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Special Section:
The COVID-19 pandemic: linking health, society and environment

Key Points:

- Aircraft meteorological observations have been badly affected by the pandemic but satellite observations have continued unaffected
- Tests show that the largest impact of aircraft observations is at 10–12 km altitude at short range
- There is no obvious degradation of forecast accuracy in 2020; variations in predictability and addition of other observations play a role

Supporting Information:

- Supporting Information S1

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The Impact of COVID-19 on Weather Forecasts: A Balanced View

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Abstract Aircraft reports are an important source of information for numerical weather prediction (NWP). From March 2020, the COVID-19 pandemic resulted in a large loss of aircraft data but despite this it is difficult to see any evidence of significant degradation in the forecast skill of global NWP systems. This apparent discrepancy is partly because forecast skill is very variable, showing both day-to-day noise and lower frequency dependence on the mean state of the atmosphere. The definitive way to cleanly assess aircraft impact is using a data denial experiment, which shows that the largest impact is in the upper troposphere. The method used by Chen (2020, https://doi.org/10.1029/2020gl088613) to estimate the impact of COVID-19 is oversimplistic. Chen understates the huge importance of satellite data for modern weather forecasts and raises more alarm than necessary about a drop in forecast accuracy.

Plain Language Summary Aircraft reports are important for weather forecasting, but satellite data are more important and satellite data have continued as normal during the hiatus due to COVID-19. The signal from loss of aircraft data is not clear above the noise from random variations in forecast skill and longer-term trends. One of the strengths of modern weather forecasting is its robustness arising from the large range of observations used.

1. Introduction

To put matters into context, we briefly describe the way that global weather forecasting is improving over time (Section 2). Part of the improvement has come from more and better observations. The year 2020 saw a large decrease in aircraft observations but also increases in satellite observations (Section 3). This paper is in part a response to Chen (2020), which the authors regard as flawed in some respects. Our reasons are that observation impacts can best be quantified through denial studies (Section 4), and that interannual variability of forecast skill (Section 5) complicates the comparison of the 2020 performance with previous years. We discuss previous publications on the subject (Section 6) and finish with conclusions (Section 7). More details about aircraft data and a "no aircraft" study from a different forecast center can be found in the supporting information.

2. Context: The Success of Global Weather Forecasting

Bauer et al. (2015) describe "the quiet revolution" of numerical weather prediction (NWP) improving forecasts such that useful skill is retained one more day into the forecast range for every decade of research and development. This is illustrated in their Figure 1, but even this smoothed time series hints at fluctuations in skill as a result of variations in predictability. One component of NWP is the data assimilation system which combines a previous forecast with information from the latest observations to create an "analysis", a set of fields that forms the initial conditions for the next forecast.

Magnusson and Källén (2013) note that improvements in NWP skill arise from model changes, improved data assimilation methods and new observations. They showed that over the period 1980–2012 new/improved observations gave less forecast improvement than model or assimilation changes. However,

