Air Transport into and out of the Industrial Highveld Region of South Africa

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ABSTRACT

Eolian dust and industrially derived sulfur aerosols have been shown to be major summer and winter constituents of the ubiquitous southern African haze layer. Industrial emissions from the South African industrialized Highveld are exported out of the region and have an impact on remote regions of the subcontinent. Simultaneous use of kinematic trajectory and thermodynamic (vertical structure) analyses are used to describe the four-dimensional nature of the atmosphere and the extent of direct and recirculated transport of elevated aerosol concentrations over and exiting the Highveld.

1. Introduction

South Africa has one of the largest industrialized economies in the Southern Hemisphere and is the only industrialized regional energy producer on the African continent (Sivertsen et al. 1995; Rorich and Galpin 1998). A large proportion of the industrial infrastructure (~75%) is concentrated on the Highveld Plateau region (~1700 m above sea level, ~30 000 km²). The industrial Highveld region accounts for approximately 90% of South Africa’s scheduled emissions of industrial dust, sulfur dioxide, and nitrogen oxides (Wells et al. 1996).

The nature and extent of the transport of air, the carrier of aerosols, trace gases, and water vapor, can be determined using trajectories. In fact, the monitoring of the long-range transport of pollutants using trajectories has been carried out for the past three decades (Eliassen 1978; Miller 1981; Moody and Samson 1989; D’Abreton and Tyson 1995, 1996; Flesch et al. 1995; Stohl 1996, 1998; Tyson et al. 1996b, 1997; Garstang et al. 1996; Swap et al. 1996; Garstang and Tyson 1997; Chiappello et al. 1997; Gatebe et al. 1999) to discriminate, for instance, between oceanic, clean continental, and polluted continental air masses. Previous long-term studies of air transport over southern Africa focused on transport pathways in relation to synoptic circulation patterns and assumed that the air masses mixed as part of these circulation patterns (Tyson et al. 1996a). The nature of the export of aerosols and trace gases out of the industrial Highveld region, in particular, is an essential starting point toward understanding the nature of the atmospheric chemistry and air transport over southern Africa as a whole. Held et al. (1996), examined ground-based and near-surface atmospheric particulate concentrations over a 5-yr period and related these to the prevailing synoptic situations with one upper-air station and a few ground anemometer sites. A localized recirculation pattern was observed to the north of the network area (270 km × 500 km) during winter, which shifted to the east under summer conditions. The need for a longer-term transport climatological description, not based on selected case studies, over a larger domain to encompass transport to remote regions and neighboring countries of South Africa at all levels of the low to midtroposphere, irrespective of the dominant synoptic circulations, is the next step in this research.

In this paper, the physical processes and evidence for large-scale recirculation and transport, both horizontally and vertically, of air into and out of the industrial Highveld region are examined in detail. A climatological description of air transport behavior, or transport climatology, that focuses on the largest anthropogenic source region of the subcontinent has not previously been examined. Temporally and spatially resolved wind fields are utilized for trajectory calculations to produce air circulation classes. Trajectories for the period 1990–94 to, and 1990–98 from, the industrial Highveld of southern Africa provide insight into the transport of clean and aerosol-laden air over and out of South Africa and, more important, on the impacts of this transport on neighboring countries and remote regions.

2. Data and methods

South Africa lies at 22°–35°S and 15°–35°E. The interior plateau Highveld region covers the latitudinal-longitudinal area of 25.2°–27.2°S, 27.2°–29.2°E (Fig. 1).
Air transport was examined arriving at and leaving the Highveld.

Trajectories to and from the Highveld were calculated using a Lagrangian kinematic model, as described by D’Abreton (1996), utilizing twice-daily (0000 and 1200 UTC) European Centre for Medium-Range Weather Forecasts three-dimensional wind velocity vectors (2.5° × 2.5° × 100 hPa) and an advection time period of 15 min. The advection process was repeated for up to 240 h. Each trajectory was calculated forward or backward in time to determine the geopotential location and height of the receptor and source regions, respectively.

