CHAPTER 3

RESULTS AND DISCUSSION

> This Chapter discusses the findings of the research. A seasonal air transport climatology for southern Africa is presented. The months of February, April, July and October are used to represent the four seasons that characterize the region. Transport is analysed per pressure level, direction and frequency of occurrence. Direct meridional and zonal transport is used to characterize the major transport plumes in the subregion.

The seasonality of transportation in the Southern African subregion is considered. By analyzing large numbers of trajectories it is possible to determine major transport plumes. Results from the trajectory analysis are divided into the four seasons that characterise the region. The transboundary nature of the trajectories from the Copperbelt is assessed through an analysis of trajectory hits per affected country. Biomass burning products are most likely to join the plume that traverses the subcontinent towards the south Atlantic and the westerly coast of the south Indian Ocean. Recirculation is identified as a major feature of aerosol transportation in the subregion. Recirculation is said to occur when air is transported away from a point of origin and then returns in the opposite direction from which it has travelled after having recurved or rotated cyclonically or anticyclonically (Tyson *et al.,* 1996). Recirculation frequently occurs as a combination of synoptic circulation types. Under recirculation conditions, the accumulation of aerosols and trace gases in the lower-to-mid troposphere is promoted by longer residence times over the land.

Trajectory analysis results show that peak Atlantic transport in southern Africa occurs in winter, reaching peak values of 64% at the 750-800 hPa levels. Transportation towards southern Africa occurs as a result of recirculating air masses that occur on average 23% of the time at all pressure levels. Other flow types remain insignificant during this time of the year, with the Cape plume occurring on average 5% of the time only at the 850 hPa level.

During the summer diverging air masses transport aerosols towards both the Atlantic and Indian Oceans, with a frequency of 38% and 30% respectively. Recirculatiom from the Copperbelt occurs 25% of the time. The African flow remains insignificant throughout the year (2%), especially during the summer when the belt of subtropical high pressure system over South Africa is displaced further south. Direct meridional transport from the Copperbelt into South Africa and out of the Cape is also as minimal throughout the year (Figure 4.5). During the autumn, transportation is predominantly westwards into the Atlantic Ocean and beyond. Maximum transportation into South Africa occurs during the spring, and during this period, a large amount of pollutants and products of biomass burning are likely to be transported into South Africa.

3.1 A SEASONAL AIR TRANSPORT CLIMATOLOGY

The five-year trajectory analysis from the Copperbelt reveals that most horizontal transport is to the west into the Atlantic Ocean, with a recirculation of air masses into Botswana, Namibia and eventually into South Africa. Recirculation is a significant transboundary transportation mode throughout the year, especially during the spring season, where it occurs with a frequency of 60% (Figure 3.1). Case studies have been conducted to illustrate the seasonality of trajectory flow in the Southern African subregion.

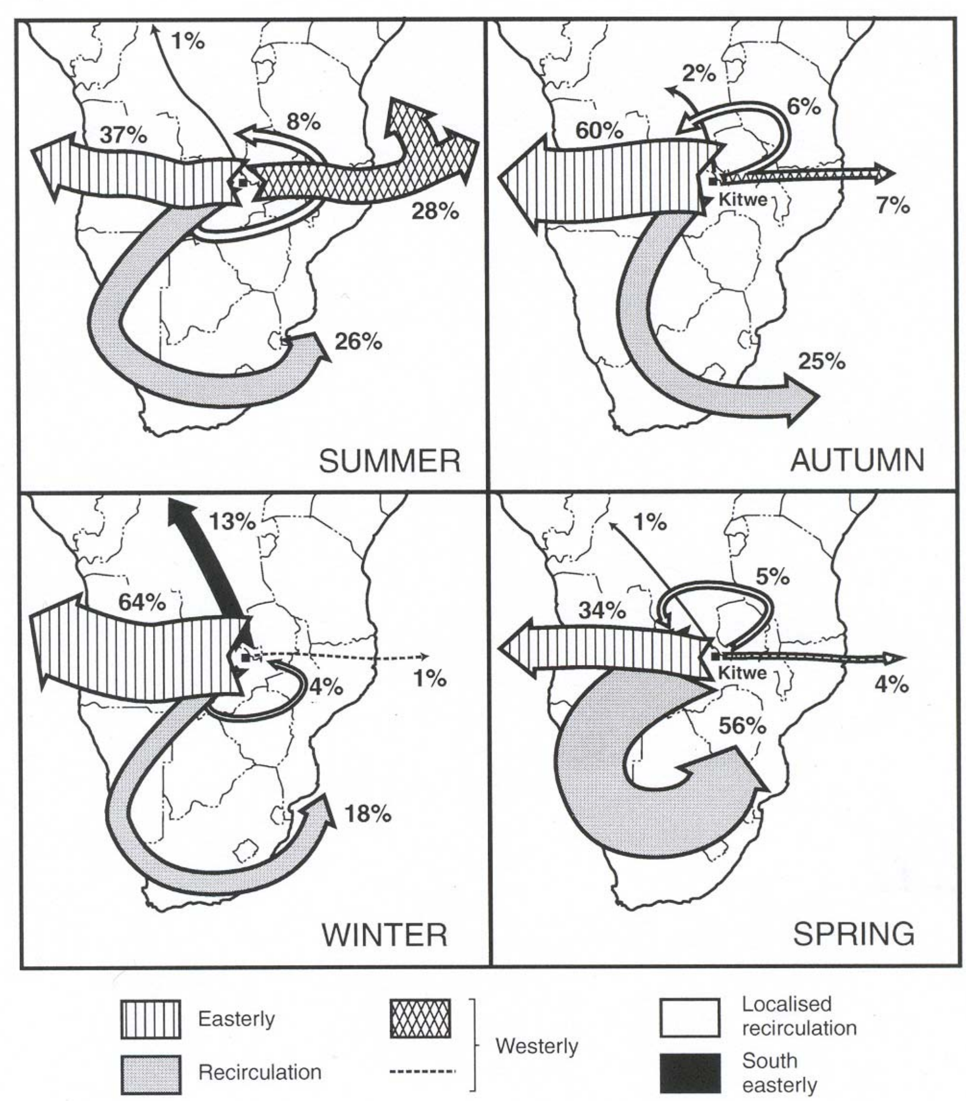


Figure 3.1 Major recirculation patterns and transport seasonality (1990-1994). Other transport patterns denotes minor northerly, southerly and westerly recirculation plumes

Aerosols are likely to be transported further during the winter and spring seasons because of the general lack of precipitation during this time of the year. Recirculation is likely to transport biomass burning products from domestic fires and biofuel consumption in the Southern African subregion. Easterly transport occurs throughout the year, and tends to circulate inland during spring (averaging 56%), summer (26%), autumn (25%) and winter (18%), (Figure 3.1).

South easterly trades from the Copperbelt occur mainly in the winter period, being determined mainly by the position of the ITCZ which lies to the north during this time of the year. In summer, the ITCZ draws air from the Indian Ocean and land masses of Southern Africa as southeasterlies. Throughout the year, smaller plumes (averaging 2%) transport the air meridionally into South Africa and the Antarctica, or northerly to as far north as India. Trajectory patterns indicate other smaller circulation types, including the westerly recirculating and the northeasterly airmasses, which occurred as minor plumes within more dominant circulation plumes throughout the year (Figure 3.1).

Vertically, transport exhibits some variations according to height. Transport of peak values from the Copperbelt occurs as easterly flow in winter and averages 64% for all pressure levels (850, 800, 750 and 700hPa), with predominant transport occurring below 700hPa. It is at the 700 and 500hPa absolutely stable layers that aerosols are trapped and eventually transported to South Africa. Recirculation peaks in October and is confined mainly to the 850 and 800hPa levels. Recirculation is less at the 700 and 750hPa levels. Individual case studies have been conducted for the four months chosen to represent the main seasons of summer, autumn, winter, and spring seasons in the southern African subregion, and a seasonal air transport climatology is presented.

Summer

During February, airflow patterns are predominantly easterly for all the five years for which trajectories have been run, and occur with a frequency of 35%. This flow occurs within barotropic quasi-stationary tropical easterly wave disturbances. These disturbances are dominant summer phenomena, and occur with a frequency of 50-60% in January in Southern Africa in general (Tyson *et al.,* 1996). In the Copperbelt area, easterly wave disturbances are particularly prevalent at the 850hPa level where they represent 40% of total transport from the source region. Easterly flow drops to about 35% of the time at the other pressure levels (Figure 3.3). Easterly flow is responsible for the transportation of pollutants from the Copperbelt directly into the Atlantic Ocean and beyond.

Westerly transport occurs on average 30% of the time during the five year period, reaching peak values of 32% at the 850hPa level (Figure 3.3). Less that 4% of the westerly transport is recirculated inland and this does not have an effect on Southern Africa, with deposition and further transportation being into the Indian Ocean and Autralasia.

Recirculation occurs, on average, 26% of the time. Recirculated airmasses from the Copperbelt reach South Africa and tend to recurve back into Zambia via Zimbabwe. This plume is likely to lead to deposition of pollutants close to the source region, and in the absence of rainfall, lead to a transboundary transportation of pollutants to Botswana, Namibia, South Africa and Zimbabwe. A minor plume recirculates pollutants within the Copperbelt itself (Figure 3.3), with an even more insignificant plume transporting material directly into South Africa via Botswana as a northerly plume.

South easterly flow does not occur, having been hindered by the ITCZ which normally lies over the southern hemisphere during this time of the year. Transportation to Angola is therefore minimal during this time of the year.

