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RECENT PROGRESS FOR ALL-SKY MICROWAVE RADIANCE ASSIMILATION IN ENVIRONMENT CANADA'S GLOBAL DETERMINISTIC WEATHER PREDICTION SYSTEM

Maziar Bani Shahabadi*, Mark Buehner, and Sylvain Heilliette

Meteorological Research Division

* Email: maziar.banishahabadi@canada.ca

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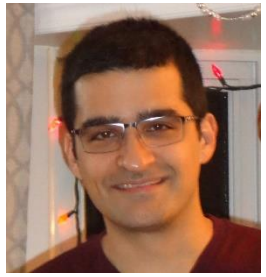

Environment and Climate Change Canada's 50th anniversary
50e anniversaire d'Environnement et Changement climatique Canada
Meteorological Service of Canada's 150th anniversary
150e anniversaire du Service météorologique du Canada

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BACKGROUND

- Satellite radiances are most assimilated observations for numerical weather prediction (NWP) (Buehner et al., 2018).

- Data assimilation (DA) systems primarily use cloud-free radiance observations due to the limitations of forecast model physics, radiative transfer model, and strong non-linearity of the observation operator to utilize cloud-affected radiance observations.

- All-sky approach: assimilating observations directly as radiances, whether they are clear, cloudy or precipitating, using models (for both radiative transfer and forecasting) that are capable of simulating cloud and precipitation with sufficient accuracy (Geer et al., 2018)

- Several other NWP centers (e.g. ECMWF, UK Met Office, NCEP, JMA), achieved the operational implementation of all-sky microwave radiance assimilation. At Environment and Climate Change Canada (ECCC), only clear-sky radiances are assimilated within the current operational Four-Dimensional Ensemble Variational (4D-EnVar) DA system.

OBJECTIVES

- This study describes the first attempt to perform all-sky assimilation of microwave radiances at ECCC in the global deterministic weather prediction system (GDPS, Buehner et al., 2015; McTaggart-Cowan et al., 2019).

- We focus on the all-sky assimilation of Advanced Microwave Sounding Unit-A (AMSUA) channels 4-5 and Advanced Technology Microwave Sounder (ATMS) channels 5-6, sensitive to atmospheric temperature variations in the lower troposphere, over oceans for non-precipitating scenes.

- In the current operational system, model cloud is not used in the observation operator. For all-sky assimilation, in addition to using model cloud in observation operator, combined cloud information from model and observation is used for quality control and assimilation of cloudy observations.

METHODOLOGY

- In all-sky assimilation, the symmetric model for observation minus background departures (OMB or innovations) stddev (Geer and Bauer, 2011) was used to derive observation error stddev as a function of hydrometeor amount.

