

Implementation of the Community Land Model (CLM) 4.5 Lake Model in the NOAA Unified Forecasting System (UFS)

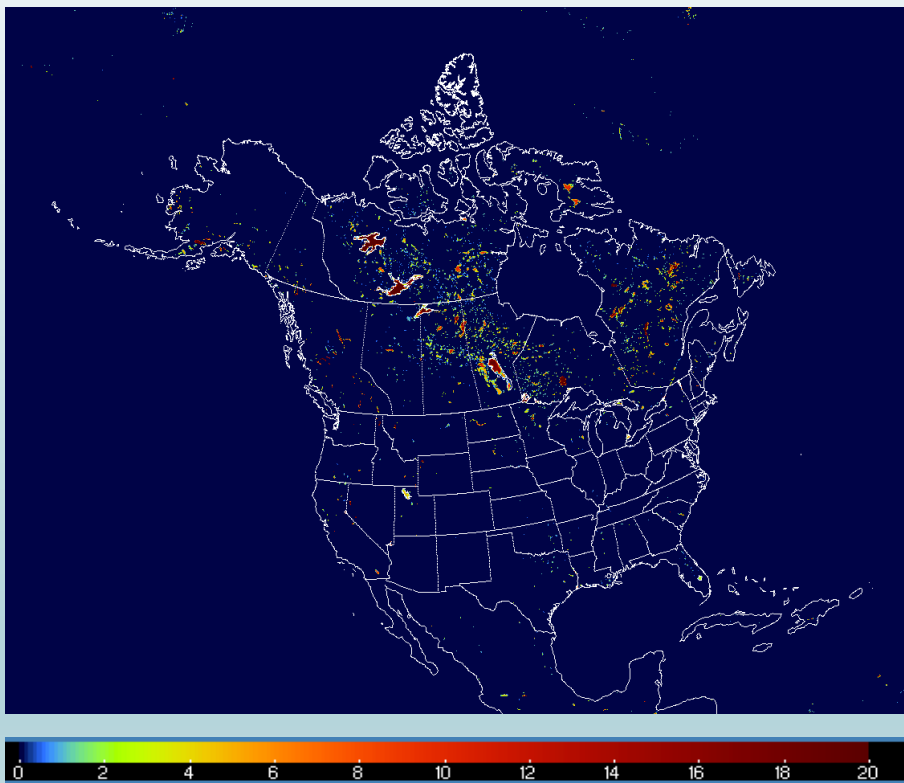
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UFS-based Rapid Refresh Forecasting System (RRFS) – a next-generation NOAA weather model

- Experimental RRFS is under testing at the NOAA Environmental Modeling Center (EMC)
- The RRFS runs on North America Domain with 3-km horizontal spacing
- RRFS physics – same as in current operational regional model HRRR:
 - RUC land-surface model
 - MYNN surface and boundary layer schemes
 - aerosol-aware Thompson microphysics
 - RRTMG radiation
- The 1D CLM lake model (CLM-Lake) - implemented in the UFS in October 2023 via Common Community Physics Package (CCPP)

GLDBv3 Lake depths in North America RRFS



- If a lake covers >75% of grid cell, then this point is assigned to be a lake
- Large lakes (>15,000 km²) are excluded from the lake mask
- The RRFS lake depth is initialized from GLDBv3 data, most of the lakes have constant depth (high-resolution bathymetry GLOBathy is in the testing stage)
- Lake variables are initialized from the previous forecast (cycled), ~10 months of cycling in the RRFS

CLM-Lake Model characteristics

Community Land Model (CLM) 4.5 Lake Model main characteristics
(see Section 9 in CLM 4.5 documentation [CLM version 4.5](#))

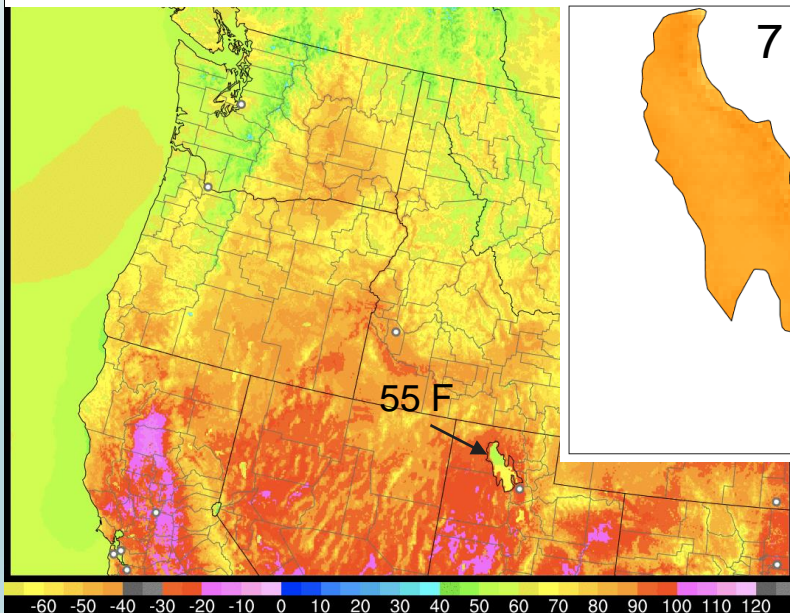
- Vertical structure:
 - Up to 5 levels in snow (if exists)
 - 10 levels in lake
 - 10 levels in bedrock
- Molecular, eddy and convective mixing;
- Freezing/thawing in snow/lake/soil, fractional lake ice;
- Surface fluxes computed using internal surface layer scheme;
- Temperature is continuous in the vertical from resolved snow layers (if present), then the lake body, and then the soil and bedrock - total 25 levels for temperature

Modifications to the CLM-Lake in RRFs

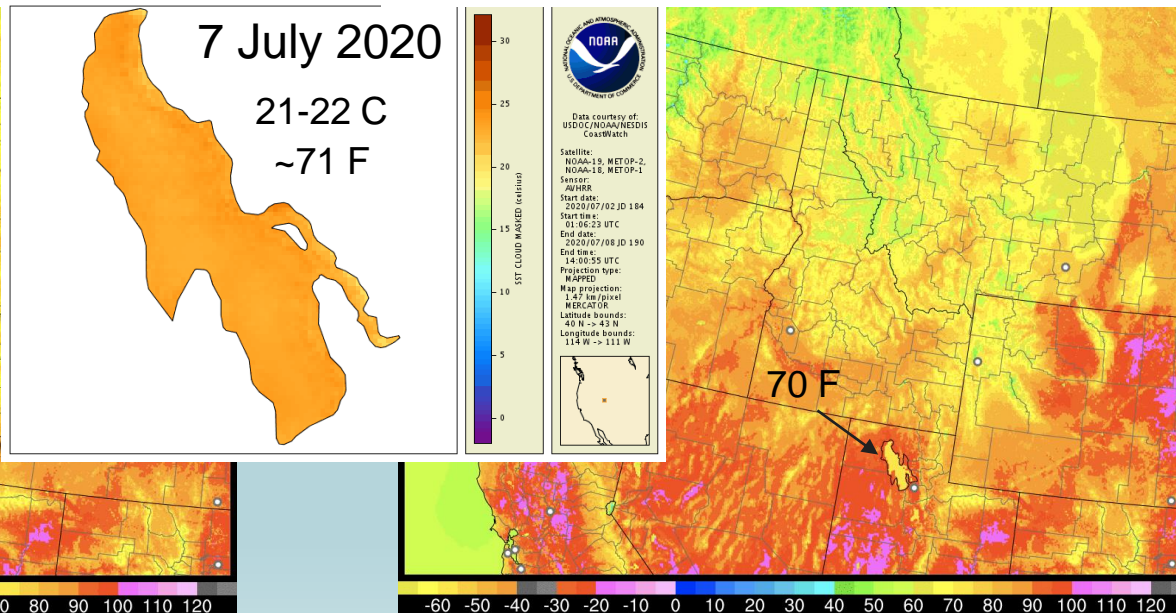
- Bug fixes in lake initialization in WRF-based version of the CLM lake model
- Changes in the main lake subroutine:
 - COARE formulation for thermal roughness length
 - Bug fix for fractional sea ice during the thawing process which was preventing from complete lake ice melting in the cycled models
 - Salinity is not resolved in the CLM lake model, therefore, modifications were made for the Great Salt Lake (GSL): use bi-monthly lake climatology to limit temperature changes ($\pm 3\text{K}$), also freezing is not allowed
- All lake variables are continuously cycled (initialized from the previous forecast, Benjamin et al. 2022, <https://doi.org/10.5194/gmd-15-6659-2022>)

The “salinity fix” for the Great Salt Lake corrects too cold lake temperatures

Skin temperature analysis before the GSL “salinity fix”

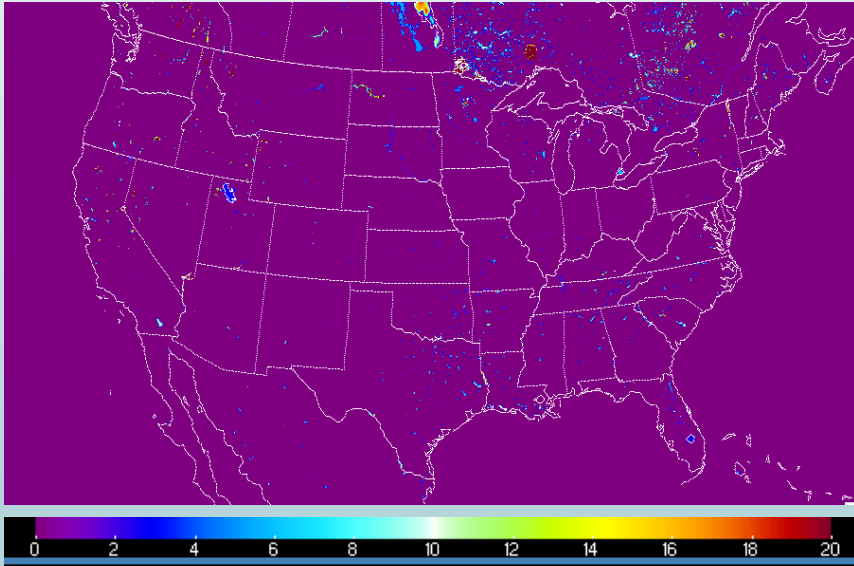


Skin temperature after the climatological bounding for the GSL



CLM-Lake's testing in cycled retrospective RRFs on CONUS domain

GLDBv3 Lake depth (m)



