.

Ageostrophic circulations and hydrostatic instabilities. Kinematic and thermodynamic methods of computing vertical motions. Tropical and extratropical condensation rates. Barotropic and equivalent barotropic atmospheres.

**ATOC 541 Synoptic Meteorology 2** (3 credits)
Analysis of current meteorological data. Quasi-geostrophic theory, including the omega equation, as it relates to extratropical cyclone and anticyclone development. Frontogenesis and frontal circulations in the lower and upper troposphere. Cumulus convection and its relationship to tropical and extratropical circulations. Diagnostic case study work.

**ATOC 551 Selected Topics 1** (3 credits)
Topics in atmospheric and oceanic sciences.

**ATOC 552 Selected Topics 2** (3 credits)
Topics in atmospheric and oceanic sciences.

**ATOC 555 Field Course 1** (3 credits)
Field studies in selected topics of the atmospheric and oceanic sciences.

**ATOC 556 Field Course 2** (3 credits)
Field studies in selected topics of the atmospheric and oceanic sciences.

**ATOC 558 Numerical Methods and Laboratory** (3 credits)
Numerical simulation of atmospheric and oceanic processes. Finite difference, finite element, and spectral modelling techniques. Term project including computer modelling of convection or large-scale flows in the atmosphere or ocean.

**ATOC 568 Ocean Physics** (3 credits)
Research methods in physical oceanography including data analysis and literature review. Course will be divided into five separate modules focusing on temperature-salinity patterns, ocean circulation, boundary layers, wave phenomena and tides.

**ATOC 616 Topics in Geophysical Fluid Dynamics** (3 credits)
Advanced topics in the dynamics of oceanic and atmospheric flows.

**ATOC 626 Atmospheric/Oceanic Remote Sensing** (3 credits)
Principles of radiative transfer applied to observing the atmosphere and oceans by satellite, radar, and other methods of remote sensing. Applications to cloud physics and climate research.

**ATOC 642 D1/D2 Weather Briefing** (1 credit)

**ATOC 646 Mesoscale Meteorology** (3 credits)
Examination of the theory of important mesoscale phenomena, including fronts, cumulus convection and its organization, and tropical and extratropical cyclones. Application of the theory with detailed case studies of these phenomena. Mesoscale processes in numerical simulations.

**ATOC 654 D1/D2 Synoptic Meteorology** (6 credits)

**ATOC 666 Topics in Ocean Circulation** (3 credits)
Recent observations of mesoscale and large-scale ocean circulation. Inverse methods and their application to tracer distributions and deep ocean circulation. Review of modern theoretical developments such as geostrophic turbulence, homogenization of potencial vorticity, ventilated thermoclines, wind and buoyancy driven ocean circulation models, and coupled ice-ocean circulation models.

**ATOC 670 Reading Course: Meteorology 1** (3 credits)
Assigned reading of a specialized topic in meteorology with formal evaluation.

**ATOC 671 Reading Course: Meteorology 2** (3 credits)
Assigned reading of a specialized topic in meteorology with formal evaluation.

**ATOC 672 Reading Course: Oceanography 1** (3 credits)
Assigned reading of a specialized topic in oceanography with formal evaluation.

**ATOC 673 Reading Course: Oceanography 2** (3 credits)
Assigned reading of a specialized topic in oceanography with formal evaluation.

**ATOC 681 Adv. in Meteorology and Physical Oceanography** (3 credits)

**ATOC 691 Master's Thesis Literature Review** (3 credits)
Review of the relevant literature in preparation for the M.Sc. research.

**ATOC 692 (or N1/N2) Master's Thesis Research 1** (6 credits)
Independent research under the supervision of the student's M.Sc. supervisor.

**ATOC 693 (or N1/N2) Master's Thesis Research 2** (6 credits)
Independent research under the supervision of the student's M.Sc. supervisor.

**ATOC 694 Master's Thesis Progress Report and Seminar** (3 credits)
Written report on the M.Sc. research progress and oral presentation of the report in seminar form to staff and students.

**ATOC 695 Master's Thesis Research 3** (6 credits)
Independent research under the supervision of the student's M.Sc. supervisor.

**ATOC 696 Master's Thesis Research 4** (6 credits)
Independent research under the supervision of the student's M.Sc. supervisor.

**ATOC 698 (or N1/N2) Thesis Research 1** (16 credits)

**ATOC 699 (or N1/N2) Master's Thesis** (12 credits)
Independent research under the supervision of the student's M.Sc. supervisor leading to the

M.Sc. thesis.

**ATOC 700  Ph.D. Proposal Seminar** (refer to p. 14–15)

**ATOC 701  Ph.D. Comprehensive (General)** (refer to pp. 13–14)

**ATOC 751 D1/D2  Seminar: Physical Meteorology** (1 credit)
Seminars on topics in physical meteorology. Students are required to present one or more seminars during the year on their thesis research and to participate actively in the seminars given by others.

**ATOC 752 D1/D2  Atmospheric, Oceanic & Climate Dynamics Seminar** (1 credit)
Seminars on topics in atmospheric, oceanic and climate dynamics. Students are required to present one or more seminars during the year on their thesis research and to participate actively in the seminars given by others.

## *RESEARCH INTERESTS OF FACULTY MEMBERS*

**Parisa Ariya** – Atmospheric and Interfacial (Atmosphere-Ocean) Chemistry

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**Research interests**

Our research is in the field of physical chemistry and analytical chemistry of relevance to the atmosphere and atmospheric interfaces (air/water/ice/snow). It focuses on the understanding of selected chemical transformations of organic compounds, as well as the understanding of trace metal pollutants in the atmosphere and at atmosphere/water/snow interfaces. Identifying such atmospheric processes can also be significant in understanding the complexity of air pollution and health hazards including airborne particulate matter (aerosols). The interaction between aerosols and clouds is a significant factor affecting the magnitude of the climate change and is a major research topic recognized by the International Panel on Climate Change (IPCC; 2007). The chemical reactions are studied through state-of-the-art kinetic and photochemical laboratory investigations. We perform highly sensitivity measurements of trace compounds to characterize chains of chemical reactions and nucleation processes, both in the atmosphere and at air/water/snow interfaces. Further research activities include complementary computational and atmospheric chemical modelling of the reaction intermediates in the atmosphere to simulate the complex physical-bio-chemical interactions. During the last five years, we also focus on development of novel green chemistry methods and techniques for removal of pollutants. The research directions in our laboratories are:

- Bioaerosols: Impact on Chemistry and Physics of the atmosphere.
- Chemical transformation of mercury in the atmosphere and air/snow/water interface.
- Halogens in the marine boundary layer and interactions with airborne organics.
- Formation of aerosols and oxidants via "dark reaction".
- Box and Cloud Modeling: Microphysics ice nucleation.
- Computational chemistry of organic-halide intermediates.
- Development novel techniques for green chemistry and Technology

**Some recent publications**

R Mortazavi, S Attiya, PA Ariya, Arctic microbial and next generation sequencing approach for bacteria in snow and frost flowers: selected identification, abundance and freezing nucleation, Atmospheric Chemistry and Physics, 15 (11), 6183-6204, 2015.

