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## Impact of interactive aerosol on the African Easterly Jet in the NASA GEOS-5 global forecasting system.

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1 The real-time treatment of interactive, realistically varying aerosol in a global  
2 operational forecasting system, as opposed to prescribed (fixed or climato-  
3 logically varying) aerosols, is a very difficult challenge that only recently be-  
4 gins to be addressed. Experiment results from a recent version of the NASA  
5 GEOS-5 forecasting system, inclusive of interactive aerosol treatment, are  
6 presented in this work. Four sets of 30 5-day forecasts are initialized from  
7 a high quality set of analyses previously produced and documented, to cover  
8 the period from 15 August to 16 September 2006, which corresponds to the  
9 NASA African Monsoon Multidisciplinary Analysis (NAMMA) observing cam-  
10 paign. The four forecast sets are at two different horizontal resolutions and  
11 with and without interactive aerosol treatment. The net impact of aerosol,  
12 at times in which there is a strong dust outbreak, is a temperature increase  
13 at the dust level, and decrease in the near-surface levels, in complete agree-  
14 ment with previous observational and modeling studies. Moreover, forecasts  
15 in which interactive aerosols are included depict an African Easterly Jet at  
16 slightly higher elevation, and slightly displaced northward, with respect to  
17 the forecasts in which aerosols are not included. The shift in the AEJ po-  
18 sition goes in the direction of observations and agrees with previous results.

## 1. Introduction

21 The role of the Saharan Air Layer (SAL) has been suggested to be relevant to weather  
22 forecasting over the tropical Atlantic since at least the early '70s [Carlson and Prospero,  
23 1972]. In addition to the thermal effect due to its intrinsically high heat content, the  
24 role of dust in terms of direct radiative effect has been intensely investigated for several  
25 decades (e.g., Carlson and Benjamin, [1980]). Surface- and space-based measurements of  
26 atmospheric optical thickness (AOT) go back to the late '70s (e.g. [Carlson and Wendling,  
27 1977]) but the possibilities of merging modern-era satellites with data such as the ones  
28 coming from Moderate Resolution Imaging Spectroradiometer (MODIS) or Cloud-Aerosol  
29 Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) give a much more accu-  
30 rate understanding of aerosols' optical properties (e.g. [Remer et al. 2008; Omar et al.  
31 2009])

32 Among the various effects of dust over the tropical atmosphere, Dunion and Velden  
33 [2003] suggested a role of dust unfavorable to tropical cyclogenesis. One point of their  
34 argument, among other issues, is the increased static stability induced by mid-troposphere  
35 warming and surface cooling. Similar findings are also obtained by Lau and Kim [2007]  
36 on a seasonal time-scale. Reale et al. [2009b], hereafter RA09b, relying upon a global  
37 data assimilation and modeling effort and the production of high quality analyses, also  
38 suggest that high dust content is associated with a thermal dipole: relatively warm at  
39 600-700 hPa and cooler at about 900 hPa or below. RA09b findings are supported by  
40 the fact that the finite-volume dynamics of the NASA GEOS-5 is particular suitable to  
41 maintain fine thermal features avoiding unrealistic dispersions.

Recent climate sensitivity experiments using general circulation models have shown that radiative effects of Saharan dust tend to draw the Atlantic ITCZ northward towards the southern edge of the dust layer, and induce large-scale north-south and east-west oriented divergent circulations that affect the African Easterly Waves and rainfall variability of the West African monsoon and climate of the Atlantic [Lau et al., 2009; Kim et al., 2010]. Wilcox et al. [2010] have shown from observational perspective that the temperature structure associated with Saharan air outbreaks is consistent with previous work, and that one of the effects of dust outbreaks is a northward shift of the Inter Tropical Convergence Zone (ITCZ). Also within the operational forecasting modeling framework, evidence has been provided by Tompkins et al. [2005] on that an improved representation of aerosol (i.e. seasonally varying instead of fixed) leads to a more correct representation of the African Easterly Jet (namely, a northward and upward shift, in agreement with observations).

In this work, the use of interactive aerosol in a global modeling framework provides results fully consistent with Lau et al. [2009], Kim et al. [2010], Wilcox et al. [2010] and confirms that the direction started by the pioneering work by Tompkins et al. [2005] needs to be further pursued.