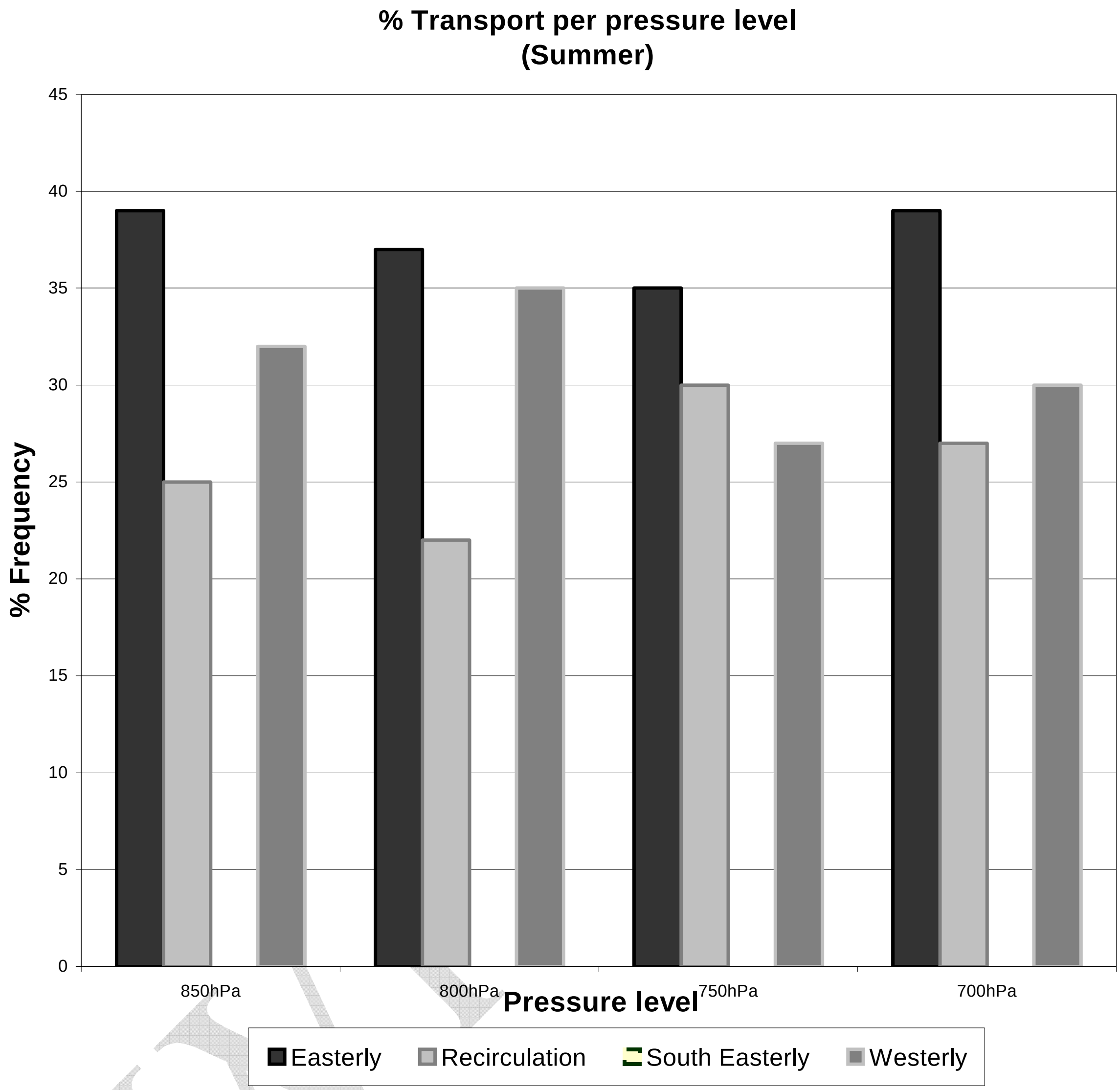


Figure 3.2 Percentage frequency of the direction of transport per pressure level during summer (1990-1994).

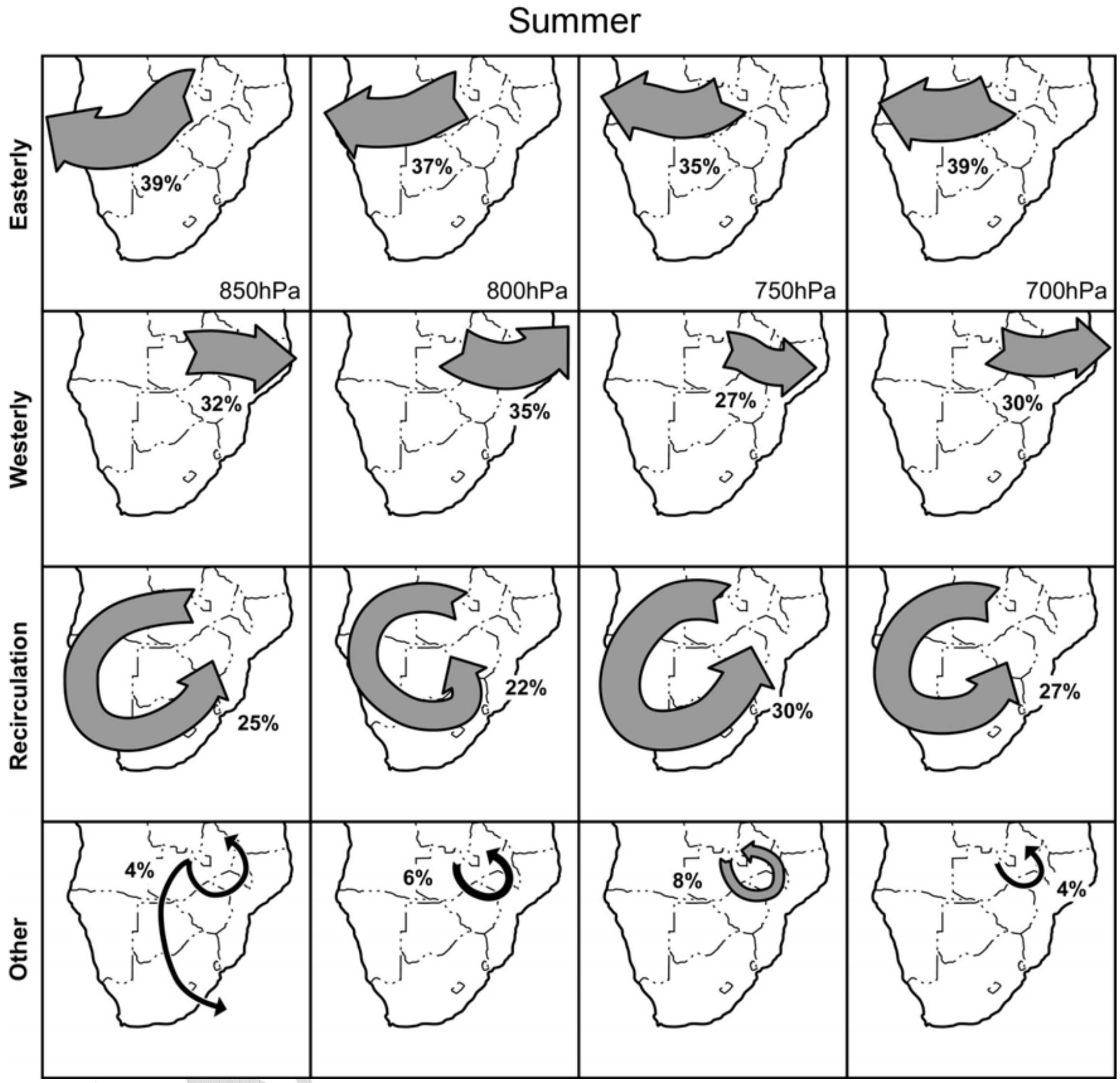


Figure 3.3 Examples of major transport types for all the pressure levels for summer for the 5-year period.

Autumn

From the year 1990 to 1994, the major plume during the autumn was easterly and this occurred on average for 60% of the time. Lower tropospheric transport for all the pressure levels is easterly and recirculation, where recirculation occurred on average 25% of the time during the five-year period. Transportation into South Africa is through a smaller recirculation plume that moves predominantly southwards along the east African coast, to exit the continent at 35ºS. This plume is likely to carry with it not only pollutants from the Copperbelt, but products of biomass burning from fuelwood combustion and savanna fires from the subregion.

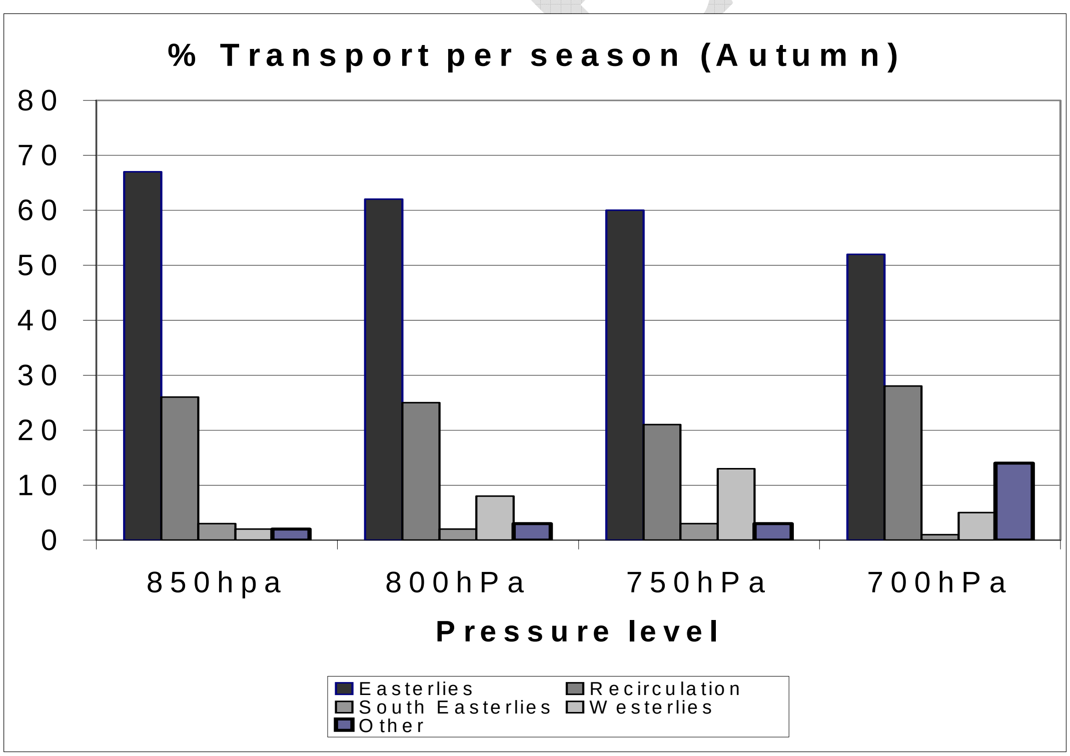


Figure 3.4 Major circulation types during Autumn (1990-1994).