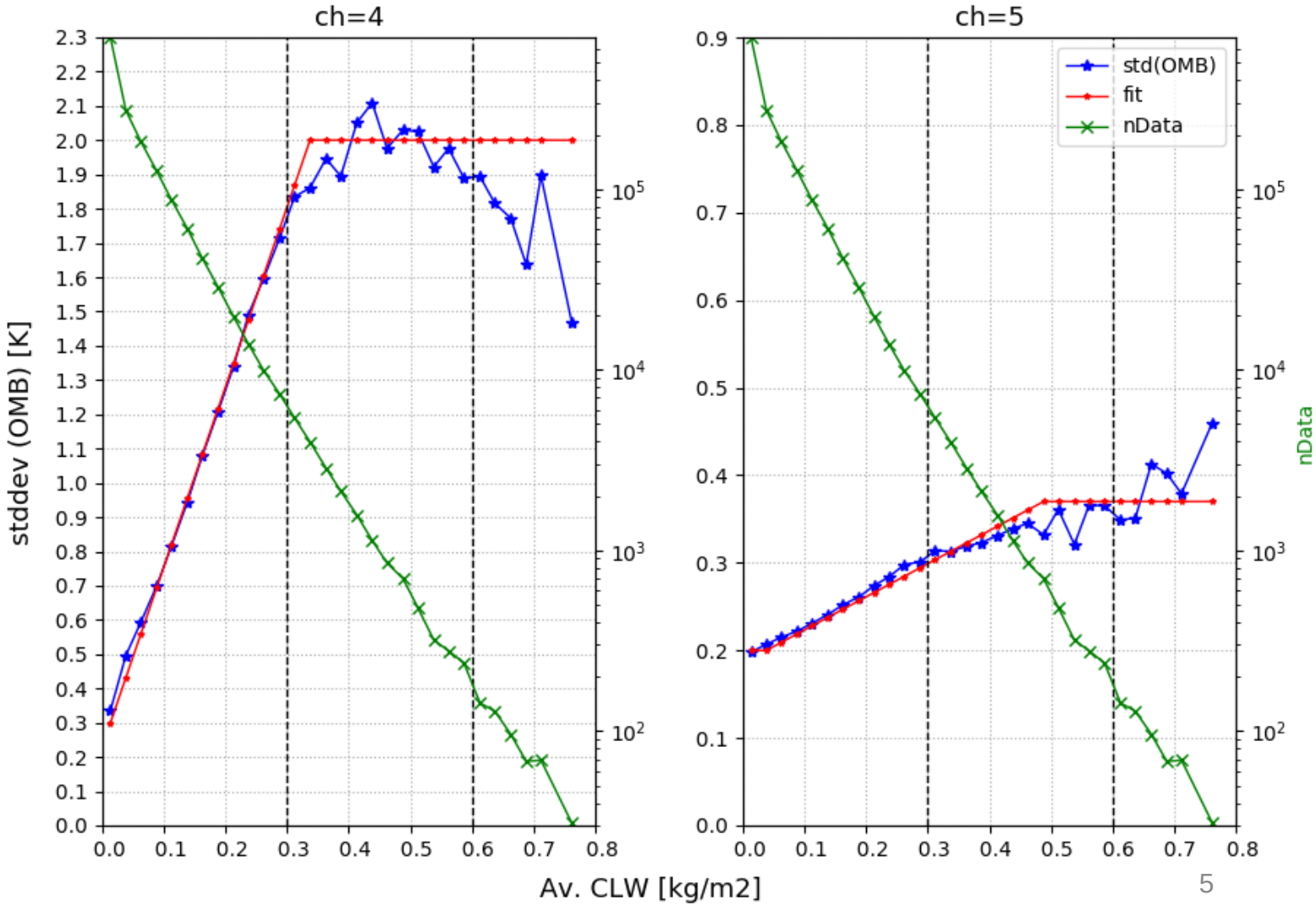
- Cloud Liquid Water (CLW), obtained from AMSUA/ATMS channel 1 and 2 brightness temperatures are used to indicate cloudiness of the pixel in observation space.

- CLW calculated from AMSUA/ATMS observations (O) and simulated (B) brightness temperatures are averaged to yield symmetric CLW estimate from model and observation.

- OMB are computed for one month, and the piece-wise linear fit to stddev(OMB) vs. CLW_{avg} is the model for innovation stddev.

MODEL FOR INNOVATION STDDEV

Fit to the stddev(OMB) to obtain the observation error as function of CLW_{avg} for AMSUA channel 4-5.