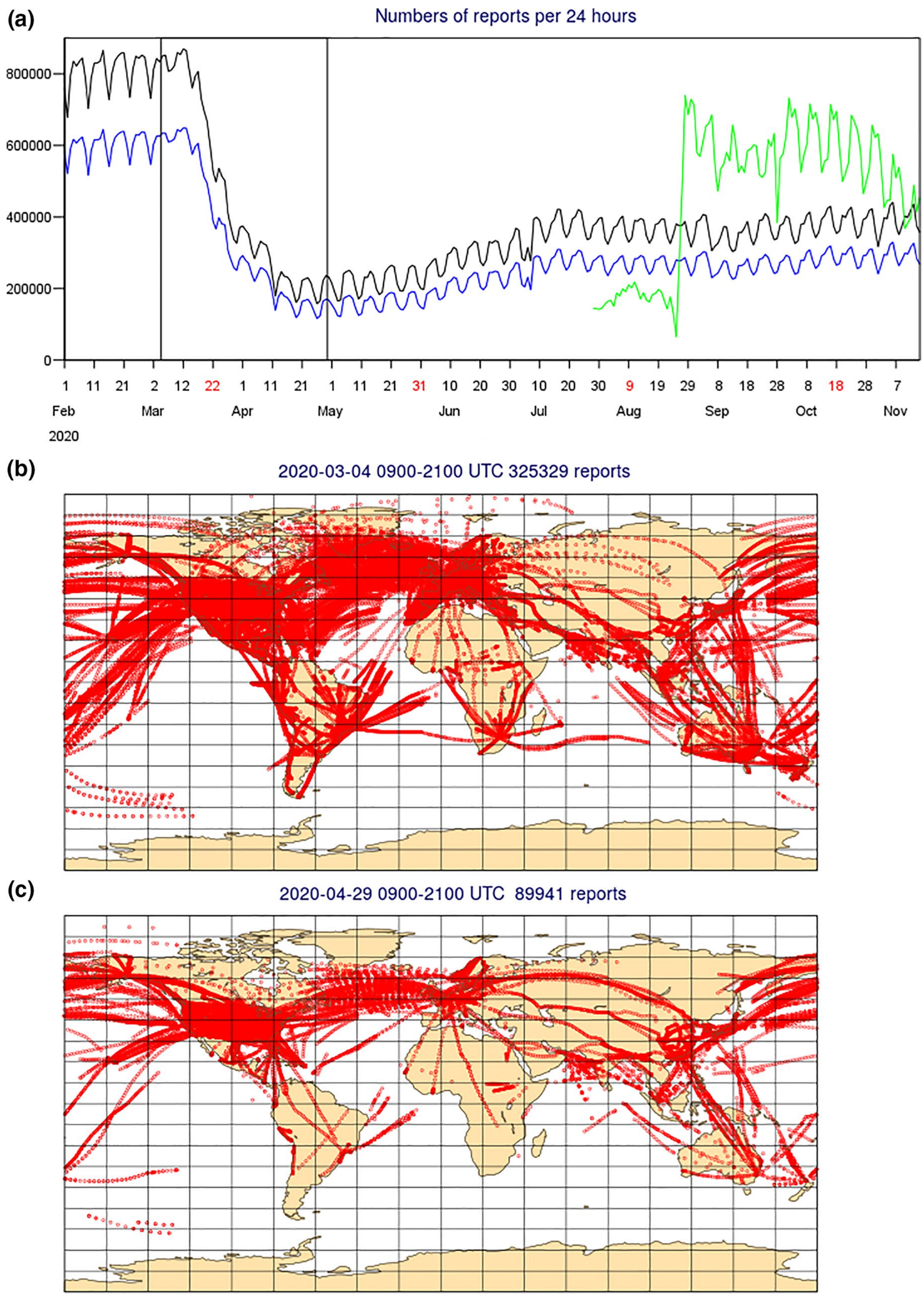

Figure 1. (a) Number of aircraft wind reports processed (black) and used (blue) at ECMWF—excluding Mode-S, green line shows the number of used Mode-S winds. The vertical lines show the dates used in (b) and (c). (b) and (c) Positions of used aircraft reports in a 12-h period (09-21 UTC) on 2020-03-04 and 2020-04-29, respectively.

improved observing systems are still important. Meteorological satellite data started to become available in the late 1970s and since then there has been a reasonably comprehensive global observing system. Satellite data have become a dominant factor in forecast skill—before 1979 skill in the southern hemisphere, where relatively few in situ observations are available, was significantly worse than in the northern hemisphere, but satellite data closed this gap whilst still improving the northern hemisphere (Uppala et al., 2005).

In this paper, the results and figures presented from the European Centre for Medium-Range Weather Forecasts (ECMWF) are broadly representative of those seen at other global NWP centers, including the Met Office, Bureau of Meteorology and the National Centers for Environmental Prediction (NCEP).

3. The Effect of COVID-19 on Aircraft Reports and Other Observing System Changes

Many aircraft reports are provided via the AMDAR program (Petersen, 2016), coordinated by the World Meteorological Organisation (WMO). Commercial aircraft measure wind and temperature for their own needs and a small fraction of these are provided to the weather forecasting community. A subset of aircraft also reports humidity observations. COVID-19 caused some reductions in Chinese aircraft reports earlier, but the main decrease in numbers started in mid-March 2020 (Figure 1a: there is also a weekly cycle with a minimum number on Sundays). In February and early March 2020, ECMWF was using about 600,000 aircraft reports per day (Figure 1b). There was a minimum in the second half of April—just under 150,000 reports per day (75% decrease)—as shown in Figure 1c, where some oceanic areas look particularly sparse. By late July, numbers had recovered to about 47% of the February values but there was a slight decline in August. Over Europe, the number of aircraft flights decreased more than the number of AMDARs because the data provider only selects some of the possible observations (such as one profile per airport per 3 h). A small proportion of reports come from cargo flights and these decreased less or even increased.

