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Influence of aerosol climatology on forecasts of the African Easterly Jet

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Abstract

The European Centre for Medium Range Forecasts recently implemented a revised annually varying aerosol climatology in their forecasting system. The new climatology greatly reduces the aerosol optical depth over the Sahara compared to the previous temporally fixed climatology. Using high resolution dropsonde data in addition to the model analyses, it is demonstrated that the direct radiative effect resulting from the aerosol modification significantly improves medium range forecasts of the African Easterly Jet, the central dynamical feature in this region.

1 Introduction

Aerosols directly affect the atmospheric radiation budget, and their inclusion in climate models significantly modifies estimates of future climate (see review by Haywood and Boucher, 2000). Due to their relatively short residence time in the atmosphere, aerosol concentrations tend to be very heterogeneous, both spatially and temporally, and therefore their direct radiative effect can manifest itself in significant modifications of the atmospheric general circulation. Aerosols also have an indirect effect on the atmosphere through their role in cloud microphysics (e.g. Twomey, 1974; Twomey et al., 1984) but this will not be addressed in this article. High aerosol concentrations are notably found over the industrial source regions of Eastern US, Europe, and East Asia. In addition, high concentrations of mineral aerosols are observed over the African Sahara which can be advected far out into the Atlantic often reaching the Americas (e.g. Perry et al., 1997; Prospero and Lamb, 2003).

Here we focus attention on the African region since substantial systematic medium range forecast biases exist there in the ECMWF integrated forecast system (IFS) model. While this model has been frequently demonstrated to faithfully reproduce many aspects of the global circulation, both Kamga et al. (2000) and Thorncroft et al. (2003) show inadequacies in the prediction of the 700 hPa African Easterly Jet (AEJ) at the 5 day range when compared to the analyses in the former study and to high resolution dropsonde data in the latter. This was despite the fact that the analysis replicates the observed AEJ with reasonable fidelity (Thorncroft et al., 2003). The accurate prediction of the jet structure is important, since it is a central component of the African monsoon system in the Sahel region and plays an important role in the initiation of both African Easterly waves and mesoscale convective complexes (Houze Jr. and Betts, 1981).

Over the last decade satellite observations and improved modelling studies have led to a more accurate picture concerning aerosol distributions. In response, the ECMWF model has recently incorporated a new aerosol climatology, significantly altering the aerosol optical depth in this region. The consequences for the forecast of the AEJ are presented here.

High resolution dropsonde data from the JET2000 campaign are used for validation purposes. These are supplemented by three months of analyses (the assessment of the atmospheric state used for forecast initialization), which are considered a reasonable proxy for the ’truth’ since the relatively sparse observations in this region are still able to effectively constrain the analysis system, relative to the much larger medium range forecast errors (Tompkins et al., 2004).

2 Aerosol Climatologies

The two aerosol climatologies used in this study correspond to those used operationally in the ECMWF forecast system before and after the 7th October, 2003. The old climatology was originally developed by Tanre et al. (1984). It provides annual mean geographical distributions for aerosol types of maritime, continental, urban and

Table 1: Maximum optical thickness in the previous Tanre et al. (1984) and revised Tegen et al. (1997) aerosol climatologies. The Tanre climate is divided into geographical regions, and has a peak desert aerosol τ of 1.9 occurring over the Sahara. The right two columns give the January and July monthly mean value for the specific aerosol categories into which the Tegen climatology is divided, and show a reduced peak of dust aerosols, which also occurs over the Sahara.

TANRE	annual	January	July	TEGEN
desert	1.9	0.184	1.01	dust-like
continental	0.2	0.235	0.231	organic
maritime	0.05	0.099	0.232	sulfate
urban	0.1	0.039	0.039	black carbon
background tropos.	0.03	0.0	0.0	background tropos.
background stratos.	0.045	0.045	0.045	background stratos.

desert aerosol, in addition to a uniformly distributed tropospheric and stratospheric 'background' aerosol loading. Radiative properties (extinction coefficient, single scattering albedo, asymmetry factor) are consistently derived for each aerosol type and the various spectral intervals of the ECMWF radiation schemes following Tanre et al. (1984).

More recently, chemical transport models have addressed the life cycles of various aerosol types. A climatology for the annual cycle of the distribution of various aerosol types has been compiled by Tegen et al. (1997). This has been implemented in the ECMWF forecast system, with the annual cycle described by monthly mean aerosol optical depth distributions. Specifically, the new ECMWF aerosol climatology was created from a set of files[1] containing the optical thickness over 72 longitudes and 45 latitudes (5 by 4 degree resolution) and 12 separate months, due to (data originator given in brackets, for details refer to Tegen and Fung, 1994; Chin et al., 1996; Liousse et al., 1996; Tegen et al., 1997):

- black carbon (Penner)
- small dust (Tegen)
- large dust (Tegen)
- small anthropogenic dust (Tegen)
- organic (Penner)
- SO4 (Chin)
- Anthropogenic SO4 (Chin)
- Sea salt (Tegen)

The radiative properties are derived following Hess et al. (1998). Table 1 compares the maximum optical thicknesses in the old and new climatologies. In particular, the old climatology was dominated by desert aerosols, with a spatial maximum optical thickness of 1.9 over the Saharan region. This annual mean figure is replaced by a spatially moving peak value of between 0.18 (December) and 1.01 (July) in the new climatology. This reduction is also confirmed by more recent in situ studies (Haywood et al., 2003). Note that the vertical distributions for all aerosol components are similar in the two climatologies, and that the new climatology has no requirement for a tropospheric background, while the stratospheric aerosol loading remains unchanged. Table 2 describes the characteristics of the aerosol components for dust category in the new climatology.

