**High Impact Weather Research Section**

**Cloud Physics Research Program**

Overview

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**BACKGROUND**

In order to deliver on mandate, which includes scientific research on the monitoring and prediction of weather and climate conditions for Canadians, the research conducted in HIWR is defined as belonging to one or more of the following four research programs:

* Radar
* Aircraft
* Nowcasting/High-Impact Weather
* Cloud Physics

The Cloud Physics (CP) program serves to improve the measurements of clouds, precipitation and radiation, both from in situ and remote sensing observations, the physical understanding of cloud processes, and the representation of clouds and cloud processes in numerical models, including those used in ECCC operational prediction systems. Within MRD and the department at large, the CP program provides a direct link between HIWR and the NWP and climate modeling activitiesas well as a path for the other three HIWR research programs to contribute indirectly.

This document provides a brief overview of the HIWR’s CP research program, with mention of a few current projects that are part of the program.

**Main Themes**

The following are the main themes of the CP program, to which the various specific on-going projects, from short-term to long-term, belong.

*1. Measurements of clouds/precipitation/radiation using specialized instruments*

This theme pertains to improving our capacity to measure clouds and cloud processes as well as to explore and develop better ways to apply such measurements to the evaluation of clouds, precipitation, and radiation in NWP models, both for standard verification and to examine and understand strengths and weakness of the model.

This includes the following:

* improvements of measurement techniques and data processing
* use of dual-polarization radar to evaluate NWP model clouds/precipitation
* use of satellite observations to examine model clouds/precipitation/radiation
* use of research aircraft observations to evaluate model cloud microphysics and to validate radar retrievals
* use of in situ or specialized remote sensing ground-based microphysical observations to evaluate model clouds/precipitation
* use of instrument simulators (for ground-based radar and satellite observations) to examine model clouds/precipitation

*2. Advancing the understanding of fundamental cloud physics*

As NWP models go to higher resolution, it becomes increasingly important to represent detailed in-cloud microphysical processes. In contrast to most subgrid-scale processes in atmospheric models, whose representation by physical parameterization schemes is necessary almost entirely due to lack of resolution (and computational resources), the scientific community lacks a complete understanding of the fundamental physics for many in-cloud process. These processes impact precipitation and radiation in clouds, thus the lack of complete understanding is an obstacle to our capacity to represent them, and/or their effects, in atmospheric models. Therefore, in addition to contributing to fundamental scientific knowledge, this theme ultimately serves to improve numerical models (theme 3).

Some examples of specific current topics include research on:

* secondary ice production
* ice crystal growth/decay rates (and change in particle shape)
* formation of freezing drizzle and freezing rain conditions
* representation of mixed-phase clouds
* 3D cloud effects on radiative transfer
* Radiative transfer in optically thin ice clouds

*3. Improvement to the representation of radiation and grid-scale clouds in numerical models*

A premise behind this theme is that regardless of the extent to which AI-based models become used for operational NWP, traditional dynamical/physical models will always play key roles in NWP, though these roles may shift from providing direct numerical guidance for weather forecasting towards training AI-based modeling systems and/or individual model components). Therefore, the capacity to parameterize physical processes related to clouds in dynamical models will always be relevant in ECCC; in fact, it will become increasingly important as NWP systems move to higher resolution, either to provide direct numerical guidance or to train AI-based systems. HIWR scientists (as well as those in other sections in MRD) have specialized expertise in the parameterization of radiative transfer and grid-scale cloud microphysics, as well as expert knowledge in the themes 1 and 2, which support theme 3.

Specific topics include the following:

* improvement of the 3D radiative transfer
* Monte Carlo radiative transfer code
* improvement and continued development of the P3 microphysics scheme
* improved links to the microphysics scheme with prognostic aerosols
* development of prediction capabilities for contrail cirrus clouds

**Current Projects**

The following are the current major projects centered around the CP research program. See Appendix for further details on each project.

*1. Radiative closure assessment for ESA’s EarthCARE satellite mission* (EarthCARE)

The EarthCARE satellite was launched in May 2024 for a 4 year-long mission. Its scientific objective is to infer cloud and aerosol properties that are needed to improve predictions made by weather and climate numerical models. ECCC has developed and maintains several EarthCARE algorithms that compute solar and thermal radiative quantities. These quantities ultimately arrive at, and define, the mission’s overarching radiative closure assessment whose objective is to perform continuous, real-time assessment of cloud and aerosol products inferred from EarthCARE’s suite of active and passive sensors. EarthCARE utilizes ECCC’s advanced three-dimensional radiative transfer models, which replace their one-dimensional counterparts that have been used in ALL other satellite missions. Not only will EarthCARE enhance understanding of aerosol-cloud-precipitation-radiation interactions, it will also provide crucial information needed to assess clouds and precipitation as predicted by NWP and climate models.

