The thermodynamic structure of the atmosphere over South Africa: Implications for water vapour transport

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Abstract

Frequent, persistent and the spatially-continuous occurrence of absolutely stable layers of air are confined to the features of the Southern African atmospheric environment. The elevated layers occur preferentially at ~850 hPa (over the coastal regions only), ~700 hPa, ~500 hPa and ~300 hPa throughout the troposphere. They are highly effective in acting as upper air boundaries that control the free diffusion of aerosols and trace gases (including water vapour) in the vertical and may have repercussions on scales ranging from local to synoptic. The seasonal stability characteristics and temporal and spatial continuity of the elevated absolutely stable layers are examined over the eastern half of South Africa and related to a previous case study of moisture transport patterns on rain and no-rain days.

Introduction

The vertical component of dispersion in the atmosphere is a function of the buoyancy present, being greatest under unstable conditions and least under stable conditions during which turbulence is suppressed (Diab, 1975; Mohan and Siddiqui, 1998). Earlier research on stability structure and inversions focused mostly on the boundary layer and the first elevated temperature inversion (Taljaard, 1955; Tyson, 1963; Hart, 1971; Diab, 1975, 1978; Tyson et al., 1976; Venter and Tyson, 1978; Snyman et al., 1990; Harrison, 1993). Temperature inversions will not be the focus of this paper. Instead, absolute stability, a less stringent measure of the degree of atmospheric stability than an inversion, yet one which is competent to determine the vertical mixing in the atmosphere, will be considered. An absolutely stable layer is defined as having a lapse rate which is less than the saturated adiabatic lapse rate. Under such conditions, free upward motion is inhibited. The formation of absolutely stable layers may be attributable to either radiative cooling from the earth's surface, horizontal advection of warmer air over a cooler surface and *vice versa*, or adiabatic warming from upper air subsidence under anticyclonic conditions (Taljaard, 1955; Oke, 1987; Preston-Whyte and Tyson, 1989; Ahrens, 1993). The stable layers often represent the level at which elevated decoupling occurs between circulations of the lower middle and middle upper troposphere.

The degree of persistent elevated absolutely stable layers was noticed first throughout the troposphere over Pretoria during the 1992 South African Fire-Atmosphere Research Initiative (SAFARI-92) period of late winter and early spring (Garstang et al., 1996). Tyson et al. (1996a), subsequently pointed out that multiple absolutely stable layers frequently occur in the atmosphere over the whole of Southern Africa. In their examination of the structures of the elevated absolutely stable layers during various synoptic circulation types over the subcontinent, Cosijn and Tyson (1996) observed that the layers were both temporally persistent and spatially continuous over the subcontinent on non-rain days, and that they influence air transport significantly.

The consequences of the layering of the atmosphere for the accumulation of anthropogenic and biogenic products throughout the troposphere are considerable. Whereas both surface and elevated absolutely stable layers may lead to local high concentrations of air pollution in the troposphere, it is the elevated layers which play an important role in controlling medium- to long-range transport and recirculation of aerosols and trace gases (Preston-Whyte and Tyson, 1989; Garstang et al., 1996; Tyson et al., 1996b). The multiple, persistent absolutely stable layers trap aerosols and trace gases (including water vapour) below their bases by inhibiting turbulent mixing in the vertical. Such situations have obvious implications for local and regional transport of water vapour and other constituents of the atmosphere. Should these penetrate through one layer, accumulation will occur below the next and so on. Once accumulation beneath a discontinuity has occurred, horizontal transport occurs preferentially at that height and tends to be capped by the layer above (Tyson et al., 1997). The effects of accumulation are evident to the naked eye at the 700 hPa and 500 hPa levels over the interior of South Africa, particularly in winter. On days when the stable layers are observed, dense dust and haze belts are likewise present at these two levels as a major discontinuity between the hazy, polluted lower tropospheric air and clear air aloft (Tyson et al., 1996a).

