Improving the hydrological cycle, surface and top of atmosphere energy budgets of the Canadian global deterministic prediction system

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Background:

The evaluation of numerical weather prediction models of the Meteorological Service of Canada (MSC) has been mostly performed using the global radiosonde network for upper air fields, and surface stations across North-America for weather elements. Atmospheric models for NWP are increasingly coupled with other components of the earth system such as the cryosphere and hydrosphere and facing an increasing demand for accurate forecasts at time scales ranging from near real time to sub-seasonal. It has become necessary to develop more comprehensive methods for model verification and improvement. In response, the Model Hydrological and Energy Budget Evaluation Project (MHEEP) has been created to evaluate and improve the mean state of all components of the hydrological cycle as well as surface and top of atmosphere energy budgets.

A) MHEEP

This protocol consists in performing four 13-month free runs (year 2009), starting from MSC analyses staggered by 1day+6 hours. Daily SST and sea-ice fraction are prescribed from MSC analyses. Ensemble annual and seasonal means are produced and compared to the following datasets:

Variable	Source 1	Source 2
Precipitation	Global Precipitation Climatology Project (provided by the NOAA/OAR/ESRL PSD)	ERA-interim
Precipitable water	Multi-Sat Merged Monthly 1-deg (Remote Sensing Systems sponsored by NASA)	ERA-interim
Liquid water path	Monthly SSMIS (Remote Sensing Systems sponsored by NASA)	ERA-interim
Cloud fraction	Combined Cloudsat-Calipso (Kay and Gettelman 2009)	ERA-interim
Latent/Sensible heat flux	Woods Hole OAFLUX	ERA-interim
TOA and Surface SW and LW fluxes	CERES-EBAF-3B / ERA-interim (NASA)	ERA-interim

Results are analysed to answer: I) What are main errors and are they physically significant? II) Is one experiment better than the other? Results are assessed variable-by-variable as well as in terms of mean TOA, atmospheric and surface energy budgets.

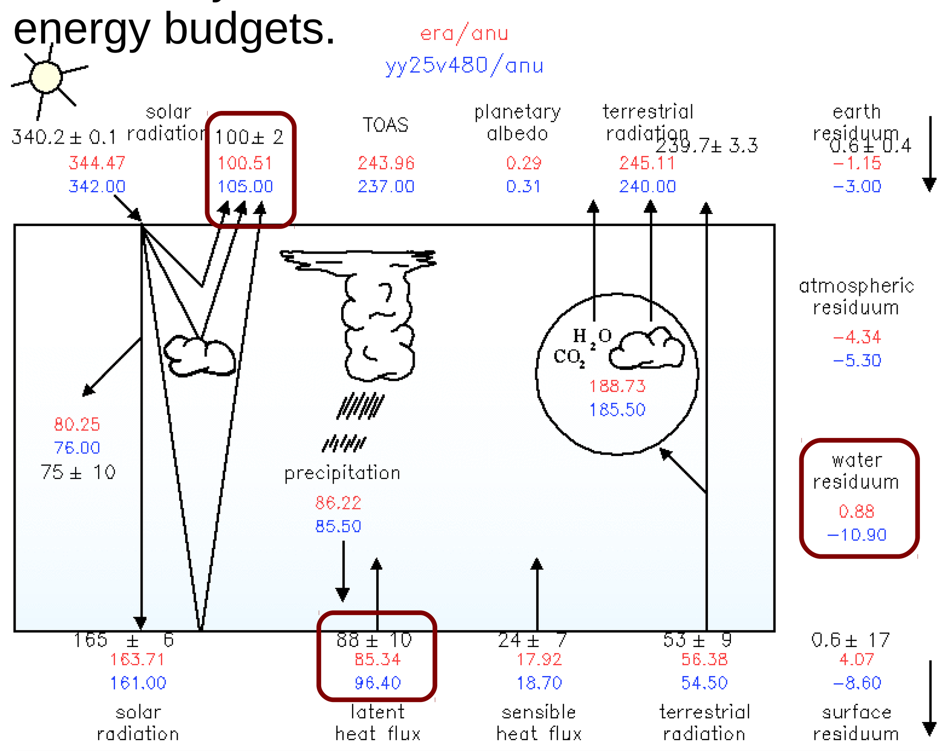


Figure A1: Annual mean energy budget summary. Black: multi-year climatologies with uncertainty. Red: ERA-int. Blue: Control runs

Main problems identified:

Water residuum: Shows a large imbalance between evaporation and precipitation.