*2. P3 microphysics scheme development* (P3)

The Predicted Particle Properties (P3) microphysics (MP) scheme was co-developed through a collaboration with MRD and NCAR (see appendix). It is used in the operational HRDPS and all experimental GEM-based high-resolution systems to represent grid-scale clouds and precipitation. P3 is one of the most sophisticated schemes of its type in the world, both in terms of conceptual design and performance (accuracy and computational efficiency). Within 2-3 years, the P3 development team (see appendix) expects to have a complete “framework” for the scheme (i.e. the prognostic variables). At this point, continued development will focus on improvements to individual parameterized processes, based on theme 2. The development team is currently working to establish P3 as a “community” bulk scheme, with use by and contributions from the international research and the operational community at large in order to accelerate the advancement of the scheme. Regardless of the rate at which international buy-in occurs, continued development of P3 will deliver on mandate by providing an important contribution to atmospheric modeling – including NWP, climate, and air quality modeling – within ECCC.

*3. Experimental real-time 1-km NWP system* (EXP\_1km)

A current point-of-focus, which applies to all of the themes of the CP program, is an experimental GEM-based 1-km system. This is a real-time experimental NWP system, originally set up as a collaboration between HIWR and CMDN, for the following purposes: 1) to explore the potential added value of 1-km (over 2.5-km) NWP in Canada; 2) to test new model verification techniques (e.g. using radar) relevant to high-resolution NWP (including the HRDPS); 3) to serves as a real-time test-bed for changes to model (e.g. to P3); 4) to showcase and examine the utility of new forecast fields related to high-impact weather (e.g. hail, winter precipitation types) that can be produced from high-resolution models with detailed microphysics.

*4. Development of a contrail avoidance prediction tool based on NWP guidance* (CoAT)

Cirrus clouds formed from aircraft contrails is currently calculated to represent about 3.5% of the total current radiative impact on climate, thus contrails contribute to global warming. ECCC’s Cross Sectoral Energy Division (of the EPB) initiated a project, led and conducted by HIWR, to develop a numerical tool to predict regions conducive for the formation of contrails as a means of providing commercial pilots guidance to change flight routes in order to minimize contrail production. In addition to research on contrails production that will be done, this project aims to develop a tool that can be implemented into one or more ECCC operational NWP systems.

**APPENDIX**

**Tools**

*Observations:*

* ECCC radar network, satellites (A-Train, EarthCARE, AOS, etc.), instrumented aircraft (field campaigns), HIWR ground-based instruments (field campaigns, Pearson and CARE sites, etc.)
* Airborne in-cloud observations from field campaigns examining
* Derived sensible weather fields from radar diagnostics (e.g. MESH, PARCA)

*Modeling:*

* GEM, CM1 (and access to HPC)
* P3 scheme, Lagrangian scheme(s) (e.g. the Super Droplet Model [SDM])
* Instrument simulators (e.g. RTTOV, COSP2, EarthCARE CPR radar simulator [from McGill], CR-Sim dual-pol simulator[s], etc.), 1D and 3D radiative transfer models for use in Environmental models and with remote sensing observations.

*Laboratory studies:*

* For the immediate future, this will not be a direct part of HIWR due to lack of equipment and local expertise. However, some researchers (e.g. A. Korolev) may work with external collaborators with appropriate laboratory equipment to progress on theme 2. Laboratory studies in support of the CP program may, however, be largely restricted to research from others.

**Collaborators and Clients**

*Internal (ECCC)*

* HIWR Radar, Aircraft, and Nowcasting program staff. For collaboration/assistance in interpreting and using specialized observations.
* RPN-A: For aspects of themes 1 and 3 of the CP program, RPN-A is a logical collaborator; however, that section’s management and representatives have stated clearly that RPN-A will not contribute any resources to research and development on 1-km NWP. Since the EXP\_1km project is a focal point for the CP program, this places a limitation on collaboration. Nevertheless, the EXP\_1km system can easily be adapted to include the HRDPS for on-going code testing, new verification techniques, etc., thus the potential for collaboration exists.
* CMDN, National Labs: For collaboration and feedback on the EXP\_1km project.
* CCCma: This group is currently planning to implement P3 in CanAM, the atmospheric component of the Canadian climate model, and has recently hired a postdoc (M. Lachapelle, based in Dorval) to begin this task. CCCma is closely collaborating with HIWR on the EarthCARE project.
* AQRD: This group is particularly interested in the use of P3 in GEM-MACH since it provides a direct link to aerosols.

*External*

* NSF NCAR: H. Morrison (MMM division) is a co-developer of the original P3 scheme and continued core development team member. A close long-term collaboration with MRD continues. The P3 core team plans to work together on the completion the P3 framework. After this, HM’s role will change with an emphasis on very high-resolution modeling research using the CM1-SDM system (at NCAR). This will contribute directly to goals 2 and of the CP program.
* Universities: The P3 development team collaborates regularly with universities in Canada (e.g. UQAM, McGill), USA (e.g. OU, etc.), and elsewhere (e.g. KNU, S. Korea). Interactions with these groups periodically lead to advances in aspects of the P3 scheme.
* Others weather centers: The P3 team has connections with various centers in the US (e.g. NOAA) and elsewhere (e.g. KMA). The team continues to promote the use of P3 external NWP systems. This is a slow process (it takes time to make major changes of this type); however, these centers are clearly aware of P3 and are paying attention.
* ESA and EarthCARE partners
* Canadian Space Agency (CSA) and High-altitude Aerosols, Water vapour, and Cloud (HAWC) – Atmosphere Observing System (AOS) partners
* European Space Agency; ECMWF; Weather centres in The Netherlands and Belgium; NASA-JPL; NASA-LaRC
* Aviation safety: FAA, TC, EASA, NASA
* Cloud physics: DOE, PNNL, BNL

