Environment and
Climate Change Canada

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Changement climatique Canada

Overview of the P3 Microphysics Scheme

Applications to Research and Operational NWP

Jason Milbrandt, ECCC
and
Hugh Morrison, NCAR

Environment and Climate Change Canada's 50th anniversary
50e anniversaire d'Environnement et Changement climatique Canada
Meteorological Service of Canada's 150th anniversary
150e anniversaire du Service météorologique du Canada

WRF-MPAS 2021 Workshop
June 7-10, 2021 (virtual)

Canada

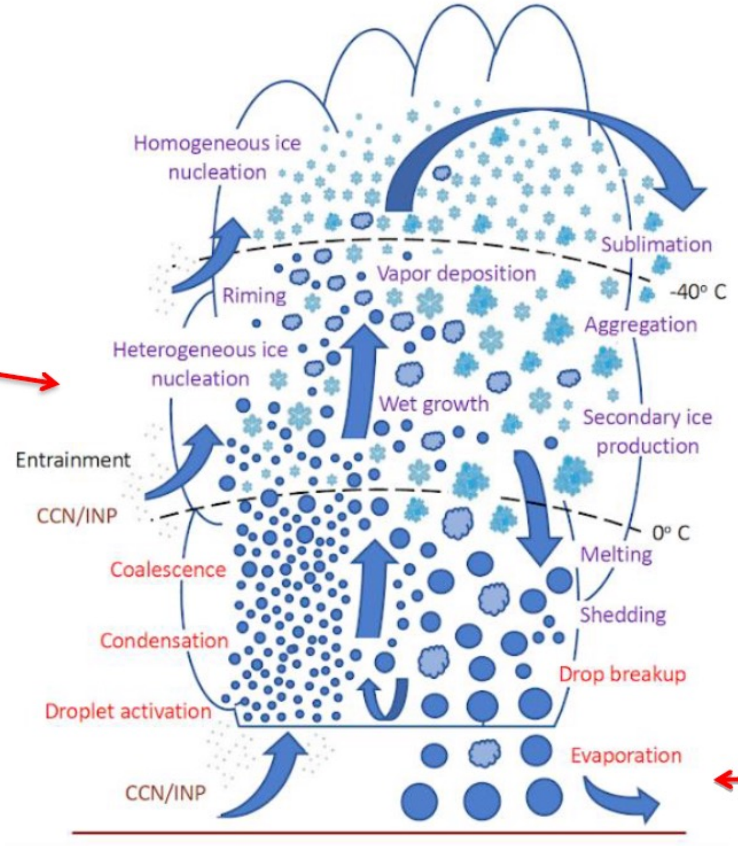
OUTLINE of PRESENTATION:

1. Overview of P3 scheme
    - Motivation (*Why build a new microphysics scheme?*)
    - Description
2. Recent developments
3. Applications

BACKGROUND: Parameterizing cloud microphysics

In atmospheric models, condensation schemes parameterize the bulk effects of a complex set of ***cloud microphysical*** and ***precipitation*** processes

HYDROMETEORS
(blue symbols)



Microphysical processes and hydrometeors in a precipitating cloud

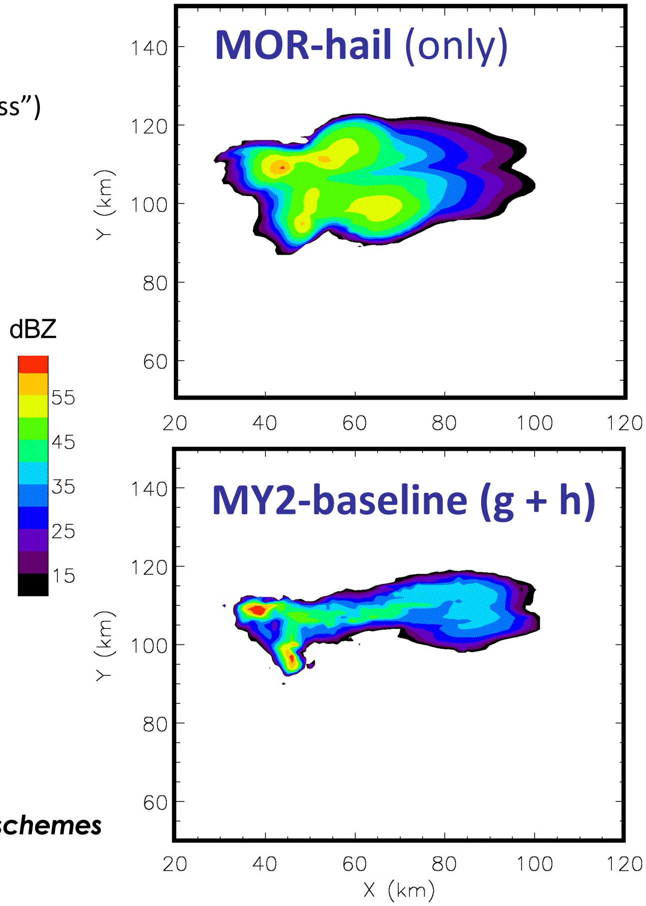
MICROPHYSICAL PROCESS

PRECIPITATION AT SURFACE

Morrison et al. (2020), *JAMES*

BACKGROUND: Comparison of detailed 2-moment schemes in WRF

- idealized 1-km supercell simulations (WRF's "em_quarter_ss")
- base reflectivity



?

Microphysics Schemes:

MOR: Morrison et al. (2005, 2009)

MY2: Milbrandt and Yau (2005a,b)

Similar 2-moment, multi-category bulk schemes

BACKGROUND: Comparison of detailed 2-moment schemes in WRF

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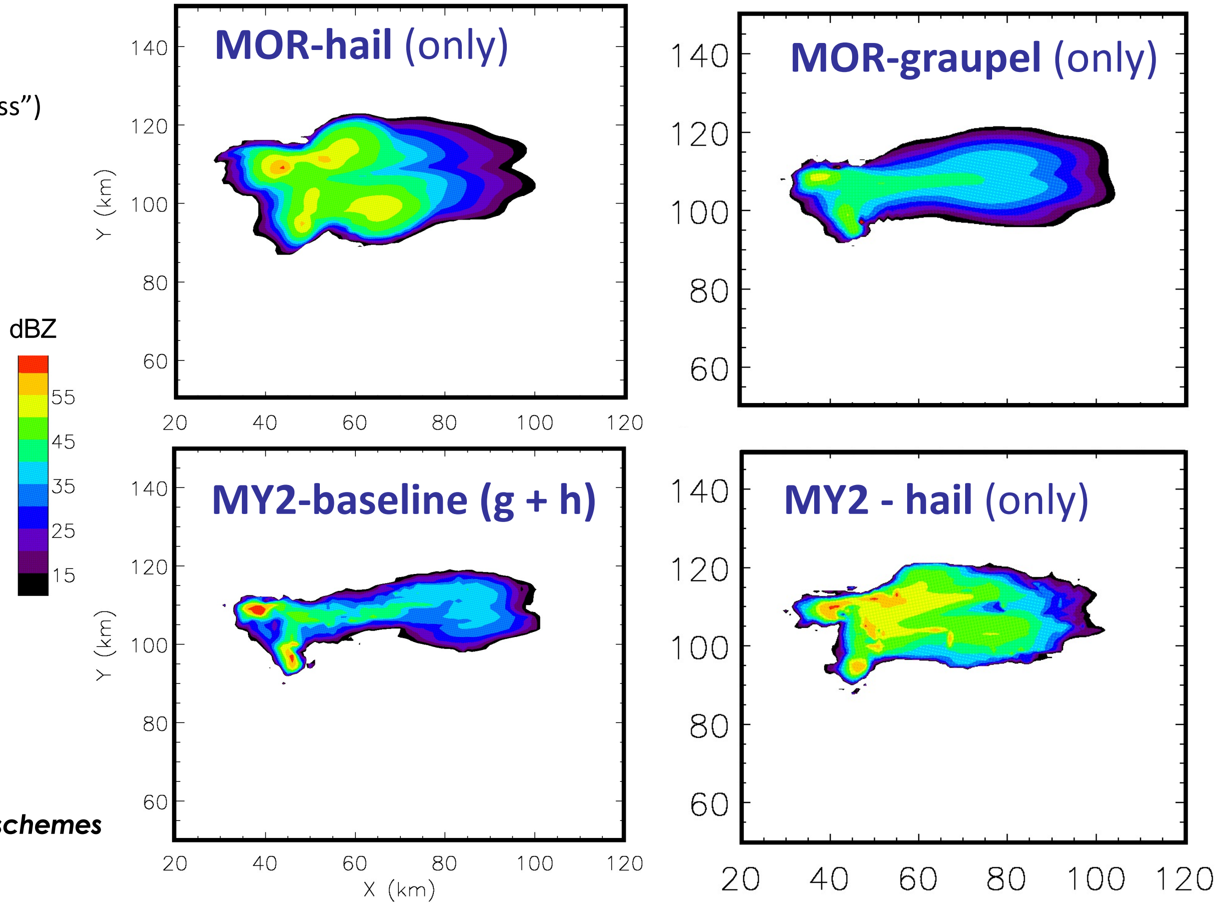

Morrison and Milbrandt (2011), *MWR*

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MOR: Morrison et al. (2005, 2009)

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BACKGROUND: Representation of ice-phase hydrometeors

TRADITIONAL APPROACH:

Partition hydrometeors into pre-defined categories:

CLOUD "ICE"

ρ_s = 500 kg m^{-3}

$m = (\pi/6\ \rho_s)D^3$

$V = a_i D^{b_i}$

"SNOW"

(ρ_s = 100 kg m^{-3})

$m = cD^2$ (or cD^3)

$V = a_s D^{b_s}$

GRAUPEL

ρ_g = 400 kg m^{-3}

$m = (\pi/6\ \rho_g)D^3$

$V = a_g D^{b_g}$

HAIL

ρ_h = 900 kg m^{-3}

$m = (\pi/6\ \rho_h)D^3$

$V = a_h D^{b_h}$

CN_{is}

CN_{sg}

("conversion" of snow to graupel)

CN_{sg}

← *abrupt / unphysical conversions*

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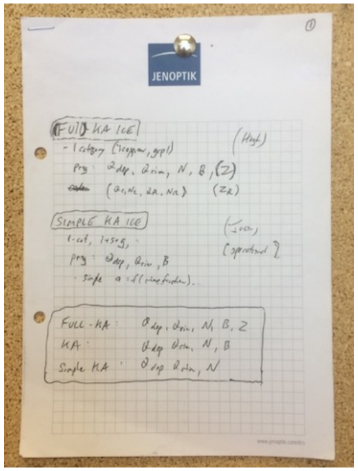
← *abrupt / unphysical conversions*

ALTERNATIVE APPROACH:

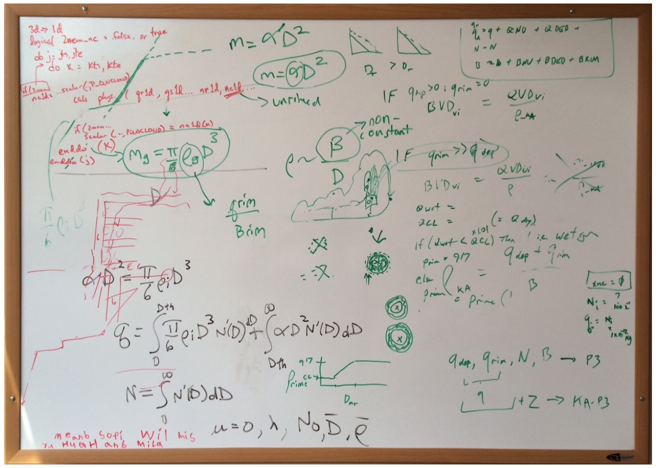
Focus on the prediction of continuously evolving physical properties of "free" ice-phase categories

