8.3 AN UPDATE ON THE TAMDAR SENSOR NETWORK DEPLOYMENT

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INTRODUCTION

Lower and middle-tropospheric observations are disproportionately sparse, both temporally and geographically, when compared to surface observations. The limited density of observations is likely one of the largest constraints in mesoscale numerical weather prediction. Atmospheric observations collected by a multi-function in-situ atmospheric sensor on aircraft, called the Tropospheric Airborne Meteorological Data Reporting (TAMDAR) sensor, contain measurements of humidity, pressure, temperature, winds, icing, and turbulence, along with the corresponding location, time, and altitude from built-in GPS are relayed via satellite in real-time to a ground-based network operations center.

The TAMDAR sensor was first deployed in December 2004 on a fleet of 63 Saab 340s operated by Mesaba Airlines in the Great Lakes region as a part of the NASA-sponsored Great Lakes Fleet Experiment (GLFE). Over the last five years, the equipage of the sensors has expanded beyond CONUS to include Alaska and Mexico on Horizon, Republic, Chautauqua, Shuttle America, PenAir, Piedmont, Frontier Alaska, AeroMexico Connect and Mesaba Airlines, as well as a few research aircraft. Upon completion of the 2009 installations, more than 6000 daily soundings will be produced in North America.

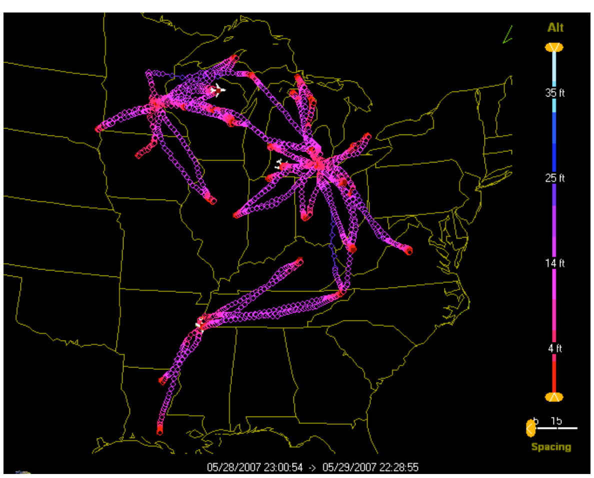

Fig. 1. Flight routes and observations for 28-29 May 2007.

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An update is provided on the status of the TAMDAR sensor network deployment and data availability, as well as an update on data quality, error statistics, and operational forecasting utility, directly from the TAMDAR soundings and through Weather Research and Forecasting (WRF) model products with various data assimilation techniques.

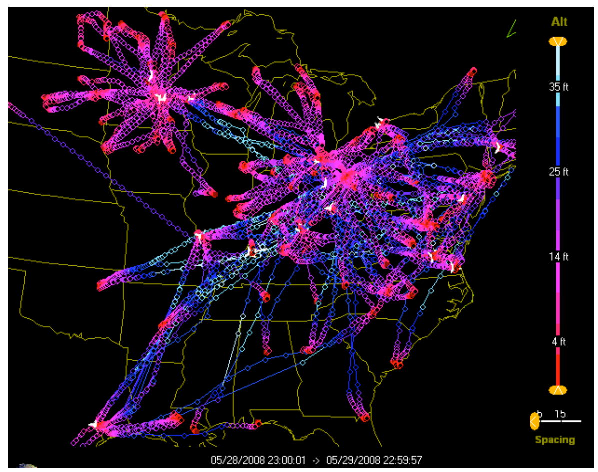

Fig. 2. Flight routes and observations for 28-29 May 2008.

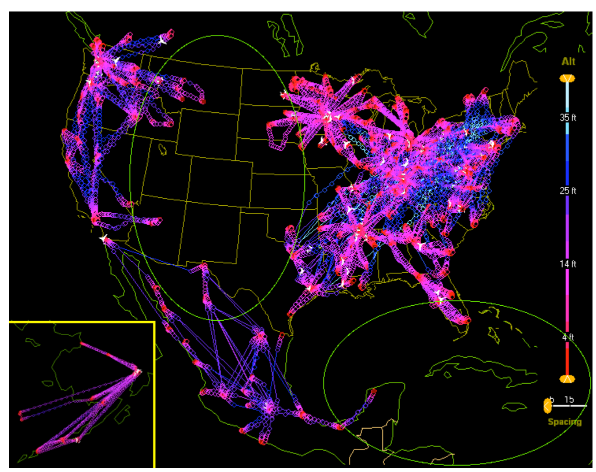

Fig. 3. Flight routes and observations for 4-5 Sept 2009.

