Reply

ORESTE REALE

Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, and University of Maryland, Baltimore County, Baltimore, Maryland

WILLIAM K. LAU

Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, Maryland

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1. Introduction

Reale et al. (2009a, hereafter RA09) investigate two African easterly waves observed during the National Aeronautics and Space Administration (NASA) African Monsoon Multidisciplinary Analysis (NAMMA) special observing mission (SOP-3) and attribute the lack of development of the first wave, referred in the paper as W1, to the possible role of dust associated with the Saharan air layer (SAL).

Braun (2010) questions those results attributing the wave dissipation to midlatitude air. The core discussion concerns a dry filament preceding the wave, the presence of dust, and the origin of the air contained in this dry filament. Unfortunately, even if we acknowledge the importance of a correct assessment of air masses, we believe that Braun (2010) contains major flaws as stated in his comment, the most serious being an arbitrary modification of Moderate Resolution Imaging Spectroradiometer (MODIS) data, in which a dust-rich area is moved eastward leaving the dry channel dust free, irrespective of the local wind motion, in an attempt to compensate for the time lag between Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) and MODIS data. In addition, Braun (2010) used downgraded National Centers for Environmental Prediction (NCEP) analyses at a horizontal resolution of 1° × 1° to perform trajectories in an attempt to demonstrate that air does not come from the Sahara. At this relatively low resolution, the detailed features under examination cannot be adequately resolved. It should be also emphasized that Braun (2010) contains poor-quality figures, in which only the broad-scale motion can be inferred and no fine structure can be detected.

In this reply, we use higher-resolution analyses at 1200 UTC (almost coincident times with *Aqua* and *Terra* passes) to emphasize how the channel of dry air associated with W1 is indeed rich in dust, in contrast with the claims by Braun (2010). Back trajectories on a 0.5° grid are also performed, leading to results drastically different from Braun (2010) and in particular showing that there is a clear contribution of Saharan air. Finally, it is shown that analyses at 1° horizontal resolution are inadequate to investigate such feature.

2. The dry air filament in the wave W1

The evolution of the wave under discussion, detected in RA09 (their Fig. 1), is shown in RA09 (their Fig. 5) between 26 and 29 August, emphasizing the intrusion of a dry air filament in the circulation and the final dissipation of the wave. In RA09's Fig. 8, a zonal cross section is produced across the wave, and a thermal dipole is detected across the core of the dry air filament, with warm air at about 600 hPa and cooler air below 875 hPa. RA09 suggest that the 600-hPa warming can be due to the presence of dust in the dry corridor and the low-level cooling results from downward shortwave reduction by dust. It is stressed that the dry air filament is a *fine* structure, of a scale that only high resolution, from the global perspective, can properly resolve.

Braun (2010) questions these results and argues that (i) the dry air is dust free and (ii) it is of midlatitude origins. To do so, he performs an analysis of the wave and compares it with the MODIS, Atmospheric Infrared Sounder (AIRS), and CALIPSO data. There are several perplexing aspects in Braun (2010):

Corresponding author address: Oreste Reale, Laboratory for Atmospheres, Code 613.0, NASA GSFC, Greenbelt, MD 20771.
E-mail: oreste.reale-1@nasa.gov

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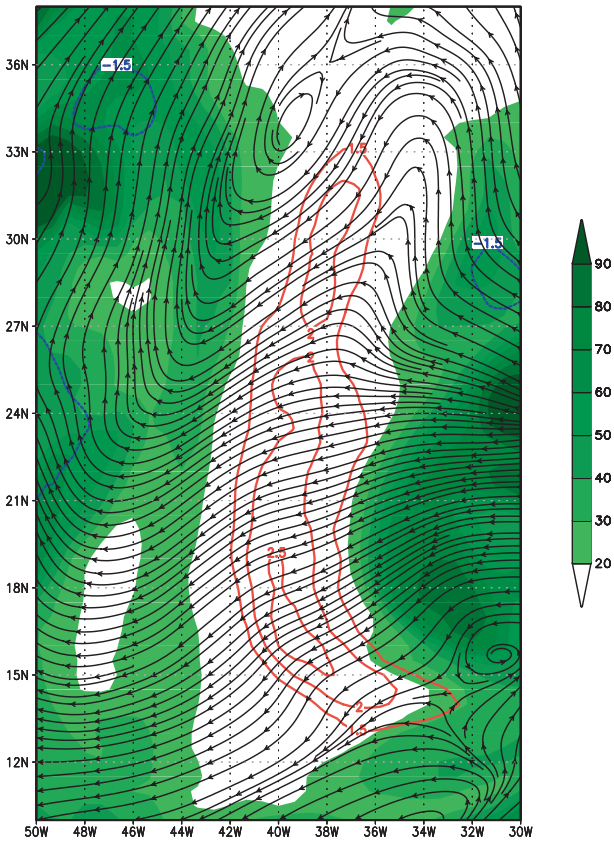

FIG. 1. Relative humidity (shaded), wind (stream lines) at 600 hPa, and temperature anomaly (red and blue contours), obtained by subtracting the zonal mean from 100° to 20°W. The white area with relative humidity less than 20% indicates the dry tongue being discussed in RA09 and in Braun (2010).

