Commercial aircraft-based observations for NWP: Global coverage, data impacts, and COVID-19

James, Benjamin, Jamison **2020**: Commercial-aircraft-based observations for NWP: Global coverage, data impacts, and COVID-19. *J. Appl. Meteor. Climatol.*, **59** (11), 1809-1825. https://doi.org/10.1175/JAMC-D-20-0010.1

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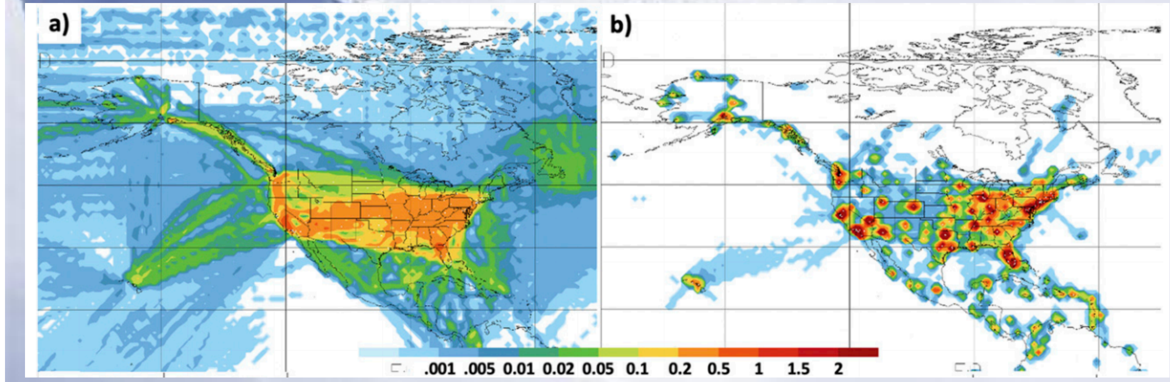
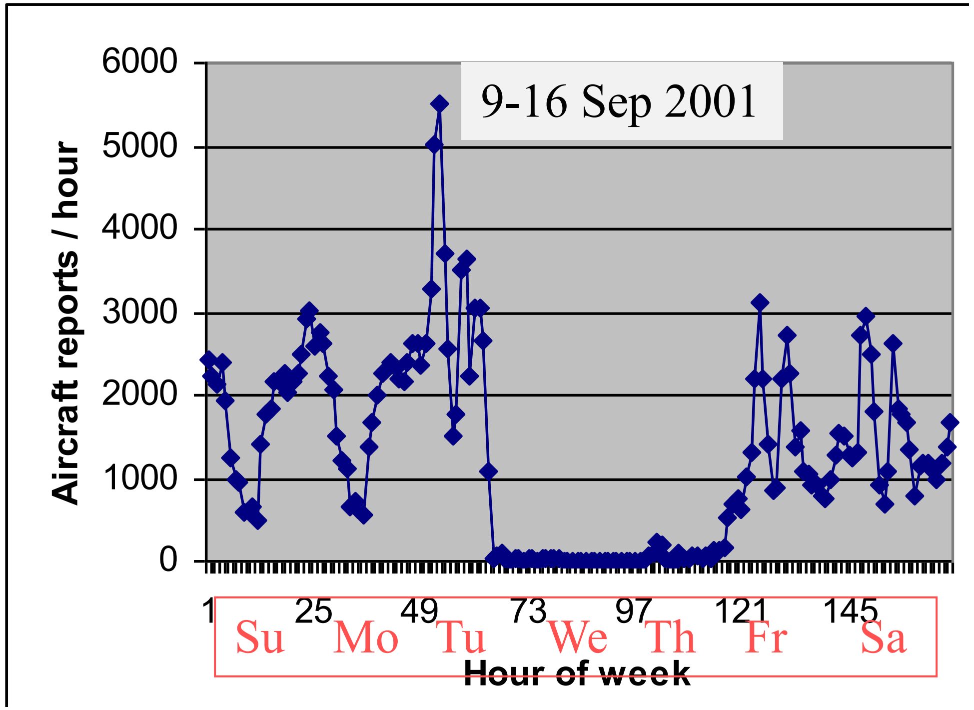


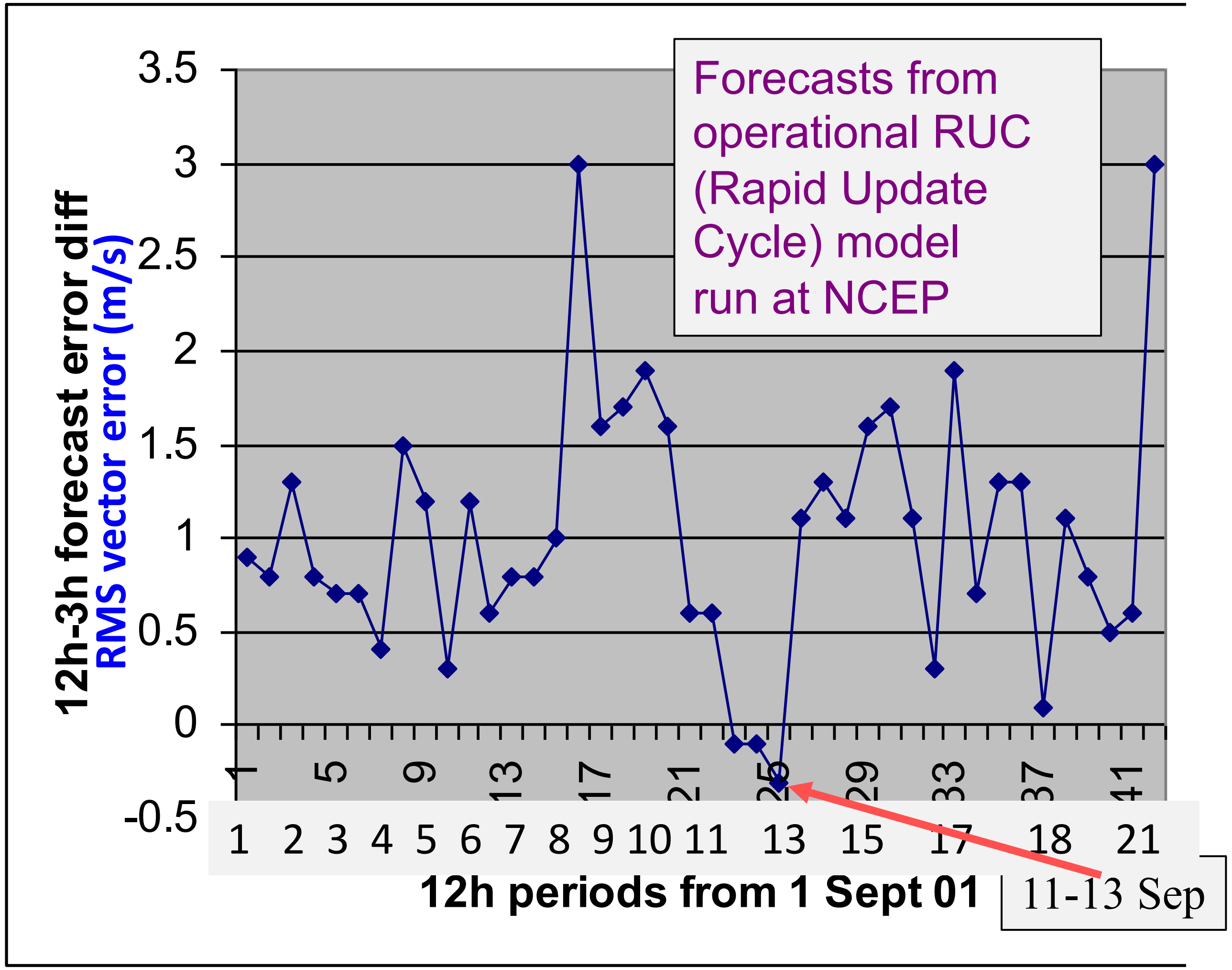
Aircraft-based observation density – March 2019

This research is partially in response to requirements and funding by the Federal Aviation Administration (FAA). The views expressed are those of the authors and do not necessarily represent the official policy or position of the FAA.

A real-time data denial experiment: 11-13 Sep 2001

Hourly aircraft reports 9-16 Sep 2001





250 hPa wind 12h-3h difference in forecast error (vs. US raobs) 1-21 Sep 2001

RAP/HRRR: Hourly-Updating NOAA Weather Forecast Models

13-km Rapid Refresh (RAP):

RAPv5 to NCEP on 2 Dec 2020

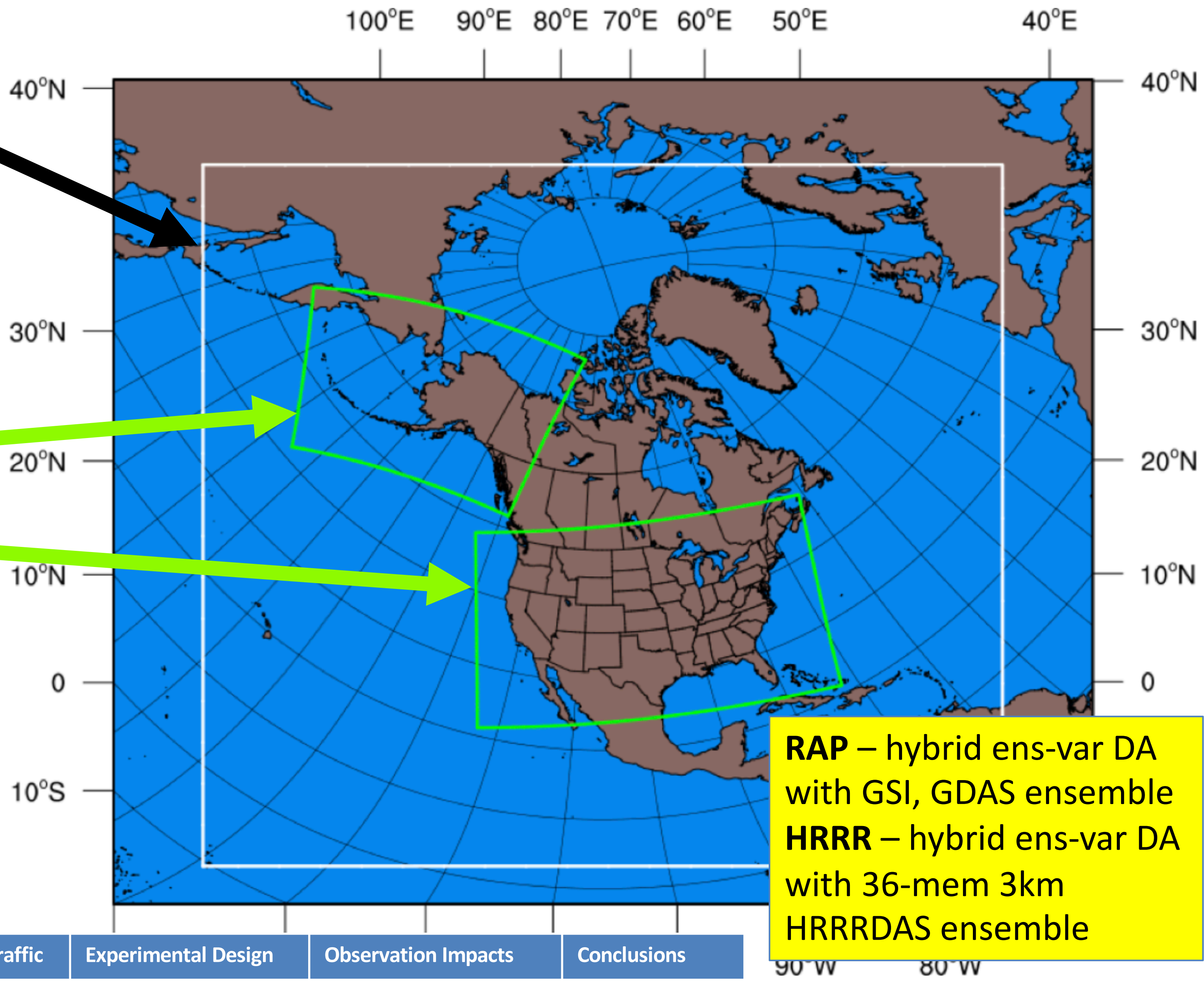
Lateral Boundary Conditions

3-km High-Resolution Rapid Refresh (HRRR):

HRRRv4 to NCEP on 2 Dec 2020

NCEP domains: CONUS and AK

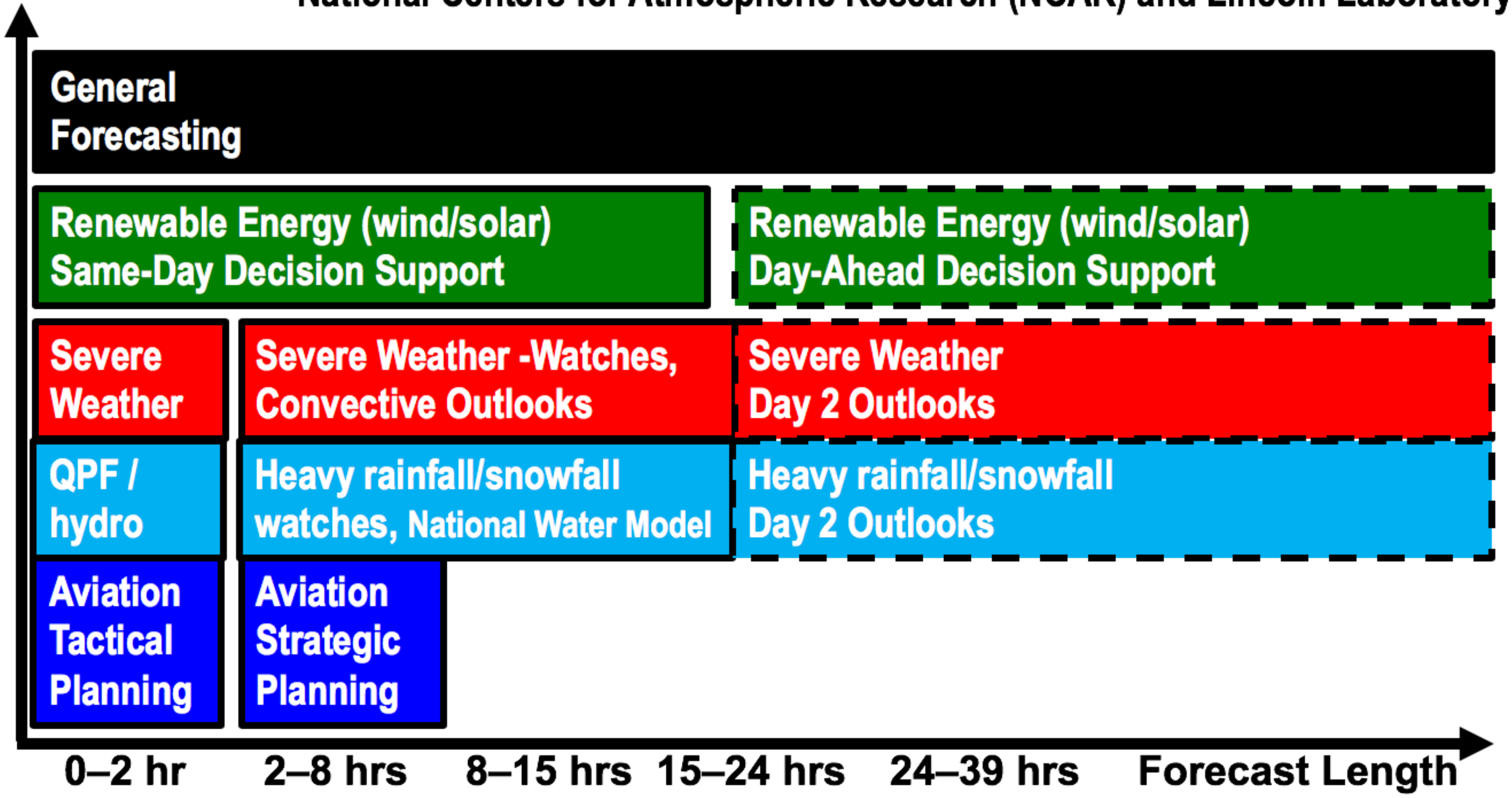
Retrospective tests shown here use the RAPv5



RAP – hybrid ens-var DA with GSI, GDAS ensemble
HRRR – hybrid ens-var DA with 36-mem 3km HRRRDAS ensemble

RAP/HRRR Users and Applications

Example: National Weather Service including Storm and Weather Prediction Centers (SPC and WPC)
Aviation Weather Center (AWC) and FAA Command Center
National Severe Storms Laboratory (NSSL) and Air Resources Laboratory (ARL)
National Centers for Atmospheric Research (NCAR) and Lincoln Laboratory (LL)

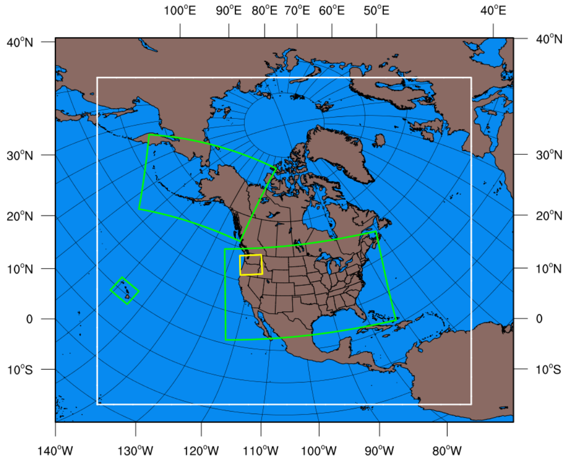


RAPv5/HRRRv4 Changes: Implemented 02 Dec 2020

Surface Characterization	Data Assimilation	Model Dynamics & Physics	Postprocessing Algorithms
Switch to MODIS albedo (higher), replace 1-deg albedo Albedo correction for solar zenith angle 15" resolution land-use data Fractional sea/lake ice concentration FVCOM data for Great Lakes temps/ice fraction VIIRS/MODIS fire-radiative power (wildfire location, intensity)	GOES-16 ABI radiances N20 CrIS-FSR/ATMS (with direct readout) GOES-16 AMVs Use aircraft/raob moisture obs above 300 hPa TC vitals for tropical cyclone position/strength HRRR Data Assimilation System (HRRRDAS) for HRRR	WRF–ARWv3.9+, including physics updates MYNN PBL update: - improved eddy-diffusion /mass-flux (EDMF) mixing Smoke tracer for wildfire smoke plumes RUC land-surface: - improved representation of snow cover - better 2m T/T_d diagnostics - lake model for small lakes Enhanced orographic gravity-wave drag Reduced 6th-order diffusion, including hydrometeors Removal of microphysics latent-heating limit Use NSSL Implicit-Explicit Vertical Advection scheme	Major revisions to cloud-cover rendering Revisions to variable-density snowfall algorithm Add HAILCAST hail-size diagnostic

Why run rapidly-updating NWP systems?

