A MAJOR UPGRADE TO ATMOSPHERIC PHYSICS PARAMETERIZATION IN GEM

UQAM Seminar – 29 January 2020

Atmospheric Physics Development Team (RPN-A, CMDN)

Environment and Climate Change Canada
Environnement et Changement climatique Canada

Canada

Outline

- General challenges of the project:
  - Increased vertical resolution
  - Conservation across physical parameterizations
- New perspectives on convection parameterization:
  - A Lagrangian view of deep convection
  - A low-CAPE convection scheme
- Surface and near-surface processes:
  - Diurnal SST variability
  - Precipitation phase and land surface interactions
- Analyzing the scope of changes
- Recent results from updated NWP systems

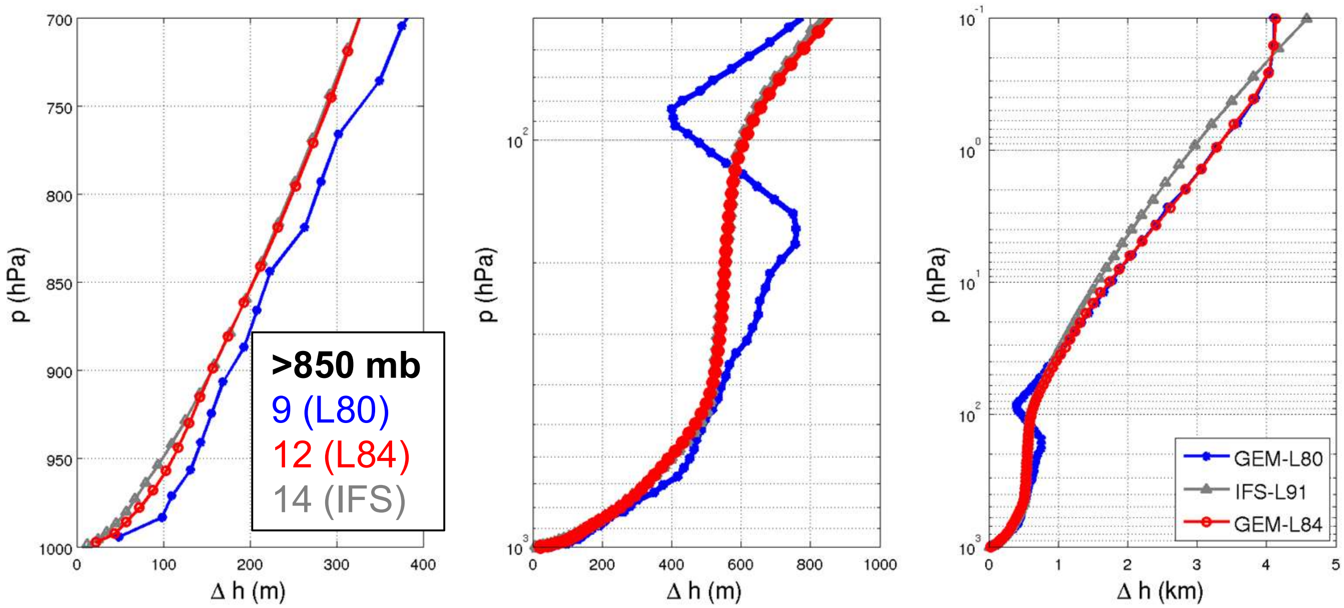
Background

- The Clouds and Precipitation Project was a 5-year effort in the Numerical Prediction Research Section (RPN-A) to modernize parameterizations of atmospheric physics for NWP:
  - Improve the representation of the global energy cycle
  - Increase the vertical resolution of the model
- During the project, 5/7 of the major atmospheric schemes were either replaced or heavily modified, and two new schemes were added
- Three major systems adopted the new parameterization suite on 3 July 2019:
  - Global Deterministic Prediction System (GDPS; 15 km)
  - Regional Deterministic Prediction System (RDPS; 10 km)
  - Regional Ensemble Prediction System (REPS; 10 km x 20)

Objective 1: Vertical Resolution (L84)

- All other major centres have lowered their bottom model levels to 5-10 m, although this change is known to take 1-2 years of dedicated effort to yield generally neutral scores

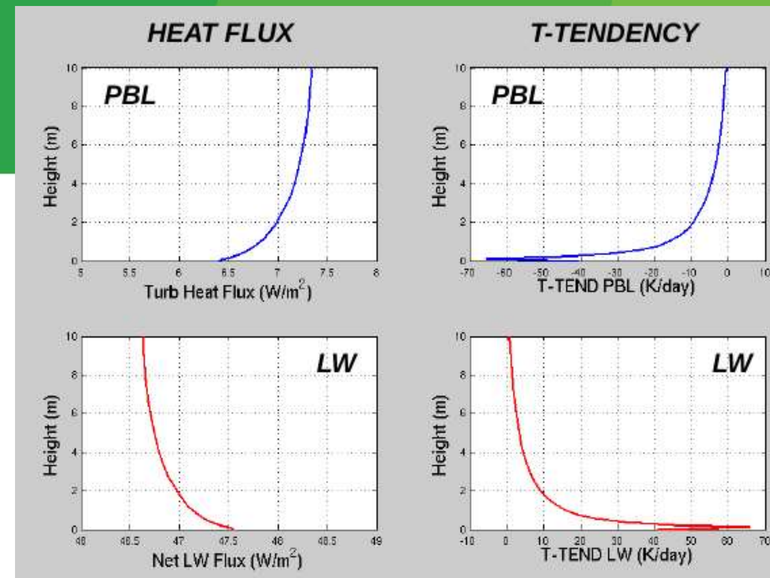
- An L84 grid with the lowest thermodynamic level at 10m replaces the operational L80 (40m) configuration

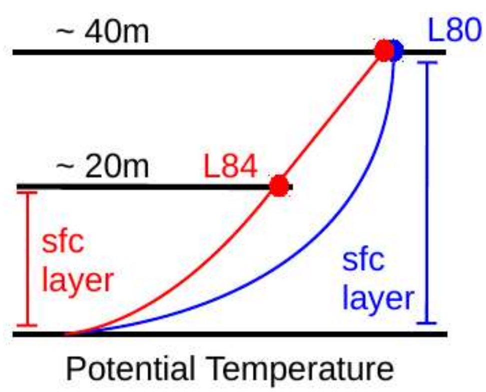


Position of levels in the operational L80 configuration (blue), the C&P L84 configuration (red), and from a recent version of the ECMWF IFS (grey) for reference. Levels are shown for the PBL (left), the troposphere (middle) and the full column (right).

Vertical Sensitivity

- Removed unphysical sensitivity to resolution and lowest-level height
  - Physical heights used instead of specific (usually NK) levels
  - Use smooth transitions or means in the vertical instead of threshold values
  - Use cubic interpolating polynomials for vertical interpolation and integration
  - Advection uses physics-computed winds at the lowest thermodynamic level
- However, some sensitivity remains:
  - Sharp vertical gradients (can be amplified by thin clouds)
  - Replacement of turbulence-parameter-ized surface layer (SL) with a prognostic SL with many sources (now within the range of stability function estimates)





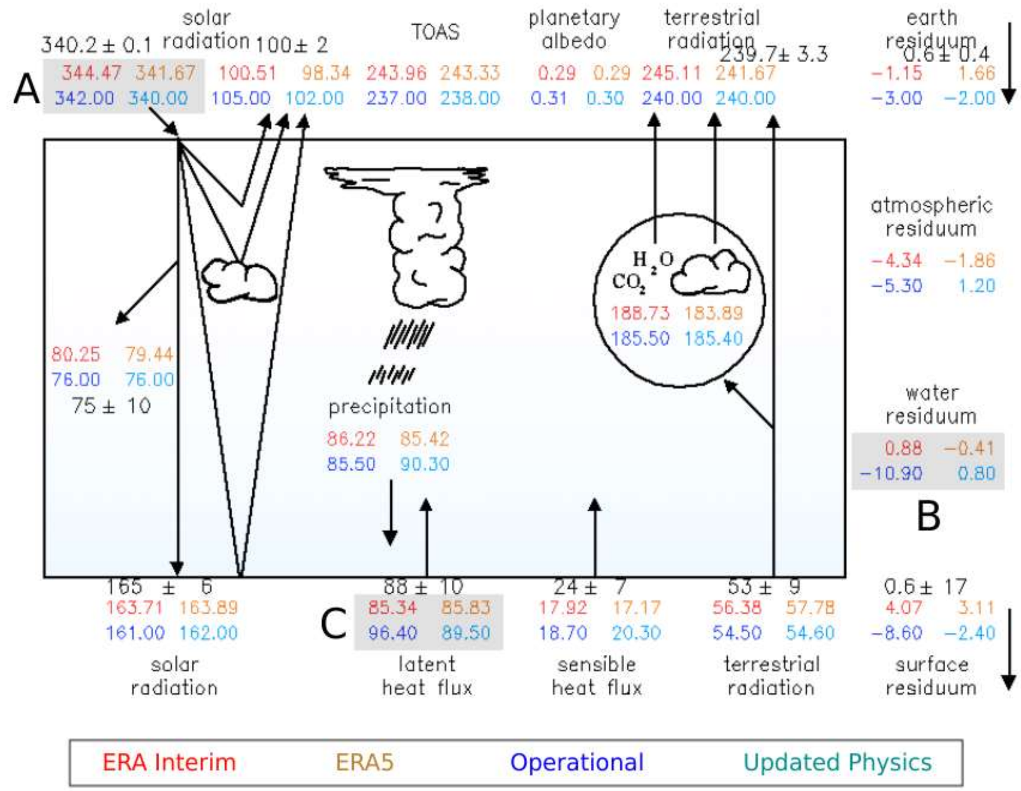
***Top**: Profiles of heat fluxes (left column) and temperature tendencies for turbulence (top) and radiation (bottom) for the lowest 10 m of the atmosphere for a very high vertical resolution SCM integration (5 cm). **Bottom**: Schematic of differences between a semi-resolved an parameterized 40 m surface layer.*

Objective 2: Global Energy Budget

Excessive precipitation should be related to large heating in clouds.

However, significant non-conservation:

- Makes budget-based physical reasoning impossible
- Makes model sensitivities unpredictable



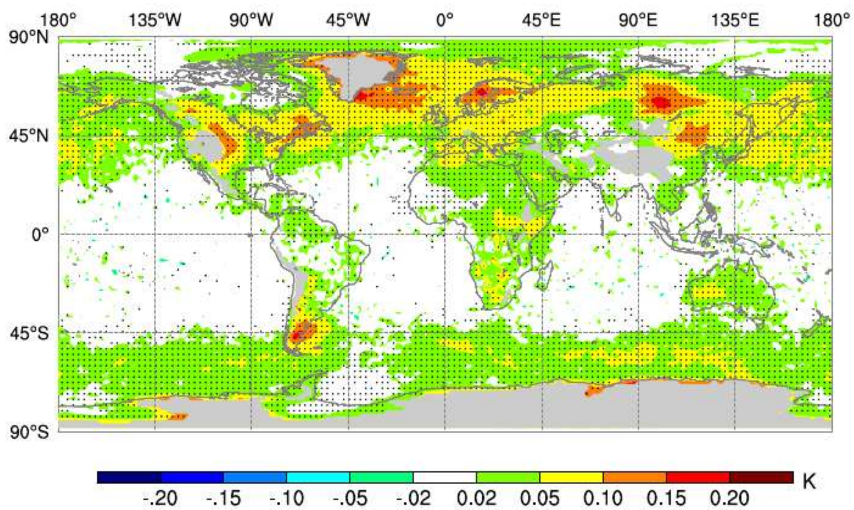
Energy budget components from 1-year MHEEP integrations using the existing (blue) and Phase-II (cyan) physics configurations compared with reanalyses.

A Conservative Approach

A scheme-by-scheme evaluation of conservation is undertaken:

Liquid water static energy: $E = c_{pm}T - L_v(T)q_c - L_s(T)q_i$

Total water: $q_t = q_v + q_c + q_i$



Internal conservation properties were improved (numerics), with a post-scheme correction applied to ensure conservation of E and q_t in each scheme individually.

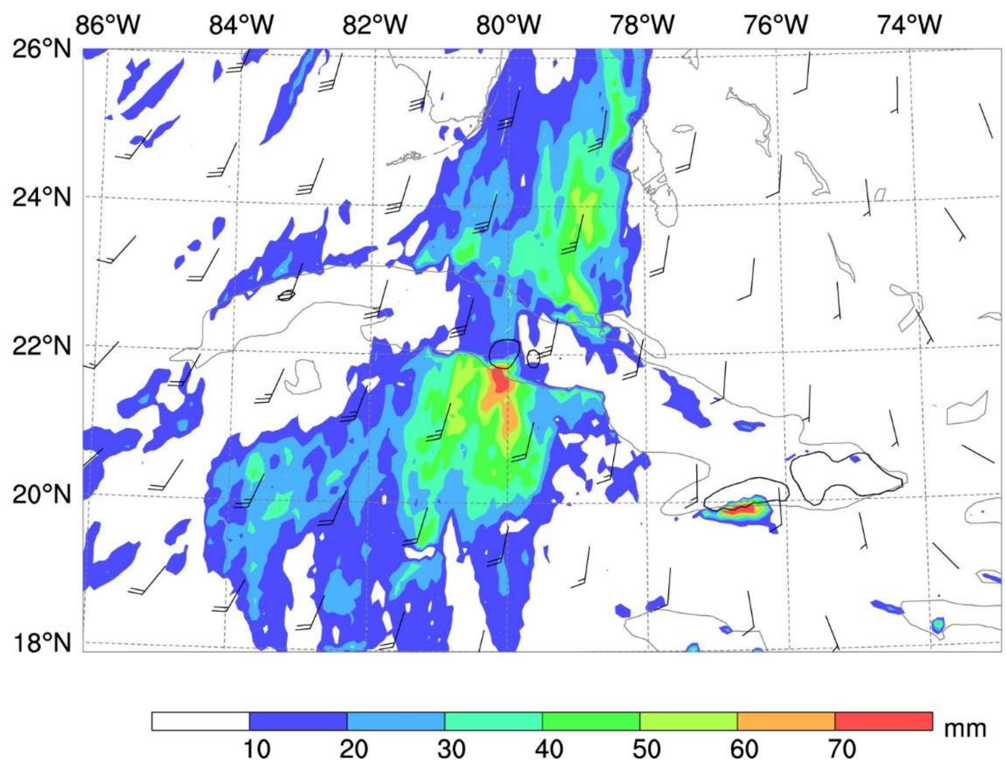
Impact of total energy conservation (dissipative heating) in the boundary layer scheme on 850 hPa temperatures after 24h of forecast time in a sequence of 44 DJF cases in the GDPS. Significant differences (Wilks 2016) are stippled.