There were reductions in surface and radiosonde (balloon) reports in some areas, although within Europe there were extra radiosonde profiles from some stations until the end of August—to mitigate the loss of aircraft data. The commercial company FLYHT offered their aircraft data free of charge during the hiatus and some NWP centers are using these although the number of extra observations is relatively small. In late July, ECMWF started using Mode-S aircraft winds over Europe which are an updated/expanded version of the observations described by de Haan (2011)—and locally very dense (green line in Figure 1a.). In October/November, the number of reports over Europe decreased again—as can be seen for Mode-S (the increase of Mode-S in late August comes from the use of a more complete data stream).

Satellite operations were largely unaffected, which is fortunate given the importance of satellite data for NWP, and, as usual, some new data streams became available. In January 2020, ECMWF started assimilating wind data from a novel lidar instrument on Aeolus, its main impact on forecasts is in the tropics and southern hemisphere—where wind information is sparse (ECMWF, 2020). In March, ECMWF started to use satellite radio occultation measurements from the COSMIC-2 mission (Schreiner et al., 2020) and in mid-May occultation measurements from the Spire company which were being made available during the hiatus. Although different global NWP systems process largely the same set of observations there are some differences in the sources of observations used and the thinning/data selection applied. All centers represented by the authors have reinforced their global observing system with the introduction of new observations during 2019/2020.

One estimate of the relative impact of different sets of observations is given by Forecast Sensitivity to Observation Impact (FSOI, Cardinali, 2009; Langland & Baker, 2004). In early 2020, aircraft provided about 13% of the total ECMWF FSOI but by April it had fallen to about 4%. With the increased numbers of observations, the FSOI from radio occultation has increased from about 4% to over 12% by June. ECMWF FSOI for all satellite data was about 74% in 2019. The calculation of FSOI involves approximations and a single measure of forecast skill. Different NWP systems will rank aircraft data slightly differently and some centers show a stronger dependence on satellite observations than others.

Table 1
Simplified Description of Main Observing Systems Used for Global NWP

System	Variables/advantages	Caveats/notes
	Satellite	
Microwave (MW) and Infrared (IR) sounders	Temperature and humidity, also sea surface temperature	Limited (IR) or very limited (MW) vertical resolution
	Near global	IR cannot see through clouds
	MW can see through clouds	Need bias correction
		Difficult to use at low levels over ice/snow
Atmospheric motion vectors (AMVs)	Winds	Some areas/levels hardly sampled
	Widespread	Height assignment difficult
Radio occultation	High resolution profiles of refractivity	Information on temperature in the stratosphere and upper troposphere; information on humidity in the lower troposphere.
	Near global	
	Does not need bias correction	
Scatterometer	Ocean surface winds	Direction ambiguity
		Semiempirical calibration
Microwave imagers	Total column water vapor (TCWV), sea ice	TCWV used over oceans
Doppler wind lidar	Line-of-sight wind profiles	Single component of wind
		Prototype needs bias correction
	In situ	
Aircraft	Wind, temperature and some humidities	Very uneven distribution
	Locally high density	Temperatures need bias correction
Radiosondes	Wind, temperature, and humidity profiles	Poor spatial and time distribution (often 2/day)
	High vertical resolution	Upper level humidity measurement is difficult
	Closest to reference measurements	
Surface	Pressure (most important), temperature, humidity, wind, sea surface temperature, snow depth	Sparse over oceans and some deserts
	Locally high density	Local effects can make some measurements unrepresentative of wider area

Table 1 summarizes the main observing systems used by global NWP, one of the points to note is that different systems have different strengths and weaknesses. For example, some measurements need bias correction whereas others act as "anchor observations" (Eyre, 2016).

4. "NoAircraft" Studies

The use of aircraft in the ECMWF assimilation system is described in Cardinali et al. (2003) and Ingleby et al. (2019). It includes the correction of aircraft temperature biases similar to that of Zhu et al. (2015). In 2019, an observing system experiment (OSE) or "data denial test" was run at ECMWF for the period January 28 to April 30, 2019: a Control using all observations was compared with a NoAircraft experiment without aircraft data, but otherwise the same. Figure 2a shows that the biggest impact is in the northern hemisphere at 250–200 hPa (about 11–12 km in height), which would be expected as most reports are delivered from typical aircraft cruising altitudes. Figures 2b and 2c show results comparing the 12-h forecasts to radiosonde temperatures and winds for the NoAircraft experiment and another experiment removing only aircraft temperature observations (NoAircraftT).