Deeds, Daniel; Ghoshdastidar, Avik; Raofie, Farhad; Guerette, Elise-Andre; Tessier, Alain; Ariya, Parisa, Development of a Particle-Trap Preconcentration-Soft Ionization Mass Spectrometric Technique for the Quantification of mercury halides in air", Analytical Chemistry, 87 (10), pp 5109-5116, 2015

Ariya, Parisa A.; Amyot, Marc; Dastoor, Ashu; Deeds, Daniel; Subir, Mahamud; Feinberg, Aryeh; Kos, Gregor; Poulain, Alexandre; Ryjkov, A; Semeniuk, Kirill; Toyota, Kenjiro, "Mercury Physicochemical and Biogeochemical Transformation in the Atmosphere and at Atmospheric Interfaces: A Review and Future Directions", Chemical Reviews (American Chemical Society), Chem. Rev., 115 (10),3760-3802, 2015

M. Subir, N. Eltouny, and P. A. Ariya, "A Surface Second Harmonic Generation Investigation of Volatile Organic Compound Adsorption on a Liquid Mercury Surface" Royal Society of Chemistry, RSC Advances, 2015, 5, 23464-23470

R. Mortazavi and P. A. Ariya, "The Impact of Renovation on Indoor Air-Borne Bacterial and Fungal Populations", Indoor and Built Environment, in press, 2015

Ali Moridnejad, Neamat Karimi, Parisa A. Ariya, A new inventory for Middle East dust source points. Environmental monitoring and assessment, 187:582, 2015

A. Feinberg, U. Kurien, P. A. Ariya, "The kinetics of aqueous mercury(II) reduction by sulfite over an array of environmental conditions", Water, Air, & Soil Pollution. Water, Air, & Soil Pollution, Volume 226: 119, 1-12, 2015

Ali Moridnejad, Neamat Karimi, Parisa A. Ariya, Newly desertified regions in Iraq and its surrounding areas: Significant novel sources of global dust particles, Journal of Arid Environments Volume 116, Pages 1-10, 2015

Connie Ye and Parisa A. Ariya, Co-Adsorption of Gaseous Benzene, Toluene, Ethylbenzene, m-Xylene (BTEX) and SO2 on Recyclable Fe3O4 Nanoparticles at 0-101 % Relative Humidities. Journal of Environmental Sciences, 31, 164-174, 2015

Lin Si and Parisa A. Ariya, Photochemical Reactions of Divalent Mercury with Thioglycolic Acid: Formation of Mercuric Sulfide Particles", Chemosphere; 119, 467-472, 2015

Steffen A., Lehnherr I, Cole A., Ariya, P. Dastoor, Durnford D., Kirk J., Pilote M. Atmospheric mercury in the Canadian Arctic. Part I: A review of recent field measurements Science of Total Environment, doi: 10.1016/j.scitotenv.2014.10.109.

Zhenzhong Hu , Maximilien Beuret , Hassan Khan, and Parisa A. Ariya Development of a Recyclable Remediation System for Gaseous BTEX: Combination of Iron Oxides Nanoparticles Adsorbents and Electrochemistry, ACS Sustainable Chem. Eng., 2014, 2 (12), 2739-2747, 2014

Nermin Eltouny, Parisa Ariya, Enhanced Reactivity toward Oxidation by Water Vapor: Interactions of Toluene and NO2 on Hydrated Magnetite Nanoparticles, The Journal of Physical Chemistry C, 118 (41), pp 23654-23663, 2014

N. Eltouny and P. A. Ariya, Competing reactions of selected atmospheric gases on Fe3O4 nano particles surfaces, Phys. Chem. Chem. Phys., 2014, 16 (42), 23056 - 23066

G. Kos, N. Adechina, V. Kanthasamy and P. A. Ariya, Volatile organic compounds in Arctic snow: Concentrations and implications for atmospheric processes", RSC, Environmental Science: Processes & Impacts 16 (11), 2592-2603

Ariya, P. A., G. Kos, R. Mortazavi, E. D. Hudson, V. Kanthasamy, N. Eltouny, J. Sun, and C. Wilde. Bio-Organic Materials in the Atmosphere and Snow: Measurement and Characterization, in Atmospheric and Aerosol Chemistry, V.F. McNeill and P.A. Ariya, Editors. 2014. p. 145-199.

McNeill, V.F. and P.A. Ariya, Atmospheric and Aerosol Chemistry Preface, in Atmospheric and Aerosol Chemistry, V.F. McNeill and P.A. Ariya, Editors. 2014

**Peter Bartello** – Geophysical Fluid Dynamics


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**Research interests**

My research employs both theoretical and numerical techniques to study fluid turbulence in the atmosphere and oceans. A major recent thrust has been the study of the statistical nature of the flow as a function of rotation and stratification. The simplifying assumptions employed at larger scales, that rotation and stratification terms in the governing equations are predominant and approximately balanced by other terms, become invalid at smaller scales. The interactions between large-scale vortices and more general turbulent and wave motions are therefore the subject of these studies, as is the effect on the turbulent transport of passive scalars such as pollutants or ozone. A simple example is whether turbulent motions preferentially send energy downscale (as in a breaking wave at the shore) or upscale (as in the merging of two eddies to make a larger one). Both are known to occur, depending on the relative strengths of rotation and stratification. Both must be accounted for in coarse-resolution models, such as the ones used for weather and climate studies, but clearly in a different way.

Since there is a reliance on numerical simulation, research on numerics and subgridscale parameterisation is undertaken in parallel. At the expense of accuracy, ocean, weather and climate models are forced to use numerical methods that allow for an enormous reduction in the true range of time and length scales. Minimizing the numerical damage as a function of flow statistics is another research priority. I am also a member of the Applied Math group in the Department of Mathematics and Statistics.

**Some recent publications**


Bartello, P. and S. M. Tobias, 2013, Sensitivity of stratified turbulence to the buoyancy Reynolds number, *J. Fluid Mech*. 725, 1-22.

Devenish, B.J., P. Bartello, J.-L. Brenguier, L.R. Collins, W.W. Grabowski, R.H.A. IJzermans, S.P. Malinowski, M.W. Reeks, J.C. Vassilicos and Z. Warhaft, 2012, Droplet growth in warm turbulent clouds, *Q. J. Roy. Met. Soc*. 138, 1401-1429.

Ait Chaalal, F., M. S. Bourqui and P. Bartello, 2012, Fast chemical reaction in a two-dimensional Navier-Stokes flow: Initial regime, Phys. Rev. E 85, 046306.

Bartello, P., "Quasigeostrophic and Stratified Turbulence in the Atmosphere". Turbulence in the Atmosphere and Oceans (ed. D.G. Dritschel), Springer, ISBN number: 978-94-007-0359-9 (2010).

Ngan, K., Bartello, P. and Straub, D.N., Predictability of rotating stratified turbulence. *J. Atmos. Sci*., 66: 1384–1400 (2009).

Sacher, W. and Bartello, P., Sampling errors in ensemble Kalman filtering – Part II application to a barotropic model. *Mon. Wea. Rev*., 137: 1640–1655 (2009).

Sacher, W. and Bartello, P., Sampling errors in ensemble Kalman filtering. Part I Theory. *Mon. Wea. Rev*., 138: 3035–3049 (2008).

Spyksma, K. and Bartello, P., Small-scale moist turbulence in numerically-generated convective clouds. *J. Atmos. Sci*., 65: 1967–1978 (2008).

Ngan, K., Bartello, P. and Straub, D. N., Dissipation of synoptic-scale flow by small-scale turbulence. *J. Atmos. Sci*., 65: 766–791 (2008).

Spyksma, K. and Bartello, P., Predictability in wet and dry convective turbulence. *J. Atmos. Sci*., 65: 220–234 (2008).


**Jacques Derome (Emeritus)** – Dynamical Meteorology and Climatology

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**Research interests**

The oceans are known to have an important influence on the mean seasonal state of the atmosphere. The Gulf Stream, for example, is largely responsible for mean winter conditions that are milder over western Europe than over eastern North America. Such east-west differences in the mean seasonal atmospheric state are also related to the influence of the main mountain barriers, such as the Rockies and the Himalayas, which deflect the flow of the atmosphere. Finally, the travelling weather disturbances affect and are themselves affected by the air currents created by the ocean currents and the mountain barriers. The interplay between the influence of the ocean currents, the mountain barriers and the travelling weather disturbances leads to mean seasonal conditions that vary not only in space, but also from year to year.

It is of considerable interest to study how the above three factors operate to determine the mean seasonal atmospheric state. Do the travelling disturbances play a crucial role? Are year-to-year fluctuations in the atmospheric mean seasonal state caused by corresponding fluctuations in the ocean conditions, or simply by interannual fluctuations in the weather disturbances? Questions of that nature are of fundamental importance in determining the degree of predictability of mean-monthly and mean-seasonal flows. Numerical modelling studies and data analyses are conducted to clarify the role of the travelling weather disturbances and of sea surface temperature anomalies on the mean seasonal state of the atmosphere.

The Historical Forecasting Project (HFP)

This project involves a collaboration with research scientists from two government laboratories. We are testing the extent to which global models of the atmosphere are able to predict mean atmospheric seasonal conditions. We seek not only to determine level of forecast skill of the models, but also to understand what physical factors contribute to that skill over different parts of the world.