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[1] all available at http://www.giss.nasa.gov/data

Table 2: Characteristics of the aerosol components for dust-like aerosols in the new climatology, adapted from Hess et al. (1998). RH is the relative humidity assumed for the computations of the relevant optical properties. The nuclei, accumulation, and coarse modes refer to various size ranges for the component particles.

Type	RH (%)	Component	Number (cm^{-3})	Volume (10^6 μ m^3/m^3)	Mass (μ g/m^3)	Density (g/cm^3)
”Desert” Dust-like	50	water soluble	2000	2.81	4.00	1.42
	50	mineral (nuclei)	270	2.88	7.49	2.60
	50	mineral (accum.)	30.5	64.7	169	2.60
	50	mineral (coarse)	0.142	17.7	46.0	2.60

The large diminution of the total aerosol optical thickness, mainly linked to that of the dust-like aerosols, is expected to increase the available solar radiation at the surface. The concurrent decrease in downward longwave radiation at the surface is much smaller ($<$ 10% of the shortwave signal). In the ECMWF model, the aerosol concentration does not impact the cloud microphysics, and thus any change in the dynamical circulation must arise from the direct radiative effect.

3 Results

3.1 Comparison to JET 2000

Two north-south sorties were conducted by the aircraft to measure transects through the AEJ on the 28th and 29th August. The latter date was shown by Tompkins et al. (2004) to be strongly affected by nearby convection. Due to the lack of predictability of such an event only the 28th August flight is used. The dropsondes from the longest continuous transect are used for comparison to a pair of 5 day forecasts conducted with the T511 resolution model (approximately equivalent to a 39 km horizontal resolution at the equator). For each sonde, the nearest model grid point to each drop location is identified, and all gridpoints in a transect of +/-5 degrees in the cross-flight direction are averaged (as in Tompkins et al., 2004). This averaging, the implicit near-grid diffusion of the model and the lower vertical resolution, all lead to smoother model fields relative to the data.

Figure 1 shows the mean bias of the zonal wind for the old and new aerosol climatologies, averaged across the transect from 8^{o}N to 19^{o}N. For this date the new aerosol climatology appears to have a beneficial impact. In agreement with previous analysis the model suffers from positive zonal wind biases implying the jet is too weak. The new aerosol climatology produces a net acceleration of the flow throughout the lower and mid troposphere in the 5 day forecast, with a mean acceleration across the transect of around 1 m s^{-1}. Root mean square errors are also reduced, dropping at the jet level of 700 hPa from approximately 6 to 4 m s^{-1}.

Examination of the model and dropsonde transects (fig. 2) reveals that the structure of the jet in the forecast has also slightly improved. In addition to increasing the core velocities in excess of 2 m s^{-1}, the greatest acceleration ($>$ 3 m s^{-1}) is at the southern end of the transect, where the errors were greatest. However, neither forecast captures the north-south tilt of the zonal wind, where the peak winds occur at a lower altitudes to the south, also seen in the NCEP July climatology of Cook (1999). It is the failure to capture this structure that leads to the peak bias occurring in the strong shear zone at 800 hPa. The structure of the jet is important since it determines the strength and location of the strong wind shear zones crucial for initiation of mesoscale organized convective systems, and thus the under-prediction of low-level shear is critical.

Since the Jet campaign dropsondes only provide information below the 400 hPa level approximately, it is informative to compare the analysis to in situ aircraft data taken above this level to see if the improvements in

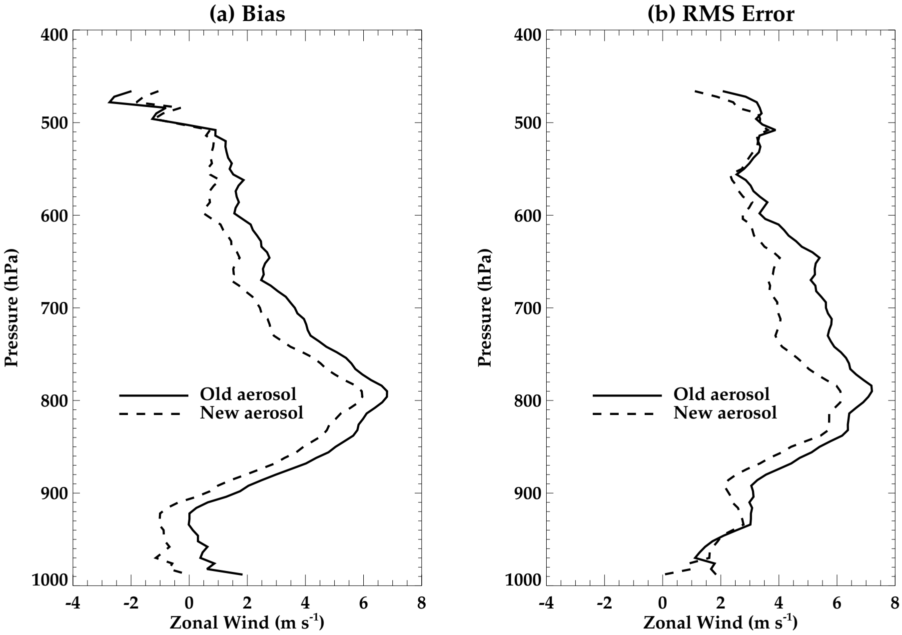


Figure 1: (a) mean bias and (b) RMS error of 5 day Zonal wind forecast using the old and new aerosol climatologies compared to the dropsonde data. Bias is calculated across the transects shown in Figure 2 below.

the AEJ are accompanied by similar changes in the Tropical Easterly Jet (TEJ) structure. The global aircraft dataset (GADS) is used, collected from British Airways 747-400 aircraft since February 1995. These reports were not assimilated in the ECMWF system. The new aerosol climatology slightly reduces the zonal wind bias in the vicinity of the TEJ between 0 and 10N (Fig. 3), achieved by a southerly displacement of the model jet towards its observed location rather than a strengthening of the jet. However, overall the impact of the new aerosol climatology on the TEJ is not significant.

