Three-dimensional kinematic trajectory modelling of water vapour transport over Southern Africa

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Abstract

Back and forward kinematic trajectory modelling has been undertaken for rain and no-rain days over the central interior of South Africa in mid-summer. No-rain days (rain days) are shown to be characterised by dry (moist) south-westerly (northerly to north-easterly) flow originating over the South Atlantic (tropical Indian) Ocean. Air parcels for tropical-temperate troughs originate over the tropical Indian Ocean and trace south and south-eastwards across Southern Africa, corresponding closely to the position of the trough-associated cloud band. Trajectory modelling of a cut-off low pressure system reveals the presence and interaction of a cold, dry, descending conveyor from the south and a warm, moist, ascending conveyor from the north.

Introduction

Moisture content of the air plays an important role in determining the thermal stability of the atmosphere and is a crucial factor in the precipitation process. By virtue of its position within the subtropical belt of high pressure, South Africa is characterised by a semi-arid to arid climate. Among important factors affecting the moisture over the region, are the low levels of moisture available from the generally sparsely vegetated continental surface (Henning, 1989; Lindesay, 1992). Consequently, most of the moisture that contributes to precipitation over Southern Africa must be imported over the subcontinent from source regions elsewhere.

Despite the importance of water vapour transport for the production of rainfall over Southern Africa, few transport analyses have been undertaken for the region. Whereas studies of atmospheric moisture have been undertaken for West Africa (Adedokun, 1983; Anyadike, 1979), South America (Rathor et al., 1989), North America (Hastenrath, 1966) and Australasia (Hutchings, 1961), similar studies only recently have been conducted for Southern Africa (Jury and Lindesay, 1991; D'Abreton and Lindesay, 1993; D'Abreton and Tyson, 1995). During the often wet mid-summer month of January conditions are characterised by enhanced northerly meridional flow, in contrast to dry conditions when westerly zonal flow is the predominant circulation characteristic (D'Abreton and Lindesay, 1993). Analysis of divergent water vapour transport reveals that transport to the south-west from the tropical Indian Ocean is the most important source for water vapour in wet Januaries over South Africa (D'Abreton and Tyson, 1995). During dry Januaries, the vapour source regions appear to be located preferentially over the south-western Indian Ocean (D'Abreton and Tyson, 1995).

In this paper, water vapour transport over Southern Africa will be examined further using Lagrangian kinematic trajectory modelling. A trajectory climatology of January water vapour transport for rain days and no-rain days over the central interior of South Africa will be developed. In addition, vapour transport for various individual rain-producing systems will be examined. Finally, changes in air parcel water vapour content will be used to indicate, in general, major water vapour source and sink regions for South Africa.

Data and methodology

The European Centre for Medium Range Weather Forecasts (ECMWF) GRIB IIIb dataset, on a 2.5° grid, has been used for three January case studies, namely those of 1980, 1981 and 1991. The selection was done on the basis of one anomalously wet month (1981), one anomalously dry month (1980) and one month with average precipitation (1991). Daily rainfall statistics have been obtained from the South African Weather Bureau for the summer rainfall regions on the plateau of South Africa. Satellite imagery is from NOAA2 and NOAA5 polar-orbiting satellite (published by the Environmental Data Service of the United States Oceanic and Atmospheric Administration) and the geostationary Meteosat imagery (published by the European Space Agency/EUMETSAT).

The trajectory model is Lagrangian, with atmospheric motion being described in terms of individual air parcels moving with air streams resulting from changing synoptic circulation patterns (D'Abreton, 1996). The model uses the explicit method of integration defined by

$$x(t+dt) = x(t) + V[x(t)]dt \qquad (1)$$

where x(t+dt) is the new three-dimensional parcel position at t + dt, x(t) is the old position a and V(t) is the parcel velocity vector. The time-step (dt) used in the analysis is 15 min. A more complete description of the trajectory methodology is to be found in D'Abreton (1996). Forward and backward trajectories have been performed from designated points of interest as origin to give 20-d trajectories for each air parcel analysed.