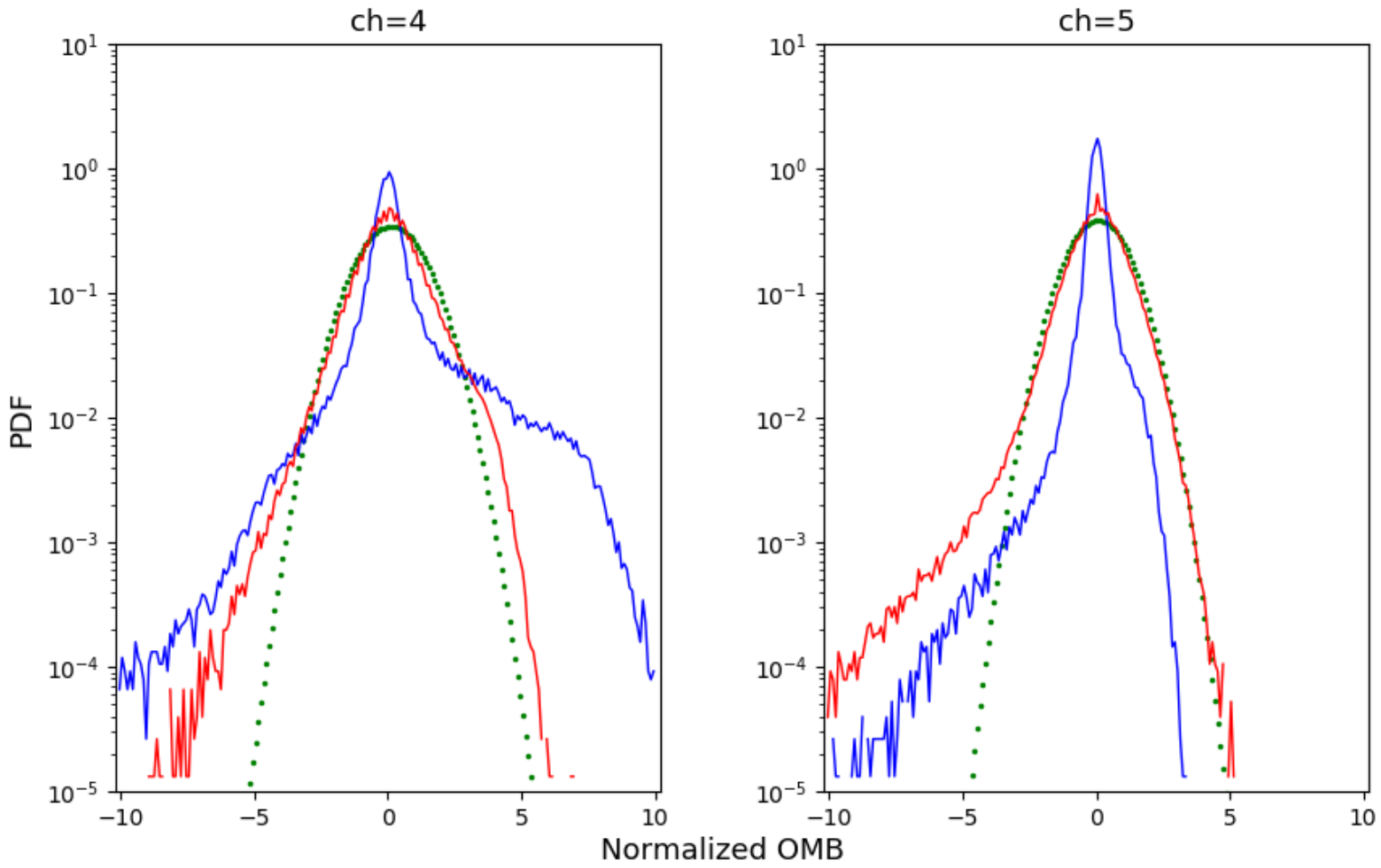


Source: Shahabadi and Buehner (2021), MWR, submitted.

MODEL FOR INNOVATION STDDEV

Histogram for AMSUA channels 4-5 OMB normalized by the entire sample stddev (blue) or by fit to all-sky innovation stddev (red). Gaussian distribution shown in green dots.

Samples are over ocean for the period from 1 to 5 July 2019.



Source: Shahabadi and Buehner (2021), MWR, submitted.

ASSIMILATION EXPERIMENTS

- Global 4D-EnVar assimilation experiments, using a forecast model with 15 km forecast model and 39 km analysis increments, were performed to examine the impact of all-sky assimilation of microwave radiances.

- Evaluating AMSUA all-sky:
  - Control: clear-sky assimilation, similar to the operational configuration at ECCC.
  - Experiment: all-sky only for AMSUA channels 4-5 (*AMSUA all-sky*).
- Evaluating ATMS all-sky:
  - Control: *AMSUA all-sky*.
  - Experiment: all-sky for AMSUA channels 4-5 and ATMS channels 5-6 (*AMSUA+ATMS all-sky*).

- Summary of changes to perform all-sky assimilation (more details in “additional slides”):
  a. Scale model cloud by 0.5 before using in observation operator.
  b. Model for the innovation stddev for quality control and assimilation of AMSUA/ATMS observations.
  c. Relaxing criteria for quality control of the AMSUA/ATMS observations.
  d. Using clear observation and model for bias correction of the AMSUA/ATMS observations.
  e. Additional observation error inflation at analysis due to cloud placement and CLW difference between observation and model (similar to Zhu et al. (2016)).

- Experiments were conducted for two periods of two months during Summer 2019 and Winter 2020.

IMPACT ON FIT OF THE BACKGROUND STATE TO OBSERVATIONS

Stddev(OMB) of thinned bias-corrected ATMS observations for AMSUA all-sky experiment, normalized by the stddev(OMB) of clear-sky experiment.

Error bars show significance interval from F-test at 95% confidence level.