Major Project Objectives

- Changes to the physics that fulfilled the basic project objectives were extensive:
  - Complete refactoring of PBL and SGO (sub-grid orography) schemes
  - Introduction of higher-order interpolants
  - Numerous corrections to numerical problems
- Much of the development was done in simplified models on tropical ocean domains to improve tropical profiles, turbulent fluxes, cloud cover and precipitation
- Model climate was improved, but NWP scores in the first series of integrations: not so much …

Convective Precipitation Structure

- Unphysical rainfall gradients were noted at coastlines
- The initiation of deep convection is largely controlled by a “trigger velocity” (w_{klcl}) that represents dry thermal updrafts
- In all systems, w_{klcl} different over land and water
- This is more notable in C&P configurations where wklcl over the ocean depends on w* and can be much smaller



Convective precipitation accumulated over 24h in a recent “best” configuration of the RDPS initialized at 1200 UTC 27 May 2018.

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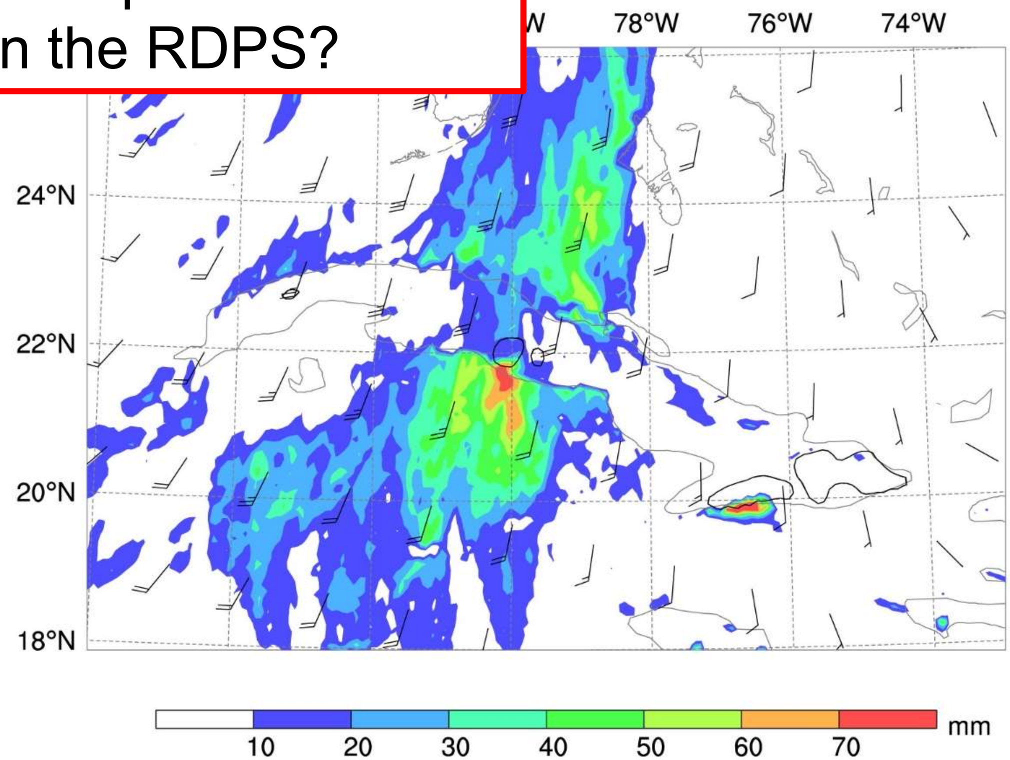
What is going wrong with our treatment of deep convective clouds in the RDPS?



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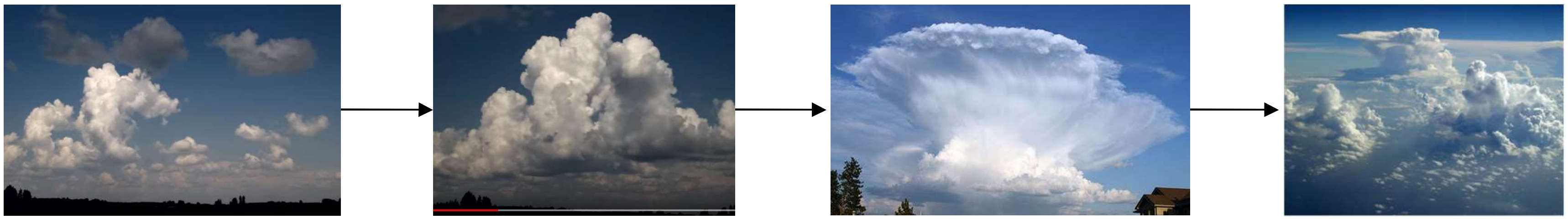
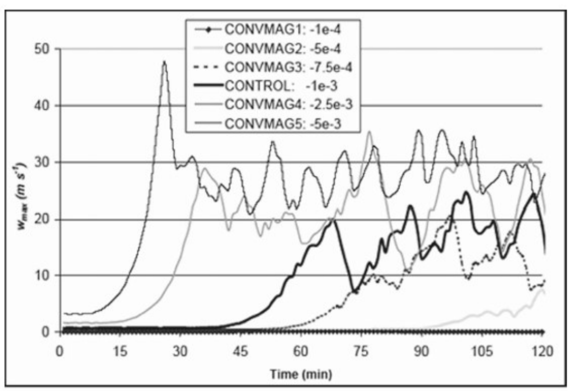
What are we Really Talking About?



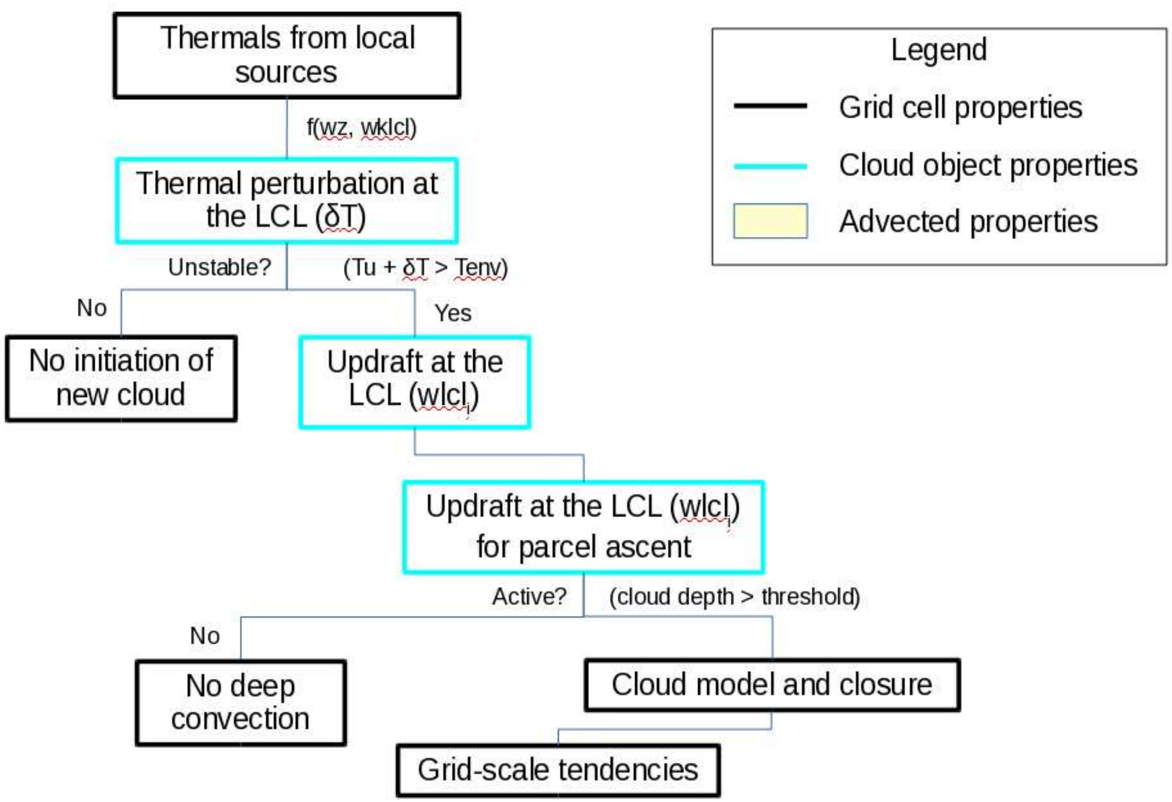
- In the (convection parameterization scheme) CPS, clouds are initiated, grow and mature on a time-scale that is similar to that of the model (~30-60 min at low Δx)
- Approaching the convective “greyzone” (~10 km), profiles within a grid cell can evolve as rapidly as cloud updrafts

Time series of simulated maximum updraft velocities for idealized storms initialized with different perturbation amplitudes (Loftus et al. 2008).



- Initiating thermals and convective clouds need to be able to evolve and move
- This Lagrangian view is more consistent with reality

Current Approach in the CPS

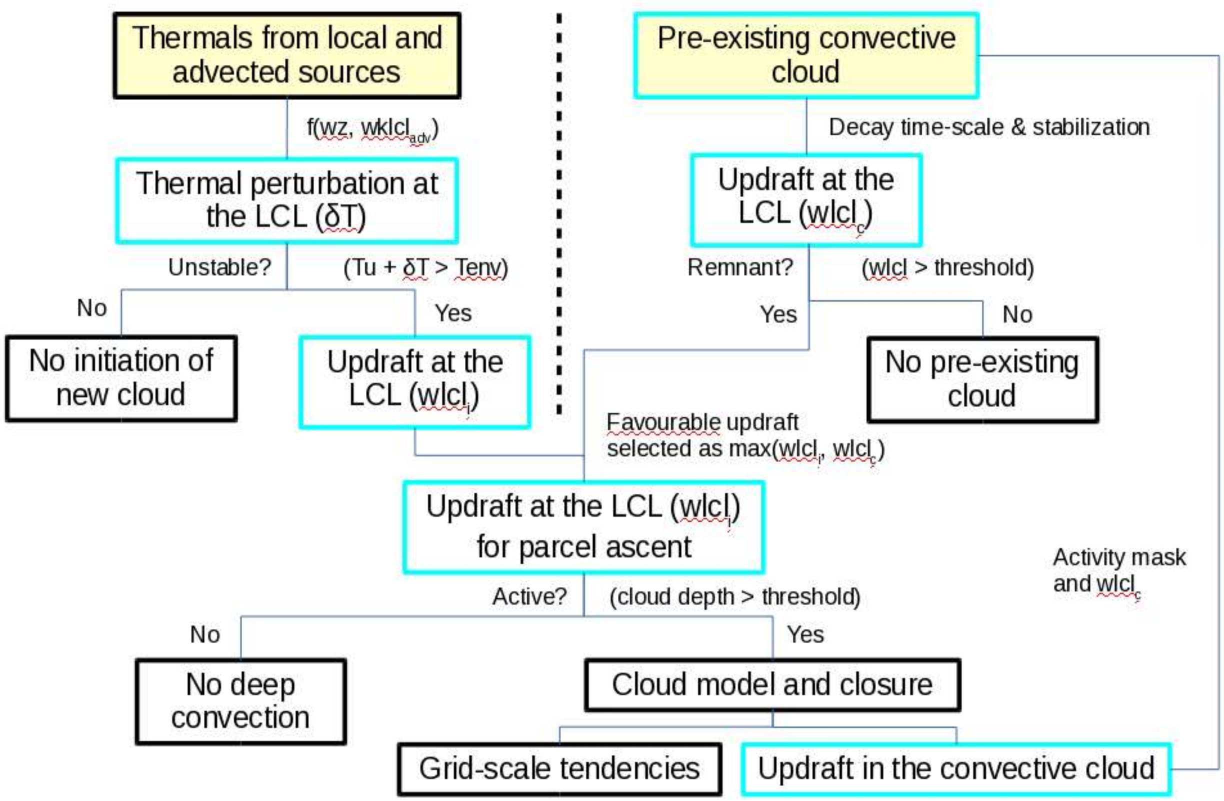


Schematic of a typical deep mass-flux based CPS, with particular focus on the convective trigger.

In an existing CPS with realistic rapid refreshing (step), convection must be continuously retriggered by dry thermals.

Removal of CAPE by the closure will stabilize the profile sufficiently to shut off convection early leading to on-off behaviour.