- **Control – w/out CLM-Lake**, **Test – with CLM-Lake**;
- The Great Lakes are excluded from the lake mask;
- Surface verification for 21 stations near lakes:
 - KPEO, KITH - Finger Lakes, NY
 - KMTC, CYQG - Lake St. Clair
 - CYRJ - Saint-Jean Lake
 - CYYW - Lake Nipigon
 - KFGN, KRRT, CYQK, KBDE, CTRA – Lake of the Woods
 - CXGH - Lake Winnipeg
 - CWOJ - Lake Manitoba
 - KVWU - Red Lake
 - KHIF, KSLC - The Great Salt Lake
 - KTVL - Lake Tahoe
 - KOSH - Lake Winnebago
 - KOBE - north of Lake Okeechobee
 - KEZS - Shawano Lake
 - CWGL - Lake Simcoe

Summer RRFS retro, 21-27 July 2022

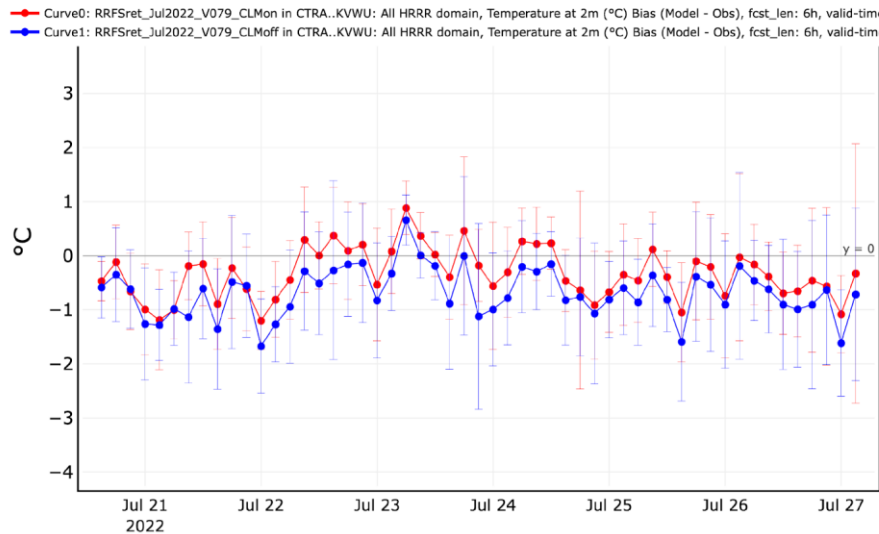
2-m temperature, 6-h forecast, lake stations

Red – with CLM-Lake
Blue – no CLM-Lake

Surface : Time Series 07/20/2022 09:00 -07/27/2022 09:00 : no diffs MATCHED

bias

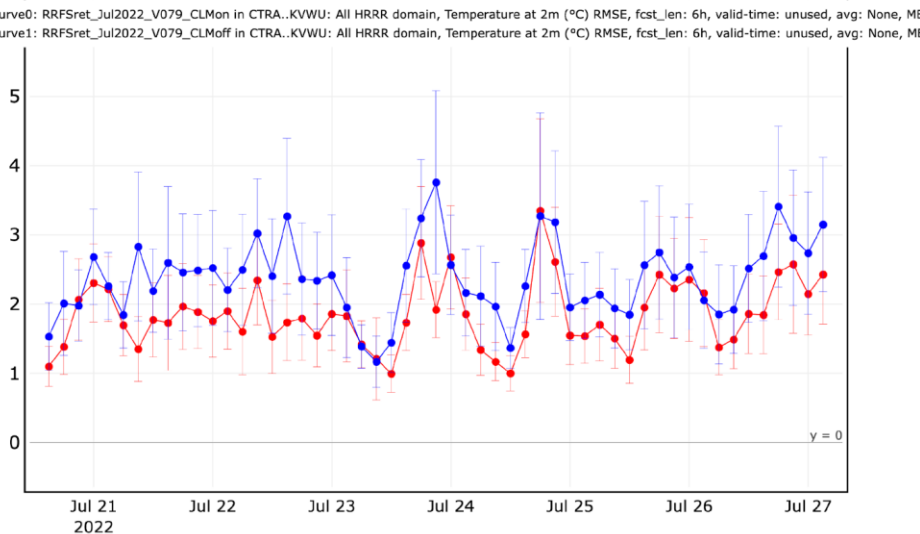
Curve0 mean = -0.3343, median = -0.3860, stdev = 0.4604
Curve1 mean = -0.6826, median = -0.6316, stdev = 0.4508



Surface : Time Series 07/20/2022 09:00 -07/27/2022 09:00 : no diffs MATCHED

RMSE

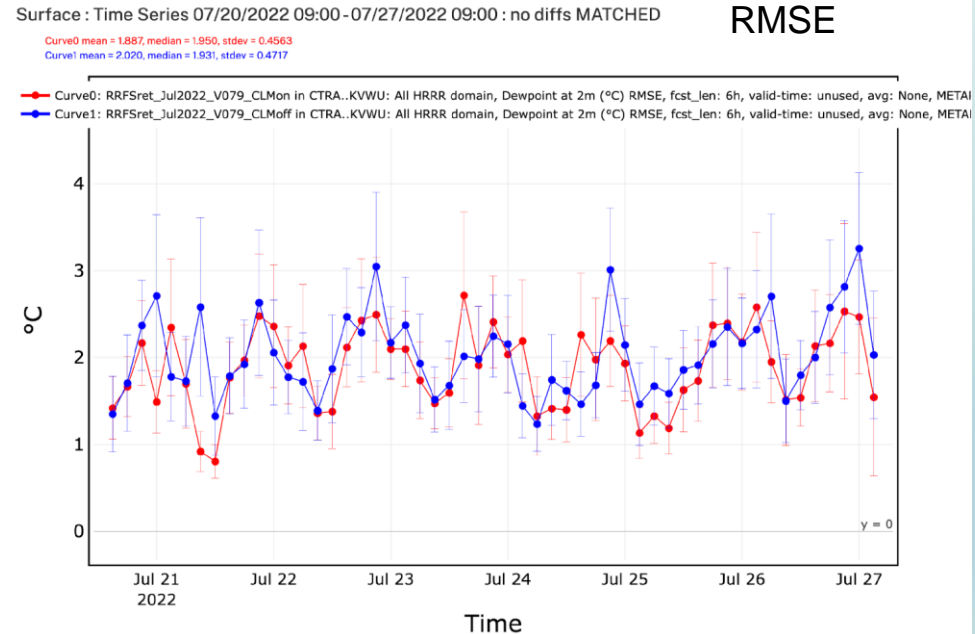
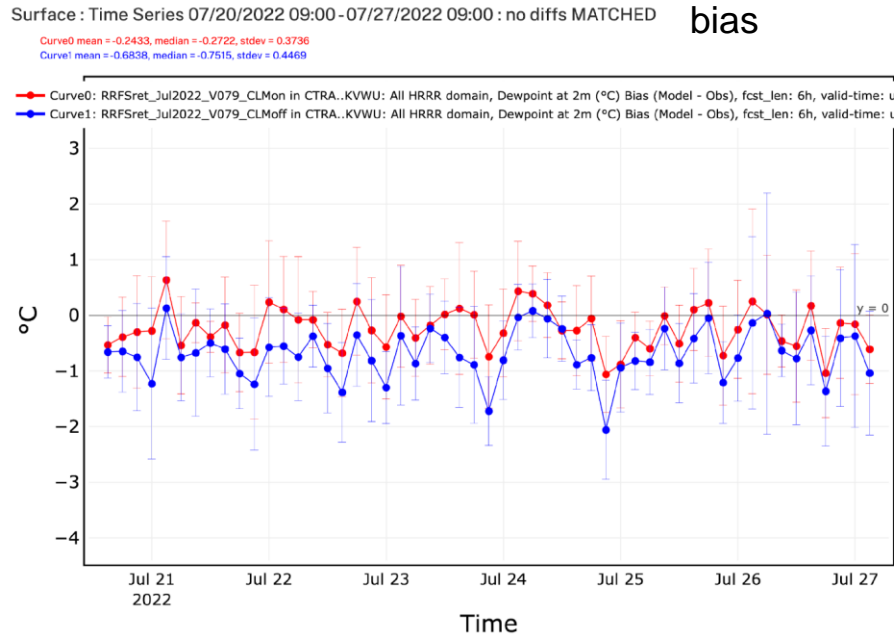
Curve0 mean = 1.845, median = 1.791, stdev = 0.4900
Curve1 mean = 2.371, median = 2.383, stdev = 0.5462



Summer RRFS retro, 21-27 July 2022

2-m dew point, 6-h forecast, lake stations

Red – with CLM-Lake
Blue – no CLM-Lake



Summer RRFS retro, 21-27 July 2022

10-m wind, 6-h forecast, lake stations

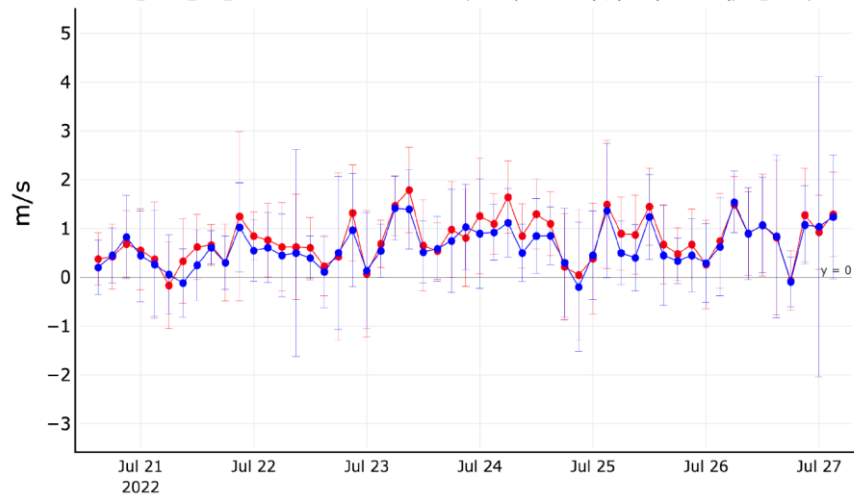
Red – with CLM-Lake
Blue – no CLM-Lake

Surface : Time Series 07/20/2022 09:00 -07/27/2022 09:00 : no diffs MATCHED

bias

Curve0 mean = 0.7703, median = 0.6823, stdev = 0.4493
Curve1 mean = 0.6340, median = 0.5412, stdev = 0.4086