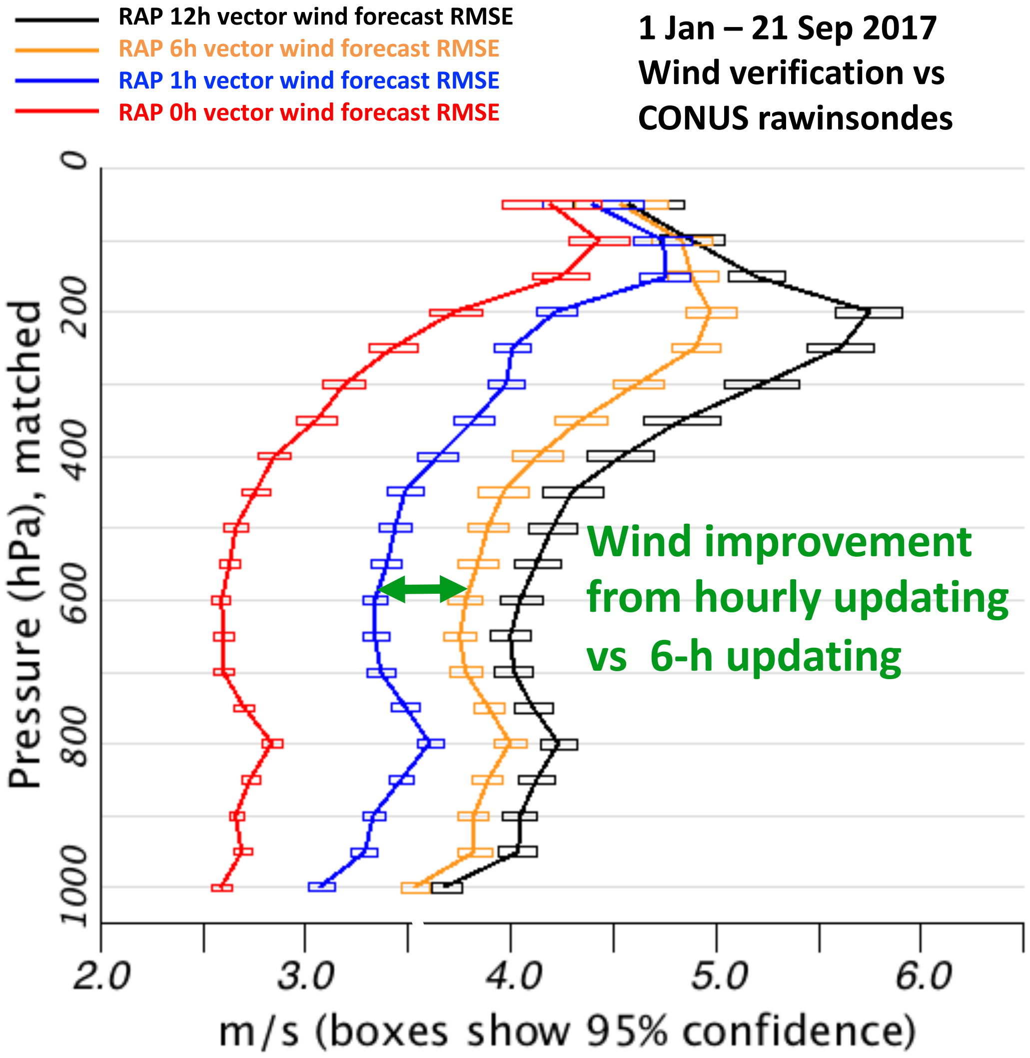
Most NWP systems are run 2x or 4x per day. Rapidly-updating NWP systems take advantage of the most recent observations, and provide updates for users needing short-term forecasts for decision-making (aviation, severe weather, energy, firefighting, etc.)



The **13km RAP and 3km HRRR models:**

2012 -13-km RAP implemented at NCEP (replacing RUC model)

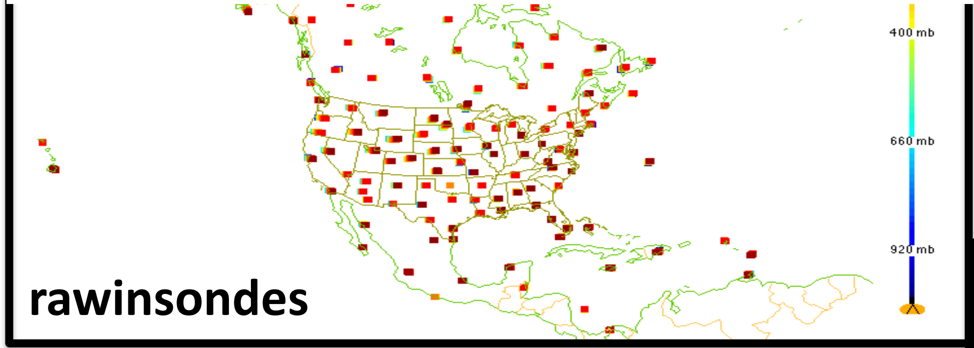
2014 - 3-km HRRR implemented at NCEP.

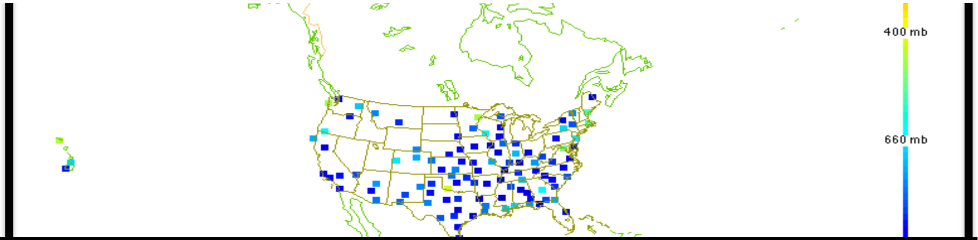


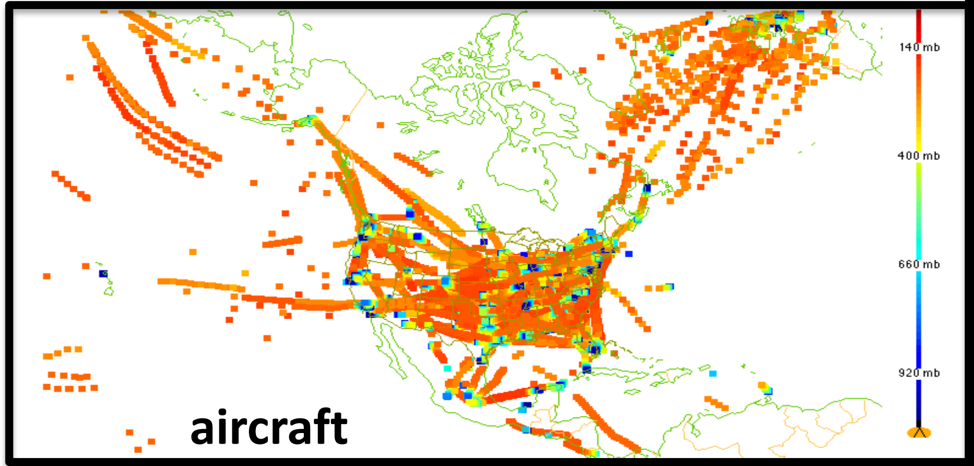
Which observations are assimilated in RAP?

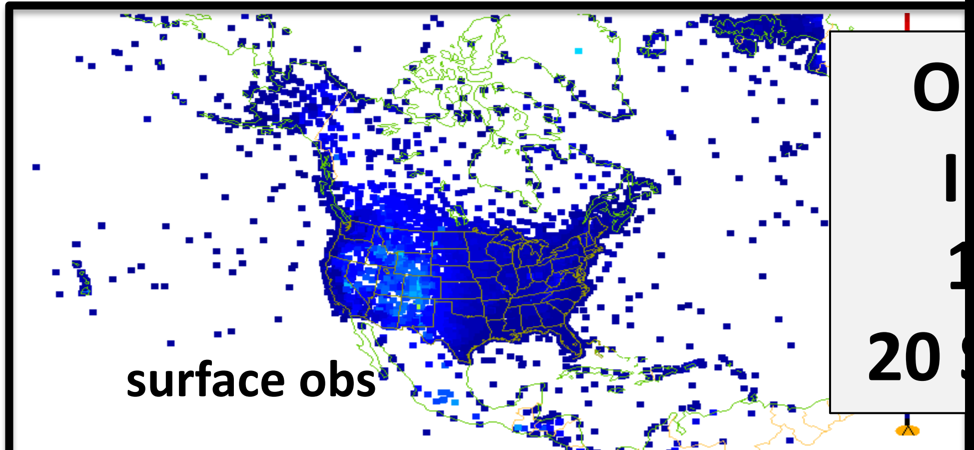
Hourly Observation Type	Variables Observed	Obs Count / Hour
Rawinsonde	Temperature, Humidity, Wind, Pressure	120
Profiler – 915 MHz	Wind, Virtual Temperature	20-30
Radar – VAD	Wind	125
Radar	**Radial Velocity**	**125 radars**
Radar reflectivity – CONUS	3-d refl ➔Rain, Snow, Graupel	1,500,000
Lightning	**(proxy reflectivity)**	**NLDN**
Aircraft	Wind, Temperature	2,000 -15,000
Aircraft - WVSS	Humidity	0 - 800
Surface/METAR	Temperature, Moisture, Wind, Pressure, Clouds, Visibility, Weather	2200 - 2500
Surface/Mesonet	**Temperature, Moisture, Wind**	**~5K-12K**
Buoys/ships	Wind, Pressure	200 - 400
GOES AMVs	Wind	2000 - 4000
AMSU/HIRS/MHS **(RARS)**	Radiances	1K-10K
GOES	Radiances	large
GOES cloud-top press/temp	Cloud Top Height	100,000
GPS – Precipitable water	Humidity	260
WindSat Scatterometer	Winds	2,000 – 10,000

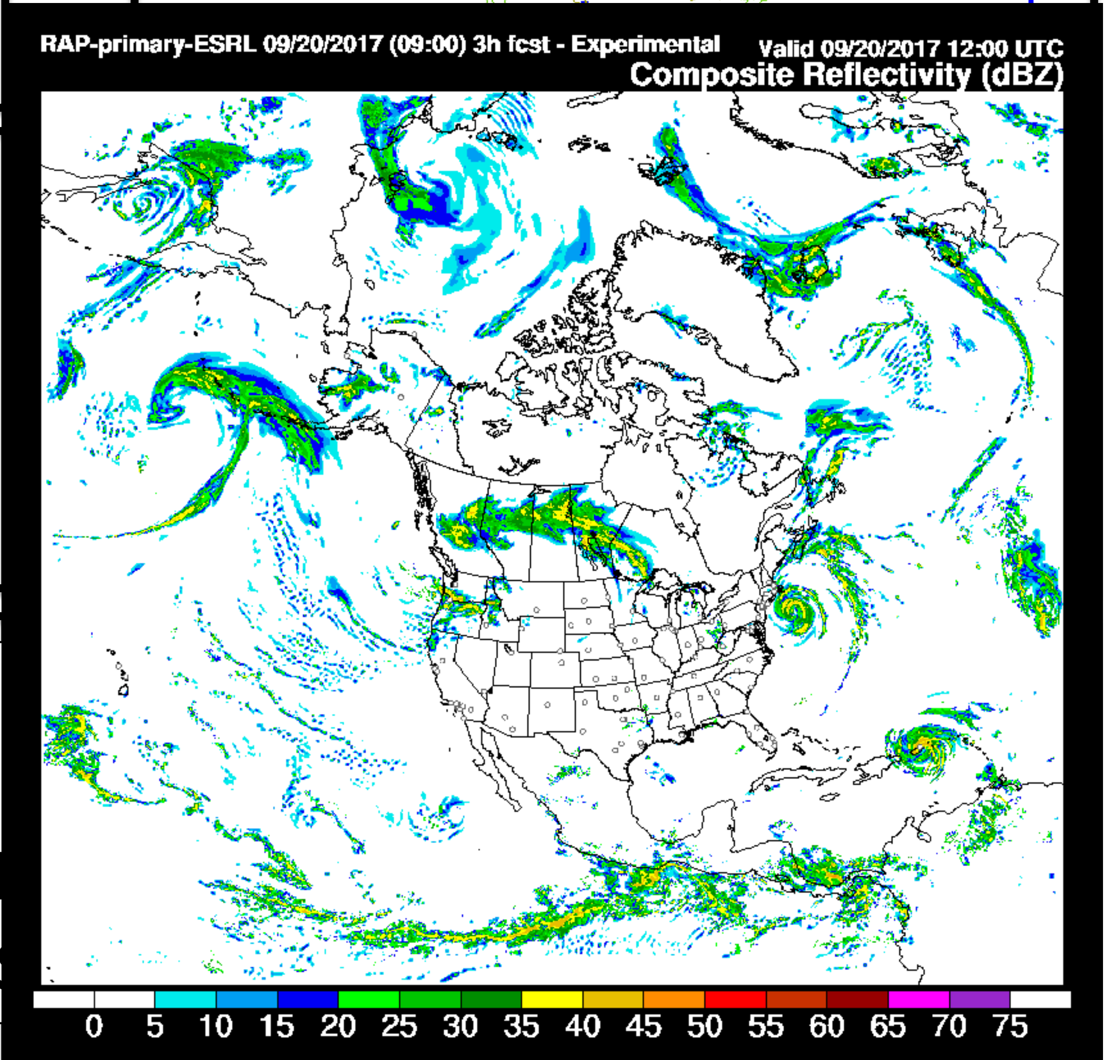
Which observations are assimilated in RAP?











Hourly cycling can also take advantage of high-density (space and time) observations especially for mesoscale features with lifetime of only a few hours.

Examples of observation coverage

How much impact do aircraft obs have within the RAP?

Data denial experiments with the RAPv3 examined the relative contribution of different types of observations:

- A - withhold rawinsonde obs - Exp. raob - control
- B - withhold aircraft obs - Exp. aircraft - control
- C - withhold profiler obs - Exp. profiler - control
- D - withhold radar reflectivity - Exp. radar - control
- E - withhold VAD winds - Exp. vad - control
- F - withhold GPS-Met precipitable water obs - Exp. gpsmet - control
- G - withhold GOES satellite obs - Exp. goes - control
- H - withhold RARS data - Exp. rars - control
- I - withhold all radiance - Exp. radiance - control
- J - withhold surface obs including METAR cloud - Exp. surface - control
- K - withhold mesonet obs - Exp. mesonet - control
- L - withhold AMVs - Exp. clouddrift - control

These results were published in several studies:

James and Benjamin **2017**: Observation system experiments with the hourly updating Rapid Refresh model using GSI hybrid ensemble-variational data assimilation. *Mon. Wea. Rev.*, **145** (8), 2897-2918. https://doi.org/10.1175/MWR-D-16-0398.1

Lin et al. **2017**: Satellite radiance data assimilation within the hourly updated Rapid Refresh. *Wea. Forecasting*, **32**, 1273-1287. https://doi.org/10.1175/WAF-D-16-0215.1

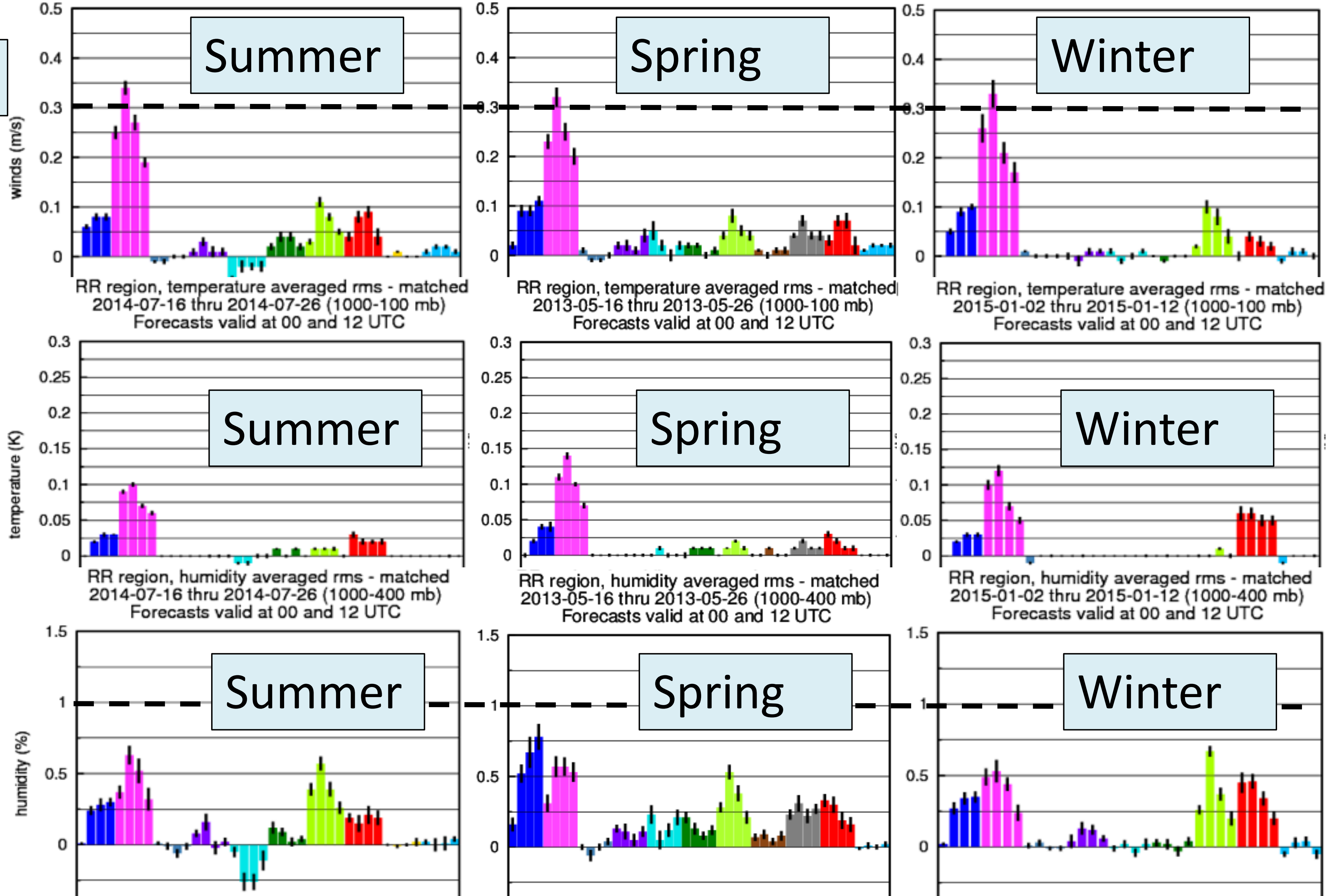
Lin et al. **2017**: Radiance pre-processing for assimilation in the hourly updating Rapid Refresh mesoscale model: A study using AIRS data. *Wea. Forecasting*, **32**, 1781-1800. https://doi.org/10.1175/WAF-D-17-0028.1

How much impact do aircraft obs have within the RAP?

Winds

Temp

RH

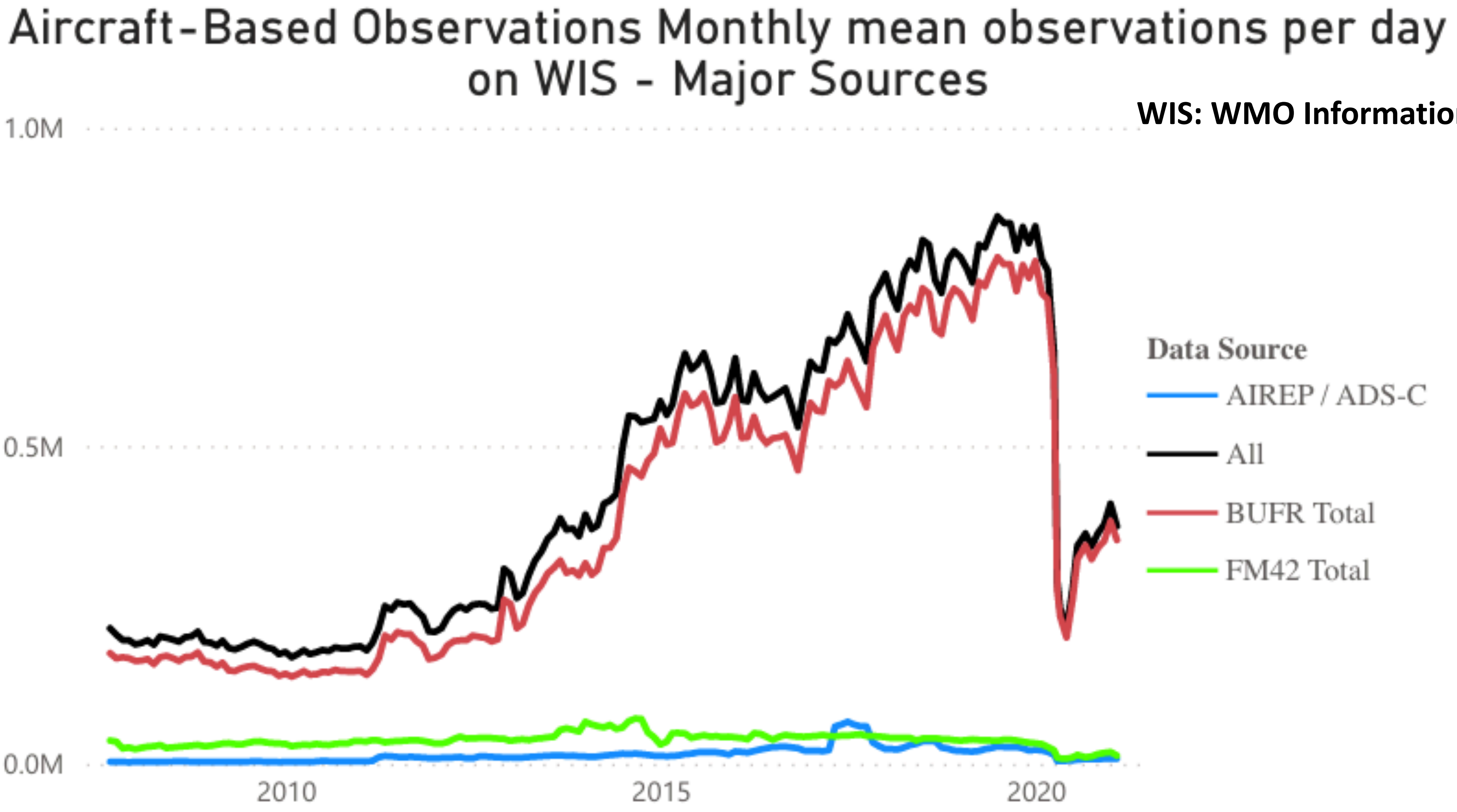


25% Error reduction

Height of bars indicates positive observation impacts on 3h, 6h, 9h, 12h forecasts

25% Error reduction

Backdrop of long-term trend in aircraft observations



WIS: WMO Information System

Eyjafjallajökull Eruption: Apr – May 2010

While such comparisons have been done on numerous occasions, there have been several 'real life' occasions or events when the positive and significant impact of AMDAR data has become apparent as a result of operational disruption or unplanned data loss.