Easterly flow during winter is largely influenced by surface synoptic conditions. Overall recirculation in the lower troposphere occurs more frequently than aloft, because of an increase of subsidence over the region as a whole (Freiman and Piketh, 2003). Tyson *et al.,* (1996) 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, during the spring of 1992. Strong subsidence is a dominant feature of the synoptics of the Copperbelt during the winter season.

Minor transport plumes from the Copperbelt are notably through south-easterly flow which traverses Angola into the Atlantic, and these occur only 2% of the time for all the pressure levels. Westerly flow is more significant, occurring on average 13% at the 750hPa level (Figure 3.5). Besides the easterly and recirculation flows in April, none of the other flow types significantly transport air into neighbouring countries during this time of the year.

Trajectories from the 700 and 750hPa levels predominantly recirculate within Zambia, Angola and Zimbabwe, with minimal transportation into South Africa. However, at the 800 and 850hPa levels, divergence results in a southward transportation of air masses into South Africa via Botswana and Namibia (Figure 3.5). A smaller plume moves out of the continent towards Australia as westerlies, and this occurred on average 7% of the time (Figure 3.5).

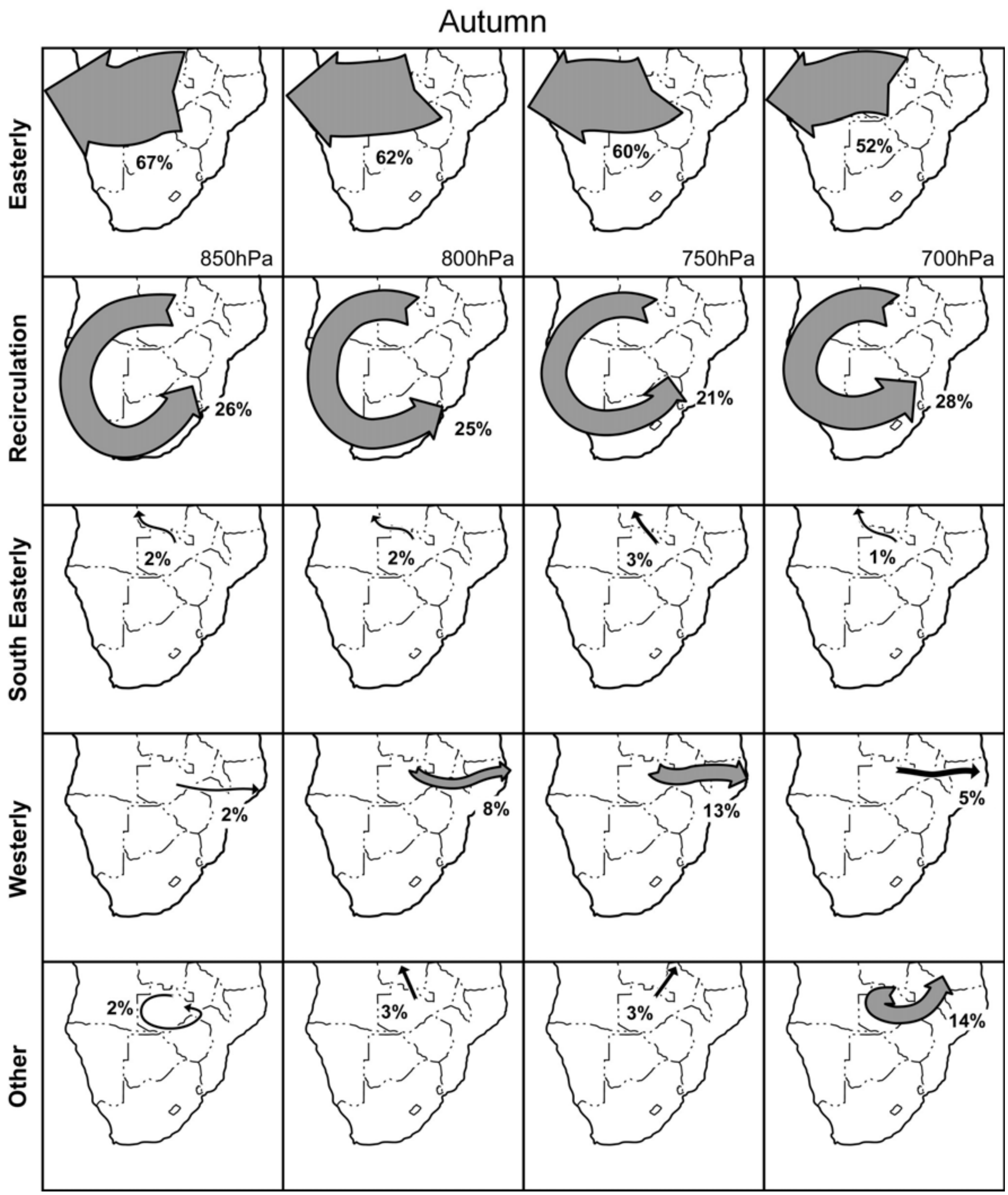


Figure 3.5 An example of frequently occurring circulation types during Autumn.

Winter

In winter, there are two main modes of transport, easterly and recirculating easterlies. The dominant mode of air transport from the Copperbelt as illustrated by trajectory flow for the five year period is easterly, and occurs on average 64% of the time for all the pressure levels (Figure 3.6). Angola is affected the most by the aerosols being transported in this plume which travels as far west as the Americas, with recirculation being centered on Namibia, Botswana and Zimbabwe. The north-western parts of South Africa are affected by this plume.

During winter, recirculation occurs as a large gyre, and occurs on a variety of scales ranging from local through regional to sub-continental. The general lack of precipitation during winter also means that less deposition takes place close to the source and a large flux of pollutants are added to those originating from the South African Highveld and recirculating within Southern Africa at this time of the year. Recirculation occurs on average 22% during winter, and has almost the same frequency at all pressure levels (Fig. 3.6). The flow moves southward in a recirculating manner descending in altitude to exit the subcontinent at about 33ºS as the Natal plume.

During July trajectories show strong divergence at 800 and 850hPa as indicated by their discontinuity on the trajectory pathways from the five-point array. At the 700 and 750 hPa levels air masses tend to flow towards the northwestwards, then recirculate locally over Angola, or exit the country as the Angolan plume. Localised recirculation accounts for a small percentage (4% at the 850hPa level). This is because of the influence of continental highs that prevail during this time of the year. These continental highs are characteristic of the region due to large scale subsidence occurring between the Hadley and the Ferrell cells, and over the southern African region, occur with a frequency exceeding 70% (Tyson *et al*., 1996).

Because of the nature of circulation patterns in southern Africa, a large percentage of pollutants are transported out of the Copperbelt into the Atlantic Ocean, whilst some are recirculated into South Africa via Angola, Namibia and Botswana. Besides industrial aerosols from the Copperbelt, the plume is likely to carry with it aeolian dust from the drier parts of the subcontinent, particularly from the western deserts in Botswana and Namibia and the semi-arid regions of Zambia and Zimbabwe, and also from the bare or sparsely covered grounds in South Africa (Piketh *et al*, 2000). Biomass burning products are likely to dominate during the burning season between August and October (Garstang *et al*., 1996).

Advection into Angola and the northern parts of Africa is through south easterly and the meridional Zaire flow that occur as a result of strong surface convergence to the north. Over the region, this occurred as a minor plume averaging 11% for all the pressure levels. In effect, maximum transportation during the winter is into the Atlantic Ocean and countries within the subcontinent. Malawi is the least affected country by aerosols being advected from the Copperbelt during this time of the year.