**OTHER Projects** ( -- Under Development -- )

*1. ECALOT*

EarthCARE Commissioning Cal/Val Campaign in Ottawa (ECALOT) aims to gather essential observational data using aircraft and surface instruments to calibrate and validate select Level 1 and Level 2 products of EarthCARE. This effort involves coordinated flight paths aligned with satellite overpasses and support from surface observation sites. The collected observational data will not only aid in calibration and validation but will also contribute to scientific research aimed at enhancing the parameterization of various components within the numerical prediction model (NWP), such as the cloud microphysical scheme and radiative transfer scheme.

*2. Arctic studies – PONEX*

3. study of Arctic weather/clouds/aerosols

**MISCELLANEOUS POINTS** ( -- Under Development -- )

*Comments on measurement techniques and data processing*

Accurate airborne measurements of cloud microphysical parameters such as ice and liquid water content, concentration of ice particles and liquid droplet concentrations, cloud particle sizes are critically important for validation of NWPs and interpretations of remote sensing ground based and satellite observations. Developing processing tools provide a quick access to the airborne in situ measurements and reduce uncertainty and errors in conversion of measured data into physical parameters. Accurate cloud microphysical measurements are important for the aviation regulatory certification in the ground-based facilities and developing aviation safety envelopes. HIWC accumulated a suite of unique airborne microphysical instrumentation.

* Continue work in collaboration with NASA and FAA on studies of accuracy of measurements and limitations of cloud microphysical instrumentation in wind tunnels, laboratory facilities. Continue working on theoretical analysis of accuracy of measurements.
* Continue development of cloud microphysical instrumentation.

The EarthCARE satellite mission and 3D radiative transfer simulation:

ESA's EarthCARE (Cloud, Aerosol and Radiation Explorer) mission - launched in 2024 - is the largest and most complex Earth Explorer to date, and will advance our understanding of the role that clouds and aerosols play in reflecting incident solar radiation back into space and trapping infrared radiation emitted from Earth's surface. EarthCARE will employ high-performance lidar and radar technology that has never been flown in space before, with the objective to deliver unprecedented datasets to allow scientists to study the relationship of clouds, aerosols and radiation at accuracy levels that will significantly improve our understanding of these highly variable parameters.

ECCC continually contributed to European Space Agency’s EarthCARE satellite mission. The contributors of this project are Z. Qu (HIWR), M. Kacimi (HIWR), H. Barker (HIWR) and J. Cole (CCCma). The goal is to development radiative closure assessment algorithm for the EarthCARE mission. The benefits for ECCC the acquisition of a better understanding of the impacts of 3D Monte Carlo radiative transfer (RT) simulation for the NWP system, and to provide efficient radiative closure tool for assessing NWP simulated clouds/precipitation.

The P3 core development team:

The P3 bulk microphysics scheme was originally co-developed by H. Morrison (NCAR) and J. Milbrandt (RPN-A at the time, now at HIWR), with the original code and first publication in 2015. Since then, M. Cholette (RPN-A) contributed a major piece of scientific and code development and continues to be a contributor. Currently, the core P3 development team consists of H. Morrison, J. Milbrandt, and M. Cholette. The team continues to maintain and actively develop the code as well as collaborate on scientific research using P3 as a primary tool.

With regards to the GEM model, the P3 code is in a unique position (compared to other code packages in the RPN-PHY library) in that it is maintained by an expert and diverse team dedicated to its continual improvement. This means that this important component of GEM benefits directly from HIWR’s CP research program, which provides expert scientific knowledge and research in addition to code maintenance, as well as from a senior scientist at NSF NCAR who not only coded the original version of P3 and is involved in continual development but is also closely connected to a large community of researchers that run P3 in other models (WRF and CM1).

**ACRONYMS**

BNL Brookhaven National Laboratory (USA)

CCCma Canadian Centre for Climate Modelling and Analysis (ECCC)

CM1 Cloud Model 1 (atmospheric model, NCAR)

CMDN *(Does anybody know?)*

CSED Cross Sectoral Energy Division (EPB)

DOE Department of Energy (USA)

EASA European Union Aviation Safety Agency

EPB Energy and Transportation Directorate (ECCC)

ESA European Space Agency

FAA Federal Aviation Administration (USA)

GEM Global Environmental Multiscale (atmospheric model, ECCC)

MESH Maximum Estimated Size of Hail

NASA National Aeronautics and Space Administration (USA)

NCAR National Center for Atmospheric Research (USA)

NRCC National Research Council of Canada

NSF National Science Foundation (USA)

NWP numerical weather prediction

P3 Predicted Particle Properties (microphysics scheme)

PNNL Pacific Northwest National Laboratory (USA)

RPN-A Atmospheric Numerical Prediction Research (MRD)

TC Transport Canada