Two such examples that demonstrate the positive impact of AMDAR on NWP are the following:

- In the days after the recent Eyjafjallajökull eruption in Iceland (April 2010), several regional European NWP models showed a dramatic loss in forecast skill due to the complete lack of AMDAR data over Europe and parts of the Atlantic.
- In the aftermath of September 11, 2001, when all civil aviation operations were suspended in the U.S., the complete loss of AMDAR data during this period resulted in a 20% loss of wind forecast skill to the NCEP Rapid Update Cycle (RUC) high resolution NWP model, with the 3 hour RUC forecast skill minus AMDAR data dropping back to nearly that of the normal 12 hour forecasts.

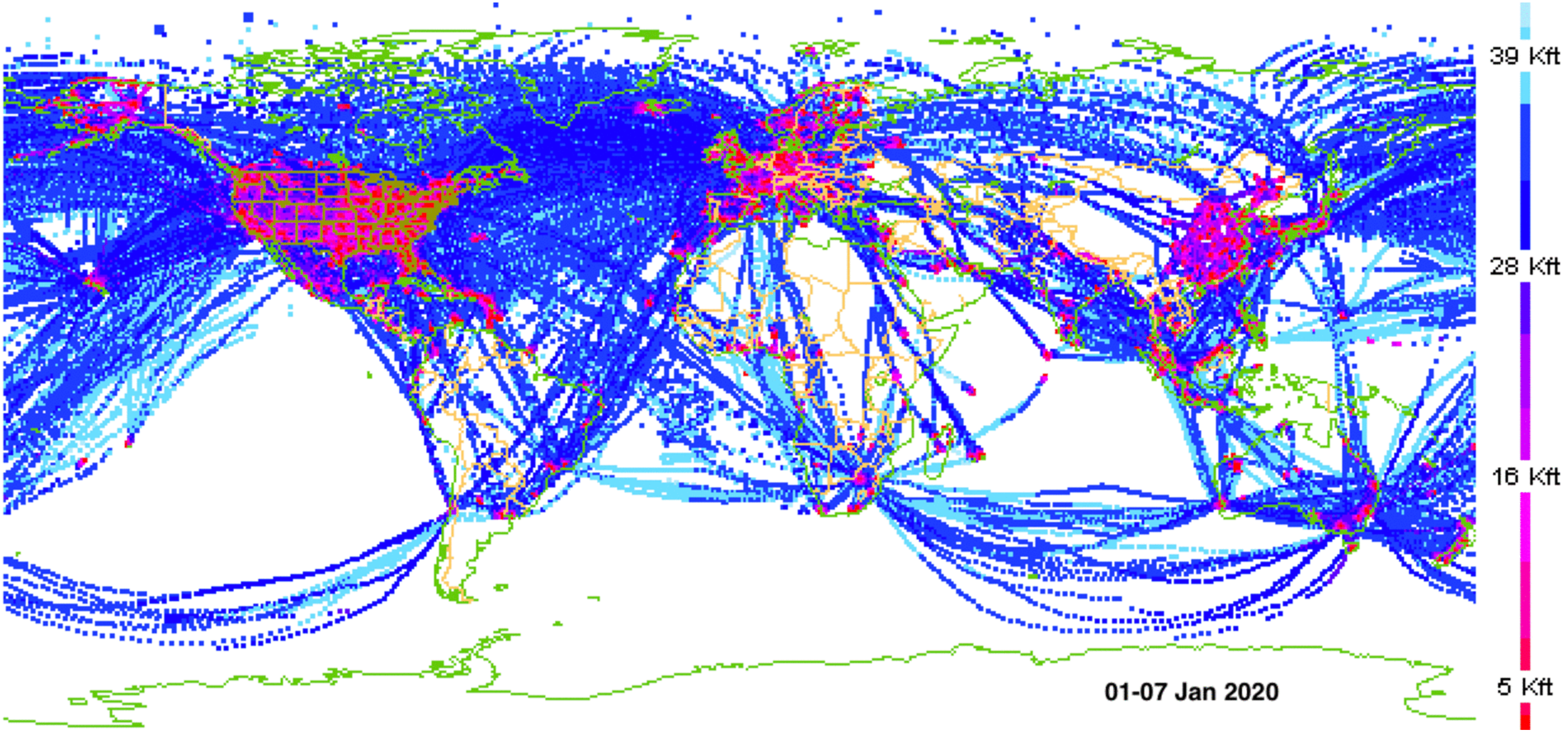
TECHNICAL REPORT No. 2014-01

WIGOS

WMO Integrated Global Observing System

The Benefits of AMDAR Data to Meteorology and Aviation

Global Air Traffic Decreases due to COVID-19



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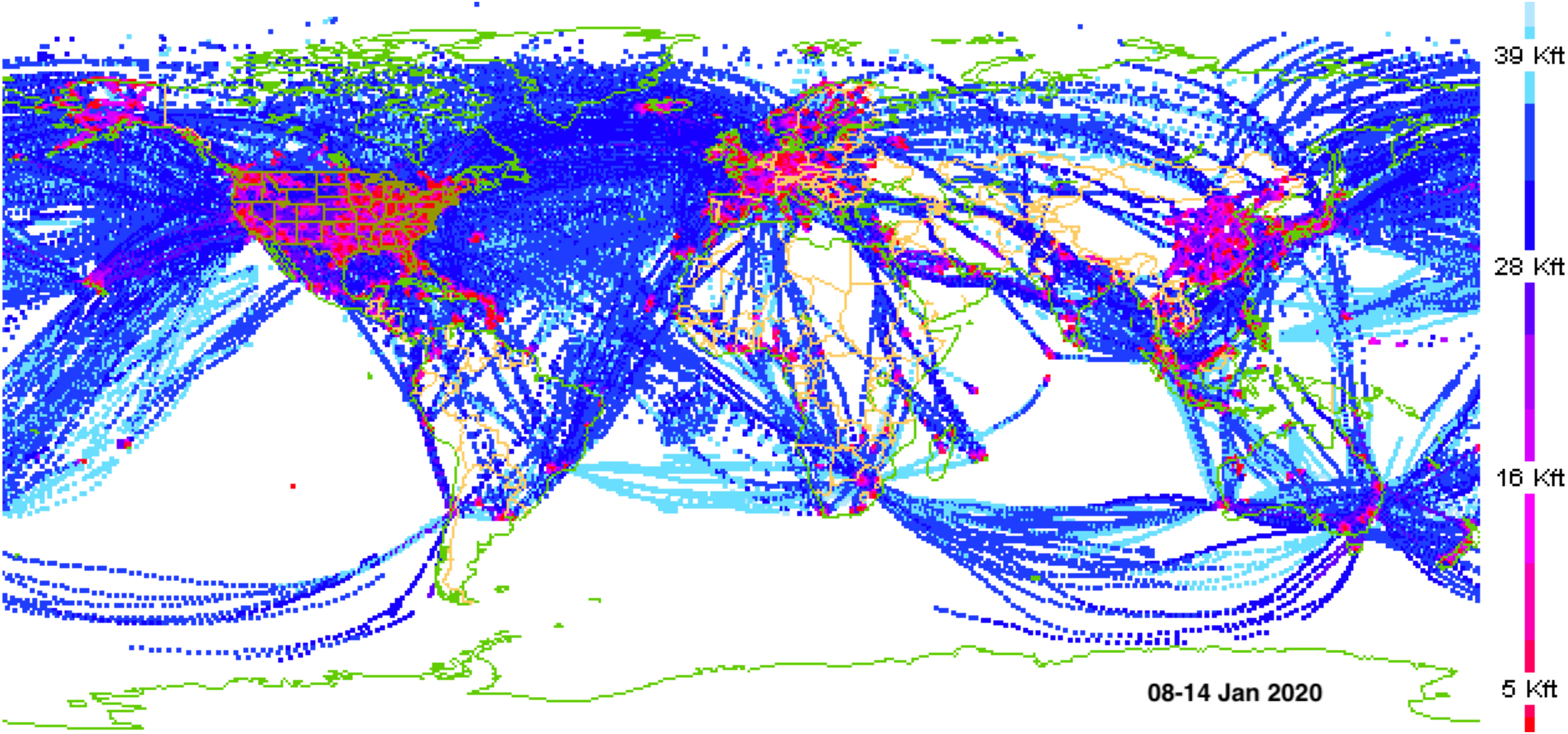

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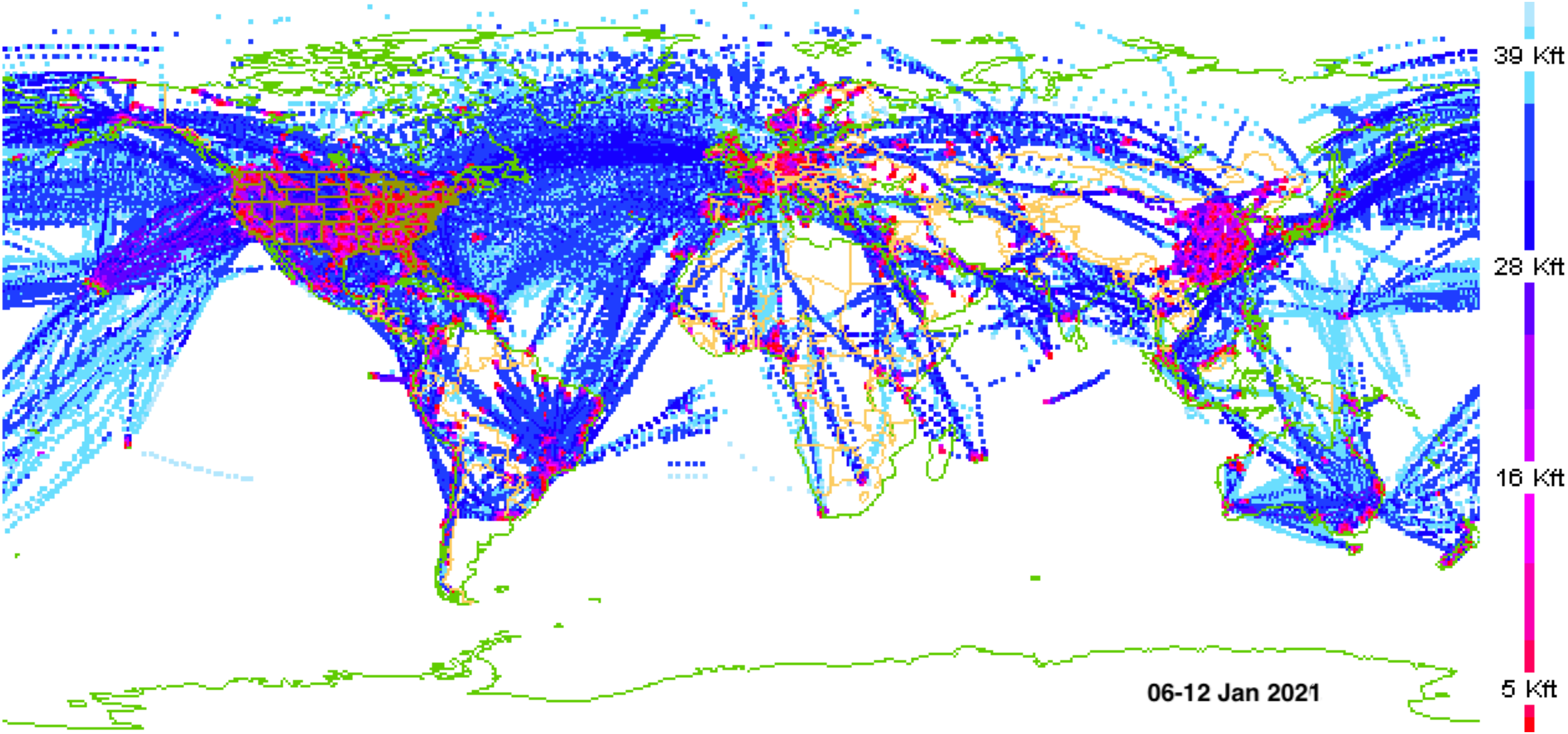
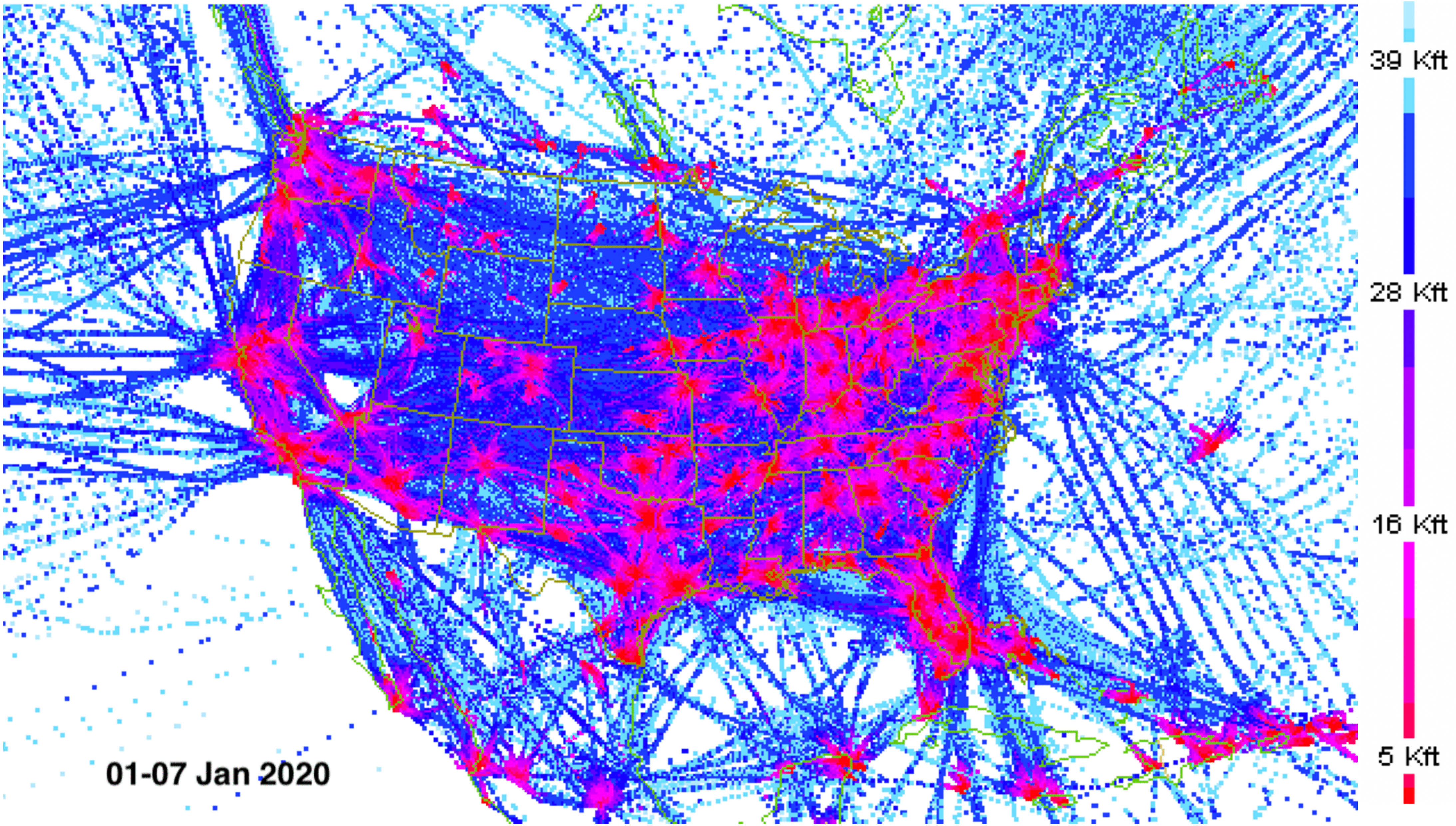
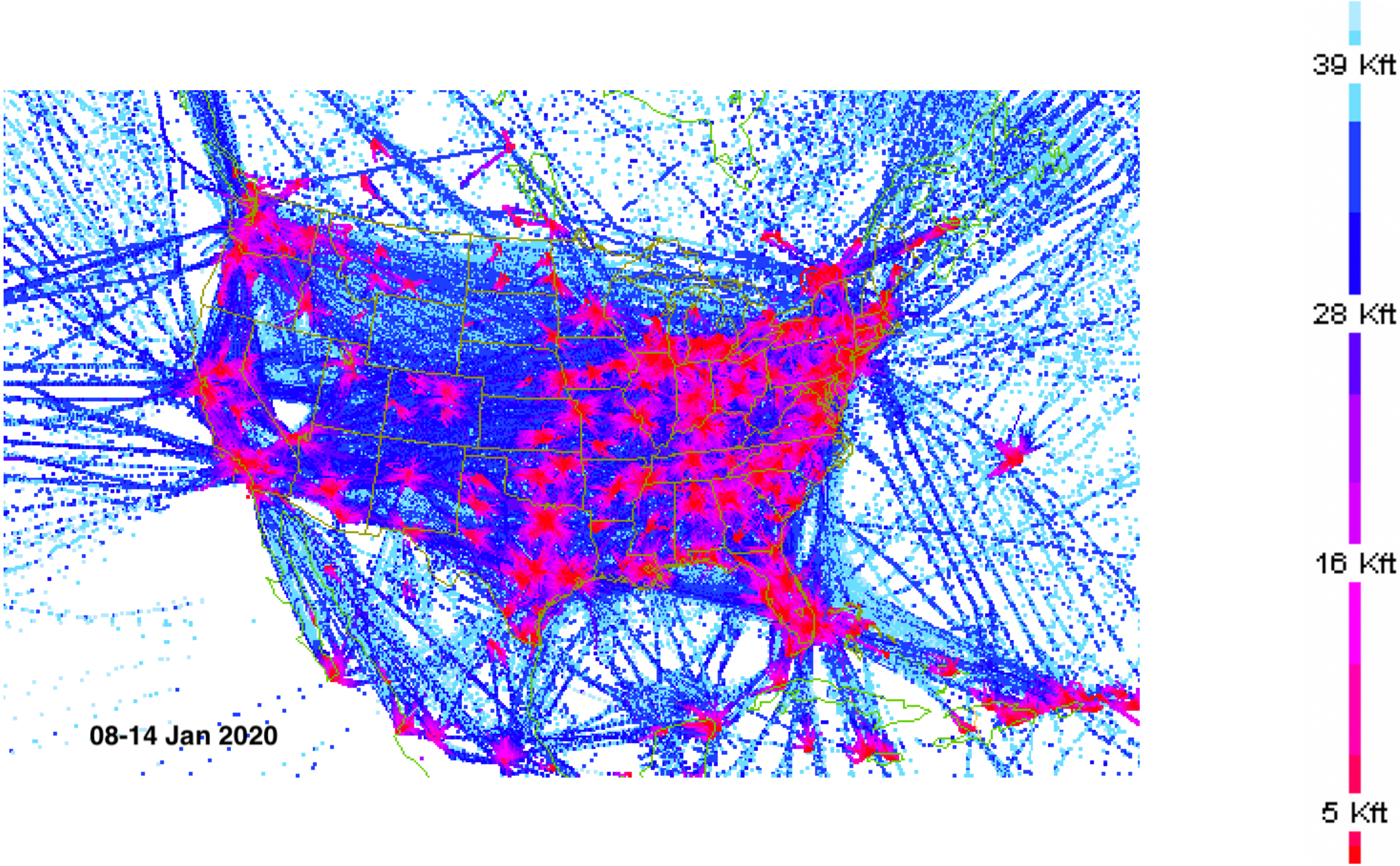