A Lagrangian Perspective on Convection



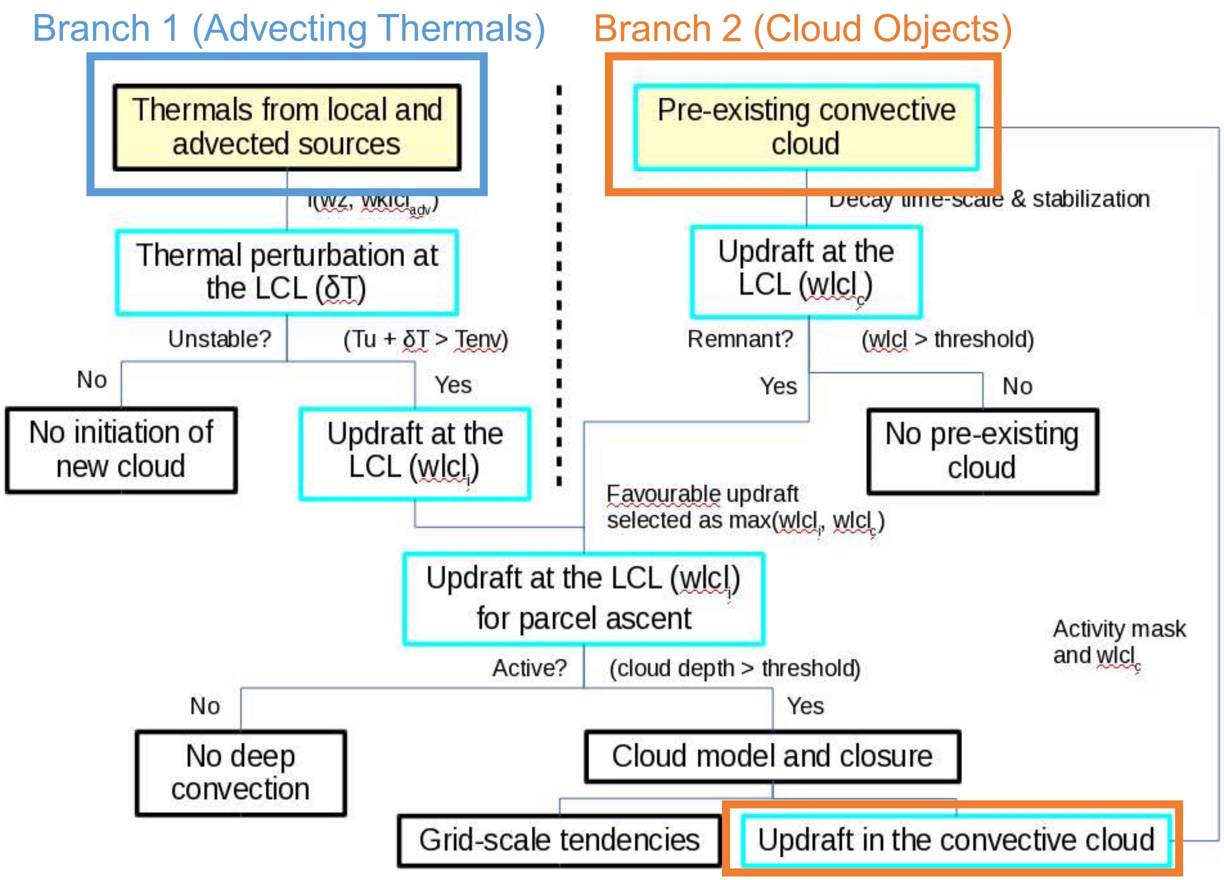
Schematic of a deep mass-flux based CPS with a branch added to represent persistence of existing convection either generated within the cell or moving into it.

In reality, rising thermals have time scales that make them evolving properties of the column.

Pre-existing deep convective cloud already has a strong updraft to tap instability, rather than relying on re-initiation at every time step.

Canada

A Lagrangian Perspective on Convection



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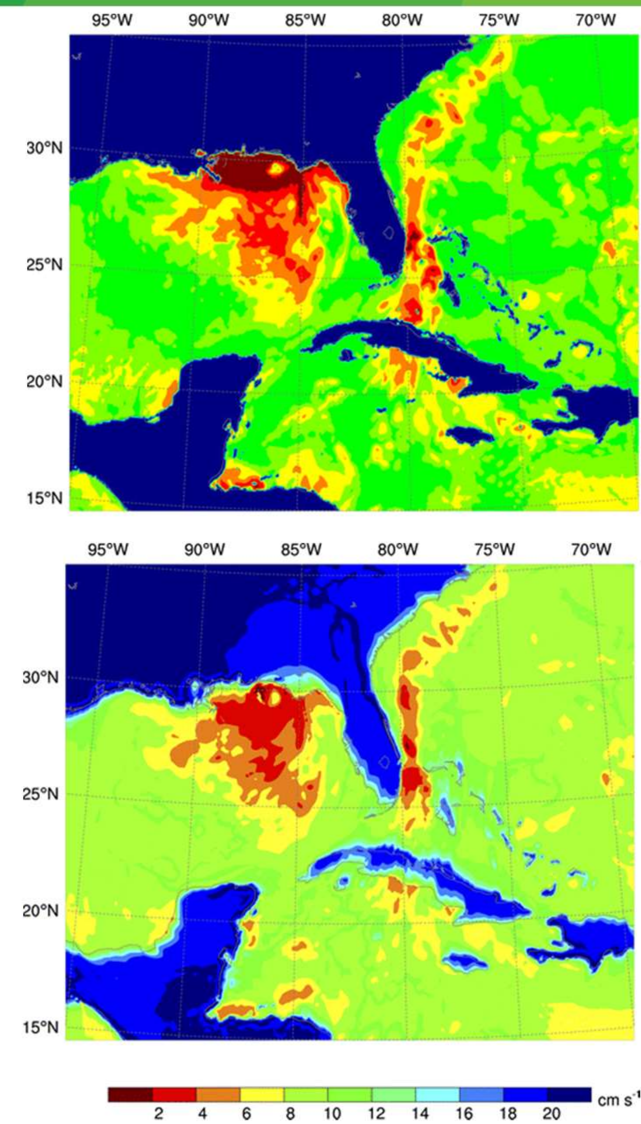
Branch 1: Convective Initiation

- Instead of using a local trigger ($\tilde{w}_{klcl}$), the thermal perturbations become parcel properties with advection and Newtonian relaxation to the local value:

$$\frac{\partial w_{klcl}}{\partial t} = -V \cdot \nabla w_{klcl} + \frac{1}{\tau_w}\left(\tilde{w}_{klcl} - w_{klcl}\right)$$

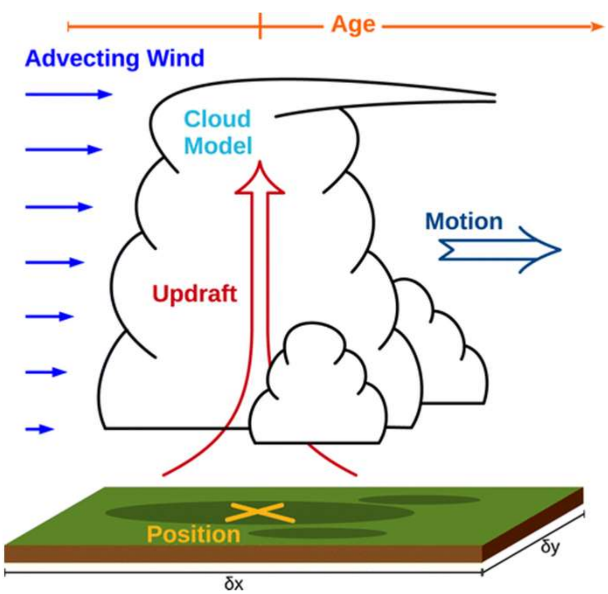
- Coastal discontinuities are smoothed as dry thermals that may initiate deep convection evolve gradually as they move between land to ocean.



Trigger velocity (w_{klcl}) at 1200 UTC 28 May 2018 after 24-h of integration with a local trigger (top) and a trigger computed as a parcel property (bottom) with τ_w=1h.

Branch 2: Cloud Objects

- Observed convection is able to sustain itself over local stable layers through updraft inertia and ingestion of air from higher levels
- This is represented within the CPS as a separate triggering branch in which the cloud base perturbations used for the cloud model come from the properties of pre-existing clouds



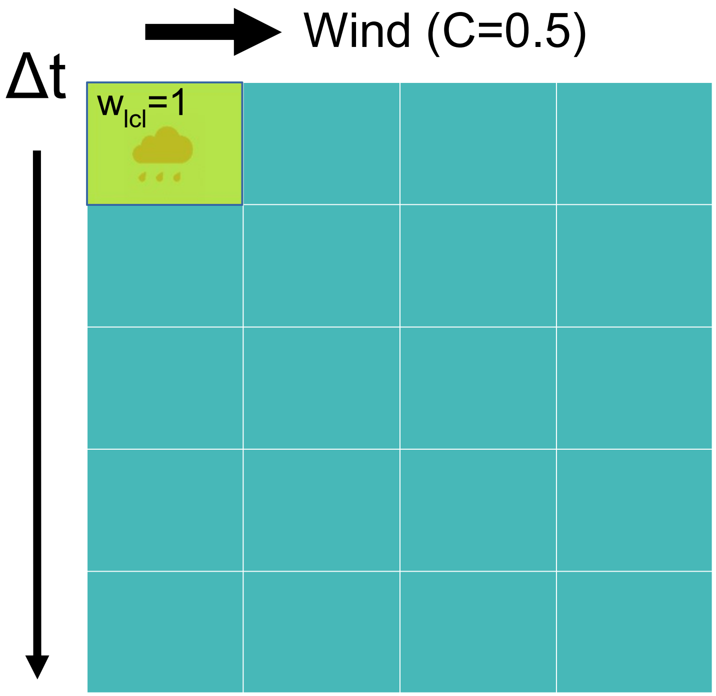
Schematic of select cloud object properties.

Considering clouds as independent entities (objects) opens up new possibilities to deal with high resolution problems related to non-equilibrium states, cloud lifecycle, and cloud movement in a physically realistic way.

Branch 2: Cloud Objects

- Under moderate winds in this case (~35 kt), clouds may move >100 km over a 1.5-2h life time or >10 RDPS gridpoints

- This means that at high resolution, we should advect[1] clouds



At initiation (Branch 1 of the CPS trigger) the new cloud is positioned within the grid cell; currently centered but could be pseudo-random.

The updraft velocity at the LCL (w_{lcl}) is evaluated at initiation.

[1] Currently, this motion does not include any propagation component as needed for cold pool or back-building-controlled motion.

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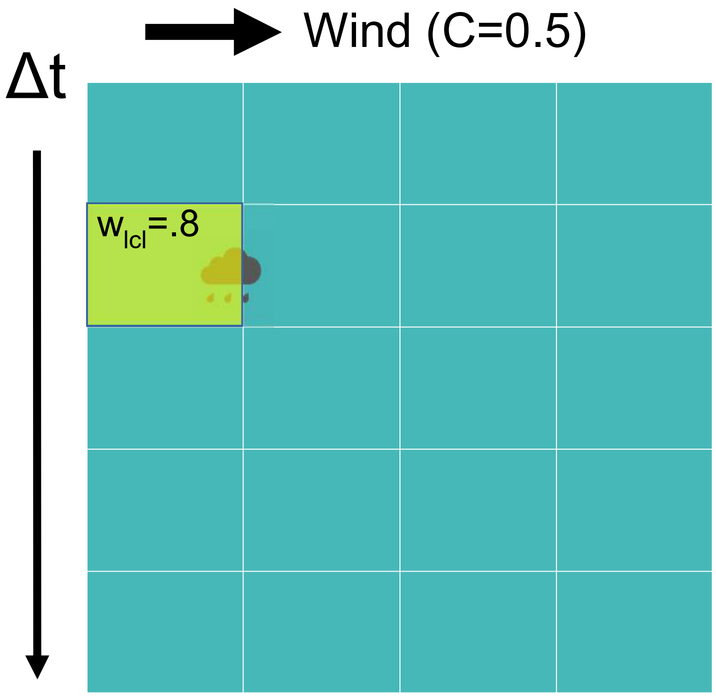

On the next step, the cloud advects downstream within the grid cell and triggers Branch 2 of the CPS to maintain convective activity.

Updraft velocity decays on a specified time scale (e.g. 1h).

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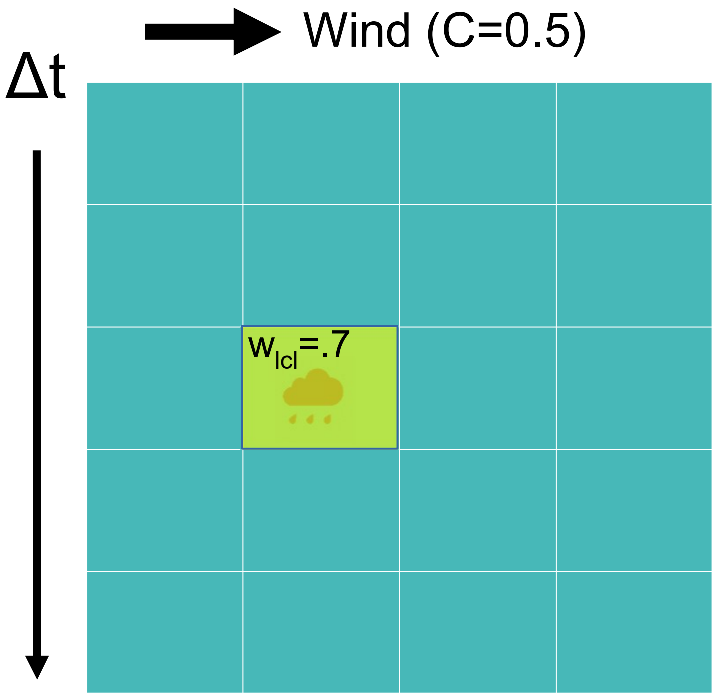

The cloud object continues to advect, now into the downstream grid cell where it continues to sustain convective activity.

