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THERMAL REMOTE SENSING OF ATMOSPHERIC BOUNDARY LAYER STRUCTURES OVER HOMOGENEOUS SURFACES

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ABSTRACT: A series of parallel striations observed on thermal satellite images over flat terrain in arid West Africa is identified as helical roll vortices in the Atmospheric Boundary Layer (ABL). This is because their length and spacing conforms to the dimensions expected for such roll structures according to climatic conditions at the time of the image. 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. Distinct and coherent localised patterns are also observed on a LANDSAT TM thermal image over open water in the Straits of Singapore, and while their origin cannot be identified, such features call for image-based atmospheric correction algorithms since radiosonde data do not account for such localised effects.

1. INTRODUCTION

Three dry season LANDSAT Thematic Mapper images of the High Plains of Hausaland in West Africa (Figure 1) show coherent thermal features not evident on the corresponding visible wavebands Mid-dry season thermal images of (of 17th January 1985 and 19th December 1986) (Figure 2) exhibit parallel striations approximately 1-2 kilometres apart, extending across the image in the predominant wind direction, except in areas corresponding to irregular and dissected terrain, where the strips are absent. Mid-dry-season conditions are warm, with persistent cool, outblowing winds from an ENE or NE direction. The strips are interpreted as Helical Roller Vortices in the atmospheric boundary layer. The third thermal image, of late dry season (17th April 1985) exhibits three cool, curved features of conical shape, of approximately 100m diameter, interpreted as dust–carrying whirlwinds. Local climatic data at the image time indicate a period of intense ground heating and weak winds giving rise to atmospheric instability.

Table 1 Climatic conditions at times of imaging*

Image date	17 April '85	17 January '85	19 December '86
Wind speed at image time (m/sec)	3.1	6.3	6.3
Wind direction at image time (°)	40	60	40
Air temperature at image time (°C)	30	17	18
Soil brightness temperature (°C)**	38-40	22-23	25-26

* Magariya climatic station: 130 kilometres north of the study area.
** Mean values, on areas of bare dry soil

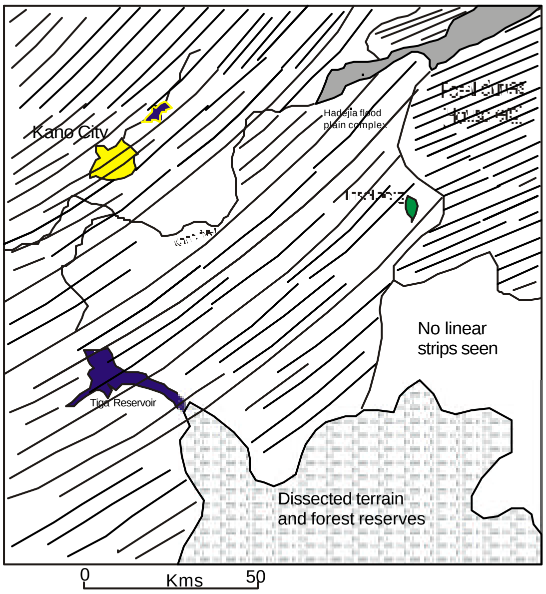

Figure 1. Study area and trajectory of strips

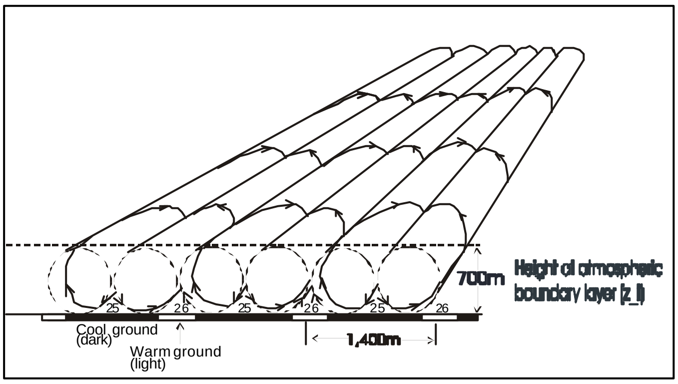

Figure 3. Helical Roller Vortices

2. IMAGE INTERPRETATION

The flat land surface of the High Plains of Hausaland in West Africa in the dry season comprises dry silty soil of barren farmlands, interspersed with senescent trees and shrubs, and small villages of traditional construction. All these are smaller than the wavelength of the thermal strips seen on both mid-dry season images. The strips are uninterrupted by such small terrain features but are wider and more pronounced in the lee of a large city (Kano) and are markedly absent in the lee of a large granite massif. The temperature difference between light and dark strips is approximately 1°C; much less that terrain-related temperature differences eg. between areas of upland and flood plain soils which differ by up to 4°C).