Transport to and from the Highveld was examined between the low and midtroposphere. Average transport pathways to the Highveld (1990–94) were determined for February (summer), April (autumn), July (winter), and October (spring) between 850 and 700 hPa. An 8-yr (1990–94 and 1996–98) trajectory climatology was calculated from the Highveld. Data from 1995 for the relevant months were not available in the dataset. Because most industrial emissions on the Highveld are from tall stacks at roughly the 775-hPa level (600–800 m above ground level; Held et al. 1996), nearby significant levels (800 and 700 hPa) were used for calculating the 8-yr trajectory climatology. A more comprehensive seasonal transport analysis from the Highveld was made for 1995–98. Trajectories starting at different geopotential initial heights, representative of the lower troposphere (800 and 700 hPa) and the middle troposphere (600 and 500 hPa) over the Highveld were calculated kinematically. The ubiquitous elevated absolutely stable layers observed over southern Africa in the low-to-midtroposphere (~700 and ~500 hPa) on nonrain (Cosijn and Tyson 1996) and rain (Freiman and Tyson 2000) days play a large part in trapping aerosols below their bases and promoting horizontal transport at those levels. The transport levels chosen for 1995–98 aimed to capture transport below and between the elevated absolutely stable layers.

Transport to and from the Highveld was analyzed and classified according to similarity, in terms of direction and travel distance. Analysis and classification of the transport were based on seasonality and tropospheric level transport. A similar ensemble technique has been utilized by Thompson et al. (1996) to get a better idea of the spatial dimensions of the identified pathways. Percentages of frequency of occurrence of each identified pathway were calculated with respect to the total number of trajectories analyzed. Direct meridional and zonal transports to and from the Highveld were determined based on the method used by Garstang and Tyson (1997), using meridional and zonal walls at 2° intervals around the point of origin at the respective levels discussed above. Initial directions of recirculation can be ascertained from these analyses but the full pathways cannot.

The percentage frequency of transport from the Highveld that traverses over South Africa’s neighboring countries was also examined. Trajectories were looked at individually to determine each international border crossed. If the trajectory analysis showed air transport exiting a country and reentering later, then the border crossing was recounted. Both total and seasonal frequencies of trajectories originating over the Highveld and crossing international borders have been calculated to determine a transboundary transport climatology (1990–94).

Trajectory models have been used successfully to study complex processes such as, for example, the recirculation of air over southern Africa (Tyson et al. 1996a). Single trajectory calculations, however, are insufficient for the study of air transport under turbulent conditions (Pickering et al. 1996), especially when they are calculated from analyzed data, which have spatial and temporal gaps of 250 km and 12 h, respectively. Trajectories were run from a five-point array centered on the Highveld to provide a qualitative indication of the pathway of the air parcels as well as to yield information on the horizontal wind shear (Kahl 1993). The 1° gridpoint interval latitudinally and longitudinally delimits the industrial Highveld region (Fig. 1). It should be emphasized that the trajectories are only an indication and not a positive long-term trend of the paths and destinations of the pollutants, especially in the examination of case studies. A modeled trajectory is an approximate calculation of the transport pathway of a small air parcel.

Examination of synoptic charts and radiosonde data for March of 1996 indicated days when particular circulation types persisted. Four-dimensional transport (x, y, z, t) to and from the Highveld for those periods was analyzed in relation to the nearest plateau or coastal upper-air station’s midday tropospheric profile (Fig. 1). Absolutely stable layers were determined from the up-

Fig. 1. The South African industrialized Highveld region (shaded) and the five-point trajectory cluster used for the trajectory climatology (indicated by the dark gray points within the shaded region). The location of the radiosonde plateau stations: Pretoria (Pta), Bloemfontein (Bln), and Bethlehem (Beth), and coastal stations: Durban (Dbn) and Port Elizabeth (PE) used are marked with black points.
per-air data where the observed lapse rate exceeded the wet (saturated) adiabatic lapse rate (Saucier 1955).

3. Results and discussion

a. Transport to the Highveld

Backward-trajectory analysis between 850 and 700 hPa indicates four major transport pathways to the Highveld. The transport pathways are produced by flow from the Atlantic Ocean, the Indian Ocean, subtropical Africa, and over southern Africa (Figs. 2a,b). The most frequently occurring transport mode is from the Atlantic Ocean (43%). Transport of air from the Indian Ocean (26%) and the African continent (25%) together contributes one-half of all transport to the Highveld. Regional-scale advection exclusively over southern Africa accounts for less than one-tenth of the transport.