CONUS Air Traffic Decreases due to COVID-19



CONUS Air Traffic Decreases due to COVID-19



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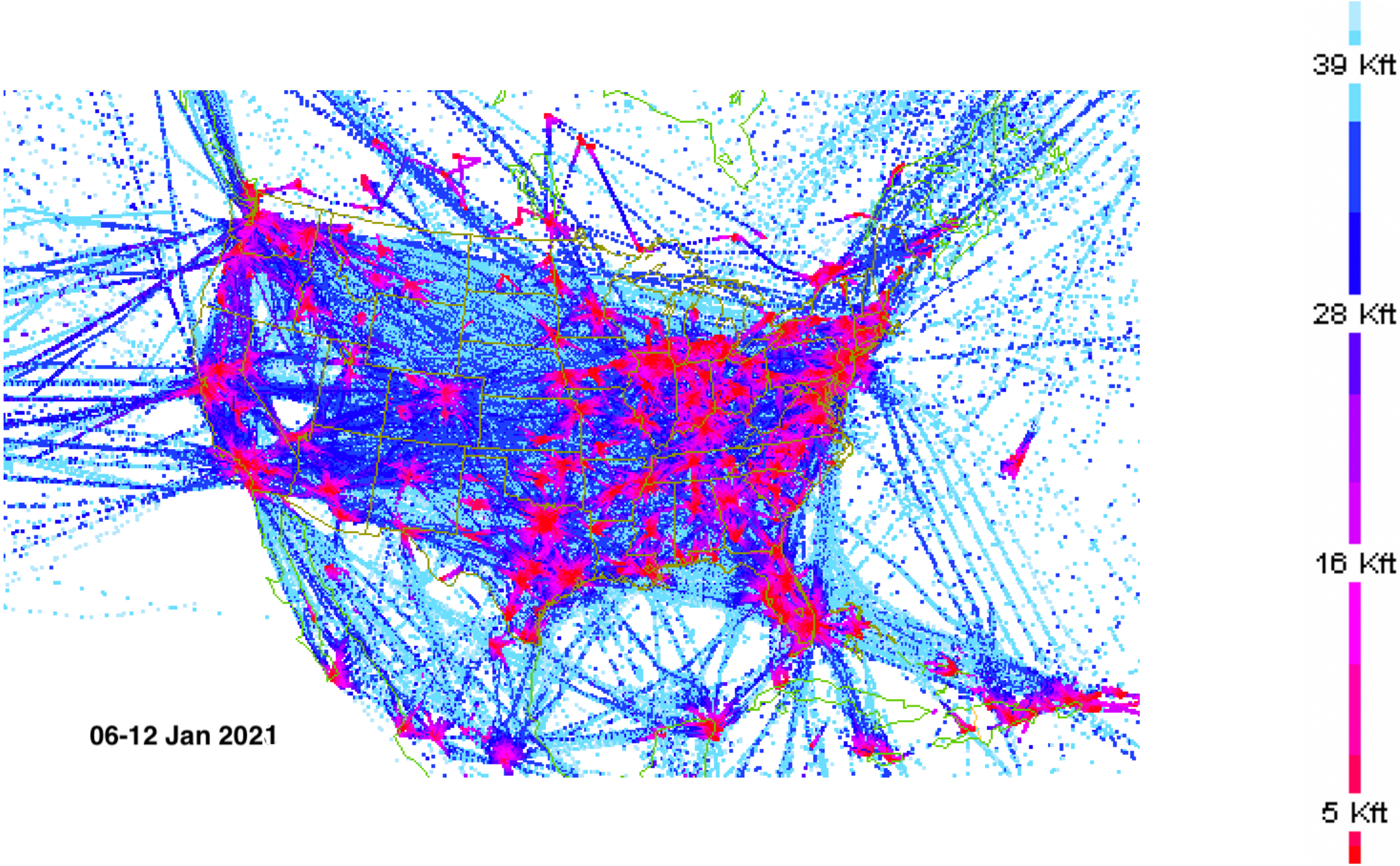
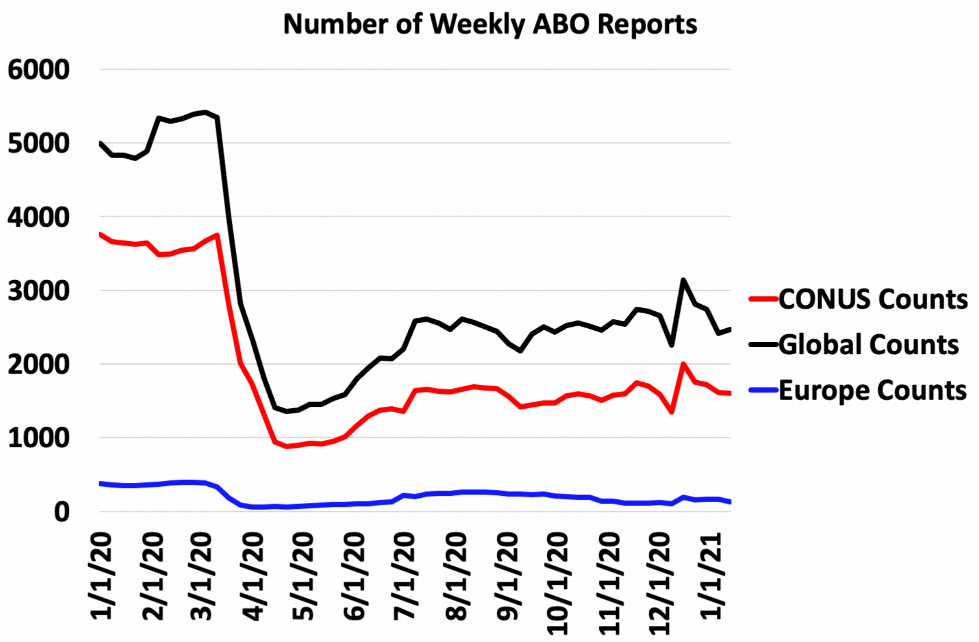


Aircraft observations during COVID-19

Global lockdowns during the COVID-19 pandemic have led to a dramatic decrease in global aircraft observations since March 2020; at the peak of the lockdowns, aircraft obs were down by ~75%, with continued observations at ~50% of pre-COVID levels as of Jan 2021.



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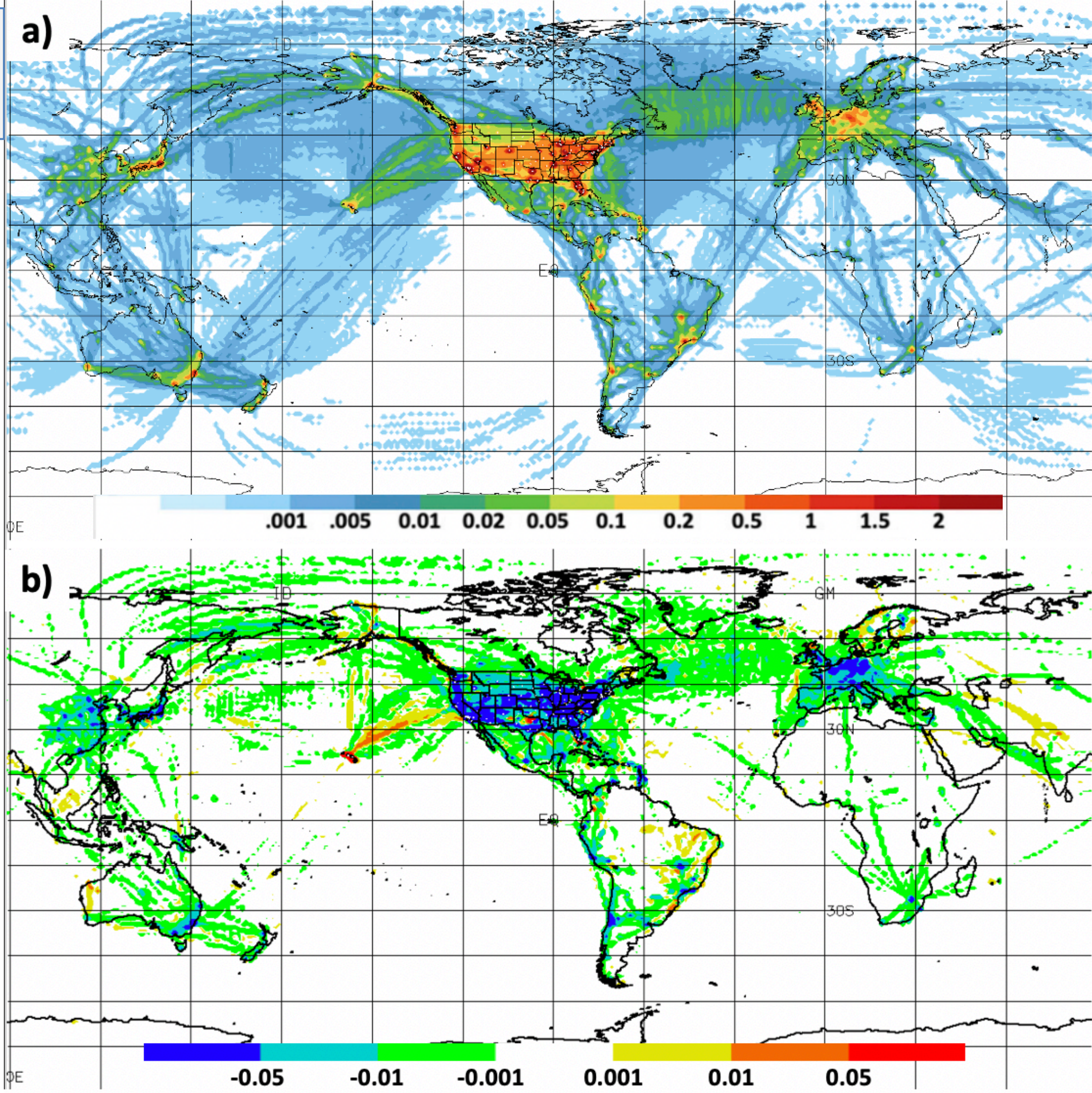

Figure 5. Global ABO coverage (number of monthly observations per km²) (a) during Mar 2019 and (b) difference in coverage between Mar 2019 and Mar 2020.

COVID-19 impacts on North American aircraft reports

In March 2019 (pre-COVID-19), aircraft observation coverage gaps exist over Arctic Canada and over oceanic regions (especially tropical eastern Pacific). Over the CONUS, lower coverage is seen over the northern plains / northern intermountain region.

During March 2020, coverage was reduced almost everywhere except for along a few flight routes and near a few hubs.

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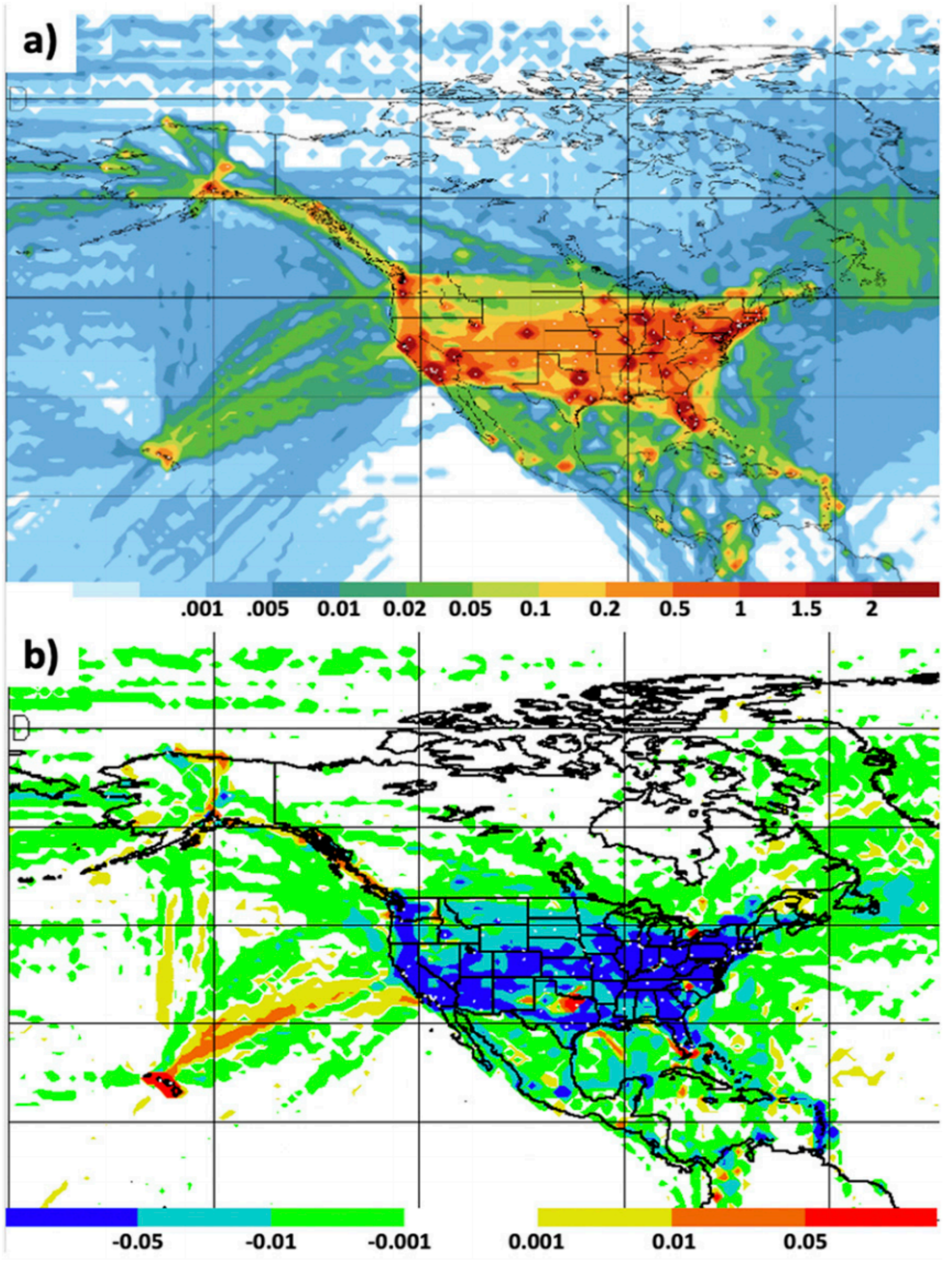
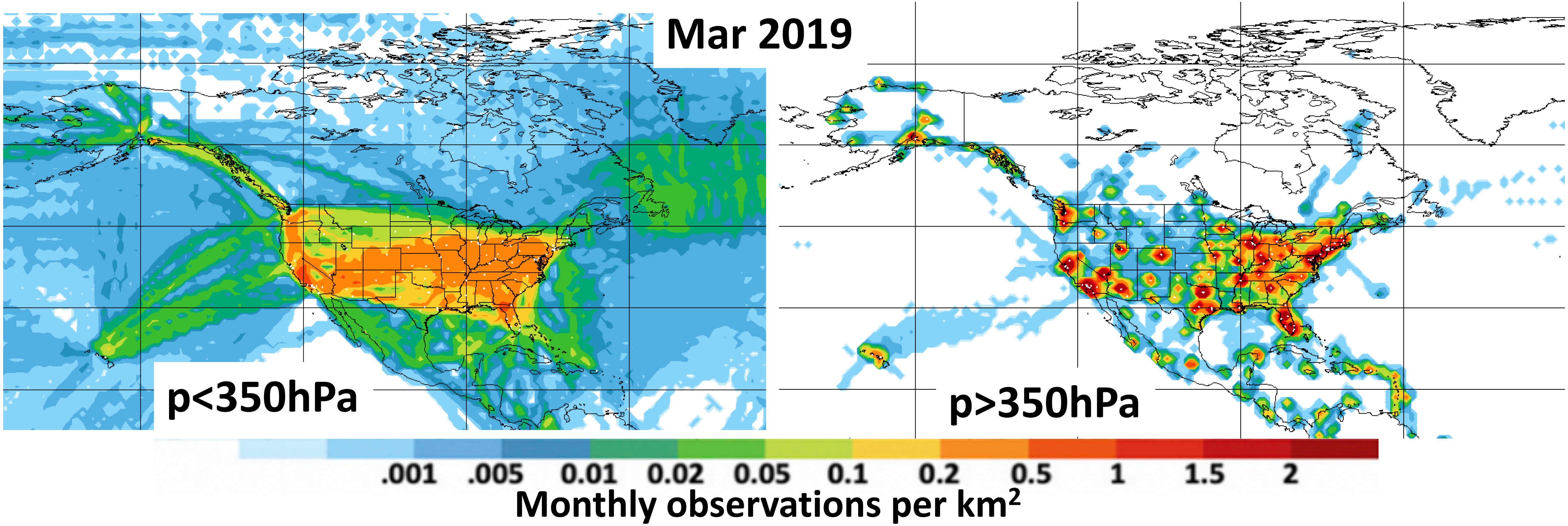


FIG. 1. North American ABO coverage (number of monthly observations per kilometer squared) during (a) March 2019, and (b) the difference in coverage between March 2019 and March 2020. Small white dots indicate CONUS airport locations.

North American aircraft observation impacts

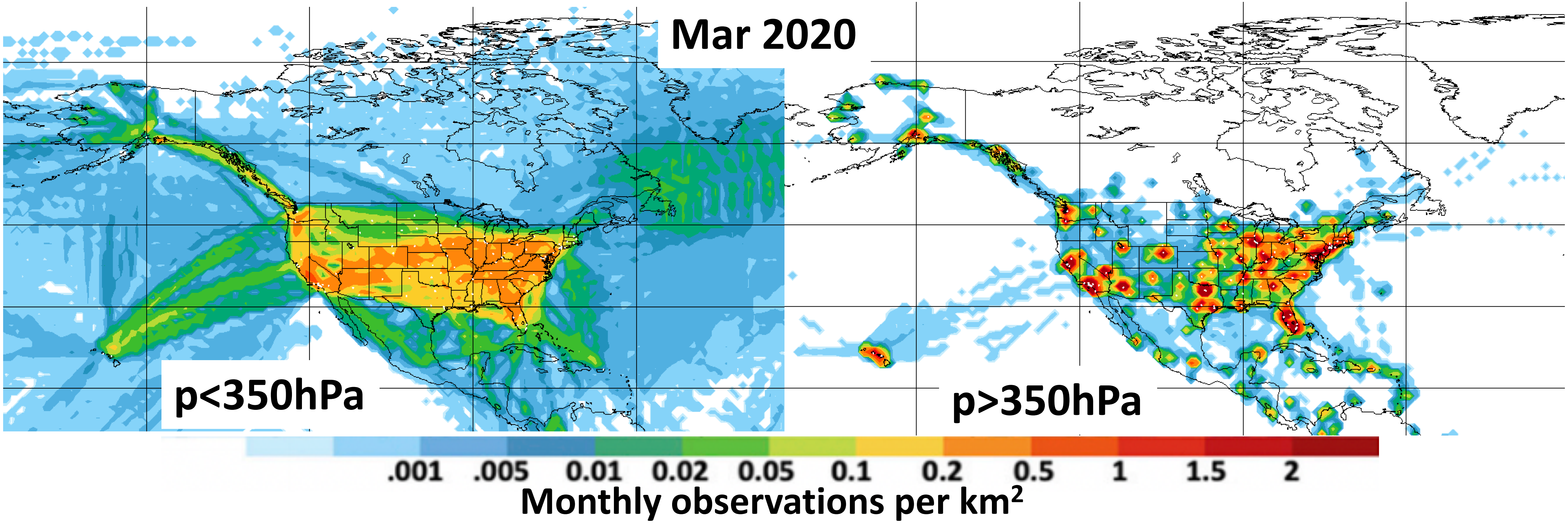


Coverage ***above 350 hPa*** highlights cruising aircraft flight routes; coverage ***below 350 hPa*** highlights ascending / descending aircraft.