An example of the flight data density for a typical day in May 2007 is shown in Fig. 1, which is essentially the same density as 2006 (with Mesaba). Equipage of sensors on additional aircraft across the continental US and Alaska began in late 2008. Jacobs et al. (2009) provided an example of the increase in observations and flights from 2007 to 2008 (cf. Fig. 1 and Fig. 2). Since 2009, AirDat has expanded the sensor network to include Alaska (Fig. 3, inset), Mexico, PacNW, and Florida (Fig. 3). Additionally for 2010, the network will be expanding into regions in the vicinity of Hawaii, Caribbean, Antilles, Central America, and the Central/Western US. This will essentially fill most of the remaining voids (green circles) seen in Fig. 3.

The paper will discuss two main aspects of the program. The first part is a correction that is applied to the magnetic deviation on the heading information provided by the flux valve-based systems in the Saab 340s. This is a crucial step in overcoming the previously assumed poor wind data. Initial results suggest that the majority of the deviation-related error can be eliminated. The second part is a brief update on the AirDat high resolution modeling and forecasting systems and upgrades.

PART 1: MAGNETIC DEVIATION CORRECTION

Generally, flux valve (magnetic based) aircraft systems, such as on the Mesaba SAAB-340s, have errors that significantly degrade the accuracy of the wind calculation. These errors (magnetic deviation) are typically a function of heading information, and can be characterized. The magnetic deviations arise from local magnetic fields, as well as not having the compass system perfectly aligned with the axis of the plane. TAMDAR firmware has a magnetic deviation lookup table to allow for corrections to the heading; however, until this study, accurate data on the nature of the magnetic deviation has been lacking. Errors less than 3-4 degrees are typically considered acceptable to an airline, and no adjustments will be made, but errors this large will seriously degrade wind calculation accuracy in meteorological data.

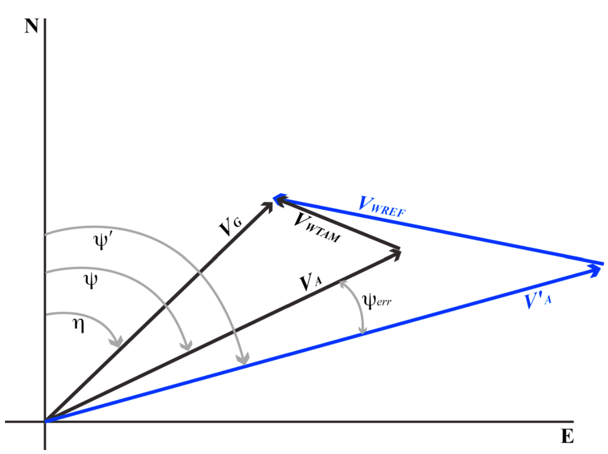

Fig. 4. Vectors showing ground track vector (V_G), TAMDAR wind vector ($V_{W,TAM}$), model wind vector ($V_{W,REF}$), aircraft track vector (V_A) based on $V_{W,TAM}$, and aircraft track vector (V_A') based on $V_{W,REF}$. The magnitude of V_A is the TAS; the angle of V_A is the heading (ψ). The ground track angle is η.

1. METHODOLOGY

The method described is designed to characterize the heading error (magnetic deviation) as a function of heading on a particular plane using the standard TAMDAR report data. The minimum required data in the standard TAMDAR report is: time and data, lat/lon and wind speed/dir. Corresponding model wind comparisons are also required.

a. Calculate the ground track vector (speed and direction) based on the latitude and longitude
b. Calculate air track vectors (TAS and heading) in 2 ways:
   i. Subtract the TAMDAR wind vector from the ground track vector, which is essentially recreating the air track used by TAMDAR to calculate winds.
   ii. Subtract the Model reference wind vector from the ground track vector.
c. Subtract the heading of the air track vector from the heading on the ground track vector to get a heading error.
d. Using a curve fit to the table of heading errors versus heading, and develop parameters for the magnetic deviation function in TAMDAR.