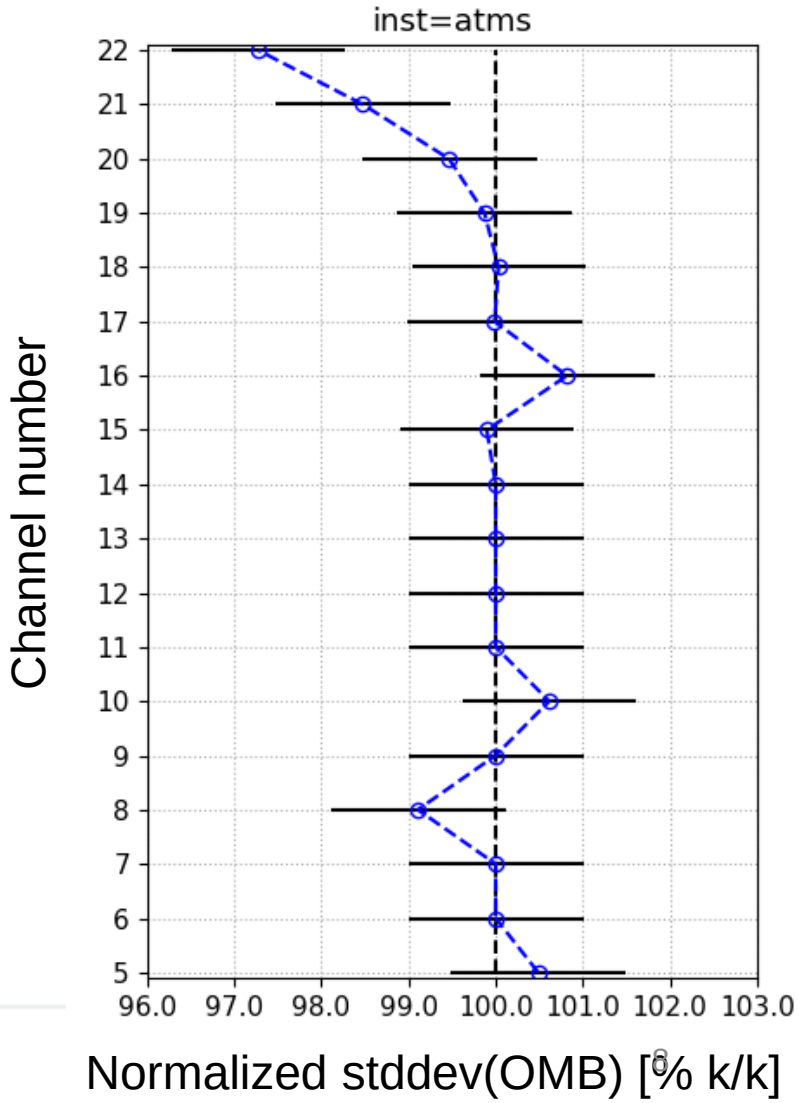
The statistics are for observations over ocean for 1 to 31 January 2020 period.

The normalized stddev(OMB) below/above 100 indicate more/less fit of background state to observation. Better estimate of change in background state as same quality control criteria and forward operator were used in experiment and control for ATMS.

Statistically significant changes in normalized stddev(OMB) for:

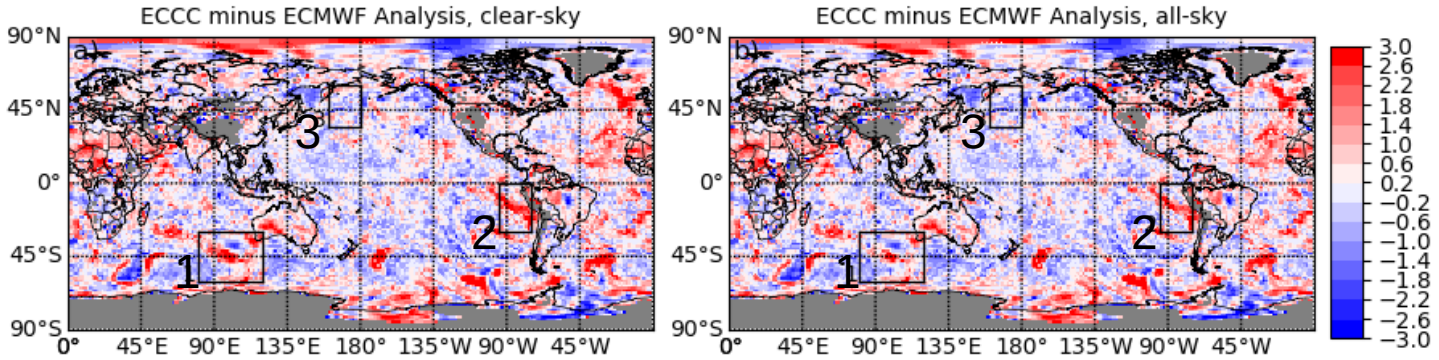
- ATMS temperature channels (5-16): 1% decrease for ch. 8.
- ATMS humidity channels (17-22): 1.5-3% decrease for ch. 21-22.

