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Thermal satellite images and boundary layer structures in desert marginal areas

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Abstract. A series of parallel striations has been observed on thermal satellite images of a desert marginal area in West Africa. The available climatic data suggest their identification as helical roll vortices of the type associated with the formation of cloud streets. This is because the wavelength of the striations conforms to the expected depth of the Atmospheric Boundary Layer (ABL) expected for such roll structures at the time of the image, and varies spatially according to the influence of ground surface roughness on ABL depth. Knowledge of helical roll vortices is usually derived from vertical temperature and wind profiles and radar reflectivity fields over time, whereas the image data presented here permit visualisation of the horizontal component, and thus examination of their interaction with surface phenomena. Association of the observed striations with systems of stabilised dunes in the study area, due to their similarity in length, direction and spacing, would support hypotheses of a causal relationship between helical roller vortices and linear dune systems.

1. Introduction

Thermal LANDSAT images of northern Nigeria (Figure 1) show a pronounced pattern of warmer (light-toned) and cooler (dark-toned) strips oriented in the prevailing wind direction (approximately NE-SW) across the image. The strips are visible on the thermal wavebands of two mid-dry season images, of 17th January 1986 and 19th December 1986. They are not seen on the visible wavebands of either image. Also they are not visible on a late dry season image of 17th April 1985. The strips continue uninterrupted across medium sized topographic features such as vegetation, small streams and settlements but both images show a 5km-wide, darker (cooler) corridor in the lee of Kano City, the width corresponding to the diameter of the city in the prevailing wind direction (Figure 2). Also there are no thermal strips downwind of a large inselberg. The temperature difference between light and dark strips is approximately 1°C, much less than terrain-related temperature differences eg. between areas of dry and wet soil which differ by up to 4°C (Table 1).

The strips are of similar orientation and spacing to sets of stabilised linear dunes noted by Grove [1958] as the 'Ancient Erg of Hausaland', and Nichol's [1991] Kano dunefield (Table 2). These relict dunes are observed on the visible wavebands of the images studied, as parallel ridges with straight crest lines. The thermal strips overlap spatially with the dunes but do not correspond to them.

Ground truth observations were carried out over an 8-week period in the mid-dry season of 1997 to test the possibility of the thermal strips being caused by the differential flow and heating of sand grains above ground level giving hot white lines. This involved the placement of six 0.5 X 0.5 X 0.5m. box traps open to the prevailing wind direction at ground level, with wet collection trays inset to the ground. The placing corresponded to alternating light and dark strips on the images. Surface temperature was recorded using contact thermistors and a heat spy radiometer, and wind data collected. No significant differences in particle

Figure 1. LANDSAT Thematic Mapper thermal image, Path 188, Row 52, of 12.19.86, showing thermal strips in the region surrounding Kano City (darker-toned area in upper left centre). Wind direction at the image time is north-easterly (40°), wind speed is 6.3 m/sec. An evident curve to the right (of 15° per 100 kilometers) corresponds to the Coriolis effect.

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Figure 2. Extract of Figure 1 showing wider thermal strips in the lee of Kano City.

entrainment or deposition near the ground, or in temperature or wind characteristics at the scale of the striations were observed. The amounts of sand collected, and mean wind speeds, were much lower than the 5m/sec. normally associated with active sand movement associated with dune formation. Subsequent to the fieldwork, the second mid-dry season image, of 17th January, 1986 was obtained, showing the thermal striations to have a slightly different position, wavelength and orientation for the two dates.

The thermal strips were thus attributed to temporary, but coherent convectional structures in the Atmospheric Boundary Layer (ABL) in the form of helical roll vortices parallel to the prevailing wind direction (Figure 3). Such rolls, which are paired and counter-rotating have previously been identified from temperature and wind profiles collected from transmission towers, airplane traverses and Doppler radar soundings, mainly in non-tropical regions [*Miura*, 1986]. Cloud streets have also been cited as evidence for roll vortices; the streets forming on updrafts at the top of each roll and their diameter and wavelength related to the depth of the ABL [*Kuettner*, 1959; *Rogers*, 1965] (Figure 3). The thermal image strips are assumed here to represent the ground surface temperature differences of the alternately ascending and descending portions of the roller vortices (Figure 3).

2. Conditions for the formation of rolls

Kuettner [1959] measured roll vortex structures evidenced by cloud streets, noting their best development over flat, homogeneous terrain and ocean surfaces during intense outbreaks of cold air which are heated from below during their progress toward warmer regions. He cites a requirement for the ocean surface to be 4°C warmer than the air above it. Other studies [eg. *LeMone*, 1973, 1976; *Rogers*, 1965] confirm the formation of roll vortices in the ABL when wind speeds are relatively high eg. 3-6m/sec. [*Louhou et al*, 1998b] and stable conditions near the ground prevent the development of a strong vertical temperature profile. Thus a stability index z_i/L [*Deardorf*, 1972] empirically equates stability with dynamic (as opposed to thermal) turbulence in the ABL, and predicts that roll (as opposed to cellular) structures would be present when (Eq. 1).

$$-z_i/L < -10 \qquad (1)$$

where
$-z_i$ = upper limit of (coherent structures in) the ABL
L (the Monin-Obukov Length) = $-k(W^{*3}/U^{*3})$, where
k = von Karman constant (0.4)
W^* = convective velocity scale
U^* = friction velocity at surface
NB. W^* is calculated from the Surface Buoyancy Flux (wb) where wb~1/30 surface heat flux

Roll vortex structures may be up to 500km long [*LeMone*, 1973] and their alignment with the prevailing wind, across the horizontal pressure gradient subjects them to the Coriolis effect.