— Curve0: RRFSret_Jul2022_V079_CLMon in CTRA..KVVU: All HRRR domain, Wind Speed at 10m (m/s) Bias (Model - Obs), fcst_len: 6h, valid-time: unused, avg: None, stdev: None, min: -0.5, max: 1.5
— Curve1: RRFSret_Jul2022_V079_CLMoff in CTRA..KVVU: All HRRR domain, Wind Speed at 10m (m/s) Bias (Model - Obs), fcst_len: 6h, valid-time: unused, avg: None, stdev: None, min: -0.5, max: 1.5

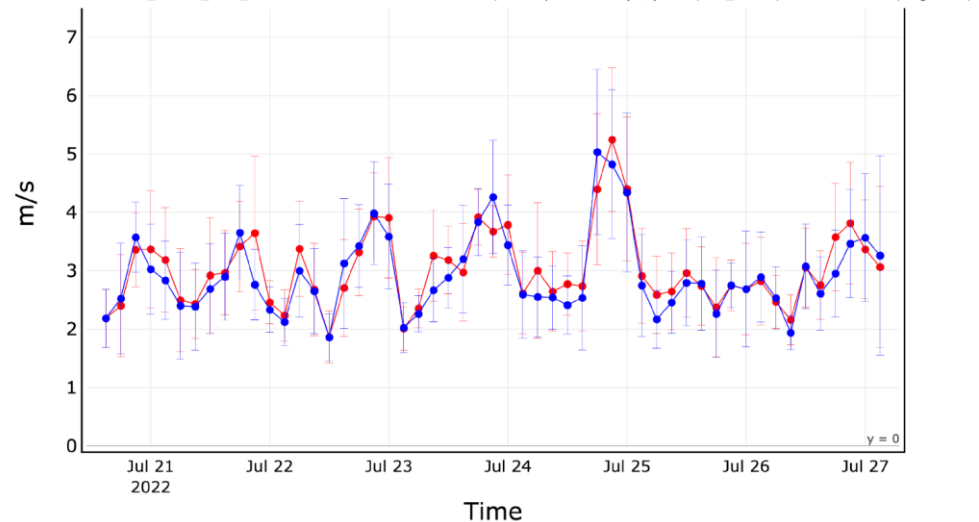


Surface : Time Series 07/20/2022 09:00 -07/27/2022 09:00 : no diffs MATCHED

RMSE

Curve0 mean = 3.027, median = 2.919, stdev = 0.6535
Curve1 mean = 2.929, median = 2.761, stdev = 0.6862

— Curve0: RRFSret_Jul2022_V079_CLMon in CTRA..KVVU: All HRRR domain, Wind Speed at 10m (m/s) RMSE, fcst_len: 6h, valid-time: unused, avg: None, stdev: None, min: 1.5, max: 4.5
— Curve1: RRFSret_Jul2022_V079_CLMoff in CTRA..KVVU: All HRRR domain, Wind Speed at 10m (m/s) RMSE, fcst_len: 6h, valid-time: unused, avg: None, stdev: None, min: 1.5, max: 4.5



Summer RRFS retro, 21-27 July 2022

2-m temperature diurnal variations, 6-h forecast, lake stations

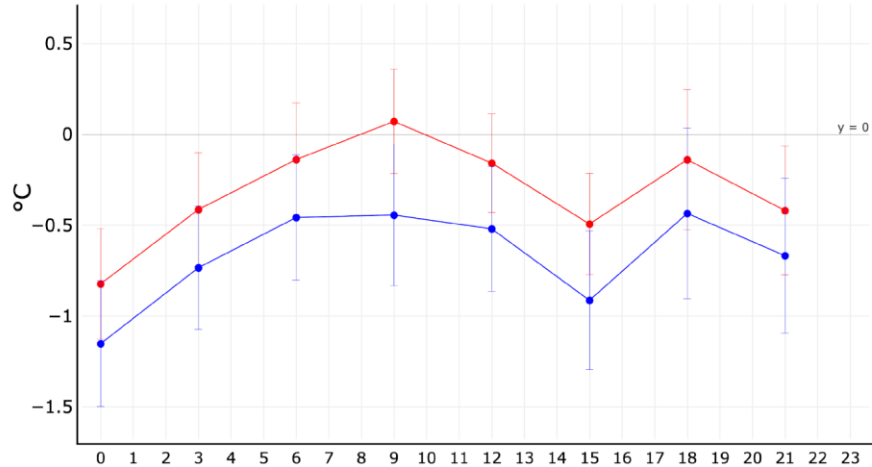
Red – with CLM-Lake
Blue – no CLM-Lake

Surface : Valid Time: no diffs MATCHED

bias

Curve0 mean = -0.3147, median = -0.2664, stdev = 0.2614
Curve1 mean = -0.6660, median = -0.5944, stdev = 0.2423

Curve0: RRFSret_Jul2022_V079_CLMon in CTRA..KVVU: All HRRR domain, Temperature at 2m (°C) Bias (Model - Obs), fcst_len: 6h, METAR, 07/20/2022 09:00 - 07/21/2022 09:00
Curve1: RRFSret_Jul2022_V079_CLMoff in CTRA..KVVU: All HRRR domain, Temperature at 2m (°C) Bias (Model - Obs), fcst_len: 6h, METAR, 07/20/2022 09:00 - 07/21/2022 09:00

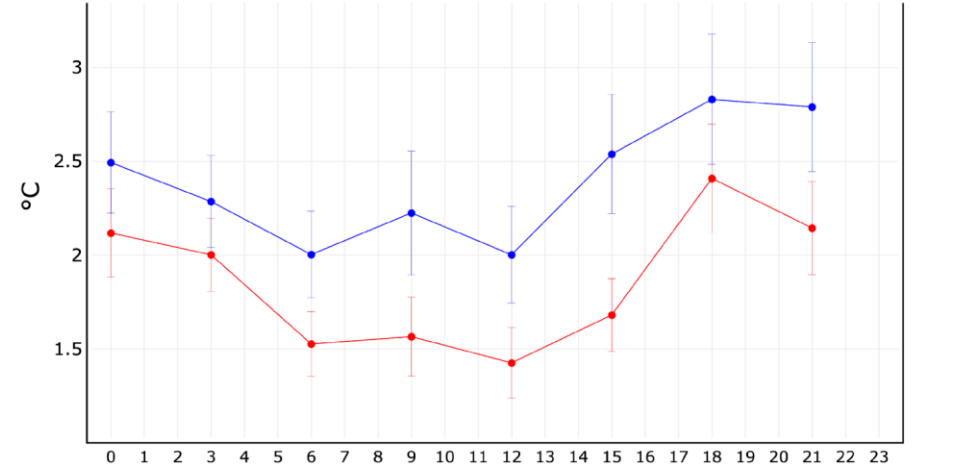


Surface : Valid Time: no diffs MATCHED

RMSE

Curve0 mean = 1.858, median = 1.841, stdev = 0.3330
Curve1 mean = 2.395, median = 2.389, stdev = 0.3009

Curve0: RRFSret_Jul2022_V079_CLMon in CTRA..KVVU: All HRRR domain, Temperature at 2m (°C) RMSE, fcst_len: 6h, METAR, 07/20/2022 09:00 - 07/21/2022 09:00
Curve1: RRFSret_Jul2022_V079_CLMoff in CTRA..KVVU: All HRRR domain, Temperature at 2m (°C) RMSE, fcst_len: 6h, METAR, 07/20/2022 09:00 - 07/21/2022 09:00



Hour of Day

Hour of Day

Summer RRFS retro, 21-27 July 2022

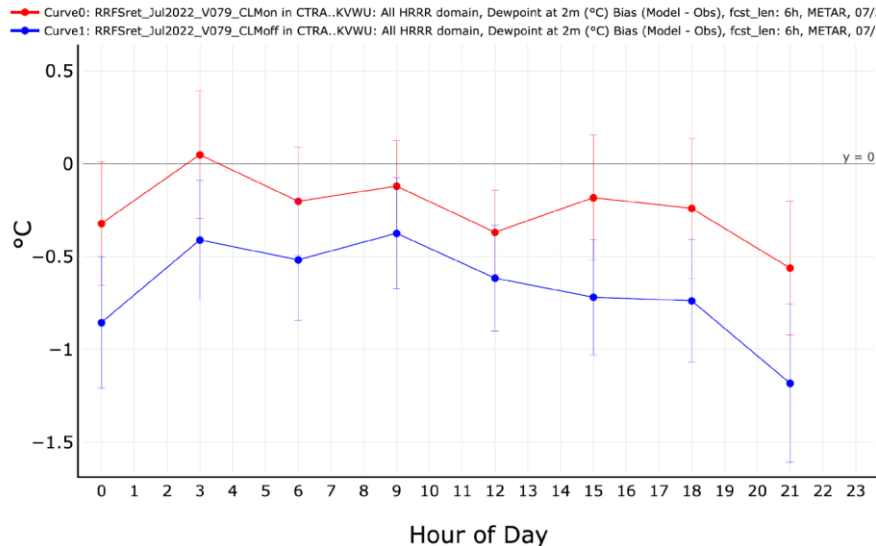
2-m dewpoint diurnal variations, 6-h forecast, lake stations