Decreased enroute observation coverage is seen over the CONUS during March 2020 compared with March 2019.

Decreased coverage seen at almost all US airports. Exceptions: Dallas-Fort Worth (due to medical supply flights in March 2020?) and Hawaii (vacationers being returned to mainland US?)

North American aircraft observation impacts



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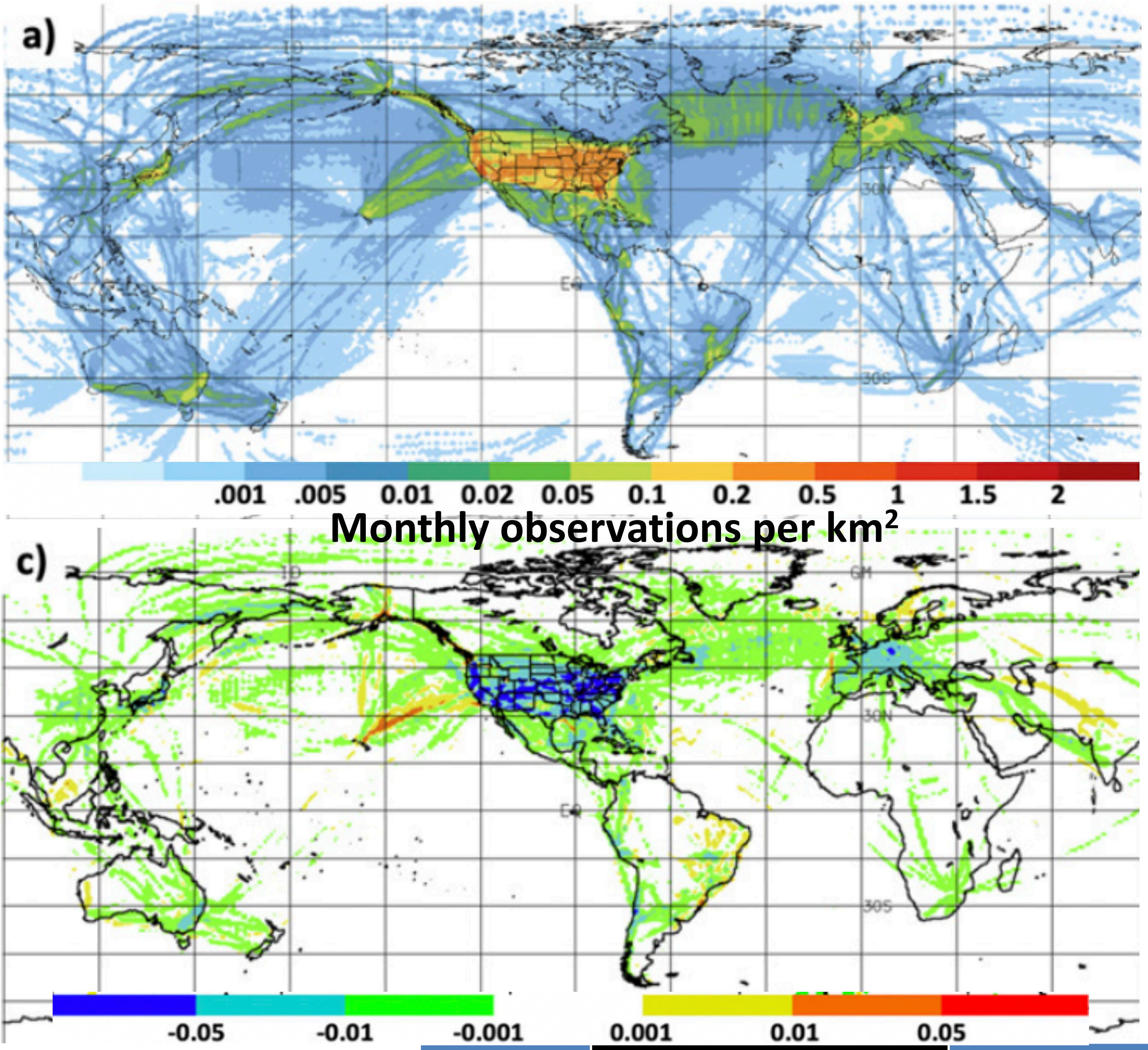
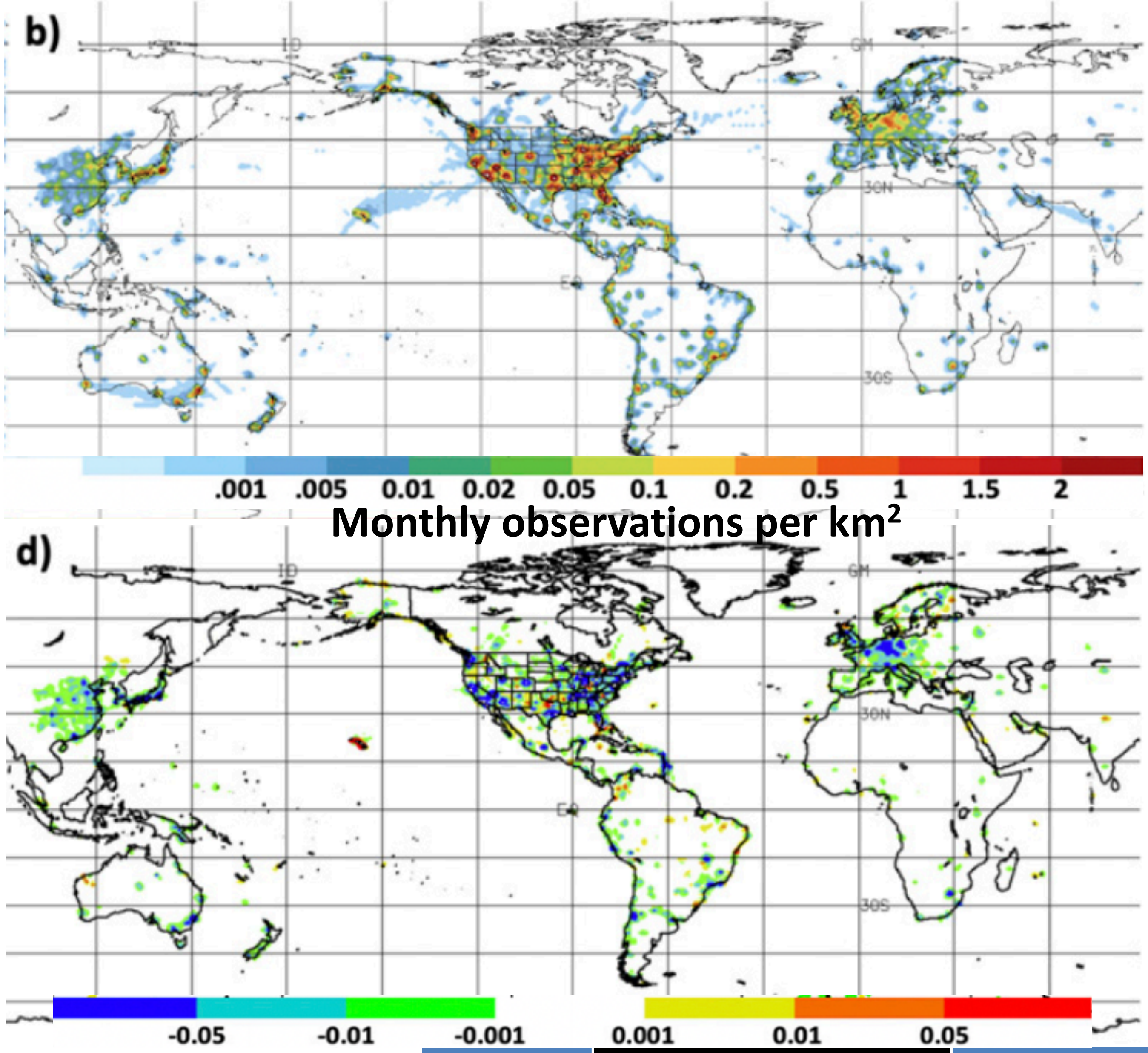
Global enroute (p<350hPa) observation impacts



Coverage decreases are seen in most international and intercontinental flight routes.

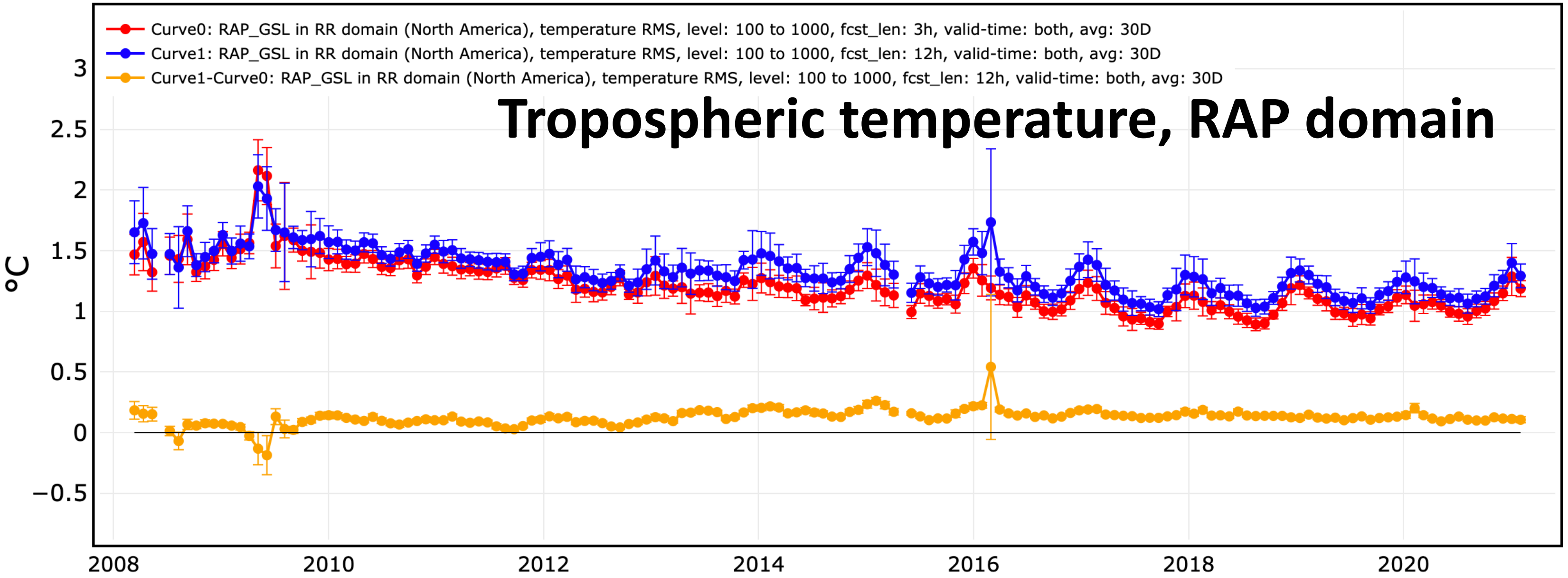
Exceptions may be due to repatriation flights, medical supply flights.

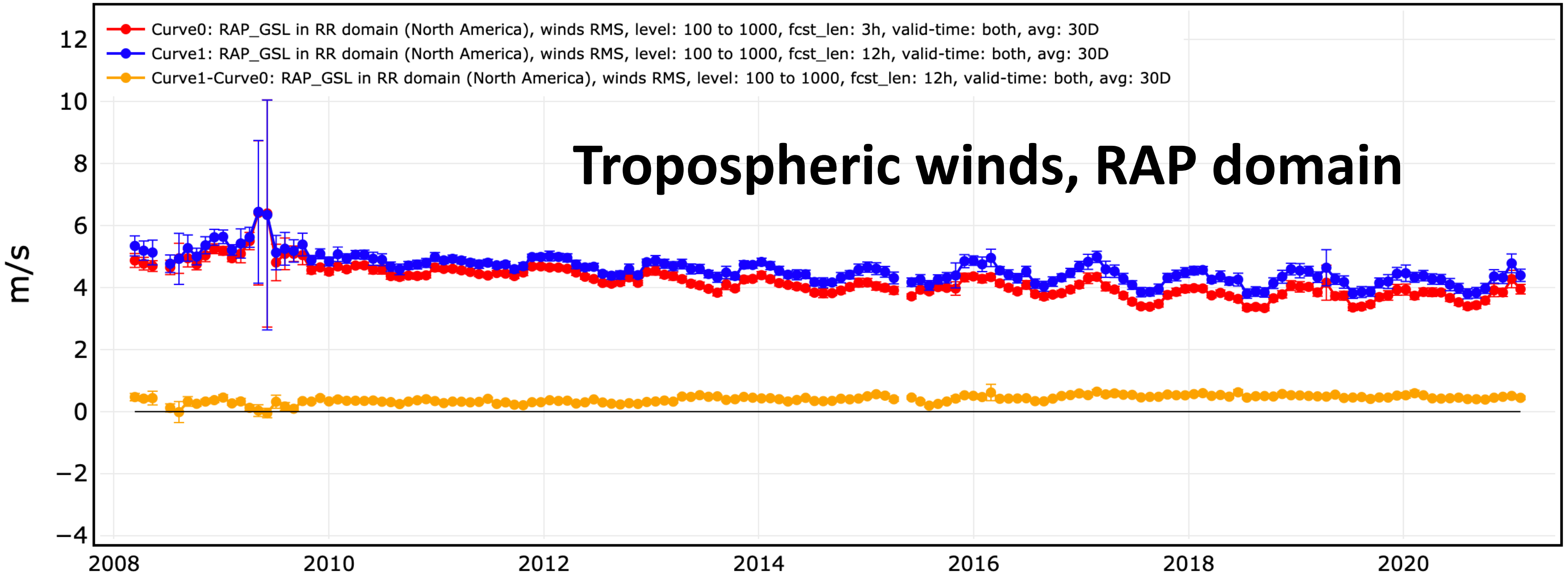
Global ascent/descent (p>350hPa) observation impacts



Almost all airport hubs exhibit a decrease in observations from March 2019 to March 2020.

What are the long-term trends in forecast skill?





12h fcsts

3h fcsts

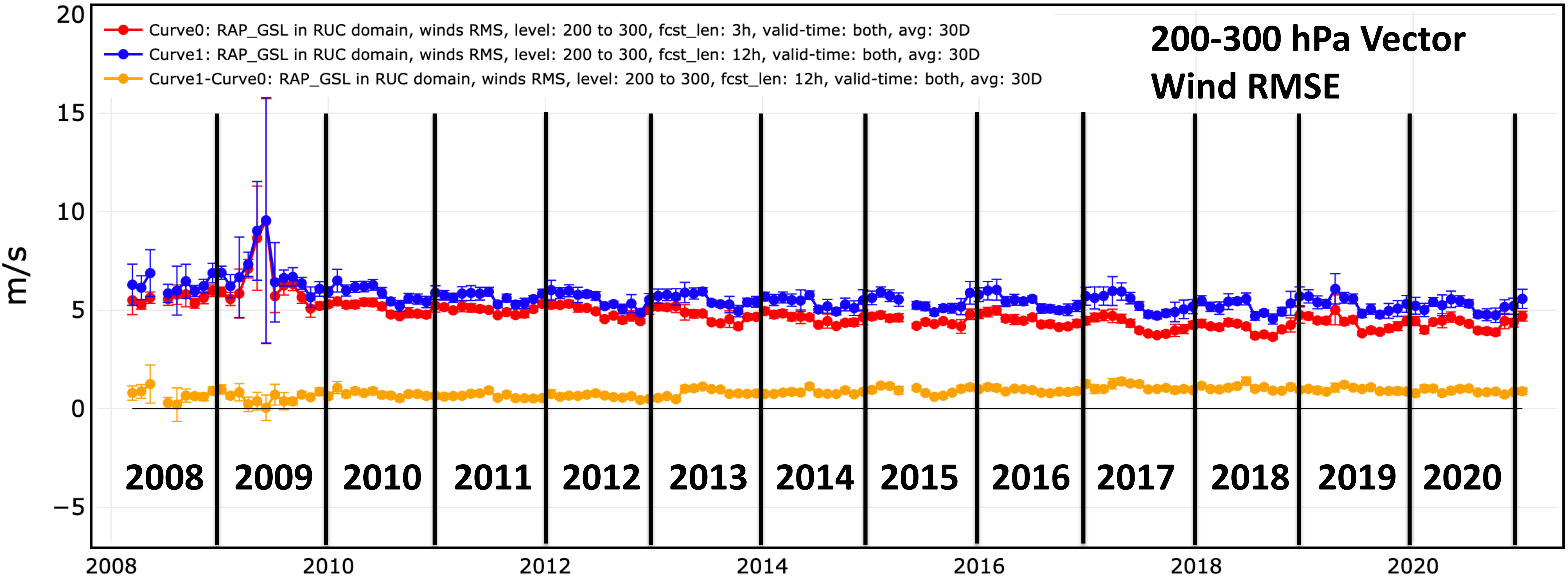
12h MINUS 3h diff

This time series contains model physics and DA changes!

Temperature and wind errors are larger in winter than summer

Long-term decreasing trend in errors!

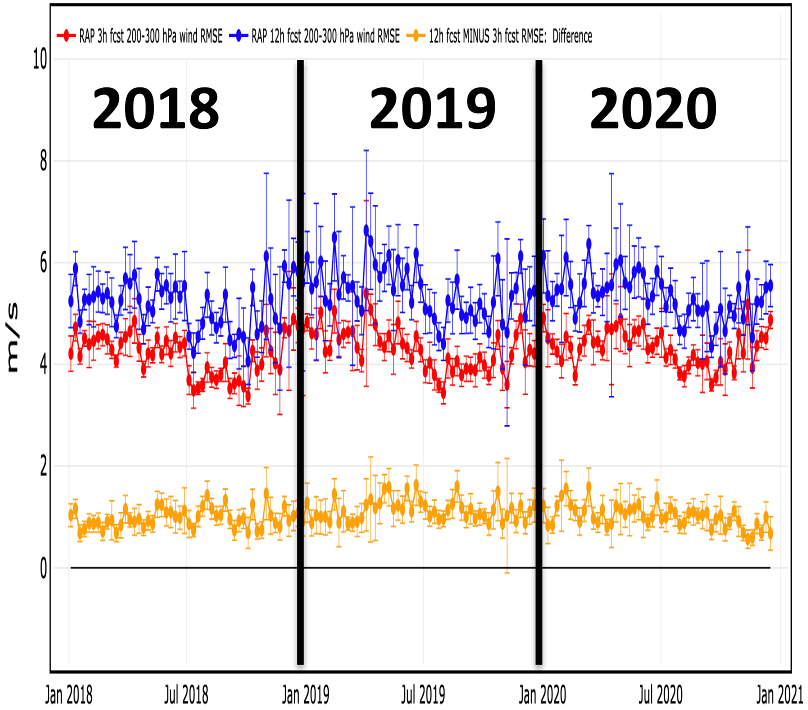
What are the long-term trends in forecast skill?



Aircraft obs are most dense around cruising level (200-300 hPa), so we look for signals here.

Long-term downward trend in wind forecast errors since 2009.

Detecting a realtime forecast degradation during COVID-19?