Latent heat fluxes: Largest error in the energy budget. This error is suspected of being responsible for a cold bias in global SST from coupled atm-ocean long term free runs.

Solar radiation fluxes: Over-estimate of planetary albedo and under-estimate of SW flux at surface.

B) MHEEP: errors of 25km global deterministic prediction system

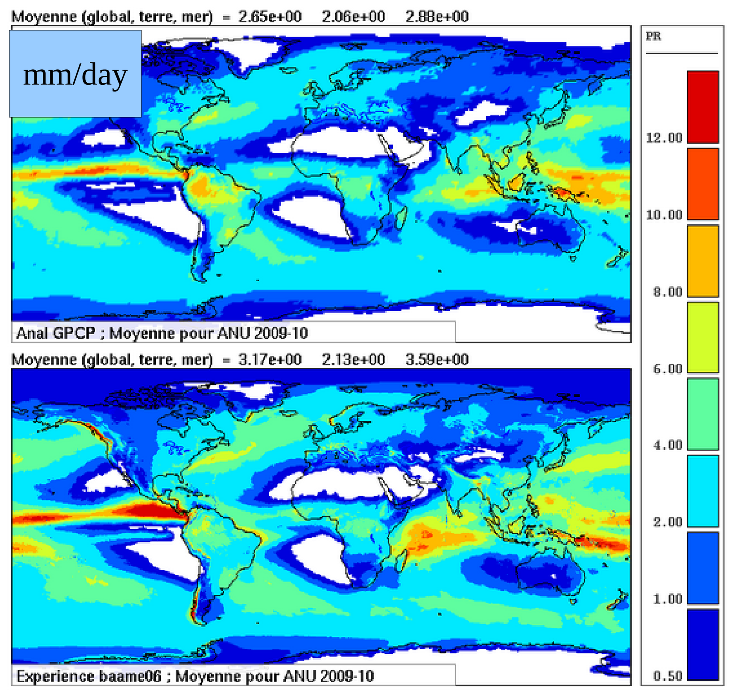


Figure B1: Annual mean precipitation Top: GPCP analysis. Bottom: with water residuum corrected.

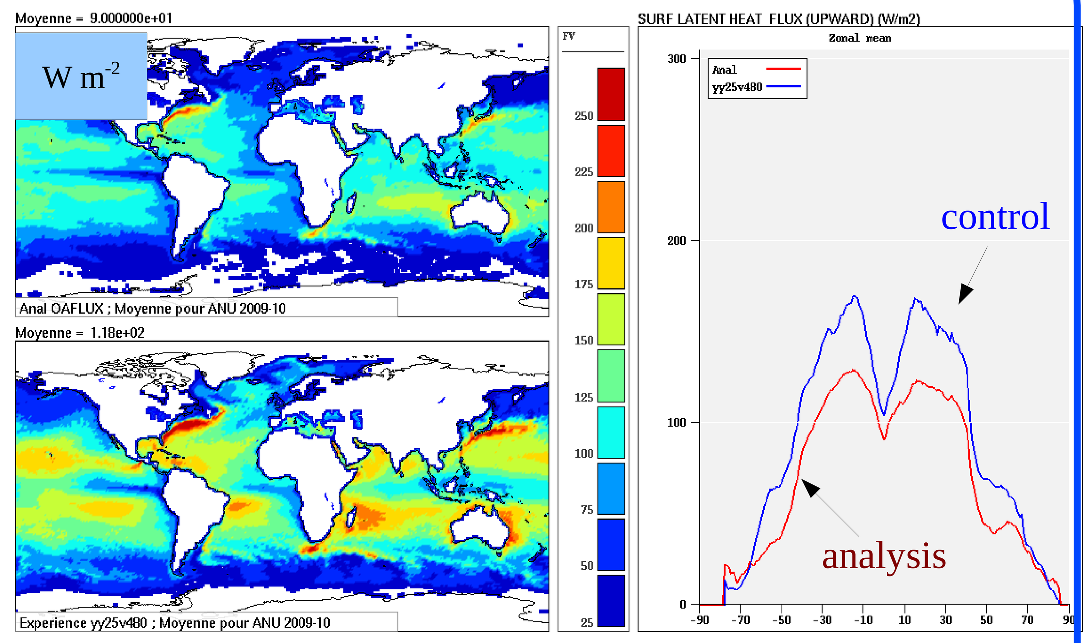


Figure B2: Left: Annual mean latent heat fluxes of control (bottom) against OAFLUX analysis (top). Right: Zonal means (control in blue).