Red – with CLM-Lake
Blue – no CLM-Lake

Surface : Valid Time: no diffs MATCHED

bias

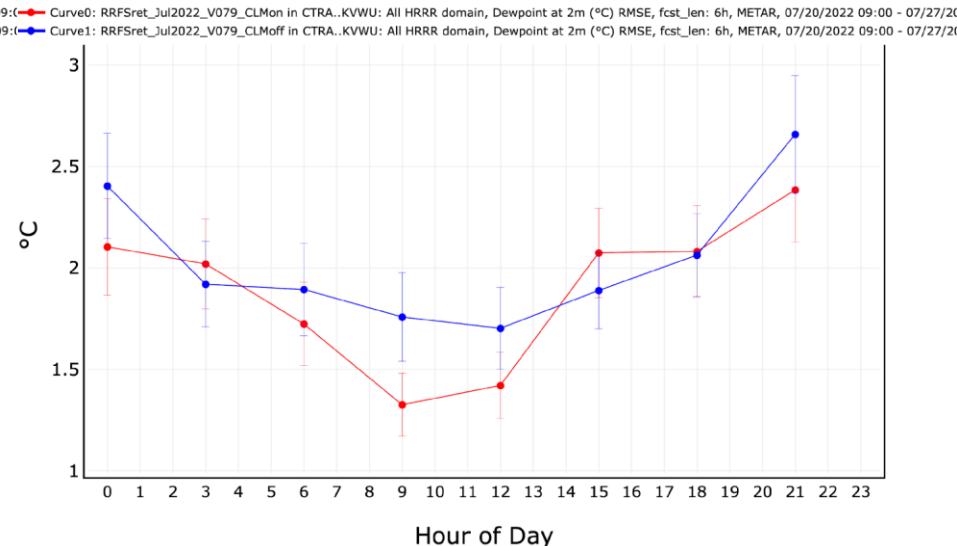
Curve0 mean = -0.2437, median = -0.2211, stdev = 0.1693
Curve1 mean = -0.6769, median = -0.6679, stdev = 0.2460



Surface : Valid Time: no diffs MATCHED

RMSE

Curve0 mean = 1.892, median = 2.047, stdev = 0.3436
Curve1 mean = 2.036, median = 1.906, stdev = 0.3099



Summer RRFs retro, 21-27 July 2022

10-m wind diurnal variations, 6-h forecast, lake stations

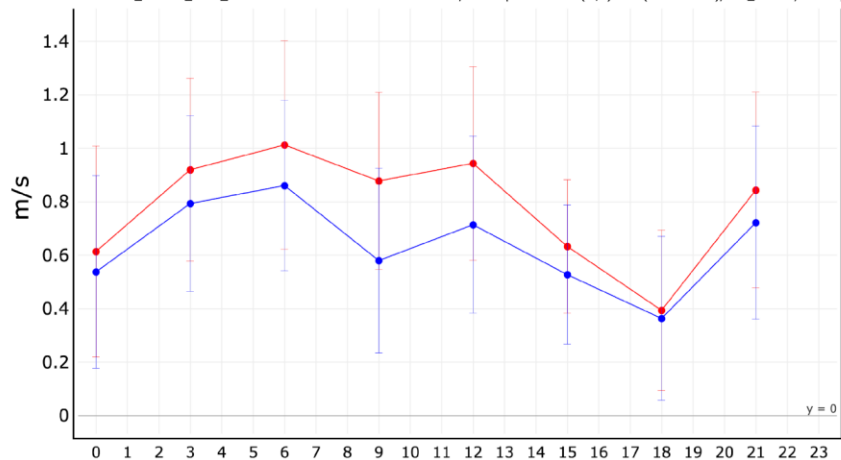
Red – with CLM-Lake
Blue – no CLM-Lake

Surface : Valid Time: no diffs MATCHED

bias

Curve0 mean = 0.7793, median = 0.8604, stdev = 0.1977
Curve1 mean = 0.6369, median = 0.6466, stdev = 0.1532

— Curve0: RRFsret_Jul2022_V079_CLMon in CTRA..KVVU: All HRRR domain, Wind Speed at 10m (m/s) Bias (Model - Obs), fcst_len: 6h, METAR, 07/20/2022
— Curve1: RRFsret_Jul2022_V079_CLMoff in CTRA..KVVU: All HRRR domain, Wind Speed at 10m (m/s) Bias (Model - Obs), fcst_len: 6h, METAR, 07/20/2022

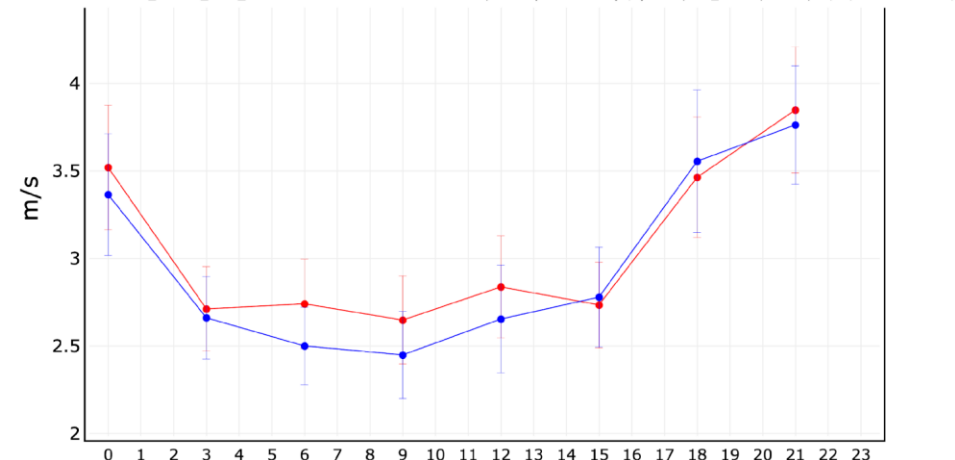


Surface : Valid Time: no diffs MATCHED

RMSE

Curve0 mean = 3.062, median = 2.789, stdev = 0.4393
Curve1 mean = 2.965, median = 2.720, stdev = 0.4810

— Curve0: RRFsret_Jul2022_V079_CLMon in CTRA..KVVU: All HRRR domain, Wind Speed at 10m (m/s) RMSE, fcst_len: 6h, METAR, 07/20/2022 09:00 - 07/20/2022 09:00 - 07/20/2022 09:00 - 07/20/2022 09:00
— Curve1: RRFsret_Jul2022_V079_CLMoff in CTRA..KVVU: All HRRR domain, Wind Speed at 10m (m/s) RMSE, fcst_len: 6h, METAR, 07/20/2022 09:00 - 07/20/2022 09:00 - 07/20/2022 09:00 - 07/20/2022 09:00



Hour of Day

Hour of Day

Summer RRFS retro, 21-27 July 2022

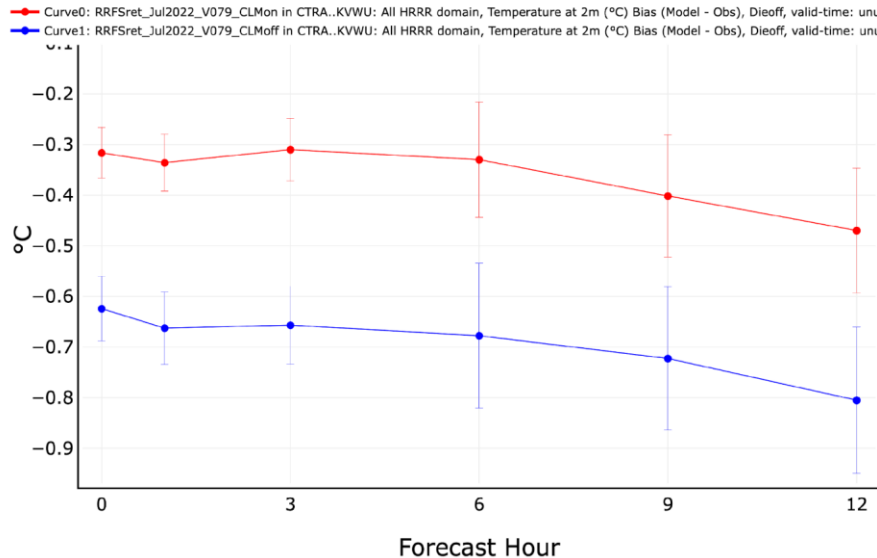
2-m temperature die-off, lake stations

Red – with CLM-Lake
Blue – no CLM-Lake

Surface : Dieoff: no diffs MATCHED

bias

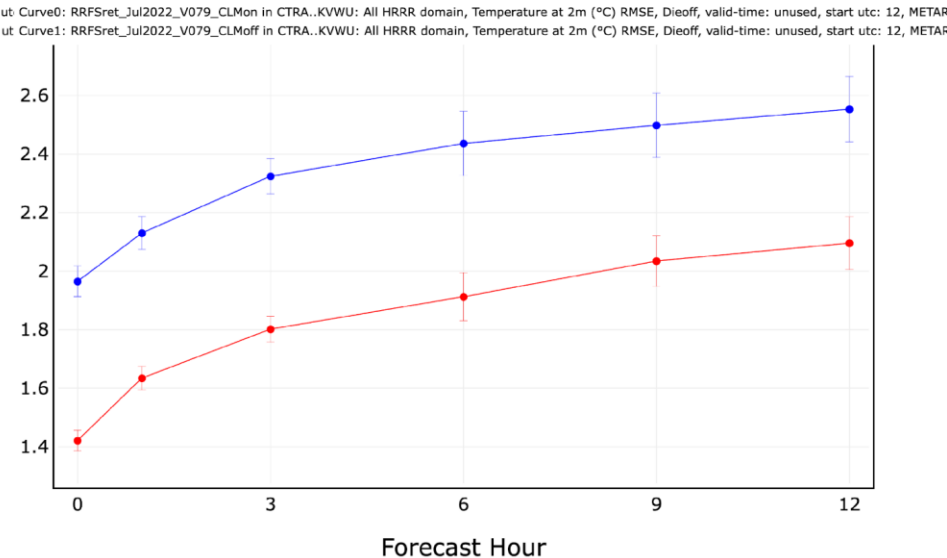
Curve0 mean = -0.3609, median = -0.3332, stdev = 0.05722
Curve1 mean = -0.6916, median = -0.6703, stdev = 0.05858



Surface : Dieoff: no diffs MATCHED

RMSE

Curve0 mean = 1.816, median = 1.857, stdev = 0.2326
Curve1 mean = 2.317, median = 2.380, stdev = 0.2089