Care is needed in interpreting verification against analyses especially at short range (discussed below), but the NoAircraft forecasts also verified respectively 12% and 9% worse at 250 hPa against radiosonde winds and temperatures for 20°N-90°N, confirming the signal of strongest impact at this height. The NoAircraftT

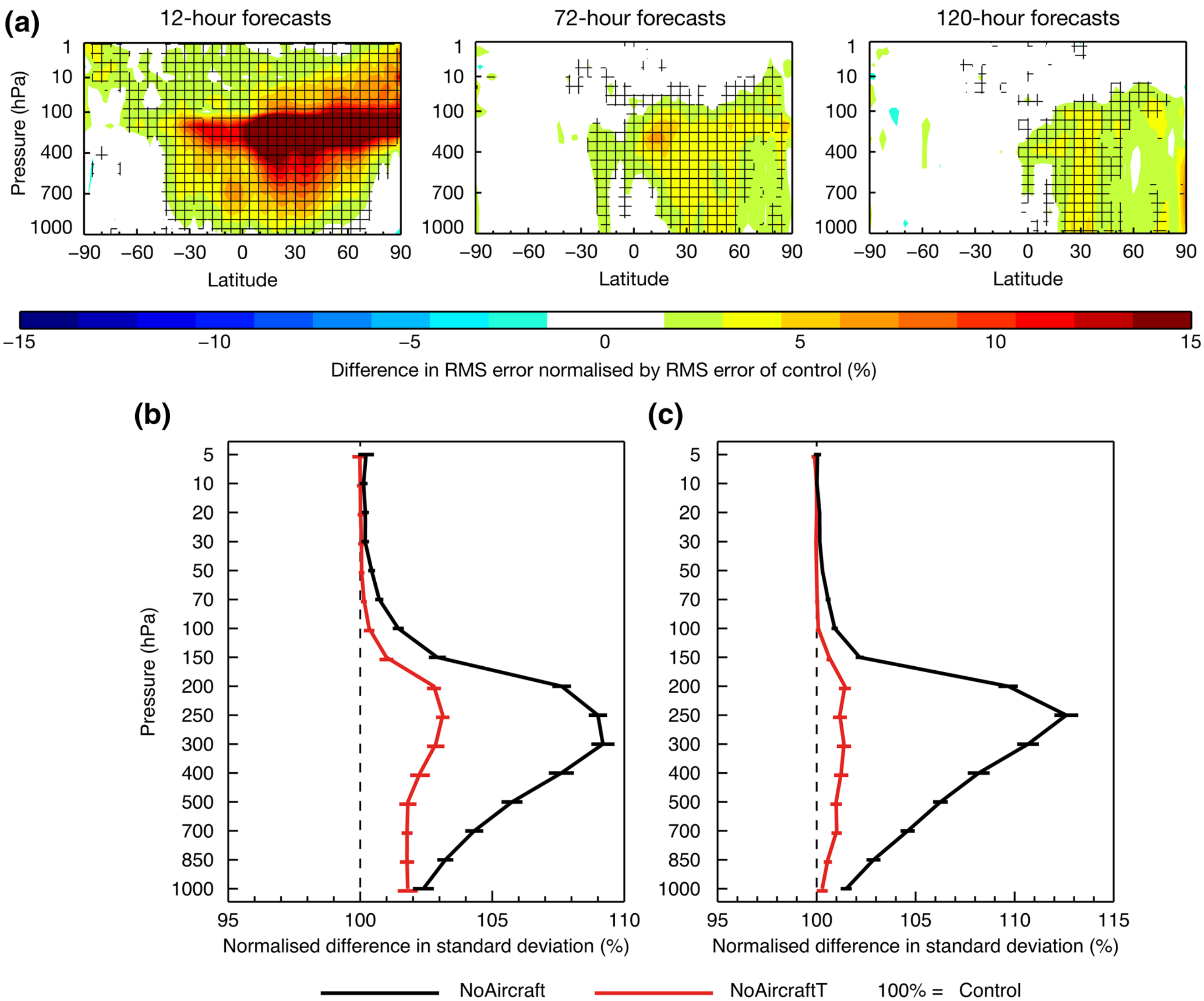

Figure 2. Impact of aircraft data on ECMWF forecasts. (a) The difference in vector wind root-mean-square (RMS) error between forecasts with and without aircraft observations, verified against ECMWF operational analyses. Yellow/red colors indicate worse forecasts without aircraft reports, and hatching indicates statistically significant differences at the 95% confidence level. The largest impacts are in the range up to 24-h ahead, but a significant impact is seen in forecasts up to 7 days ahead (only selected ranges shown). (b) and (c) The impact on 12-h forecast fit to (b) radiosonde temperature and (c) radiosonde wind, for latitudes 20°N-90°N. The black line is for the NoAircraft experiment (as above), the red line is for an experiment without aircraft temperature—both normalized by control values. The horizontal bars show 95% confidence intervals.

experiment reveals that most of the impact comes from aircraft winds rather than the temperatures. The NoAircraft impact at the surface is small at short range. Aviation is also a major user of short-range upper tropospheric forecasts, both for safety and efficiency. Head and tail winds affect the time taken for a particular flight and, based on the short-range wind forecast, the amount of fuel taken on board is tailored to the expected conditions.

Met Office OSEs for 90 days from August 15, 2019 (see supporting information) show a similarly large impact from aircraft data around 250 hPa at short range, decreasing over time. The effect on the position forecasts of tropical cyclones (TCs, also known as hurricanes) was also examined with the NoAircraft forecasts being very similar at most ranges but slightly worse at longer forecast ranges (position errors 2.5% worse at 6-days range, but this was not statistically significant). TCs extend throughout the troposphere, although the winds are strongest in the lower troposphere. Commercial aircraft (at upper levels over the ocean) will tend to fly around the convective activity, thus it seems likely that their impact on short-range TC forecasts will be relatively small. There will have some impact on TC track forecasts in the medium-range, but satellite data are probably more important (e.g., McNally et al., 2014).