Air from the south and central Atlantic is most likely to be free of industrial emissions. When associated with pronounced ridging behind a cold front, some recirculation of aerosols from southern Africa will occur under this transport mode. African transport may carry pollutants from central-southern Africa, especially the Zambian “copper belt,” over South Africa. Although production has declined in recent years, emissions from the Zambian copper belt are still a significant source of aerosols over southern Africa (Meter et al. 1999). Southern African transport reaching the Highveld frequently carries previously injected industrial aerosols and trace gases (D’Abreton and Tyson 1996; Piketh et al. 1998).

Transport of tropical air southward is commonly associated with summer rainfall over South Africa (Tyson 1986). The moisture flux over the subcontinent on midsummer rain days is usually from the Indian Ocean north of Madagascar (D’Abreton and Tyson 1996). On non-rain days, however, it is associated with transport from the Atlantic.

Significant seasonal variation exists in the transport of air to the Highveld in the lower troposphere (850–700 hPa; Table 1). Most noticeable is the high percentage (54%) of Indian Ocean transport that occurs during summer, owing to the high number of easterly wave perturbations at this time of year (Tyson et al. 2000). By contrast, peak Atlantic transport (51%) occurs in winter with the equatorward expansion of the circumpolar westerlies at this time of the year. African flow is least important during the summer when the belt of subtropical high pressure systems over South Africa is displaced further south (Newell et al. 1972). Subcontinental flow, generally through recirculation, is consistent throughout the year.

Transport to the Highveld is based on back-trajectory analysis at a specific height. Transport pathways to the Highveld at different starting pressure levels illustrate some discontinuities in all direct transport modes (Table 2). Transport from the Indian Ocean appears to be more prominent in the lower-tropospheric levels (850–750 hPa), and Atlantic Ocean transport is more dominant at higher elevations (750–700 hPa). Medium- to long-range African transport occurs mostly at the 700-hPa

### Table 1. Seasonal variation (%) of transport types advecting to the Highveld (850–700 hPa).

<table>
<thead>
<tr>
<th>Season</th>
<th>Atlantic</th>
<th>Indian</th>
<th>African</th>
<th>Recirculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>34</td>
<td>54</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>Autumn</td>
<td>46</td>
<td>16</td>
<td>27</td>
<td>11</td>
</tr>
<tr>
<td>Winter</td>
<td>51</td>
<td>10</td>
<td>33</td>
<td>6</td>
</tr>
<tr>
<td>Spring</td>
<td>39</td>
<td>26</td>
<td>30</td>
<td>5</td>
</tr>
</tbody>
</table>

Fig. 2. (a) Transport pathways and percentage frequency of occurrence of air advecting to the Highveld: The shaded arrows indicate an ensemble of trajectories between 850 and 700 hPa. (b) Direct meridional and zonal transports to the Highveld during summer and winter.
TABLE 2. Variation in percentage frequency of occurrence of each transport mode toward the Highveld at different starting levels.

<table>
<thead>
<tr>
<th>Starting level (hPa)</th>
<th>Indian Ocean</th>
<th>Atlantic Ocean</th>
<th>African Recirculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>700</td>
<td>18</td>
<td>47</td>
<td>30</td>
</tr>
<tr>
<td>750</td>
<td>26</td>
<td>44</td>
<td>23</td>
</tr>
<tr>
<td>800</td>
<td>27</td>
<td>40</td>
<td>25</td>
</tr>
<tr>
<td>850</td>
<td>33</td>
<td>39</td>
<td>21</td>
</tr>
</tbody>
</table>

level. Recirculation does not vary significantly with height.

b. Transport from the Highveld

There are two main transport modes of air masses, aerosols, and trace gases out of the industrial Highveld region. The first is direct transport, in which material is advected directly with little delay in a westerly (to the Indian Ocean), easterly (to the Atlantic Ocean), northerly (to the south Indian Ocean), or southerly (toward equatorial Africa) transport mode. The second is recirculated transport, in which material recirculates back toward the point of origin over the subcontinent on a regional or subcontinental scale (Fig. 3). Low-to-midtropospheric flow from the Highveld exports industrial pollutants over and out of southern Africa.