Lagrangian methods have been applied extensively in the evaluation of synoptic-scale transport of anthropogenically-produced air pollutants and biogenic aerosols and trace gases (Eliassen, 1978; 1980; Eliassen and Saltbones, 1975; Krishnamurti et al., 1993; Tyson et al., 1996a; Garstang et al., 1996). In this paper an attempt is made to apply the principles used in studies of the

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Lagrangian transport of aerosols and trace gases to water vapour transport. The water vapour tendency equation has been used to calculate the approximate water content of the air parcel at each point along the trajectory. The tendency equation is given by:

$$\frac{\delta q}{\delta t} + V\cdot\nabla q + \omega \frac{\delta}{\delta t} + (p - e)$$

where q is specific humidity, V is the horizontal wind vector and the vertical velocity. Sub-grid scale processes have been ignored. The major assumption made is that water vapour is a passive tracer. This assumption is flawed in that evaporation (e) and precipitation (p) processes in the parcel are not represented in the model. Notwithstanding, the model represents processes occurring on a larger spatial scale than the grid scale and gives a useful indication of the moisture convergence or divergence within air parcels and, in general, a highly informative representation of large-scale moisture transport.

A statistical analysis of back trajectory pathways for 18 rain and 19 no-rain days has been performed using a modified version of a programme developed at the University of Virginia (Tyson et al., 1996a; Garstang et al., 1996). Frequencies and percentages of trajectories passing through imaginary walls of longitude at various latitudes and altitudes are calculated, transport fields are delineated and maximum frequency pathways determined. The approach has considerable potential for assessing the contrasting pathways of mid-summer water vapour transport to the central summer rainfall region of South Africa during wet and dry conditions.

Vertical transport of water vapour has been calculated from the relationship

$$w q = w q + w^*q^* + w'q' \qquad (3)$$

where the total vertical water vapour transport is equal to the sum of the mean circulation, standing eddy and transient eddy vertical water vapour transport.

Trajectory fields

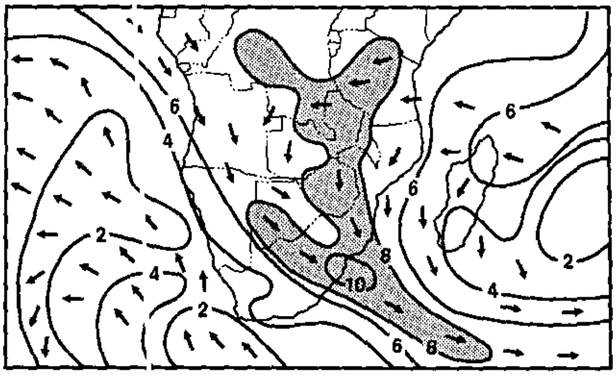
An indication of moisture transport into a region, or into a specific synoptic weather system, may be gained from superimposed specific humidity and atmospheric flow fields. Such is the case for transport into a tropical-temperate trough occurring on 24 January 1981 (Fig. 1a). Transport over a given region over a number of days may be assessed from Hovmöller diagrams. A case in point is the mid-January 1981 propagation of vertically-integrated 850-300 hPa precipitable moisture from north-east to south-west through 20° of longitude over the northern parts of Southern Africa (from A to B in Fig. 1b). Use of individual trajectories and integrated trajectory fields offers an even better way of assessing moisture transport.

Back trajectories from a point of origin over the Pretoria-Witwatersrand-Vereeniging (PWV) region in the Gauteng Province of South Africa have been selected for analysis on days in January 1980, 1981 and 1991 in which rainfall greater than 5 mm fell (classified here as rain days), and for days with no rainfall (classified as no-rain days) over the area. Previously it had been shown that the 700 hPa level is the level of greatest importance for moisture transport during rain events over the summer rainfall region of the South African plateau (D'Abreton and Tyson, 1995; Van den Heever, 1995). Consequently, moisture transport at the 700 hPa level provides the major focus for investigation in this study.

Back trajectories reveal that on rain days the 700 hPa moisture transport field is characterised by easterly-component flow from the tropical Indian Ocean north of Madagascar (Fig. 2a). The mean frequency transport pathway indicates an easterly onshore flow over tropical Africa at approximately 10°S. About 37 per cent of the trajectories involved in transporting moisture into precipitating systems over the PWV area cross the meridian at 40°E 6 d prior to reaching the point at which rainfall occurs. Four days before precipitation, the moisture being transported has reached, on average, a position at about 27°E,17°S over Zambia en route to central South Africa. Average specific humidities increase from 9.5 g·kg^{-1} over the tropical Indian Ocean at 50°E to 10.5 g·kg^{-1} over the northern Mozambique/southern Tanzanian coast and increase further to 11.9 g·kg^{-1} over Zambia (Fig. 2a). Back trajectory modelling indicates that 75 per cent of the total moisture transport into January rainfall events over the PWV area has passed over Zimbabwe and Zambia.