→ the *Predicted Particle Property* (P3) approach

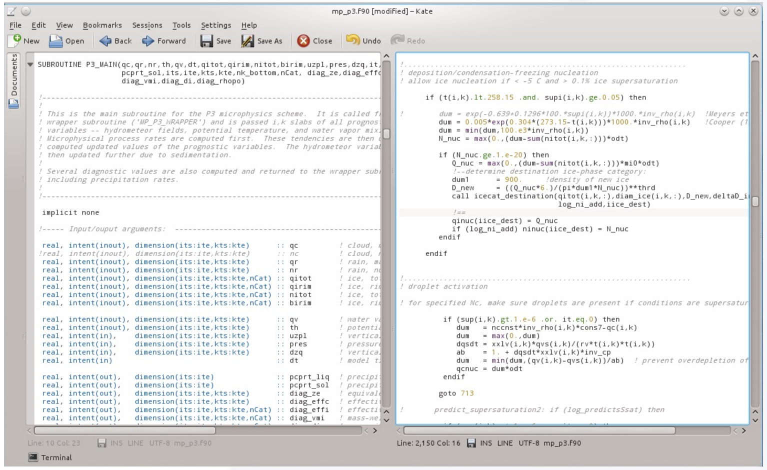
THE P3 SCHEME: Development



The back of the envelop
(ICCP 2012 stationary)



The drawing board
(Hugh's office, August 2013)



```
SUBROUTINE P3_MAIN(qc,qr,nr,th,qv,dt,qitot,qirim,nitot,birim,uzpl,pres,dzq,it,
                   pcprt_sol,its,ite,kts,kte,nk_bottom,nCat, diag_ze,diag_effc
                   diag_vmi,diag_di,diag_rhopo)

!----------------------------------------------------------------------------
!
! This is the main subroutine for the P3 microphysics scheme.  It is called fr
! wrapper subroutine ('MP_P3_WRAPPER') and is passed i,k slabs of all prognost
! variables -- hydrometeor fields, potential temperature, and water vapor mixi
! Microphysical process rates are computed first.  These tendencies are then c
! computed updated values of the prognostic variables.  The hydrometeor variab
! then updated further due to sedimentation.
!
! Several diagnostic values are also computed and returned to the wrapper subr
! including precipitation rates.
!
!----------------------------------------------------------------------------

 implicit none

!----- Input/ouput arguments:  ---------------------------------------------

 real, intent(inout), dimension(its:ite,kts:kte)      :: qc        ! cloud, m
!real, intent(inout), dimension(its:ite,kts:kte)      :: nc        ! cloud, n
 real, intent(inout), dimension(its:ite,kts:kte)      :: qr        ! rain, ma
 real, intent(inout), dimension(its:ite,kts:kte)      :: nr        ! rain, nu
 real, intent(inout), dimension(its:ite,kts:kte,nCat) :: qitot     ! ice, tot
 real, intent(inout), dimension(its:ite,kts:kte,nCat) :: qirim     ! ice, rim
 real, intent(inout), dimension(its:ite,kts:kte,nCat) :: nitot     ! ice, tot
 real, intent(inout), dimension(its:ite,kts:kte,nCat) :: birim     ! ice, rim

 real, intent(inout), dimension(its:ite,kts:kte)      :: qv        ! water va
 real, intent(inout), dimension(its:ite,kts:kte)      :: th        ! potentia
 real, intent(in),    dimension(its:ite,kts:kte)      :: uzpl      ! vertical
 real, intent(in),    dimension(its:ite,kts:kte)      :: pres      ! pressure
 real, intent(in),    dimension(its:ite,kts:kte)      :: dzq       ! vertical
 real, intent(in)                                     :: dt        ! model ti

 real, intent(out),   dimension(its:ite)              :: pcprt_liq ! precipi
 real, intent(out),   dimension(its:ite)              :: pcprt_sol ! precipi
 real, intent(out),   dimension(its:ite,kts:kte)      :: diag_ze   ! equivale
 real, intent(out),   dimension(its:ite,kts:kte)      :: diag_effc ! effecti
 real, intent(out),   dimension(its:ite,kts:kte,nCat) :: diag_effi ! effecti
 real, intent(out),   dimension(its:ite,kts:kte,nCat) :: diag_vmi  ! mass-we
```

```
!.....................................................................
! deposition/condensation-freezing nucleation
! allow ice nucleation if < -5 C and > 0.1% ice supersaturation

     if (t(i,k).lt.258.15 .and. supi(i,k).ge.0.05) then

!          dum = exp(-0.639+0.1296*100.*supi(i,k))*1000.*inv_rho(i,k)  !Meyers et
        dum = 0.005*exp(0.304*(273.15-t(i,k)))*1000.*inv_rho(i,k)   !Cooper (1
        dum = min(dum,100.e3*inv_rho(i,k))
        N_nuc = max(0.,(dum-sum(nitot(i,k,:)))*odt)

        if (N_nuc.ge.1.e-20) then
           Q_nuc = max(0.,(dum-sum(nitot(i,k,:)))*mi0*odt)
           !--determine destination ice-phase category:
           dum1      = 900.     !density of new ice
           D_new     = ((Q_nuc*6.)/(pi*dum1*N_nuc))**thrd
           call icecat_destination(qitot(i,k,:),diam_ice(i,k,:),D_new,deltaD_i
                                   log_ni_add,iice_dest)
           !==
           qinuc(iice_dest) = Q_nuc
           if (log_ni_add) ninuc(iice_dest) = N_nuc
        endif

     endif


!.....................................................................
! droplet activation

! for specified Nc, make sure droplets are present if conditions are supersatur

         if (sup(i,k).gt.1.e-6 .or. it.eq.0) then
            dum   = nccnst*inv_rho(i,k)*cons7-qc(i,k)
            dum   = max(0.,dum)
            dqsdt = xxlv(i,k)*qvs(i,k)/(rv*t(i,k)*t(i,k))
            ab    = 1. + dqsdt*xxlv(i,k)*inv_cp
            dum   = min(dum,(qv(i,k)-qvs(i,k))/ab)  ! prevent overdepletion of
            qcnuc = dum*odt
         endif

        goto 713

!       predict_supersaturation2: if (log_predictsSsat) then
```

The original code

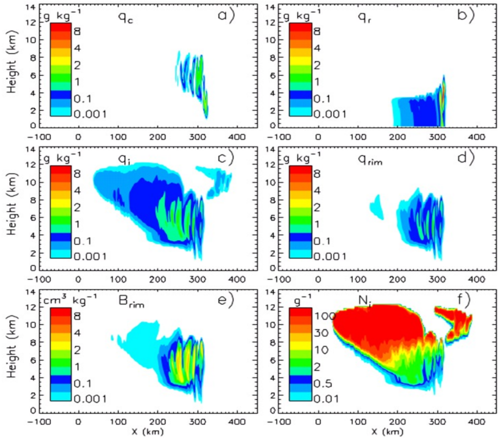
P3 was co-developed by Hugh Morrison (NCAR) and Jason Milbrandt (ECCC)

NCAR

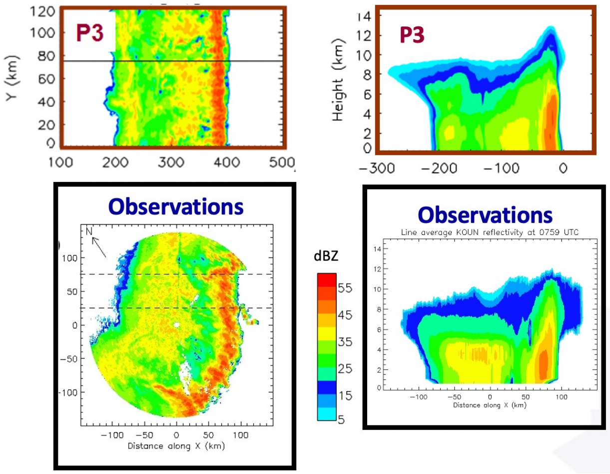
Environment and Climate Change Canada

Morrison and Milbrandt (2015), *JAS*
Milbrandt and Morrison (2016), *JAS*

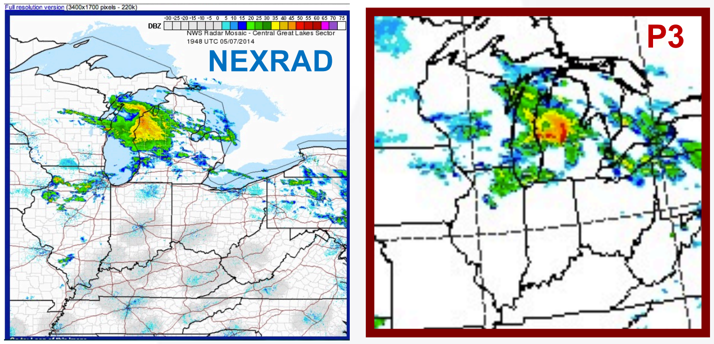
THE P3 SCHEME: Initial tests



Idealized WRF 2D squall line



Semi-idealized WRF 3D squall line



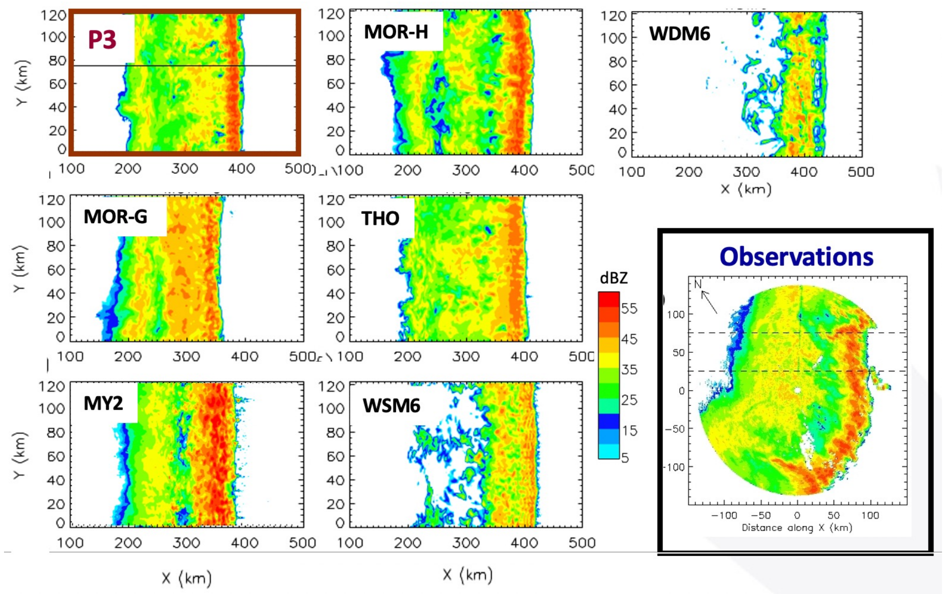
Real-time tests

Morrison and Milbrandt (2015), *JAS*

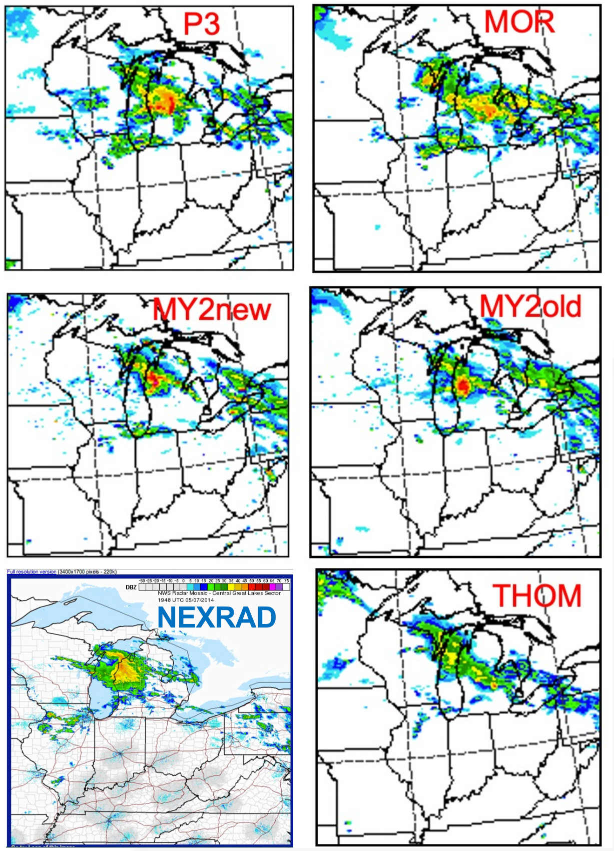
Morrison et al. (2015), *JAS*

Oklahoma University CAPS Ensemble,
HWT 2014 Spring Experiment

THE P3 SCHEME: Comparison to existing (traditional) schemes



Semi-idealized WRF 3D squall line



Real-time tests

Morrison et al. (2015), *JAS*

Oklahoma University CAPS Ensemble,
HWT 2014 Spring Experiment

OVERVIEW OF P3: Prognostic (advected) variables

LIQUID PHASE: 2 categories, 2-moment:

Q_c – cloud mass mixing ratio [kg kg^{-1}]

Q_r – rain mass mixing ratio [kg kg^{-1}]

OPTIONAL: N_c – cloud number mixing ratio [#kg^{-1}]

N_r – rain number mixing ratio [#kg^{-1}]

ICE PHASE: OPTIONAL: *nCat* categories, 4-6 prognostic variables each:

$Q_{dep}(n)^*$ – deposition ice mass mixing ratio [kg kg^{-1}]

$Q_{rim}(n)$ – rime ice mass mixing ratio [kg kg^{-1}]

OPTIONAL: $Q_{liq}(n)$ – liquid portion of total ice mixing ratio [kg kg^{-1}]

$N_{tot}(n)$ – total ice number mixing ratio [# kg^{-1}]

$B_{rim}(n)$ – rime ice volume mixing ratio [m^3 kg^{-1}]

OPTIONAL: $Z_{tot}(n)$ – reflectivity mixing ratio [m^6 kg^{-1}]

OPTIONAL: Subgrid-scale cloud fraction (diagnostic)

[*] $Q_{tot} = Q_{dep} + Q_{rim}$, total ice mass mixing ratio (actual advected variable)

OVERVIEW OF P3: Prognostic variables → Predicted physical properties

A given free category can represent most types of ice-phase hydrometeors

Prognostic Variables:

$\boldsymbol{Q_{dep}}$ – deposition ice mass mixing ratio [kg kg^{-1}]

$\boldsymbol{Q_{rim}}$ – rime ice mass mixing ratio [kg kg^{-1}]

$\boldsymbol{Q_{liq}}$ – liquid mass mixing ratio [kg kg^{-1}]

$\boldsymbol{N_{tot}}$ – total ice number mixing ratio [# kg^{-1}]

$\boldsymbol{B_{rim}}$ – rime ice volume mixing ratio [m^{3} kg^{-1}]

$\boldsymbol{Z_{tot}}$ – reflectivity mixing ratio [m^{6} kg^{-1}]

Predicted Properties:

$\boldsymbol{F_{rim}}$ – rime mass fraction, $F_{rim} = Q_{rim} / (Q_{rim} + Q_{dep})$ [--]

$\boldsymbol{\rho_{rim}}$ – rime density, $\rho_{rim} = Q_{rim} / B_{rim}$ [kg m^{-3}]

$\boldsymbol{D_m}$ – mean-mass diameter, $D_m \propto Q_{tot} / N_{tot}$ [m]

$\boldsymbol{V_m}$ – mass-weighted fall speed, $V_m = f(D_m, \rho_{rim}, F_{rim})$ [m s^{-1}]

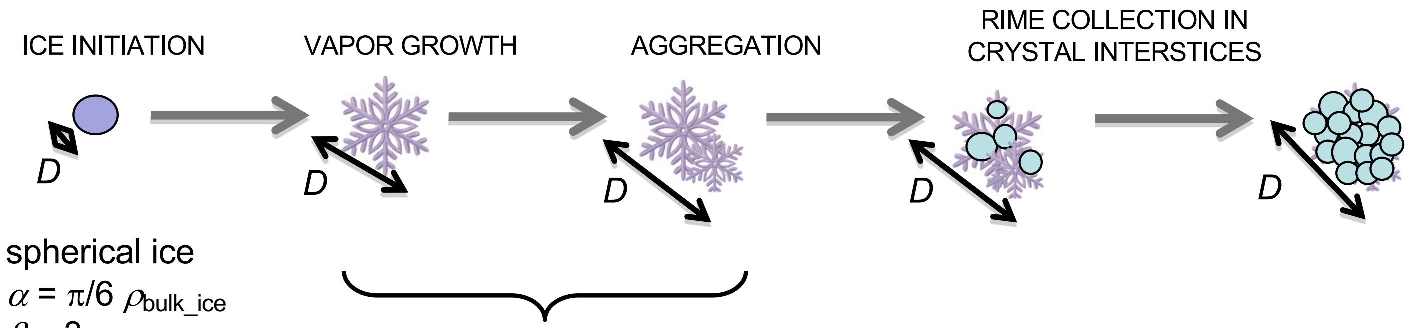
etc.

Diagnostic Particle Types:

Based on the predicted properties (rather than pre-defined)

OVERVIEW OF P3: Conceptual model of ice particle growth

Particle properties (e.g *m*-*D* relations*) for process rate calculations are based on conceptual model of particle growth following Heymsfield (1982)



spherical ice
$\alpha = \pi/6\ \rho_{bulk\_ice}$
$\beta = 3$

unrimed crystals
α = const
$\beta \sim 2$

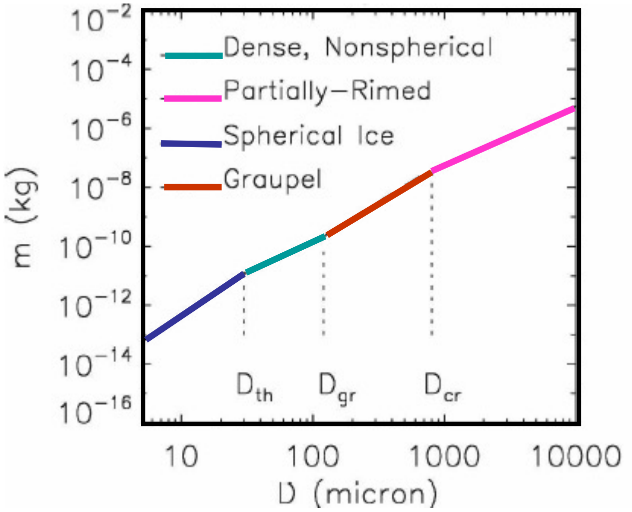
partially rimed crystal
$\alpha = f(F_{rim}, \rho_{rim})$
$\beta \sim 2$

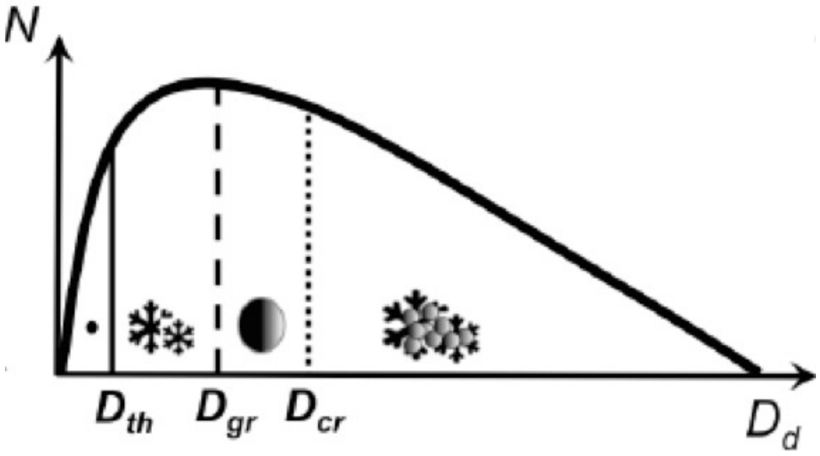
spherical graupel
$\alpha = \pi/6\ \rho_{grpl}$
$\beta = 3$

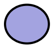
* mass-diameter relation:
$m(D) = \alpha D^{\beta}$

OVERVIEW OF P3: *m-D* relations and gamma size distributions

General: **1 > F_{rim} > 0; for a given ρ_{rim}**

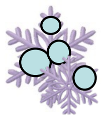




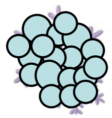


spherical
unrimed
$m(D) = \alpha_1 D^{\beta 1}$

non-spherical
unrimed
$m(D) = \alpha_2 D^{\beta 2}$



non-spherical,
partially rimed
$m(D) = \alpha_3 D^{\beta 3}$



spherical
completely rimed
$m(D) = \alpha_4 D^{\beta 4}$

m-D figure from Morrison and Grabowski (2008)

PSD figure c/o M. Cholette

OVERVIEW OF P3: Process rates (and other quantities)

Computing process rates ~ computing $M_x^{(p)}$

$$Q^+ = Q^0 + \underbrace{\Delta Q\big|_{PROC\_1}} + \Delta Q\big|_{PROC\_2} + \ldots$$

$$\Delta Q\big|_{PROC\_1} = \Delta t \cdot \frac{1}{\rho} \underbrace{\int_0^\infty \frac{dm(D)}{dt}\Big|_{PROC\_1} N(D)dD}_{\propto X_1 \quad \text{(and } X_2\text{, …)}}$$

$$X_1 = \int_0^{D_{th}} D^a N_0 e^{-\lambda D} f(\alpha_1, \beta_1, \ldots) dD + \int_{D_{th}}^{D_{gr}} D^b N_0 e^{-\lambda D} f(\alpha_2, \beta_2, \ldots) dD$$

$$+ \int_{D_{gr}}^{D_{cr}} D^c N_0 e^{-\lambda D} f(\alpha_3, \beta_3, \ldots) dD + \int_{D_{cr}}^{\infty} D^d N_0 e^{-\lambda D} f(\alpha_4, \beta_4, \ldots) dD$$

- Relevant sums of sub-moments are pre-computed (accurately) and stored in a look-up tables
- At run time, values of X_1, X_2,.. are accessed (quickly) via look-up table → actual computation of $\Delta Q|_{PROC\_x}$ is fast

OVERVIEW OF P3: Illustration of predicted properties (and implicit particle types)

●

$F_r \sim$ 0-0.1
$\rho \sim$ 900 kg m^{-3}
$V \sim$ 0.3 m s^{-1}
$D_m \sim$ 100 µm
→ ***small crystals***

◆

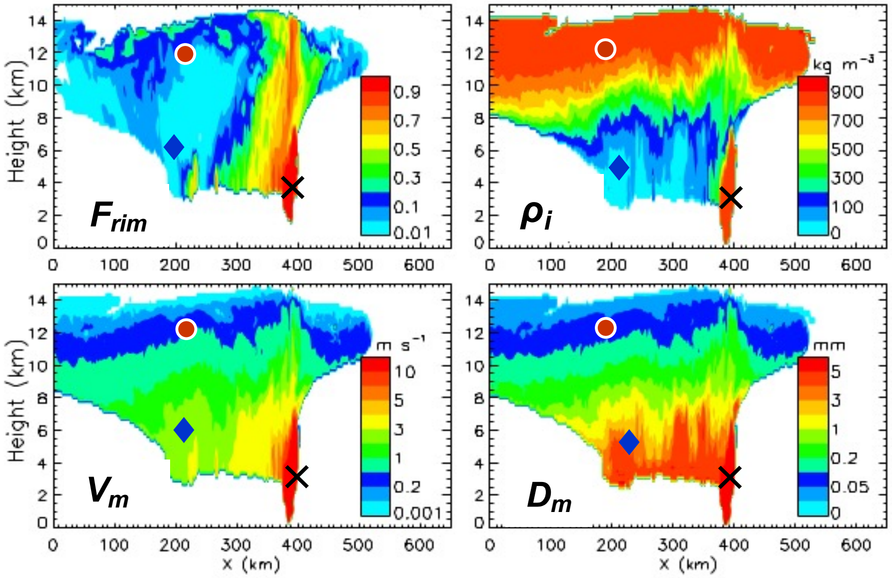
$F_r \sim 0$
$\rho \sim$ 50 kg m^{-3}
$V \sim$ 1 m s^{-1}
$D_m \sim$ 5 mm
→ ***aggregates***

×

$F_r \sim 1$
$\rho \sim$ 900 kg m^{-3}
$V >$ 10 m s^{-1}
$D_m >$ 5 mm
→ ***hail***

etc.