1) 8-YR TRANSPORT CLIMATOLOGY IN THE LOWER TROPOSPHERE

Lower-tropospheric (800–700 hPa) forward trajectories for an 8-yr period from the Highveld indicate direct and recirculated air transport (Fig. 4a). The main transport routes for air originating over the Highveld are to the southwest and south Indian Ocean (together totaling 45%) and regional- to subcontinental-scale recirculation over the interior (33%). The overall recirculating time ranges from 2 to 9 days, depending on the scale of circulation.

A large proportion of industrial air parcels exported out of the Highveld exit the subcontinent into the Atlantic and Indian Oceans under the influence of the bar-
otropic easterly and baroclinic westerly waves that affect the tropical and temperate latitudes, respectively, within 1–3 days. As much as 41% of all transport, however, affects countries bordering South Africa through direct or recirculated transport. Transport to equatorial Africa exports aerosols and trace gases out of South Africa to neighboring countries, especially Mozambique, Zimbabwe, and Botswana. Under stable atmospheric conditions, however, material from the Highveld may reach countries as far north as Zaire and Kenya (Gatebe et al. 1999).

Within the temperate latitudes, most tropospheric pollutants undergo heterogeneous gas reactions and dry deposition. Farther north, however, in the tropical latitudes, moisture plays a dominant role in chemical reactions and cloud interaction, specifically in the lower troposphere, and wet deposition dominates. Of the total air transport, 14% is to the Atlantic Ocean in the Angolan plume. Transport in an easterly direction occurs mostly at low levels, owing to subsidence over the western subcontinent and South Atlantic Ocean (Tyson et al. 1996b). Botswana and Namibia are affected by this transport.

Recirculation frequently occurs as a combination of synoptic circulation types. The net result is an anticyclonic-type flow pattern. Remote regions of southern Africa, as well as less-industrialized neighboring countries, are affected by recirculating air parcels within a few hours to 2–7 days. Under recirculating air, the accumulation of aerosols and trace gases in the low to midtroposphere is promoted by longer residence times over the land (Seinfeld 1986; Langner and Rodhe 1991). The recirculation of air masses out of the Highveld region on the macroscale over the subcontinent or off of the African continent has been observed for some time (Tyson et al. 1996a).

Air transport from the Highveld displays certain variations according to season (Fig. 4b). During winter, one-half of all transport exits to the east over the Indian Ocean. A similar volume of air (39% and 43%) affects remote parts of South Africa and neighboring countries during winter and summer, respectively, through direct transport to equatorial Africa and recirculating transport. Easterly disturbances during summer transport material to the Atlantic Ocean. Transport to the central Indian Ocean dominates in winter.

Characteristic vertical displacement is linked to the transport paths out of the Highveld. Under the influence of direct westerly flow, the air becomes elevated in height with time and distance from their points of origin, predominantly over the eastern half of the country, especially when convective activity is prevalent (Fig. 5). Transport from the Highveld out to the Indian Ocean under such transport is short with sharp ascents in height over the interior and a stabilization of all the trajectories at ~350 hPa, below the height of the ~300-hPa absolutely stable layer (Fig. 5). Advection under this transport mode generally occurs at the base of or between the elevated stable layers.

Advection within the easterly disturbances toward the more atmospherically stable west coast of South Africa is associated with a descent in height, especially if the air exits within the easterly air stream off of the West Coast (Fig. 6). Garstang et al. (1996) observed a similar descent in height within the Angolan plume transport off of the West Coast. Transport time is longer than under westerly transport (3.5–4 days), and the trajectories maintain a relatively constant rate of descent at different heights.

Anticyclonic recirculation occurs on a variety of scales. Local recirculation is not as apparent because of the coarse resolution of the data. The vertical displacement of air recirculating toward the east on a regional to subcontinental scale is one of ascent (Fig. 7). When recirculating air changes direction of flow, the consequent vertical displacement is reversed. It is at this point that transport at a specific level peaks or dips to its highest or lowest height, respectively (Fig. 7).