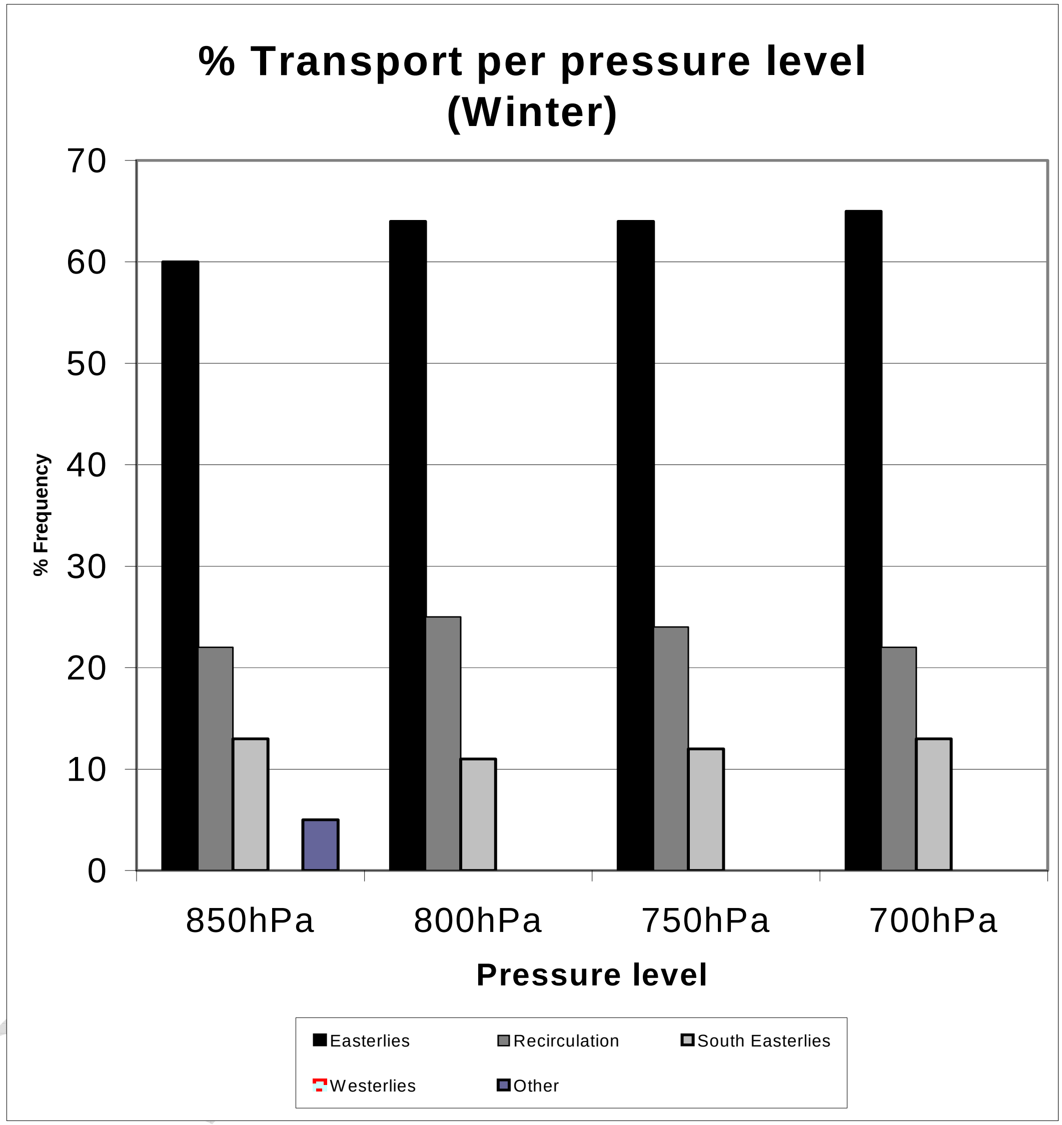


Figure 3.6. Percentage frequency of the direction of transport per pressure level during winter (1990-1994).

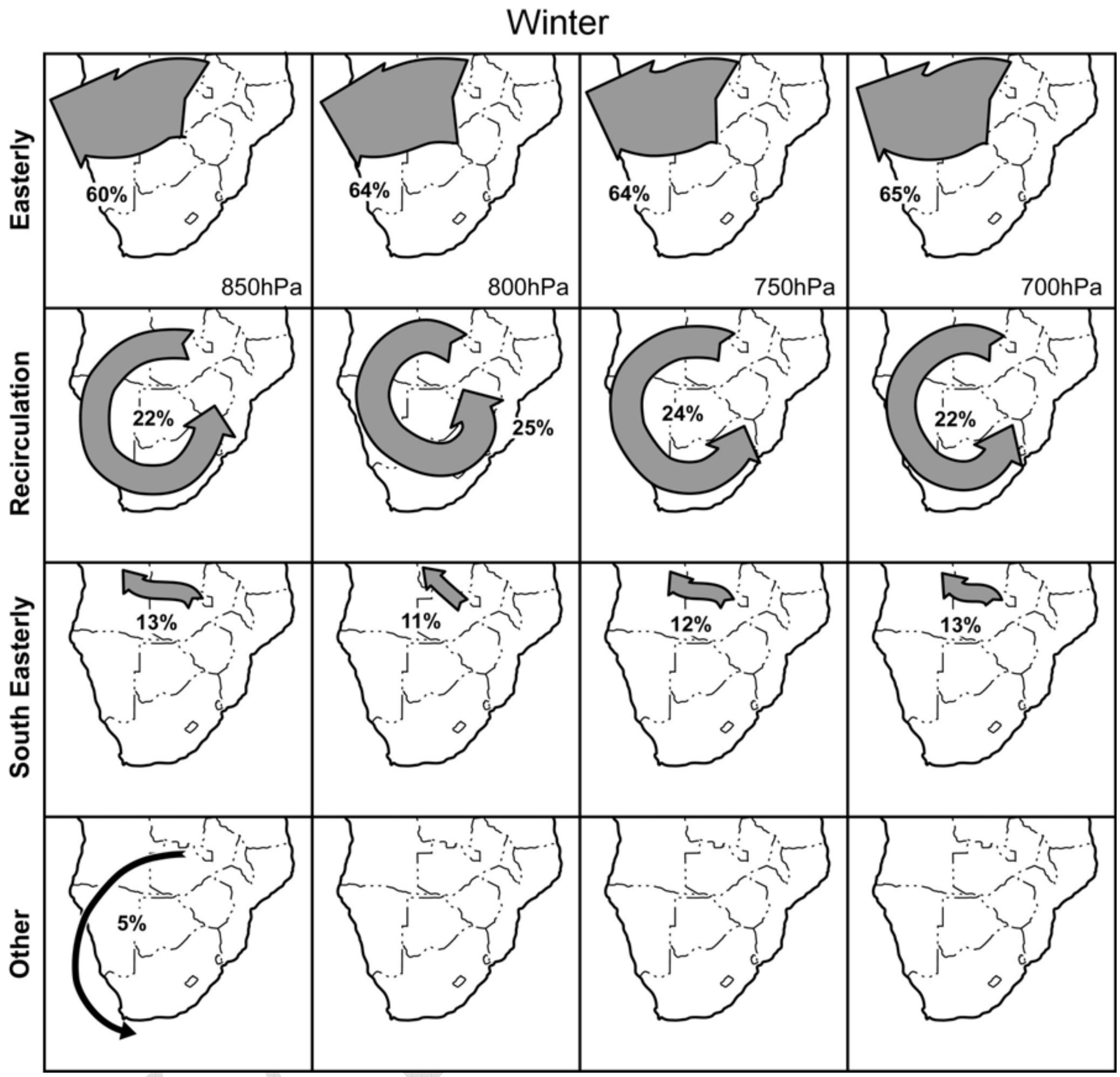


Figure 3.7 Air transport from Kitwe is towards the Atlantic and recurve towards southern Africa as meridional flow.

Spring

During the spring, southern Africa is dominated by recirculating easterlies, which dominate 56% of the time (Figure 3.8). It is within this recirculation gyre that aerosols from copper processing in the Copperbelt and products of biomass burning in the subregion are transported into South Africa. For all pressure levels, air is transported to the west (Figure 3.9), then returns at about 10ºE and flows southwards into South Africa, and exits the continent between 25 and 30ºS.

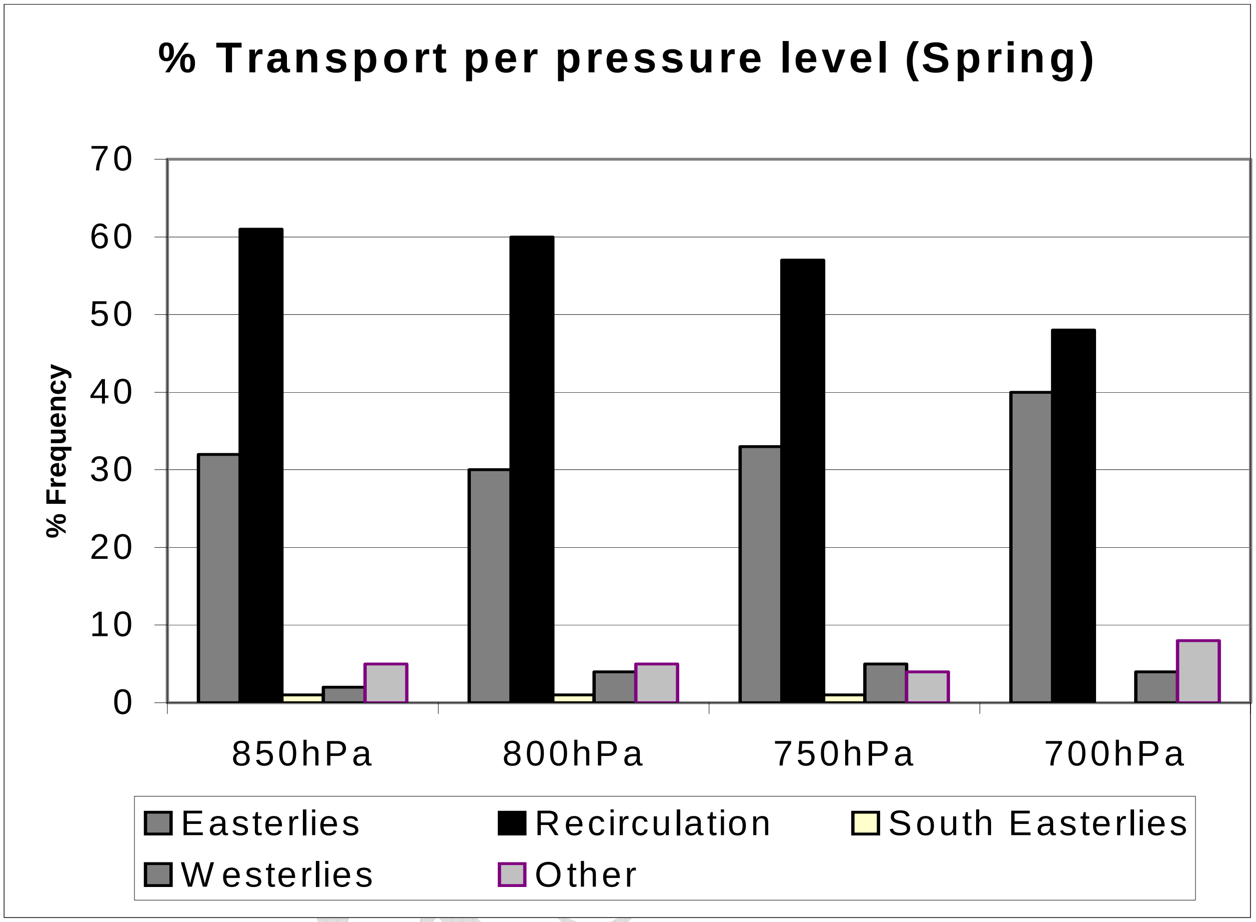


Figure 3.8 Percentage frequency of the direction of transport per pressure level during the month of October (1990-1994).