Bulk physical properties:

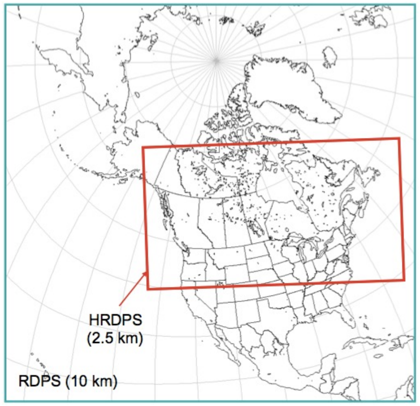


Vertical cross section of model fields

Note – *only* *<u>one</u>* *(free) ice-phase category*

OPERATIONAL APPLICATION : Use in a 2.5-km NWP system

High Resolution Deterministic Prediction System (HRDPS*)



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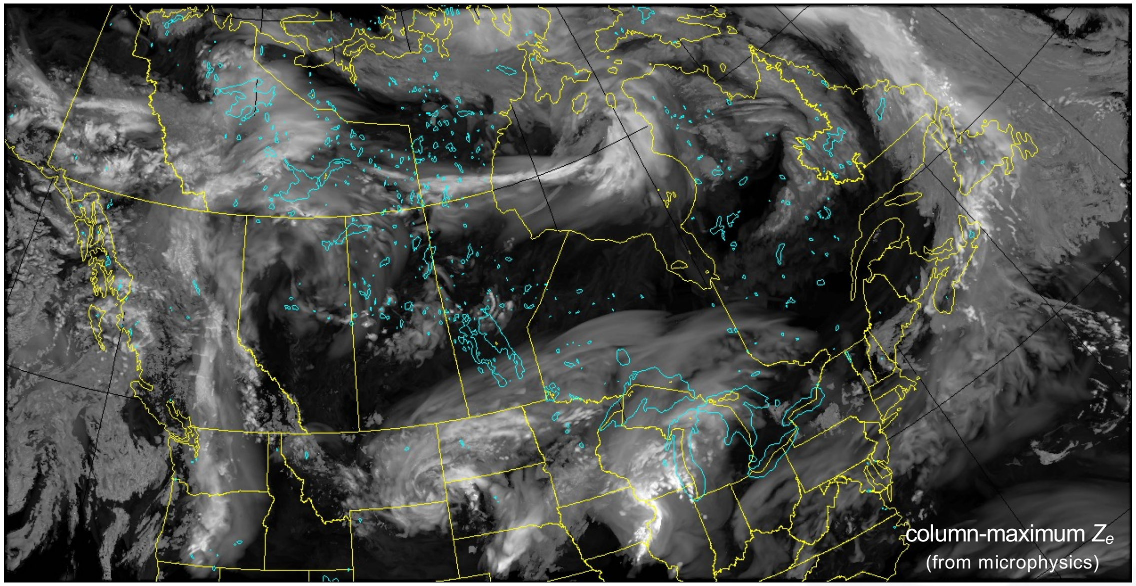

- experimental pan-Canadian 2.5-km NWP system set up in 2014 (with MY2 microphysics)
- became officially “operational” in spring 2018 (*MY2 replaced by P3*)
- soon to have 3D data assimilation (including radar data, via LHN)
- to become the primary source of short-term numerical guidance at ECCC

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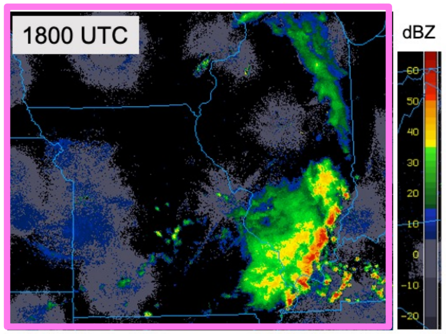
* Milbrandt et al. (2016), *WAF*

OPERATIONAL APPLICATION : Use in a 2.5-km NWP system

NEXRAD obs:

Z, 1-km CAPPI

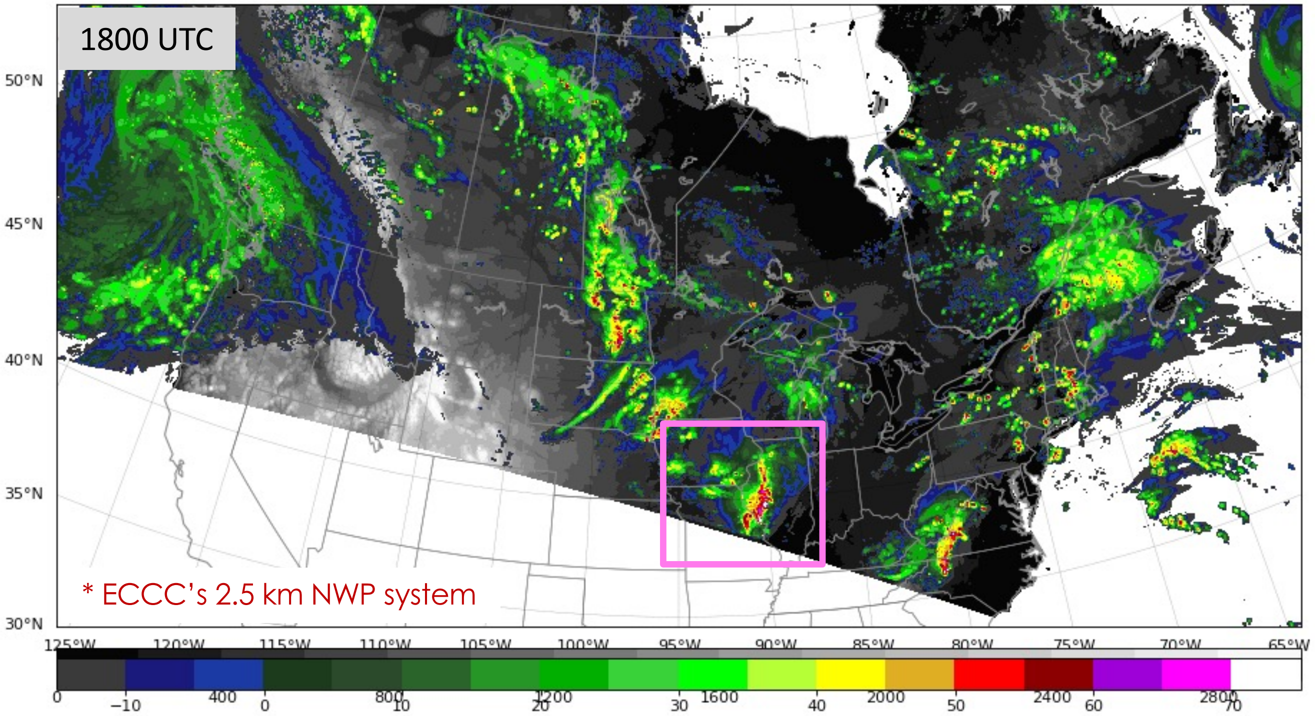


HRDPS

3-moment P3 (v4.0.2)

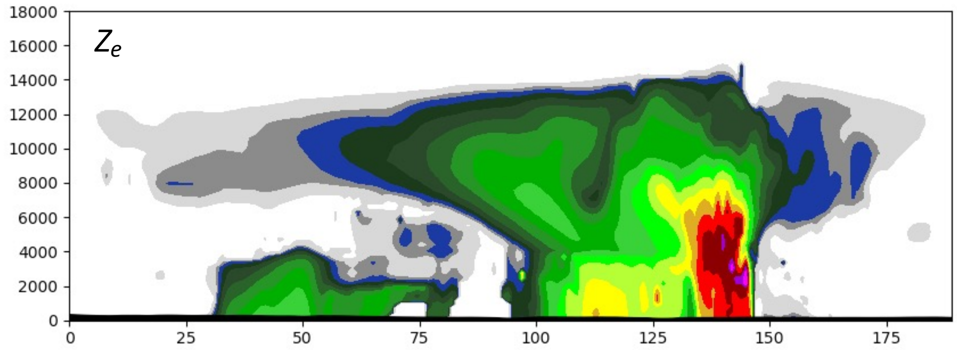
Z_e (column-max)