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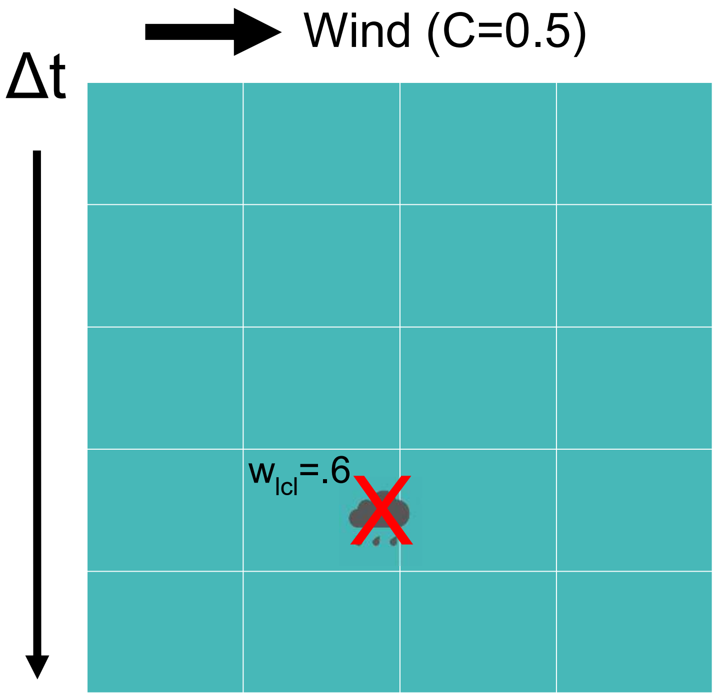

At the next step, the cloud updraft is no longer sufficient to sustain convection.

If no new convection is possible (Branch 1 trigger fails), then convective activity stops.

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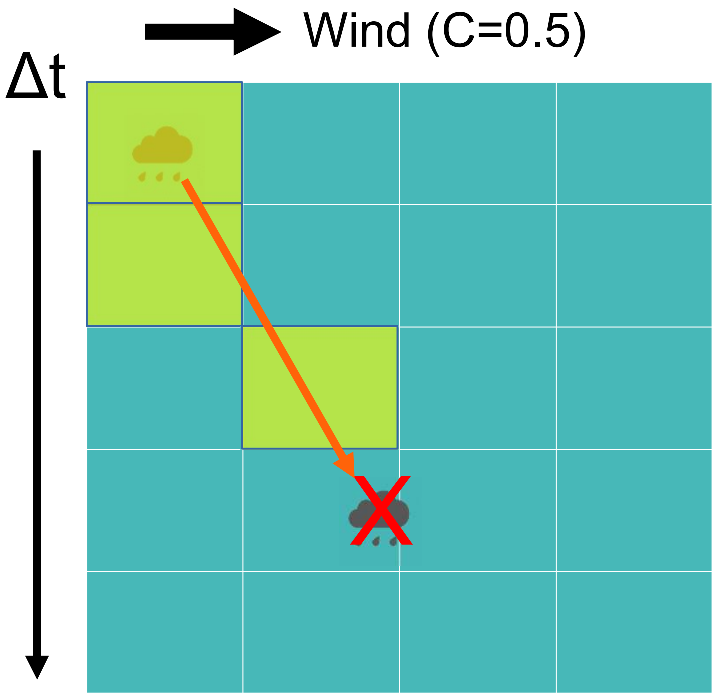


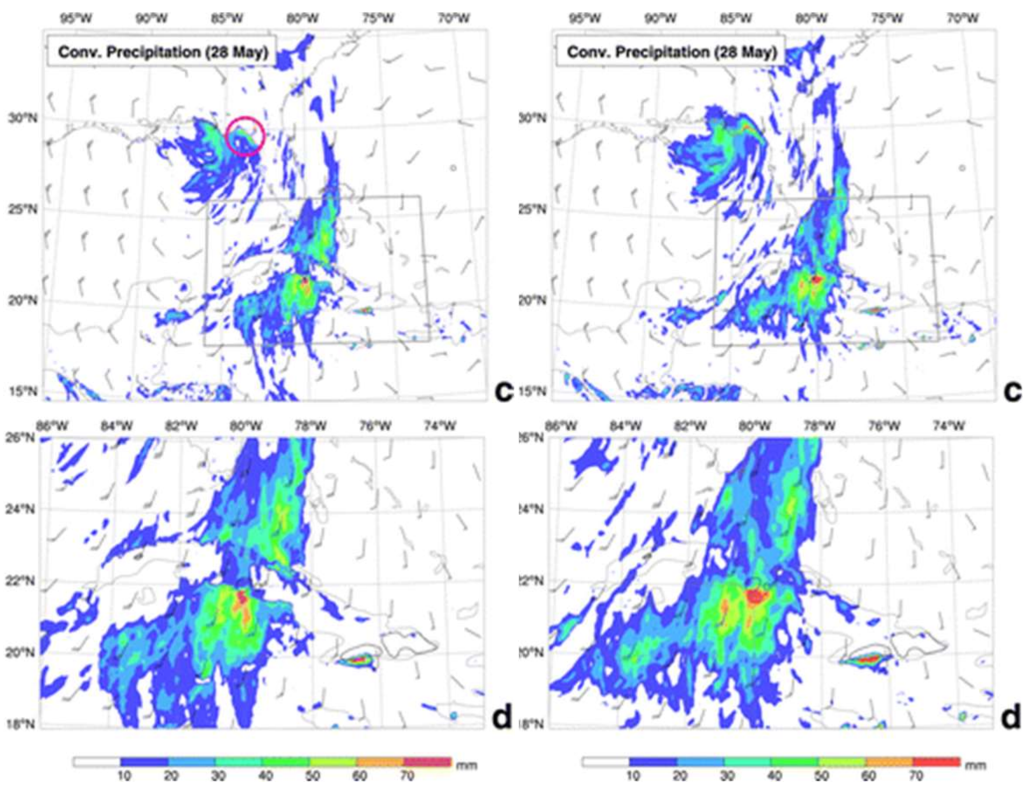
The result is a persistent cloud object whose properties evolve as it advects across the grid.

Although convective activity (a grid scale quantity) propagates discretely, the cloud object is continuous on the subgrid.

[1] Currently, this motion does not include any propagation component as needed for cold pool or back-building-controlled motion.

A Lagrangian Perspective on Convection

Control Lagrangian Conv.

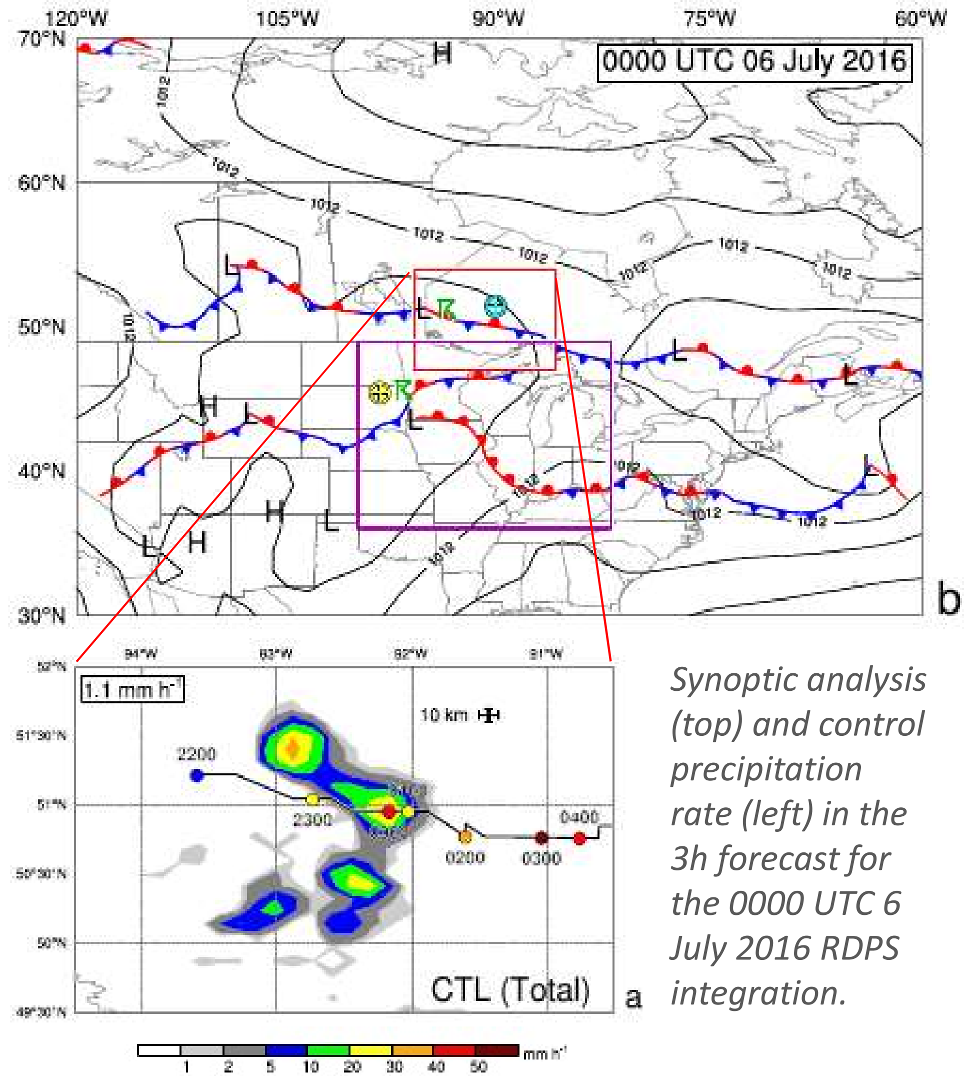


Accumulation of convective precipitation over a 24 h forecast initialized at 1200 UTC 27 May 2018 in a control integration (left) and with Lagrangian convection (right). A zoom on the Cuban domain is shown in the bottom row.

- Combining the convective initiation (advected w_{klcl}) and cloud object treatments yields a Lagrangian view of convection
- The discontinuities in convective precipitation appear to have been removed both over Cuba and along the Gulf Coast
- The precipitation maximum on the windward side of Groupo Guamuaya appears physically reasonable (D. Kirshbaum)

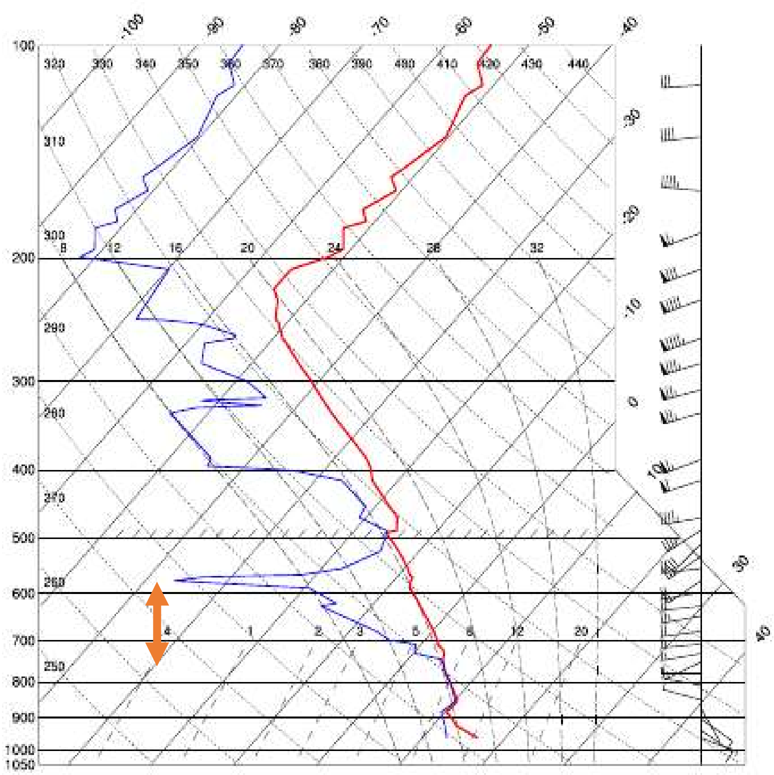
Precipitation “bulls-eyes” in the RDPS

- Forecasters have reported excessive point precipitation in the RDPS for many years
- A case study from 6 July 2016 is used to understand the bulls-eye mechanism
- Precipitation is almost entirely generated by the grid-scale condensation scheme despite a convective nature in MRMS (radar) estimates
- A classic “grid-point” storm



Synoptic analysis (top) and control precipitation rate (left) in the 3h forecast for the 0000 UTC 6 July 2016 RDPS integration.

Convection in a Moist-Neutral Sounding

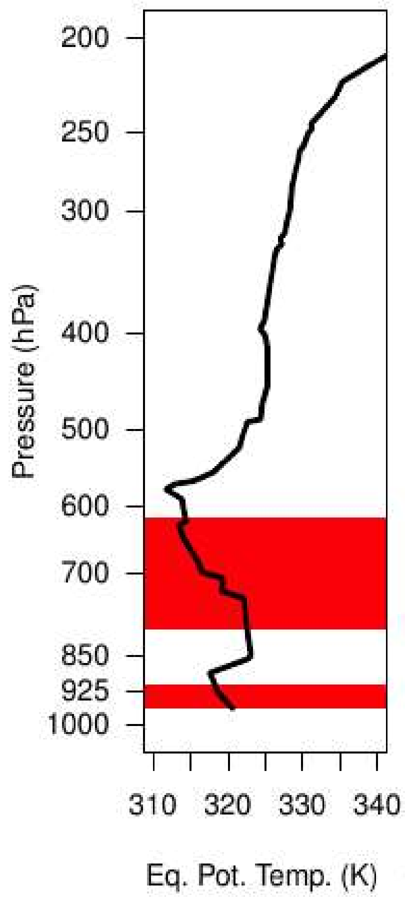


WPL sounding (green crosshairs on previous slide) for 0000 UTC 6 July 2016.