## 2. The Model and Data Assimilation System

The global data assimilation and forecasting system used is the NASA GEOS-5, which combines the Gridpoint Statistical Interpolation (GSI) analysis algorithm developed by the National Centers for Environmental Predictions (NCEP) (e.g. Wu et al., [2002]), and modified by the NASA Global Modeling Assimilation Office (GMAO), with the NASA atmospheric global forecast model, is documented in Rienecker et al., [2008]. The fore-

cast model shares the same dynamical core [Lin, 2004] with the so-called finite-volume  
General Circulation Model (fvGCM), also known as the GEOS-4, but contains a different  
set of physical parametrizations, partly developed by the NASA GMAO. The Aerosol  
interactive component is a new feature which is currently implemented also in the opera-  
tional version of the GEOS-5 and is a further step with respect to the previous transport  
model described in Colarco et al. [2010], which merged the Goddard Chemistry, Aerosol,  
Radiation and Transport Model (GOCART) with the GEOS-4. The version described  
by Colarco et al. [2010] allows the treatment of dust, sea salt, carbonaceous and sulfate  
aerosols, producing realistic aerosol distributions (validated against ground- and satellite-  
based measurements) which are consistent with the dynamics and the meteorological  
fields produced by the GEOS-4. In the version used in this study, aerosol transport pro-  
cesses (advection, diffusion, convection) are provided by the host GEOS-5 model, with the  
aerosol specific processes (emission, deposition, simplified sulfate chemistry) as in Colarco  
et al. [2010]. The direct aerosol radiative effect is included in the GEOS-5, while indirect  
effects on cloud/precipitation processes are not included at present.

### 3. The Experiments

Four sets of 30 5-day forecast experiments at two horizontal resolutions ( $0.5^\circ \times 0.67^\circ$   
and  $0.25^\circ \times 0.33^\circ$ , both with 72 vertical levels), are performed. They are initialized  
daily at 00z, starting at 00z 15 August 2006, from the same set of analyses used in  
RA09b. These were produced by assimilating all conventional and satellite observations  
used operationally at that time, but with a much denser coverage from the Atmospheric  
Infrared Sounder (AIRS), obtained by ingesting cloudy retrievals instead of clear-sky

186 radiances. As discussed in Reale et al. [2009a] and in RA09b, AIRS-derived information  
187 in partly cloudy regions improves the analyses in the tropics. However, the experiments  
188 described in this article are characterized by the inclusion or exclusion of interactive  
189 aerosol, and are named  $NOA_{xx}$  (no aerosol) and  $IAA_{xx}$  (interactive aerosol) with the  
190 suffix  $_{xx}$  indicating the  $0.50^\circ$  or  $0.25^\circ$  forecasts respectively.

#### 4. Results

191 As a preliminary metric to assess the impact of interactive aerosol, the anomaly corre-  
192 lation for all sets of 30 5-day forecasts is computed against operational NCEP analyses.  
193 The impact is virtually zero: the insertion of interactive aerosol does not affect the *globally*  
194 *averaged* skill of the system. In FS1 the anomaly correlations of  $NOA_{50}$  and  $IAA_{50}$  are  
195 compared; the  $0.25^\circ$  forecasts provide identical results (not shown). The lack of global  
196 impact of the interactive aerosol is understandable because the production of dust is con-  
197 fined to few areas of the world, and does not occur at all times even in the dust-producing  
198 regions. However, it is important to notice that the forecast skill does not degrade as a  
199 consequence of the insertion of aerosols, which represents a major change in the model's  
200 physics.

201 At the same time, it is crucial to emphasize that, for states of the atmospheres associated  
202 with *specific* weather systems, at times in which dust production is strong, and selected  
203 regions are analyzed, the impact of aerosol insertion is very large and dynamically relevant.  
204 In this work we focus on the impact on the African Easterly Jet (AEJ) which flows,  
205 with a predominantly easterly component, at about 650 hPa and about  $15^\circ - 20^\circ N$ , and  
206 which is partly controlled by horizontal temperature gradients over the Sahelian region.