3.2 Seasonal impact

The JET2000 aircraft observations appear to show a positive impact of the new aerosol climatology on the 5 day model forecast of zonal winds in the region of the AEJ. However, it is inadvisable to generalize conclusions drawn from a single forecast. To see if the trends observed for this single date hold more generally, four months of 5 day forecasts from June to September (the peak AEJ season) in 2003 using two versions of the ECMWF model are examined, again at T511 resolution. The two model versions used are referred to as 'cycles' 26r1 and 26r3 (the former was operational at this time). In terms of the physical parameterizations used in the nonlinear forecast model, the principal difference between these cycles was the introduction of the new aerosol climatology in the latter.

The four month average of the 5 day forecast zonal wind is shown in Fig. 4. Using the analyses as a proxy for the truth, the model version using the new aerosol climatology is improved in many attributes. In agreement with the JET2000 results, there is a net acceleration of the zonal flow at the southern flank of the jet axis by a comparable 2.4 m s^{-1}, which is maximized between -5W and 10E. This acceleration extends the region of maximum jet winds much further eastwards, bringing the forecast into much closer agreement with the 26r3 (and 26r1, not shown) analyses. This agreement is not only for the east-west extent of the jet axis, but it is also clear that the 4 month average forecast reproduces the north-south tilt of the jet. Previous versions of the model were similar to the 26r1 four month average depicted here, with a zonal jet structure (Cook, 1999). The improvements are not restricted to the jet; the over strong 700 hPa westerlies at 5N are also reduced. Overall, the five day forecast of zonal wind is significantly improved compared to the analysis, and all the changes

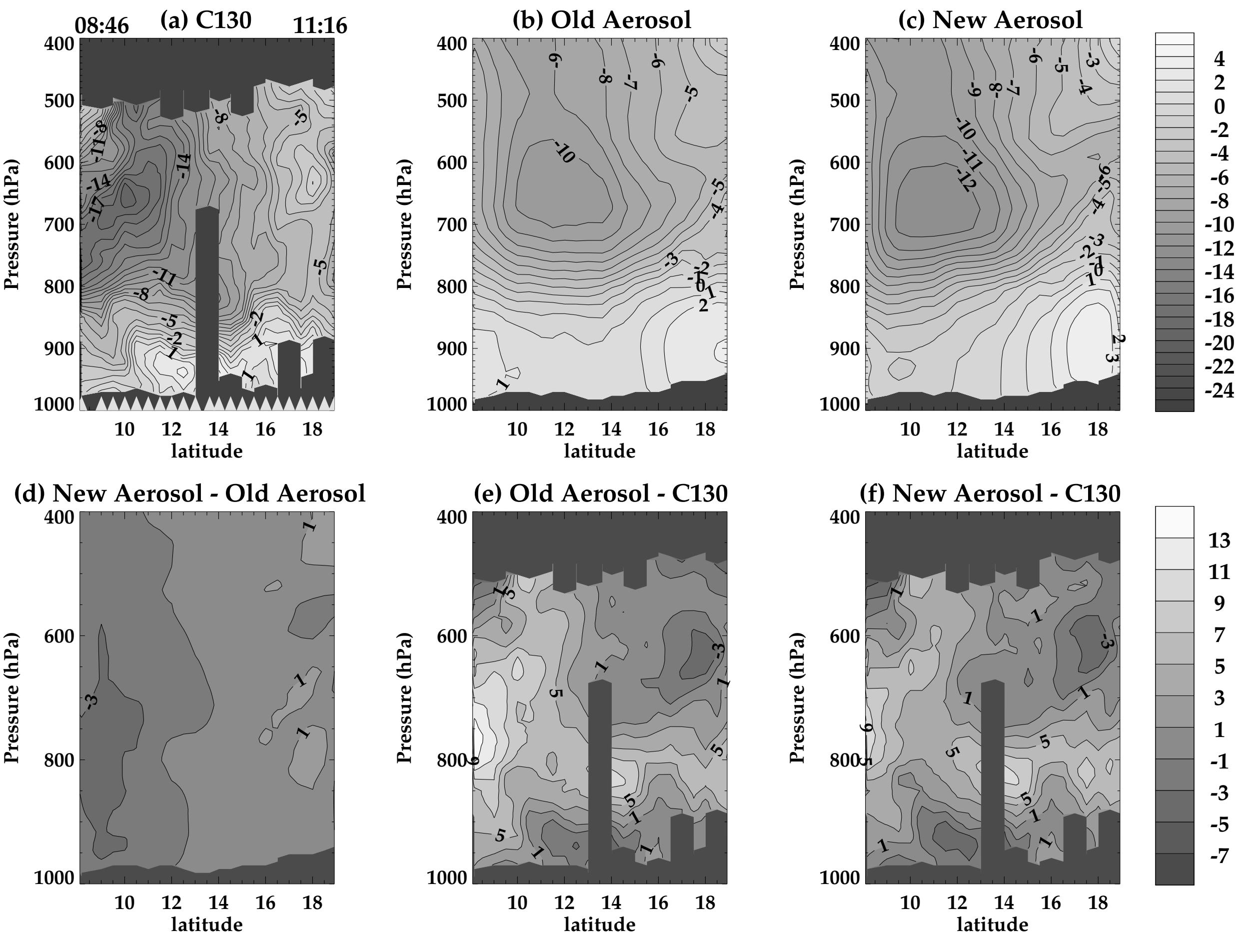


Figure 2: (a) Zonal wind from the dropsondes (locations marked with white triangles at bottom of figure), the forecast with (b) old and (c) new aerosol climatologies. For clarity, the data in panel (a) is vertically smoothed with a 40 hPa box car window. Panels (d-f) zonal wind show differences.

appear to be consistent with the comparison of the single forecast to the high resolution dropsonde data.