Drawing on a range of studies Sato and Riishojgaard (2016) noted aircraft data as being amongst the five most important observing systems contributing to global NWP (the others being microwave sounders, hyperspectral infrared sounders, radiosondes, and atmospheric motion vectors). As discussed in Section 3 radio occultations have become more important in 2020.

5. Verification Scores in 2020 Versus Previous Years

All forecast centers regularly verify their forecasts by comparing them to estimates of the truth: verification for 2020 is examined and compared to previous years to see if there is any clear signal from the loss of aircraft data. The truth estimates can be from observations or analysis fields and various performance measures are computed (see https://www.cawcr.gov.au/projects/verification/). Recent ECMWF performance is shown in Haiden et al. (2019), also online under https://www.ecmwf.int/en/forecasts/charts. At short-range (1 or 2 days) verification is particularly dependent on the choice of reference, see Figure 3 of Lawrence et al. (2019). Analysis error can sometimes be correlated with short-range forecast error. Observation error can usually be considered independent, but the effective sample size is smaller and radiosonde coverage over the oceans and in the Southern Hemisphere is poor. Because of the noise in verification scores very long experiments are needed to establish statistical significance for modest changes (Geer, 2016). The issues with noise and statistical significance are even more pronounced for smaller verification areas. Centers verify both deterministic and probability forecasts for a large range of variables, and 500 hPa geopotential height is often used to emphasize large-scale pattern impacts. Surface temperature and precipitation fields contain smaller scale features and are more difficult to analyze and predict accurately. Thus it is more difficult to obtain statistically stable results for these fields.

Given the results in Figure 2, we expect to see the largest impact in the upper troposphere and short-range forecasts and so Figure 3 shows time series of wind errors for ECMWF 1-day forecasts including 250 hPa—keeping the above mentioned limitations of short-range forecast verification with analyses in mind. The errors are larger at 250 hPa than the other levels shown, because this corresponds approximately to the mid-latitude jet stream. There is no jump in March 2020 that can be associated with the drop in aircraft numbers but there is considerable day-to-day variation and some indications of part of a seasonal cycle.