- Convective ingredients: lift, moisture and instability (Doswell et al. 1996)
- The pre-convective Pickle Lake sounding shows:
  - Warm advection (frontal overrunning: lift)
  - Saturation to 750 hPa (moisture)
  - Little/no convective available potential energy (CAPE)
  - A deep layer of potential instability because of dry layer aloft
- The CPS in GEM is CAPE-dependent and therefore remains inactive

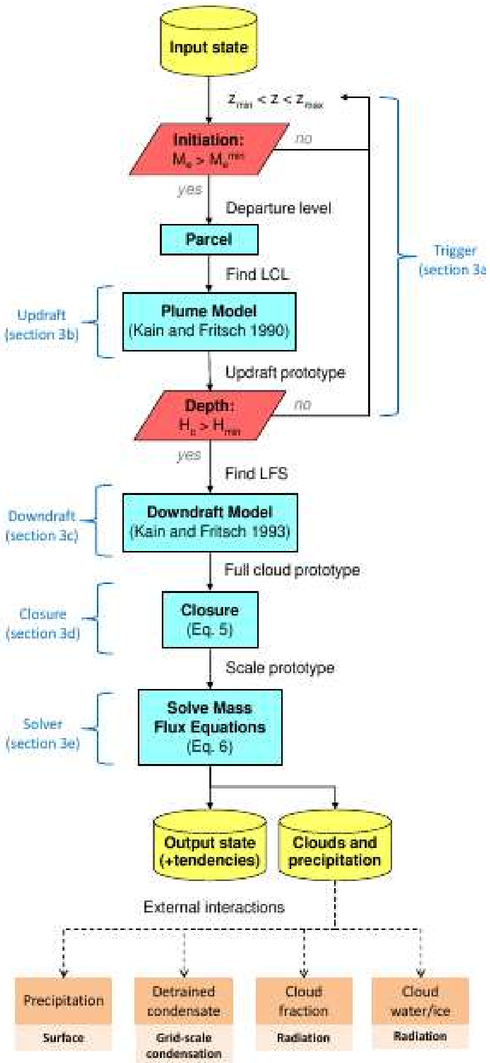
Potential Instability

- Equivalent potential temperature (θ_e) decreases with height in the profile
- Potential instability is a "near-instability" that is realized by layer lifting (Sherwood 2000):
  - Synoptic/mesoscale forced ascent lifts the layer
  - Bottom of layer condenses first
  - Release of latent heat steepens lapse rate above because of the difference between moist (bottom) and dry (top) adiabatic expansion
- A quasi-equilibrium conditional instability is generated: CAPE is consumed by convection and remains low (Kreitzberg and Perkey 1976)



WPL ϑ_e profile of for 0000 UTC 6 July 2016. Layers of potential instability in a filtered profile are highlighted in red.

A Low-CAPE Convection Scheme



Schematic of the low-CAPE convection scheme.

- Without CAPE, the grid-scale condensation scheme couples with model dynamics to create under-resolved grid-scale updrafts and excessive precipitation

- A new low-CAPE convection scheme:

Trigger

1) resolved updraft mass flux > $1\text{x}10^{7}$ kg m^{-2} s^{-1}
2) a convectively unstable layer aloft
3) CAPE is low (< 250 J kg^{-1} in tests; implies little/no deep convection)

Cloud Model adapted from Kain-Fritsch deep CPS

Closure

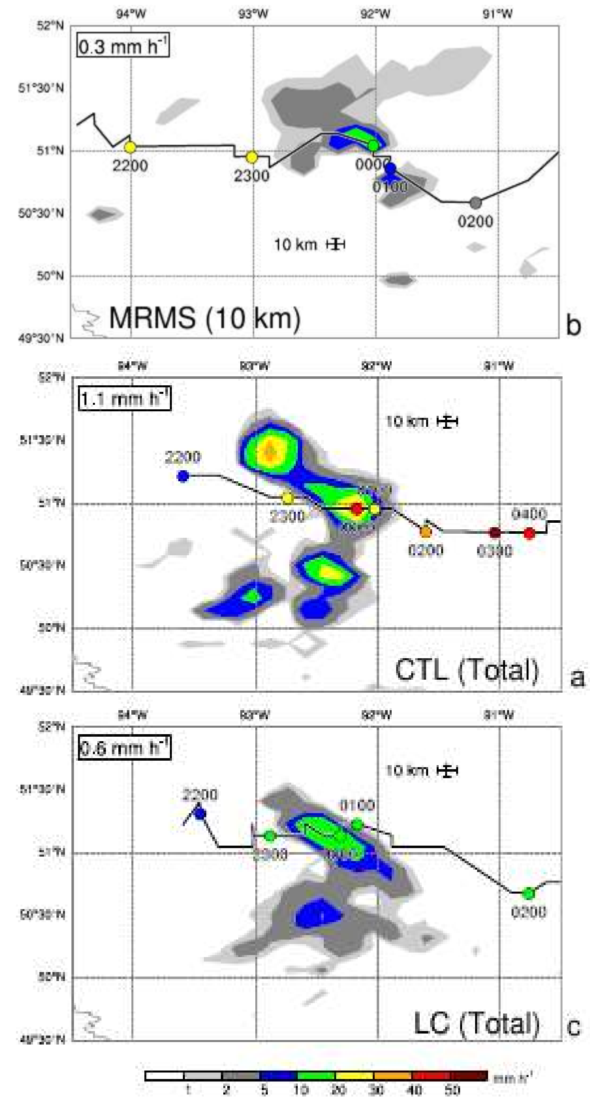
1) cloud base mass flux: $M_u = \rho w$

Mass Flux Equations are adapted from Kain-Fritsch deep CPS and solved implicitly following approach of the PBL scheme

- Called the “mid-level” scheme for consistency with ECMWF and UKMO

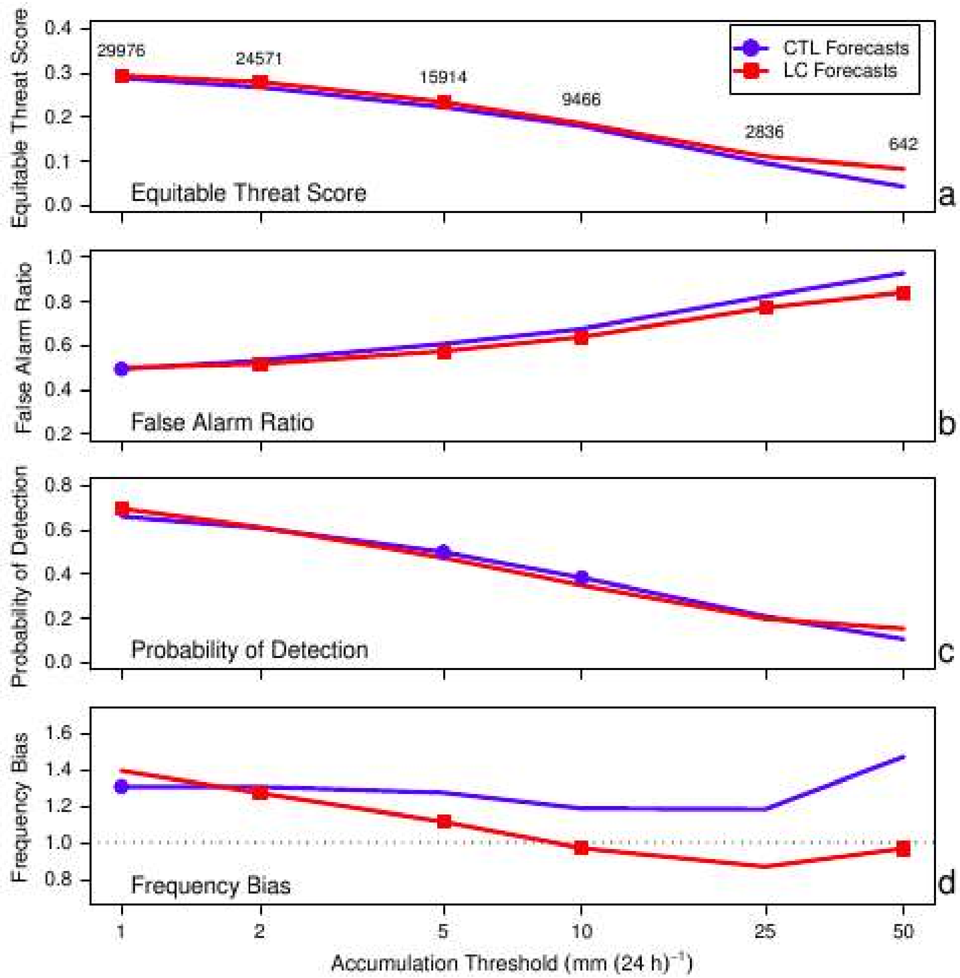
A Low-CAPE Convection Scheme

- The low-CAPE (LC) scheme successfully "short-circuits" the grid-point storm mechanism by processing instability through parameterized moist turbulence
- Precipitation rates fall towards MRMS estimates, and the storm does not stall at peak intensity
- Potential instability was present in this case, but any non-CAPE instability (including symmetric) can trigger the low-CAPE scheme



Precipitation rates at 0000 UTC 6 July 2016 from radar estimates (top), in the control integration (middle) and in the run with the low-CAPE scheme active (bottom).

Impact of Low-CAPE Convection



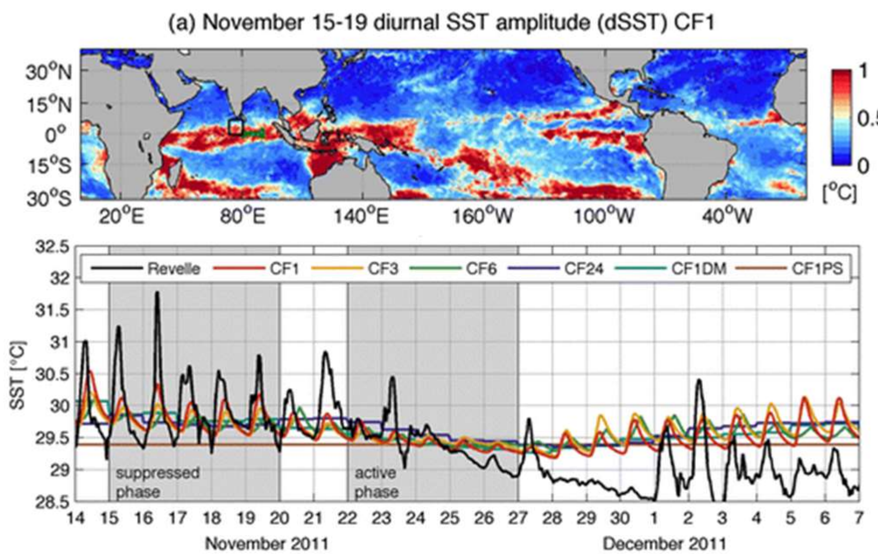
- The low-CAPE scheme leads to improvements in QPF scores
- POD stays high while FAR drop, implying the removal of spurious storms
- The FAR is dramatically improved, acquiring the negative slope expected from representativeness issues with this comparison

Day-2 scores for North American QPF against synoptic gauge observations for July-August 2016 for forecast sequences run without (blue) and with (red) the low-CAPE convection scheme.

Diurnal SST Variability

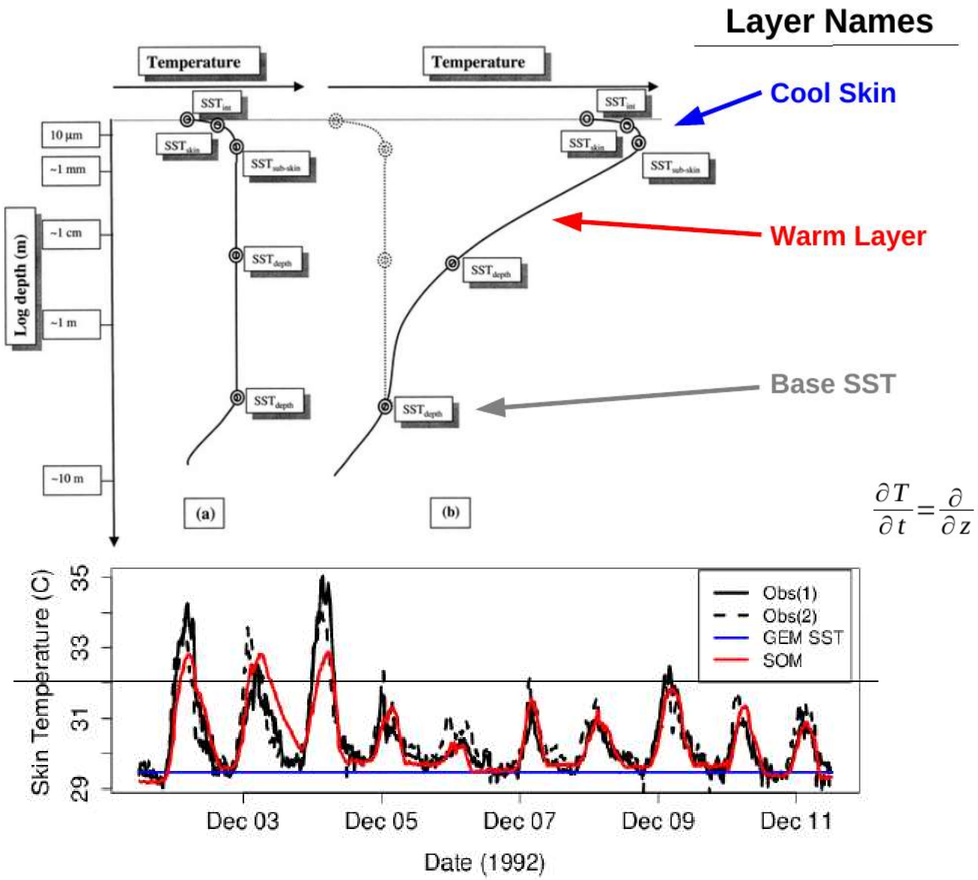
- All uncoupled short- and medium-range forecasts at CMC use a fixed SST that represents the “base” temperature rather than the interfacial temperature needed for flux calculations
- The ocean therefore acts as an infinite heat source
- Upper-ocean feedback may affect radiative-convective equilibrium and set the time-scale for the Madden-Julian Oscillation (Slingo et al. 2003):

Suppressed MJO → Clear skies and light winds → SST increase → Destabilization → Active MJO



Diurnal SST amplitude (top) and time series (bottom) for active and suppressed phases of the MJO during the DYNAMO project in the Indian ocean (Seo et al. 2014).