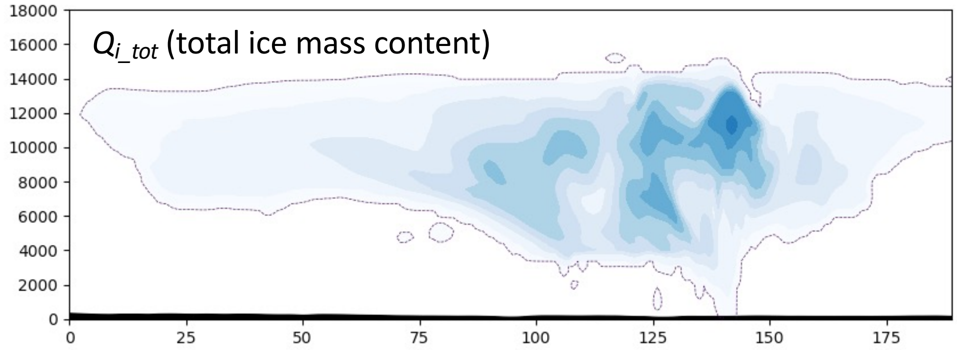
18-h fcst

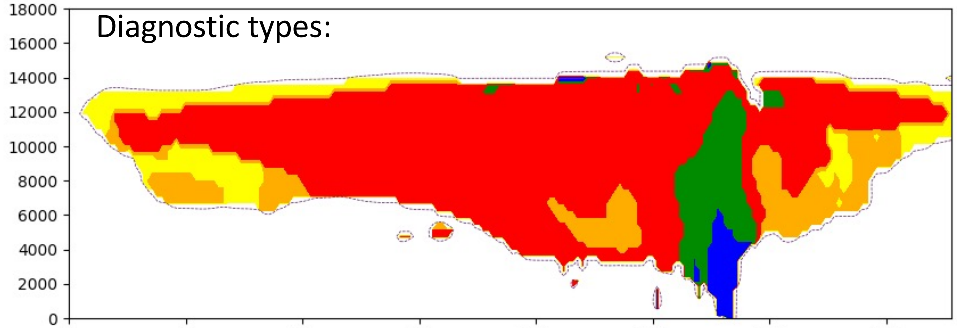


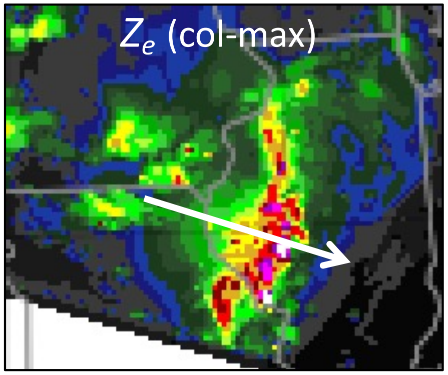
* ECCC's 2.5 km NWP system

OPERATIONAL APPLICATION : Use in a 2.5-km NWP system





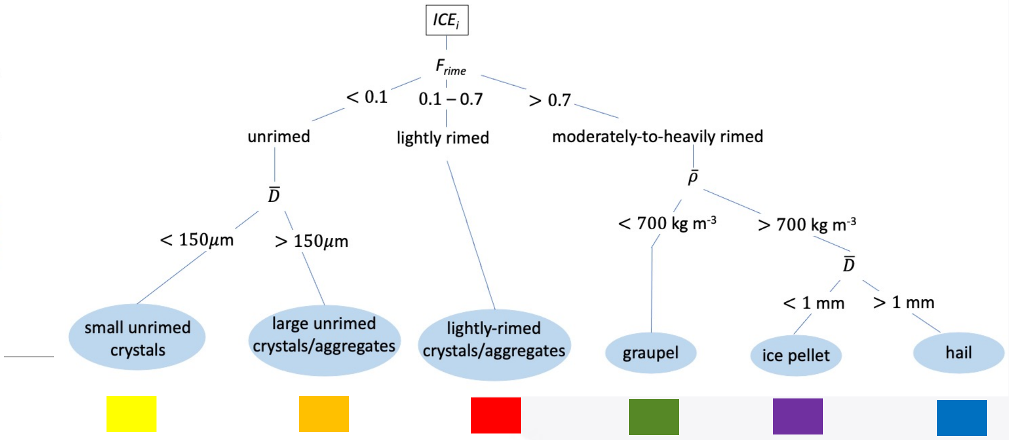




GEM (HRDPS, 2.5 km) simulation using P3

- 1 ice category
- no liquid fraction (missing bright band)
- 3-moment ice

Diagnostic Particle Types: (per category)

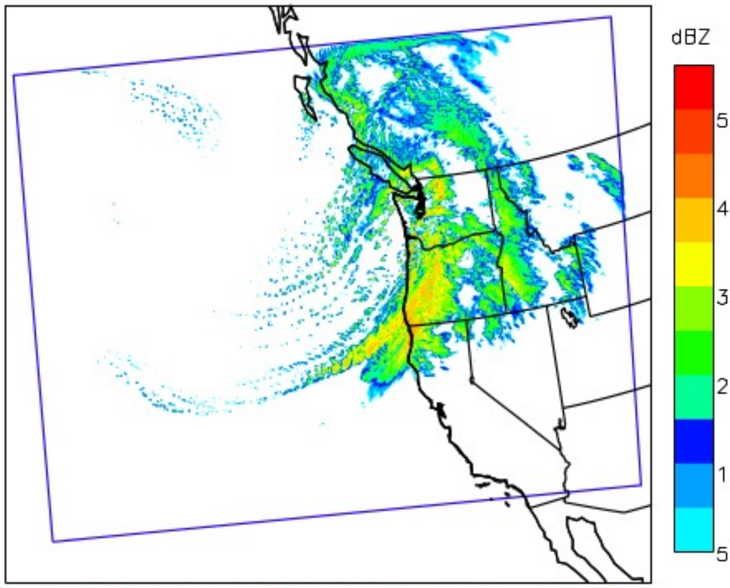


EFFECTS OF P3: Precipitation shifts in mountainous regions

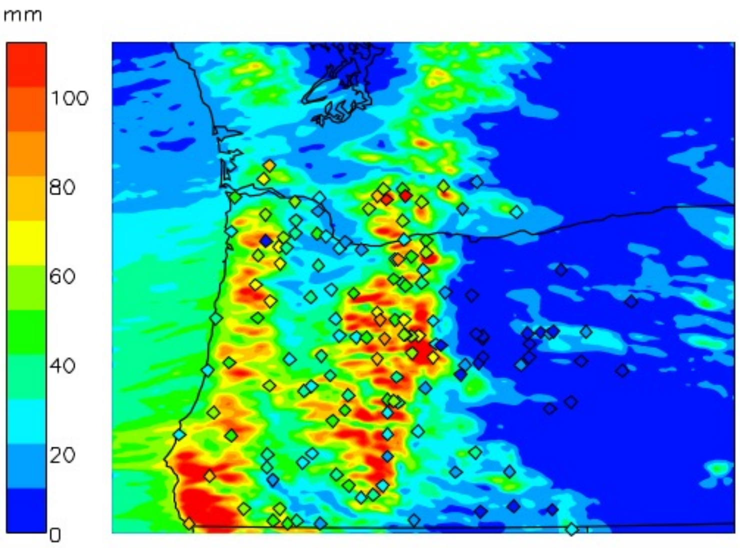
Frontal/orographic case:

IMPROVE-2, 13-14 December 2001

- WRF_v3.4.1, ∆x = 3 km, 72 stretched vertical levels



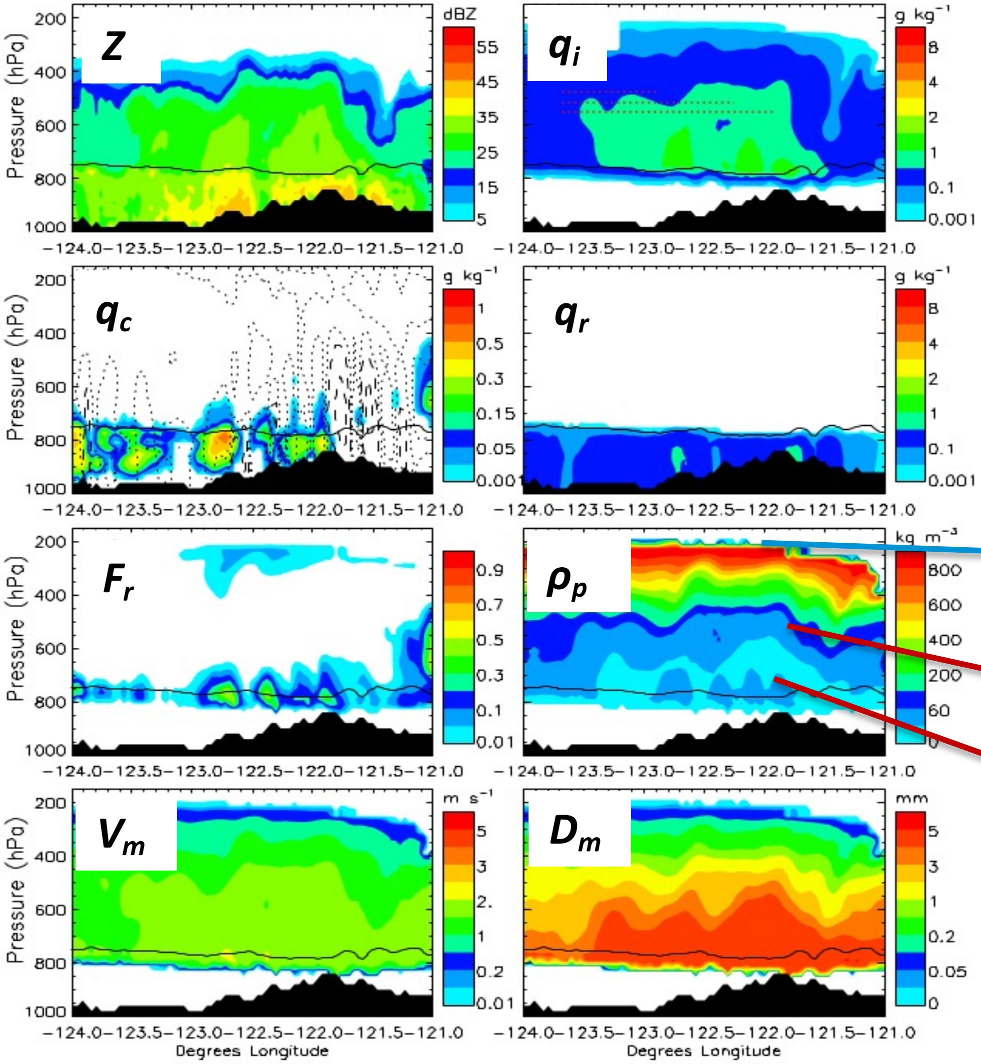
Simulated lowest level radar reflectivity at 00 UTC December 14

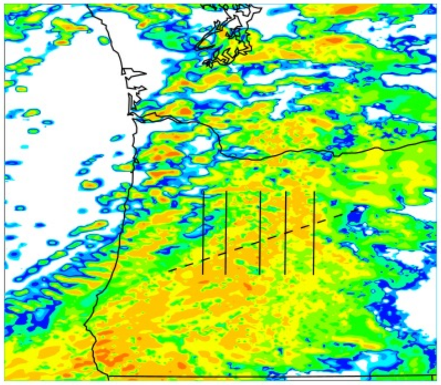


Accumulated surface precip from 14 UTC December 13 to 08 UTC December 14

Morrison et al. (2015), *JAS*

EFFECTS OF P3: Precipitation shifts in mountainous regions





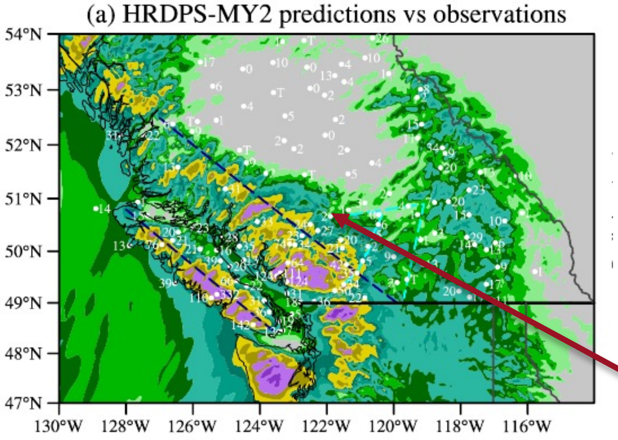
Small, dense ice

Low-density, unrimed snow

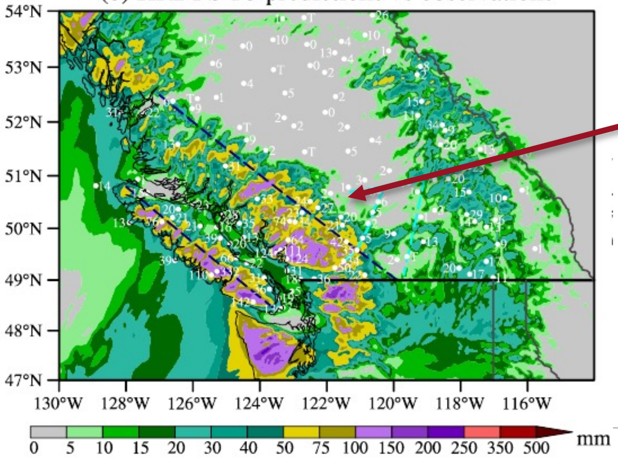
Low-density graupel

Morrison et al. (2015), *JAS*

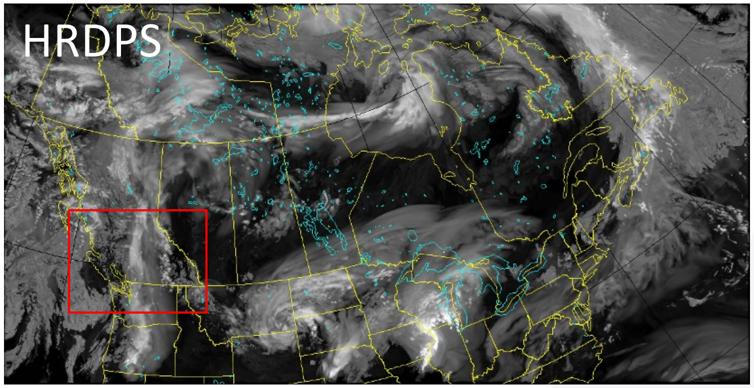
OPERATIONAL APPLICATION: Precipitation shifts in mountainous regions