Summer RRFS retro, 21-27 July 2022

2-m dew point die-off, lake stations

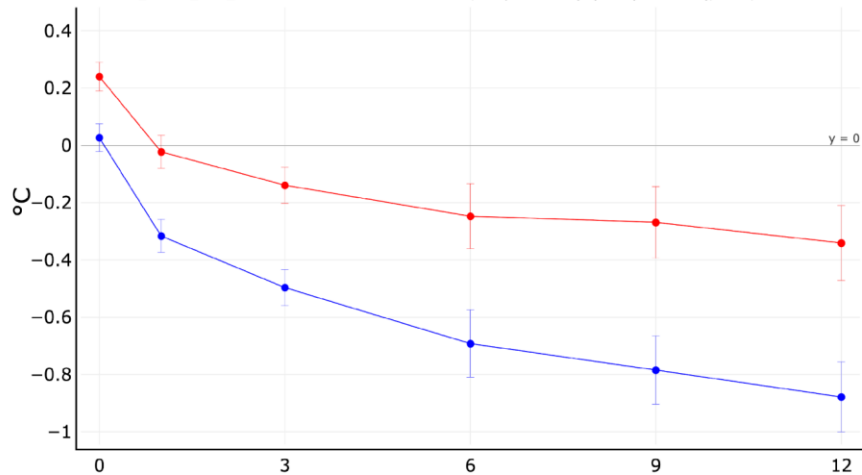
Red – with CLM-Lake
Blue – no CLM-Lake

Surface : Dieoff: no diffs MATCHED

bias

Curve0 mean = -0.1303, median = -0.1938, stdev = 0.1941
Curve1 mean = -0.5239, median = -0.5947, stdev = 0.3080

— Curve0: RRFSret_Jul2022_V079_CLMon in CTRA..KVVU: All HRRR domain, Dewpoint at 2m (°C) Bias (Model - Obs), Dieoff, valid-time: unused, stz
— Curve1: RRFSret_Jul2022_V079_CLMoff in CTRA..KVVU: All HRRR domain, Dewpoint at 2m (°C) Bias (Model - Obs), Dieoff, valid-time: unused, stz



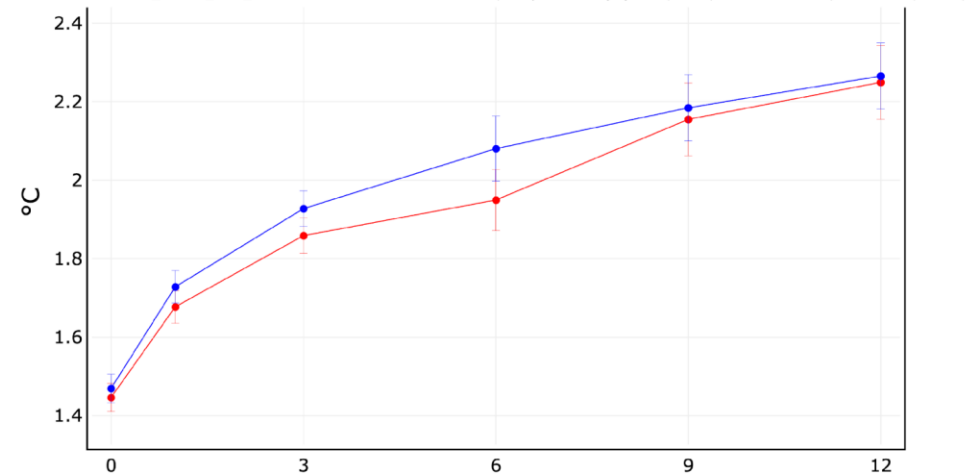
Forecast Hour

Surface : Dieoff: no diffs MATCHED

RMSE

Curve0 mean = 1.889, median = 1.904, stdev = 0.2727
Curve1 mean = 1.942, median = 2.004, stdev = 0.2745

— Curve0: RRFSret_Jul2022_V079_CLMon in CTRA..KVVU: All HRRR domain, Dewpoint at 2m (°C) RMSE, Dieoff, valid-time: unused, start utc: 12, METAR, 0
— Curve1: RRFSret_Jul2022_V079_CLMoff in CTRA..KVVU: All HRRR domain, Dewpoint at 2m (°C) RMSE, Dieoff, valid-time: unused, start utc: 12, METAR, 0



Forecast Hour

Summer RRFS retro, 21-27 July 2022

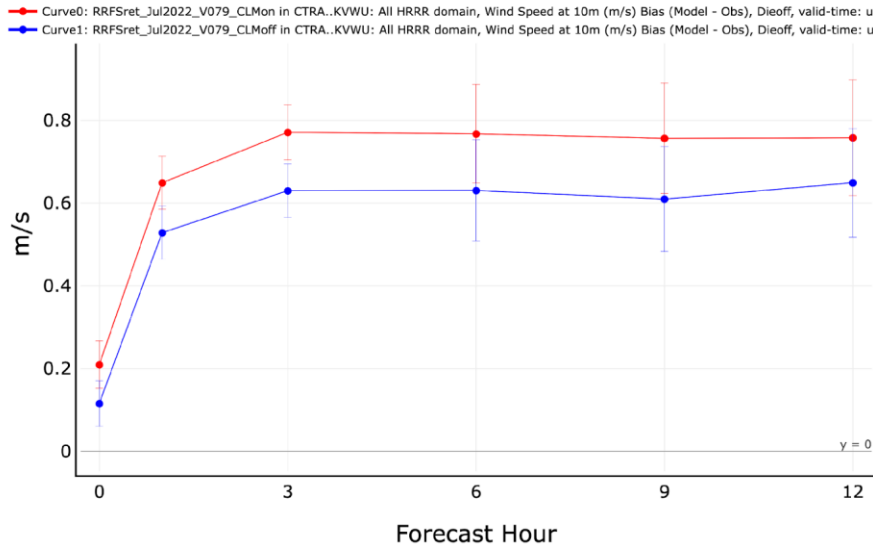
10-m wind die-off, lake stations

Red – with CLM-Lake
Blue – no CLM-Lake

Surface : Dieoff: no diffs MATCHED

bias

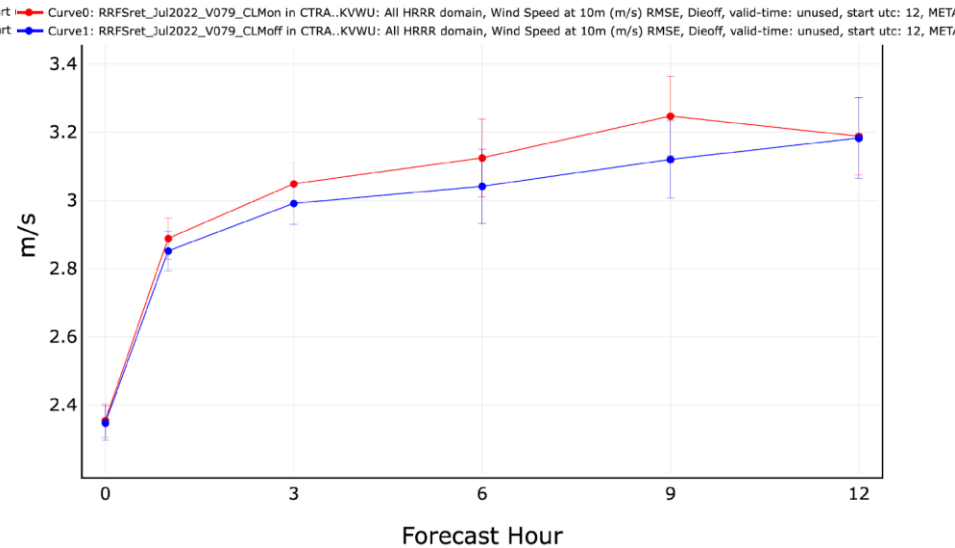
Curve0 mean = 0.6516, median = 0.7570, stdev = 0.2023
Curve1 mean = 0.5269, median = 0.6195, stdev = 0.1881



Surface : Dieoff: no diffs MATCHED

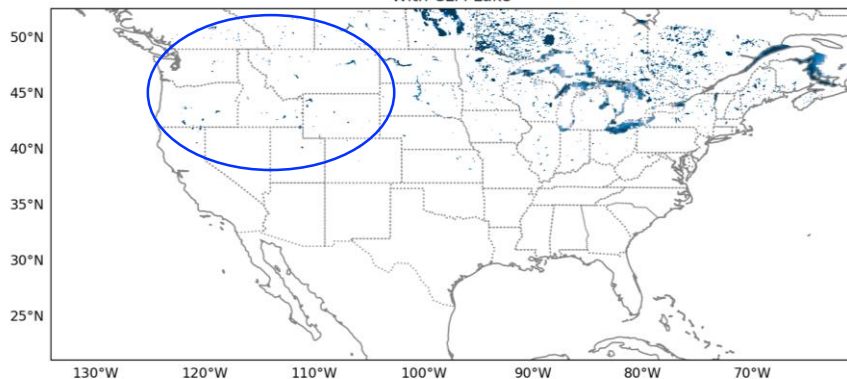
RMSE

Curve0 mean = 2.975, median = 3.086, stdev = 0.2999
Curve1 mean = 2.922, median = 3.016, stdev = 0.2772

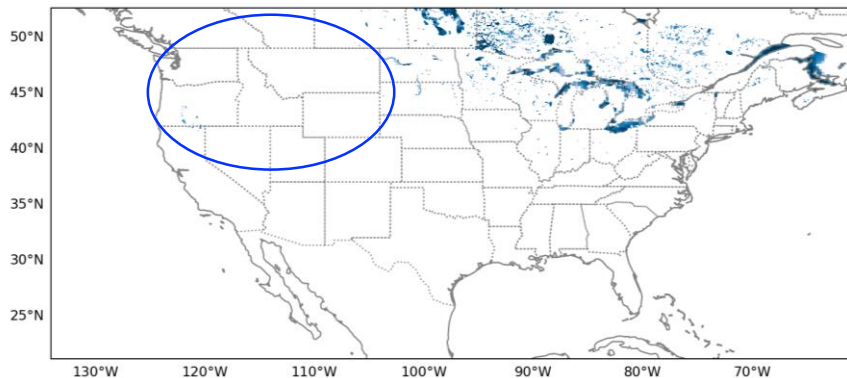


Winter RRFS retro, 1-9 February 2022

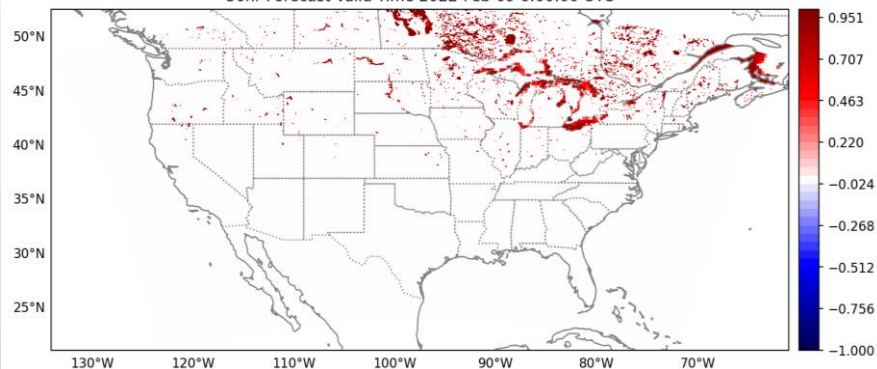
Ice Concentration at 36hr Forecast
Valid Time 2022-Feb-09 6:00:00 UTC
With CLM Lake