2) SEASONAL VARIATIONS IN LOW-TO-MIDTROPOSPHERIC TRANSPORT

For 1995–98, 631 trajectories exiting the industrial Highveld region were analyzed in the low (800–700
hPa) and midtroposphere (600–500 hPa). Recirculated transport dominates during summer and winter at all heights, followed by transport to the south Indian Ocean (Fig. 8).

Recirculation of air out of the Highveld on all scales is high. Under prevailing summer surface and upper-air synoptic conditions, overall recirculation is higher in the upper troposphere (44%), where stability is greater (Fig. 8). In contrast, during winter, overall recirculation in the lower troposphere (43%) occurs more frequently than aloft (30%), because of an increase of subsidence over the region as a whole (Fig. 8). Tyson et al. (1996a) similarly found recirculation at the central meridian roughly bisecting southern Africa to occur approximately 44% of the time in the lower troposphere, with stable continental high pressure systems prevailing over the interior, over August–October 1992.

Direct transport to the Indian Ocean is significant during summer and winter at all levels. It occurs most frequently in the middle troposphere during winter (52%). The direct exit of air to the equatorial Atlantic Ocean occurs exclusively during summer at all levels but peaks in the lower troposphere (14%; Fig. 8a). Throughout the year, the lowest frequency of occurrence of direct westerly transport from the Highveld to the Indian Ocean occurs at 800 hPa and increases steadily with height, reaching a maximum frequency of occurrence in the midtroposphere, below the ~500-hPa absolutely stable layer. Irrespective of the season, on average, approximately 4 times as much northerly transport occurs in the lower troposphere than in the middle troposphere (Fig. 8). Decoupling of the air is observed between 700 and 600 hPa. Direct southerly transport toward equatorial Africa is constant throughout the year at all levels, averaging ~10%.

Large-scale circulation fields and transport modes may be substantially different during wet and dry spells (Tyson 1986; Harrison 1988; Lindesay 1988; D’Abreton and Lindesay 1993; D’Abreton and Tyson 1995). Bearing in mind the 8-yr trajectory climatology (1990–94 and 1996–98), it appears that the seasonal winter penetration of westerly disturbances into the interior was somewhat stronger during the drier years of 1990–94 (South African Weather Service 2000). This period coincided with a strong El Niño episode that peaked during 1992.

A more comprehensive air transport analysis was done for the 4-yr 1995–98 trajectory climatology. In the 8-yr trajectory climatology, prematurely ending recirculating trajectories to the east were accounted for as direct transport to the east toward the Indian Ocean. Similar values are observed for the 8- and 4-yr climatologies when the direct plume trajectories to the Atlantic Ocean are combined with the recirculated air indices.

c. Transport impacts at remote parts of southern Africa

A large percentage of transport from the Highveld affects remote parts of South and southern Africa. This
Fig. 8. Transport from the Highveld industrial region in (left) summer and (right) winter at (a) 800–700 hPa and (b) 600–500 hPa, 1995–98.

Fig. 9. (a) Percentage frequency with which the borders of each country in southern Africa are crossed by trajectories originating over the Highveld for 1990–94. Countries: Angola (ANG), Botswana (BOT), Burundi (BUR), Democratic Republic of the Congo (DRC), Kenya (KEN), Lesotho (LES), Madagascar (MAD), Malawi (MAL), Mozambique (MOZ), Namibia (NAM), Rwanda (RWU), Swaziland (SWAZ), Tanzania (TANZ), Zambia (ZAM), and Zimbabwe (ZIM). (b) A graphic representation thereof.

4. Conclusions

Preferred transport pathways are spatially organized both horizontally and vertically, with persistent elevated absolutely stable layers exerting a major controlling influence. Almost one-half of all of the air reaching the Highveld (43%) is clean marine air advected within the westerly disturbances over the southern parts of South Africa. As much as 25% of all transport to the Highveld is already aerosol laden from subtropical Africa.
Stohl, A., 1996: Trajectory statistics—A new method to establish