Source: Shahabadi and Buehner (2021), MWR, submitted.



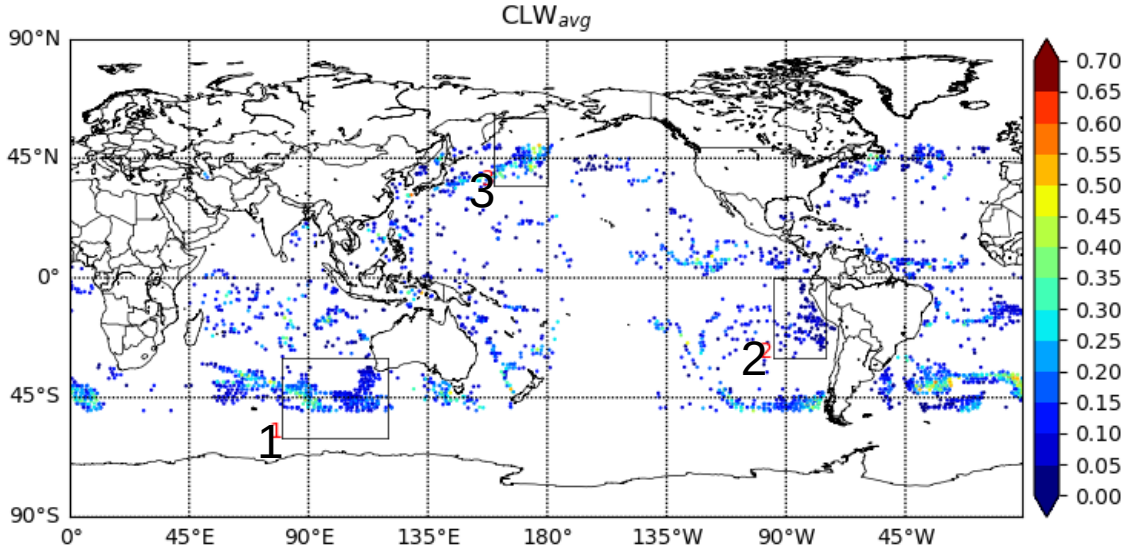
IMPACT ON TEMPERATURE ANALYSIS

- Difference in 850 hPa temperature analysis (K) at 00 UTC 1 July 2019 between ECMWF and (a) clear-sky and (b) AMSUA all-sky experiments



- Compared to the clear-sky, the AMSUA all-sky experiment analysis is more consistent with ECMWF temperature analysis in regions 1-3.

- Locations and the CLW_{avg} values for these observations are shown.