105 To detect and understand the impact of interactive aerosols is not an easy or obvious  
106 task, because of the intrinsically noisy nature of the radiative forcing associated with  
107 dust, the overlapping with strong thermal signal due to the diurnal cycle, and finally the  
108 inhomogeneous distribution of dust, rapidly varying in space and time. In this work, we  
109 aim to show an example of a clear signal associated to a major dust outbreak. We select  
110 the strong outbreak observed during the Special Observing Phase (SOP-3) of NAMMA,  
111 moving from Africa to the Atlantic between 25 and 28 August. RA09b suggest that  
112 this event produced a temperature dipole (cool at about 900 hPa and warm at about 600  
113 hPa), whose effect propagated well into the Atlantic. However, RA09b did not have yet the  
114 capability of interactive aerosol and is based on a comparison between the MODIS AODs,  
115 and on the temperature structure in the GEOS-5 analyses and integrations [Reale and  
116 Lau 2010]. In this work we rediscuss the presence of a thermal dipole possibly associated  
117 with dust, in lieu of this new NASA tool.

118 As a first step, it is important to verify that the above-referred dust outbreak is rep-  
119 resented well in the simulations. Figure 1 compares the outbreak as represented through  
120 the total mass column dust obtained from the 36-hour GEOS-5 forecast initialized at 00z  
121 24 August, and a composition of AOTs obtained from MODIS instruments on board both  
122 Aqua and Terra satellites, corresponding to the verification time of 12z 25 August. The  
123 Figure shows that the GEOS-5 reproduces a strong dust outbreak intercepting the African  
124 coastline at about  $20^{\circ} - 30^{\circ}N$ , recurving southward at about  $20^{\circ}W$  and northwestward  
125 at about  $25^{\circ}W - 35^{\circ}W$ .

135 Figure FS2 shows the same outbreak, as captured by a 36-hour forecast initialized on  
136 the following day, at 00z 25 August 2006. By comparing the observed AOD from 12z 26  
137 August with the forecast, it can be seen that GEOS-5 again captures well the westward  
138 propagation of the dust edge, and even produces a very thin low-dust channel between the  
139 two major high dust regions centered at about  $15^{\circ}N$ ,  $30 - 40^{\circ}W$  and  $25^{\circ}N$ ,  $20 - 30^{\circ}W$ ,  
140 respectively. On these grounds, it can be safely stated that there is a major dust outbreak  
141 in the GEOS-5, and that its timing and scale correspond well with the MODIS data.

142 The second step is to investigate the impact of this dust outbreak on the temperature  
143 structure, as represented by the GEOS-5. Figure 2 shows the temperature impact of  
144 aerosols at longitude  $10^{\circ}W$ , from the same simulations in Fig. 1. An evident strong  
145 thermal dipole, very similar to the one discussed in RA09b and previously by Dunion and  
146 Velden [2004] can be observed: a heating of about  $1^{\circ}C - 1.5^{\circ}C$  between 850 and 500 hPa,  
147 and a cooling in the lower, near-surface, levels. A very similar pattern in the  $IAA_{25}$  minus  
148  $NOA_{25}$  temperature structure across the same latitude range and at longitude  $10^{\circ}W$  can  
149 be seen also in FS 3, where the corresponding aerosol impact on temperature is computed  
150 from the 36 hour forecast initialized on the following day (00z 25 August) and verified at  
151 12z 26 August. The simulations at  $0.50^{\circ}$  provide consistent results (not shown) but with  
152 diluted values and smoother gradients. As discussed in RA09b and Reale and Lau (2010),  
153 the resolution of  $0.25^{\circ}$  is better than  $0.50^{\circ}$  to investigate the fine structure of the AEJ.  
154 For this reason, we show only the  $IAA_{25}$  in the following pictures.

155 Because the AEJ and the wind over the region are strongly controlled by lower-level  
156 temperature gradients, a change in the thermal structure must have an impact on the



146 AEJ and more generally on the circulation. Figure 3 shows the vertical profiles extracted  
149 from a 108 hour forecast in the GEOS-5 integrations ( $NOA_{25}$  and  $IAA_{25}$ ) and compared  
150 with the profiles of temperature and zonal wind component, obtained from the vertical  
151 ground-based soundings from the Cape Verde Islands, at  $14.9^{\circ}N, 23.5^{\circ}W$  (radiosonde  
152 data available online at: <http://namma.msfc.nasa.gov>). The most evident impact on  
153 temperature is a warming up to  $1^{\circ}C$  between 900 and 700 hPa, and a slight cooling from  
154 the near-surface levels up to 900 hPa. The zonal wind panel shows that the verifying  
155 analysis and the observational profile match very well, but the 108 hour  $NOA_{25}$  forecast  
156 has a negative bias with respect to the observations, of about  $4ms^{-1}$ , from the surface to  
157 800hPa. The impact of the aerosol is very evident in the lower levels, reducing the bias of  
158 about 40%. When no dust production is present, the impact on temperature and zonal  
159 wind is negligible (not shown). Also, above 600hPa, the impact of the aerosol is virtually  
160 zero (not shown).