Standard forecast verification scores from eight different NWP centers are shown in Figure 4: a seasonal cycle can be clearly seen as can some indication of a downward trend over time. Summer 2019 was unusually predictable (more apparent in the high values of anomaly correlation). This may have been due to a strong negative North Atlantic Oscillation (NAO) index (see https://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/month_nao_index.shtml). There is some evidence, mainly for the boreal winter, that negative NAO is linked to higher predictability (Ferranti et al., 2015; Langland & Maue, 2012), its role in spring/summer 2019 is somewhat speculative. It is also useful to compare with results from a reanalysis, such as ERA5 (Hersbach et al., 2020)—see supporting information.

Most importantly, these time series show that forecast skill in spring 2020 did not fall outside the range of values seen for the same season in previous years. We do not claim that the loss of aircraft observations due to COVID-19 has no effect, only that the signal is too small to be statistically detectable by a simple comparison of forecast skill in 1 or 2 months of 2020 against the skill of previous years.

6. Discussion

Using a regional forecast system, James and Benjamin (2017) report that aircraft are the most important observing system over North America. In an updated study, James et al. (2020) found that removing 80% of the aircraft data gave less than 80% of the impact of removing all the aircraft data (the boundary conditions came from a global forecast system using all aircraft data, this would have a small effect at short range). We expect a slight reduction in the impact per observation as data density increases and this is also seen for other observation types (e.g., Poli et al., 2008).