No Lake Model



Ice Concentration Differences: Lake Minus No Lake
36hr Forecast Valid Time 2022-Feb-09 6:00:00 UTC



- Without CLM-Lake ice is initialized from the global model based on the satellite information
- With CLM-Lake
 - lake ice is created in the CLM-Lake and evolves in the cycled RRFS
 - many small lakes are frozen after a week of cycling compared to global data
 - higher ice concentrations for most lakes

CLM-Lake in the real-time cycled RRFS

- The 1D CLM-Lake is implemented in the RRFS in January 2024
- Lake variables are evolving in RRFS for ~10-month
- Comparisons to the current NOAA operational regional model HRRR cycled since August 2018 for ~75 months

Real-time RRFS versus HRRR, both have CLM-Lake

14 April – 14 May 2024

Red – RRFS
Blue – HRRR

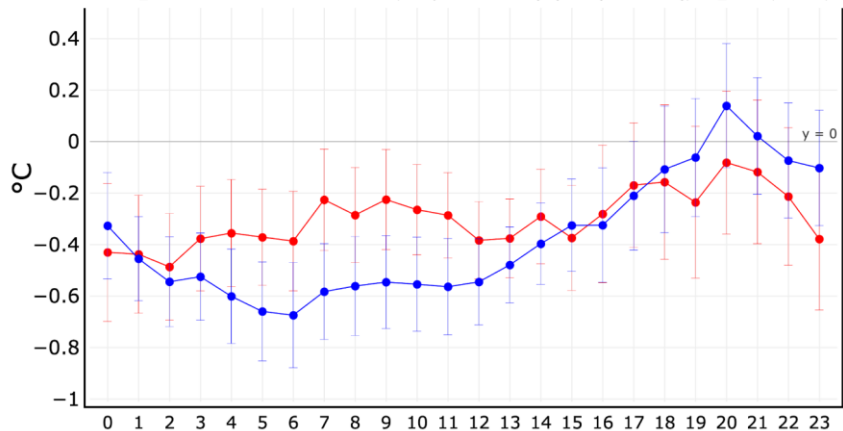
2-m temperature diurnal variations, 6-h forecast, lake stations

Surface : Valid Time: no diffs MATCHED

bias

Curve0 mean = -0.3001, median = -0.2890, stdev = 0.1041
Curve1 mean = -0.3779, median = -0.4675, stdev = 0.2315

Curve0: RRFS_A_NA_3km in CTRA..KVWU: All HRRR domain, Temperature at 2m (°C) Bias (Model - Obs), fcst_len: 6h, METAR, 04/14/
Curve1: HRRR_OPS in CTRA..KVWU: All HRRR domain, Temperature at 2m (°C) Bias (Model - Obs), fcst_len: 6h, METAR, 04/14/2024 1



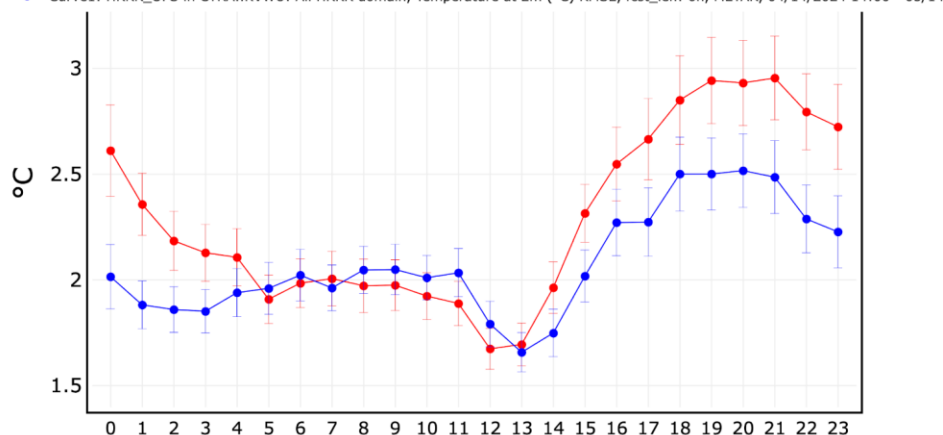
Hour of Day

Surface : Valid Time: no diffs MATCHED

RMSE

Curve0 mean = 2.295, median = 2.156, stdev = 0.4122
Curve1 mean = 2.079, median = 2.019, stdev = 0.2440

Curve0: RRFS_A_NA_3km in CTRA..KVWU: All HRRR domain, Temperature at 2m (°C) RMSE, fcst_len: 6h, METAR, 04/14/2024 14:00 -
Curve1: HRRR_OPS in CTRA..KVWU: All HRRR domain, Temperature at 2m (°C) RMSE, fcst_len: 6h, METAR, 04/14/2024 14:00 - 05/14



Hour of Day

Real-time RRFS versus HRRR, both have CLM-Lake

14 April – 14 May 2024

2-m dewpoint diurnal variations, 6-h forecast, lake stations

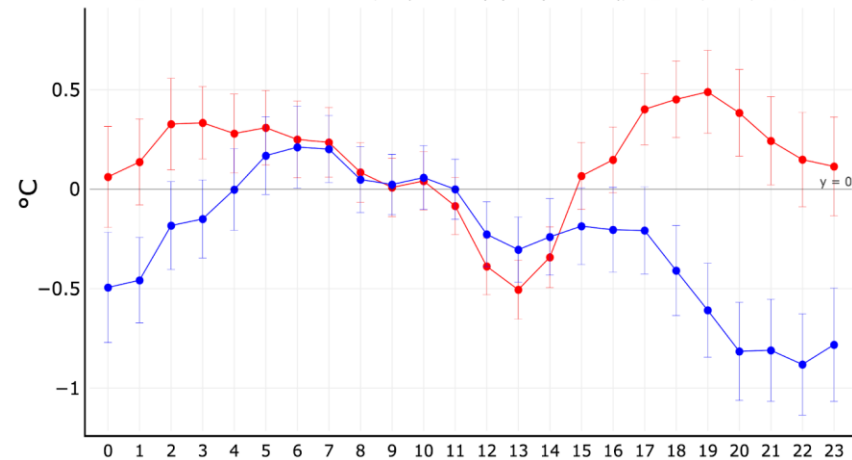
Red – RRFS
Blue – HRRR

Surface : Valid Time: no diffs MATCHED

Curve0 mean = 0.1328, median = 0.1478, stdev = 0.2515
Curve1 mean = -0.2608, median = -0.2062, stdev = 0.3272

bias

Curve0: RRFS_A_NA_3km in CTRA..KVVU: All HRRR domain, Dewpoint at 2m (°C) Bias (Model - Obs), fcst_len: 6h, METAR, 04/14/2024 14:00 - 0
Curve1: HRRR_OPS in CTRA..KVVU: All HRRR domain, Dewpoint at 2m (°C) Bias (Model - Obs), fcst_len: 6h, METAR, 04/14/2024 14:00 - 05/14/2



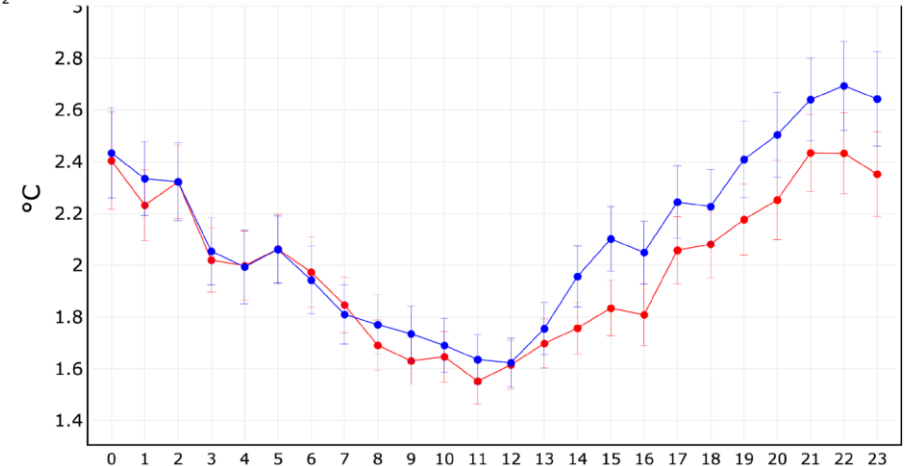
Hour of Day

Surface : Valid Time: no diffs MATCHED

Curve0 mean = 1.994, median = 2.009, stdev = 0.2794
Curve1 mean = 2.109, median = 2.057, stdev = 0.3269

RMSE

Curve0: RRFS_A_NA_3km in CTRA..KVVU: All HRRR domain, Dewpoint at 2m (°C) RMSE, fcst_len: 6h, METAR, 04/14/2024 14:00 - 05/14/2024 14:00
Curve1: HRRR_OPS in CTRA..KVVU: All HRRR domain, Dewpoint at 2m (°C) RMSE, fcst_len: 6h, METAR, 04/14/2024 14:00 - 05/14/2024 14:00