This is not a ground based correction; the ground processing is only done once to determine the aircraft heading system biases, and this data is then uploaded to TAMDAR, which then corrects the heading in real time before the wind calculation is performed and inserted into the report for downlinking.

The ground track vector can be calculated from the latitude and longitude change between adjacent points (Fig. 4). The air track vector is calculated in the 2 ways described above by the formulas

$$\vec{V}_A = \vec{V}_G - \vec{V}_{W_{TAM}} \tag{1}$$

and

$$\vec{V}_A' = \vec{V}_G - \vec{V}_{W_{REF}} \tag{2}$$

where V_A and V_A' are the aircraft track vectors (TAS and heading [ψ]); V_A is based on TAMDAR, and V_A' is based on the model (considered truth for this analysis). V_G is the ground track vector (speed and angle [η]), and $V_{W,TAM}$ and $V_{W,REF}$ are the wind vectors. The heading error is defined by:

$$\psi_{err} = \psi - \psi' \tag{3}$$

where ψ is the heading based on TAMDAR winds, and ψ' is the heading based on reference (model) winds.

The accuracy of the calculated ground track angle (η) has no effect on the accuracy of the heading error calculation (ψ_{err}). This is because the same ground track is used for both air track calculations, so any ground track angle error will cancel. This can be seen in Fig. 4: any change in η due to an error will affect both ψ and ψ' equally. A ground speed error will, however, have some impact on heading error. Also, an error in η will result in the associated heading to be slightly in error, but since magnetic deviation changes rather slowly with heading, a small heading error is not expected to be significant.

2. PHASE 1: DATA ANALYSIS

The final data set for analysis for each plane will be a table of 2 columns: heading (ψ) versus heading error (ψ_{err}). Each row in the table will be one observation. To get the most amount of data, both the AirDat RTFDDA, GSD RUC and GSD RR were used to obtain V_A' for the final data set; however, to ensure that the results were not dependent on the particular model, analysis was also done with data from the RUC combined with RR, and RTFDDA separately. The results confirm that the data looked similar whether the RUC/RR or the RTFDDA was used, thus a combination of the data sets was justified. A curve fit to the data then provides the basis for the correction parameters for that particular TAMDAR probe.

Considerations and caveats:

a. For data set construction, it is probably best to restrict the data to that when the airplane is in cruise (i.e., flying in a straight line).
b. Since the ground track must be calculated using AMDAR report data, the resolution of the lat/lon will affect the accuracy. This should appear as random error (quantization error), and is expected to be averaged out in the curve fit process. The resolution of the lat/lon is 1/10th of a minute. At a speed of 250 knots, this error would be a random ground track angle error of about 0.5 deg.
c. The best data will include flights involving heading for at least 8 compass points. This may require a few months of data for a particular plane.
d. There are several models that can be used, and would prove more robust when used in parallel. They are the AirDat RTFDDA, the GSD RR-RUC and the NAM; however, the NAM data should not be combined with the RTFDDA or RUC since the performance may be significantly different. Additionally, it may be possible to use ACARS data.

Assumptions

a. Model errors are not correlated with the heading of the aircraft (i.e., the model does not know which direction the airplane is flying).
b. Model wind speeds are not significantly biased.
c. The primary cause of errors in the TAMDAR winds is due to heading errors, not TAS errors (Moninger et al. 2006).
d. The heading errors of the aircraft are a function of heading only. This is likely the case, as heading errors are typically caused by fixed, local magnetic effects in the aircraft.
e. The magnetic variation correction applied by TAMDAR (from the Garmin GPS) is accurate. Since we see significant variations in wind quality from the Mesaba fleet, and they all use the same GPS, the magnetic variation is assumed not to be the main contributor to the error.
f. The calculated heading used for the table of heading and heading error is sufficiently accurate. Since the magnetic deviation changes rather slowly with heading, sufficient accuracy is expected.
g. The particular plane being used has not had the flux valve system recalibrated during the period of data analysis. This is beyond our control, but from discussions with Mesaba and SAAB we know that even though heading checks are done, an actual calibration does not happen very often. Other maintenance that may affect flux valve accuracy is also possible, but not within our ability to determine. Since wind quality is constantly monitored, any changes due to maintenance that degrade winds significantly will be quickly noted.