If zonal averages through the jet axis are examined (Fig. 5) the structure of the jet is also seen to have improved with the new aerosol climatology. While the jet is still weaker than the analysis by approximately 2 m/s, the new aerosol climatology results in a jet in the 5 day forecasts that resembles the analysis much more closely, in terms of latitudinal and height location of the peak winds, the wind shear zone below the jet, and the strength of the low level westerlies.

As stated above, the new aerosol climatology only impacts the forecast via its direct effect on the radiative forcing of the atmosphere. Figure 6 quantifies this by contrasting the 5-day mean total columnar solar absorption, averaged for the 4 months. The impact is significant, with total absorption differences exceeding 45 W m^{-2}. The atmospheric cooling induced by the introduction of the new aerosol climatology (which has significantly less solar absorption) is concentrated in the planetary boundary layer (PBL) and lower troposphere, thus stabilizing the atmosphere. This is partially offset by increases in surface sensible heat flux, mostly ranging from 15 to 20 W m^{-2} across the region (Fig. 7).

The increase in stability increases atmospheric subsidence and suppresses deep convection. Miller and Tegen (1999) already emphasized that the vertical extent and magnitude of the aerosol forcing can influence the circulation through its feedback with convection. Deep convection can self-aggregate, for example through positive feedbacks with the land surface or coldpool activity (e.g. Taylor and Lebel, 1998; Simpson, 1980). The largest change in subsidence occurs in the regions that undergo deep convection in the control model, indicating that such a feedback is operating. The Intertropical Convergence Zone (ITCZ) thus migrates to the south. One consequence is that the low level south-westerly monsoon flow is less strong and low level moisture is advected less far north. This is beneficial since comparison to low altitude aircraft data by Thorncroft et al. (2003) indicated that the monsoon flow was too strong in the ECMWF model. Reductions of up to 4K mean equivalent potential temperature (θ_e) at the lowest model level occur in association with the southerly displacement of the ITCZ (Fig. 6). This indicates one possible strong feedback since the lower θ_e values will further suppress convection.

The over-strong monsoon flow and associated northward migration of the ITCZ in the mid-range forecast resulted in the weak geostrophic jet winds in earlier model versions (see fig 1 of Tompkins et al., 2004), which depend on the contrast between the dry and moist convective regions to the north and south, respectively (Thorncroft and Blackburn, 1999). The more accurate radiative forcing associated with the improved aerosol climatology prevents the northward ITCZ migration and thus allows the AEJ to be sustained in the forecast.

Further analysis of the tropospheric-deep temperature and moisture profiles at reveal that the most significant differences are restricted to the PBL monsoon flow described above. Figure 8 shows area mean tephigrams for 5 degrees averages across the jet axis from 5 to 25 N. Starting at 5N, the structure follows a moist adiabat throughout the troposphere as expected. At low levels there is minimal difference between the two aerosol climatologies, although the new aerosol climatology is generally drier, especially in the boundary layer, as noted earlier. Moving further north the difference in humidity remains, with the new climatology always drier, until 25N. In the Sahara region, 20-25N, it is notable that the humidity profiles differs significantly only in the lowest 200 hPa of the atmosphere.

Closer examination of the temperature profile also reveal a significant reduction in stability. Above 800 hPa the limited reduction in relative humidity could be associated with an increase in the northerly meridional wind component, which combined with a reduction in stability at 20N below 600 hPa, indicates that the increase in surface sensible heat fluxes shown in Fig. 7, is acting to strengthen turbulence and the associated heat low

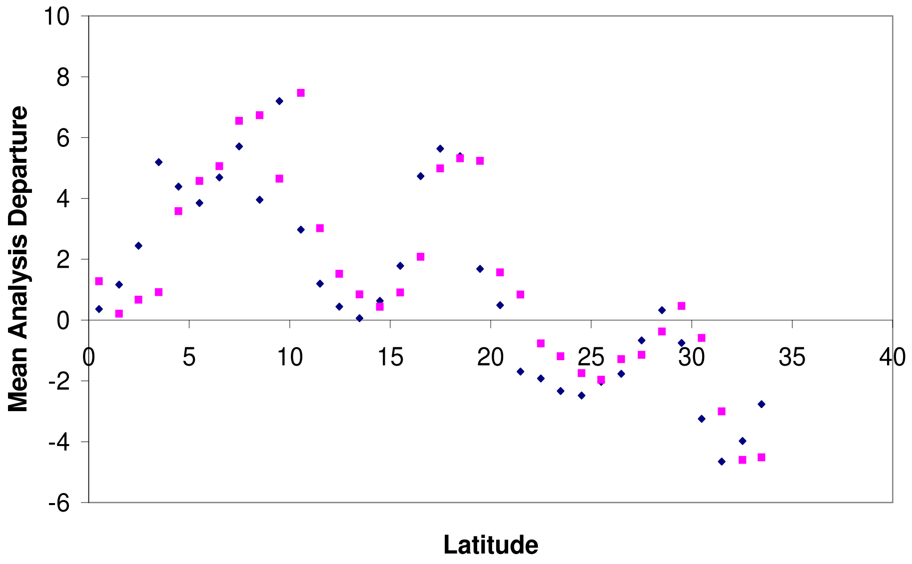


Figure 3: Differences in zonal wind between all GADS aircraft observations between a longitudes 10W/10E and the analysis for the old (diamonds) and new (squares) aerosol climatologies. The GADS data lies between the 150 and 250 hPa pressure levels.