3. Image interpretation

Thermal LANDSAT TM images, in the 10.5-12.5µm region, record sensible heat emitted from the ground surface. Temperature variations on the image usually correspond to differences in the type of surface materials or to differences in moisture content, the latter due to variations in the ratio of latent to sensible heat flux [*Jensen*, 2000]. Since the Kano high plains in mid-dry season are characterised by dry, bare sandy soil and senescent, scattered trees and shrubs, latent heat flux, except in wet, low-lying areas, is negligible. Village settlements are small (smaller than the wavelength of the strips) and except for Kano City, much of the area imaged lacks significant textural or topographic variation. Such thermally homogeneous ground conditions are optimal for the formation of regular boundary layer structures as well as for remote detection of related thermal ground patterns. The thermal structures are not visible on the eastern portion of the image corresponding to Grove's [1958] relict dunefield having a relief of approximately 30 meters.

Table 1. Brightness values (°C) and Kano climatic data for image features (LANDSAT TM Band 6)

Image date	17 April '85	17 January '86	19 December '86
Dark strips		22.5-23	25-26
Light strips		23-24	26-26.5
Kano City	35	19-21	21.5-25
Dark strips lee of Kano city		21.5-22	25.6-26
Water surfaces	24	17-19	19.5-23
Wet soil (eg. irrigated) areas	33	20-21	22.5-23.5
Bare dry soil		38-40	
Dust storm eddy	34-36		
Wind speed at image time (m/sec)	3.1	6.3	6.3
Air temperature at image time (°C)	30	17	18
Wind direction at image time (°)	40 (NE)	60 (ENE)	40 (NE)
Approximate height of ABL (m) *	1500	500-700	500-700

* data from Niamey climatic station and regional reanalysis data from NCEP/NCAR both give approximate values of ABL depth for the image time on clear days in April, January and December respectively.

Table 2. Details of image strips and stabilised dunes

	spacing (m)	orientation	age (k.yr.BP)*
Hausa erg (Grove, 1958)	600-1000	NE-SW	12-15, 30-35 at base
Kano dunefield (Nichol, 1991)	1900	ENE-WSW	30-35
Thermal image strips 19 Dec. 1986	1400	NE-SW	
Thermal image strips 17 Jan. 1986	1800	ENE-WSW	

* Stokes and Horrocks (1998)

Since dry sandy soil has low diffusivity, the majority of the daytime radiative surplus is carried into the atmosphere by turbulence [*Oke*, p.81]. In the case of the 19th December image (Figure 1) the seasonally prevailing winds from a north-easterly direction (wind sped 6.3m/sec.) and free radiation in a clear atmosphere during the previous night would delay surface heating (mean image-derived surface temperature values 25°C; air temperature 18°C) at the image time. The combination of cool and moderately strong winds subject to surface friction, and buoyancy due to a warmer ground surface would be likely to produce helical rolls aligned in the wind direction (a low -*z_i/L* ratio) (1).

Climatic data (Table 1) indicate that an ABL depth of approximately 500-700m is common at the image time for both December and January images. Thus the wavelength of the strips (1.4 and 1.8 kilometers on each mid-dry season image respectively) corresponds to the expected ratio of roll wavelength to ABL depth, of approximately 2:1 or 3:1 [*Kuettner*, 1959; *Hanna*, 1968; *LeMone*, 1973, 1976; *Louhou* et al, 1998b] (Figure 3).

3.1 Lee effect

A city or large settlement constitutes a heat sink up to mid-morning, due to a lag in heat accumulation caused by the low thermal conductivity of building materials. Thus image-derived surface temperatures for Kano City are approximately 4° cooler than surrounding areas. Additionally, the dark image strips in the lee of Kano City are wider (approximately 2.2 km across) and darker (approximately 1° cooler) than those in unobstructed areas (Figure 2). The latter is thought to be due to reduced turbulence downwind of the city during the previous night creating a cooler ground surface than in unobstructed areas (as noted by Mattson [1962] using infrared thermography in Sweden). The wider image strips are also explainable by boundary layer phenomena: thus ABL depth would tend to increase over rougher surfaces such as a city [Oke, 1987, p.54] resulting in wider vortex spacing in the lee of rougher objects.