The Indian Ocean region north of Madagascar coincides with an area of relatively high (> 120 W·m^{-2}) vertical oceanic latent heat flux (Hastenrath and Lamb, 1979). This is the primary

a) Specific humidity field (g·kg^{-1})



b) Precipitable water, 850 - 300 hPa (mm)

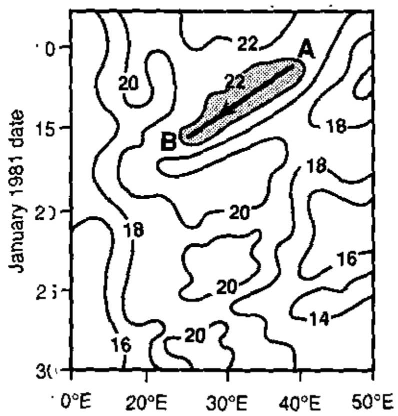


Figure 1

a) Superimposed specific humidity (g·kg^{-1}) and 700 hPa flow fields for 24 January 1981

b) Daily march of precipitable water (mm) integrated between 850 and 300 hPa over the period 10 to 30 January 1981.

Shading indicates specific humidities > 8 g·kg^{-1} in (a) and precipitable water > 22 mm in (b).

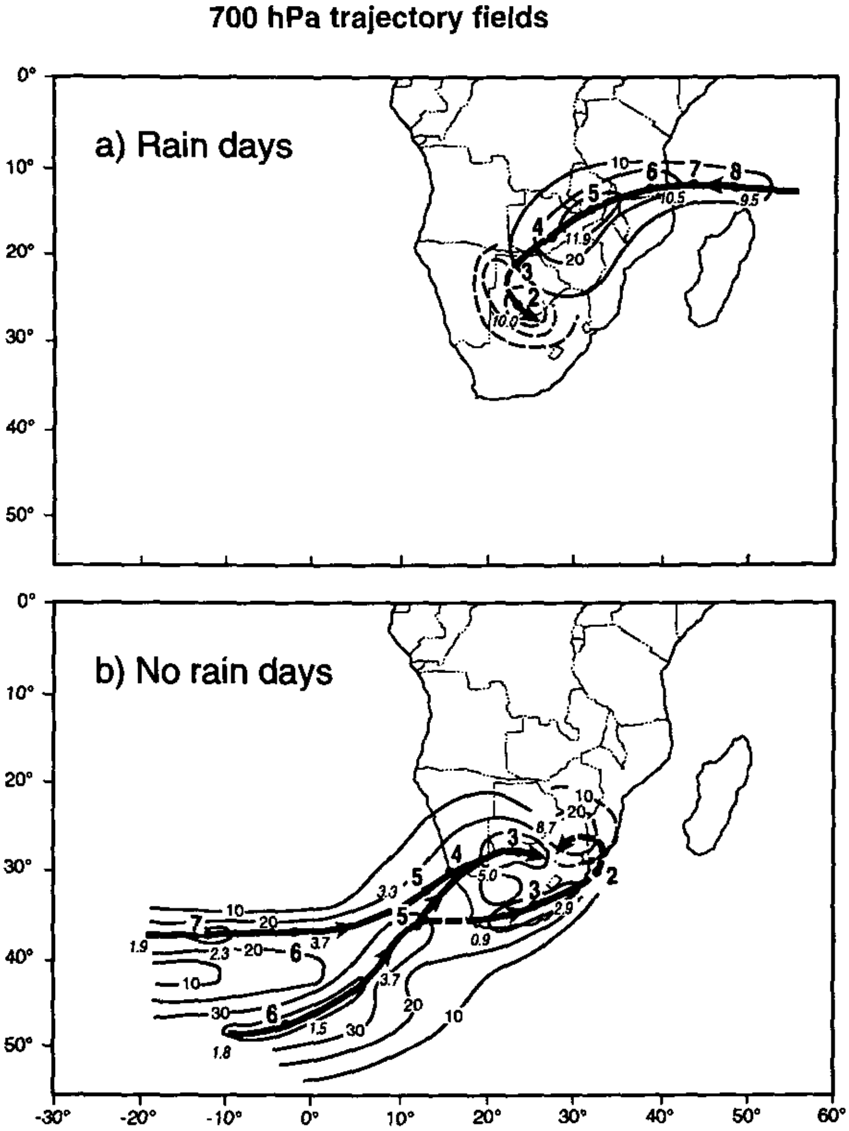


Figure 2
Mean trajectory fields for (a) rain days and (b) no-rain days in January over the PWV region. Contours give percentage occurrence of trajectories and heavy lines the maximum frequency pathway of trajectories. Large, bold numbers denote average times of travel (d) from the PWV region. Italicised values give meridionally-averaged specific humidities (g·kg^{-1}) of mean air parcels at specific longitudes.