Fine-weather conditions over South Africa occur around 80% of days in the year (Schulze, 1965; Harrison, 1984) and encourages the development of absolutely stable layers in the atmosphere. The predominantly stable troposphere promotes the trapping of material between the layers and only abates with deep convection and the occurrence of unstable barotropic easterly disturbances or with the passage of intense baroclinic westerly disturbances.

The persistence and strength of the discontinuities have implications for rainfall, with the lower layers in particular acting as vertical boundaries constraining turbulent mixing and hindering the development of convective precipitation (Ching et al., 1984; Lyons and Calby, 1986). The ~700 hPa level appears to most frequently control the level of maximum flux divergence of water vapour over the summer rainfall region of the South African plateau (D'Abreton and Lindesay, 1993; D'Abreton and Tyson, 1995; 1996). The role of the ~700 hPa stable layer in governing

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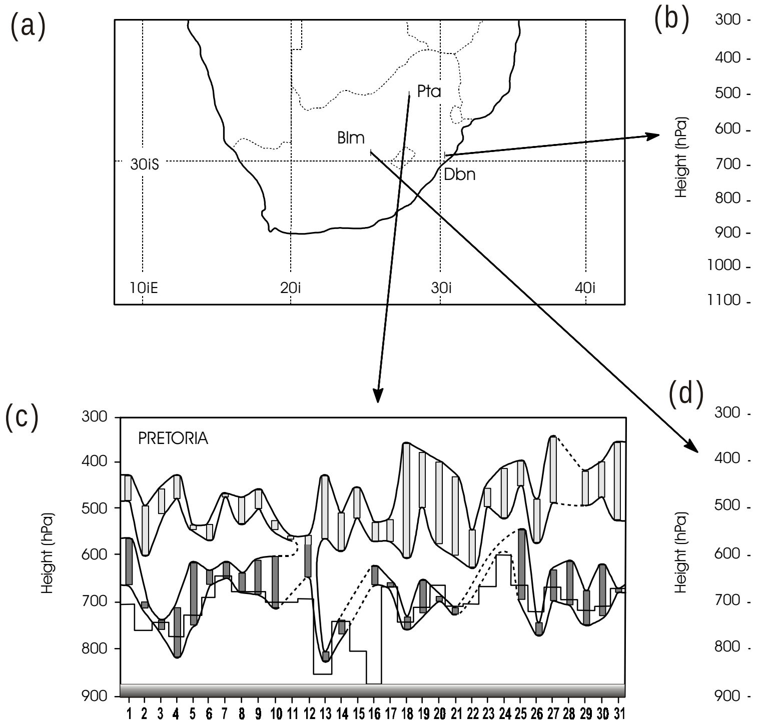


Figure 1
(a) Location of the radiosonde stations used and the occurrence of elevated absolutely stable layers during March 1996 over (b) Durban, (c) Pretoria and (d) Bloemfontein

horizontal moisture transport over the subcontinent needs further investigation, as too does the verification of past climatologies of the stable layer structuring of the atmosphere over Southern Africa.

In this paper, the hypothesis that elevated absolutely stable layers occur at preferential altitudes in the atmosphere above South Africa will be examined. In addition, seasonal temporal persistence and spatial continuity over the eastern half of South Africa will be considered in terms of the daily variability of the layers on rain and non-rain days. Finally, previously-analysed water vapour transport over Southern Africa will be examined in terms of the thermodynamic structure of the troposphere on rain and no-rain days.

Data and methodology

Radiosonde-derived daily lapse rates for the plateau stations of Bethlehem, Bloemfontein and Pretoria, and the coastal stations of Port Elizabeth and Durban, have been used to determine the absolute stability of the troposphere over South Africa (Fig. 1a).