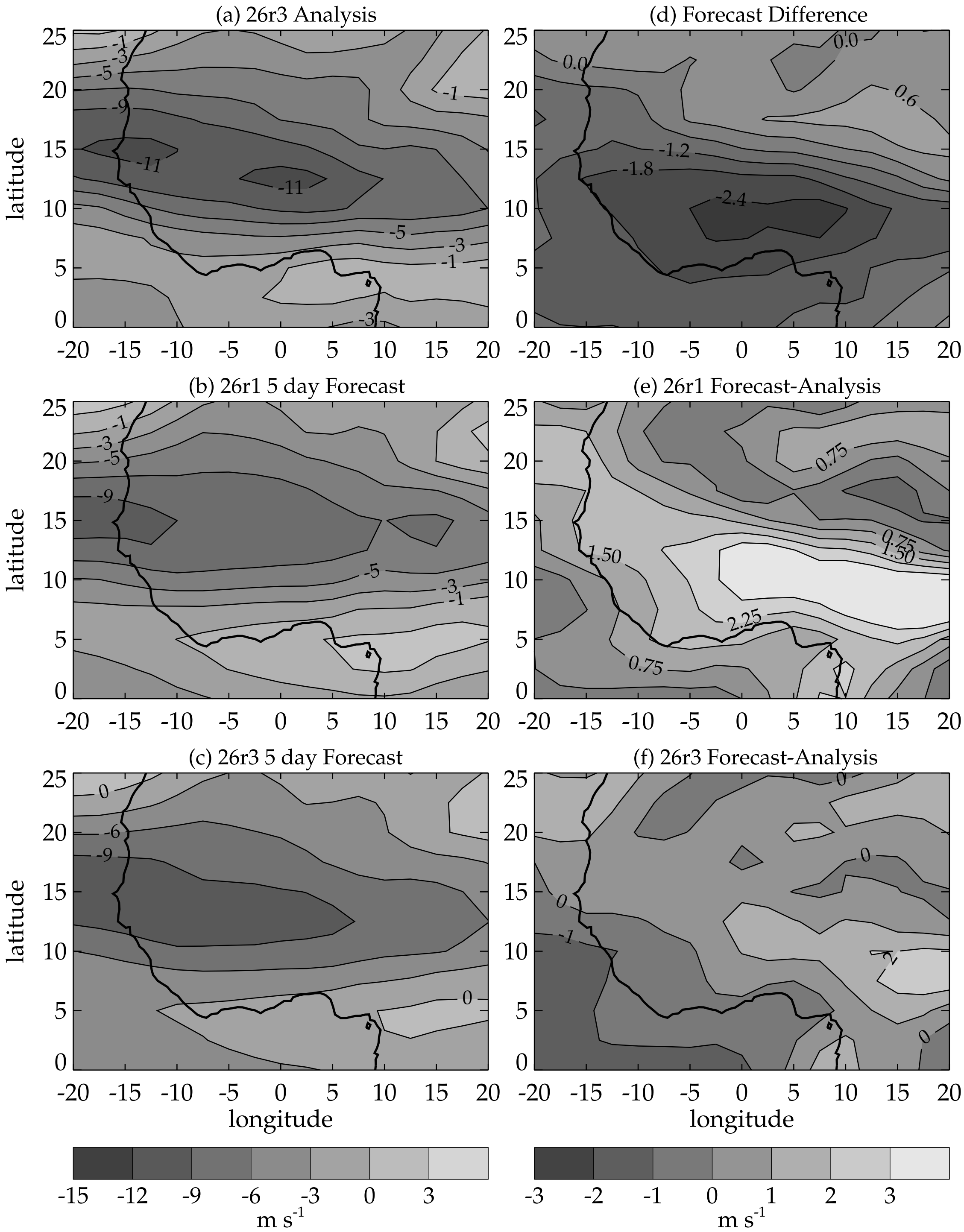
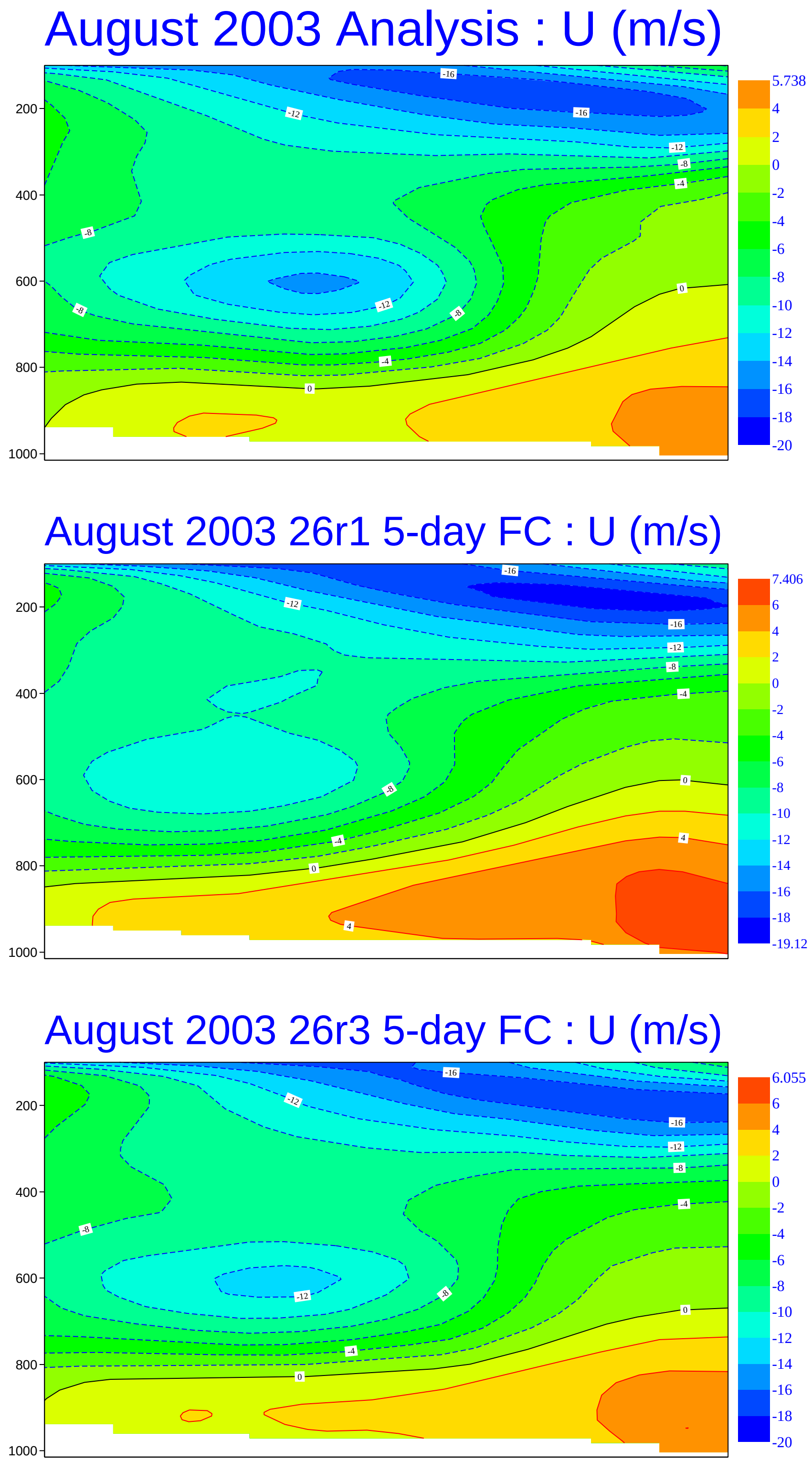