The dynamics of the Arctic and North Atlantic Oscillations

Year-to-year fluctuations in the mean-seasonal atmospheric conditions tend to occur with preferred geographical patterns, called modes of variability. We are interested in better understanding what drives these modes of variability. To what extent are the world's oceans involved in generating these modes? To elucidate this type of question, we perform numerical experimentations with a global atmospheric model driven by specified, empirical diabatic heating. We supplement this with the analysis of global observational data sets. Often the data analyses suggest mechanisms that can be tested with numerical experiments, and vice versa.

**Some recent publications**

Yao, W., Lin, H. and Derome, J., Submonthly forecasting of winter surface air temperature in North America based on tropical organized convection. *Atmosphere-Ocean*, 49: 51–60 (2011).

Jia, X., Lin, H. and Derome, J., Improving seasonal forecast skill of North American surface air temperature in fall using a post-processing method. *Mon. Wea. Rev*., 138: 1843–1857 (2010).

Kharin, V.V., Teng, Q., Zwiers, F.W., Zhang, X., Boer, G.J., Derome, J. and Fontecilla, J.S., Skill assessment of seasonal hindcasts from the Canadian Historical Forecast Project. *Atmosphere-Ocean*, 47: 204–223 (2009).

Jia, X., Lin, H. and Derome, J., The influence of tropical Pacific forcing on the Arctic Oscillation. *Clim. Dyn*., 32: 495–509 (2009).

Lin, H., Brunet, G. and Derome, J., An observed connection between the North Atlantic Oscillation and the Madden-Julian Oscillation. *J. Climate*, 22: 364–380 (2008).

Lin, H., Brunet, G. and Derome, J., Forecast skill of the Madden-Julian Oscillation in two Canadian atmospheric models. *Mon. Wea. Rev*., 136: 4130–4149 (2008).

Jia, X., Lin, H. and Derome, J., The influence of tropical Pacific forcing on the Arctic Oscillation. *Clim. Dyn*., 15 (2008).

**Frédéric Fabry** – Radio Meteorology and Precipitation Physics

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**Research interests**

McGill operates several remote sensing instruments on a continuous basis for research and monitoring purposes. These systems observe the shape, intensity, and movement of radar targets, allowing us to get a 4-D view of the state of the atmosphere and in particular of precipitation. We use these tools both to improve our understanding of precipitation microphysics and dynamics as well as to develop new methods and algorithms for short-term forecasting, or nowcasting, of severe weather.

My work spans from trying to enhance our understanding of the precipitation process and storms to developing new instruments and techniques to make better measurements and forecasts. At this time, I am focusing on the following topics:

Nowcasting of precipitation and severe weather

Precipitation and severe weather are two of the most difficult phenomena to predict accurately, yet they are probably the ones with the greatest impact on human activities. Until now, for very short term forecasts, nothing performs better than using radar data and extrapolating them in time. These short term forecasts are used for a variety of applications such as aviation weather and flood forecasting. We are interested in improving the accuracy of nowcasting as well as quantifying the quality and predicting the uncertainty of the forecasts.

More and more, we use radar and other remote sensing data to help start regional-scale (or mesoscale) forecasting models using what is known as data assimilation. But current approaches used in data assimilation are not ideally suited to take advantage of the information provided by radar and remote sensing. Since these tools provide our best view and data to characterize storms, we are rethinking the way to do data assimilation to best use their information.

Remote sensing of humidity and applications

Water vapour is the fuel of storms and minute changes in the distribution of moisture can completely alter storm development. Yet water vapour distribution is a poorly measured quantity, especially at the mesoscale. We developed a radar-based technique that can provide near-surface moisture information whereby we use the change in the travel time of radar waves between fixed points (such as the ground targets observed by a radar) to infer changes in the refractive index of air caused by changes in near-surface humidity. While on one end, we are working on fine-tuning that technique and making measurements in a variety of field experiments, one the other end we are analyzing the data to see to what extent its information can be used for improving storm initiation prediction.

We are also exploring the possibility of using microwave radiometry to measure temperature and humidity remotely. Microwave radiometry is a specialization of remote sensing that deals with the study and the use of the emissions of microwaves from the atmosphere. Microwave radiometers, the instruments that measure these emissions, are used to obtain information on temperature, humidity, and cloud amounts, fields that we have great difficulties to characterize otherwise. Until now, microwave radiometers were designed to only measure the vertical profiles of atmospheric parameters. We are currently designing and testing an instrument that scans the atmosphere much like a radar does, in an attempt to get 2-D or 3-D information on temperature, and humidity. Here too, the instrument will be used to evaluate its ability to improve severe storm forecasting, especially at the early stages of storm development.

**Recent publications**

Fabry, F., *Radar Meteorology – Principles and Practice.* Cambridge University Press, Cambridge, 272 pp (2015).

Radhakrishna, B., F. Fabry, J. J. Braun, and T. Van Hove, Precipitable water from GPS over the continental United States: diurnal cycle, intercomparisons with NARR, and link with convection initiation. *Journal of Climate*, 28: 2584–2599 (2015).

Bellon, A., and F. Fabry, Real-time radar reflectivity calibration from differential phase measurements. *Journal of Atmospheric and Oceanic Technology*, 31: 1089–1097 (2014).

Themens, D., and F. Fabry, Why scanning instruments are a necessity for constraining temperature and humidity fields in the lower atmosphere. *Journal of Atmospheric and Oceanic Technology*, 31: 2462–2481 (2014).

Fabry, F., C. Augros, and A. Bellon, The case of sharp velocity transitions in high vertical wind shear when measuring Doppler velocities with narrow Nyquist intervals. *Journal of Atmospheric and Oceanic Technology*, 30: 389–394 (2013).

Radhakrishna, B., I. Zawadzki, and F. Fabry, Post-processing model predicted rainfall fields in the spectral domain using phase information from radar observations. *Journal of Atmospheric Sciences*, 70: 1145–1159 (2013).

Radhakrishna, B., I. Zawadzki, and F. Fabry, Predictability of precipitation from continental radar images. Part V: Growth and decay. *Journal of Atmospheric Sciences*, 69: 3336–3349 (2012).

Park, S., and F. Fabry, Estimation of near-ground propagation conditions using radar ground echo. *Journal of Atmospheric and Oceanic Technology*, 28: 165–180 (2011).

Park, S., and Fabry, F., Simulation and interpretation of the phase data used by radar refractivity retrieval algorithm. *Journal of Atmospheric and Oceanic Technology*, 27: 1286–1301 (2010).

Fabry, F., and Sun, J., For how long should what data be assimilated for the mesoscale forecasting of convection and why? Part I: on the propagation of initial condition errors and its implications for data assimilation. *Monthly Weather Review*, 138: 242–255 (2010).

Fabry, F. and Sun, J., For how long should what data be assimilated for the mesoscale forecasting of convection and why? Part II: on the observation signal from different sensors. *Monthly Weather Review*, 138: 256–264 (2010).

Fabry, F., and Seed, A., Quantifying and predicting the accuracy of radar-based quantitative precipitation forecasts. *Advances in Water Resources*, 32: 1043–1049 (2009).

**John R. Gyakum** – Synoptic and Dynamic Meteorology

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**Research interests**

Our research group conducts research on the analysis and forecasting of extreme weather and climate processes. The research focuses on the pertinent dynamics associated with extreme precipitation, wind, and cyclogenesis. The synoptic-scale environments associated with such a rich variety of extreme weather are documented with the goal of improving short-term weather forecasts. We are also studying the orographic modulation of wind and precipitation by the Saint Lawrence valley, with the goal of understanding the valley's role in the channelling of winds, and in enhancing precipitation amounts beyond what can be expected for similar weather systems in level terrain. In addition, the meteorological impacts of transitioning tropical cyclones in eastern Canada are being studied in the context of 1) extratropical re-intensification mechanisms, and 2) the associated extreme rainfalls.

**Current projects**

- Dynamic and thermodynamic analyses of freezing rainstorms in North America
- Case studies of extreme rainfall events in North America
- Diagnostic studies of atmospheric blocking events over the North Pacific Ocean.
- Northern Hemisphere available potential energy life cycles
- Analyses of baroclinic conditioning prior to extreme extratropical oceanic cyclogenesis
- Historical analyses of cold-season extreme synoptic circulation structures

**Some recent publications**

Gervais, M., E. Atallah, J. R. Gyakum, and L. B. Tremblay, 2015: Arctic air masses in a warming world. J. Climate, submitted.