Source: Shahabadi and Buehner (2021), MWR, submitted

IMPACT ON UPPER-AIR FORECAST

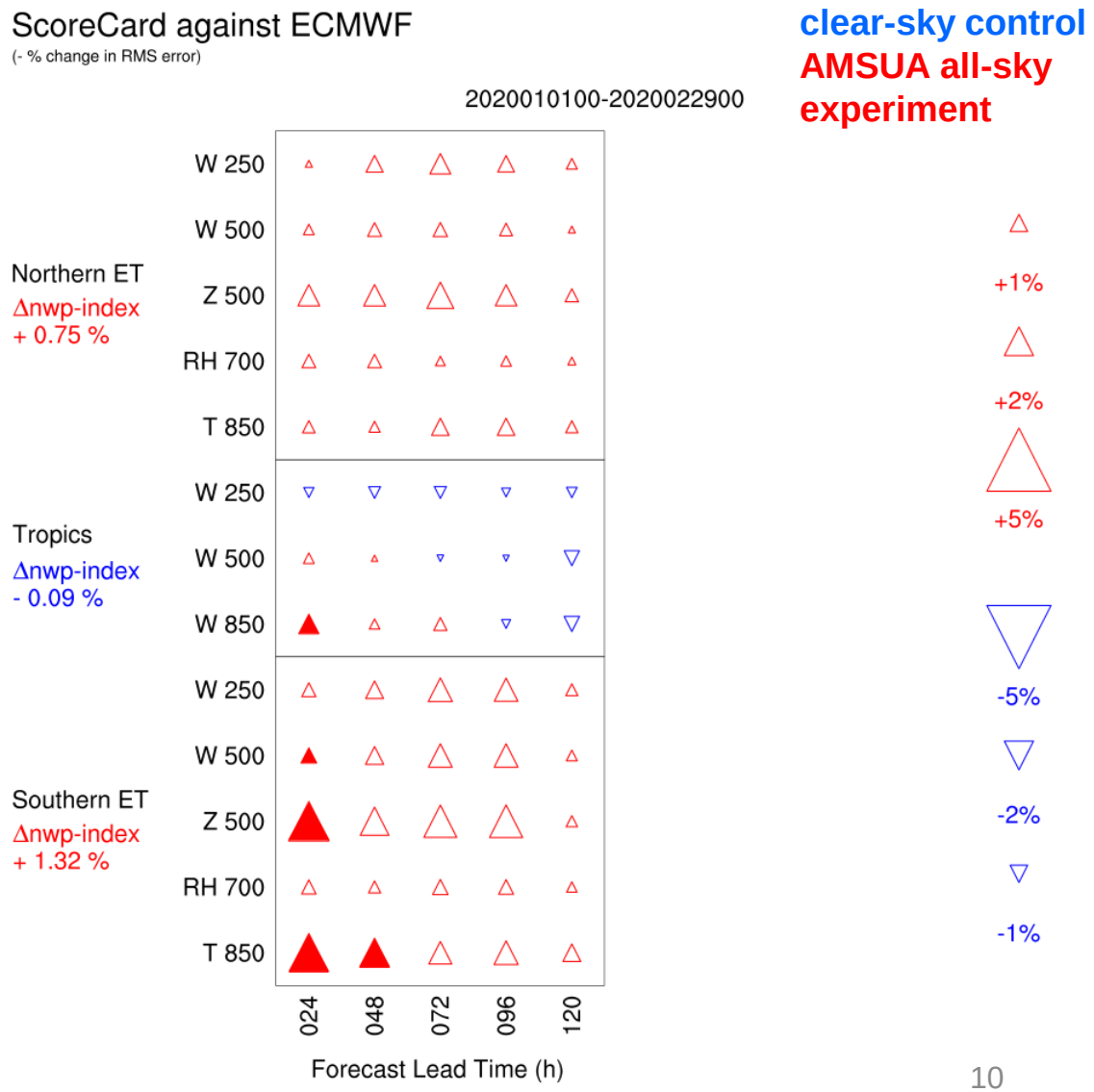
The scorecard for change in forecast RMSE for winter 2020 clear-sky and all-sky experiments. Red (Blue) triangle indicates better AMSUA all-sky (clear-sky), compared to the reference ECMWF analyses.

Filled symbols show 90% statistical significance with bootstrap method.

Variables compared: wind (W), geopotential height (Z), relative humidity (RH), and temperature (T) at 250, 500, 700, 850 hPa levels and Northern extra-tropics, Tropics, and Southern extra-tropics domains.

3-4% statistically significant reduction in 850 hPa forecast RMSE in Southern Extratropics up to 2 days in AMSUA all-sky experiment.

One month long Summer 2019/Winter 2020 ATMS all-sky experiment does not show statistically significant impact on forecast skills (not shown).



SUMMARY

- This study describes the first attempt to assimilate cloud-affected AMSUA channels 4-5 and ATMS channels 5-6 over oceans for non-precipitating scenes in the global deterministic weather prediction system (GDPS) at ECCC.

- Symmetric model for the stddev(OMB) is used for background check and defining the stddev of observation error.

- The numbers of assimilated AMSUA/ATMS temperature channels are increased by 5-12%.

- 1-4% reduction in error stddev for the analysis and forecasts of all variables up to maximum 4 days in AMSUA all-sky experiment. No statistically significant impact on forecast skills when performing ATMS all-sky.

- All-sky assimilation of AMSUA channel 4-5 in GDPS is approved for operational implementation in Fall 2021. All-sky assimilation of ATMS channels 5-6 in GDPS will be proposed for next operational implementation in Fall 2023.