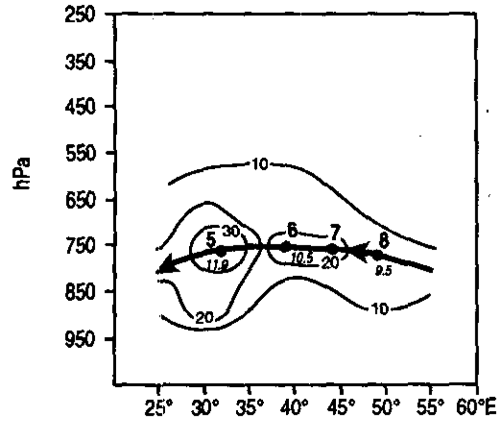
moisture source area where the air acquires its mean specific humidity of 9.5 g·kg^{-1} on average 8 d before reaching central South Africa. The increase in specific humidity as the air is transported in a north-easterly stream over the continent south of the equator and over greater Southern Africa is the result of moisture convergence in air streams themselves converging (D'Abreton and Tyson, 1995).

Anticyclonic curvature of the moisture stream occurs over northern Botswana so that for the last 2 d of its transport the moisture stream approaches the PWV from the north-west, at which time, either by moisture divergence or precipitation, the mean specific humidity is 10.0 g·kg^{-1}. Of moisture-bearing trajectories traced back from the PWV during January rain events, 37 per cent approach the area from the north-west. The remainder approach directly from the north or from the north-east.

Backward trajectories for no-rain days during January are markedly different to those of rain days (Fig. 2b). Rainless days are characterised by a south-westerly moisture transport from the South Atlantic Ocean to the south-west of Cape Town. Under such conditions, approximately 40 per cent of the moisture transport in the field shown in Fig. 2b passes through the Greenwich meridian. Of the moisture transport reaching the PWV with a westerly component on rainless days, almost all crosses 20^{0}E about 3.5 d before reaching its destination over Gauteng in two streams, one over the southern coastal regions, the other via the Northern Cape. By comparison to specific humidities in the northerly component air streams on rain days, those on the no-rain days in the southerly component air streams are low. Thus just under six days before reaching the PWV the average specific humidity in the transport field on the Greenwich Meridian at 25^{0}S is 3.7 g·kg^{-1} and at about 45^{0}S is 1.5 g·kg^{-1}. The average moisture contents at 25^{0}E for the two main moisture streams are 5 g·kg^{-1} and 0.9 g·kg^{-1} for the northern and southern paths respectively (Fig. 1b).

In excess of 40 per cent of the moisture trajectories approach the PWV from the west along the maximum frequency pathway in the northerly airstream during rainless days; 30 per cent of the moisture trajectories approach from the east along the maximum frequency pathway of the southerly stream after having recurved anticyclonically from the south-west in their passage across the east coast of South Africa (Fig. 2b). In recurving over the coastal waters of the Indian Ocean, the average moisture content increases from 3 to 4 g·kg^{-1} along the south-east coast to more than 8 g·kg^{-1} over the Witwatersrand (Fig. 2b). This increase may be explained by the passage of the air over the waters of the Agulhas Current, where latent heat flux from the sea surface is greater than 120 W·m^{-2} (Hastenrath and Lamb, 1979). This mechanism is in agreement with earlier observations of a water vapour source