Grotjahn, R., R. Black, R. Leung, M. F. Weaver, M. Barlow, M. Bosilovich, A. Gershunov, W. J. Gutowski, J. R. Gyakum, R. W. Katz, Y.-Y. Lee, Y.-K. Lim, and Prabhat, 2015: North American Extreme Temperature Events and Related Large Scale Meteorological Patterns: A Review of Statistical Methods, Dynamics, Modeling, and Trends. Climate Dynamics, in press.

Milrad, S., J. R. Gyakum, and E. H. Atallah, 2015: A meteorological analysis of the 2013 Alberta Flood: Antecedent large-scale flow pattern and synoptic-dynamic characteristics. Mon. Wea. Rev., 143, 2817-2841.

Plante, M., S.-W. Son, E. Atallah, J. R. Gyakum, and K. Grise, 2015: Extratropical cyclone climatology across eastern Canada. International Journal of Climatology, 35, 2759-2776.

Gervais, M., J. R. Gyakum, E. Atallah, and B. Tremblay, 2014: How well are the distribution and extreme values of daily precipitation represented in the Community Climate System Model? A comparison to reanalysis, satellite, and gridded station data. J. Climate, 27, 5219-5239.

Milrad, S. M., J. R. Gyakum, E. H. Atallah, and K. Lombardo, 2014: On the dynamics, thermodynamics, and forecast model evaluation of two snow-burst events in southern Alberta. Wea. Forecasting, 29, 725-749.

Gervais, M., L. B. Tremblay, J. R. Gyakum, and E. H. Atallah, 2014: Representing extremes in a daily gridded precipitation analysis over the United States: impacts of station density, resolution, and gridding methods. J. Climate, 27, 5201-5218.

Small, D., E. H. Atallah, and J. R. Gyakum, 2014: An objectively determined blocking index and its northern hemisphere climatology. J. Climate, 27, 2948-2970.

Milrad, S. M., E. H. Atallah, J. R. Gyakum, and G. Dookhie, 2014: Synoptic typing and precursors of heavy warm-season precipitation events at Montreal, Quebec. Wea. Forecasting, 29, 419-444.

Grise, K. M., S.-W. Son, and J. R. Gyakum, 2013: Intraseasonal and interannual variability in North American storm tracks and its relationship to equatorial Pacific variability. Mon. Wea. Rev., 141, 3610-3625.

Hryciw, L. M., E. H. Atallah, S. M. Milrad, and J. R. Gyakum, 2013: A meteorological analysis of important contributors to the 1999-2005 Canadian Prairie drought. Mon. Wea. Rev., 141, 3593-3609.

Milrad, S. M., E. H. Atallah, and J. R. Gyakum, 2013: Precipitation modulation by the Saint Lawrence Valley in association with transitioning tropical cyclones. Wea. Forecasting, 28, 331-352.

Turner, J. K., J. R. Gyakum, and S. M. Milrad, 2013: A thermodynamic analysis of an intense North American arctic air mass. Mon. Wea. Rev., 141, 166-181.

Splawinski, S., J. R. Gyakum, and E. H. Atallah, 2012: The role of anticyclones in replenishing surface cold air and modulating freezing rain duration. McGill Science Undergraduate Research Journal, 7, 54-60.

Ressler, G. M., S. M. Milrad, E. H. Atallah, and J. R. Gyakum, 2012: Synoptic-scale analysis of freezing rain events in Montreal, Quebec. Wea. Forecasting, 27, 362-378.

Razy, A., S. M. Milrad, E. H. Atallah, J. R. Gyakum, 2012: Synoptic-scale environments conducive to orographic impacts on cold-season surface wind regimes at Montreal, Quebec. J. Climatology and Appl. Meteorology, 51, 598-616.

Hanesiak, J. M., R. E. Stewart, B. R. Bonsal. P. Harder, R. Lawford, R. Aider, B. D. Amiro, E. Atallah, A. G. Barr, T. A. Black, P.Bullock, J. C. Brimelow, R. Brown, H. Carmichael, C. Derkson, L. B. Flanagan, P. Gachon, H. Greene, J. R. Gyakum, W. Henson, E. H. Hogg, B. Kochtubajda, H.

Leighton, C. Lin, Y. Luo, J. H. McCaughey, A. Meinert, A. Shabbar, K. Snelgrove, K. Szeto, A. Trishchenko, G. van der Kamp, S. Wang, L. Wen, E. Wheaton, C. Wielki, Y. Yang, S. Yirdaw, and T. Zha, 2011: Characterization and summary of the 1999-2005 Canadian Prairie Drought. Atmos.-Ocean, 49, 421-452.

Splawinski, S., J. R. Gyakum, and E. H. Atallah, 2011: Atmospheric circulation structures associated with freezing rain in Quebec City, Quebec. McGill Science Undergraduate Research Journal, 6, 50-55.

Milrad, S. M., J. R. Gyakum, E. H. Atallah, and J. F. Smith, 2011: A diagnostic examination of the eastern Ontario and western Quebec wintertime convection event of 28 January 2010. Wea. Forecasting, 26, 301-318.

Turner, J. K., and J. R. Gyakum, 2011: The development of Arctic air masses in Northwest Canada and their behavior in a warming climate. J. Climate, 24, 4618-4633.

Small, D., E. Atallah, and J. R. Gyakum, 2011: Wind Regimes along the Beaufort Sea Coast Favorable for Strong Wind Events at Tuktoyaktuk. J. Climatology and Appl. Meteorology, 50, 1291-1306.

**Yi Huang** – Atmospheric Radiation and Physical Climatology

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**Research interests**

We strive to improve the understanding of Earth climate and its variations from a radiation perspective. We use satellite observations, global climate models and radiative transfer models to gain fundamental understanding of the physical factors that govern the radiation energy budget of the climate system. The topics of the problems that we address include: 1) radiative transfer theories, 2) atmospheric radiation: its distribution and variation, in relation to other climatic variables, 3) remote sensing: using radiative measurements as a tool to infer atmospheric states and monitor climate change.

**Current projects**

- Understand the dependency of radiation flux on atmospheric variables by means of radiative transfer theories and computations.
- Monitor and attribute the changes in Earth radiation energy budget, based on satellite

observations.

- Improve the understanding of radiative forcing and feedback at both global and regional scales.

**Some recent publications**

Sun, Y. and Huang, Y. (2015), An investigation of convective moistening of the lower stratosphere using satellite data, Earth and Space Science, 2, doi:10.1002/2015EA000115.

Huang, Y., M. Zhang, Y. Xia, Y. Hu and S. Son (2015), Is there a stratospheric radiative feedback in global warming simulations? Climate Dynamics, doi: 10.1007/s00382-015-2577-2.

Bani Shahabadi, M. and Y. Huang (2015), Measuring stratospheric H2O with an airborne spectrometer: Simulation with realistic detector characteristics, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing. doi: 10.1109/JSTARS.2014.2382336.

Blanchette, J., and Huang, Y. (2015), Earth Infrared radiation spectra during Global warming hiatus. McGill Science Undergraduate Research Journal, 10(1): 14-17.

Huang, Y., and M. Bani Shahabadi, (2014), Why logarithmic: A note on the dependence of radiative forcing on gas concentration. J. Geophys. Res. - Atmos., 119, doi:10.1002/2014JD022466.

Bani Shahabadi, M. and Y. Huang, (2014), Logarithmic radiative effect of water vapor and spectral kernels, J. Geophys. Res. – Atmos., 119 (10), 6000-6008, doi: 10.1002/2014JD021623.

Bani Shahabadi, M. and Y. Huang, (2014), Measuring stratospheric H2O with an airborne spectrometer, J. Atmos. and Oceanic Tech., 31, 1502-1515. doi: http://dx.doi.org/10.1175/JTECH-D-13-00191.1

Huang, Y. and M. Zhang, (2014), The implication of radiative forcing and feedback for poleward energy transport, Geophy. Res. Lett., 41(5), 1665-1672, doi: 10.1002/2013GL059079.