FUTURE WORK

- Refinement of current all-sky methodology:
  - Adding outer-loop to the 4D-EnVar system to improve cloud representation used in DA systems.
  - Upgrading the innovation stddev model: scan/latitude dependency.
- Extend all-sky assimilation to microwave humidity sounding channels: upgrading observation operator to RTTOV-SCAT
- Extend all-sky assimilation to the microwave imagers and infrared sounding instruments.
- All-sky assimilation over land.

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THANK YOU

ADDITIONAL SLIDES

CHANGES TO MODEL CLOUDS

- In the current operational system, model cloud is not used in the observation operator.

- For all-sky assimilation, in addition to using model cloud in observation operator, combined cloud information from model and observation is used for quality control and assimilation of cloudy observations.

- Comparison of the background and observation components of CLW_{avg} (CLW_{FG} and CLW_{obs}) showed the background state clouds are largely overestimated (CLW_{FG}>CLW_{obs}).

- OMB values change considerably due to overestimation in model cloud (~10K).

CHANGES TO MODEL CLOUDS

- We rely on the background state clouds in DA since there is no outer-loop during current 4D-EnVar minimization at ECCC.

- To protect the analysis, the background clouds are scaled globally by a multiplicative factor, applied to the vertical cloud profile, before using it in the observation operator.
  - Simple solution to reduce the overall model cloud overestimation, but does not change the error due to horizontal mislocation of model clouds.

- We conducted multiple sensitivity experiments by running assimilation cycles with different cloud scaling factor and the factor 0.5 yielded the best forecast results for low tropospheric mean temperature and humidity biases.

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CHANGES TO BACKGROUND CHECK

- Use model cloud in the observation operator.
- Use of state dependent innovation stddev (σ^{all}) values for quality control of the observations. Observation is rejected if OMB > $F.\sigma^{all}$
- Moderately cloudy AMSUA channels 4-5 observations ($CLW_{avg} < 0.6$ kg m^{-2}) are assimilated (as opposed to $CLW_{obs} < 0.3$ kg m^{-2} in the clear-sky stream).
- Removal of observations affected by extreme scattering: Cloud effect is measured as the difference between the simulated or observed radiance with clear-sky simulated radiance of channel 5 (sensitive to scattering):

  $BT_{ch5\ cloudy} - BT_{ch5\ clear} < -0.5$ K OR

  $BT_{obs} - BT_{ch5\ clear} < -0.5$ K
- There is an increase in number of QC-passed observations by **5-12%**.

CHANGES TO BIAS CORRECTION

Original bias correction:

- An unbiased analysis by assimilating non-radiance observations in 3DVar system.

- Linear regression by fitting the quality controlled and thinned radiance observations to the past seven days of these 3DVar analyses to estimate the bias model coefficients.

- Bias model predictors are 1000-300, 200-50, and 50-5 hPa geopotential height thicknesses, and a scan-dependent bias.

Changes for all-sky assimilation:

- In addition to using model cloud in the observation operator, only quality controlled radiances where model and observed cloud information both indicate clear-sky condition ($CLW_{avg} < 0.05$ kg m^{-2}) are used to compute bias correction coefficients.

- The choice is justified as: 1-Majority of the observations are clear-sky; 2- cloud-affected observations have large OMB values and large impact on the estimated bias correction values; 3- bias correction of clear-sky observations are not affected by the remaining model cloud bias.

CHANGES TO 4D-ENVAR

- Cloud variable is added to the list of analyzed variables, even though its increment is discarded and not used at forecast step. Two additional mechanisms affect non-cloud analyzed variables during all-sky assimilation: 1-background error cross-covariance with cloud field; 2- mapping the cloudy radiances to the non-cloud state variable through Jacobians.

- Additional observation error inflation during analysis to reduce weight of observations during analysis step when there is disagreement between model and observation:

  1) cloud misplacement:

  $(CLW_{obs}-0.02)(CLW_{FG}-0.02)<0$ & $|CLW_{obs}-CLW_{FG}|>0.005$ -> **E1**=|OMB|

  2) cloud over/under estimation:

  E2=13 . $|CLW_{obs}-CLW_{FG}|$. IF . σ^{all}

  inflatedObsError = $((IF . \sigma^{all})2 + (\mathbf{E1}+\mathbf{E2})^2)^{0.5}$ (IF: inflation factor)