Recirculatioin is strongest at the 800 and 850hPa levels (Figure 3.8). At this level, transportation is to the south via Namibia and Botswana (Figure 3.9). At mid-tropospheric levels (700hPa) transportation is mainly to the west across the Atlantic into South America (Figure 3.9).

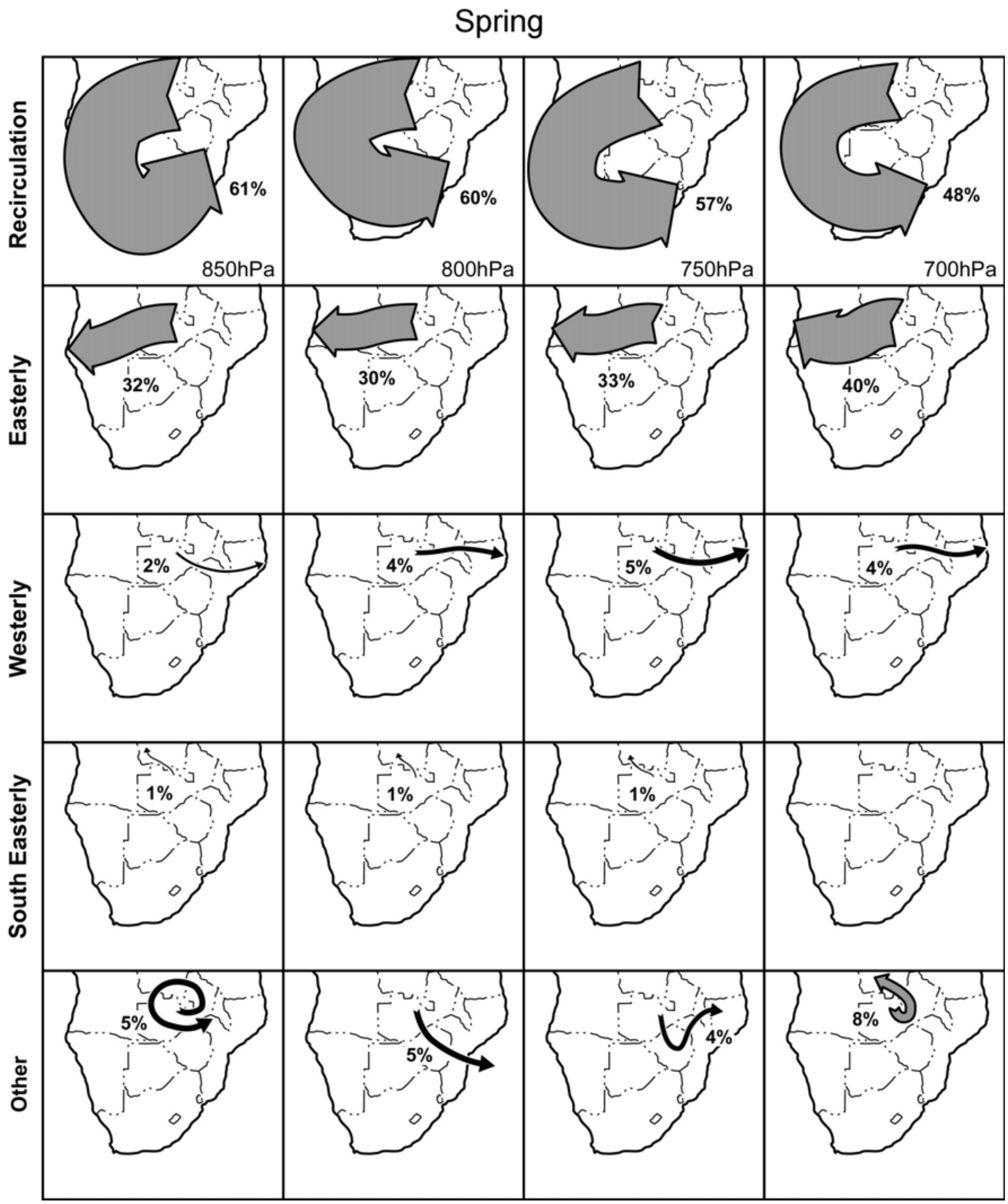


Figure 3.9 Major transport plumes during the spring for the five-year period.

4% of the trajectories consist of minor westerly flow and localized recirculation within Zambia, and direct transportation into the Indian Ocean and beyond. South easterly flow into the Democratic Republic of Congo remains minimal (1%) (Figure 3.9).

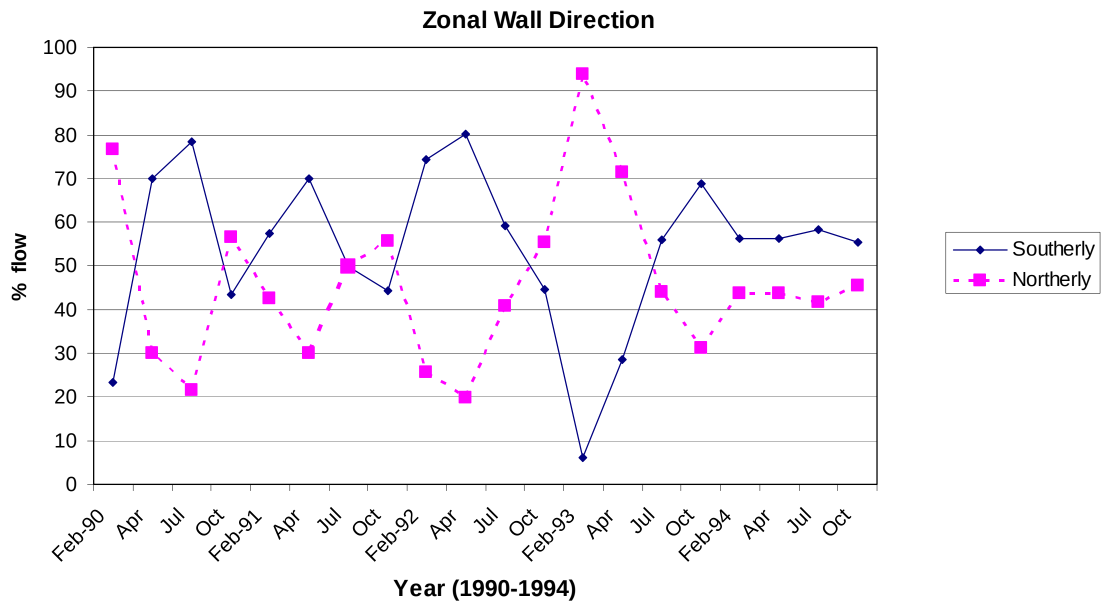
During spring, therefore, there is a considerable amount of transportation of pollutants from the Copperbelt and products of biomass burning from the neighbouring countries such as Zimbabwe, Namibia and Botswana into South Africa. Figure 3.9 shows that transportation is not only into the Atlantic during this time of the year, but also over the southern parts of the subcontinent.

3.2 MERIDIONAL AND ZONAL FLOW

An independent wall analysis has been carried out to determine the 3-dimensional meridional and zonal transport from the Copperbelt. This analysis has been carried out to complement trajectory plots that have been drawn for the region, and the results largely mirror each other.

Initial easterly and westerly flow has been determined for meridional flow, as has been initial northerly and southerly transport for zonal flow. Walls were drawn at 2º intervals from 10-40º S, and 10-40ºW, to cover the whole of southern Africa to the south of 10ºS. Vertically, walls were created from 150-950hPa. The 700 and 850hPa levels were then extracted in order to capture transport behaviour between these frequent and spatially continuous absolutely stable layers, which are prominent features of the southern African atmospheric environment.

Meridional transport indicates that 85% of initial trajectories took an easterly flow whereas 14.7% of the trajectories were westerly. Zonally, 54% of the initial trajectories were southerly and 46% were northerly. In effect, therefore, dominant flow from the region as determined from initial flow direction is easterly into the Atlantic Ocean and beyond (Figure 3.10). Easterly flow is a dominant winter and spring phenomenon. Plumes in a zonal and meridional direction join to give a recirculation component to the flow pattern in the subregion, especially during the winter and spring seasons.