Li, Y. D. Thompson, Y. Huang and M. Zhang, (2014), The signature of the Northern annular mode in tropospheric clouds, and the cloud radiative effect on the climate variability, Geophy. Res. Lett., 41(5), 1681-1688, doi: 10.1002/2013GL059113

Zhang, M. and Y. Huang, (2014), Radiative forcing of quadrupling CO2. J. Climate, 27, 2496–2508. doi: http://dx.doi.org/10.1175/JCLI-D-13-00535.1

Huang, Y., (2013), On the longwave climate feedback. J. Climate, 26, 7603–7610, doi:10.1175/JCLI-D-13- 00025.1.

Wielicki, B. and coauthors, (2013), Achieving climate change absolute accuracy in orbit, Bull. American Meteorological Society, 94, 1519–1539. doi: 10.1175/BAMS-D-12-00149.1.

Huang, Y., (2013), A simulated climatology of spectrally decomposed atmospheric infrared radiation, J. Climate, 26, 1702–1715, doi: 10.1175/JCLI-D-12-00438.1.

## **Daniel Kirshbaum** – Mesoscale Meteorology


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### Research interests

Mesoscale dynamics and moist convection: Moist convection is a major source of severe weather and plays a key role in the climate system. Because convective clouds form at very small spatiotemporal scales and are fundamentally turbulent and chaotic, they are inadequately understood and poorly resolved in weather and climate models. This poor resolution introduces large forecast uncertainties, which can be partially mitigated by ensemble methods (for convection-permitting models) or well-formulated physical parameterization schemes (for larger-scale models).

The initiation of convective clouds in a conditionally unstable atmosphere is often constrained by mesoscale processes that lift air to its level of free convection (LFC). The dynamics of such processes (including mountain flows, fronts, drylines, and outflow boundaries) are thus another topic of intensive study in my group. However, lifting to the LFC is only a necessary condition for convection initiation—other dynamical and microphysical processes (e.g., vertical wind shear, entrainment of dry environmental air, and the formation of ice) control whether such a cloud will ascend through the troposphere and produce precipitation. My research uses a combination of observations and models of varying complexity to investigate the dynamics, microphysics, and predictability of moist convection and its attendant precipitation. It also aims to quantify key related processes using simple mathematical models, to facilitate the improvement of cumulus parameterization.

### Current projects

- The impact of mesoscale ascent on the vertical development of cumulus convection.
- The transition from shallow-to-deep convection
- Physical mechanisms behind quasi-stationary convective storms.
- Orographic precipitation: morphology, sensitivities, and prediction.
- Parameterization of shallow and deep convection in large-scale models.
- Predictability of convective precipitation in convection-permitting weather forecast models.

### Some recent publications

Wang, C.-C. and D. J. Kirshbaum, 2015: Thermally forced convection over a mountainous tropical island. *J. Atmos. Sci.*, 72: 2484-2506. DOI: 10.1175/JAS-D-14-0325.1.

Kirshbaum, D. J. and J. G. Fairman, Jr., 2015: Cloud trails past the Lesser Antilles. *Mon. Wea. Rev.*, 143: 995-1017. DOI: 10.1175/MWR-D-14-00254.1.

Cannon, D. J., D. J. Kirshbaum, and S. L. Gray, 2014: A mixed-phase bulk orographic precipitation model with embedded convection. *Q. J. R. Meteorol. Soc*., 140: 1997-2012.

Hanley, K. E., D. J. Kirshbaum, N. M. Roberts, and G. Leoncini, 2013: Sensitivities of a squall line over central Europe in a convective-scale ensemble. *Mon. Wea. Rev.*, 141: 112–133.

Kirshbaum, D. J. and A. L. M. Grant, 2012: Invigoration of cumulus cloud fields by mesoscale ascent. *Q. J. R. Meteorol. Soc*., 138: 2136-2150.

**Henry G. Leighton (Emeritus)** – Physical Meteorology

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**Research interests**

Cloud chemistry and atmospheric aerosols

The interactions between atmospheric aerosol particles and clouds and precipitation have important implications for climate and air quality. Aerosols influence cloud properties. The chemical composition, size distribution and concentration of the aerosol will affect the concentration of cloud droplets, which in turn may impact on the radiative properties of the cloud, the cloud lifetime and the precipitation efficiency of the cloud. On the other hand clouds may impact on aerosol properties. Aerosols that are dissolved in cloud droplets may undergo chemical changes. Subsequent evaporation of the cloud will result in an aerosol that contains larger particles and with altered chemical composition. Precipitation carries the aerosol to the surface. The significance of the wet deposition of the aerosols will depend on the chemical composition of the aerosol and its concentration. We are studying these interactions by means of high resolution numerical models and are comparing the results of these simulations with results from aircraft measurements of aerosols.

Radiation, clouds and precipitation

Regional climate models are important tools to increase understanding of the processes that determine regional climate, fluctuations in the local climate, extremes and the regional climate change in response to global warming. In the Canadian context, a major study of the hydrology of the Mackenzie River Valley (Mackenzie GEWEX Study—MAGS) has recently concluded and currently there is a research network exploring the recent Prairie drought of 1999–2003 (Drought Research Initiative—DRI). In both of these studies the Canadian Regional Climate Model was used to help understand the processes that determined the hydrology of the region in the former study and the characteristics of the drought in the latter. In order to have confidence in the analyses resulting from the model it is useful to compare the model results as extensively as possible with observations. Precipitation is an important variable in both studies and so it is essential that the models reproduce the cloud fields, and their radiative impacts as observed by satellites, and also the relationships between cloud properties as measured from satellites and precipitation measured at the surface. We are contributing to understanding the Prairie drought by combining out analyses of satellite and surface observations with the output from CRCM simulations.

**Some recent publications**

Sun, J., Ariya, P.A., Leighton, H.G. and Yau, M.K., The mystery of ice multiplication in warm-based precipitating shallow cumulus. *Geophys. Res. Letter*, 37: L10802 (2010).

Guo, S. and Leighton, H.G., Satellite-derived aerosol radiative forcing from the 2004 British Columbia wildfires. *Atmosphere-Ocean*, 46: 203–212 (2008).

Paunova, I.T. and Leighton, H.G., Aerosol–cloud interactions in a mesoscale model. Part I: sensitivity to activation and collision–coalescence. *Journal of the Atmospheric Sciences*, 65(2): 298–308 (2008).

Paunova, I.T. and Leighton, H.G., Aerosol–cloud interactions in a mesoscale model. Part II: sensitivity to aqueous-phase chemistry. *Journal of the Atmospheric Sciences*, 65(2): 309–330 (2008).

**Timothy M. Merlis** – Canada Research Chair in Atmospheric and Climate Dynamics

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**Research interests**

We research atmospheric circulations and their role in climate changes.

Our goal is to elucidate physical mechanisms underlying the response of atmospheric circulations, surface temperature and precipitation, and tropical cyclones to changes in radiative forcing. Systematic experimentation with numerical climate models allows us to develop climate theories that encompass not only Earth's current and future climate, but also the broader range of possible climates.

For more information, visit the group website: www.meteo.mcgill.ca/~tmerlis.

**Some recent publications**

Merlis, T.M., Direct weakening of tropical circulations from masked CO2 radiative forcing. *Proceedings of the National Academy of Science* (2015).

Merlis, T. M., Interacting components of the top-of-atmosphere energy balance affect changes in regional surface temperature. *Geophysical Research Letters*, 41, 7291-7297, doi:10.1002/2014GL061700 (2014).

Merlis, T. M., I.M Held, G.L Stenchikov, F. Zeng, and L. W. Horowitz, Constraining transient climate sensitivity using coupled climate model simulations of volcanic eruptions. *Journal of Climate*, 27, 7781-7795 (2014).

Merlis, T.M., M. Zhao, and I.M. Held, The sensitivity of hurricane frequency to ITCZ changes and radiatively forced warming in aquaplanet simulations. *Geophysical Research Letters*, doi:10.1002/grl.50680 (2013).

Merlis, T. M., T. Schneider, S. Bordoni, and I. Eisenman, The tropical precipitation response to orbital precession. *Journal of Climate*, **26**, 2010-2021 (2013).