161 The radiative effect of dust is controlled by diurnal cycle and the distribution of aerosol  
162 is very noisy; therefore, to obtain a clearer signal on the wind field and of the AEJ  
163 structure, a 5-day average across the forecast initialized on August 25th is performed.  
164 There is an evident northward and upward shift in the AEJ structure, in the zonal wind  
165 and temperature fields at  $10^{\circ}W$  (FS 4) consequent to this thermal anomaly, in agreement  
166 with Tompkins et al. [2005], and expected from the thermal wind relationship. We  
167 see a similar thermal anomaly at  $10^{\circ}E$  and a corresponding northward shift in the AEJ  
168 (FS 5). The shift is also very evident on any longitude between  $20^{\circ}W$  and  $20^{\circ}E$  (not  
169 shown) and, to a lesser extent, also in the  $IAA_{50}$  experiments (not shown). The scarcity

of observations from the area (which prevents from providing a clear depiction of the  
AEJ from observations only) does not allow the validation of this northward shift in a  
more rigorous way. To compare the AEJ with reanalyses is also not meaningful since  
no reanalysis is produced from a system containing realistic, interactive aerosol at this  
time. However, these experiments demonstrate that the effect of interactive aerosol in the  
model, without degrading the global forecasting skill, alter significantly the circulation  
over the dust-affected region and provide an improved vertical profile at one validation  
point.

## 5. Discussion

The introduction of interactive aerosol, varying in agreement with the meteorology, is a  
serious challenge requiring consideration. In this work it is shown that the usual metrics  
to asses improvement in forecasting skill, such as 500 hPa anomaly correlation plots, are  
not suitable to evaluate the impact of the insertion of interactive aerosol treatment. On  
the contrary, for areas and events affected by dust aerosols, it is important to design mean-  
ingful, event-focused, metrics. In this work a major dust outbreak observed during the  
NAMMA campaign in August 2006 is investigated with the aid of the GEOS-5 forecasting  
system inclusive of interactive aerosol component. It is first shown that the forecast of  
dust total column mass qualitatively agrees with the MODIS merged AOTs from both  
Aqua and Terra, and then that the effect of the aerosol on the temperature structure is  
completely consistent with previous observational and modeling works, producing a ther-  
mal dipole (warmer at the aerosol level, cooler below). In particular, it is shown that the  
effect of this thermal anomaly projects into the dynamics and produces an improved 108

hour forecast of temperature and wind profiles, validated against an existing sounding.  
A 5-day average across the forecast, to dampen the noisy structure of the dust-induced  
signal, shows that the net effect of the aerosol simulation is a northward (and, to a lesser  
extent, upward) shift of the AEJ, in agreement with other modeling studies. FS 4 and 5  
also suggest a northward displacement of the westerly low-level monsoonal flow, in agree-  
ment with Wilcox et al. [2010] and related modeling results [e.g. Lau et al 2009]. In  
this work we have also performed the same analysis for another dust outbreak occurred  
around 10-13 September: wind and temperature anomalies of the same sign are obtained,  
albeit of a weaker magnitude, being the outbreak also substantially weaker (not shown).

## 6. Concluding Remarks

In this article we show that the use of interactive aerosol in the GEOS-5 data assimila-  
tion and forecasting system does not impact the global skill but substantially changes the  
thermal structure over northwestern tropical Africa, during an observed dust outbreak,  
affecting the circulation and particularly the AEJ representation. We validate the changes  
in temperature and wind with a vertical sounding, showing that the insertion of interactive  
aerosol improves the forecast up to day five for this particular event. However, the limi-  
tation of this work is to rely upon modeled aerosol production and distribution. The next  
step, namely real-time use of satellite-derived aerosol information in global models, is a  
very recent development of the most advanced data assimilation systems. In this regard,  
the NASA GMAO is currently attempting to assimilate real-time AOTs from MODIS,  
which may represent the future direction for this kind of research.