Approximately one years worth of RUC, RR-RUC and RTFDDA data from July 2008 to July 2009 were used for each plane. An example of the raw data for one plane can be seen in Fig. 5. Note that the trend appears sinusoidal, which is a common trend for magnetic deviation corrections. Every plane studied had a similar sinusoidal appearance to the data with differing phase, offset and amplitude.

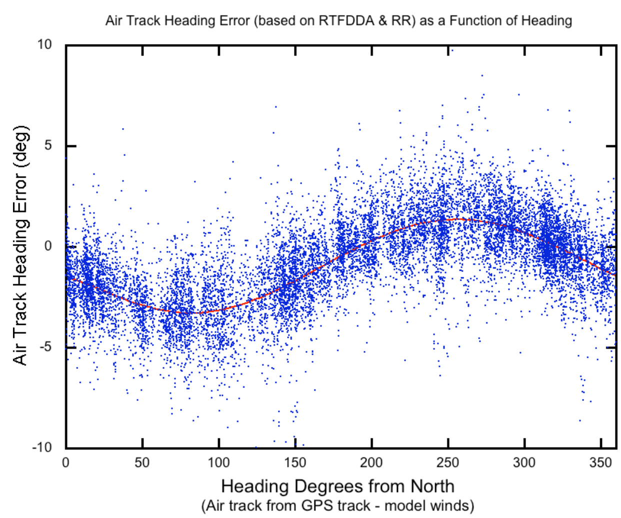

Fig. 5. An example of the raw data with a sinusoidal fit. Heading is on the x axis and magnetic deviation relative to the model comparison calculation in on the y axis.

For reasons noted above, it was decided to use a sinusoidal fit as a function of heading (ψ). The sinusoid fits the data well, and also has the advantage of wrapping around at 360 degrees with no discontinuity.

Data were filtered to eliminate points where the aircraft was maneuvering, or the data were questionable for other reasons. Since the phase, offset and amplitude is uniquely different for each plane, this eliminates the possibility of biases existing that are not related to the plane.

The next step was to take these results and translate the magnetic deviation sinusoid to cal constants for the TAMDAR 8-point correction table. TAMDAR uses this table to define a piece-wise linear fit function.

3. PHASE 2: FIELD TEST

On 20 October 2009, magnetic deviation correction data were uploaded to the associated TAMDAR units. It is confirmed that heading errors are a major source of TAMDAR wind errors. Given a large quantity of reliable model reference, the quality of wind data from aircraft with poor quality magnetic heading systems can be significantly improved.

For each of the 36 Mesaba Saabs, the average disagreement between TAMDAR wind measurements and AirDat RTFDDA QA and GSD Rapid Refresh predictions was determined before the experiment and again after uploading magnetic deviation correction calibration constants to 19 Mesaba TAMDAR units (Phase 2). An average TAMDAR-Model wind vector disagreement was determined for observations where temperature passed inline QA and the Roll flag was G (good data).

Aircraft Category	Avg wind vector disagreement wrt RTFDDA & RR before Phase2 (kts)	Avg wind vector disagreement wrt RTFDDA & RR during Phase2 (kts)	Reduction (kts, positive values show improvement)	Reduction adjusted for model performance (kts)
Controls (unchanged for Phase2)	6.96	8.19	-1.22	0
Corrected (corrected for Phase2)	**8.86**	**7.62**	**1.24**	**2.46**
	Avg. disagreement **includes** model error			

Table 1. Wind vector disagreement wrt. models for control group and corrected group both before, and after, Phase 2. The far right column (bottom row) shows the error reduction in knots.

Table 1 shows the average wind vector disagreement for the control group and experimental (corrected) group of sensors with respect to the AirDat RTFDDA and GSD RR/RUC models before and during the experimental period (Phase2). The model performance on the control group was worse during the experimental period than before indicating the model itself was not performing as well during this time (i.e., the control had negative improvement of -1.22 knots). The right hand column shows the values adjusted to correct for the model performance. During Phase2, the corrected values reduced the error in wind observations by 2.46 knots. With roughly half of the overall error attributable to the model itself, this reduction is an improvement of approximately 50%. Thus, the right hand column was included to correct for that change. AirDat intentionally selected the aircraft with poor wind performance for heading error analysis and correction (i.e., the "corrected" group). Planes with small flux-valve errors do not benefit much from the change.