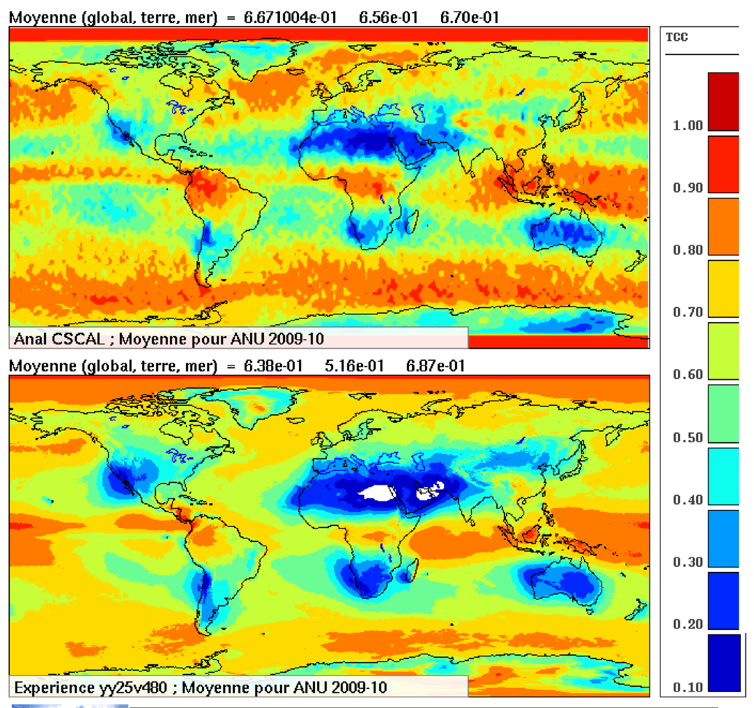


Figure B3: Annual mean true cloud cover. Top: Cloudsat-Callipso product. Bottom: Control runs

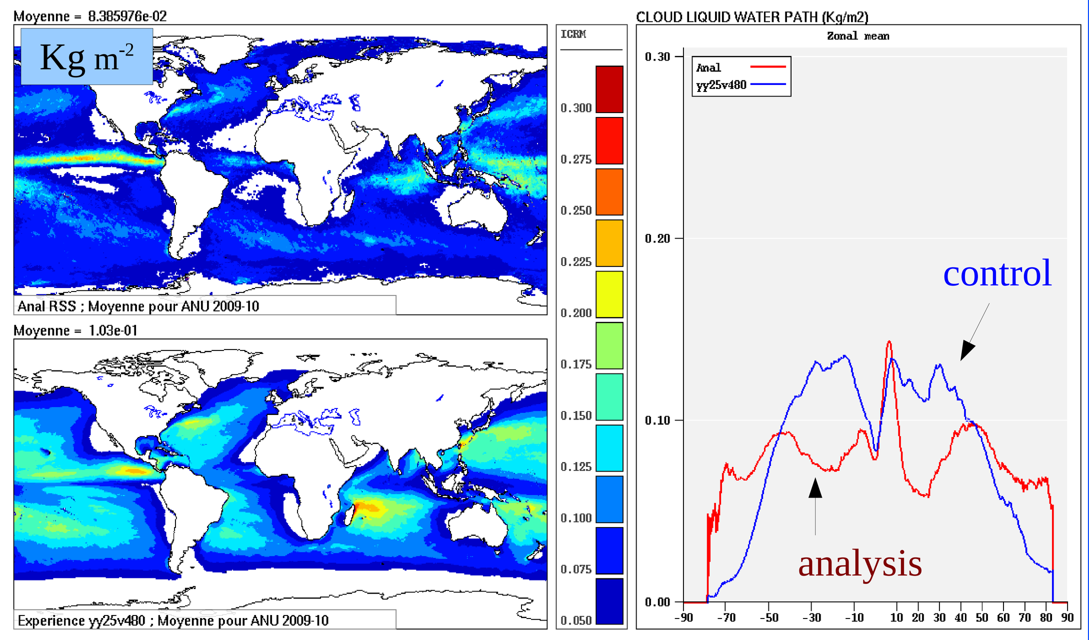
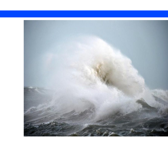