Figure 4: Mean zonal wind from 4 months of (a) Daily 12Z Analyses (b) 5d forecast using old climatology and (c) 5d forecasts using new climatology. Panels (d-f) show the relevant differences.



August 2003 Analysis : U (m/s)

August 2003 26r1 5-day FC : U (m/s)

August 2003 26r3 5-day FC : U (m/s)

Figure 5: Aug 2003 mean zonal cross section through jet, averaged between 0 and 5E, from 5N to 20N. Top: Analysis, Middle: 5-day FC with cycle 26r1 (old aerosol climatology) and bottom: 5-day FC with cycle 26r3 (new aerosol climatology)

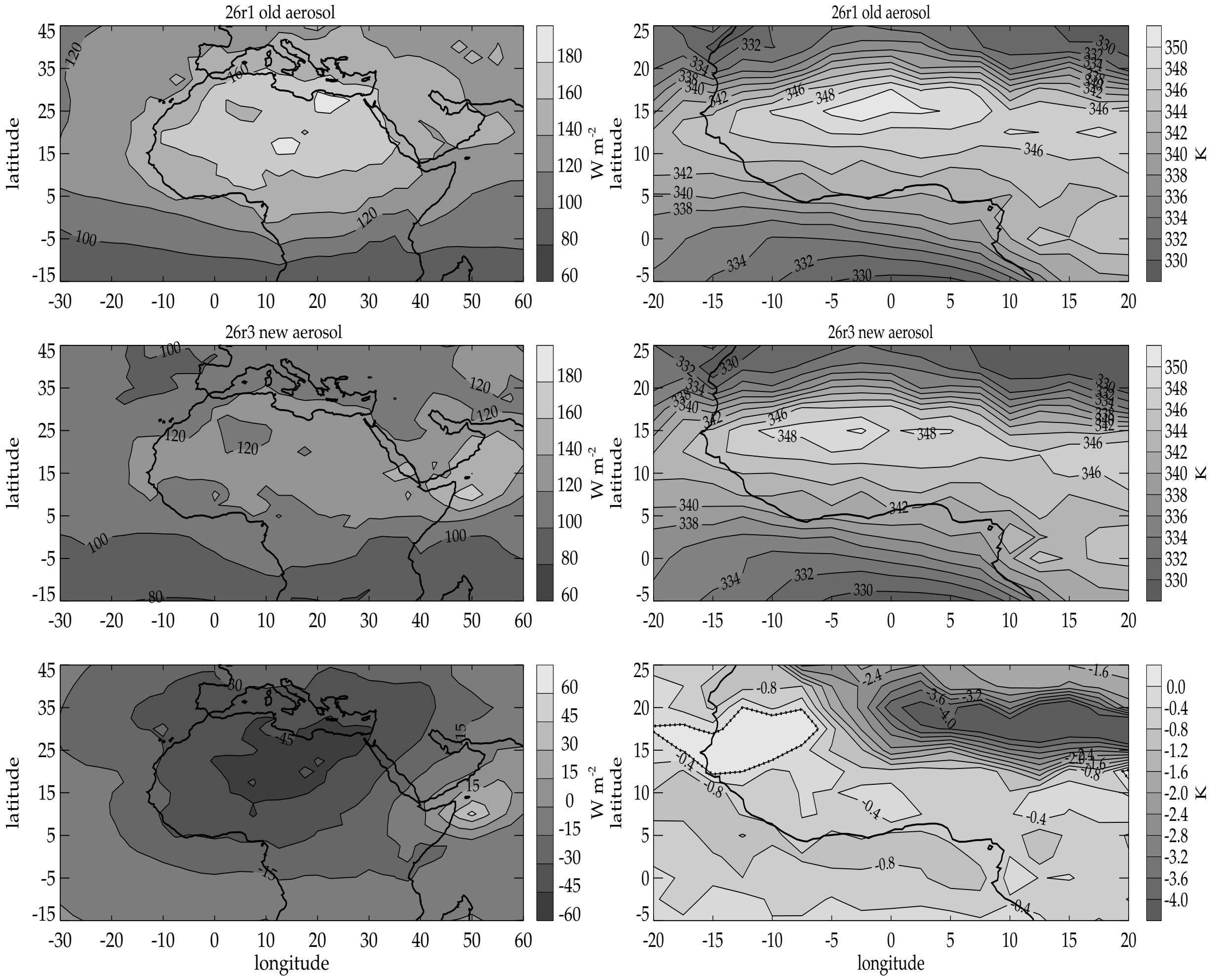


Figure 6: (left panel) total columnar solar absorption and (right panel) θ_e at the lowest model level, for 4 months of 5 day forecasts using the new and old aerosol climatologies. Lower panels indicate the difference between the two climatologies. Note that the right panel shows a smaller geographical region to highlight the major feature θ_e in the difference field.

circulation with the new aerosol climatology. The is consistent with the deepening of the diagnosed boundary layer depth which is shown in the right panel of Fig. 7. The consequential midlevel drying could further regulate the deep convection the south (Sultan and Janicot, 2003).