(a) HRDPS-MY2 predictions vs observations



(b) HRDPS-P3 predictions vs observations



MY2: over-prediction on lee side of mountains

(due to excess hydrometeor drift in MY2)

P3: reduced (improved) precipitation on lee side

(due to increased fall speed of lightly-rimed snow)

Note: This difference is largely anecdotal (from ECCC forecasters in Vancouver), but systematic

Mo et al. (2018), *MWR*

MAJOR DEVELOPMENTS:

ARTICLE	DEVELOPMENT
Morrison and Milbrandt (2015), *JAS*	Description of original P3 scheme
Morrison et al. (2015), JAS	*Comparison to traditional schemes in WRF*
Milbrandt and Morrison (2016), *JAS*	Multi-ice category version
Cholette et al. (2019), *JAS*	Prognostic liquid fraction on ice version
Paukert et al. (2019), *JAMES*	Triple-moment rain version*
Jouan et al. (2020), *WAF*	Subgrid cloud fraction version
Milbrandt et al. (2021), *JAS*	Triple-moment ice version

→ We have been actively developing P3 to be a versatile microphysics scheme, usable in a wide range of meteorological conditions and spatial scales (i.e. towards unified physics)

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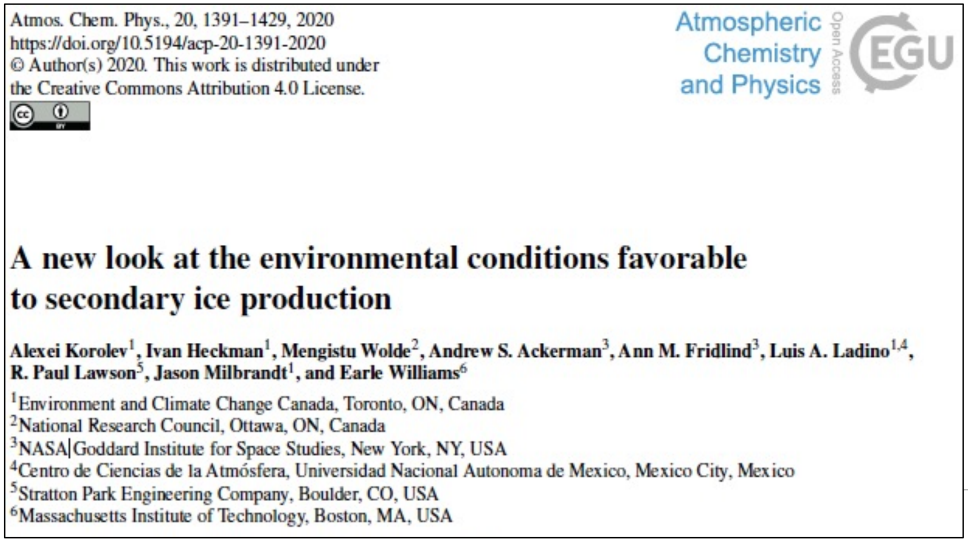
* Not yet merged with "official" P3

MAJOR DEVELOPMENTS: Multiple free ice-phase categories

Application:

Secondary ice production (SIP)



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Atmospheric Chemistry and Physics

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EGU

A new look at the environmental conditions favorable to secondary ice production

Alexei Korolev[1], Ivan Heckman[1], Mengistu Wolde[2], Andrew S. Ackerman[3], Ann M. Fridlind[3], Luis A. Ladino[1,4], R. Paul Lawson[5], Jason Milbrandt[1], and Earle Williams[6]

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[2]National Research Council, Ottawa, ON, Canada
[3]NASA Goddard Institute for Space Studies, New York, NY, USA
[4]Centro de Ciencias de la Atmósfera, Universidad Nacional Autonoma de Mexico, Mexico City, Mexico
[5]Stratton Park Engineering Company, Boulder, CO, USA
[6]Massachusetts Institute of Technology, Boston, MA, USA

DEVELOPMENT

- Multi-ice category version

Prognostic liquid fraction on ice version

Triple-moment rain version

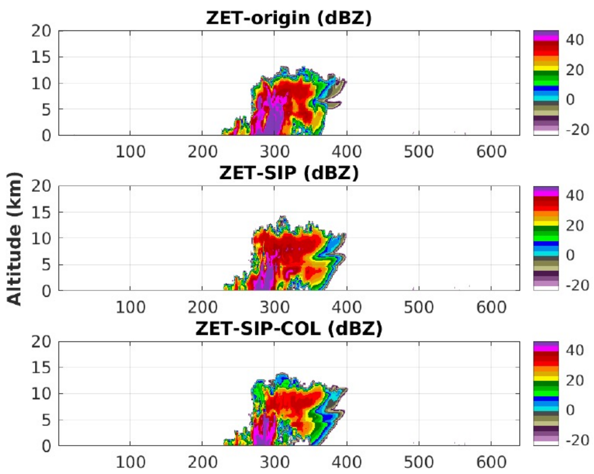
Subgrid cloud fraction version

Triple-moment ice version

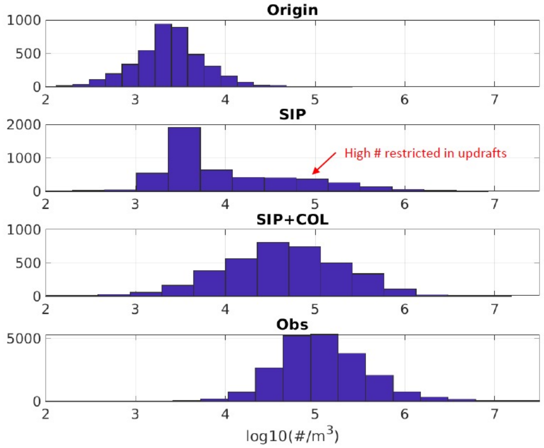
MAJOR DEVELOPMENTS: Multiple free ice-phase categories

HIWC Case simulation using GEM (*dx* = 250 m; *nCat* = 4)

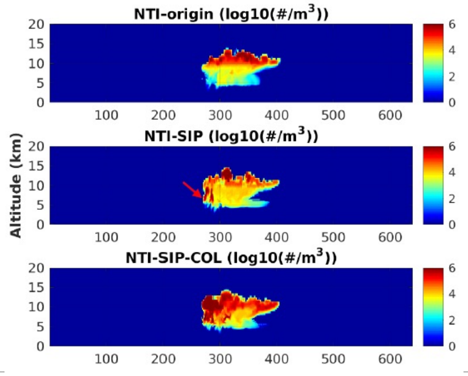
GEM (60 min)



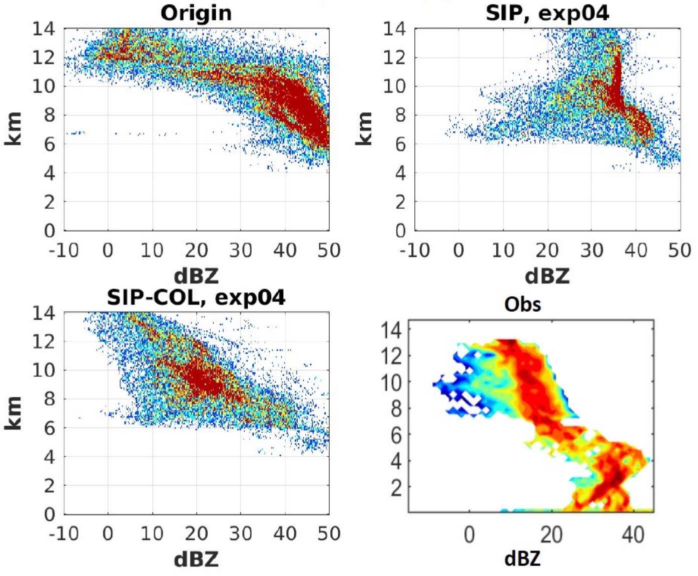
Distribution of ice number concentration (alt =~6 km)



GEM (60 min)



45 min (Uz > 5.0 m/s)



Model-obs comparison points based on common dynamics, not co-location

Observations: data of 6 flights during the Cayenne campaign in May, 2015.

c/o Zhipeng Qu, ECCC

MAJOR DEVELOPMENTS: Triple-moment ice

Application:

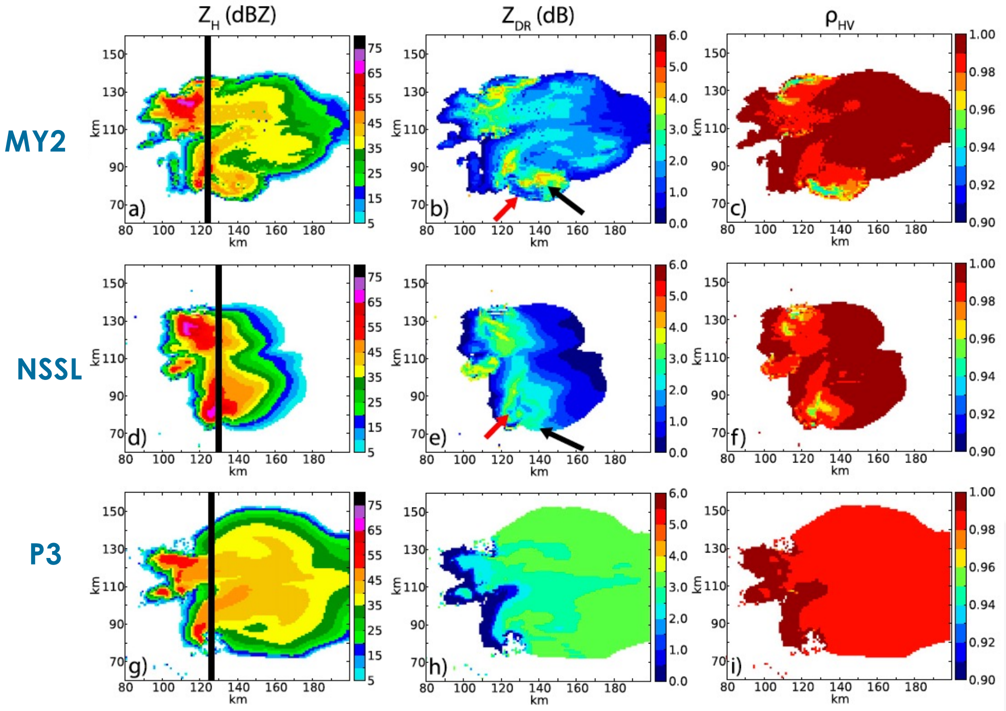
Hail

DEVELOPMENT

- Multi-ice category version
- Prognostic liquid fraction on ice version
- Triple-moment rain version
- Subgrid cloud fraction version
- Triple-moment ice version