Data for midday radiosonde ascents were obtained from the South African Weather Bureau for summer (March 1996 and December 1997) and winter (June 1996 and May-June 1998) conditions. Absolutely stable layers are defined where the observed lapse rate exceeds the wet (saturated) adiabatic lapse rate. The daily midday mixing layer is defined as the layer adjacent to the ground over which pollutants or any constituents emitted within the layer or entrained into it become mixed by convection or mechanical turbulence within a time scale of about one hour or less (Beyrich, 1993). The mixing depth is estimated by the height at which the dry adiabatic extension of the surface temperature intersects the environmental lapse rate. The mean monthly conditions and standard deviations for individual elevated absolutely stable layers are calculated for each station. In total 498 radiosonde ascents were analysed.

Only non-surface absolutely stable layers are considered for analysis. Drawing on SAFARI-92 and subsequent work (Garstang et al., 1996; Cosijn and Tyson, 1996), the stable layers evaluated have been assigned to specific height categories. If uncertainty arose with respect to the allocation of a specific layer to a category, the midday ascents of the previous and subsequent days have been examined. If the layer had separated away from or joined clearly defined layers, it was included in that layer. If the environmental lapse rate approximated the saturated adiabatic lapse rate, it was considered neutral and ignored.

Results and discussion

As hypothesised, the daily occurrence of the elevated absolutely stable layers during summer and winter fell into previously-observed layer distributions: the lowest occurs exclusively over the coastal regions below the mean height of the escarpment, at about the 850 hPa level (altitude ~1500 m); the second is associated with the top of the plateau mixing layer, at around 700 hPa (altitude ~3000 m). The primary layer, associated with the level of the maximum subsidence, occurs in the region of 500 hPa (~5000 m). The base of the coastal 850 hPa layer develops at approximately the maximum height of the mixing layer. All the layers exhibit a wave-like continuity with time.

Frequency of occurrence of the elevated absolutely stable layers

Over the plateau, the mean frequency of occurrence of the ~500 hPa stable layer on all days is 93% in summer and 78% in winter (Table 1). Cosijn (1996) and Cosijn and Tyson (1996) in their seven year study of conditions on no-rain days, found the ~500 hPa layer to be more persistent in winter. The ~700 hPa layer has a 69% and

TABLE 1
Percentage Frequency of Occurrence, Means and Standard Deviations of Elevated Absolutely Stable Layers Over the Plateau and Coastal Stations

	850 hPa		700 hPa		500 hPa	
Month	**Summer**	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**
Station						
Plateau						
Bethlehem			81	97	99	68
Bloemfontein			46	97	85	77
Pretoria			79	98	96	88
Mean			69	97	93	78
Std dev.			16	1	6	8
Coast						
Port Elizabeth	88	83	84	67	85	73
Durban	97	81	74	81	92	82
Mean	93	82	79	74	89	78
Std dev.	5	1	5	7	4	5

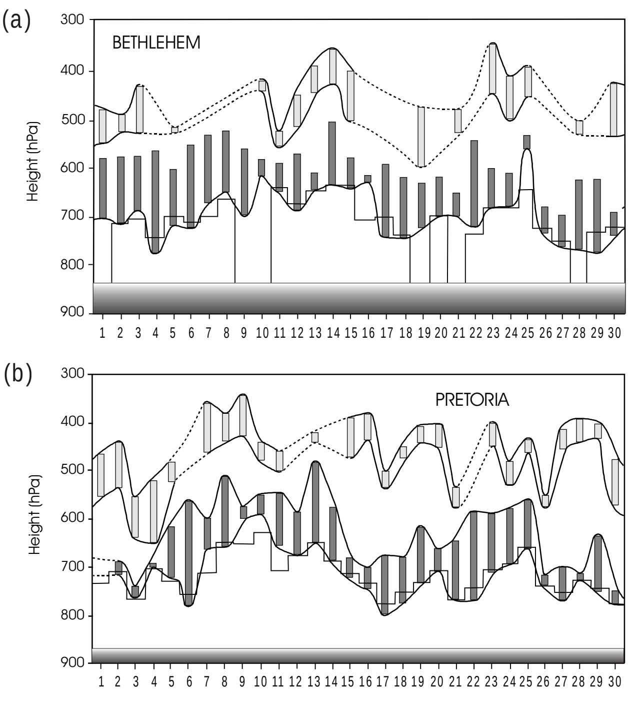


Figure 2
Elevated absolutely stable layers during June 1996 over (a) Bethlehem and (b) Pretoria