A Simple Warm Layer and Cool Skin



Top: *Components of diurnal SST variability (Dunlon et al. 2008).* ***Bottom****: Sea surface temperature during the part of the TOGA-COARE IOP (black), compared with the results of the "fairall" diurnal SST parameterization run with observed driving data (red).*

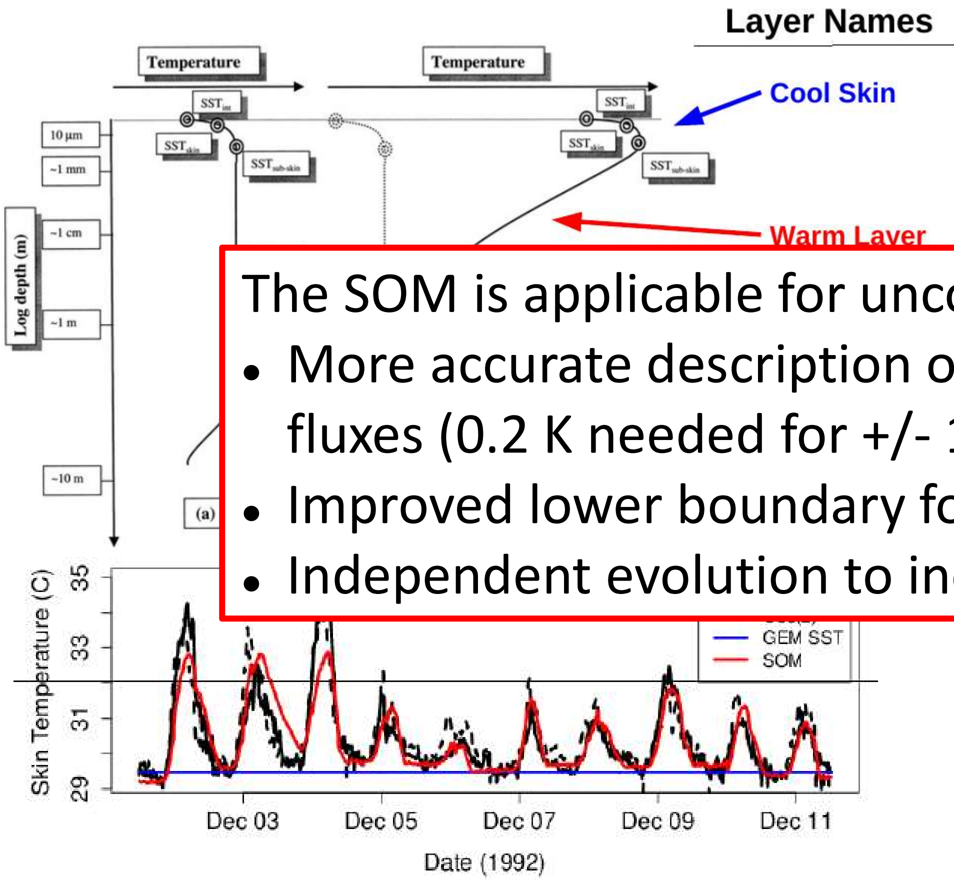
The simplified ocean model (SOM; Zeng and Beljaars 2008) applies a first-order closure to a diffusion equation with a radiative source:

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\left(K_w + k_w \right) \frac{\partial T}{\partial z} \right) + \frac{1}{\rho_w c_w} \frac{\partial R}{\partial z}$$

K_w = turbulent diffusion coefficient
k_w = molecular diffusion coefficient
ρ_w = density of sea water
c_w = volumetric heat capacity of water
R = net solar radiative flux

There are no ocean dynamics in the SOM, so it cannot represent eddy ring movement, hurricane cold wakes or the seasonal cycle of base SST.

A Simple Warm Layer and Cool Skin



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The simplified ocean model (SOM; Zeng and Beljaars 2008) applies a first-order closure to a

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The SOM is applicable for uncoupled systems:

- More accurate description of interface temperature for fluxes (0.2 K needed for +/- 10 Wm^{-2})
- Improved lower boundary for radiance retrievals
- Independent evolution to increase ensemble spread

There are no ocean dynamics in the SOM, so it cannot represent eddy ring movement, hurricane cold wakes or the seasonal cycle of base SST.

High Impact Weather: Freezing Rain

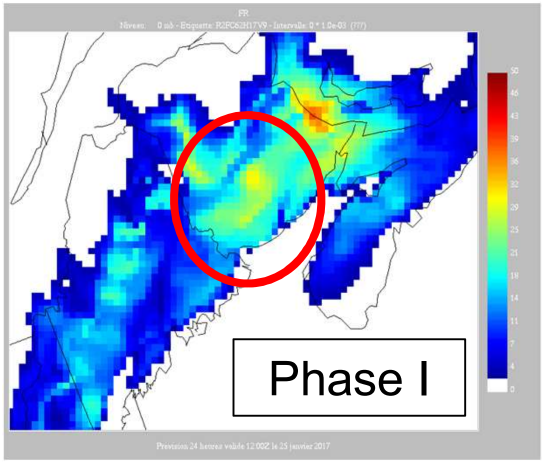
- Subjective evaluations of freezing rain guidance during the C&P project suggested that results varied by system:

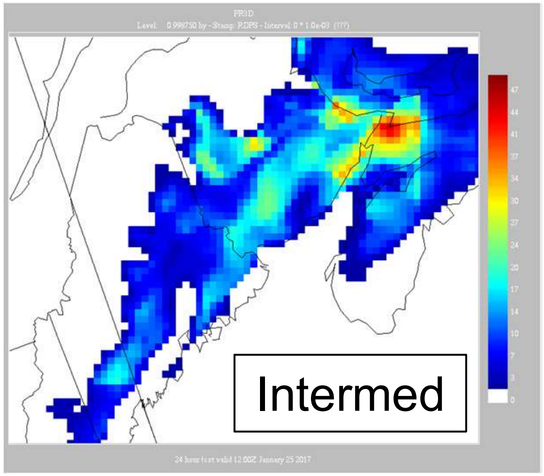
  GDPS: Improvement due to use of "moistke" PBL and local mixing length

  RDPS: Degradation in the form of reduced area and total accumulation

- In the majority of events, precipitation accumulated as rain rather than freezing rain, despite a general winter cold bias

- Comparing with SVS integrations, freezing of liquid precipitation within the snow pack was found to lead to rapid warming



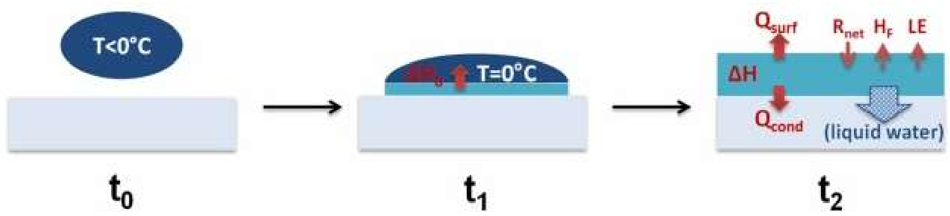


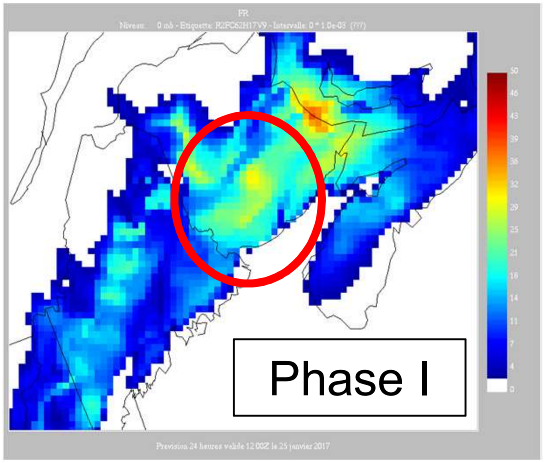
Accumulation of freezing rain in a 24 h integration initialized at 1200 UTC 24 January 2017 using the Phase I RDPS (top) and an intermediate RDPS configuration (bottom; ignore small-LAM edge effects).

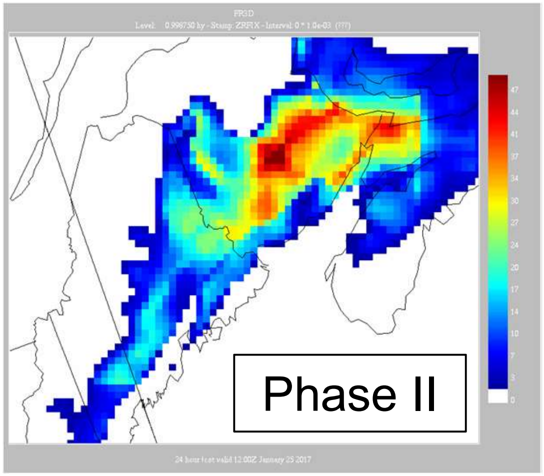
High Impact Weather: Freezing Rain

- At cold temperatures, freezing precipitation creates an glaze ice layer rather than penetrating the snow pack

Schematic of ice layer energy budget.







- Following Queno et al. (2018), freezing rain is diagnosed for T2m < 0°C
- This freezing rain is treated as a solid (ice) precipitation to prevent refreezing
- Cooled near-surface temperatures result in increased freezing rain accumulation

Accumulation of freezing rain in a 24 h integration initialized at 1200 UTC 24 January 2017 using the Phase I RDPS (top) and the Phase II RDPS configuration (bottom; ignore small-LAM edge effects).

Putting it All Together …

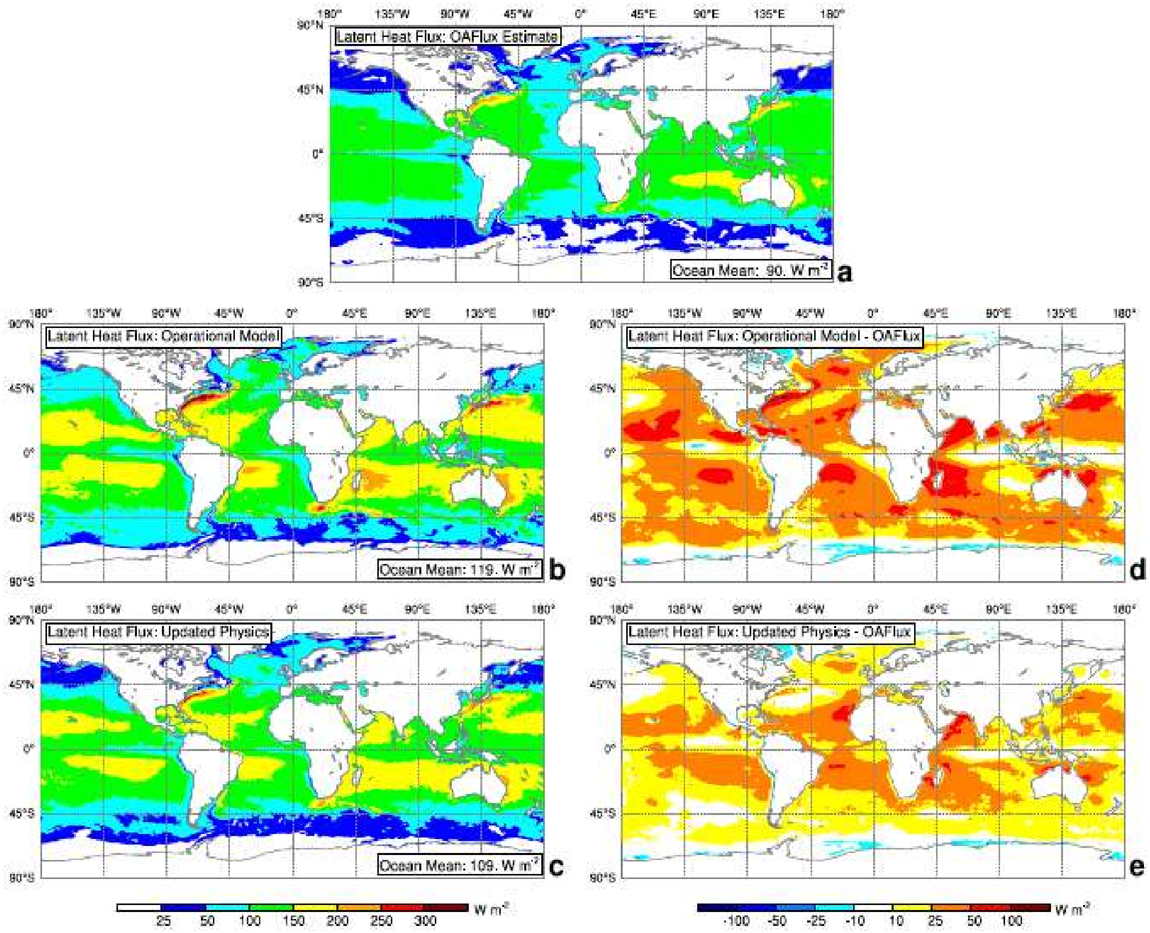
- In total, more than 130 non-negligible changes were made to the GEM physics suite in the July 2019 upgrade of the global (GDPS) and regional (RDPS, REPS) forecasting systems at CMC

Scheme	Description	Direct effect	Impact on NWP
Boundary layer	Mixing length calculation	Adjusts mixing based on the turbulence regime of the flow	Reduces winter boundary layer cold bias (RDPS), and reduces overmixing at the expense of introducing a cold bias (GDPS)
Deep convection	Adjustment time scale	Convective adjustment time scale is related to overturning	Improves cloud and precipitation structure
Deep convection	Cloud objects	Implements a Lagrangian view of convection in which clouds persist and evolve over time	Improves cloud and precipitation structure
Deep convection	Cloud radius	Reduced cloud radius over ocean	Lowers oceanic convective cloud tops and improves upper-air scores
Deep convection	Convective momentum transport	Redistributes momentum in the vertical during moist convection	Improves tropospheric wind standard errors
Dynamics	Moisture conservation	Eliminates numerical sources/sinks of water vapor and condensate	Reduces overprecipitation bias
General	Dissipative heating	Conserves total energy	Reduces lower-level cold bias
Grid-scale clouds	Enforce conservation	Tendencies are corrected to ensure that E and q_t are conserved	Reduces overprecipitation bias and warms the midtroposphere
Midlevel convection	Represent elevated convection	Replaces some grid-scale condensation scheme activity with parameterized convection	Reduces total precipitation and grid point storms, and improves objective precipitation scores
Orographic blocking	Subgrid-scale orographic fields	Reduced blocking by removing double-counting	Improves orographically influenced flows and increases lee-side precipitation
Radiation	Updated version	Changes absorber properties and bands for radiative transfer calculations	Increases upper-stratospheric warmbias
Surface layer	Minimum Obukhov length	Maintains land-atmosphere coupling under stable conditions	Reduces winter screen-level cold bias

Changes made during the modernization of the atmospheric physics suite that have the largest impact on NWP guidance quality.