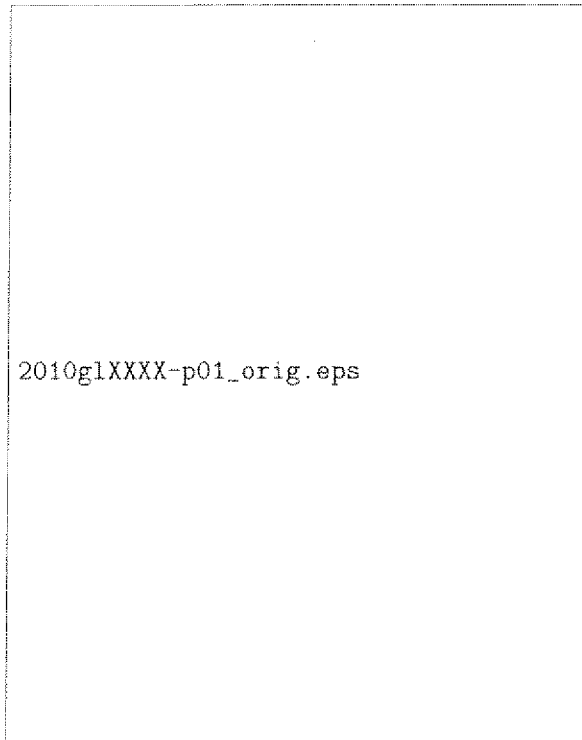
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**Figure 1.** 36-hour forecast (initialized at 00z 24 Aug 2006) of total mass column aerosol from the GEOS-5, and MODIS optical depth for 12z 25 Aug 2006.

A vertical meridional cross-section of temperature at 10°W in the GEOS-5 simulation. The plot shows temperature in degrees Celsius on the y-axis and pressure in hPa on the x-axis. The plot is oriented vertically on the page. The text '10°W' is written vertically along the left side of the plot area.

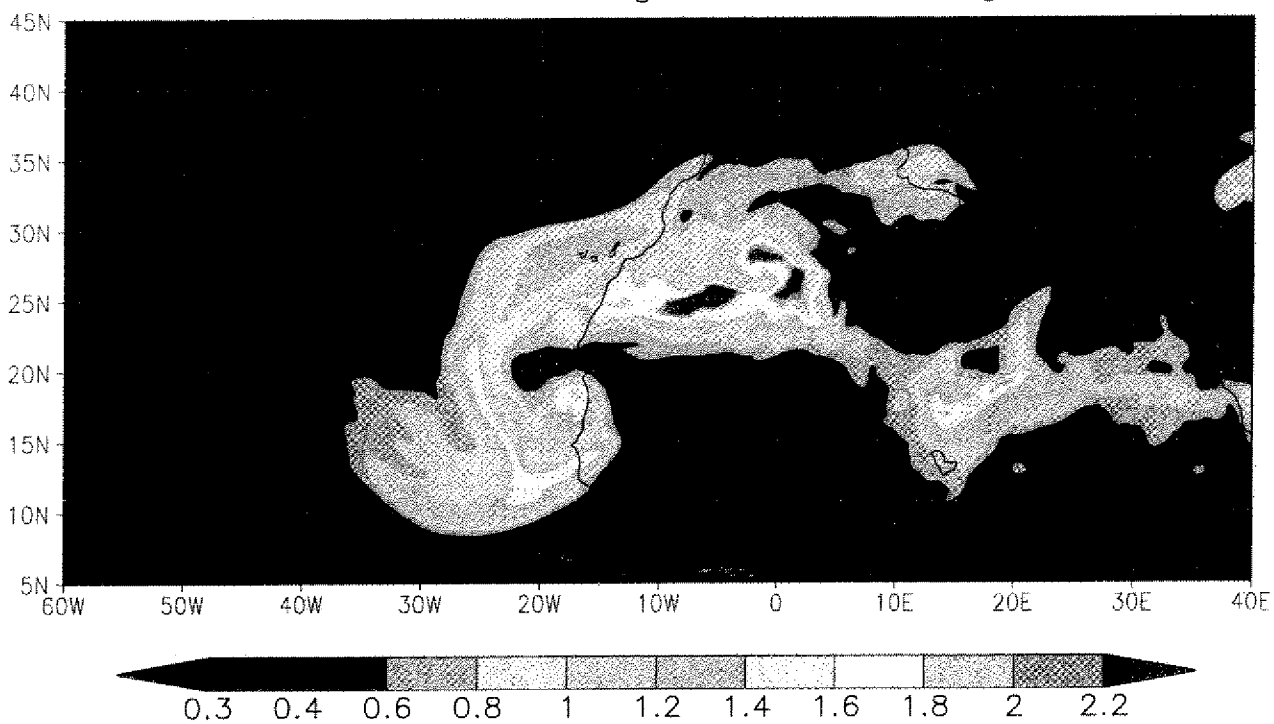
**Figure 2.** Vertical Meridional cross-section of temperature ( $^{\circ}C$ ) at  $10^{\circ}W$  in the GEOS-5  $NOA_{25}$  simulation for 12z 25 Aug 2006, (36 hour forecast, initialized at 00z 24 Aug). Shaded:  $IAA_{25}$  minus  $NOA_{25}$  difference.