97% frequency in summer and winter. The frequency of occurrence decreases (increases) from the ~500 hPa to the ~700 hPa layer during summer (winter) over the plateau. Over the east coast, comparable mean frequencies are 89% and 78% respectively for the ~500 hPa layer and 79% and 74% for the ~700 hPa layer. The ~850 hPa layer over the coast has a mean frequency of occurrence of 93% in summer and 82% in winter. The persistence of the layers over the coast is similar during summer and winter with a decrease in the mean frequency of occurrence from the ~500 hPa to the ~700 hPa layer and a sharp increase from the ~700 hPa to the ~850 hPa layer.

The important point to be made about the ~500 hPa and ~700 hPa layer is not the seasonal differences over plateau and coastal areas, but that over eastern South Africa as a whole the stable layers have a remarkably high mean daily frequency of occurrence (exceeding 4 out of 5 d) throughout the year. Likewise, on average, the 850 hPa layer of the coast is observed more frequently than 4 out of 5 d in the year. The consistency of day-to-day occurrence of all the layers is illustrated in Fig. 1. In the case of March 1996 over Durban, the ~850 hPa layer occurred on every single day (Fig. 1b).

As Garstang et al. (1996) found during SAFARI-92, the daily persistence of the absolutely stable discontinuities over Southern Africa may be considerable: for the 31 d of March 1996, the ~500 hPa stable layer oscillated continuously about its mean height for 30 d over Pretoria and Bethlehem and 18 d over Durban. On only one day, toward the end of the run, was it missing over Pretoria (Fig. 1c) and Bethlehem. By contrast, the ~700 hPa layer over Pretoria was disrupted by easterly waves and lows, associated with surface convergence and the eroding of the layer, while over Durban ridging highs and passing shallow westerly disturbances disrupted the ~700 hPa layer at almost weekly intervals, allowing mixing into the layer above (Fig. 1b). During the winter of June 1996, in comparison, when the plateau stations were dominated by a continental high pressure system on 77% of days and the occasional cold front, the ~700 hPa stable layer oscillated about its mean height for a maximum period of the full 30 d over Bethlehem (Fig. 2a) and 29 d over Pretoria (Fig. 2b). For a reason as yet unexplained, and most strangely, the 500 hPa layer, in comparison, persisted for a maximum period of only 8 d over Pretoria and Bloemfontein. In all the instances, the time sections show how the layers oscillate in height from day to day.

Over both coastal and plateau areas, in both summer and winter, the ~500 hPa stable layer occurs with a mean frequency of around 4 out of 5 d or more (Table 1), as a consequence of the large-scale subsidence associated with anticyclonic curvature in the wind field. The frequency of occurrence of the ~500 hPa is higher over the plateau during winter due to a combination of increased subsidence closer to the core of the stable continental high pressure system and deep convective, advective and frontally-active circulation types over the coast during summer. The ~700 hPa layer, in contrast, shows greater variability. Over the plateau the layer occurs more frequently in winter (97 % of days) than in summer (69 %); over coastal areas the seasonal variation is less and the feature occurs on 3 out of 4 to 4 out of 5 d throughout the year. The coastal stable layer at ~850 hPa occurs on more than 4 out of 5 d throughout the year and appears to be more frequent in summer than in winter. Unlike the ~500 hPa layer which is subsidence-controlled, the ~700 hPa layer over the plateau and the ~850 hPa layer over coastal areas are affected a great deal by boundary layer processes. In the latter case, in addition to the anticyclone-associated subsidence, ocean to atmosphere heat fluxes, diabatic controls, topographical influences and sea-breezes contribute to the development of the stability of the ~850 hPa layer.