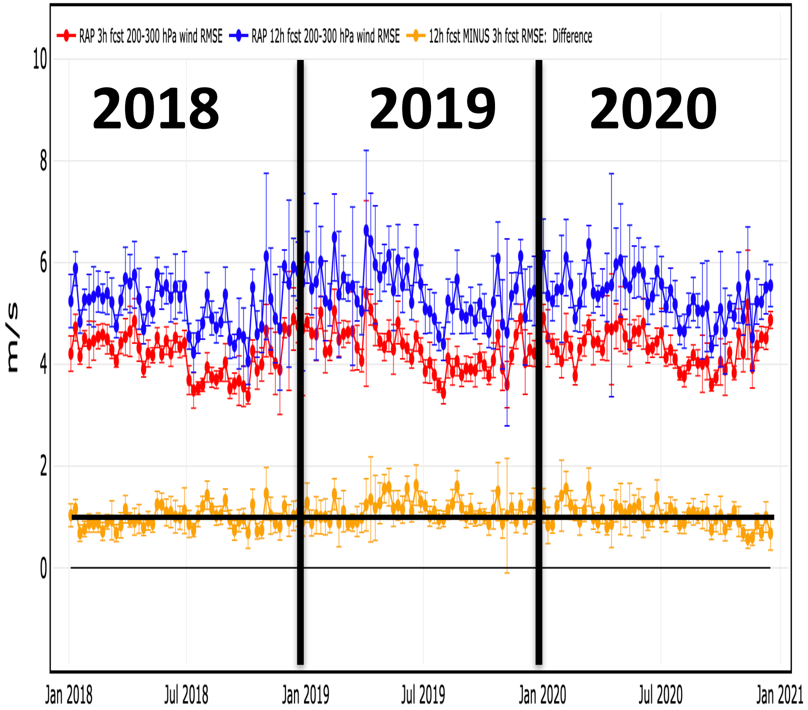
12h-3h forecast error
RMS vector error 200-300 hPa
Vs. raobs - CONUS

The COVID-19 decrease in aircraft obs is not as dramatic as the 100% dropout over the US during Sep 2001 or the airspace closure due to the Icelandic Eyjafjallajökull eruption in Apr-May 2010.

Detecting a realtime signal is challenging due to the small signal-to-noise ratio; day-to-day forecast skill is strongly dependent on the meteorological situation.

Therefore, we designed a retrospective experiment to quantify the COVID-19 degradation.

Detecting a realtime forecast degradation during COVID-19?



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RAPv5 denial experiments on aircraft observation impacts

We carried out a set of data denial experiments focused specifically on aircraft observation impacts. These were designed before the COVID-19 pandemic hit.

We then designed a special experiment assimilating only observations from a single airline to imitate real-time flight reductions during COVID-19: this amounted to an 80% reduction in T, q, and uv observations over the RAP domain.

Comparing forecast skill during this experiment with the control experiment (which assimilated all observations) allows a quantification of the degradation stemming from COVID-19.

EXPERIMENT	JULY 2018	FEBRUARY 2019
No raob	Y	Y
No aircraft	Y	Y
Withhold 80% of aircraft obs	Y	Y
No enroute aircraft (p < 350 hPa)	Y	Y
No ascent/descent aircraft (p > 350 hPa)	Y	Y
No aircraft moisture obs	Y	Y
No TAMDAR	Y	Y

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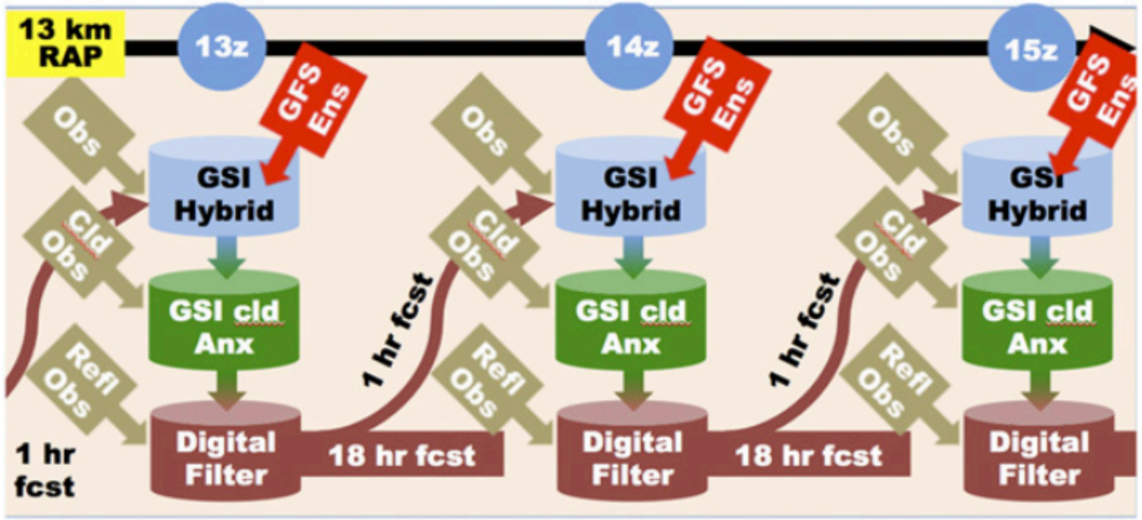
RAPv5 model configuration



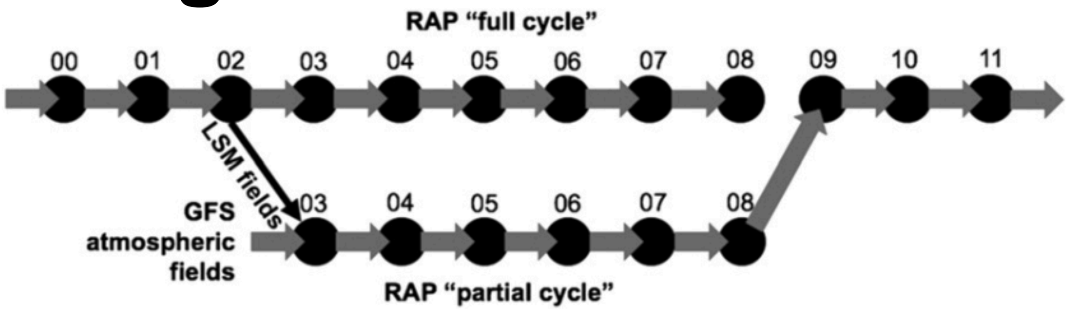
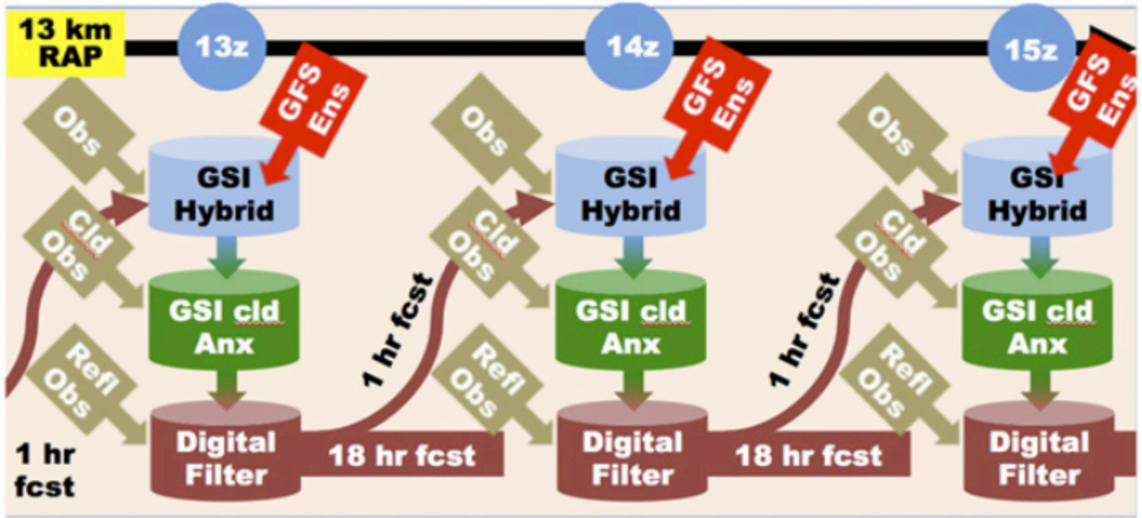


FIG. 10. Configuration of the RAP partial cycling. Black circles represent the RAP data assimilation with a background supplied by a prior forecast (represented by the gray arrows). At 0300 UTC, a parallel "partial cycle" is initialized from GFS atmospheric fields but using the full-cycle land surface model (LSM) state. A background from this partial cycle is used for the data assimilation in the primary "full cycle" 6 h later, at 0900 UTC. The procedure is repeated during 1200–2300 UTC.

The RAP consists of an hourly assimilation-forecast cycle, with twice-daily partial cycle from GFS.

Benjamin et al **2016**: A North American hourly assimilation and model forecast cycle: The Rapid Refresh. *Mon. Wea. Rev.*, **144** (4), 1669-1694. https://doi.org/10.1175/MWR-D-15-0242.1

RAPv5 model configuration



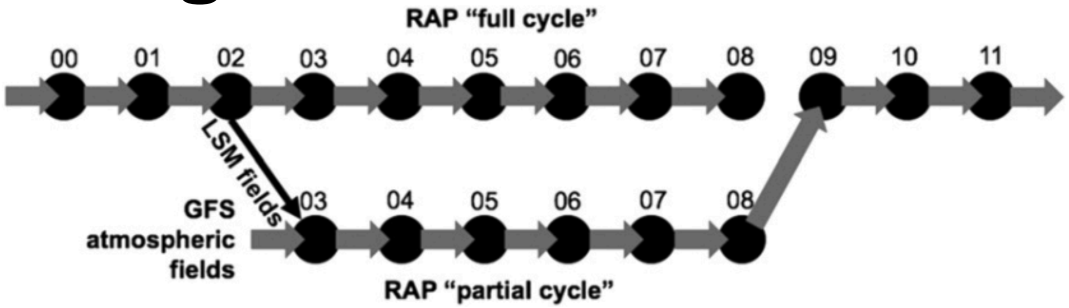


FIG. 10. Configuration of the RAP partial cycling. Black circles represent the RAP data assimilation with a background supplied by a prior forecast (represented by the gray arrows). At 0300 UTC, a parallel "partial cycle" is initialized from GFS atmospheric fields but using the full-cycle land surface model (LSM) state. A background from this partial cycle is used for the data assimilation in the primary "full cycle" 6 h later, at 0900 UTC. The procedure is repeated during 1200–2300 UTC.

The RAP consists of an hourly assimilation-forecast cycle, with twice-daily partial cycle from GFS. Hybrid ensemble-3DVar DA uses covariances from GDAS.

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Hu et al **2017**: GSI 3D ensemble-variational hybrid data assimilation using a global ensemble for the regional Rapid Refresh model. *Mon. Wea. Rev.*, **145** (10), 4205-4225. https://doi.org/10.1175/MWR-D-16-0418.1

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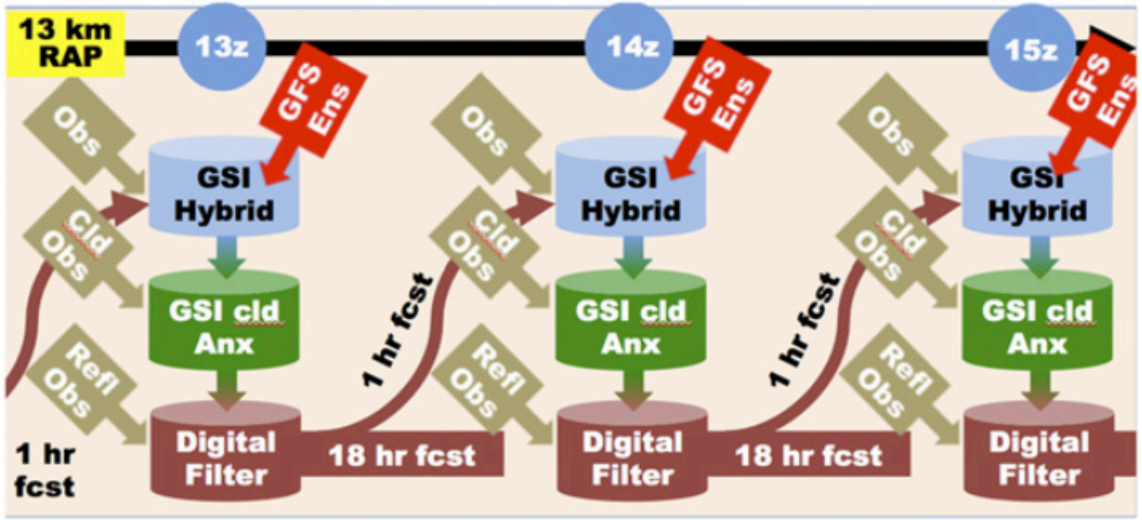


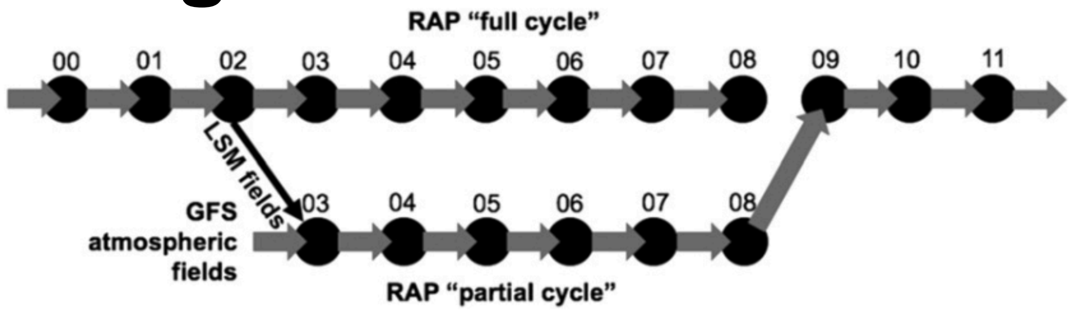


FIG. 10. Configuration of the RAP partial cycling. Black circles represent the RAP data assimilation with a background supplied by a prior forecast (represented by the gray arrows). At 0300 UTC, a parallel "partial cycle" is initialized from GFS atmospheric fields but using the full-cycle land surface model (LSM) state. A background from this partial cycle is used for the data assimilation in the primary "full cycle" 6 h later, at 0900 UTC. The procedure is repeated during 1200–2300 UTC.

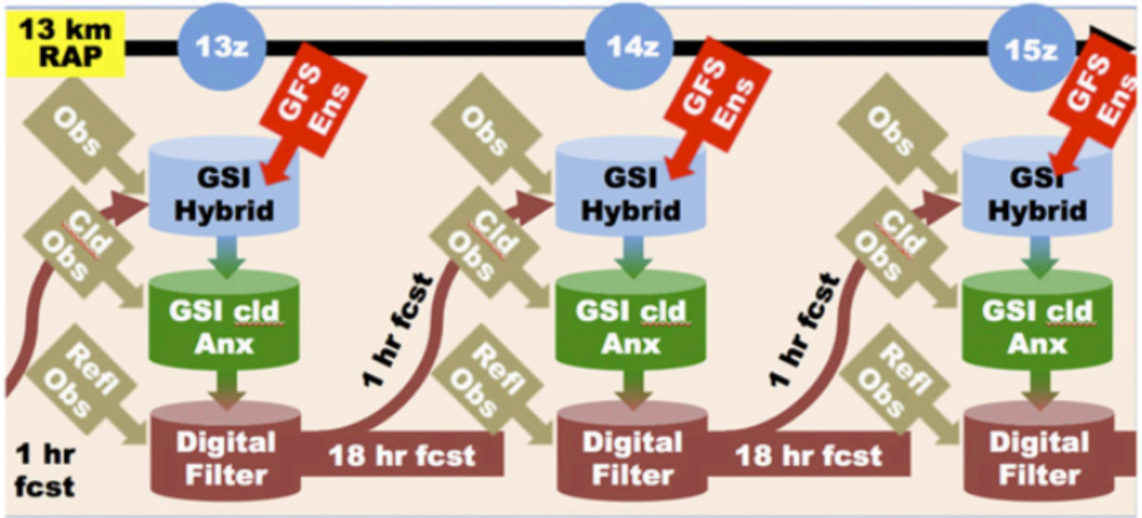
The RAP consists of an hourly assimilation-forecast cycle, with twice-daily partial cycle from GFS. Hybrid ensemble-3DVar DA uses covariances from GDAS. A stratiform cloud-hydrometeor analysis is carried out based on available cloud obs.

Benjamin et al **2016**: A North American hourly assimilation and model forecast cycle: The Rapid Refresh. *Mon. Wea. Rev.*, **144** (4), 1669-1694. https://doi.org/10.1175/MWR-D-15-0242.1

Hu et al **2017**: GSI 3D ensemble-variational hybrid data assimilation using a global ensemble for the regional Rapid Refresh model. *Mon. Wea. Rev.*, **145** (10), 4205-4225. https://doi.org/10.1175/MWR-D-16-0418.1

Benjamin et al **2021**: Stratiform cloud-hydrometeor assimilation for HRRR and RAP model short-range weather prediction. Revised Manuscript submitted to *Mon. Wea. Rev.*

RAPv5 model configuration



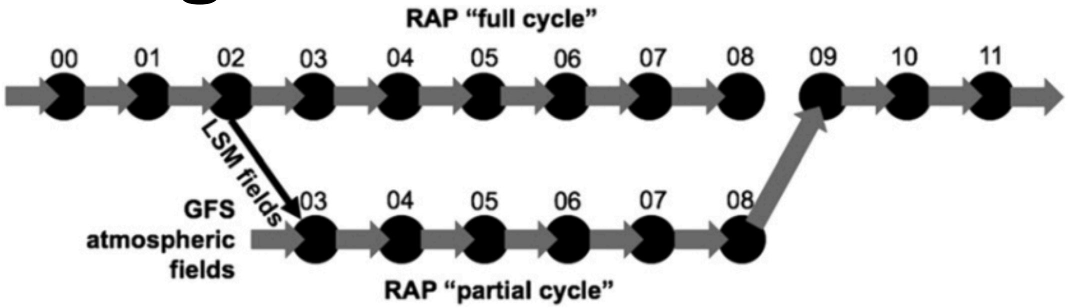


FIG. 10. Configuration of the RAP partial cycling. Black circles represent the RAP data assimilation with a background supplied by a prior forecast (represented by the gray arrows). At 0300 UTC, a parallel "partial cycle" is initialized from GFS atmospheric fields but using the full-cycle land surface model (LSM) state. A background from this partial cycle is used for the data assimilation in the primary "full cycle" 6 h later, at 0900 UTC. The procedure is repeated during 1200–2300 UTC.

The RAP consists of an hourly assimilation-forecast cycle, with twice-daily partial cycle from GFS. Hybrid ensemble-3DVar DA uses covariances from GDAS. A stratiform cloud-hydrometeor analysis is carried out based on available cloud obs. A digital filter initialization reduces small-scale noise.