- Improving the global energy cycle and increasing the vertical resolution were the goals of the Clouds and Precipitation project
- An improved model climate implies more realistic physics

Improved Turbulent Latent Heat Fluxes

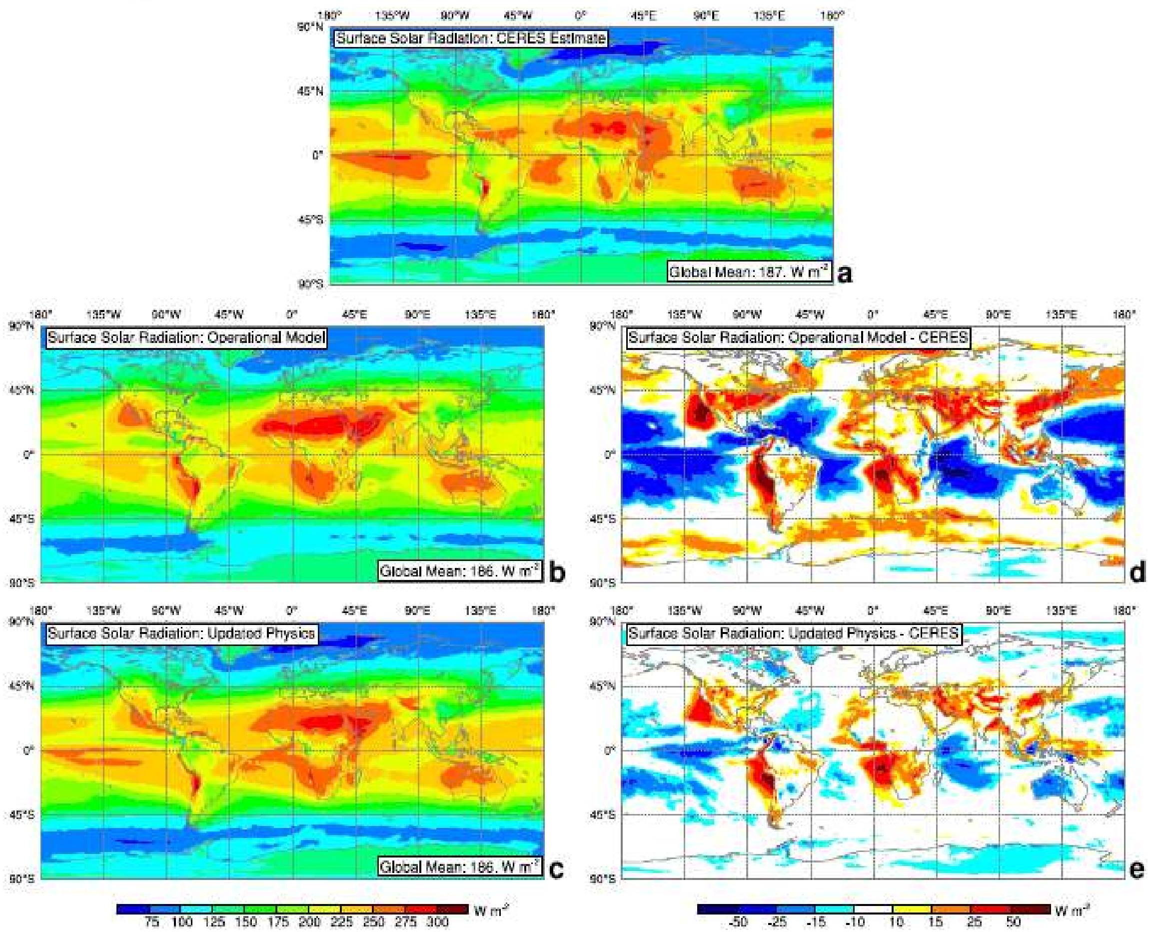


Mean annual oceanic latent heat flux from the observational OAFlux dataset (top), operational GDPS (middle) and Phase-II GDPS (bottom). Differences between MHEEP integration results and the OAFlux estimate are shown in the right column.

The operational over-estimate of oceanic latent heat fluxes is dramatically reduced in all regions.

This improves an important "driver" of the global energy cycle.

Improved Clouds and Solar Radiation



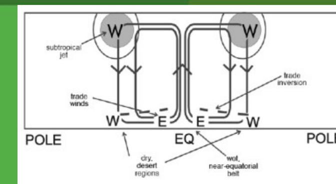
Mean annual incoming solar radiation from the observational CERES dataset (top), operational GDPS (middle) and Phase-II GDPS (bottom). Differences between MHEEP integration results and the CERES estimate are shown in the right column.

The cloud field responds to surface moisture flux changes and turbulent exchanges between the boundary layer and free troposphere.

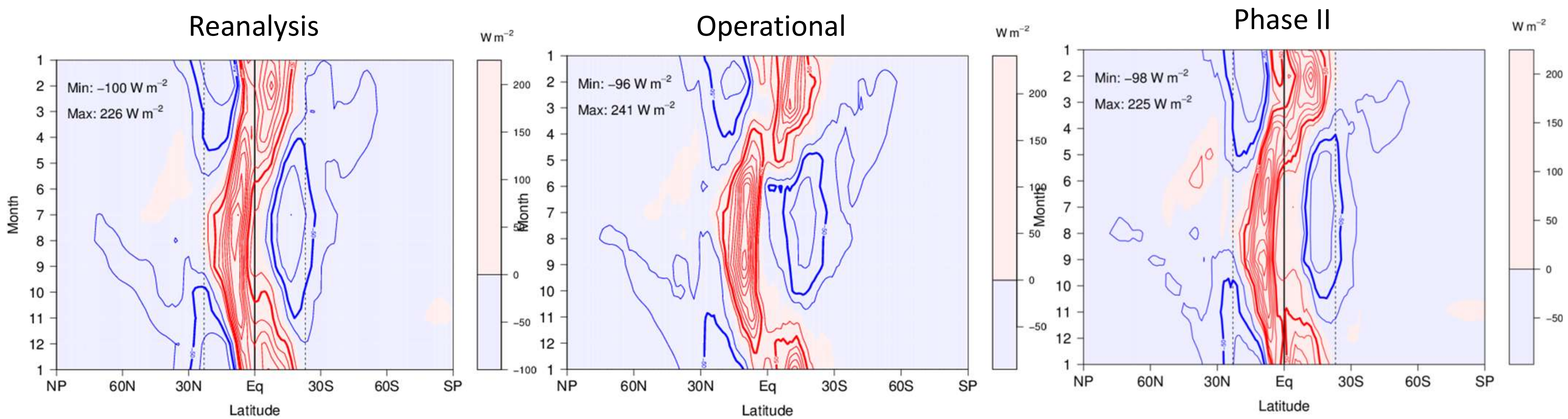
Decreased cloud cover increases surface irradiance across the tropics: similar to obs.

Canada

An Improved Global Circulation

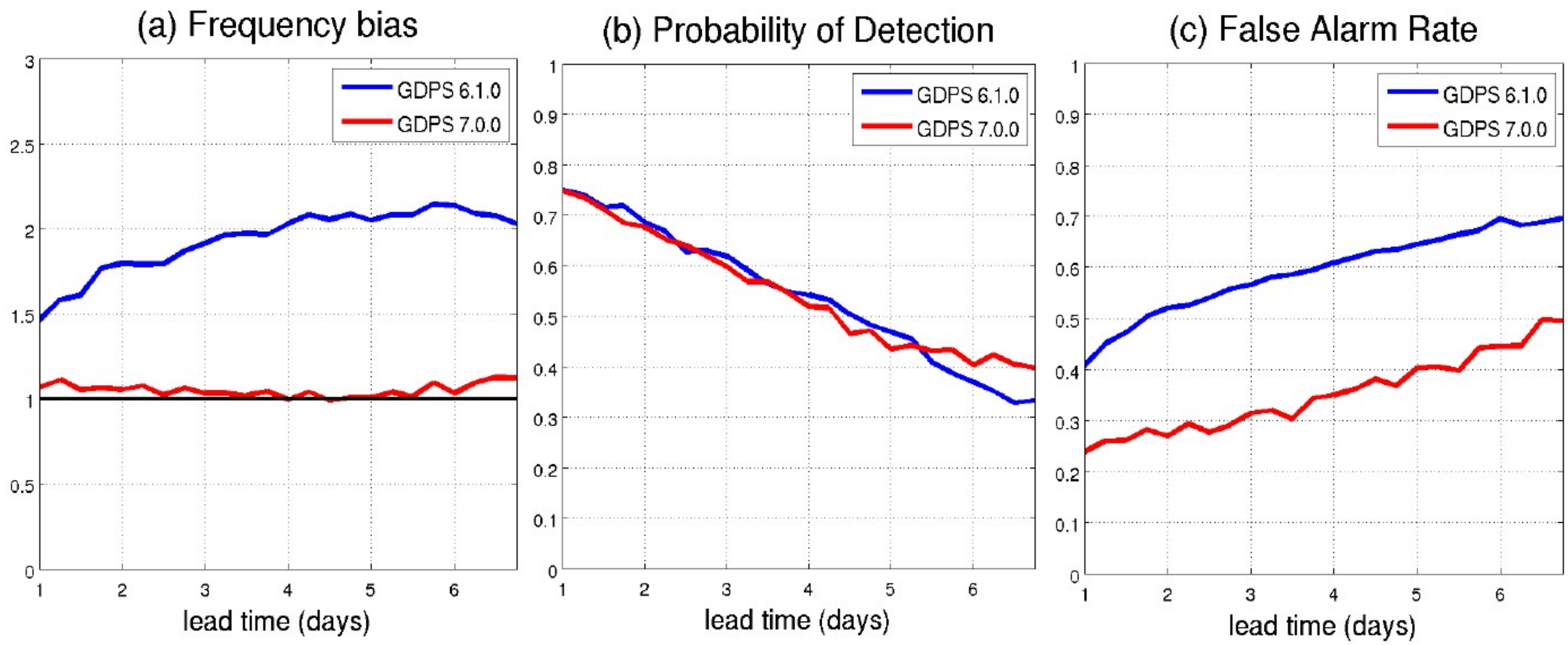


The ITCZ in the Phase-II configuration does not "jump" in transition seasons, and has a winter subsiding branch that is more consistent with reanalysis estimates: an improved meridional circulation.



Seasonal cycle of vertically integrated diabatic heating in the 315K-370K “middleworld” layer in the ERA-Interim analysis (left), an operationally configured operational (middle) and Phase-II configuration (right).

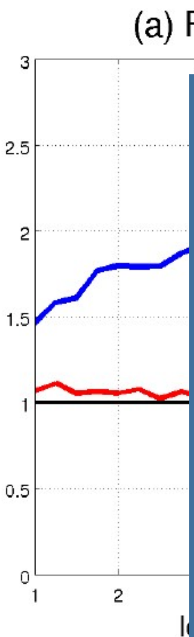
Impact on Tropical Cyclones



Global tropical cyclone statistics for the operational (blue) and Phase-II (red) physics configurations. Scores are based on tracking results from a JJA assimilation cycle.

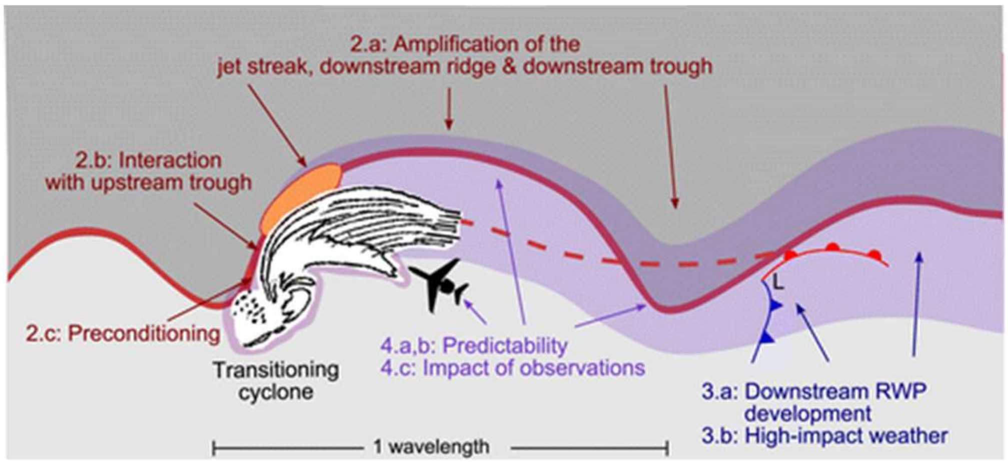
The notorious hyperactivity of the model is largely eliminated (!) by the introduction of momentum transport in the deep convection scheme, with a possible over-reduction of storm intensity.

Impact on Tropical Cyclones



Global tropical cyclone statistics for the operational (blue) and Phase-II (red) physics configurations. Scores are based on tracking results from a JJA assimilation cycle.

But I'm in Canada… should I care about tropical cyclones?