Figure B4: Cloud liquid water path annual mean. Top left: RSS analysis. Bottom left: Control runs. Right: Zonal means (control in blue)

Discussion: Water residuum error was caused by the shallow convection scheme, which did not conserve water vapor. Enforcing conservation reduces imbalance but results in a significant increase in precipitation (over-estimate, see B1). Latent heat flux errors **(+ 30 W m-2)** are widespread but particularly strong over tropical oceans. There is a general under-estimate of cloud cover over land while both cloud cover and liquid water paths are too high over the tropical oceans. These cloud biases contribute to the solar radiation flux biases.

C) Attacking excessive latent heat fluxes



Strategy (I) - Surface properties over oceans: adding salinity effects for evaporation, diurnal cycle of the SST, smooth-surface based roughness lengths for heat and moisture.

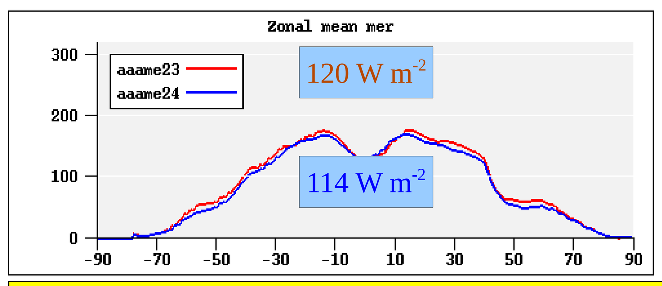


Figure C1: MHEEP annual zonal means for latent heat fluxes over oceans. Red: Control. Blue: with sfc modifications

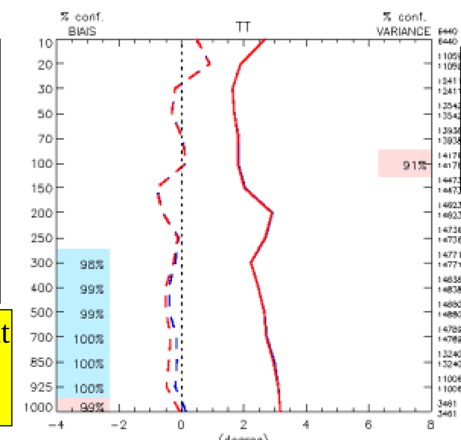


Figure C2: Bias (dash) and standard deviation of Temperature error against radiosondes (Model-Obs) for 120h progs over winter 2011 for the North Hem. **Blue** denotes control runs

Discussion: Modest decrease of 6 W m-2 obtained. In NWP mode, cooling of 0.5 K in most of troposphere ensues.

Strategy (II) - Planetary boundary layer scheme and deep convection(CPS): ocean latent heat flux bias correlated with a near-surface dry bias, addressed using an updated cloud treatment in the TKE-based PBL scheme, revised mixing lengths for stable/unstable layers, and deeper downdraft detrainment in the CPS.

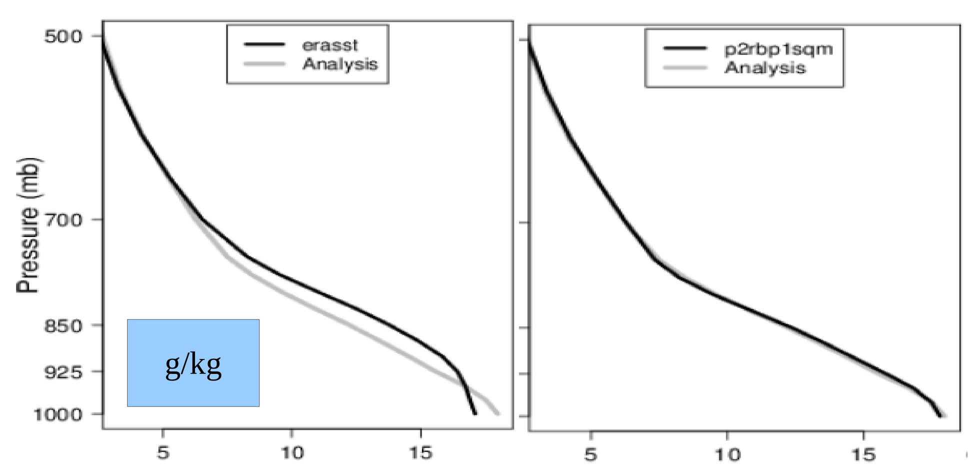


Figure C3: Left : Mean profiles of specific humidity of 24hr control model forecast (black) and verifying ERA-int analysis (grey) over NW pacific. Right: With PBL and CPS modifications (black)