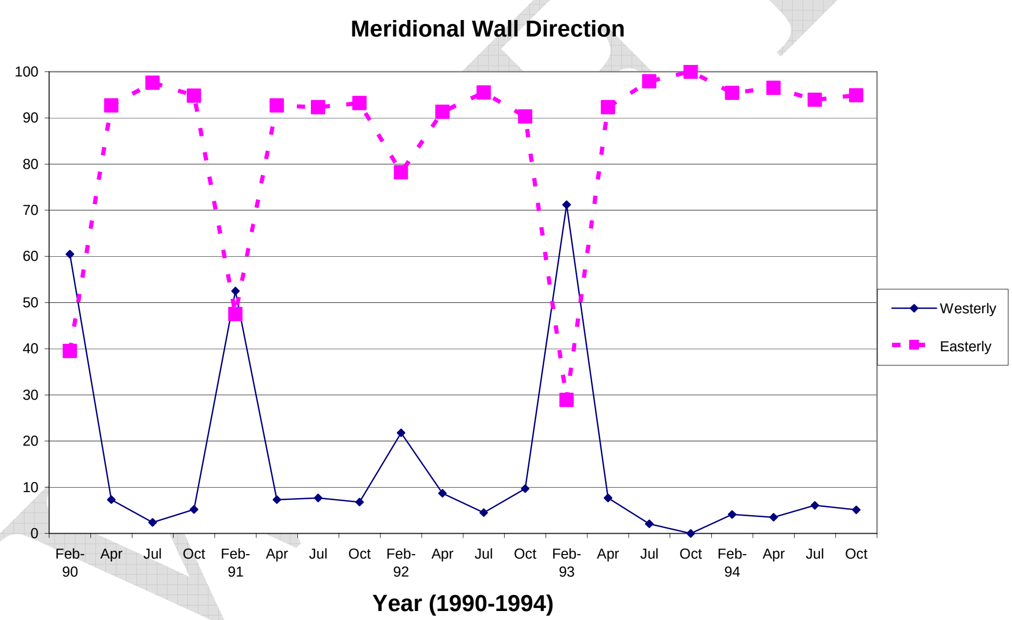


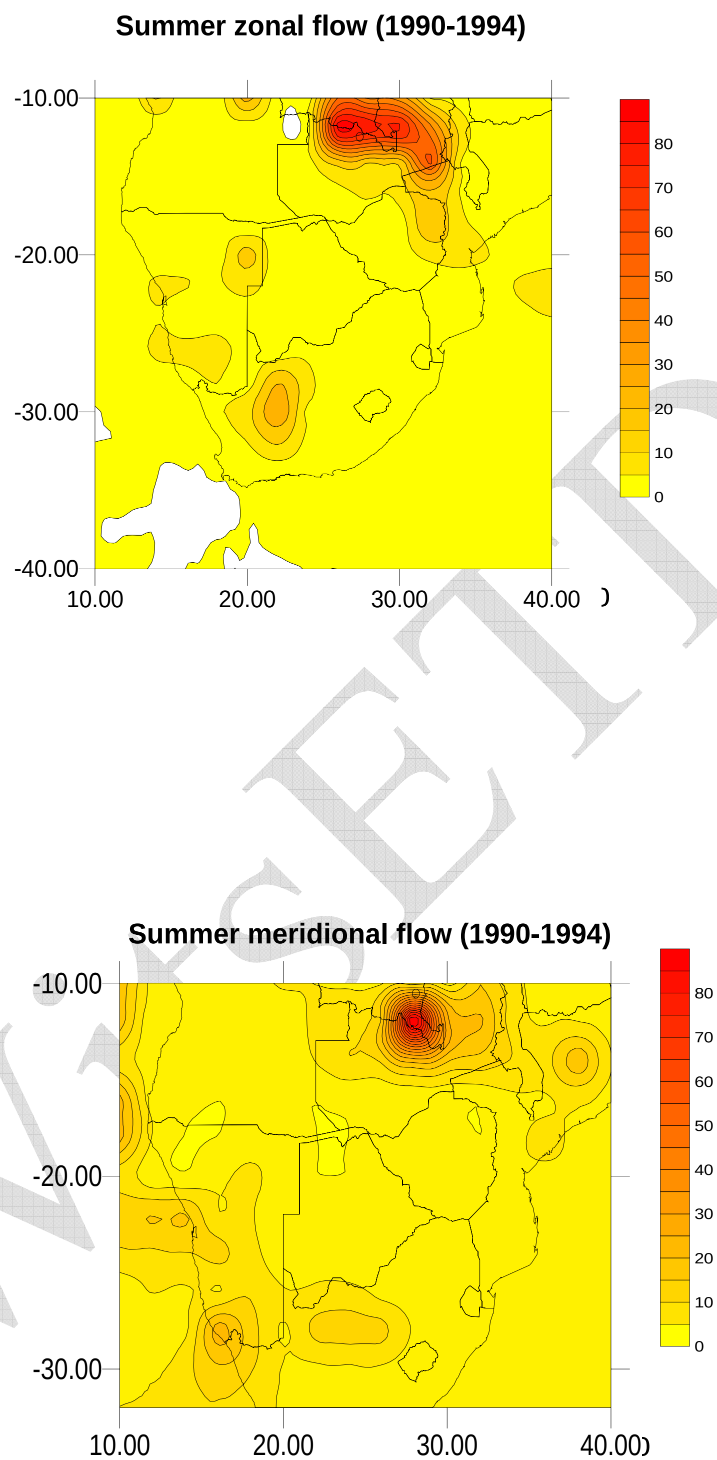
Figure 3.10 Initial transport direction for five-year seasonal meridional (a) and zonal flow (b) for the southern African subregion..

Seasonal case studies have been conducted to give an estimate of transport direction from Kitwe. Contour plots have been drawn to illustrate plume behaviour from the starting point, and to compliment the trajectory analysis that has already been carried out. Transportation that contributes to that generated from the Highveld in South Africa is noted.

Summer

The dominant mode of transportation during summer is easterly flow into Angola and the Atlantic Ocean (40%). This easterly component of trajectory flow is predominantly meridional, where transport is to the north of 10ºS into Angola. Aerosol transportation into South Africa is through a smaller recirculation gyre that occurs on average 25% of the time, and was highest at 750hPa (30%). This flow tends to recurve at around 10ºE towards South Africa via Namibia. Westerly flow into the Atlantic and beyond reaches peak values of 30% for all pressure levels. Localised recirculation around the Copperbelt also transports pollutants into neighbouring Malawi, and averages 6% (Fig 3.11a).

(a)



(b)

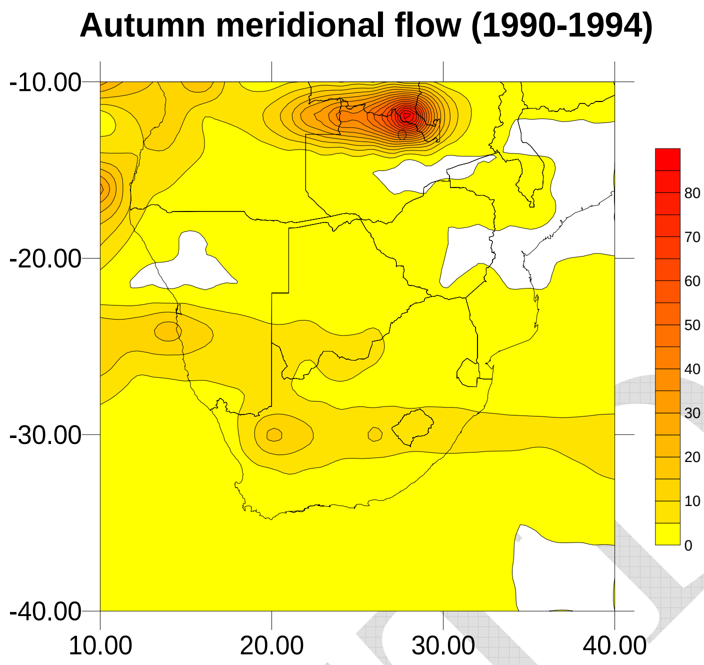
Figure 3.11 Direct merdional (a) and zonal (b) transport from the Copperbelt. Transport into South Africa is through a recirculation plume that occurred on average 25% of the time (b).

Autumn

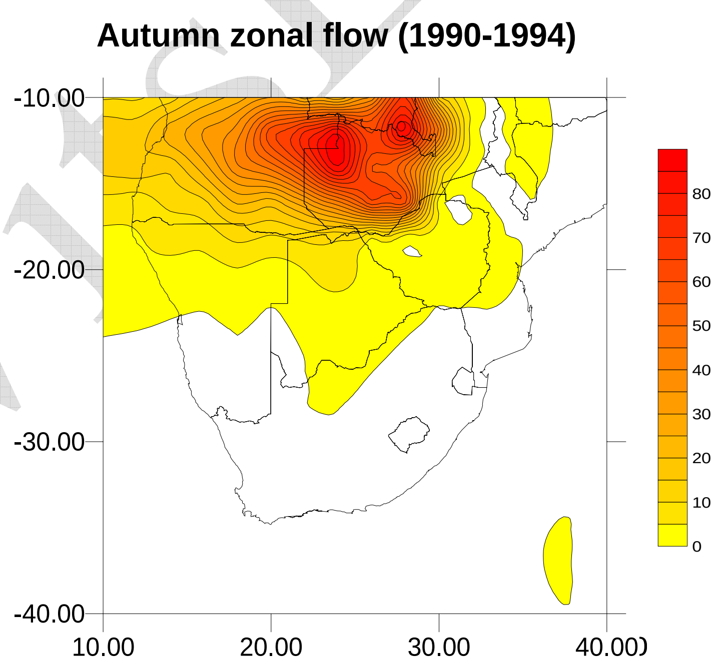
Direct zonal and meridional transport in autumn is dominantly easterly for all pressure levels (60%). Recirculation occurs approximately 25% of the time and under this recirculation gyre, aerosols and other products of biomass burning are transported into South Africa and out of the southern African subcontinent at around 31ºS towards Australasia (Figure 3.12a). Because of the general lack of rainfall in autumn, airborne particles are likely to be transported farther.

Meridional easterly and recirculation flow is demonstrated by a strong plume that traverses Angola towards the Atlantic. Easterly flow is dominant at the 850 hPa level, and is followed by recirculation at much lower levels of the atmosphere.