3.2 Late dry season (inter-monsoon) image

The likely presence of roll structures, as well as roll spacing, is inversely related to atmospheric stability [*Miura*, 1986, p.36; *Louhou*, 1998b] (Equations 1 and 2). Thus, on the April 1985 image no thermal strips are visible. At this time of year low wind speeds and intense ground heating often create strong instability phenomena such as miniature, dust–carrying whirlwinds. Three such features can be seen on the April thermal image, as cooler, curved features of conical shape approximately 100m at maximum (figure 4). Climatic data at the image time on 17th April 1985 show intense ground heating (air temperature 32°C and image-derived ground temperature 38-40°C) and low wind speeds (3.1m/sec), and a deep ABL. These conditions would be associated with instability in the ABL, increasing the -zi/L ratio (Eq. 1) well beyond the conditions for roll structures to form.

4. Thermal strips and stabilised dunes

The theory that large (kilometer scale) helical roll vortices are responsible for the formation of linear dunes in deserts [*Bagnold*, 1953; *Hanna*, 1962; *Warren*, 1979] remains controversial, since these structures have not previously been observed in tropical arid, or dune landscapes

The thermal strips are at a similar direction and spacing to systems of fossil dunes which are observable on the visible wavebands of the images studied. The most remarkable point of similarity is the regularity of spacing (1-2 kilometers apart) and length (over 100 kilometers). These dimensions also correspond to those most commonly reported for other stabilised and active linear dune systems on all continents.

The thermal strips have a narrow light-toned (warm) zone and a wider (cool) zone in a ratio of approximately 1/3-4. A similar ratio is generally observed between dune and interdune areas in linear dune systems [*Livingstone*, 1988].

The thermal strips are also markedly absent in the lee of a large inselberg, but show no response to small landscape features such as trees and compounds. This, as well as a marked Coriolis backing effect (Figure 1), resembles the known spatial morphology of linear dune systems.

An alternative theory, the Flow Diversion Model [*Tsoar*, 1985; *Bristow* et al., 2000] attributes linear dunes to the directional change of air flow across the crest line in a bi-directional wind regime. The theory is based on investigations of processes operating on only a single dune. It

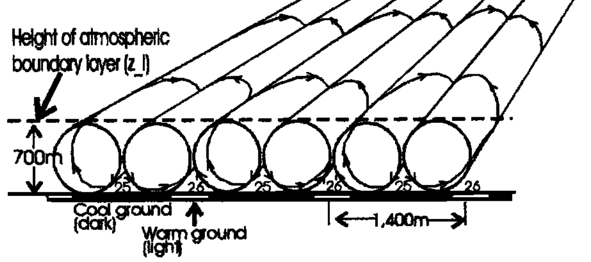

Figure 3. Geometric aspects of helical roll vortices and their hypothetical relationship to the image strips and climatic data for image date 19th December 1986. Numbers represent temperature (°C).

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[1] The stability ratio could not be calculated for the area at the time of the images due to the lack of meteorological data for obtaining the surface heat flux.

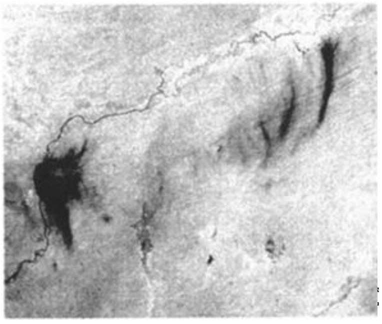

Figure 4. LANDSAT TM thermal image, Path 188, Row 52, of 04.17.85, with linear contrast enhancement, showing three cooler, conical shaped features, which are not visible on other wavebands. The ENE-WNW lineations represent the 'Ancient Erg of Hausaland' (Grove, 1958).

ignores interdune areas, as well as the systematic interrelationship between dunes over a whole dunefield. The theory also fails to explain adequately how the dunes were initiated. The Roll Vortex model on the other hand invokes large scale air movements over an extensive, flat terrain, the alternating pattern of dune and interdune resulting from different phases of the same vortex movement.

5. Discussion

The identification of the thermal image strips as helical roll vortices is supported by the available in situ climatic data on conditions of the ABL at the image time. Other attempts to visualise vortex structures by constructing vertical sections of the ABL from tower- and aircraft-based atmospheric platforms over time, both from standard instruments [*LeMone*, 1973] and from radar reflectivity fields [*Louhou et al*, 1998a] lack the direct horizontal dimension and synoptic scale of the present image observations and depend on the direction and location of the flight trajectory. The synoptic visualisation afforded by the LANDSAT thermal images (2) of the length, direction, spacing and regularity of the vortex structures permits their comparison with the remnants of a linear dunefield; the marked similarity suggesting a causal relationship. If this relationship is accepted, the evidence also supports the inclinations of scientists to infer palaeowinds from fossil dune orientations.

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[2] Vortex structures identified from observations of cloud streets on weather satellite images such as the NOAA AVHRR (spatial resolution 1.1 kilometers) (eg. Miura, 1986) are much larger than those of the present study, which would not have been resolved on AVHRR images. For these, the 120m spatial resolution of the LANDSAT thermal data is ideal.

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