Hour of Day

Real-time RRFS versus HRRR, both have CLM-Lake

14 April – 14 May 2024

10-m wind diurnal variations, 6-h forecast, lake stations

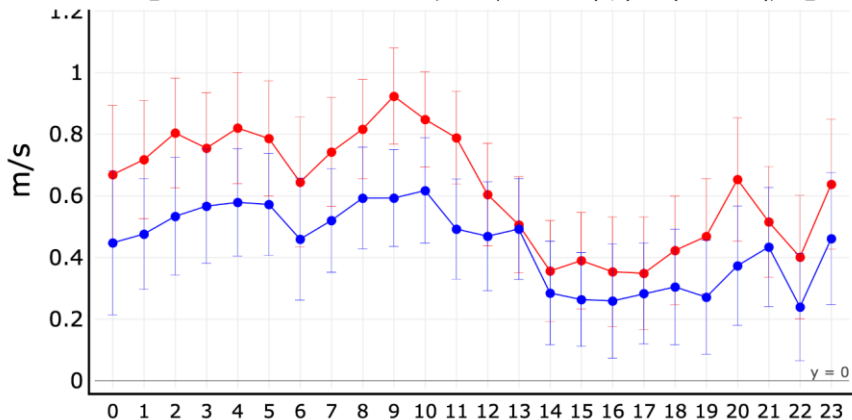
Red – RRFS
Blue – HRRR

Surface : Valid Time: no diffs MATCHED

Curve0 mean = 0.6235, median = 0.6484, stdev = 0.1781
Curve1 mean = 0.4405, median = 0.4647, stdev = 0.1223

bias

Curve0: RRFS_A_NA_3km in CTRA..KVWU: All HRRR domain, Wind Speed at 10m (m/s) Bias (Model - Obs), fcst_len: 6h
Curve1: HRRR_OPS in CTRA..KVWU: All HRRR domain, Wind Speed at 10m (m/s) Bias (Model - Obs), fcst_len: 6h, METAR



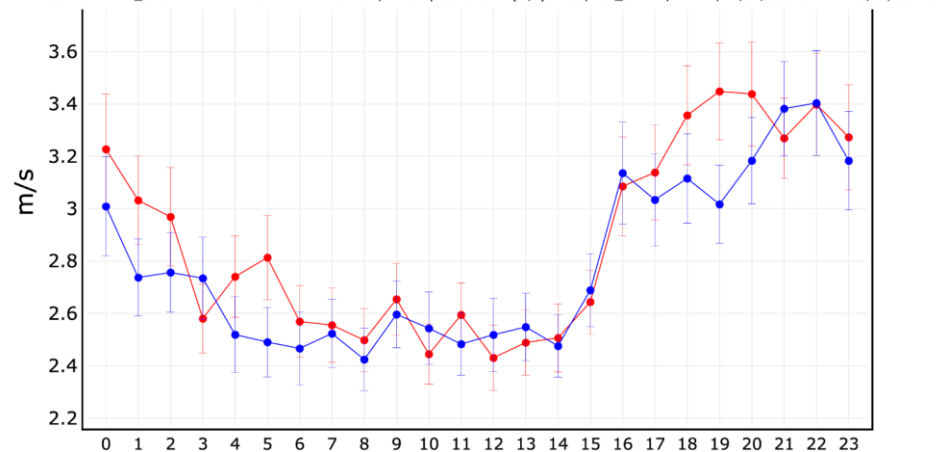
Hour of Day

Surface : Valid Time: no diffs MATCHED

Curve0 mean = 2.881, median = 2.777, stdev = 0.3553
Curve1 mean = 2.790, median = 2.711, stdev = 0.3119

RMSE

Curve0: RRFS_A_NA_3km in CTRA..KVWU: All HRRR domain, Wind Speed at 10m (m/s) RMSE, fcst_len: 6h, METAR, 04/14/2024 14:00 - 05/14/2024 14:00
Curve1: HRRR_OPS in CTRA..KVWU: All HRRR domain, Wind Speed at 10m (m/s) RMSE, fcst_len: 6h, METAR, 04/14/2024 14:00 - 05/14/2024 14:00



Hour of Day

Real-time RRFS versus HRRR, both have CLM-Lake

14 April – 14 May 2024

2-m temperature die-off, lake stations

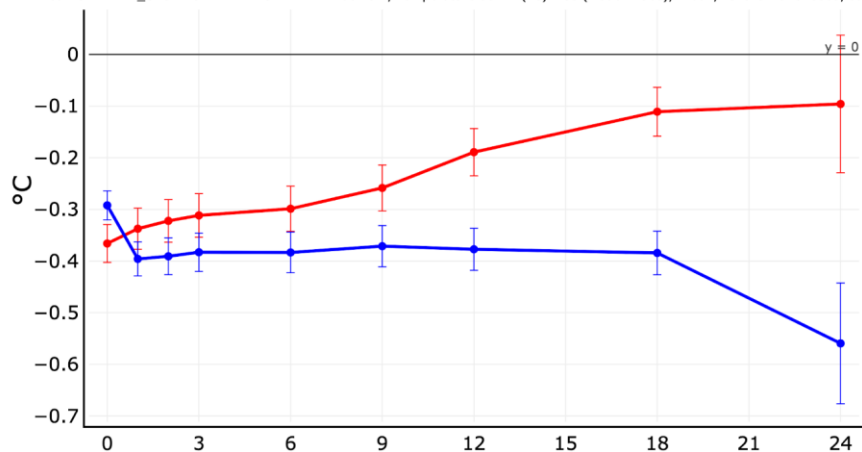
Red – RRFS
Blue – HRRR

Surface : Dieoff: no diffs MATCHED

bias

Curve0 mean = -0.2544, median = -0.2987, stdev = 0.09380
Curve1 mean = -0.3930, median = -0.3833, stdev = 0.06572

Curve0: RRFS_A_NA_3km in CTRA..KVVU: All HRRR domain, Temperature at 2m (°C) Bias (Model - Obs), Dieoff, valid-time: unused, start utc: 12, METAR, 04/14
Curve1: HRRR_OPS in CTRA..KVVU: All HRRR domain, Temperature at 2m (°C) Bias (Model - Obs), Dieoff, valid-time: unused, start utc: 12, METAR, 04/14

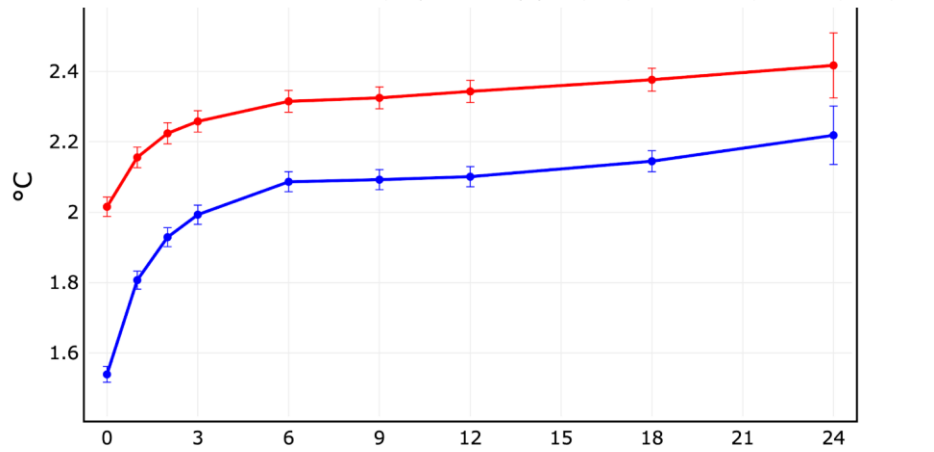


Surface : Dieoff: no diffs MATCHED

RMSE

Curve0 mean = 2.270, median = 2.315, stdev = 0.1171
Curve1 mean = 1.990, median = 2.066, stdev = 0.1968

Curve0: RRFS_A_NA_3km in CTRA..KVVU: All HRRR domain, Temperature at 2m (°C) RMSE, Dieoff, valid-time: unused, start utc: 12, METAR, 04/14
Curve1: HRRR_OPS in CTRA..KVVU: All HRRR domain, Temperature at 2m (°C) RMSE, Dieoff, valid-time: unused, start utc: 12, METAR, 04/14



Forecast Hour

Forecast Hour

Real-time RRFsv1 versus HRRR, both have CLM-Lake 14 April – 14 May 2024

2-m dew point die-off, lake stations

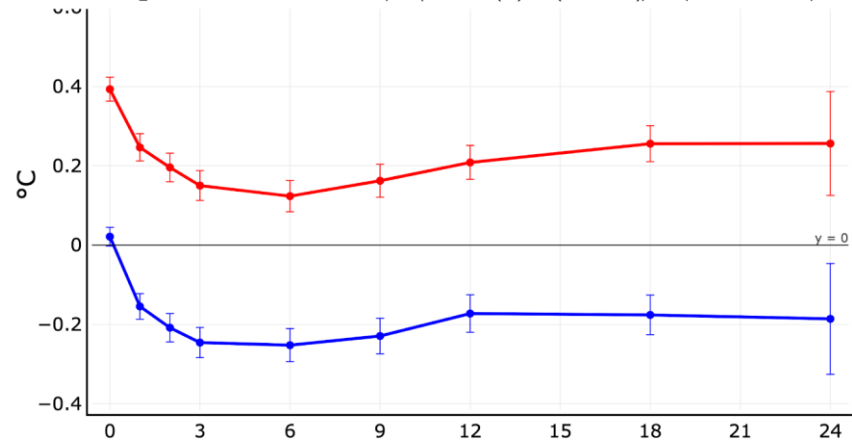
Red – RRFs
Blue – HRRR

Surface : Dieoff: no diffs MATCHED

Curve0 mean = 0.2213, median = 0.2084, stdev = 0.07562
Curve1 mean = -0.1781, median = -0.1859, stdev = 0.07745

bias

Curve0: RRFs_A_NA_3km in CTRA..KVVU: All HRRR domain, Dewpoint at 2m (°C) Bias (Model - Obs), Dieoff, valid-time: unused, start utc: 1
Curve1: HRRR_OPS in CTRA..KVVU: All HRRR domain, Dewpoint at 2m (°C) Bias (Model - Obs), Dieoff, valid-time: unused, start utc: 12, MET