In areas of dissected and forested terrain where the strips are not evident, the thermal waveband is significantly correlated with all other wavebands the lowest and highest correlations, with bands 4 and 5, have correlation coefficients of r=0.41, and r=0.63, respectively. However, in areas of the image covered by the thermal strips, there is no significant correlation between the thermal waveband and any of the visible wavebands (Table 2). This further suggests that the strips are unrelated to ground features.

Table 2. Correlation between thermal waveband and other bands (TM4 = lowest and TM5 = highest)

	Band 4 (NIR)	Band 5 (NIR)
Dissected terrain (no thermal strips)	0.41	0.63
Area of thermal strips	0.04	0.12

Streaks of similar uniformity and spacing noted by Otterman (1976) on visible wavebands of LANDSAT MSS images of arid regions of Iran-Pakistan and the USA, were attributed to dust mobilisation at the surface. Otterman equates their linear morphology with atmospheric instability of the type noted by Kuettner (1959) which give rise to cloud streets in more humid regions, and refers to them as **dry streets.**

Otterman's observations of dust streaks corresponded to wind speeds of approximately 20m/sec. However, mean wind speeds in Kano during the dry season, of 3-6m/sec are too low for large scale dust mobilisation. The possibility of the

Figure 2. LANDSAT TM thermal band of 19th December 1986, showing region around Kano city, northen Nigeria, with banded straitions in a NE-SW direction and curving according to the Coriolis effect.

thermal streaks being caused by differential flow of sand grains above ground giving hot white lines was investigated by dust collection at ground level throughout the mid-dry season of 1997. The results indicated negligible local mobilisation of dust at the surface in the study area. Furthermore, Otterman observed the features on visible wavebands only, whereas the present striations are only visible in the thermal waveband. Additionally there is little possibility of the features being due to other atmospheric phenomena such as thin banded stratus, since climatic data for semi-arid Africa indicate that air temperature rarely approaches dew point temperature during mid-dry season at levels below 5000m. The observed features are thought to be present in the atmospheric boundary layer (below 1500metres).

At the image time, three months into the dry season, latent heat loss at the surface is negligible except for within flood plains. Since dry sandy soil has low diffusivity, the majority of the the daytime radiative surplus is carried into the atmosphere by turbulence. 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.

In the case of the 19th December image, prevailing winds were from a north-easterly direction, and free radiation in a clear atmosphere during the previous night would delay surface heating (mean image values 25°C; air temperature 18ºC) 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 Roller Vortices aligned in the wind direction. Such features have been cited as responsible for the formation of linear dunefields in arid regions (Bagnold, 1953; Hanna, 1969). The evident similarity in direction and spacing of the currently observed structures to existing belts of fossil dunes in the study area (Grove, 1958; Nichol, 1992) supports this theory.

3. CHARACTERISTICS OF HELICAL ROLL VORTICES

Helical roll vortices are temporary, but coherent convectional structures in the Atmospheric Boundary Layer (ABL) 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) (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). The depth of the Atmospheric Boundary Layer (ABL) in the study area at the image time is generally 500-700metres, which satisfies the ratio of ABL depth to vortex wavelength, often noted, of 1:2-3.

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 4ºC warmer than the air above it. Other studies (eg. LeMone, 1976; Louhou et al, 1998) confirm the formation of roll vortices in the ABL when wind speeds are relatively high eg. 3-6m/sec. () and stable conditions near the ground prevent the development of a strong vertical temperature profile. Thus a stability index (z_i/L) 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

and L (the Monin-Obukov Length) $= -k(W^{*3}/U^{*3})$ (2)

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 and their alignment with the prevailing wind, across the horizontal pressure gradient subjects them to the Coriolis effect.