- The most serious problem is in his Fig. 2, where the author arbitrarily shifts eastward the dust border of 3°, conveniently removing it from the dry tongue. We believe that this alteration of MODIS data is totally arbitrary and unacceptable. The dust boundary is not a rigid body that can be shifted eastward with simple interpolation: it is instead part of a rotating system, undergoing scale changes, so that the motion of any part of the wave should consider the local motion field (vertically integrated across levels containing dust) and not simply the mean propagation of the wave. In particular, the motion in the dry tongue, which is in the more advanced part of the wave, contains a meridional component that Braun (2010) completely fails to recognize.
- Despite the importance of high resolution stressed in RA09, and the warning that the Saharan air boundary is a *fine structure*, Braun's Fig. 1 contains small and cluttered images, in which nothing but very large-scale features can be detected.
- Braun performs back trajectories from NCEP analyses, failing to mention that he does not use the full-resolution NCEP analyses (which at that time were at a resolution of about half of a degree) but rather the interpolated NCEP analyses at a downgraded resolution of 1° × 1°. With these wind fields, Braun concludes that all the air in the dry tongue is of midlatitude origin. We will show in this reply that the analyses used by Braun do not solve at all the feature that RA09 discusses and are therefore inadequate to perform meaningful backward trajectories.

In Fig. 1 we present the dry filament under discussion, plotting relative humidity and wind at 600 hPa. In addition, the temperature anomaly at 600 hPa, obtained by subtracting the zonal mean computed between 100° and 20°W, is superimposed. The major disagreement between RA09 and Braun (2010) is that we claim that the dry air is of predominantly Saharan origin, contains dust, and is warm at 600 hPa (and cool below) because of the radiative effects of dust. Braun (2010) claims that the dry air is of midlatitude origin, does not contain dust, and is warm because of subsidence.

3. Dust and back trajectories

Figure 2 shows the 600-hPa relative humidity at 1200 UTC superimposed on the MODIS data (deep blue; merging together *Aqua* and *Terra* passes, occurring both approximately at 1200 UTC). A dry tongue at about 40°W, emphasized by relative humidity values smaller than 20%, is evident from this picture. For visualization clarity, a dashed purple line is traced between 21° and 17°N to join two points in which atmospheric optical depth (AOD) = 0.15 is measured by MODIS. From the picture, values of AOD greater than 0.15 or 0.20 cover the entire eastern half the dry tongue. In clear sky, AOD of 0.15 is a significant value, and it cannot be argued that dry air with AOD greater than 0.15 or 0.2 is dust free. It is also important to note that the southwest edge of the dry tongue, at about 10°–20°N and 35°–45°W, contains values greater than 0.15 or even 0.2, associated with the dust outbreak called SAL1 by Braun (2010). Therefore, Fig. 2 shows that dust is present on two sides of the dry tongue (the eastern dust body being called SAL2 by Braun), and values of AOD less than 0.15 only occur in a relatively narrow band and occupy less than half of the dry tongue in the latitude range of 15°–25°N. The major disagreement with Braun comes from the edge of SAL1, which he shifts 3° eastward in his Fig. 2 and is masked by the small size and low quality of his remaining pictures.

From our Fig. 2, a number of back trajectories are performed using the fields obtained by the Goddard Earth Observing System (GEOS-5) analyses at a resolution double the one used by Braun. The results show