4. CONCLUSIONS

Historically, it has been assumed that heading information supplied by flux-valve magnetic sensor devices to an aircraft's compass system would not be able to provide wind data accurate enough to add value in numerical weather prediction. With the TAMDAR-based technique employed here, the majority of the aircraft's unique magnetic deviations can be filtered out, and the limitations of the heading system overcome. More long-term analysis needs to be conducted to refine this technique; however, preliminary analysis suggests that flux valve-based heading systems are capable of providing wind data similar to laser ring gyro-based inertial navigation systems on similar sized aircraft.

PART 2: MODELING UPDATE

1. RTFDDA-WRF

Over the last year, AirDat and NCAR have worked together to implement a version of RTFDDA-WRF, which is an “observation-nudging” FDDA–based method built around the WRF-ARW core. This system is able to assimilate synoptic and asynoptic observational data sets, including various surface data (e.g., METAR, SYNOP, SPECI, ship, buoy, QuikScat seawinds, mesonets, etc.), and various upper-air observations (e.g., TEMP, PILOT, wind profilers, aircrafts (TAMDAR), satellite winds, dropsondes, radiometer profilers, RAOBS, Doppler radar VAD winds, etc.).

Several recent improvements have been made to the observation nudging scheme, including the ability to assimilate multi-level upper-air observations using vertical coherency principles. Additional improvements have been made to the terrain-dependent nudging weight corrections, including a ray-searching scheme, which eliminates the influence of an observation to a model grid-point if the two sites are physically separated by a significant mountain ridge or a deep valley. This is outlined in greater detail in Childs et al (2010).

Additional research is currently underway to develop an analysis nudging technique, which can be used to take advantage of a 3DVAR analysis that assimilates non-direct remote sensing observations. This technique is at the center of the proposed “Hybrid” RTFDDA-WRF system, which AirDat and NCAR expect to be implementing over the first 6 months of 2010.

The operational North America AirDat RTFDDA grid configuration features an outer grid of 12 km spacing with 74 vertical sigma levels, of which the highest concentration reside in the mixed layer, as well as near the jet stream level. The inner domain has a 4 km grid spacing that also has 74 vertical levels.

Once the “Hybrid” RTFDDA-WRF system is released, an Atlantic Basin tropical grid will also be configured to run in real time from July through October. The physics and dynamics configuration will be slightly different from the North American grid to better represent tropical dynamics.

The RTFDDA-WRF has the ability to use all the synoptic and asynoptic (e.g., TAMDAR) observations. The initial RTFDDA-WRF system began cycling on 6-h intervals to 72 hours in late July 2009. The initial configuration used the Lin microphysics scheme, the Kain-Fritch cumulus scheme (no CP for the 4 km), the YSU boundary layer, and the NOAH LSM. The radiation was handled by the RRTM (longwave) and Dudhia (shortwave). The general performance of the configuration was very good, but there were several adjustments and upgrades that have been (and will be) implemented over the next 6 months.

Several of the data sets that are assimilated into the RTFDDA-WRF analysis are observed on height levels. Height-based data assimilation code was added to replace the conversion of the height levels to pressure levels, which allows the model to assimilate the observations directly on the native observation levels. The assimilation of higher resolution SST data (RTG SST HR) was also implemented along with a switch to the Morrison two-moment microphysics scheme.

There are several upgrades planned for the first part of 2010. A Kalman Filter-based bias correction algorithm will be applied during the post processing to correct systematic forecast errors. This method has been shown to substantially improve forecasts for 2-m temperatures and 10-m winds. The other major planned upgrade for 2010 is the Hybrid based assimilation, which will allow the combination of the best attributes of both variational assimilation, and RTFDDA-based nudging assimilation. The benefits will include expanding the outer 12 km domain, and greatly improving tropical cyclone and ocean forecasts. This assimilation technique provides the capability of assimilating the full suite of satellite-based radiance and sounder data, which is critical to increasing the forecast accuracy and skill in data-sparse regions.