Zonal transport is characterized by trajectories that circulate within Zambia and to the north, and within Zimbabwe to the south. These trajectories eventually take on an easterly flow towards the Atlantic (Figure 3.12b). Direct westerly transport remains minimal during this time of the year (10%).



(a)



(b)

Figure 3.12 Meridional transport is into the Atlantic (a), with a smaller circulation plume that transports aerosols into South Africa. Zonal transport is mainly easterly into the Atlantic Ocean and beyond (b).

Winter

In winter, aerosol transportation is dominantly easterly for both the meridional and zonal flow (63%). Meridionally, aerosol transportation is into Angola and the Atlantic. Recirculation into Namibia, Botswana and South Africa (Figure 3.13a) is significant at all pressure levels, and accounts for 20% of the transport. Within this recirculation gyre, products of biomass burning, which are prevalent during the dry period of the year, join those originating from copper processing in the Copperbelt. The plume picks up pollutants from the South African Highveld to eventually exit the continent at around 31ºS. Smaller south easterly plumes transport pollutants into Angola, and these average 10% of the time.

(a)

(b)

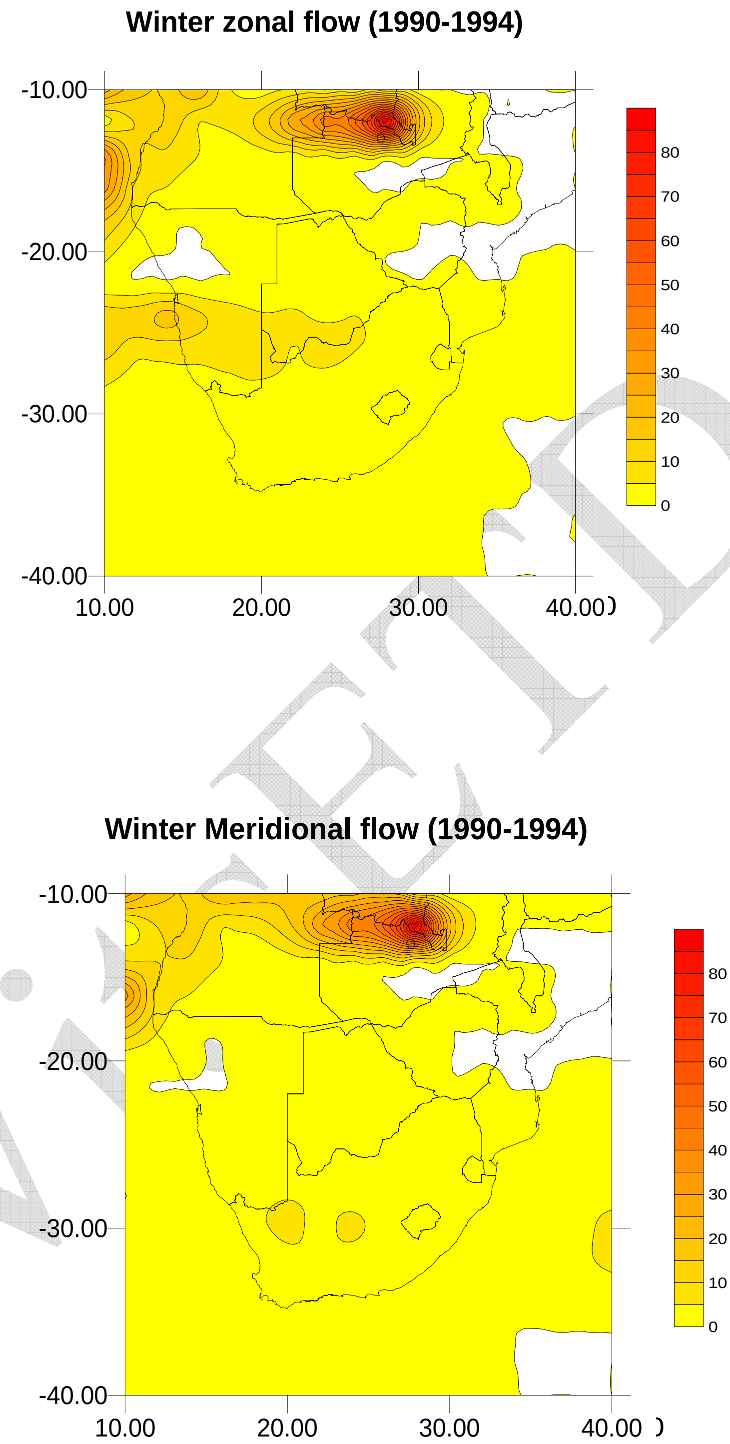


Figure 3.13. In winter aerosol transportation into South Africa is through zonally circulating transport occurring in average 25% of the time for all pressure levels. Otherwise predominant transport is into the Atlantic Ocean through easterly flow (b).

Spring

During spring, there is strong meridional and zonal transportation of aerosols from Kitwe into South Africa. Recirculation accounts for 60% of transportation, and significantly, transport is into South Africa. Recirculation is strongest with zonal flow (Fig 3.14a) where large parts of Namibia and Botswana are also affected. The plume traversing to South Africa from the Copperbelt is likely to carry with it products of biomass burning from other countries in the southern African subregion. Spring is the major burning season in southern Africa so transport should have a strong biomass burning component. Aerosols from the Copperbelt join those from the South African Highveld (Fig 3.14a and b) to exit the continent along the South African east coast towards the Indian Ocean and beyond. Easterly transport into the Atlantic averages 35%. Direct transport into the Indian Ocean and beyond is insignificant, and averages 3%. Localised disturbances result in minor plumes recirculating pollutants within the Copperbelt itself.

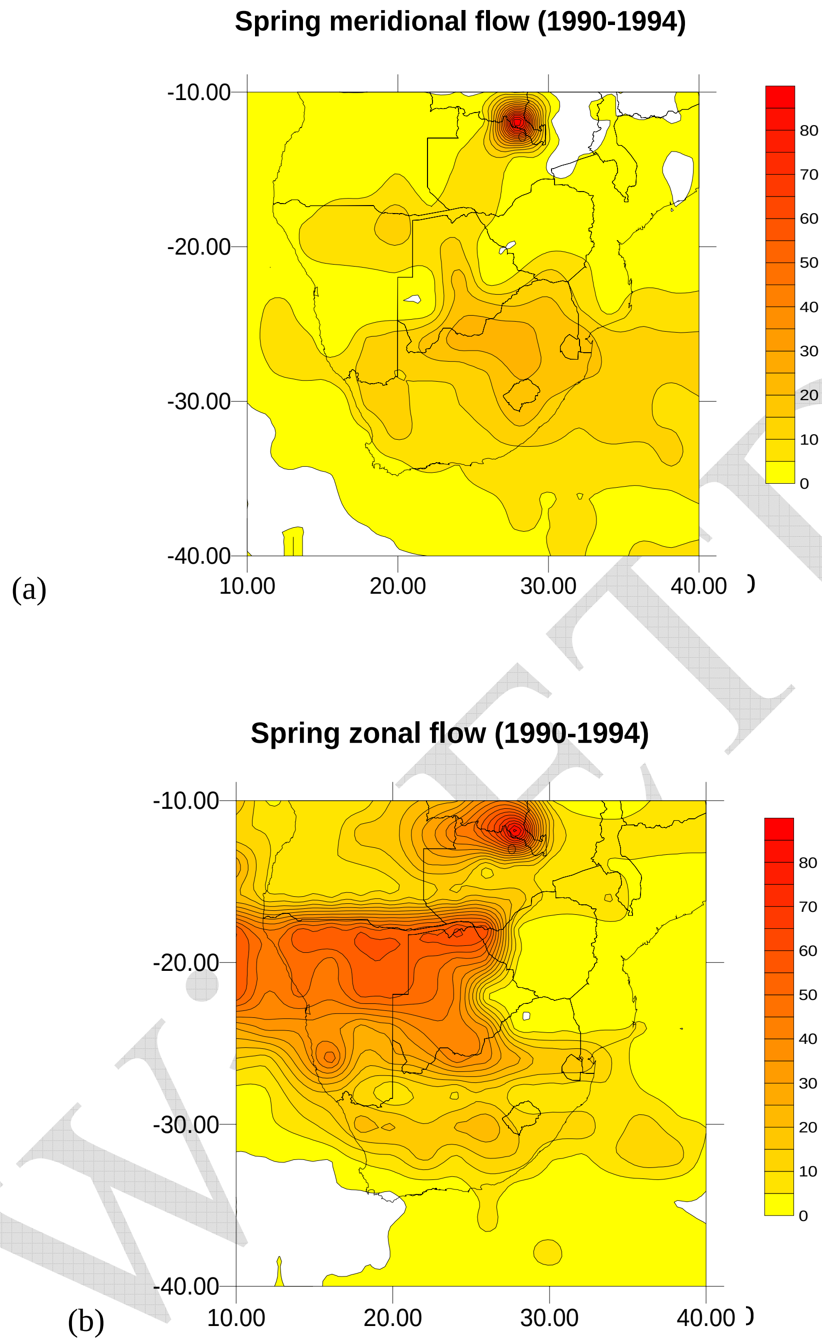


Fig 3.14 Flow from Kitwe indicating meridional flow to the south via Namibia and Botswana and localized recirculation within the Copperbelt (a). The zonal component contributes substantially to pollutant transportation into South Africa.

3.3 REGIONAL PERCENTAGE FLOW

Large-scale off-shore transport of aerosols and trace gases in large plumes from the Copperbelt to the Atlantic and Indian Ocean are a common occurrence. Recirculation is a major atmospheric transport phenomenon especially during the spring season, when aerosols are transported to countries neighbouring Zambia and to the south.