**Lawrence A. Mysak (Emeritus)** – Ocean, Climate and Paleoclimate Dynamics

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**Research interests**

Professor Mysak is director of the Earth System Modelling Group (ESMG) which is part of the Department of Atmospheric and Oceanic Sciences. The main goal of the research in the ESMG is to develop and apply various models of the Earth system to better understand decadal and longer term climate variability and change. Analysis of climate data and data model intercomparison studies are also important activities of the ESMG. Currently, the ESMG is working on the following projects:

- Testing Ruddiman's early anthropogenic hypothesis regarding the slow atmospheric $CO_2$ increase during the Holocene using an intermediate complexity climate model (the UVic Earth system model) (collaborating with Ph.D. student Chris Simmons and Prof. Damon Matthews from Concordia University).

- A data study on the impact of climate changes during the last 50 years on skating rinks in Canada (collaborating with M.Sc. student Nikolay Damyanov and Prof. Damon Matthews from Concordia University).

- Modelling of Pleistocene megafauna-forest vegetation interactions and their impact on climate using the UVic Earth system model (collaborating with M.Sc. student Marc-Olivier Brault, Prof. Damon Mathews from Concordia University, and Prof. Jaime Palter).

For further information on these and other projects, visit the ESMG website.

**Some recent publications**

Simmons, C.T. and Mysak, L.A., Stained glass and climate change: How are they connected? *Atmosphere-Ocean*, accepted for publication (2011).

Carozza, D.A., Mysak, L.A. and Schmidt, G.A., Methane and environmental change during the Paleocene-Eocene thermal maximum (PETM): modeling the PETM onset as a two-stage event. *Geophysical Research Letters*, 38: L05702 (2011).

Antico, A., Marchal, O., Mysak, L.A. and Vimeux, F., Meridional moisture flux in the atmosphere and deuterium excess in polar ice: insight from a zonally averaged ocean-atmosphere model. *Journal of Climate*, 23: 4841–4855 (2010).

Antico, A., Marchal, O., Mysak, L.A., Time-dependent response of a zonally averaged ocean-atmosphere-sea ice model to Milankovitch forcing. *Climate Dynamics*, 34: 763–779 (2010).

Jahn, A., Tremblay, L.B., Newton, R., Holland, M.M., Mysak, L.A. and Dmitrenko, I.A., A tracer study of the Arctic Ocean's liquid freshwater export variability. *Journal of Geophysical Research*, 115, C07015 (2010).

Jahn, A., Tremblay, L.B., Mysak, L.A. and Newton, R., Effect of the large-scale atmospheric circulation on the variability of the Arctic Ocean freshwater export. *Climate Dynamics*, 34: 201–222 (2010).

Simmons, C.T. and Mysak, L.A., The transmissive properties of medieval and renaissance stained glass in European churches. *Architectural Science Review*, 53: 251–274 (2010).

Yang, S., Carozza, D.A. and Mysak, L.A., Re-tuning the Walker-Kasting global Carbon cycle box model using a parameter sensitivity analysis. *McGill Science Undergraduate Research Journal*, 5: 67–72 (2010).

Sedláček, J. and Mysak, L.A., A model study of the Little Ice Age and beyond: changes in ocean heat content, hydrography, and circulation since 1500. *Climate Dynamics*, 33: 361–475 (2009).

Sedláček, J. and Mysak, L.A., Sensitivity of sea ice to wind stress and radiative forcing since 1500: A model study of the Little Ice Age and beyond. *Climate Dynamics*, 32: 817–831 (2009).

Wang, Y., Roulet, N.T., Frolking, S. and Mysak, L.A., The importance of Northern Peatlands in global carbon systems during the Holocene. *Climate of the Past*, 5: 683–693. *Corrigendum*, 5: 721–722 (2009).

Lemieux, J.F., Tremblay, L.B., Thomas, S., Sedláček, J. and Mysak, L.A., Using the generalized minimum RESidual (GMRES) method to solve the sea-ice momentum equation. *Journal of Geophysical Research*, 113: C10004 (2008).

Mysak, L.A., Glacial inceptions: past and future. *Atmosphere-Ocean*, 46: 317–341 (2008).

**Thomas Preston** – Atmospheric Chemistry


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**Research interests**

Our research group is focused on developing methods for the study of microphysical and chemical processes in atmospheric aerosol particles. Some topics of interest include: hygroscopicity and water transport, efflorescence and deliquescence, oxidative aging, and liquid-liquid phase separation.

The primary experimental method used by our group is optical trapping. This allows aerosols to be studied at the single particle level where physical parameters can then be determined with high precision and accuracy. Elastic and inelastic light scattering measurements from single particles are taken over time and are used to determine size and composition. We are also interested in the modelling of the interaction of electromagnetic radiation with particles as this is necessary for the interpretation of measurements and important for the development of future instrumentation.

In summary, our lab uses single particle spectroscopy and modelling to understand fundamental thermodynamic and kinetic processes in atmospheric aerosols.

**Some recent publications**

Mason, B. J., Cotterell, M., Preston, T. C., Orr-Ewing, A., and Reid, J. P. (2015) Direct measurements of the optical cross sections and refractive indices of individual volatile and hygroscopic aerosol particles. Journal of Physical Chemistry A. 119: 5701–5713.

Cotterell, M., Mason, B. J., Preston, T. C., Orr-Ewing, A., and Reid, J. P. (2015) Optical extinction efficiency measurements on fine and accumulation mode aerosol using single particle cavity ring-down spectroscopy. Physical Chemistry Chemical Physics. 17: 15843–15856.

Preston, T. C., and Reid, J. P. (2015) Angular scattering of light by a homogeneous spherical particle in a zeroth-order Bessel beam and its relationship to plane wave scattering. Journal of the Optical Society of America A. 32: 1053–1062.

Stewart, D. J., Cai, C., Nayler, J., Preston, T. C., Reid, J. P., Krieger, U. K., Marcolli, C. and Zhang, Y. H. (2015) Liquid–liquid phase separation in mixed organic/inorganic single aqueous aerosol droplets. Journal of Physical Chemistry A. 119: 4177–4190.

Rickards, A. M. J., Song, Y.-C., Miles, R. E. H., Preston, T. C., and Reid, J. P. (2015) Variabilities and uncertainties in characterising water transport kinetics in glassy and ultraviscous aerosol. Physical Chemistry Chemical Physics. 17: 10059–10073.

**David N. Straub** – Physical Oceanography

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**Research interests**

My research focuses on geophysical fluid dynamics applied mainly to the ocean circulation. This includes geostrophic turbulence and the energetics of ocean circulation.Essentially, I seek to describe how energy moves around between different length scales and classes of motion. For example, in the context of geostrophic flows in channel or periodic geometries, it is well known that energy cascades upscale in both horizontal and verical wavenumber space to form quasi-zonal barotropic jets. In a basin setting, however, western boundaries complicated this picture and allow for a short-circuiting of this inverse energy cascade. Moreover, while quasi-zonal jets are observed throughout the mid-latitude ocean, the energy is not concentrated in the barotropic mode and, although various mechanism have been proposed, a clear understanding of their dynamics and formation mechanisms remains elusive. Other work focuses on interaction of near-inertial and geostrophic modes. In particular, I have been involved in trying to assess the extent to which forced near-inertial motion may be able to extract kinetic energy from the ocean mesoscale, where most of the geostrophic kinetic energy resides. Finally, I am also involved in a number of projects relating to atmosphere dynamics and to how nonlinearities in the ocean's equation of state might affect its dynamics. Typically, this research involves numerical simulations to test various ideas, generally with particular attention paid to energy exchanges between scales and classes of motion.

**Some recent publications**

Asselin, O, P. Bartello, and D.N. Straub, 2016. On quasigeostrophic dynamics near the tropopause.
Phys. of Fluids, Vol 28, doi: 10.1063/1.4941761

Taylor, S. and D. N. Straub, 2016. Forced near-inertial motion and dissipation of low-frequency kinetic energy in a wind-driven channel flow. J. Phys. Oceanogr., Vol 46, #1. pp. 79-93.
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Gertz, Aaron and David N. Straub, 2009, Near-inertial Oscillations and the Damping of Mid-latitude Gyres, J. of Phys. Oceanogr., Vol. 39, #9. pp. 2338-2350. * MSc student under my supervision.

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J. Atmos. Sci. 66, 1384-1400. Research Associate under my co-supervision.