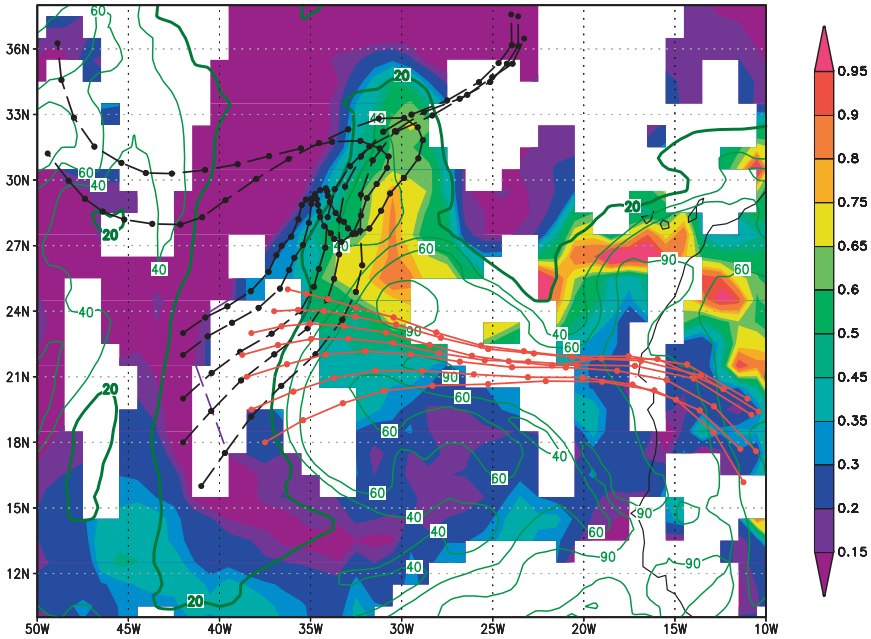

FIG. 2. MODIS (*Aqua* + *Terra*) optical depth at 1200 UTC 27 Aug 2006 (shaded). Missing data are in white. For clarity, a purple dashed line is traced to indicatively join values of AOD = 0.15 in the dry channel. Also shown is relative humidity at 600 hPa (solid contour). The thick 20% contour indicates the dry tongue seen in Fig. 1. Selected back trajectories are red if started to the east of 40°W, indicative of Saharan origin, and black if started from west of 40°W, suggesting a non-Saharan origin. Dots indicate 6-h intervals.

that all the trajectories starting to the east of the purple line, at 600 hPa and in a latitude range of 17°–25°N, can be traced back to the Sahara. The choice of the 600-hPa level to start the trajectories is determined by the fact that the warm anomaly is stronger at that level, as can be seen in RA09's Fig. 8.

On the contrary, only the tracks initiated from a narrow filament to the west of the purple line, at about 18°–24°N, 41°–42°W and centered on the low-dust channel with AOD less than 0.15, show a non-Saharan origin. Tracks starting more to the west, within the high AOD values associated with the SAL1 outbreak, also show a Saharan origin (not shown here for clarity and also because Braun agrees on this).

We are plotting only a fraction of the trajectories performed: the black tracks, unlike the ones in red, tend to be more erratic (the tracks starting north of 22°N and at about 43°W tend to loop and veer westward), but all have origins from subtropical high pressure systems in the Atlantic. To name this air "midlatitude air" is also a misnomer by Braun, in that we think this air has been residing for a long time within slow subtropical anticyclonic circulations. Because of the high uncertainties in the inverse trajectory problem, we do not think that this air can be traced to a specific location outside the subtropical Atlantic anticyclones: therefore, in terms of its origin, it could be either modified continental tropical air or modified maritime extratropical air (or a blend of the two).

Setting aside the naming of this air mass, which is not relevant to the present discussion, the important result is that the trajectories in Fig. 2 show that most of the air in the dry tongue is rich in dust, except for a filament (spanning less than half of the width of the dry channel) in which MODIS AOD is less than 0.15.

4. The importance of the analysis: Quality and resolution

Braun (2010), stating that RA09 uses GEOS-5 forecasts, overlooks the prominence given by RA09 to the problem of improving the quality of the analyses in the tropics. To create a set of high-quality analyses used in RA09, the full GEOS-5 data assimilation system was run, in a version almost identical to the one used to produce the Modern Era Retrospective Analysis for Research and Applications (MERRA, documented by Bosilovich 2006). In addition to all data used operationally, and the optimization of satellite-derived information featured in GEOS-5, for this particular study RA09 used AIRS cloudy retrievals (as opposed to clear-sky radiances) to ensure a better coverage in proximity of developing storms. This approach (Susskind et al. 2006) has shown specific advantages with