Percentages have been calculated for all pressure levels on the frequency of the passage of trajectories for countries neighbouring and to the south of Zambia. Two major pathways have been identified for the region (Figure 3.15). The Angolan plume transports aerosols directly into the Atlantic Ocean and beyond. This plume dominates and transports air from the Copperbelt into the Atlantic (33% of the time) at lower levels owing to subsidence over the western sub-continent and South Atlantic Ocean. This plume is most pronounced in wet years when shifts in the planetary zonal wind fields result in easterly wind anomalies over low southern latitudes (Garstang *et al.*, 1995). The Natal plume is associated with recirculation and a subsequent transport of air into the Indian Ocean and beyond. This plume transports air to the southwestern Indian Ocean at higher levels at a mean height of 525hPa, but at no higher than the 400hPa level. The plume consists of transport into South Africa via Namibia and Botswana, and occurs on average 18% of the time. Direct transport from the Copperbelt into the Indian Ocean is also via Zimbabwe Malawi and Mozambique. Much more air is transported into the Atlantic Ocean in the Angolan plume than reaches the Indian Ocean via the Natal plume, which occurs under dry, large-scale circulation fields (Tyson *et al*, 1996). Tyson *et al.*

(1996) have also found out that recirculation over the north western continental areas of Namibia, Angola and Zambia is significantly less than that occurring to the south-east over South Africa, Zimbabwe and Mozambique when high pressure conditions prevail.

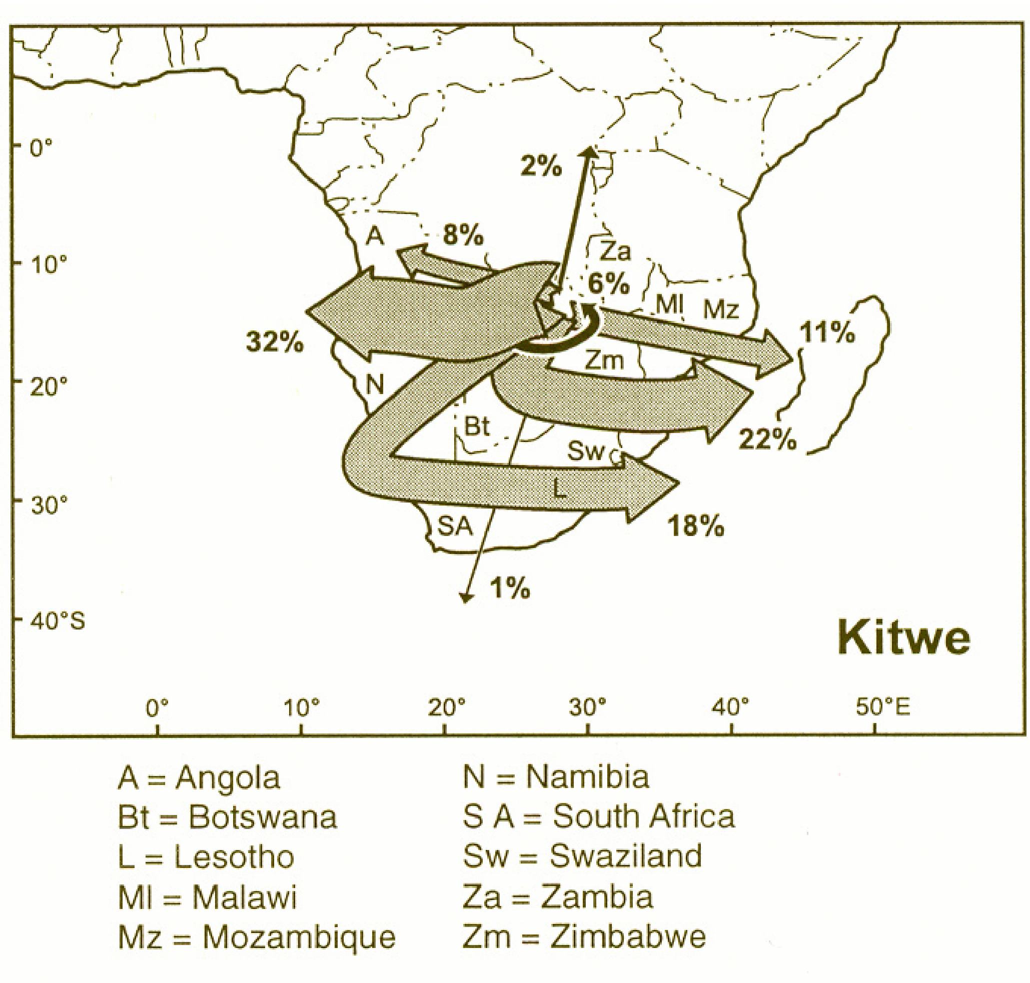


Figure 3.15 Major circulation patterns in the southern African subregion from the Copperberbelt.

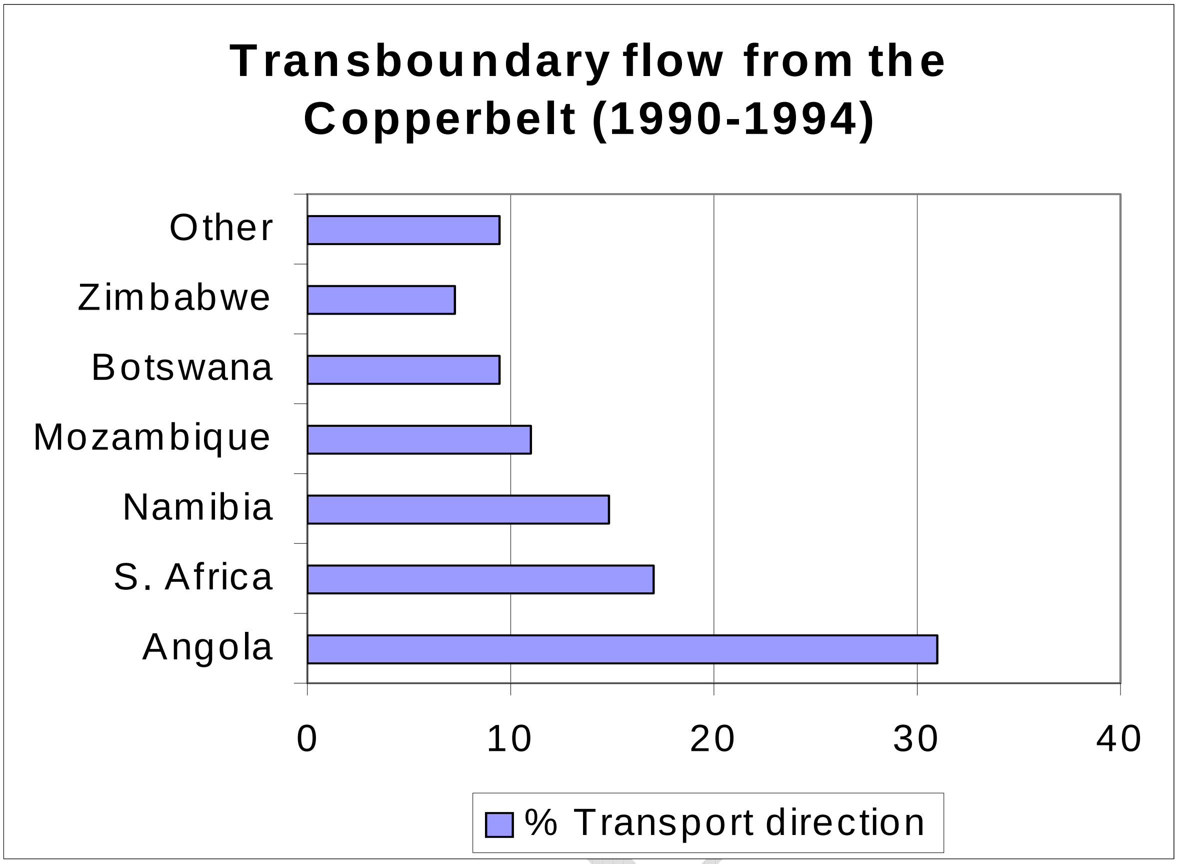


Figure 3.16 Percentage frequency of trajectory passage of air at all pressure levels from the subregion. 'Other' denotes countries such as Lesotho and Swaziland and Malawi.

The largest airflow from the Copperbelt is over Angola (32%), which is a westward flow towards the Atlantic Ocean (Figure 3.16). Part of this flow is recirculates southwards and contributes to the flow that eventually enters South Africa as a westerly flow. This flow is likely to transport not only sulphur pollutants from the Copperbelt, but products of biomass burning and aeolian dust from the Southern African subregion, especially during the dry winter and spring seasons. 18% of the airflow enters South Africa via Namibia, 22% via Botswana, and 11% flows as a straight westerly flow out of Zambia and out into the Indian Ocean via Mozambique.

Trajectory analysis has also shown that zonally air is transported out of the Copperbelt between 20-30ºE towards the equator (2%) and out of the continent via the Cape towards the South Atlantic (1%) (Figure 3.15).

****

This study has revealed that there is a substantial amount of pollutant transportation in the Southern African sub-region from the Zambian Copperbelt. Forward trajectories calculated from Kitwe indicate that at all pressure levels transport is characterised by easterly flow into the Atlantic Ocean and beyond, and widespread recirculation. Recirculation transport is into South Africa, via Angola, Namibia and Botswana and out into the Indian Ocean and beyond at around 25-30°S. This plume carries with it sulphur pollutants from copper processing in the Copperbelt, and biomass burning products from savanna fires in the region. Observations and modeling of trajectories reveal that the plume may reach Australasia on occasions. As the plume leaves South Africa it tends to rise owing to the convergence and ascent of air with poleward geostrophic flow and a constant pressure gradient occuring in the mean wind-field on the western margin of the center of the south Indian Ocean.

Modelled plume behaviour using the Wall analysis has demonstrated the variabililty of trajectory flow in the subregion. Such variability is consistent with modeled Lagrangian flow that has been used to determine the seasonality of trajectory flow from the same starting point for the same time period.