**Bruno Tremblay** – High Latitude Climate and Climate Variability

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**Research interests**

The presence of sea ice (and snow) at high latitudes plays an important role in the state and variability of the high latitude and global climate through various processes and feedback mechanisms. These include the ice-albedo feedback, the ventilation of the relatively warm ocean in leads in winter, the fluxes of salt and fresh water implied when ocean water freezes in one location while the ice melts in some other location, and the insulation effect sea ice which reduces the heat flux and momentum transfer between the atmosphere and the ocean.

I am interested in the high latitudes and their effect on global climate, and climate change. The idea of a summer ice-free Arctic (the Antarctic-analogue) is discussed more and more in the community. Important changes in the high latitude have already been observed. These include the melting of the permafrost, the warming of the eastern Arctic atmosphere, the reduction in ice extent and thinning of sea ice cover, the positive trend in Eurasian river runoff, etc.

**Outstanding questions**

- What is the relative importance of ocean heat fluxes and surface radiative fluxes the projected sea-ice decline?
- How will these changes impact the fresh water and heat budget of the Arctic? And the fresh water exchange between the Arctic and the northern North Atlantic where deep convection is present?
- Are these changes forced by local ocean-atmosphere interactions? Or are they forced remotely (e.g., by the warming of the tropical Indian and western Pacific Oceans) through teleconnection patterns?
- How will negative feedbacks associated (for instance) with the potential increase in summer cloud cover and fresh water flux to the northern North Atlantic affect the response of the high latitude to this warming?
- In a globally warmed world, we expect an increased hydrological cycle. Can we see trends in high latitude precipitation in the instrumental record? Is this trend coherent with the trend in river runoff?

**Current projects**

- The study of the fresh water and heat budget of the Arctic Ocean (including both sea ice and the surface ocean waters) and its effect on the density driven ocean circulation and meridional ocean heat fluxes in the Arctic Ocean. This work is done in collaborations with Alexandra Jahn (Colorado State University) and Marika Holland (NCAR) on the modeling side, and Peter Schlosser and Robert Newton from the Lamont Doherty Earth Observatory (LDEO) of Columbia University (CU) on the observational side.

- The transport of ice rafted debris in the Southern Ocean (as reconstructed from ocean cores) by iceberg and its relation with present day and past climate. This work is done in collaboration with Trevor Williams from University of Texas.

- The study of sea ice deformation under applied loading (rheology), and the energetics of sea ice. This work is done in collaboration with Andrew Roberts (Naval Postgraduate School, Monterey, CA) and Jean-Francois Lemieux (Environment Canada).

- The future of the perennial sea ice cover in the Arctic Ocean - and the relative importance of sea ice export, vertical ocean heat flux and air-ice heat fluxes in potentially creating a summer ice-free Arctic. This work is done in collaboration with Marika Holland (NCAR).

- The effects of inertial oscillations on air-sea interactions, internal wave generation and vertical ocean mixing in ice-covered seas. This work is done in collaboration Luc Rainville (Applied Physics Laboratory – UW).

- Transport of pollutant, sediment and nutrients by Arctic sea ice. This work is done in collaboration with Stephanie Pfirman (Barnard College), Robert Newton (LDEO) and Gavin Schmidt (NASA-GISS).

- Seasonal forecasting of the minimum sea ice extent using a Lagrangian Trajectory model. This work is done in collaboration with Stephanie Pfirman (Barnard College Columbia University) and Robert Newton (LDEO)

- The impact of the low-level temperature inversion on the surface radiative balance in the Arctic Ocean. This work is done in collaboration with Jen Kay (Colorado State University).

- Modeling and in-situ buoy data study of landfast ice in the Archipelago. This study is done in collaboration with Andy Mahoney (University of Alaska Fairbanks).

**Some recent publications**

Tremblay, L.B., G.A. Schmidt, Is ice-rafted sediment in a North Pole marine record evidence for perennial sea-ice cover?, Philosophical Transaction of the Royal Society A, **373**: 20140168. http://dx.doi.org/10.1098/rsta.2014.0168

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Gervais, M., L.B. Tremblay, J.R. Gyakum, Eyad Atallah, “Representing extremes in gridded precipitation analyses: impacts of station density, resolution, and gridding methods”, Journal of Climate, 27:14, 5201-5218. doi: http://dx.doi.org/10.1175/JCLI-D-13-00319.1, 2014.

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Bouchat, A., L.B. Tremblay, “ Energy dissipation in viscous-plastic sea-ice models”, J. Geophys. Res. Oceans, 119, doi:10.1002/2013JC009436, 2014

**Man K. (Peter) Yau** – Cloud Physics and Dynamics

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**Research interests**

1. Improving quantitative precipitation forecasts

NSERC and Hydro-Quebec has been supporting our Industrial Research Chair Program on “Improving short-term forecast of precipitation”. The efficient generation and distribution of hydro-electric power depends on accurate forecast of inflows in reservoirs and drainage basins, which in turn is affected significantly by the quality of the forecast of the type and amount of precipitation. During the first mandate of the Industrial Research Chair program (2009-2014), various tools have been developed to improve the forecast of when, where, how much, and what type of precipitation would occur over a lead time of one to two days. During the second mandate (2014-2019), this forecast lead time will be increased to one week which would be highly beneficial for capacity management of hydroelectric power.

Specific projects during the second mandate include the development of a unified aerosol-microphysics multi-moment scheme across model resolutions, the improvement on the representation of upright and slantwise convection in the Canadian computer weather prediction models, and the evaluation of quantitative precipitation and hydrological forecasts over global and regional scales as a result of the better representation of convective and cloud/precipitation processes.

2. Studies on hurricanes

Hurricanes are violent vortices in the atmosphere. For hurricane prediction, two major problems remain. One is to forecast the rapid intensification (RI) of the storm and the other is to forecast when a storm will form.

Convection in the eyewall can affect RI in two ways. First, latent heating released in cloud processes is a main source of energy. Its spatial distribution affects RI especially when bursts of convection occur inside the radius of maximum wind. Second, latent heating in the eyewall produces a hollow tower of potential vorticity (PV) that supports propagating vortex Rossby waves (VRW) which may become unstable to mix eyewall PV into the eye to effect intensity change. Additionally, VRWs in a hurricane vortex can radiate gravity waves leading to another instability known as radiative pumping. However, this instability can be damped at a critical radius inside/outside the vortex core where the angular velocity of the waves matches the fluid rotation rate. The understanding of these instabilities is important to improve hurricane forecasting.

Our current research projects focus on the following scientific questions:
a) How microphysical processes regulate the distributions of latent heating and water loading which may bear strongly on hurricane intensity?
b) How do instabilities and the critical radii affect hurricane intensity change?
c) How does a pouch form during the early genesis stage of a hurricane?
Theoretical analysis, high resolution computer modeling, and diagnostic studies are being utilized to yield answers to the above questions.

**Some recent publications**

Asaadi, A., G. Brunet, and M.K. Yau, 2015a: On the dynamics of the formation of the Kelvin cat's eye in tropical cyclogenesis. Part I: Climatological investigation. J. Atmos. Sci., (under revision).

Asaadi, A., G. Brunet, and M.K. Yau, 2015b: On the dynamics of the formation of the Kelvin cat's eye in tropical cyclogenesis. Part II: Numerical simulations. J. Atmos. Sci., (submitted).

Chen, S.S., P. Bartello, M.K. Yau, P.A. Vaillancourt, and K. Zwijsen, 2015: Cloud droplet collisions in turbulent environment: Collision statistics and parameterization. J. Atmos. Sci. (under revision).

Fekri, M., and M.K. Yau, 2015a: A study of rain forecast error structure based on radar observations over a continental-scale spatial domain. Mon. Wea. Rev. (under revision).

Fekri, M., and M.K. Yau, 2015b: An information-theoretical score of dichotomous precipitation forecast. Mon. Wea. Rev. (under revision).

Surcel, M., I. Zawadzki, and M.K. Yau, 2015b: The case-to-case variability of the predictability of precipitation by a Storm-Scale Ensemble Forecasting system. Mon. Wea. Rev. (accepted)

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Menelaou, K., and M.K. Yau, 2014: On the role of asymmetric convective bursts to the problem of hurricane intensification: Radiation of vortex Rossby waves and wave-mean flow interactions. J. Atmos. Sci., 71, 2057-2077.