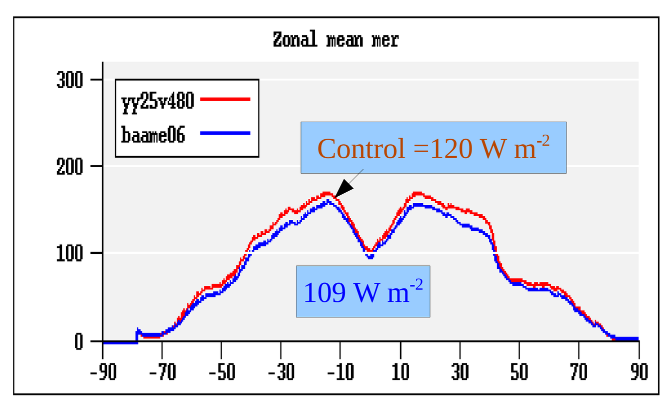


Figure C4: As for C1. Further decrease in fluxes

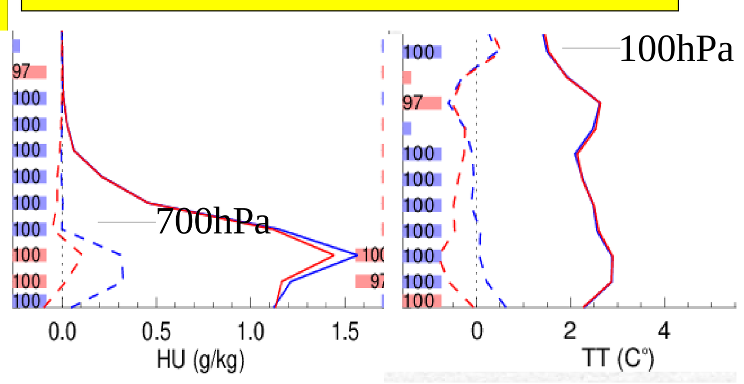
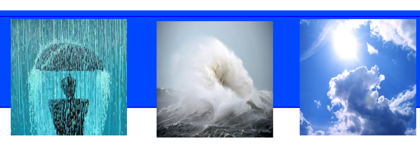


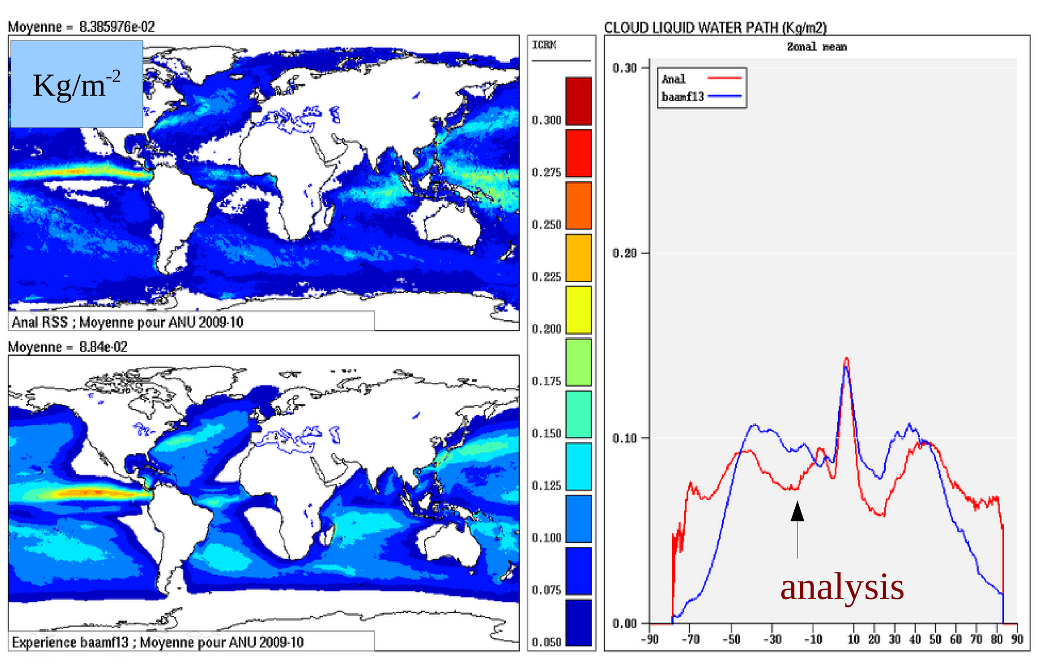
Figure C5: Bias (dash) and standard deviation of Humidity and temperature error against analysis (Model-ERA-int) for 120h progs over winter 2014 for the North Hem. **Blue** denotes control runs