It is also interesting to hypothesize the effect the change in low-level stability and associated dry convection can have on the mean monsoon dynamics. Parker et al. (2005) have recently analysed both observations and model output to highlight the strong diurnal regulation of the low level monsoon flow. While the geostrophic winds peak in the late afternoon, the actual monsoon winds are at a diurnal minimum at this point, peaking instead in the early morning, almost exactly out of phase. The weak late afternoon winds are due to turbulent mixing in the PBL, transporting momentum, and acting as a brake on the flow. Parker et al. (2005) further suggest that inadequate turbulent mixing in models could lead to over-strong monsoon flows. It is therefore not impossible that the decrease in atmospheric stability and increase in dry convection occurring with the new aerosol climatology could also be playing a role in the improvement of the low level monsoon flow, with its resulting effect on the location of the deep convective zone and the AEJ. This warrants further investigation beyond the scope of this note.

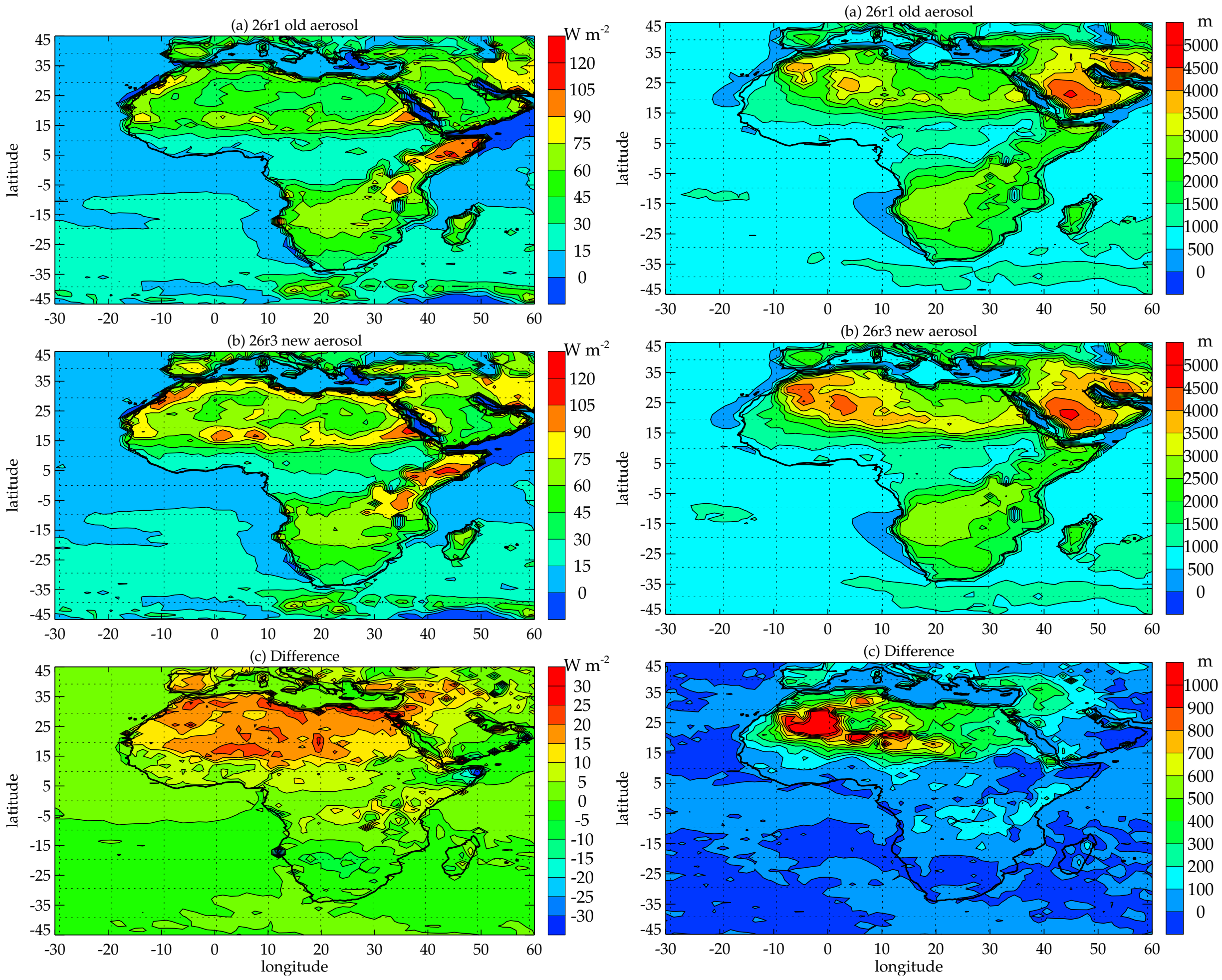


Figure 7: (Left panel) Surface sensible heat flux and (right) boundary layer depth, for 4 months of 5 day forecasts using the new and old aerosol climatologies. Lower panels show new minus old differences.