2. 4DVAR-WRF

The 4DVAR-WRF prototype was built in 2005, and has been under continuous refinement since then, including the development of a TAMDAR observation operator and additional optimizations to the variational code to maximize the impact of TAMDAR data. It runs as a combination of WRF (latest released version 3.1.1), WRF+ (the WRF tangent linear model and adjoint model) and WRF-Var (the release version 3.1.1 with 4D-Var extensions) executables.

It uses system calls to invoke the three executables, disk I/O to handle the communication among WRF, WRF+ and VAR, and can run on a single processor as well as multi-processors. The cost function also includes a penalty term, *Jc*, to control noise during the minimization. The current version being tested includes a simple vertical diffusion with surface friction scheme, and a large-scale condensation scheme in addition to the full dynamics in WRF+.

4D-Var can assimilate the same observation types as 3D-Var does, and it can assimilate more observations from non-moving platforms, such as SYNOP, than 3D-Var. There are many adjustable parameters in WRF-Var, such as the variances and scale lengths of the background errors. Most of these parameters have been adjusted for optimizing the 3D-Var performance.

The 4DVAR-WRF is significantly more computationally expensive to run than the RTFDDA-WRF. Due to the expensive computational cost, the present configuration can only run a single 12 km North American domain, which is the same as configured for the RTFDDA-WRF. A tropical grid similar to the RTFDDA-WRF will also be configured.

The 4DVAR-WRF also has the ability to use all the synoptic and asynoptic (e.g., TAMDAR) observations. The multivariate background covariances used in 3DVAR and 4DVAR formally impose constraints that ensure slow manifold adjustment by the observations. This also helps prevent “spin-up” problems that exists in all cold-start operational models, as well as reduces the likelihood that gravity wave noise will be produced.

The 4DVAR is capable of assimilating observations that are not actual analysis variables. An example is satellite radiance observations, which must pass though a forward model to transform them to temperature and moisture innovations. This is one advantage that 4DVAR has over a nudging DA scheme.

The main limitation to the 4DVAR methodology is it is computationally expensive to run. Additionally, tangent linear and adjoint models have somewhat limited physics parameterizations. However, at the vertical and horizontal grid spacing that AirDat will be initially using, the linearized physics should prove robust enough for the desired forecast applications.

Recently, AirDat has added the new one-dimensional ocean water model to the 4DVAR tropical grid configuration. Nolan (2009) has shown that the addition of this model improves the boundary-layer heat fluxes in the model and leads to more realistic cyclone intensity. The 4DVAR tropical configuration YSU PBL scheme with the modified ocean roughness lengths was also updated with new parameters for the Western Atlantic Basin to be consistent with Donelan (2004).

The current 4DVAR data assimilation system uses multiple, concurrent executables, based on the WRF modeling framework. To increase stability and operational efficacy, the 4DVAR system will need to be combined into a single executable based on the sequential code of the ESMF framework.

Large forecast skill improvements have been observed using direct assimilation of satellite radiance data. The WRFDA modeling system has the capability to directly assimilate radiance data, including observations from the NOAA, AMSU, AIRS, GPSRO and METOP platforms. The direct assimilation of radar velocity and reflectivity data is also desired. As of December 2009, AirDat has been assimilating radiance data into the 3/4DVAR system.

Additional steps are being taken to improve the impact of TAMDAR observations by assimilating the data based on ascent, cruise and descent error profiles. Studies at AirDat and GSD have shown that the error statistics are different depending on the “leg” of the flight (Moninger et al. 2008).

Imbalance between the wind and mass fields in the analysis can be introduced by objective analysis techniques such as 3/4DVAR. This noise can lead to spurious precipitation, numerical instabilities and can damage the forecast and subsequent data assimilation through a noisy first-guess field. The digital filter initialization (DFI) is one of the methods to remove the imbalance, and has been shown to reduce numerical spin-up problems. Obviously, AirDat modelers are extremely interested in very accurate short-term temperature and precipitation forecasts, both of which can be improved using a DFI.

The analysis increments for an observation at the beginning of the 4DVAR assimilation window are the same as would be produced in a 3DVAR assimilation system. At each cycle of assimilation, the initial covariance matrix is fixed, static and flow independent. In order to appropriately propagate the flow dependent covariances to the subsequent cycle, a Kalman Filter or hybrid variational approach is needed, which is something that is being studied.

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