Discussion: comparison with ERA-int analyses shown in fig C3-left shows a possible excessive mixing and/or drying in the PBL for unstable regimes. Modifications to PBL scheme and CPS lead to improved humidity profiles (C3-right), further reduction in latent heat fluxes (C4) and improved humidity scores(C5-left). However, a cold bias (C5-right) results.

D) Balancing act



Eliminating water residuum error (A1), reducing latent heat fluxes and correcting humidity profile errors in pbl has improved the hydrological and energy budgets. However the resultant precipitation over-estimate and cold tropospheric bias are not acceptable in an NWP context. It was necessary to revert to a Charnock-based thermal surface roughness length over oceans to reduce cold bias. Other changes were made including: new shallow convection scheme (modified Bechtold 2001), CPS triggering dependent on convective scale velocity over oceans, convective momentum transport by deep convection.



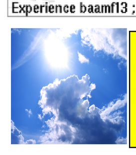


Figure D1: MHEEP Cloud liquid water path annual mean. Top left: RSS analysis. Bottom left: Final runs. Right: Zonal means (final runs in blue)

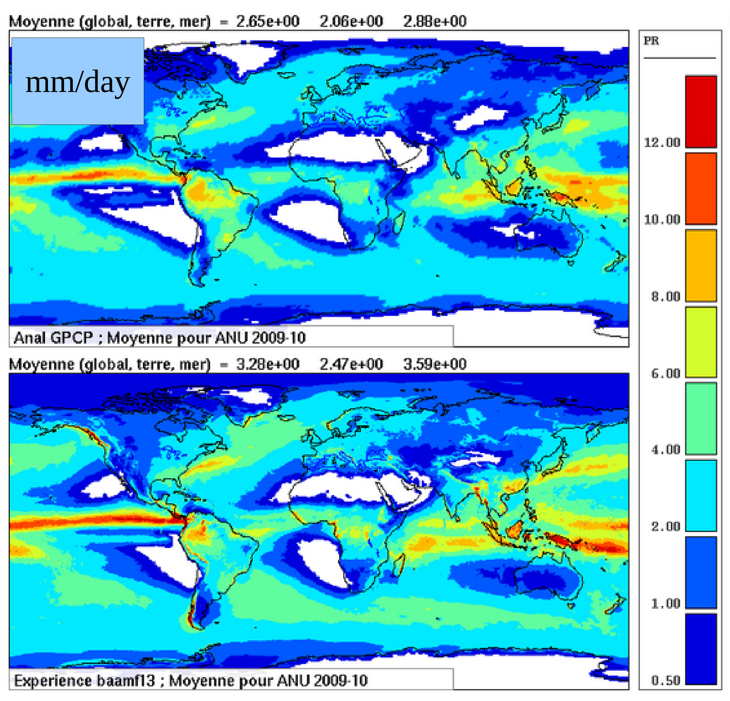


Figure D2: MHEEP Annual mean Precipitation. Top: GPCP analysis. Bottom: Final runs

Discussion: Last set of model changes has reduced cold bias (not shown) but has further increased over-estimate of precipitation. However, overall spatial structure of both the precipitation and cloud liquid water paths has improved relative to control runs (see fig. B1 and B4). Solar radiative fluxes have also improved (not shown).

Conclusions: The MHEEP protocol has proven a useful tool to monitor impacts of model changes on the global hydrological and energy budgets. Improvements in these fundamental elements does not automatically translate into gains for medium range forecasting. A large set of model physics changes have been tested and should be included in an upcoming upgrade of the Canadian global deterministic prediction system. However, precipitation over-estimate accompanied by a tropospheric cold bias remains an issue to understand and resolve.

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