TABLE 2 PERCENTAGE FREQUENCY OF THE MERGED LAYERS OVER BETHLEHEM (BETH), BLOEMFONTEIN (BLM), PRETORIA (PTA), PORT ELIZABETH (PE) AND DURBAN (DBN)							
Month	**Layers (hPa)**	**BETH**	**BLM**	**PTA**	**PE**	**DBN**	**Total (%)**
Summer	850-700 700-500	 2	 0	 2	14 11	5 20	19 35
Winter	850-700 700-500	 8	 9	 2	12 0	4 6	16 25

TABLE 3 TOTAL NUMBER OF DAYS THE 850 hPA AND 700 hPa OR 700 hPa AND 500 hPa LAYERS WERE MISSING OVER THE COASTAL REGION				
		Jun-96	**Dec-97**	**MayJun-98**
Port Elizabeth	850 hPa 700 hPa 700 hPa 500 hPa	1 	 2	
Durban	850 hPa 700 hPa 700 hPa 500 hPa			3 1

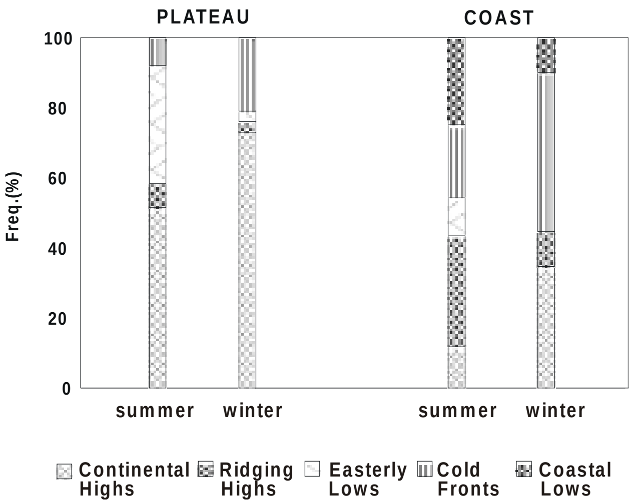


Figure 3
Percentage frequency of occurrence of synoptic conditions at the surface over the plateau and the coast

Synoptic conditions

The prevailing synoptic circulation controls the vertical divergence and convergence, which in turn directly control the temporal and spatial structures of the elevated absolutely stable layers throughout the troposphere (Taljaard, 1955; Diab, 1975; Preston-Whyte and Tyson, 1989).

Over the plateau, the anticyclonic conditions associated with large-scale subsidence and surface divergence occur on average 73% of the time in winter (Fig. 3). Coastal stations are affected on average only ~35% of the time these stable continental high-pressure conditions dominate. However, stable pre-coastal low and pre-frontal conditions occur on a further 25% of days and, together with the occurrence of fine conditions associated with transient ridging highs, ensure the subsidence that supports the development of the ~700 hPa and ~500 hPa stable layers over the coastal regions. The frequencies of occurrence of the synoptic conditions given in Fig. 3 approximate those presented by Vowinckel (1956).

Vertical convergence and convective activity associated with easterly wave disturbances, unlike the divergent anticyclonic conditions, hinder the formation of or dissipate stable layers. Easterly lows affect the interior plateau almost exclusively during summer, but may also affect the eastern coastal regions as the belt of subtropical high pressure systems over South Africa are located further south in summer (Newell et al., 1972).