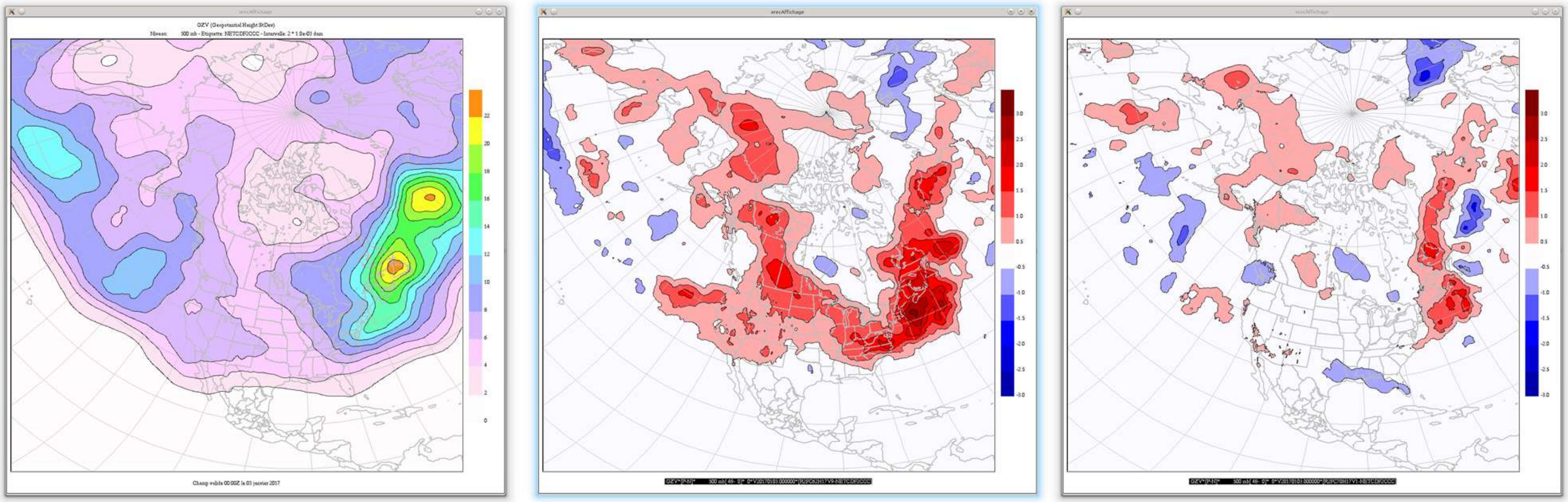
Schematic of flow interaction during extratropical transition (Keller et al. 2019).

A transitioning TC perturbs the jet, and can trigger a Rossby wave packet that affects forecasts downstream.

The n… …inated (!) by the in… …onvection scheme, with a possible over-reduction of storm intensity.

Impact on the Midlatitude Storm Tracks

ERA5 | Operational - ERA5 | PHASE II - ERA5



Variance of winter 500 hPa heights in the 2.5-7d window in ERA5 (left), the operational (centre) and Phase-II RDPS (right).

The excessive synoptic-scale variability (hyperactivity) of the operational system is largely eliminated in all Phase-II configurations, leading to an improved representation of the storm track.

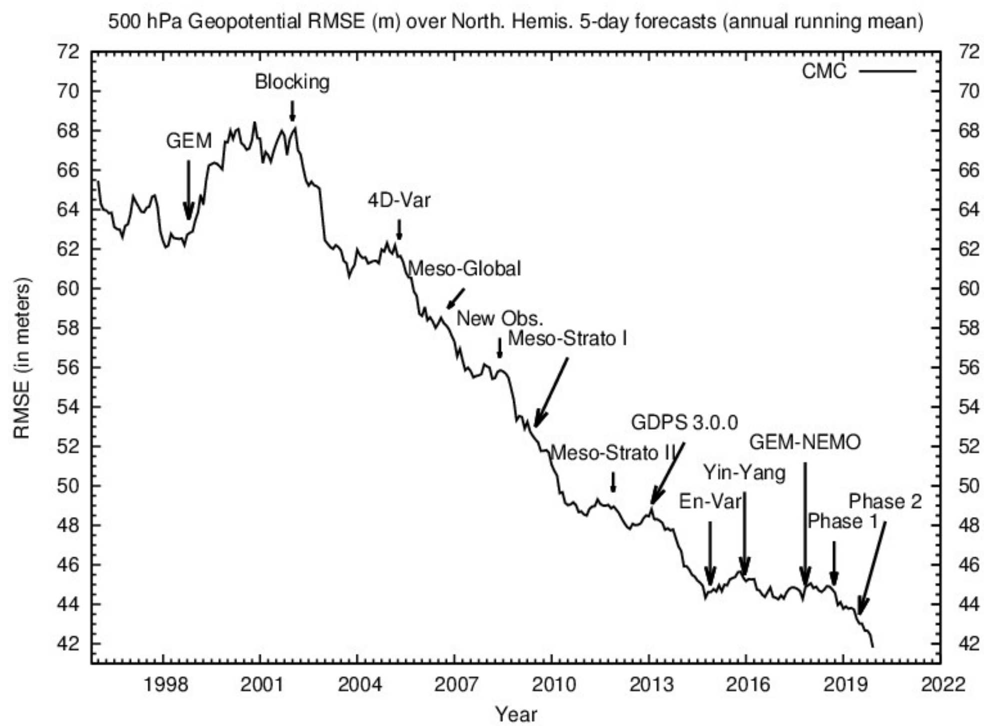
Outcome of General Circulation Study

- The focus on the global energy budget ensures that changes to the physical parameterizations are well-balanced and physically realistic
- The overactive hydrological cycle is calmed, and the general circulation is improved
- Tropical cyclone false alarms a reduced, and midlatitude storm tracks are improved
- Guidance appears to have been improved for high impact, poorly predicted events

Recent Model Performance

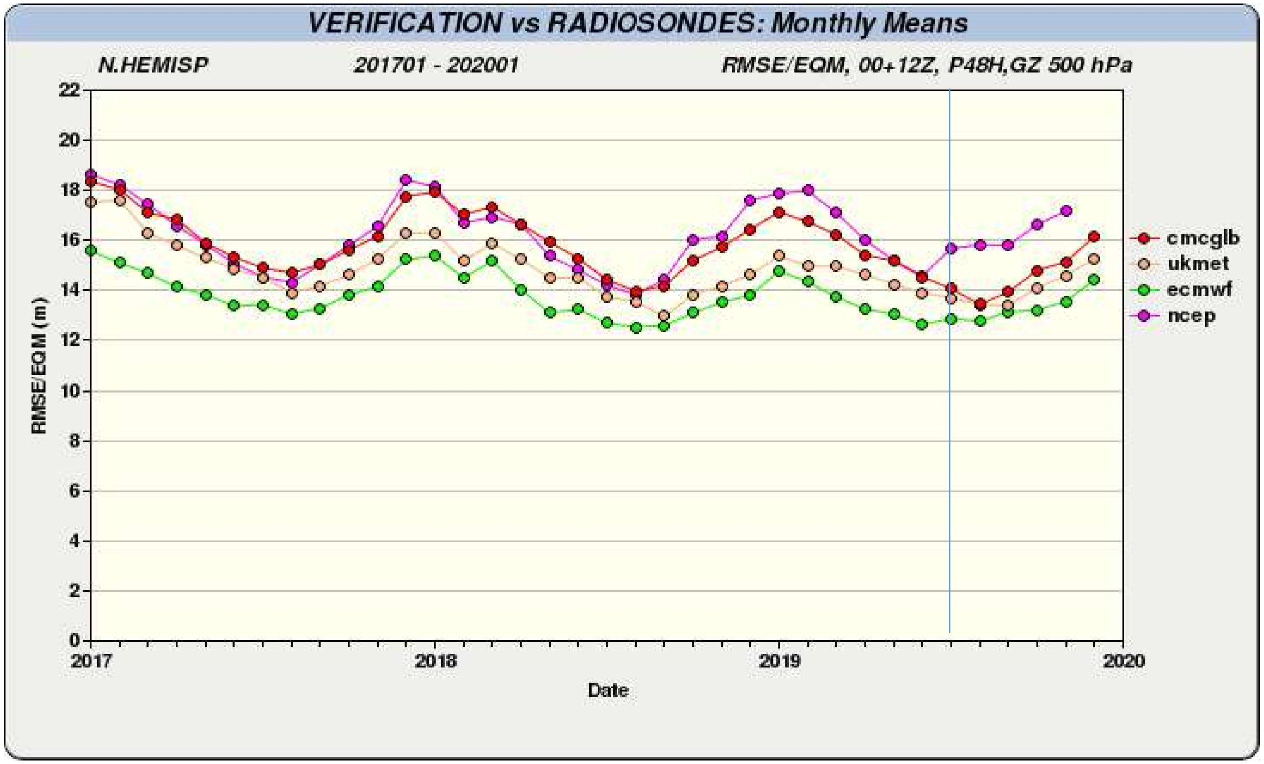
Operational systems are under constant development at the CMC; however, some upgrades have more impact than others.

The 2019 physics upgrade ("Phase 2") seems to be leading to significant error reduction as expected.



Evolution of 500 hPa RMSE over the Northern Hemisphere in the 120 h forecast from the GDPS, with significant operational upgrades identified. A one-year running mean implies that the full impact of Phase II has not been realized.

Recent Model Performance

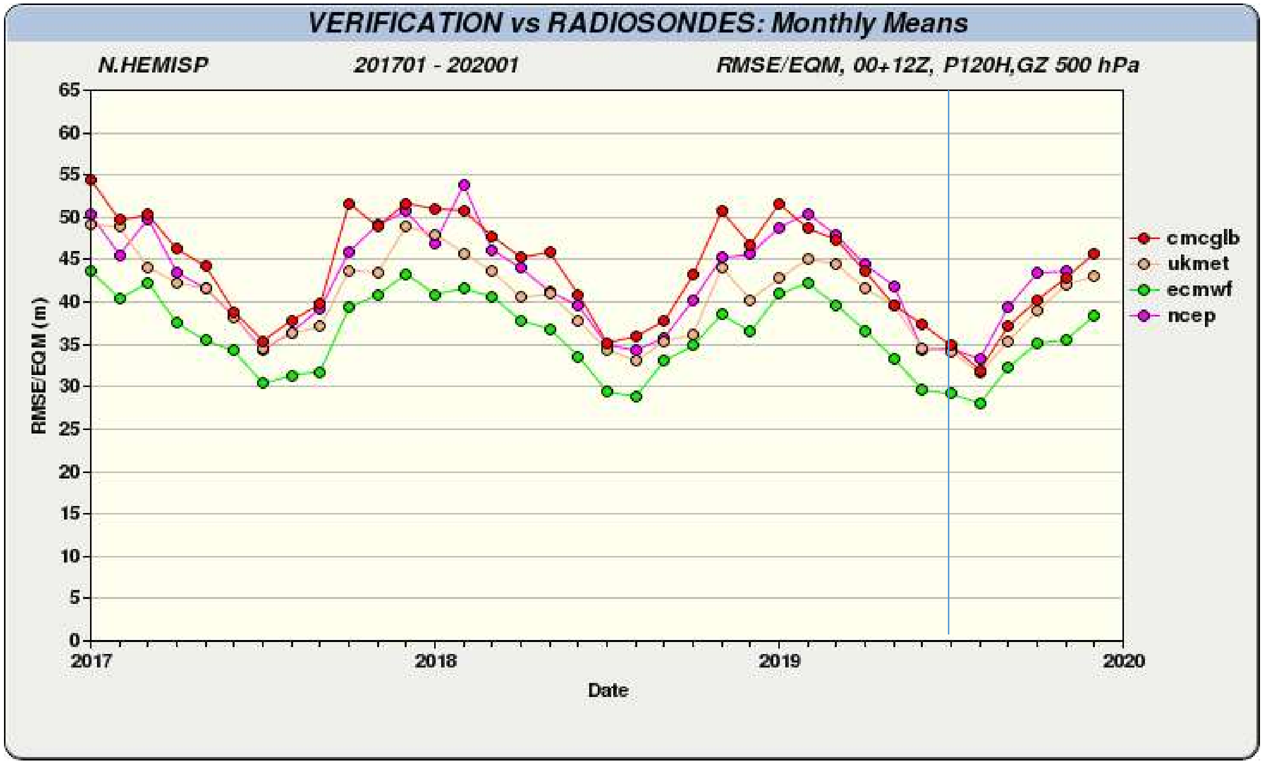


Global model RMSE of 500 hPa heights in the 48h forecast over North America, evaluated using radiosonde data. Vertical line shows ~3 July 2019.

Since 3 July 2019 implementation, the GDPS (red; "glbo") has performed well.

Short-range scores over North America compare well with those from the Met Office and ECMWF.

Recent Model Performance



Global model RMSE of 500 hPa heights in the 120h forecast over the Northern Hemisphere, evaluated using radiosonde data. Vertical line shows ~3 July 2019.

Medium-range forecast errors increase in the winter for all centres.

The GDPS is competitive with other major models at longer lead times over the hemispheric domain.

Discussion

- Major changes to the RPN Physics suite were made over a 5-year development period, using a new hierarchy of models and M-climate tests
- The first step of improving the fundamentals of the parameterizations was followed by a 2-year effort to arrive at a configuration for NWP
- Changes to the representation of convection and turbulent mixing had a large impact on the quality of forecast guidance
- We are looking forward to working with you from this improved starting-point to find ways to further improve the model physics for weather and climate

Resources

- All C&P project development is documented in the PA (Physics of the Atmosphere) group meeting webpage

  https://wiki.cmc.ec.gc.ca/wiki/RPN_Phy/PA

- Recent publications document the project and specific items:

McTaggart-Cowan and Coauthors, 2019: Modernization of atmospheric physics parameterization in Canadian NWP. *J. Adv. in Model. of Earth Sys.*, **11**, 3593-3635.

McTaggart-Cowan, R., P. A. Vaillancourt, A. Zadra, L. Separovic, S. Corvec and D. Kirshbaum, 2019: A Lagrangian perspective on parameterizing deep convection. *Mon. Wea. Rev.*, **147**, 4217-4149.

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