MAJOR DEVELOPMENTS: Triple-moment ice

MOTIVATION: *P3 lacks radar signatures for hail* (e.g. Z_{DR} arc)



<u>Idealized 1-km supercell simulations</u>

- 3 different multi-moment microphysics schemes
- dual-pol radar simulator applied

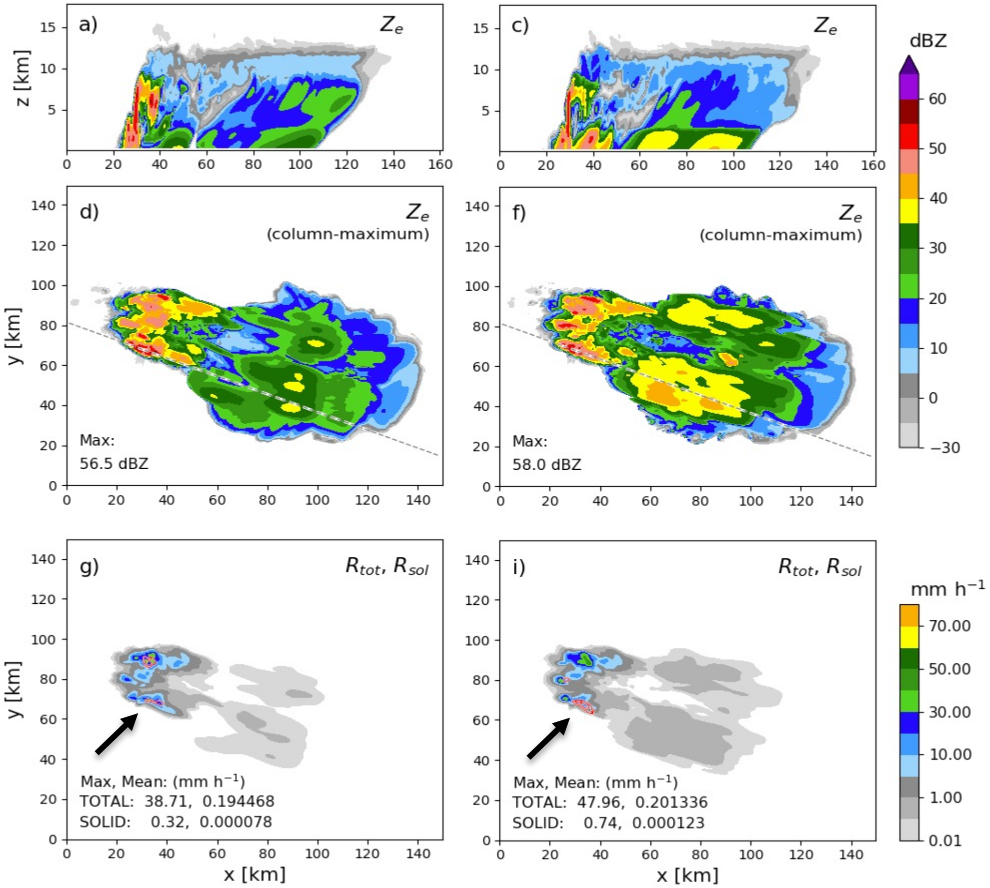
Johnson et al. (2019), *MWR*

MAJOR DEVELOPMENTS: Triple-moment ice

Idealized 250-m WRF simulations of a hail-producing supercell:

2-moment
strict max. D_{mean}

3-moment
no max. D_{mean}



Milbrandt et al. (2021), *JAS*

MAJOR DEVELOPMENTS: Representation of mixed-phase precipitation

Application:

Mixed-phase precipitation

DEVELOPMENT

Multi-ice category version

● Prognostic liquid fraction on ice version

Triple-moment rain version

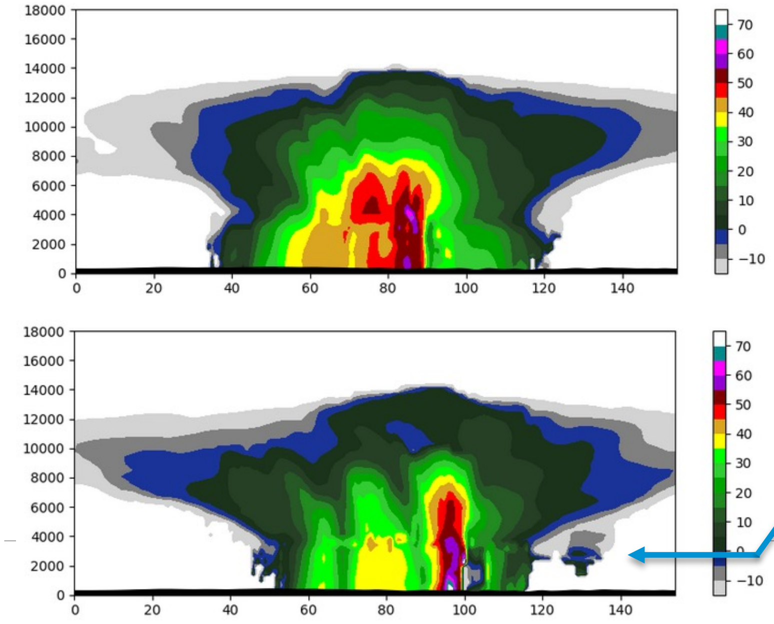
Subgrid cloud fraction version

Triple-moment ice version

MAJOR DEVELOPMENTS: Representation of mixed-phase precipitation

Application:

Mixed-phase precipitation



DEVELOPMENT

Multi-ice category version

● Prognostic liquid fraction on ice version

Triple-moment rain version

Subgrid cloud fraction version

Triple-moment ice version

Improved bright band due to more realistic simulation of mixed-phase particles and processes (melting, re-freezing, etc.)

2.5-km GEM simulation

c/o Melissa Cholette, ECCC

MAJOR DEVELOPMENTS: Sub-grid cloud (and precipitation) fraction

Application:

Large-scale (coarse-res) models

DEVELOPMENT

Multi-ice category version

Prognostic liquid fraction on ice version

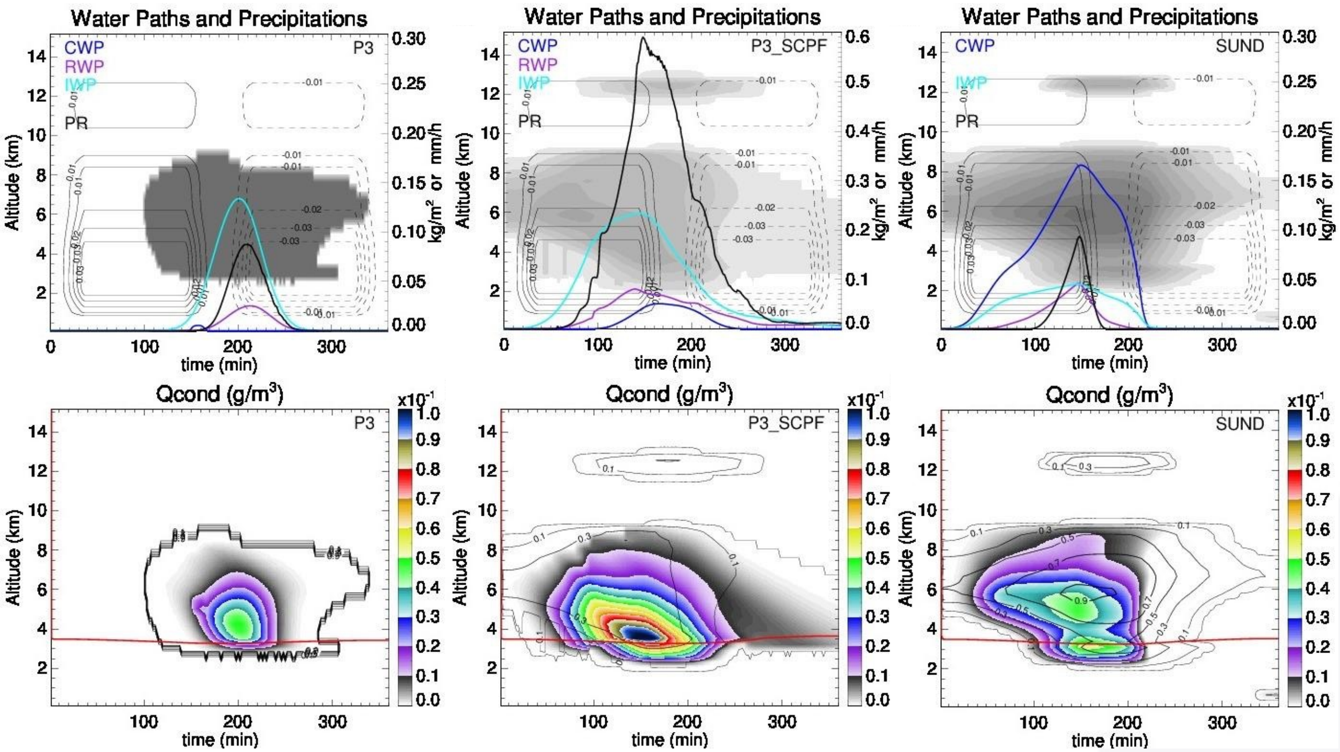
Triple-moment rain version

- Subgrid cloud fraction version

Triple-moment ice version

MAJOR DEVELOPMENTS: Sub-grid cloud (and precipitation) fraction

P3 **P3 + SCF** **Sundqvist**

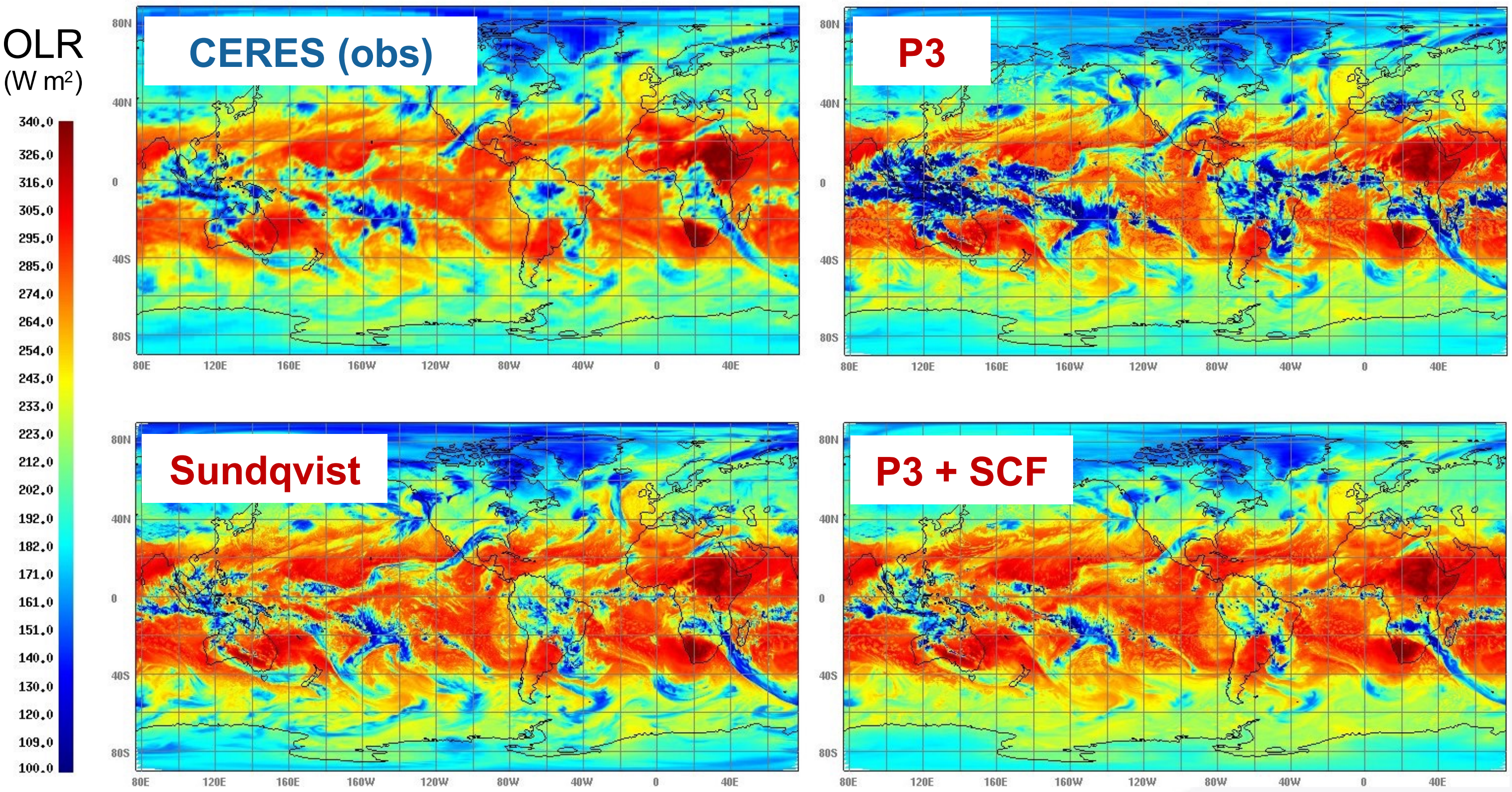


1D kinematic model simulations

Jouan et al. (2020), *WAF*

MAJOR DEVELOPMENTS: Sub-grid cloud (and precipitation) fraction

OLR (TOA) from global (25 km) GEM simulations:



Jouan et al. (2020), *WAF*

MAJOR DEVELOPMENTS:

Application:

- Secondary ice production (SIP)
- Hail
- Mixed-phase (winter) precipitation
- Large-scale (coarse-res) models

etc.

DEVELOPMENT

Multi-ice category version

Prognostic liquid fraction on ice version

Triple-moment rain version

Subgrid cloud fraction version

Triple-moment ice version

Examination of the impacts of the recent developments to P3 on various applications (with emphasis on high-impact weather in NWP) is on-going

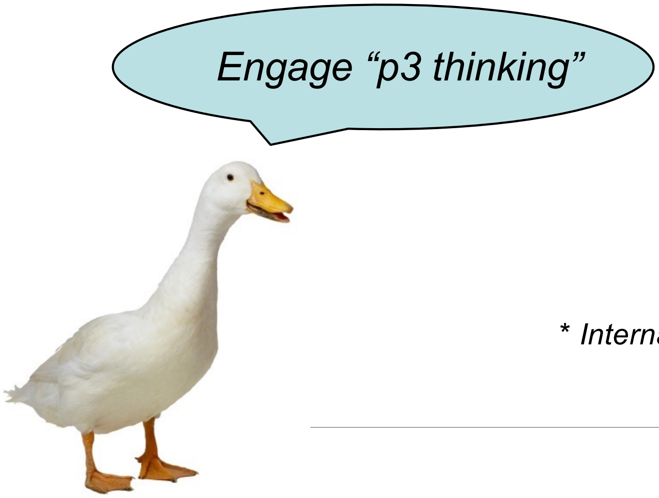
IMPACTS of the P3 development

IMPACTS of the P3 development

- We convinced the cloud modeling community to shift paradigms

BULLET POINT FROM *ICMW 2016* CONCLUSIONS: *

> "In order to advance the parameterization of ice-phase microphysics (in bulk and bin schemes), the modeling community should move towards the paradigm of free ice-phase categories."



* *International Cloud Modeling Workshop 2016* (Exeter, UK);
Reported at *ICCP 2016* (Manchester, UK)

IMPACTS of the P3 development

- We convinced the cloud modeling community to shift paradigms
- P3 has been implemented into 9 atmospheric models

  (2 LES, 2 CRMs, 3 mesoscale models, 2 GCMs)
- Main tool for several PhD and postdoctoral research projects

IMPACTS of the P3 development

- We convinced the cloud modeling community to shift paradigms
- P3 has been implemented into 8 atmospheric models
  (1 LES, 2 CRMs, 3 mesoscale models, 2 GCMs)
- Main tool for several PhD and postdoctoral research projects
- 449 references* to our first 3 (main) papers (276 to Part 1)
- *Morrison and Milbrandt (2015)* won NCAR Publication Award for *2018 Paper of the Year***

---

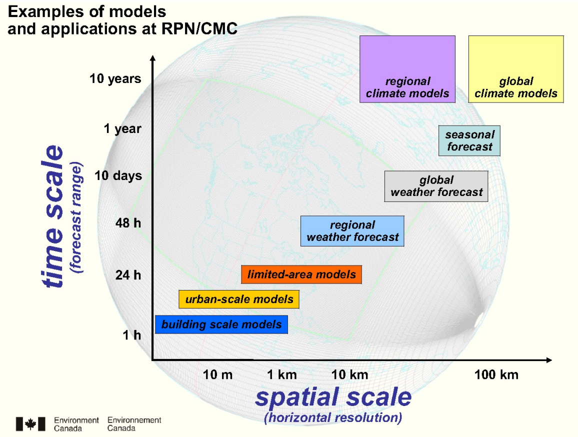
* source: Google Scholar, 8 June 2021

** chosen out of ~2000 papers published in previous 5 years

IMPACTS of the P3 development

- We convinced the cloud modeling community to shift paradigms
- P3 has been implemented into 8 atmospheric models

  (1 LES, 2 CRMs, 3 mesoscale models, 2 GCMs)
- Main tool for several PhD and postdoctoral research projects
- 449 references to our first 3 (main) papers (276 to Part 1)
- *Morrison and Milbrandt (2015)* won NCAR Publication Award for *2018 Paper of the Year*
- Used operationally in ECCC; currently being adapted and tested for use in all GEM-based NWP systems (from 250 m to global ensemble)



COMPUTATIONAL COST: Speed of main P3 code (excluding advection)

Timing Tests for 3D WRF Simulations

Scheme	**Squall line case** (Δx = 1 km)	**Orographic case** (Δx = 3 km)	**# prognostic variables**
P3	0.436 (**1.043**)	0.686 (**1.013**)	**7**
MY2	0.621 (1.485)	1.012 (1.495)	12
MOR-H	0.503 (1.203)	0.813 (1.200)	9
THO	0.477 (1.141)	0.795 (1.174)	7
WSM6	0.418 (**1.000**)	0.677 (**1.000**)	**5**
WDM6	0.489 (1.170)	0.777 (1.148)	8

Average wall clock time per model time step (units of seconds.)
Times relative to those of WSM6 are indicated parenthetically.

→ the P3 scheme itself (excluding cost of advection) is relatively efficient

Morrison et al. (2015), *JAS*

COMPUTATIONAL COST: Advection of prognostic microphysical fields

Regular advection:

Each variable is advected independently

Approximate cost (increase in total integration time):

- Eulerian scheme (WRF): + 3-5% per variable
- semi-Lagrangian scheme (GEM, UM): + 1.5-2.5% per variable

Scaled Flux Vector Transport*

- “Lead” variable (e.g *Qx*) is advected normally
- Advection of “slave” variables (e.g. *Nx*) is computed from appropriately scaled fluxes of lead variable

→ *only a very small cost for the advection of slave variables*

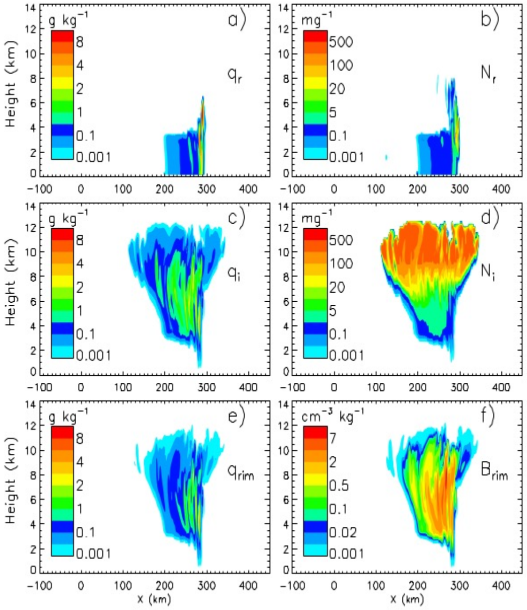
---

* Morrison et al. (2016), MWR

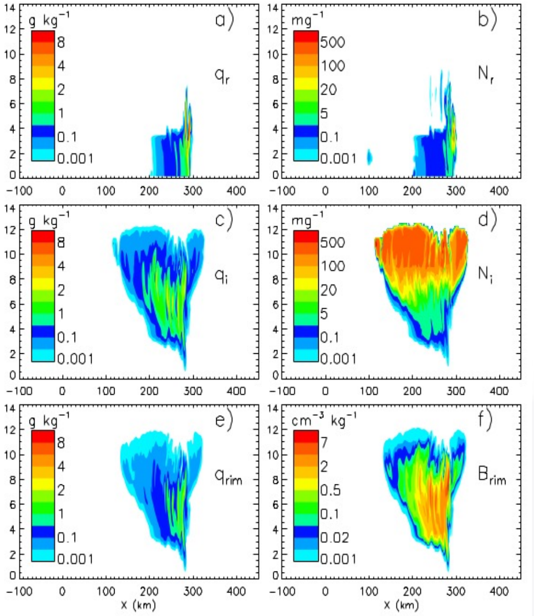
Advection of Prognostic Hydrometeor Variables

2D WRF simulations (w/ P3, nCat =1)

w/ 5th order PD



w/ SFVT*



Nearly identical results; but

11% reduction in <u>total</u> integration time

* Morrison et al. (2016), MWR

COMPUTATIONAL COST: Outlook with consideration of SFVT

Qc

Qr

Qi_tot

NWP

1-ice category

Qc Nc
Qr Nr Zr
Qi_dep
Qi_rim
Qi_liq
Ni
Bi
Zi

11 variables

w/ SFVT:

3 leads

8 slaves

Research

2 (or 3) ice categories

Qc Nc
Qr Nr Zr
Qi_dep(1) Qi_dep(2) Qi_dep(3)
Qi_rim(1) Qi_rim(2) Qi_rim(3)
Qi_liq(1) Qi_liq(2) Qi_liq(3)
Ni(1) Ni(2) Ni(3)
Bi(1) Bi(2) Bi(3)
Zi(1) Zi(2) Zi(3)

17 (23) variables

w/ SFVT:

4 (5) leads

13 (18) slaves

MOST of the COST

Qi_tot = Qi_dep + Qi_rim + Qi_liq

---

also, N_a (aerosol number concentration) [future development]

Concluding comments

- The property-based approach to parameterize ice-phase microphysics in bulk schemes is a conceptual and practical step forward from the traditional category-based approach
- P3 (specifically) has been shown to be versatile for use in a wide range of meteorological conditions and in a wide range of atmospheric models (from LES to GCM)
- Due to current scientific gaps in understanding of natural cloud microphysics, P3 suffers from the same limitations and approximations (AKA guesses) as all schemes – further research in fundamental cloud physics is still required