Deep vertical convection associated with the passage of vigorous, unstable baroclinic westerly disturbances produces strong convergence and uplift, leading to the formation of both cumulus and stratiform clouds and rain. These disturbances occur throughout the year, but mainly during the winter half and mainly over the coastal and southern regions as the descending limb of the Ferrel and Hadley cells in the Southern Hemisphere shifts equatorward. Local, isolated or scattered cumulus convection in summer will dissipate the absolutely stable layers locally, but their spatial continuity and temporal persistence will remain largely unaffected on a macro scale.

Merged and missing layers

Not all absolutely stable layers occur at the preferentially observed levels. Periodic merging of layers on singular days or even over several days may occur (Table 2). Merging of the ~700 hPa and ~500 hPa layers has been noted on as much as 35% and 25% of the time during summer and winter respectively. At several stations there is evidence that on certain days a layer split from the main 500 hPa layer, and formed a small sublayer between the ~700 hPa and ~500 hPa layers (Fig. 1d).

Missing layers were observed at all stations when absolutely stable layers were absent from the categorised layer heights. The occurrence of missing layers allows mixing of aerosol and trace gases to the elevated stable layer above. Missing layers usually occur for a day or two. Occasionally, layers may be absent for longer: the ~700 hPa layer over Bloemfontein was missing for a maximum period of 5 d during December 1997 when easterly lows dominated. It is rare that the ~700 hPa and ~500 hPa layers are absent at the same time over the plateau (only once in 106 d). It is likewise uncommon for multiple layers to be missing simultaneously over coastal areas (Table 3). The elevated absolutely stable layers tend to persist even with complex synoptic situations. The layers are a major feature of the troposphere over the subcontinent.

Mean heights

During summer, base heights of the ~700 hPa and ~500 hPa layers over the plateau occur on average at 717 hPa and 532 hPa respectively over the eastern half of South Africa. The bases have a standard deviation of 25 hPa (277 m) and 21 hPa (233 m) and a mean range of 750 hPa to 688 hPa and 559 hPa to 500 hPa respectively over the plateau region as a whole. The ~700 hPa and ~500 hPa discontinuities have an average depth during summer of

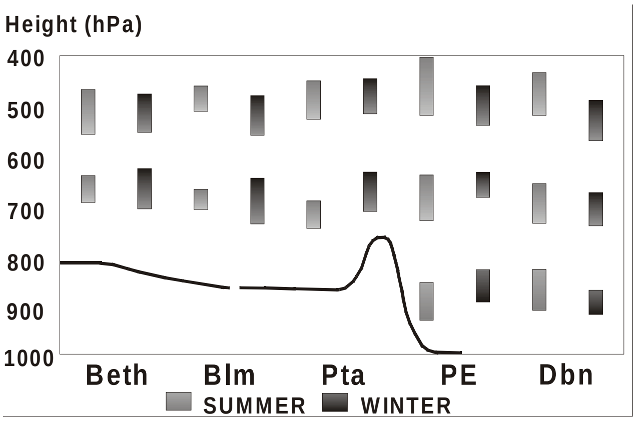
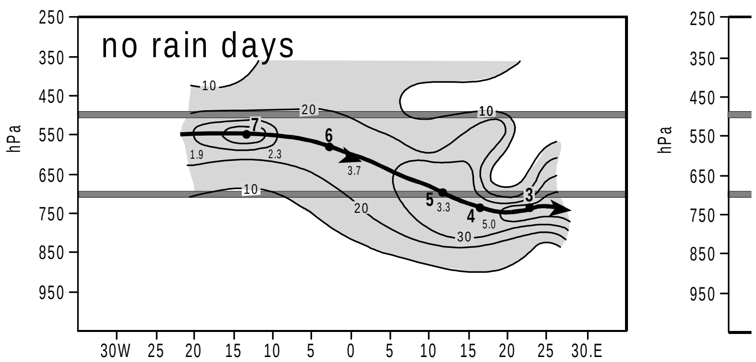


Figure 4 (left)
Mean heights of absolutely stable layers during summer and winter over Bethlehem (BETH), Bloemfontein (BLM), Pretoria (PTA), Port Elizabeth (PE) and Durban (DBN). Standard deviations for the base heights of the layers are illustrated by vertical lines.