4. SIGNIFICANCE OF THE OBSERVATIONS

The observations have the following significance:-
(i) The interpretation of the striations as helical roller vortices of the type responsible for the formation of linear dunefields, suggests that Quaternary winds and regional pressure belts when the fossil dunes of the study area were formed (Grove, 1958; Nichol, 1992) were of a similar direction to those of today.
(ii) Dune formation takes place in the cool dry season of outblowing anticyclonic winds
(iii) Wind direction and strength can be interpreted from striations on thermal satellite images
(iv) Height of the Atmospheric Boundary Layer at the image time can be estimated.

5. SINGAPORE IMAGE

A LANDSAT TM thermal image of 24.5.89, of the Straits of Singapore exhibits distinct parallel striations between Singapore and the Indonesian Riau islands (Figure 4). The striations are oriented in a NNW-ESE direction, approximately 20° to the left of the contemporary surface wind, and the temperature difference between light and dark strips is approximately 2°C (table 3).

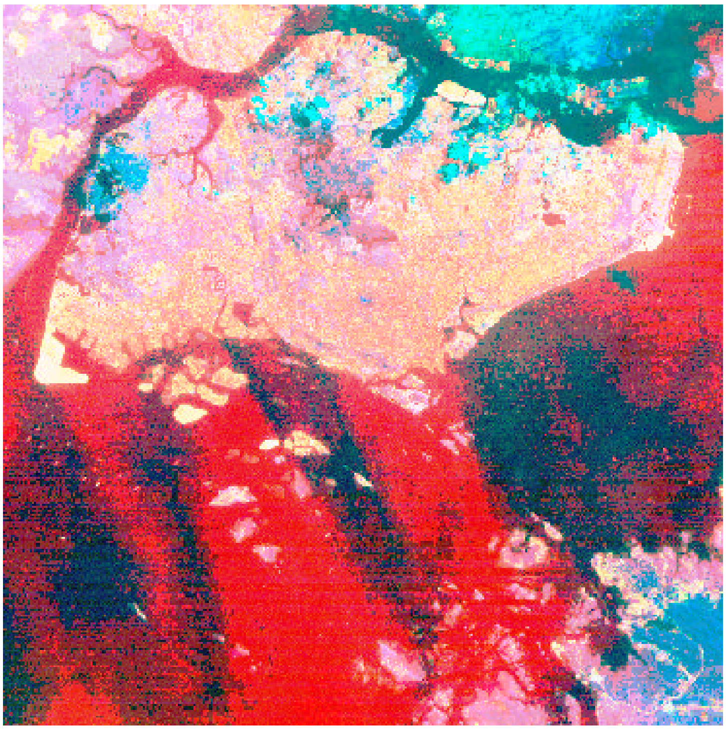

Figure 4. LANDSAT TM false colour composite of Singapore and Singapore Straits, comprising: Band 4 (blue), Weighted average of Band 3 and Band 5 (green), and Band 6 (red). Linear contrast enhancement applied.

Table 3. Image DN values from LANDSAT 5 Thematic Mapper, of 24.05.89

	Warm strips	Cool strips
Band 1	82	79
Band 2	33	31
Band 3	28	25
Band 4	10	9
Band 5	10	8
Band 6	123	126
Band 7	4	4

The thermal strips have sharp outlines, and bear no relationship to bathymetry, since depth contours are oriented approximately east-west, parallel to Singapore's south coast, and at right angles to the strips. They are also aligned obliquely to the dominant tides and currents, and thus appear unrelated to them. The image values of sediment plumes draining from coastal estuaries are unchanged across the boundary of the strips and thus also appear unrelated to them. The strips are not evident on the visible wavebands using typical display parameters and the image appears to be of a high quality, cloud- and haze-free. However, stretching of the image histogram representing sea, makes the striations slightly visible on all wavebands (Table 3).

Dew and morning fog are frequent occurrences in the tropics and the diurnal vapour pressure curve at Singapore is highest at 9am (approximately 30Mb) (Nieuwolt, 1977, p.93). Humidity close to the earth is near saturation and only a slight cooling, as when air moves out over the sea, causes condensation. Various explanations have been given for banded patterns over the ocean surface, mostly caused directly or indirectly by wind effects. However, none adequately explain the present observations.

A possible explanation is the variability of water vapour absorption in time and space (Lillesand, 2000, p.416) which may be configured by wind effects across a coastline combined with topographic features on land. Such an interpretation would reinforce the need for image-derived methods of atmospheric correction of thermal images, since radiosonde data applied across a whole image would clearly not account for such localised effects.

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