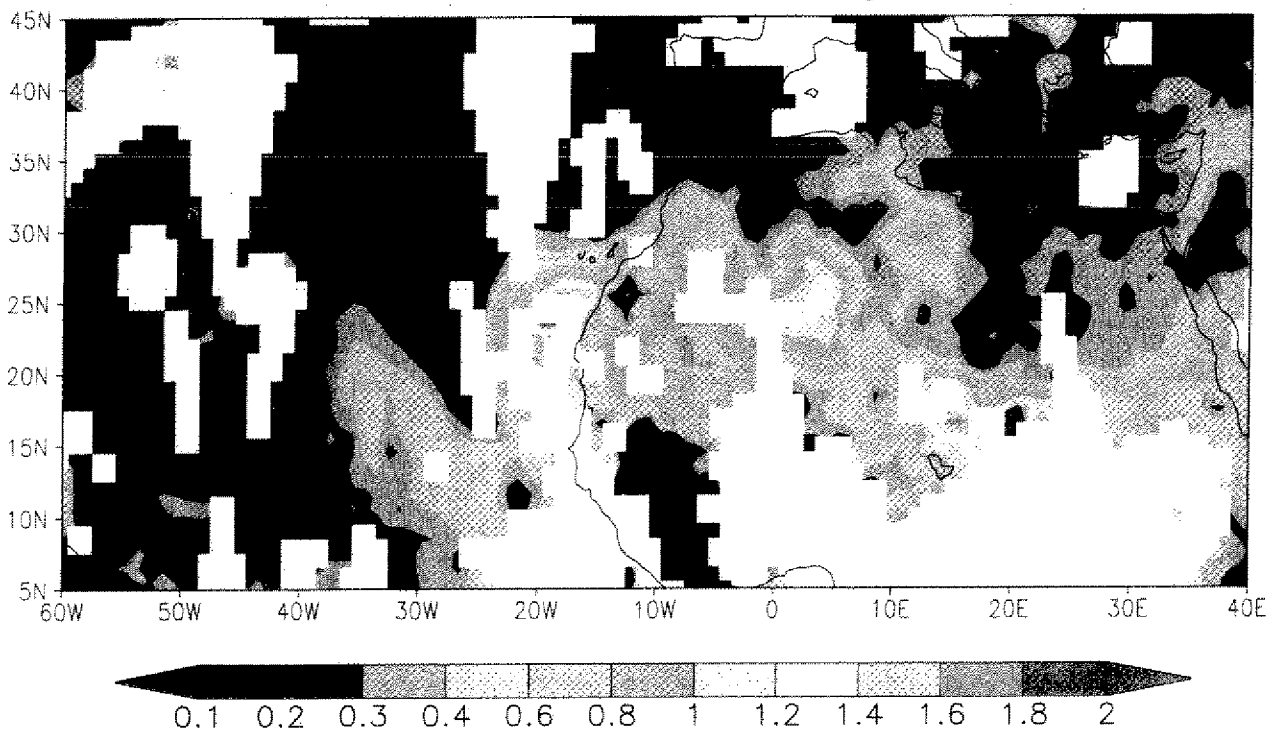


**Figure 3.** Vertical profiles of Temperature ( $^{\circ}C$ , left panel) and zonal wind  $u$  ( $ms^{-1}$ , right panel) at Cape Verde  $14.92^{\circ}N, 23.49^{\circ}W$  in the GEOS-5  $NOA_{25}$  (green) simulation for 12z 29 Aug 2006, (108 hour forecast, initialized at 00z 25 Aug), verifying analyses (black), compared