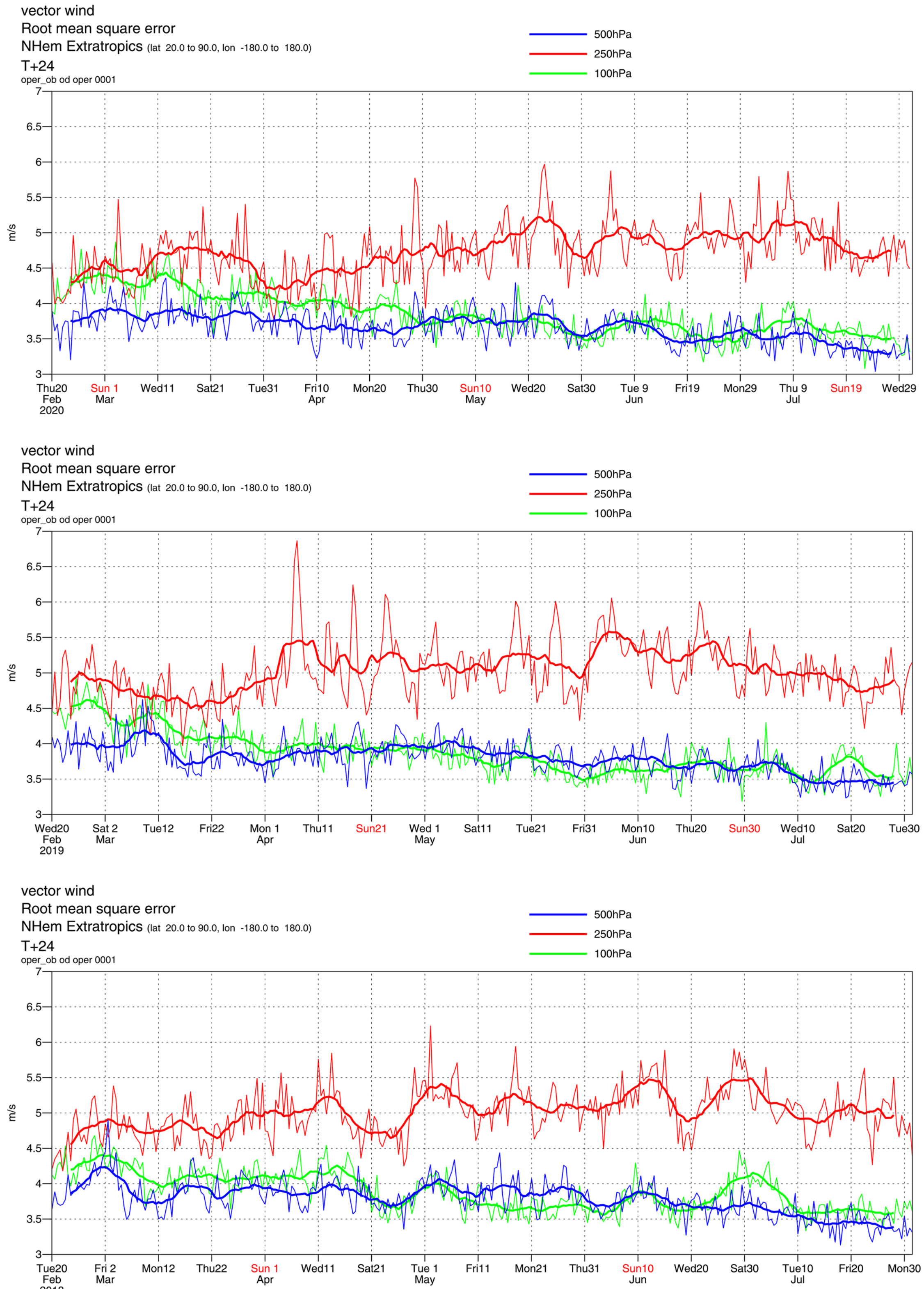

Figure 3. Verification of operational ECMWF 24-h wind forecasts for 20°N-90°N against analyses at three levels for 2018 (bottom), 2019 (middle), and 2020 (top). The thin lines show values every 12 h, the thick lines a 7-day running mean.