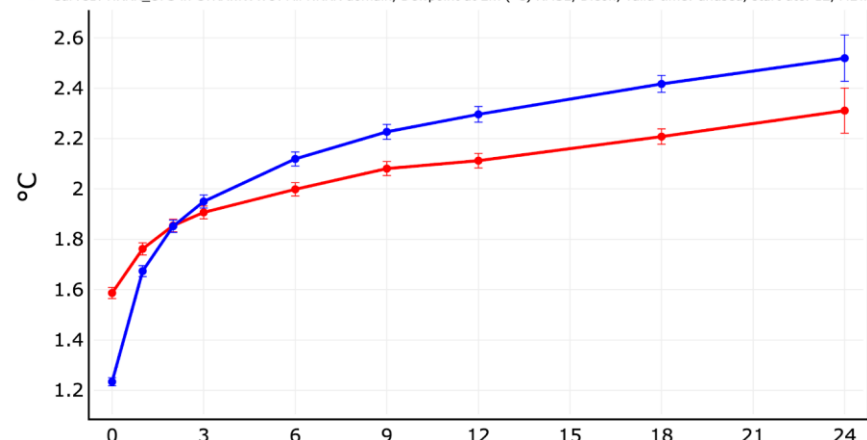
Forecast Hour

Surface : Dieoff: no diffs MATCHED

Curve0 mean = 1.980, median = 1.998, stdev = 0.2141
Curve1 mean = 2.032, median = 2.119, stdev = 0.3808

RMSE

Curve0: RRFs_A_NA_3km in CTRA..KVVU: All HRRR domain, Dewpoint at 2m (°C) RMSE, Dieoff, valid-time: unused, start utc: 12, METAR, 04/14/2024
Curve1: HRRR_OPS in CTRA..KVVU: All HRRR domain, Dewpoint at 2m (°C) RMSE, Dieoff, valid-time: unused, start utc: 12, METAR, 04/14/2024



Forecast Hour

Real-time RRFsv1 versus HRRR, both have CLM-Lake 14 April – 14 May 2024

10-m wind die-off, lake stations

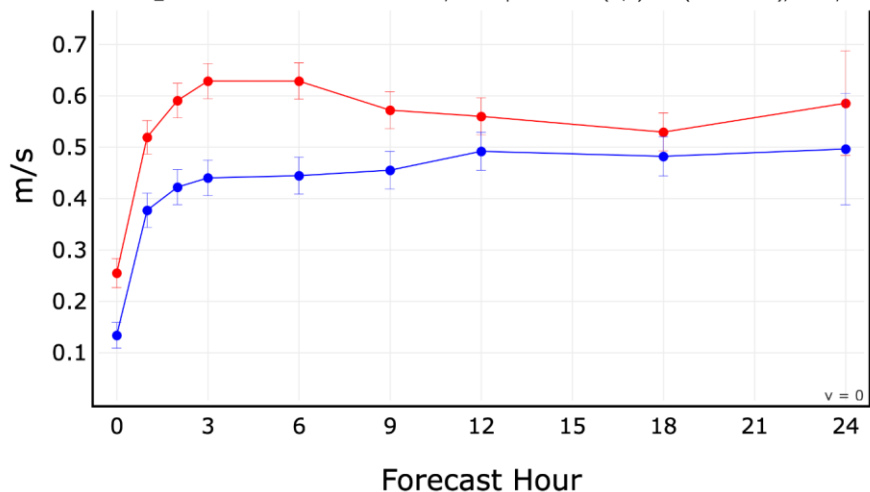
Red – RRFsv1
Blue – HRRR

Surface : Dieoff: no diffs MATCHED

Curve0 mean = 0.5408, median = 0.5718, stdev = 0.1072
Curve1 mean = 0.4158, median = 0.4443, stdev = 0.1058

bias

Curve0: RRFs_A_NA_3km in CTRA..KVWU: All HRRR domain, Wind Speed at 10m (m/s) Bias (Model - Obs), Dieoff
Curve1: HRRR_OPS in CTRA..KVWU: All HRRR domain, Wind Speed at 10m (m/s) Bias (Model - Obs), Dieoff, valid-

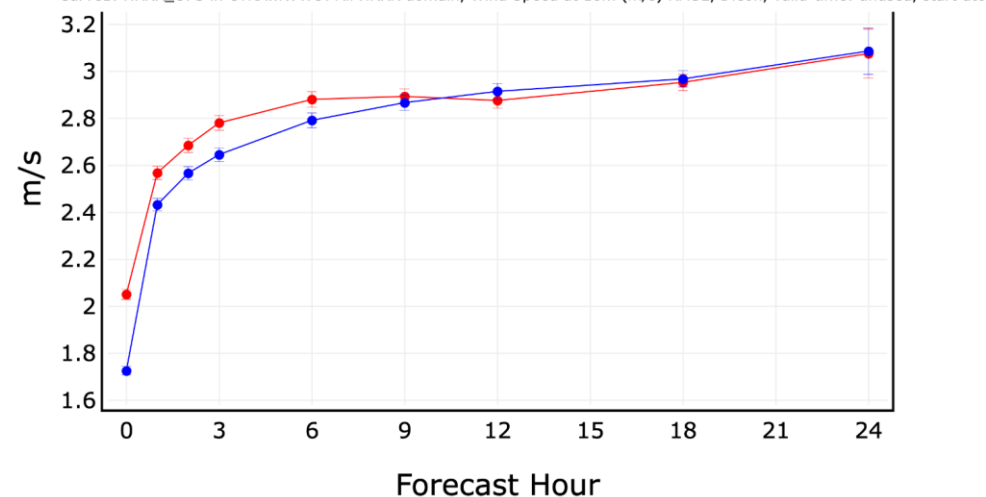


Surface : Dieoff: no diffs MATCHED

Curve0 mean = 2.751, median = 2.876, stdev = 0.2844
Curve1 mean = 2.666, median = 2.791, stdev = 0.3852

RMSE

Curve0: RRFs_A_NA_3km in CTRA..KVWU: All HRRR domain, Wind Speed at 10m (m/s) RMSE, Dieoff, valid-time: unused, st
Curve1: HRRR_OPS in CTRA..KVWU: All HRRR domain, Wind Speed at 10m (m/s) RMSE, Dieoff, valid-time: unused, start utc

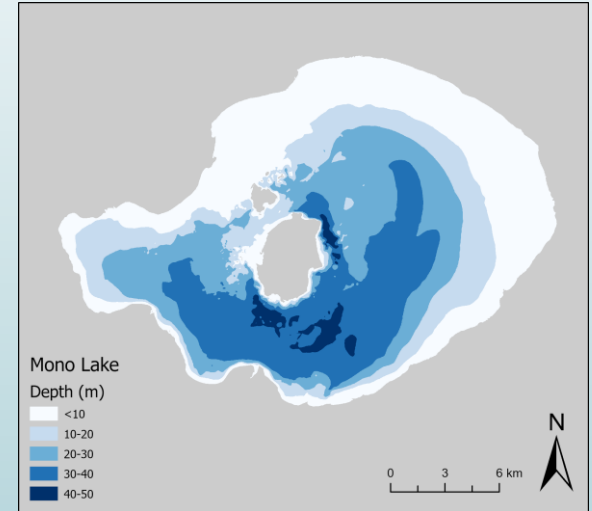
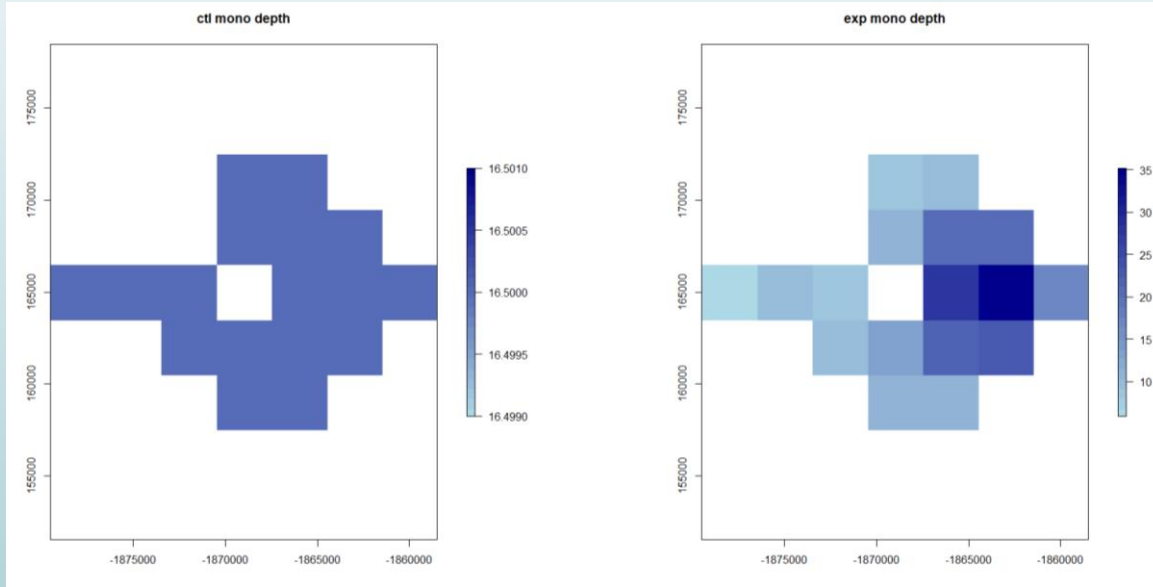


High-resolution GLOBathy compared to GLDBv3

GLOBv3

Mono Lake

GLOBathy



Khazaei, B., Read, L.K., Casali, M., Sampson, K.M, and Yates, D.N.,2022:
GLOBathy, the global lakes bathymetry dataset. *Sci Data* **9**, 36
<https://doi.org/10.1038/s41597-022-01132-9>

Data from: Raumann, Christian G, et al.
“Digital Bathymetric Model of Mono Lake,
California.” *U.S. Geological Survey*, 2002,
<https://doi.org/10.3133/mf2393>.
Map made by Eamon Espey, University of
Michigan

Conclusions and future work

- CLM-Lake is available in the NOAA Unified Forecasting System
- Lakes' set-up in the domain requires preliminary work to remove larger lakes ($>15,000 \text{ km}^2$), where 1D CLM-Lake is not capable to represent lake processes realistically
- Lake depths in the UFS are currently initialized from GLDBv3 data, constant depth for most lakes
- *Work underway* to replace GLDBv3 with the high-resolution GLOBathy information, variable depths for most lakes
- Lake variables are cycled controlled by atmospheric DA to evolve towards realistic balanced state (Benjamin et al. 2022)
- CLM-Lake improves surface predictions in the vicinity of the lakes
- RRFs (shorter cycling period) is compatible with HRRR for stations near lakes