4 Conclusions

Aerosols can alter the atmospheric circulation through their direct radiative forcing. Here, the impact of an improved aerosol climatology on 5-day forecasts of the African Easterly jet is examined. A pair of 5 day forecasts were compared to high resolution dropsonde data from the JET2000 campaign. The first forecast used the annually fixed aerosol climatology of Tanre et al. (1984). The second forecast instead used an updated climatology described by Tegen et al. (1997) with reduced aerosol loading over Africa. The new aerosol climatology significantly improves some aspects of the jet structure and strength. In addition, 4 months of 5 day forecasts were compared using the contrasting aerosol distributions. This demonstrated a clear improvement with the new climatology, with the jet strengthened, elongated to the east, and less zonal, in agreement with the analyses.

It is proposed that the modification suppresses deep convection by stabilizing the atmosphere, preventing the ITCZ from progressively migrating north during the forecast. A strong reduction in boundary layer equivalent potential energy is noted, and thus a feedback between deep convection and low level moist advection is likely. A further role could be played by the increase in dry convection to the north, enhancing the turbulent friction

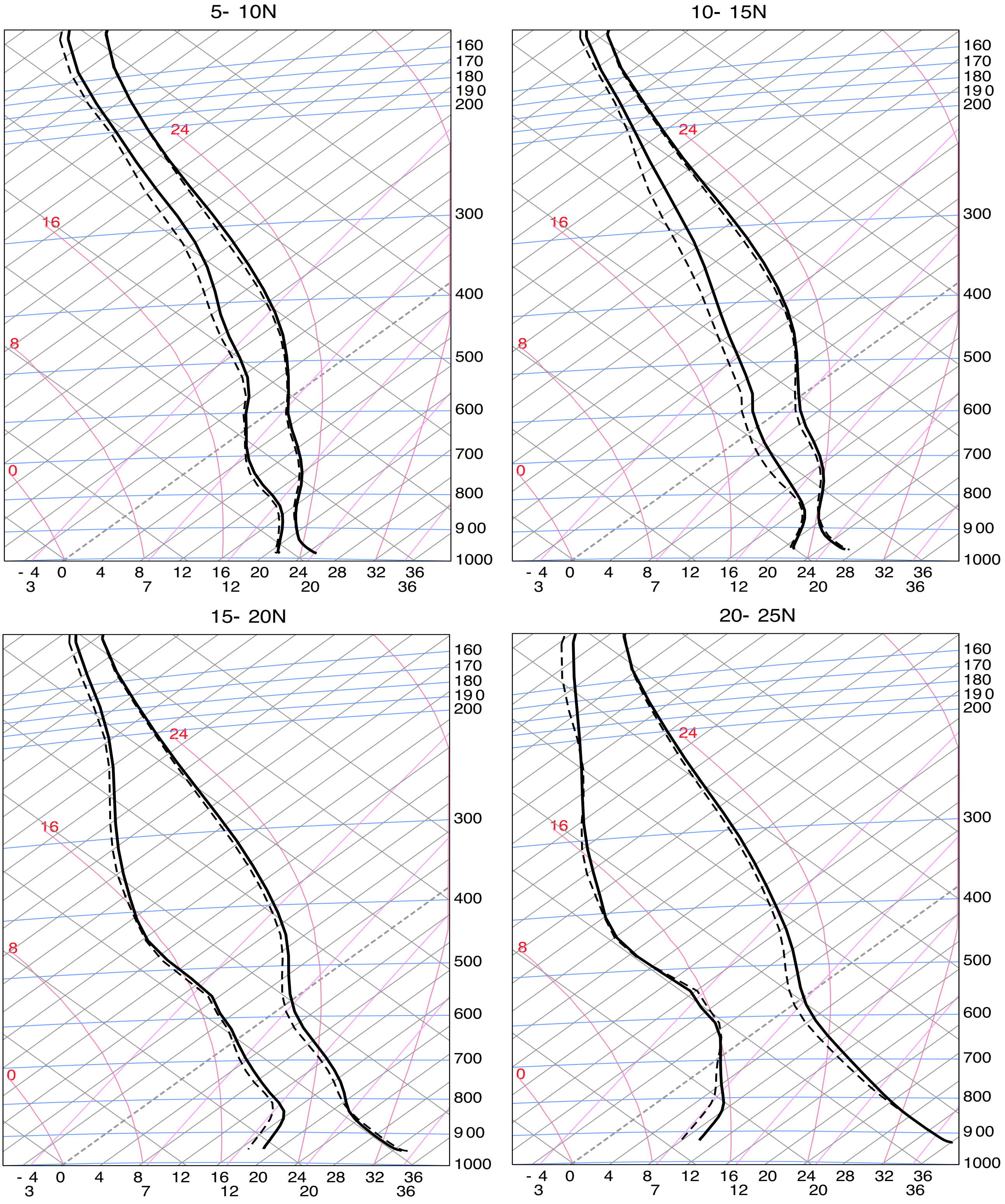


Figure 8: Tephigrams showing August 2003 mean temperature (right hand lines) and humidity (left hand lines) for old aerosol (solid) and new aerosol (dashed lines) climatologies. All tephigrams are for a longitudinal average of 0-10E, and divide the region 5N-25N into 4 regions of 5 degree latitudinal averages.

of the monsoon flow and the strength of the heat-low circulation. The strengthening of the jet also improves the representation of the low level shear zone in zonal wind. While the wind shear is crucial in this region for the initiation of organised convective systems, it is unclear whether such an impact can be appreciated in the present model; wind shear does not affect the deep convective mass fluxes in the parametrization of Tiedtke (1989). That said, the present horizontal resolution of T511 (circa 39km) is on the edge of resolving some of the organised motions in such systems, and with the planned increase in resolution to T799 (circa 25km) in 2005 it is likely that such mesoscale motions will begin to be resolved, and the representation of wind shear will become more critical.

Future work will investigate the wider implications of the new aerosol climatology on the large-scale circulation through teleconnections.

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