Figure 5 (bottom left and right)
Trajectory fields in the vertical for (a) rain and (b) non-rain days during January over the central South Africa. Contours give percentage occurrence of trajectories and heavy lines the maximum frequency pathway of trajectories. Large, bold numbers denote average times of travel (days). Italicised values give meridionally-averaged specific humidities (g.kg^{-1}) of mean air parcels at specific longitudes (D'Abreton and Tyson, 1996). The ~500 hPa and ~700 hPa absolutely stable layers are shown as shaded horizontal lines.



50 hPa and 73 hPa respectively. In winter, the base heights of the 700 hPa and 500 hPa stable layers occur on average at 720 hPa and 544 hPa, with a standard deviation of 15 hPa (166 m) and 24 hPa (266 m). The 700 hPa and 500 hPa discontinuities have an average depth during winter of 84 hPa and 76 hPa respectively (Fig. 4).

The lowest mean heights of the ~700 hPa and ~500 hPa layers are observed over the plateau stations where subsidence is greatest. In comparison with previous observations (Cosijn, 1996), there is no correlation between lower base heights and increased frequencies of occurrence of the layers. The mean base of the ~500 hPa stable discontinuity is little affected by different synoptic types and maintains a topography similar to that of the underlying ~700 hPa layer. No significant differences exist between the depths of the different layers; all are shallow. All have depths of around 50 to 90 hPa (546 to 961 m) (Fig. 4). Cosijn (1996) observed similar results.

Implications for water vapour transport

A case study of Lagrangian-kinematic 700 hPa moisture transport over the central highveld of Southern Africa on no-rain (no rainfall) and rain (rainfall >5 mm) days during January has been presented by D'Abreton and Tyson (1996). Significant differences in transport patterns existed between rain and non-rain days (Fig. 5). With rain days, the locus of maximum tropical water vapour transport from the tropical Indian Ocean north of Madagascar was almost invariant at around the level at which the ~700 hPa stable layer usually occurs. In complete contrast, on no-rain days, transport is from the mid-southern Atlantic Ocean region, initially constrained by and beneath the ~500 hPa layer. Thereafter, the air subsides, increasing its stability, until its final transport over eastern South Africa appears to be constrained by the ~700 hPa layer. Previously it has been observed that the level of maximum water vapour transport during rain events in the summer rainfall region of the South African plateau occurs at around 700 hPa (D'Abreton and Lindesay, 1993; Van den Heever, 1995; D'Abreton and Tyson, 1995, 1996). Despite the fact that the ~700 hPa absolutely stable layer is so thin, its spatial ubiquity and temporal persistence appear to ensure that the layer is of considerable significance in controlling the transport of water vapour over much of South Africa.

Conclusion

The multiple, persistent elevated absolutely stable layers that occur over South Africa trap aerosols and trace gases (including water vapour) below their bases by inhibiting turbulent mixing in the vertical. Consequently, the transport of water vapour and other components in the atmosphere is limited to and constrained by the space between the layers. The layers are little influenced by prevailing synoptic circulations, except when disrupted by deep baroclinic disturbances or cumulonimbus convection. In the latter case, the disruption tends to be localised rather than widespread. The predominantly subsiding South African troposphere promotes the development of the ~500 hPa and ~700 hPa layers on average by up to 4 out of 5 d throughout the year over the eastern half of the country.

The ~500 hPa absolutely stable layer controls the distribution of aerosols in the atmosphere over South Africa and always marks the top of a distinct haze layer in both summer and winter. The ~700 hPa stable layer plays an important role in governing water vapour transport over the South African plateau. Hitherto largely ignored as controls of South African climate, the persistent stable layers now appear to be of fundamental importance, not only in determining transport of aerosols and trace gases within and beyond the region, but also in respect of the general climate.

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