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Chosson, F., P.A. Vaillancourt, J.A. Milbrandt, M.K. Yau, and A. Zadra, 2014: Adapting two-moment microphysics schemes across model resolutions: subgrid cloud and precipitation fraction and microphysical sub-time step. J. Atmos. Sci., 71. 2635-2653.

Menelaou, K., M.K. Yau, and Y. Martinez, 2013a: Impact of asymmetric dynamical processes on the structure and intensity change of two-dimensional hurricane-like annular vortices, J. Atmos. Sci., 70, 559-582.

Lavaysse, C., M. Carrera, S. Belair, N. Gagnon, R. Frenette, M. Charron, and M.K. Yau, 2013: Impact of surface parameter uncertainties within the Canadian Regional Ensemble Prediction System. Mon. Wea. Rev., 141, 1506-1526.

Menelaou, K., M.K. Yau, and Y. Martinez, 2013b: On the origin and impact of polygonal eyewall in the rapid intensification of hurricane Wilma (2005), J. Atmos. Sci., 70, 3839-3858.

Yip, Z.K., and M.K. Yau, 2012: Application of artificial neural networks on North Atlantic tropical cyclogenesis potential in climate change. J. Atmos. Oceanic Technol., 29, 1202-1220.

Sun, J., H.G. Leighton, M.K. Yau, and P.A. Ariya, 2012: Numerical evidence for cloud droplet nucleation at the cloud-environment interface. Atmos. Chem. Phys., 12, 12155–12164.

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## **Isztar Zawadzki (Emeritus)** – Cloud Physics and Radar Meteorology

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### Research interests

Doppler radars are highly sophisticated instruments for the remote sensing of the atmosphere. Operational scanning radars provide, every five minutes or so, a volume scan of the atmosphere.

Radar echoes from this volume give information on the spatial distribution of precipitation content and the scatterers velocity in the radar beam direction (radial velocity component in spherical coordinates). These observations are made with a resolution and area coverage sufficient to study most of the severe weather phenomena and the mesoscale organization of precipitation systems. This direct sounding of nature, however, is insufficient for unambiguous physical interpretation of the measurements. The radial velocity is but one component out of three. The interpretation of the radar received power is ambiguous due to the variety of scatterers (rain, snow, hail, graupel, etc.), each with its own electromagnetic properties.

Numerical models of atmospheric phenomena, on the other hand, give an approximation to a complete phenomenological description of the atmosphere. However, for a model to reproduce a particular weather event on the mesoscale, sufficient information on the event must be introduced into the model. This may take the form of a time series of measurements such as those provided by the radar. Thus, radar and models have complementary features and the recent advances in both fields are such that we are ready to attempt the integration of radar.

**Some recent publications**

Zawadzki, Jung, E., and Lee, G.W., Snow Studies. Part I: a study of natural variability of snow terminal velocity. *Journal of the Atmospheric Sciences*, 67: 1591–1604 (2010).

Chung, K.-S., Zawadzki, I., Yau, M.K. and Fillion, L., Short-term forecasting of a midlatitude convective storm by the assimilation of single–doppler radar observations. *Mon. Wea. Rev*., 137: 4115–4135 (2009).

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Lee, C.K., Lee, G.W., Zawadzki, I. and Kim, K.E., Spatial variability of rain drop size distributions during stratiform rain events. *J. App. Met. Clim*., 48: 270–283 (2008).

Heyraud, C., Szyrmer, W., Laroche, S. and Zawadzki, I., Modeling of the melting layer. Part IV: brightband bulk parametrization. *J. Atmos. Sci*., 65: 1991–2001 (2008).

Bellon, A., Lee, G.W., Kilambi, A. and Zawadzki, I., Real-time comparison of VPR-corrected daily rainfall estimates with gage mesonet. *J. Appl. Meteorology*, 46: 726–741 (2007).

Hocking, W.K., Carey-Smith, T., Tarasick, D.W., Argall, P.S., Strong, K., Rochon, Y., Zawadzki, I. and Taylor, P.A., Detection of stratospheric ozone intrusions by windprofiler radars. *Nature*, 450: 281–284 (2007).

Vasić, S., Lin, C.A., Zawadzki, I., Bousquet, O. and Chaumont, D., Evaluation of precipitation from numerical weather prediction models using values retrieved from radars and satellites. *Monthly Weather Review*, 135: 3750–3766 (2007).

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Germann, U., Zawadzki, I. and Turner, B., Scale dependence of predictability of precipitation from continental radar images. Part IV: limits to prediction. *J. Atmos. Sci.*, 63: 2092–2108 (2006).

Bellon, A., Lee, G.W. and Zawadzki, I., Error statistics of VPR corrections in stratiform precipitation. *J. Appl. Meteorology*, 44: 998–1015 (2005).

Szyrmer, W., Laroche, S. and Zawadzki, I., A microphysical bulk formulation based on scaling normalization. Part I: description. *J. Atmos. Sci*., 62: 4206–4221 (2005).

**Andreas Zuend** – Aerosol Chemistry and Physics

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### Research interests

My group works in the field of Atmospheric Chemistry and Physics with a focus on the chemical and microphysical processes governing the formation and transformations of atmospheric aerosols.

Atmospheric aerosols are tiny particles suspended in the air. Despite the small mass contribution of aerosol particles when compared to the major gaseous constituents of a volume of air, this particulate form of matter in the atmosphere is of fundamental importance for urban and regional air quality and the global climate system. Aerosols are among the least understood and quantified climate agents, affecting Earth's radiation balance directly as well as indirectly via their crucial role in the formation of cloud droplets and influence on cloud microphysics. Part of the lack of knowledge is due to the complexity and variety of primary and secondary particle sources, the chemical composition, phases, and physical states of aerosols and the evolution of these properties during the lifetime of aerosols in the troposphere.

**Current projects**

Our research projects are motivated by the need to understand the chemical thermodynamics, reactions, and mass transfer kinetics of complex mixtures consisting of tens to thousands of oxidized organic compounds, water, and inorganic electrolytes that form and characterize the majority of aerosols in the troposphere.

We apply existing atmospheric chemical mechanisms and state-of-the-art thermodynamic models and develop new numerical methods and system analysis tools for the characterization and prediction of aerosol particle composition, phases and phase transitions at environmental conditions. These tools allow us to improve the process-level understanding of atmospheric aerosol formation and evolution and enable the direct comparison to laboratory experiments and field studies performed by various collaborating groups.

Projects include the development of theory and reliable numerical algorithms for the calculation of liquid-liquid phase separation, liquid-solid equilibria, water content and acidity of complex chemical mixtures representing ambient and laboratory aerosols. We also work on coupled gas-particle partitioning schemes ranging from high to low complexity for applications in chemical box models (0D) and implementation in 3D atmospheric chemistry transport and climate models.

Box models are, for example, applied to study the formation of so-called secondary organic aerosols from emissions and photochemical processing of volatile organic compounds above the Athabasca Oil Sands region in northern Alberta.

Find out more about our current research projects by visiting the group website or by contacting me directly.

**Some recent publications**

Hodas, N., Zuend, A., Mui, W., Flagan, R. C., and Seinfeld, J. H.: Influence of particle-phase state on the hygroscopic behavior of mixed organic–inorganic aerosols, *Atmos. Chem. Phys.*, 15, 5027–5045, 2015.

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Lei, T., Zuend, A., Wang, W. G., Zhang, Y. H., and Ge, M. F.: Hygroscopicity of organic compounds from biomass burning and their influence on the water uptake of mixed organic ammonium sulfate aerosols, *Atmos. Chem. Phys.*, 14, 11165–11183, 2014.

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Zuend, A. and Seinfeld, J. H.: A practical method for the calculation of liquid–liquid equilibria in multicomponent organic–water–electrolyte systems using physicochemical constraints, *Fluid Phase Equilib.*, 337, 201–213, 2013.

Hersey, S. P., Craven, J. S., Metcalf, A. R., Lin, J., Lathem, T., Suski, K. J., Cahill, J. F., Duong, H. T., Sorooshian, A., Jonsson, H. H., Shiraiwa, M., Zuend, A., Nenes, A., Prather, K. A., Flagan, R. C., and Seinfeld, J. H.: Composition and hygroscopicity of the Los Angeles Aerosol: CalNex, *J. Geophys. Res.: Atmos.*, 118, 3016–3036, 2013.

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