with observed soundings (purple) at the Cape Verde, from SOP-3 campaign. In the left panel the orange line represents the  $IAA_{25}$  minus  $NOA_{25}$  difference; in the right panel, the actual  $IAA_{25}$   $u$  component of the wind.

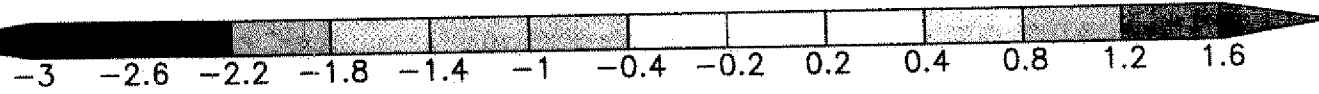
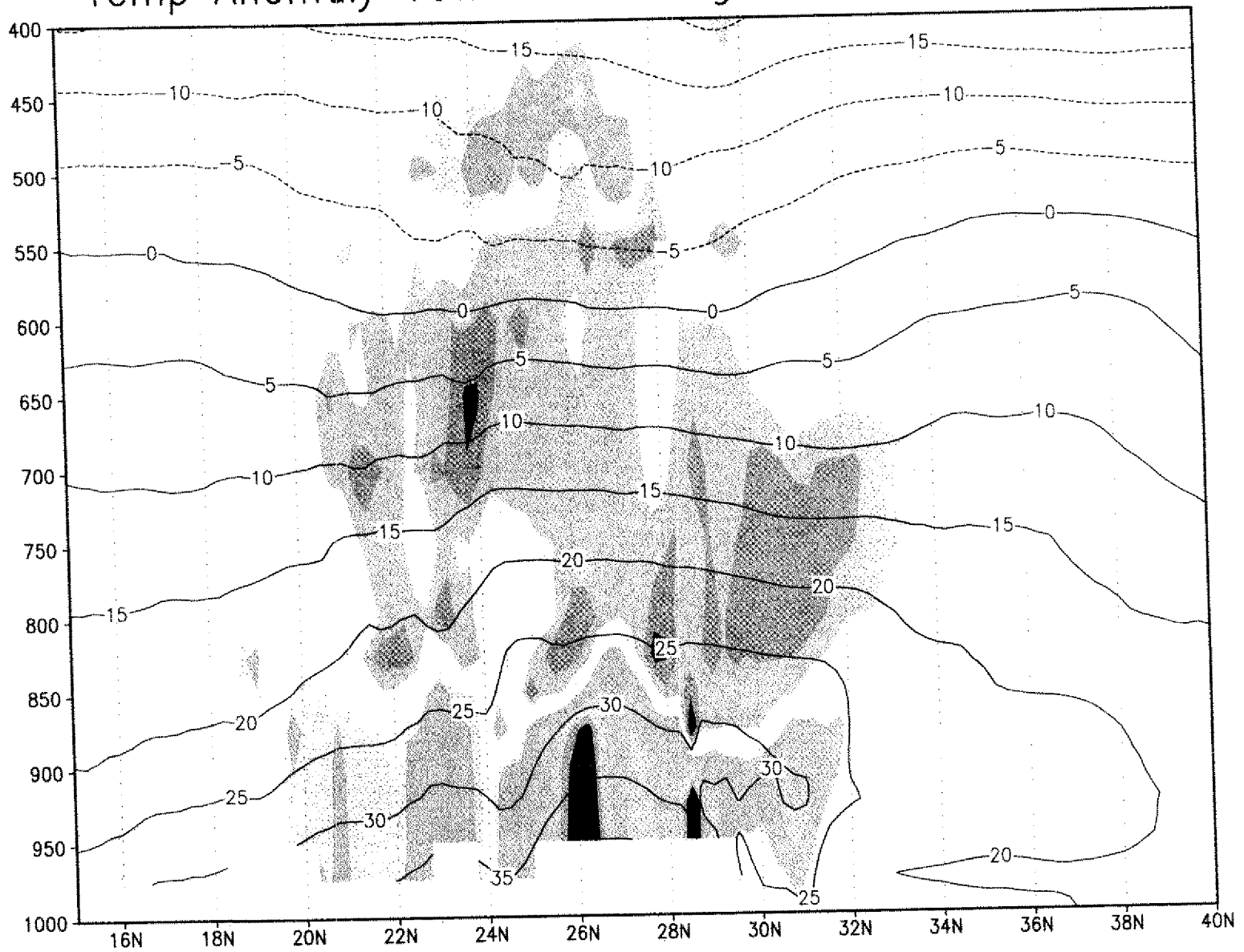
GEOS-5 In00z24Aug Ver12z25Aug 36hFc