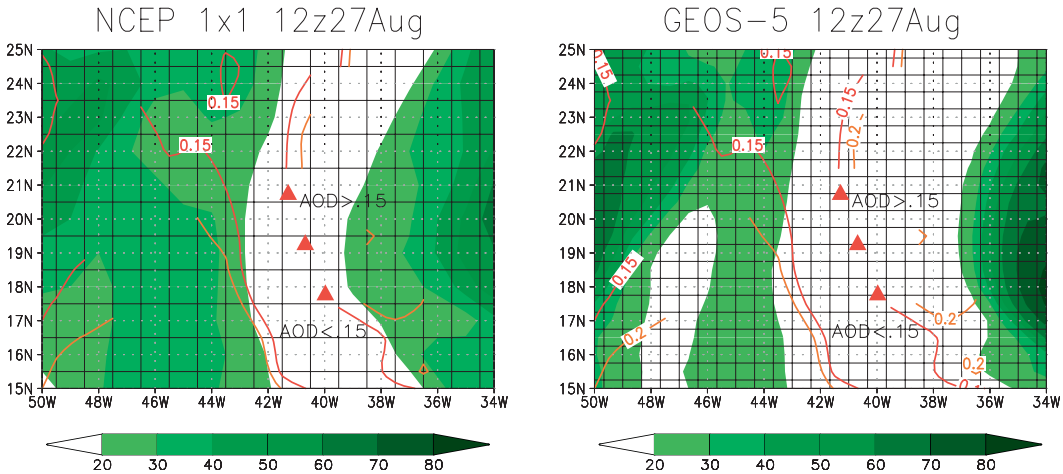

FIG. 3. Zoomed-in detail of relative humidity (shaded). (left) Grid from the NCEP analyses at the downgraded resolution of 1° used by Braun (2010) to perform backtrajectories and (right) corresponding high-resolution grid from the GEOS-5 analyses. AOD contours from MODIS (only 0.15, red, and 0.2, orange) are added. The triangles are intended to represent a possible edge of the 0.15 contour across missing data. Values greater than AOD = 0.15 are on the eastern side of the dry channel, as represented in the GEOS-5 analyses, and also on the southwestern side. AODs smaller than 0.15 occur only on a small part of the dry tongue.

respect to the clear-sky radiance approach in tropical cyclone studies (Reale et al. 2009b; Zhou et al. 2010). The analyses produced were validated extensively also using NAMMA data.

Finally, it was emphasized in RA09 that, in addition to quality, the resolution is also a crucial factor in discussing the role of SAL and the development of waves from a global perspective. RA09 argued that 1° analyses are not adequate. In particular, the modeling showed that even 0.5° was not optimal, and of the two sets of forecasts (at horizontal resolution of 0.5°and 0.25°) initialized from the 0.5° analyses, the forecasts produced at 0.25° were substantially better.

To show clearly how questionable is the idea of tracing the origin of the air associated with the dry tongue using wind fields at 1° horizontal resolution, as Braun (2010) does, we present in Fig. 3, side by side, a zoomed-in detail of the relative humidity fields at 600 hPa, as seen in the downgraded 1°NCEP analyses used by Braun (2010), and the corresponding picture obtained from the 0.5° GEOS-5 analyses. Over these pictures, the MODIS contours of AOD = 0.15 and AOD = 0.20 are superimposed to emphasize the approximate border of the high dust edge to the east (SAL2). The focal point of this reply is to show that a large fraction of the dry tongue also coincides with AOD values higher than 0.15.

Finally, the actual grids of both analyses are also presented. It is evident that in the downgraded NCEP analyses the entire channel of dry air is generally only three or four grid boxes wide. Moreover, the width of the dry air filament corresponding to AOD higher than 0.15 is about 100–200 km wide and is represented by only one or two grid boxes. To perform back trajectories of this feature is not realistic because of the uncertainties induced by poor sampling.

On the contrary, the representation of the dry tongue in the GEOS-5 analyses comprises a width of about 10 grid boxes, and the fraction of it with AOD values higher than 0.15 is at least five or six grid boxes wide. An attempt to trace back the origin of this air mass is more meaningful.

It is important to stress how different is the representation of the dry tongue between the two analyses: not only are the humidity gradients at the edge of the dry tongue sharper, but also the very size of the tongue is substantially larger in the GEOS-5 analyses.

From the GEOS-5 analyses, we have found that each and every trajectory performed east of the 0.15 AOD contour ends up in the Sahara, as seen in Fig. 2. On the contrary, only trajectories performed on the central-western side of the tongue, centered at about 41°–42°W, which is the core of the AOD minimum, end up in the Atlantic.

5. Concluding remarks

In RA09, the effect of Saharan air on Atlantic tropical cyclogenesis is investigated with a high-resolution global data assimilation system (DAS), that uses, in addition to all the operational data, a much improved coverage from the Atmospheric Infrared Sounder (AIRS), as compared to the one used by operational forecasts, following Susskind et al. (2006). RA09 study a wave named W1 and attribute its dissipation to a dry air intrusion. The thermal

structure of the dry air filament, with a dipole (warm at about 600 hPa and cool at about 900 hPa and below), is in agreement with previous studies on the SAL by Dunion and Velden (2004), Lau and Kim (2007), and the most recent work by Wong et al. (2009), and is indicative of radiative effect of dust. Braun (2010) argues that the air filament is dust free and is of midlatitude origin.

In this reply, we state our disagreement with Braun (2010) by showing that MODIS AOD values are indeed higher than 0.15 or 0.2 across most of the dry channel and correspond remarkably well with the temperature anomaly shown in Fig. 1. We also perform back trajectories that point to a Saharan origin for the fraction of the dry air with high AOD values (Fig. 2). We finally show the profound difference between GEOS-5 analyses and the downgraded 1° NCEP analyses used by Braun. The findings in this reply appear to further strengthen the results by RA09.

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