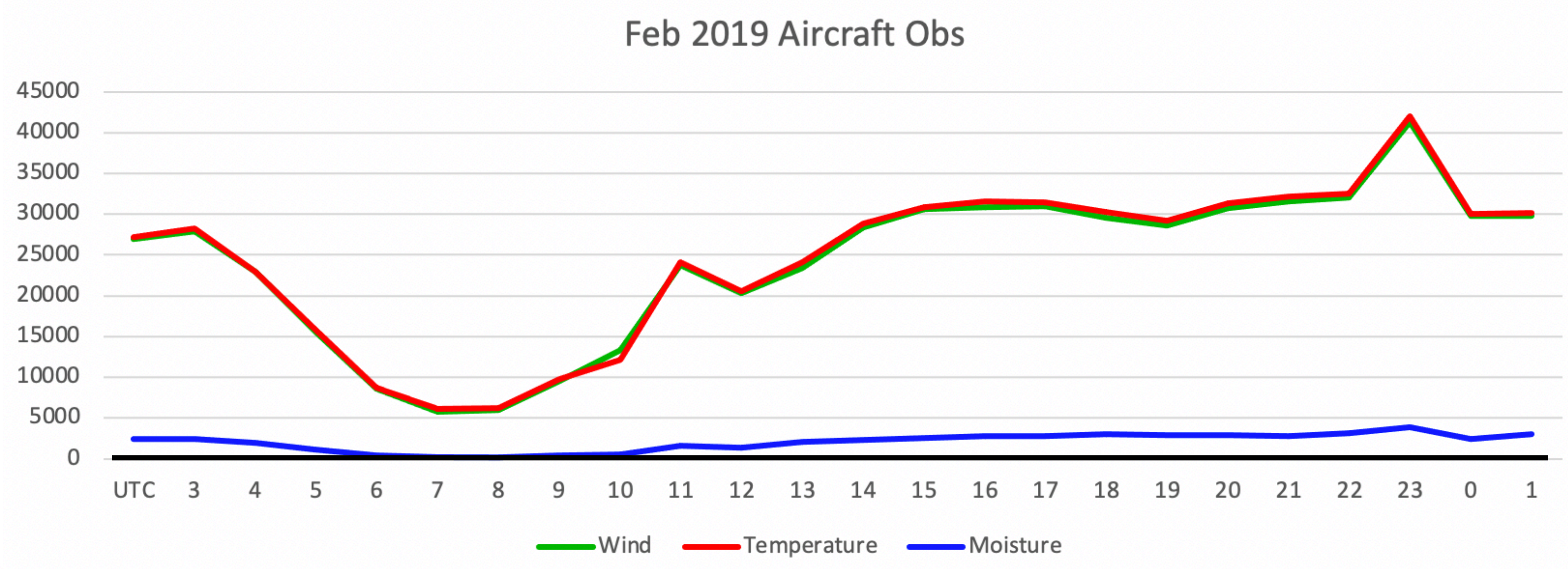
Benjamin et al **2016**: A North American hourly assimilation and model forecast cycle: The Rapid Refresh. *Mon. Wea. Rev.*, **144** (4), 1669-1694. https://doi.org/10.1175/MWR-D-15-0242.1

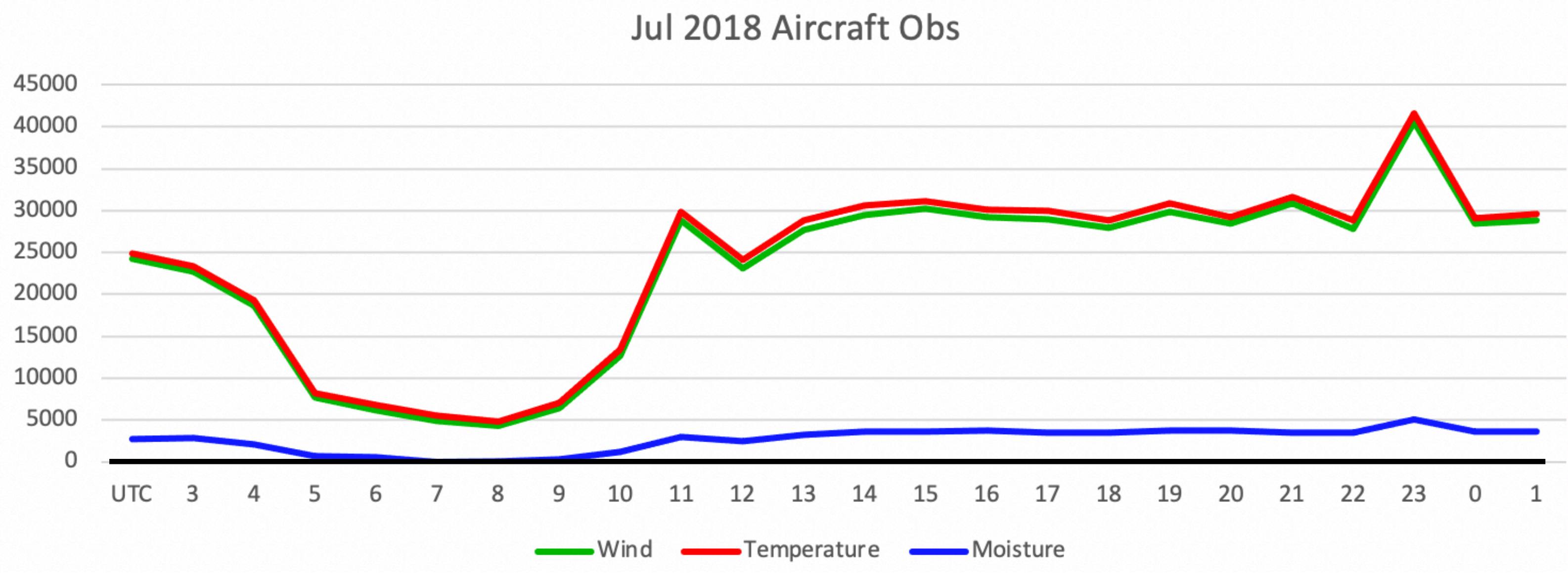
Hu et al **2017**: GSI 3D ensemble-variational hybrid data assimilation using a global ensemble for the regional Rapid Refresh model. *Mon. Wea. Rev.*, **145** (10), 4205-4225. https://doi.org/10.1175/MWR-D-16-0418.1

Benjamin et al **2021**: Stratiform cloud-hydrometeor assimilation for HRRR and RAP model short-range weather prediction. Revised Manuscript submitted to *Mon. Wea. Rev.*

Peckham et al **2016**: Implementation of a digital filter initialization in the WRF model and its application in the Rapid Refresh. *Mon. Wea. Rev.*, **144** (1), 99-106. https://doi.org/10.1175/MWR-D-15-0219.1

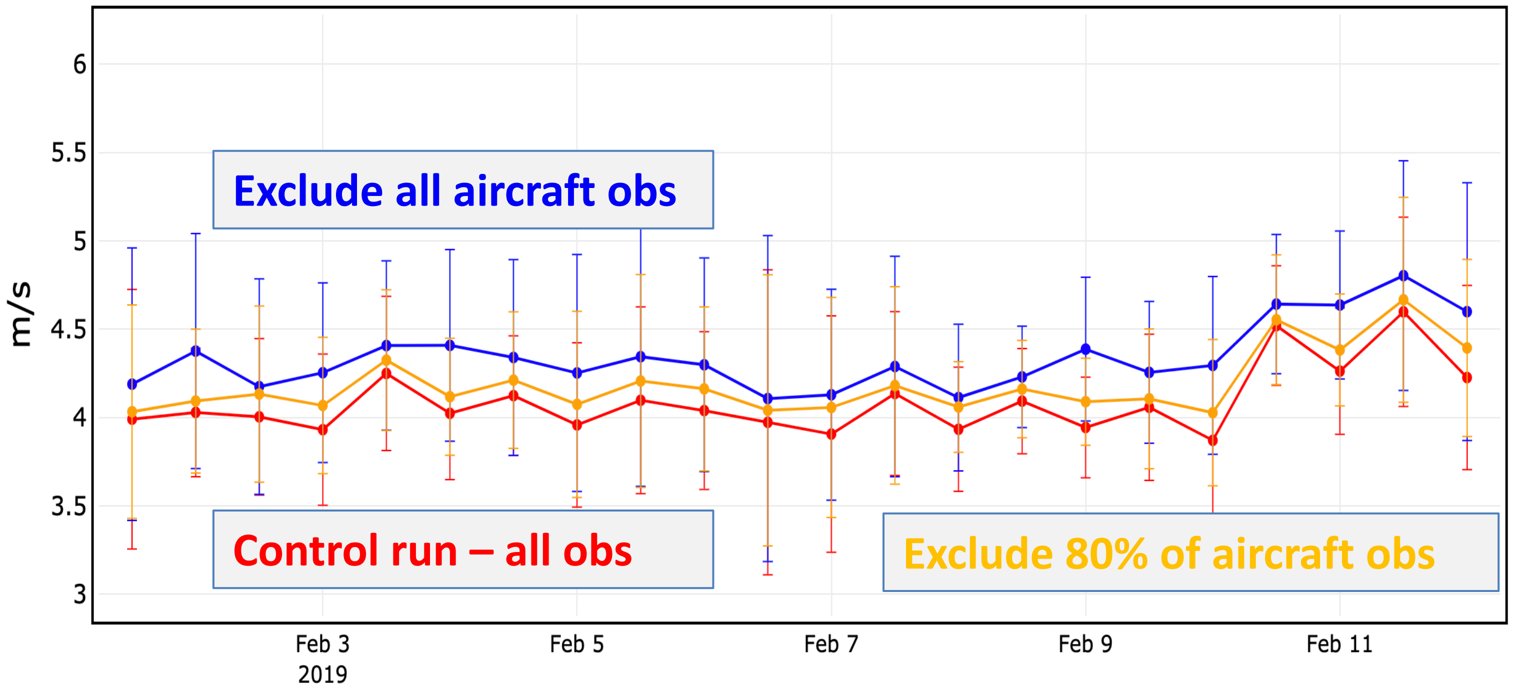
Volume of obs assimilated around the clock



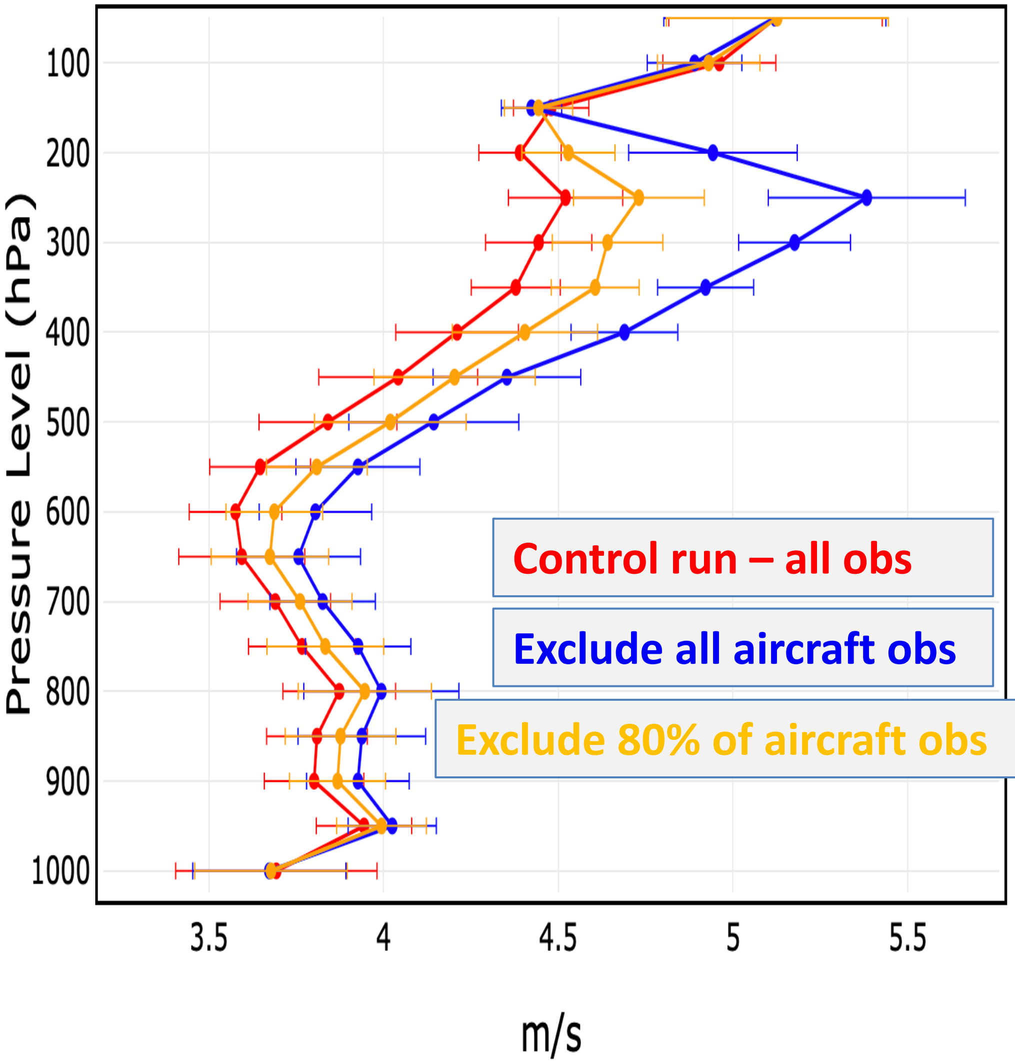


Background | COVID-19 Impacts on Air Traffic | **Experimental Design** | Observation Impacts | Conclusions

Checking for temporal and vertical consistency in obs impacts

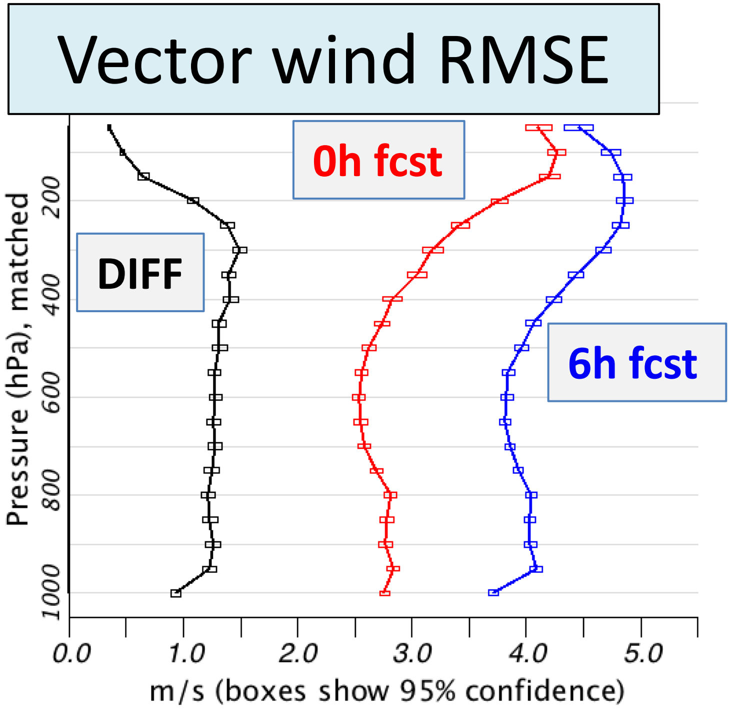


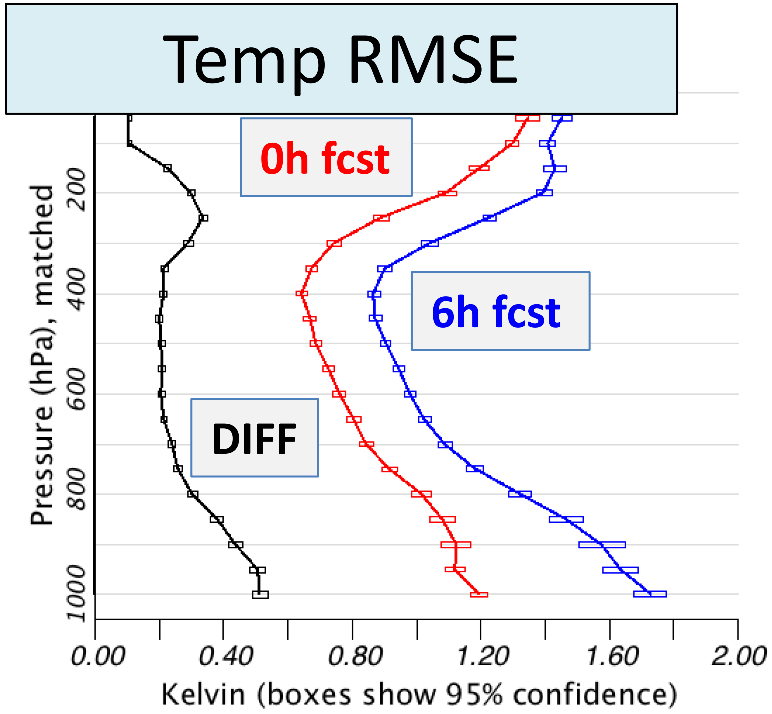
Time series of 3h 1000-100 hPa vector wind RMSE

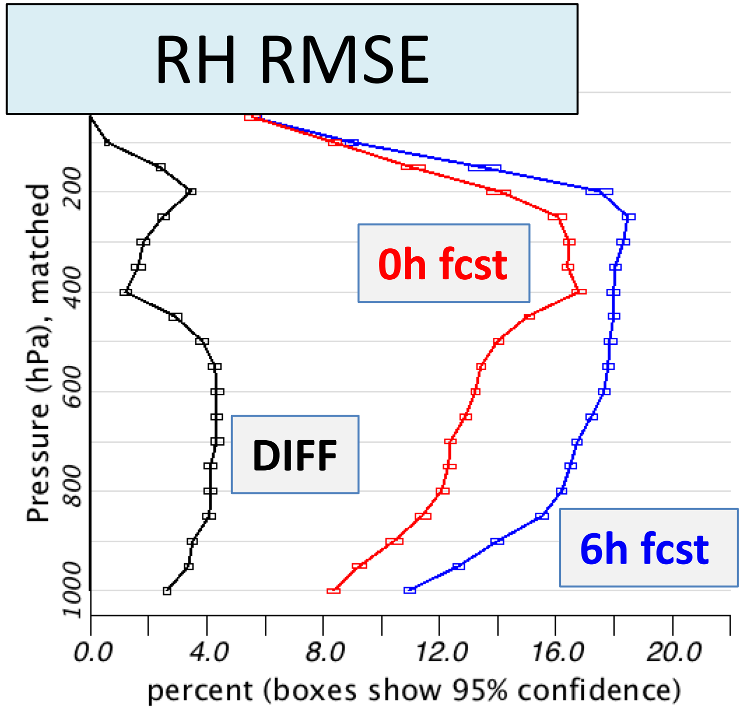


Profile of 3h fcst vector wind RMSE

Normalizing percentage difference for 6h forecast minus 0h analysis



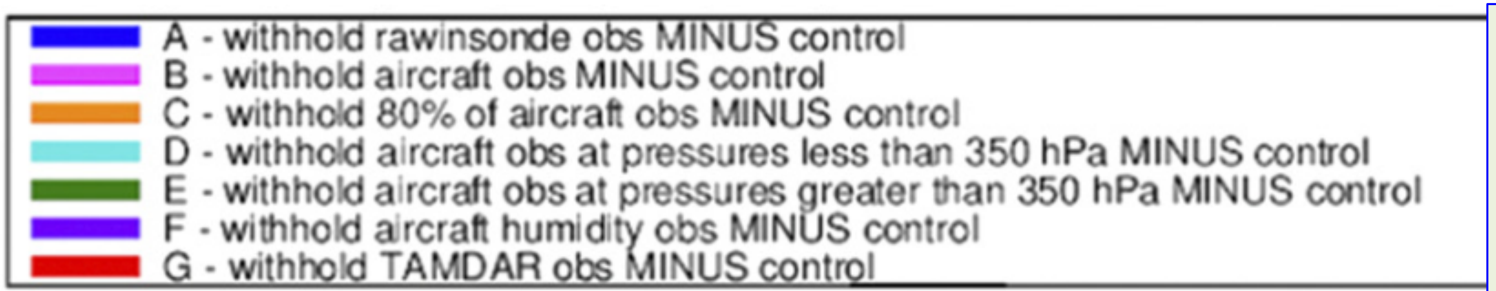




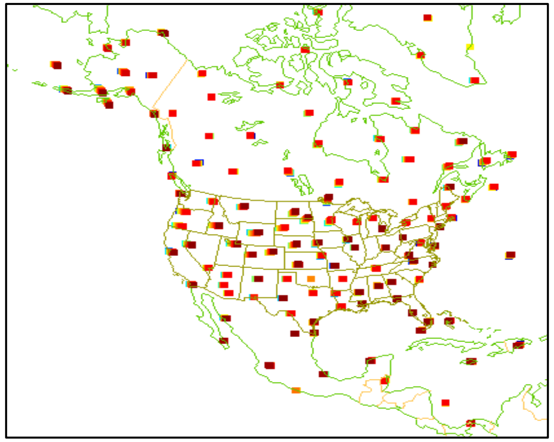
Approximate mean fit to rawinsonde observations (for calendar year 2015)	Wind (1000-100 hPa)	Temperature (1000-100 hPa)	RH (1000-400 hPa)
6h forecast	~4.5 m/s	~1.5 K	~16%
0h analysis (best fit to obs)	~3.0 m/s	~1.0 K	12%
6h fcst minus 0h analysis (maximum possible improvement)	~1.2 m/s	~0.4 K	4%
25% of max possible improvement	**~0.3 m/s**	**~0.1 K**	**1%**

James, Benjamin, **2017**: OSEs with RAP model, GSI. *Mon. Wea. Rev.*

RAP observation denial experiments



Control run assimilates all normal observations used in RAP.