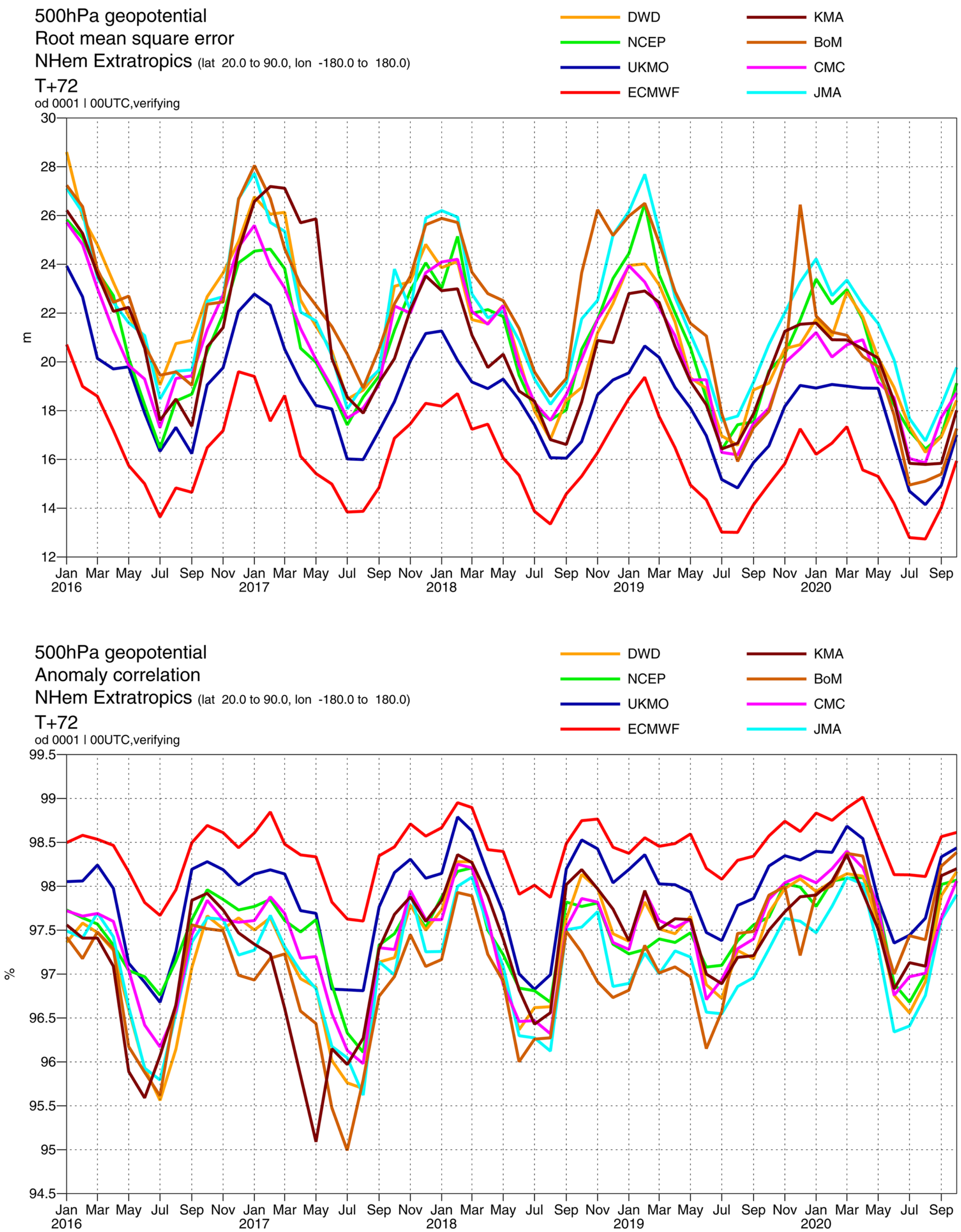

Figure 4. Verification of 3-day 00 UTC forecasts of 500 hPa geopotential height against their own analyses. Top root-mean-square, bottom anomaly correlation (small/large values are "good," respectively). DWD: Deutscher Wetterdienst (Germany), NCEP: National Centers for Environmental Prediction (USA), UKMO: Met Office (UK), KMA: Korea Meteorological Administration, BoM: Bureau of Meteorology (Australia), CMC: Canadian Meteorological Center, JMA: Japan Meteorological Administration.

Chen (2020) is entitled "COVID-19 pandemic imperils weather forecast"—perhaps overdramatic. Given the variation of forecast skill on various timescales we regard the comparison of skill from different periods to infer aircraft impact as used by Chen as oversimplistic. There is no evidence that the "signal" calculated by Chen is specifically due to COVID-related reductions to aircraft reports, rather than a consequence of interannual variations in predictability. One complicating factor is that spring/summer 2019 was unusually predictable as discussed above. Chen compared NCEP Global Forecast System (GFS) forecasts with corresponding Global Data Assimilation System (GDAS) analyses. For completeness, we note that the GFS underwent a major upgrade in June 2019 (https://www.noaa.gov/media-release/noaa-upgrades-us-global-weather-forecast-model) and that the analyses would not usually be called reanalyzes as Chen does (the GDAS changes from year to year whereas a reanalysis system uses the same system for a multiyear or multidecade period).

Observation impacts tend to be largest at short range and decrease with forecast range (e.g., Figure 2a above; Lawrence et al., 2019) whereas Chen suggests that the impact increases with forecast range—his results are more suggestive of predictability than of observation changes. He only shows surface fields even though the largest impact of aircraft data is in the upper troposphere.

Finally, Chen understates the huge role that satellite data plays in modern NWP ("cloud properties from satellites are important for rainfall forecasts"): satellite data provide near-global coverage with information predominantly on temperature and humidity, with less but still substantial information on wind.

7. Conclusions

Aircraft reports suffered a 75% decline in numbers from mid-March to mid-April 2020; in May the number started increasing again. Despite the loss of data there is no clear signal in the forecast skill—partly because the skill shows considerable variability on daily, seasonal, and interannual timescales (Figures 3 and 4). However, aircraft reports have been shown via a range of evaluation measures to be important for NWP: from data denial studies run using 2019 data we are confident that short-range forecast skill would have been higher in March to July 2020 with a "normal" number of aircraft reports—especially in the upper troposphere. It should be emphasized that a denial study is the worst-case scenario, whereas during the COVID-19 pandemic we did still receive at least 25% of aircraft observations, which probably gave more than 25% of the "normal" aircraft impact (see Section 6). Locally some areas did experience a complete loss of aircraft observations.

Observation coverage can fluctuate for several reasons, for example a satellite or an instrument can fail. Maintaining the breadth of the global observing system helps to improve the robustness of weather forecasts. Aircraft form one of about six leading observing systems that contribute most to global NWP. Different observing systems have different strengths and weaknesses (Table 1). At short-range aircraft are the largest contributor to forecast skill over North America (James & Benjamin, 2017). Prior to the pandemic there were plans for increased aircraft reports via a collaboration between the International Air Transport Association and WMO and other sources like Mode-S and third-party data: such extra aircraft reports will be a welcome contribution and will likely contribute to improved forecast skill.

Overall, we can find no evidence that the decrease in aircraft observations has handicapped numerical forecasts of extreme weather to an extent large enough to incur significant economic impact.

Data Availability Statement

Verification scores from multiple NWP centers calculated according to WMO recommendations are available from https://apps.ecmwf.int/wmolcdnv/. Operational analysis and forecast data from 12 global NWP centers are available from https://confluence.ecmwf.int/display/TIGGE. To access ERA5 reanalysis fields see https://confluence.ecmwf.int/display/CKB/How+to+download+ERA5. Observations (GDAS Daily BUFR Files) are available from https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/global-data-assimilation-system-gdas.

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