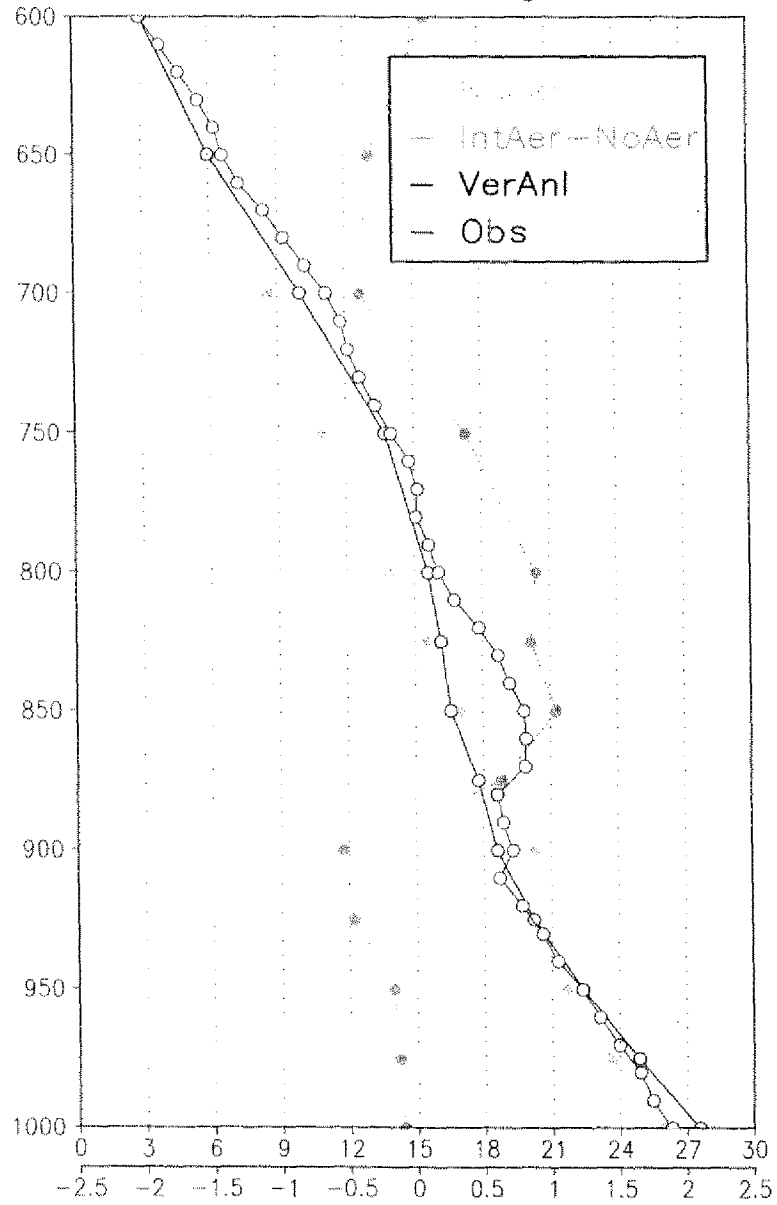
MODIS 12z 25Aug



# Temp Anomaly 10W In00z24Aug Ver12z25Aug 36HFC



T 12z29Aug



U 12z29Aug