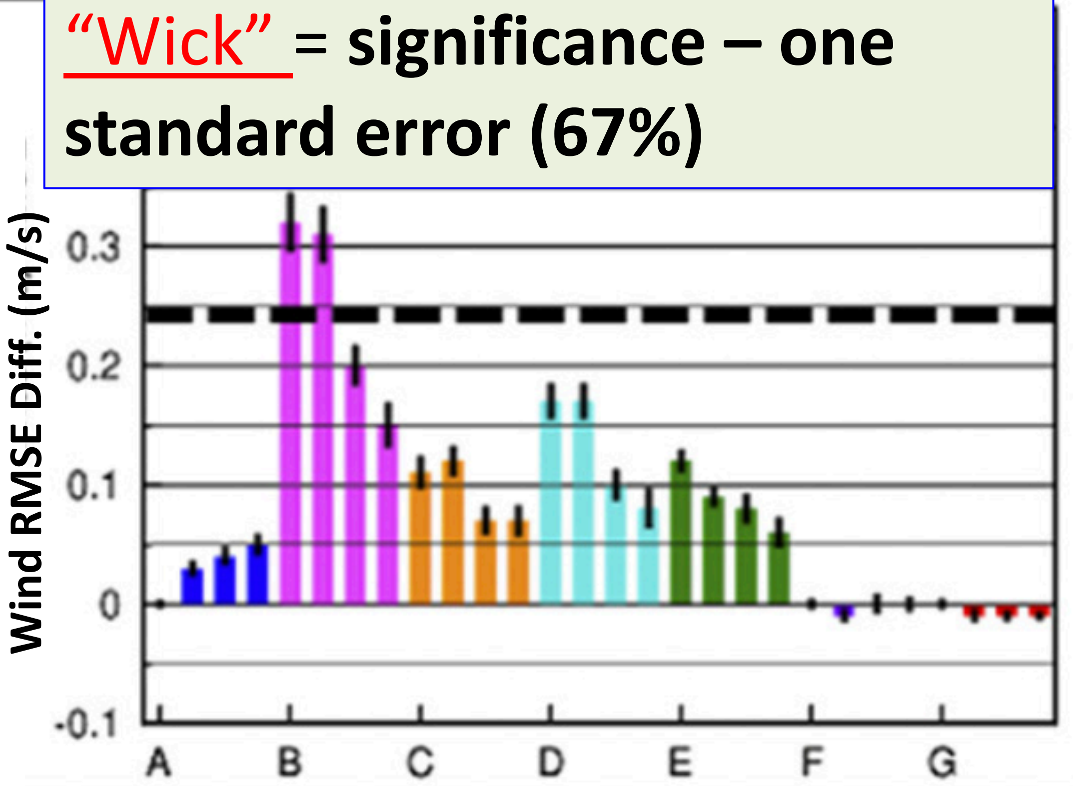


Data denial experiments exclude a single observation type.

Forecast verification is carried out against North American raobs (taken at 00 and 12 UTC each day).

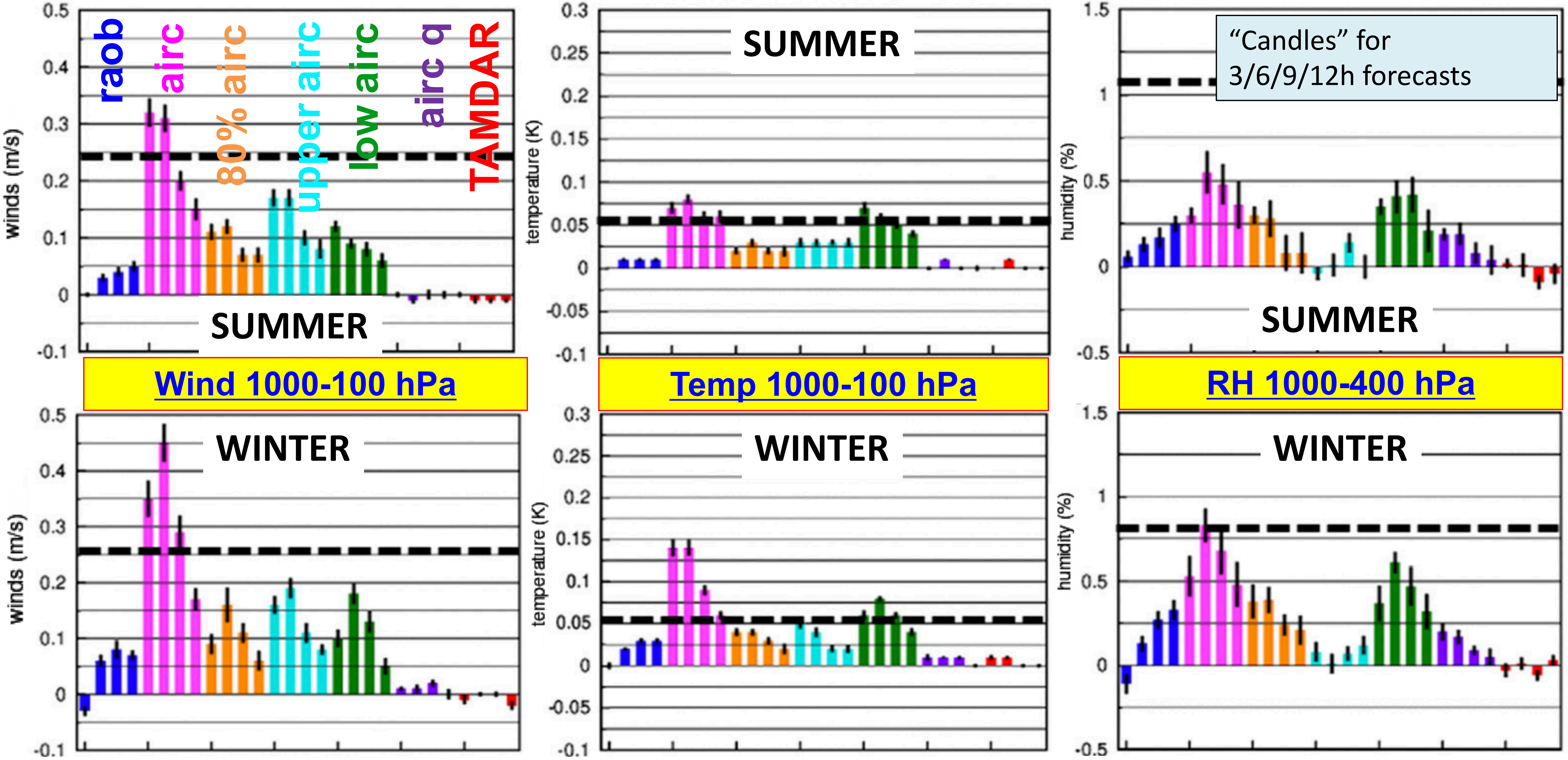
Statistical significance is assessed using the uncertainty on the mean impact (i.e., the standard error) across all raob times during each retro period. One standard error = 67%.

"Birthday candle" height = ***Forecast skill degradation*** for 3/6/9/12h forecasts.
"Wick" = **significance – one standard error (67%)**

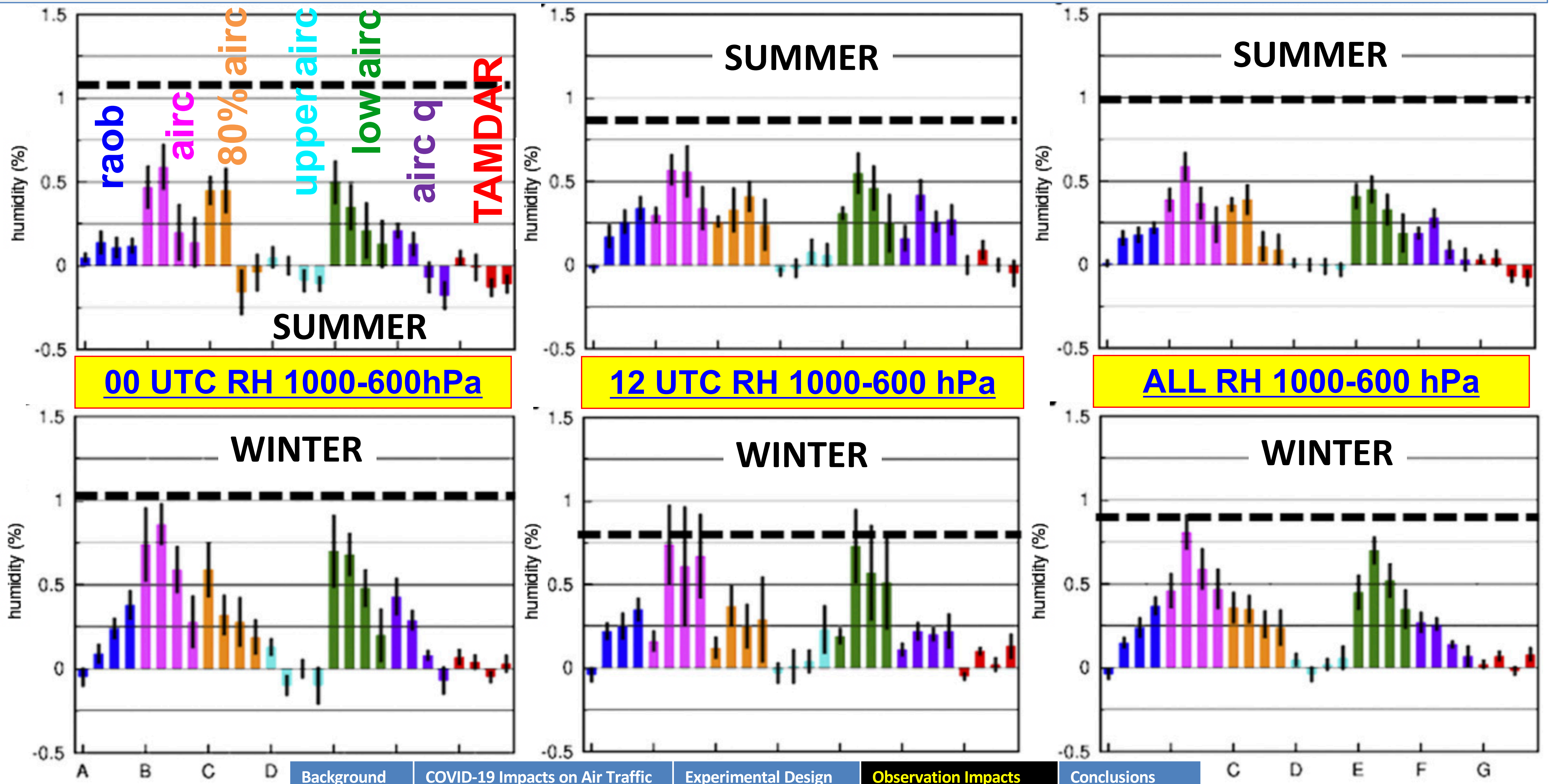


Wind forecast impact 1000-100 hPa -summer

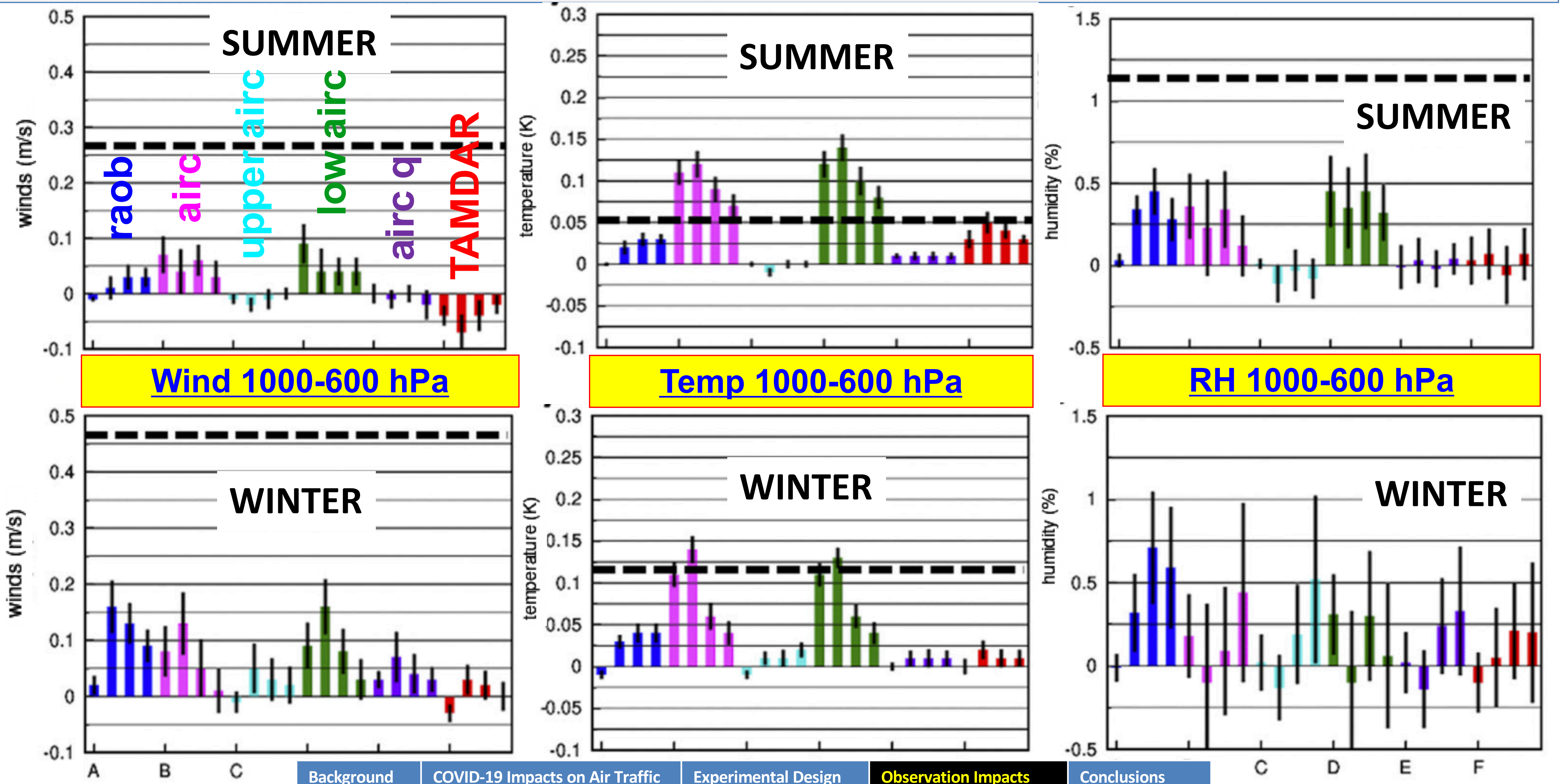
Aircraft-related RAPv5 Obs Impact Results



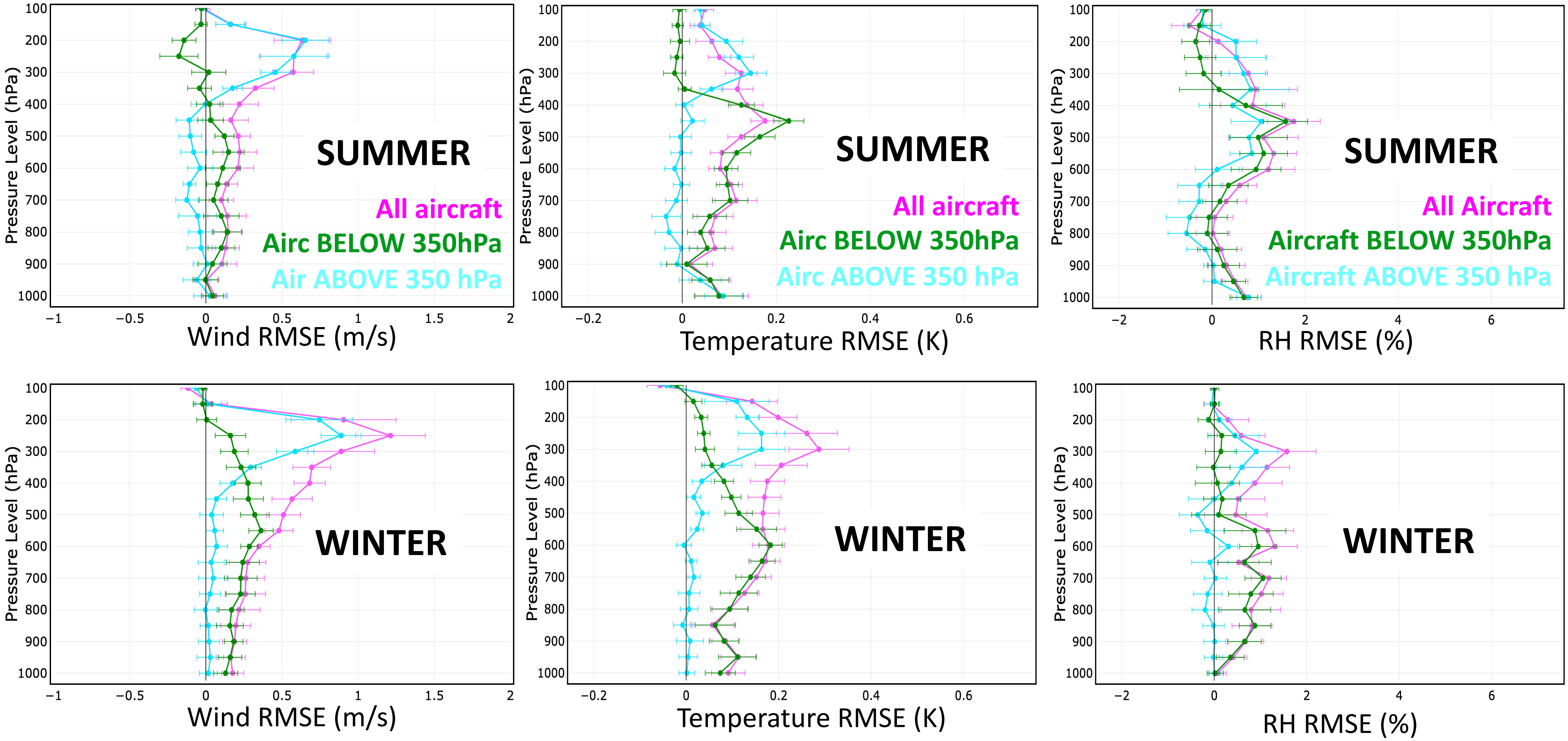
Aircraft-related RAPv5 Obs Impact Results: RH FORECASTS



Aircraft-related RAPv5 Obs Impact Results: ALASKA



Ascent/Descent vs. Enroute Obs: 6h forecast impacts



Comparing 100% aircraft denial vs. 80% aircraft denial

Percent increase in RMSE due to excluding 100% of aircraft obs

Variable	Summer	Winter	Overall
Winds	30	40	35
Temp	30	50	40
RH	12	25	18
All Vars	24	38	31

Percent increase in RMSE due to excluding 80% of aircraft obs

Variable	Summer	Winter	Overall
Winds	10	15	12
Temp	10	20	15
RH	5	10	8
All Vars	8	15	12

Normalizing errors by 6h to 0h RMSE difference (slide 8) allows comparison of 100% to 80% denial experiments

- Overall, more aircraft impact seen in **winter** than in **summer**
- For 6h forecast errors over troposphere for CONUS with RAP:
  - **30% higher errors** without any aircraft obs
  - **12% higher errors** without 80% of aircraft obs

James, Benj, Jamison **2020**: Commercial-aircraft-based obs for NWP: Global coverage, data impacts, and COVID-19. *J. Appl. Meteor. Climatol.*, **59** (11), 1809-1825. https://doi.org/10.1175/JAMC-D-20-0010.1

Conclusions

- Aircraft obs remain the ***most important*** obs type for rapidly-updating short-range regional NWP models. (2020 paper update from 2017 paper)
- Impacts likely underestimated in this retrospective study due to unreduced aircraft ob assimilation in GFS (through lateral boundary conditions and via partial cycling).
- COVID-19: Realtime NWP impacts are challenging to detect, but controlled experiments reveal statistically significant increased 6-12h forecast error over US in RAP model from reduced aircraft reports.
- Averaged across summer and winter seasons, and across tropospheric temperature, winds, and RH, ***excluding 80% of aircraft obs*** leads to a ***12%*** short-range forecast degradation, compared with ***30%*** degradation when ***all aircraft obs*** are denied.

- ***Published articles:***

  Overall obs impact assessment with RAPv3: https://doi.org/10.1175/MWR-D-16-0398.1

  Aircraft-specific experiments and COVID-19: https://doi.org/10.1175/JAMC-D-20-0010.1

Future Work

- Data denial experiments with FV3-based modeling systems, GFS and RRFS
- Investigation of the impact of potential new observation sources including:
  - Mode-S aircraft observations
  - Radiosonde descent observations
  - UAV observations?
- Realtime observation impacts monitoring through the Forecast Sensitivity Observation Impact (FSOI) technique (Dr. Liaofan Lin, GSL/CIRA)
- Comparison of OSE results vs. FSOI results