a) Rain



b) No rain

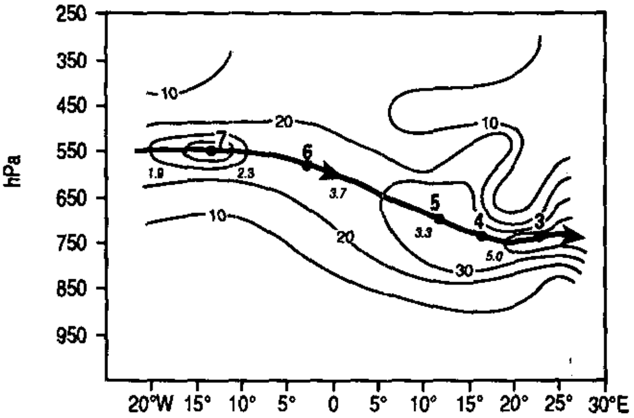
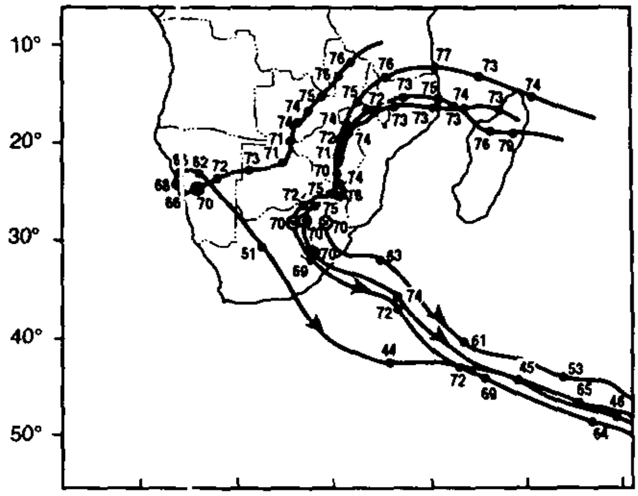


Figure 3
Trajectory fields in the vertical for (a) rain and (b) no-rain days during January over the PWV region. Labelling is as in Fig. 2

700 hPa trajectories

a) daily pressure levels (hPa x10)



b) daily specific humidities (g.kg⁻¹)

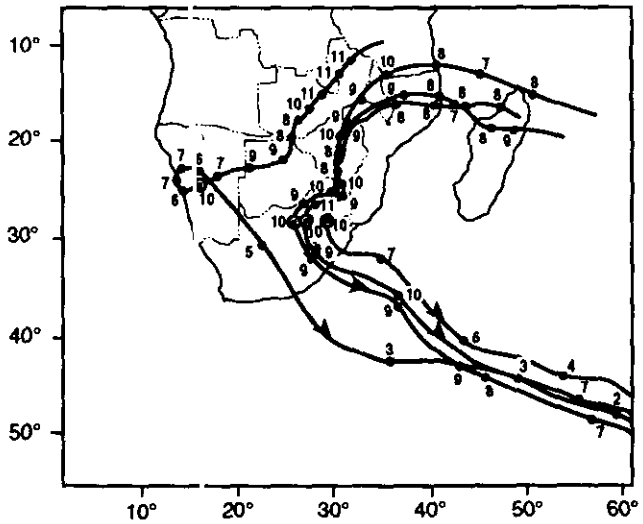


Figure 4
Backward and forward 700 hPa trajectories starting from selected points over South Africa (designated by heavy dots) starting on 22 January 1981 to show daily (a) pressure levels (hPa x 10) and (b) specific humidities (g·kg⁻¹)

over the region during dry Januaries (D'Abreton and Tyson, 1995). For rain-day conditions, air parcels originating from the tropical Indian Ocean north of Madagascar undergo almost no vertical displacement as they move toward South Africa (Fig. 3a). For the case studies examined, the maximum frequency pathway along which most moisture was transported maintained an almost constant height between 800 and 750 hPa over a period of 8 d and over an approximate distance of 4 500 km from source region to the PWV. By contrast, in the case of no-rain days, the mean trajectory pathway along which most moisture is transported indicates slope-wise descent of air parcels from the 550 hPa level over the central Atlantic Ocean to the 750 hPa level over the subcontinent (Fig. 3b). In excess of 150 hPa of subsidence occurs in approximately 7 d.

A case study of a tropical-temperate trough

Tropical-temperate troughs and their associated cloudbands have been the subject of much research in recent years (Harangozo and Harrison, 1983; Harrison, 1984; Harrison, 1986; Jury and Lindesay, 1991; D'Abreton, 1993; Van den Heever, 1995). These important rain-producing systems have been found to account for up to 60 per cent of the rainfall in January over the summer rainfall region of South Africa (Harrison, 1984). The composite circulation systems are formed when an upper-level westerly wave interacts with a surface-induced, semi-stationary easterly wave. Subtropical convection is enhanced in the region as a result of surface convergence to the east of the wave and middle and/or upper-level divergence ahead of the upper wave. Along the leading edge of the upper westerly wave momentum, water vapour and latent heat are transported poleward out of the tropics and subtropics in clearly identifiable cloud bands. Copious amounts of rainfall may occur when these north-west to south-east oriented cloud bands occur preferentially over the summer-rainfall region of South Africa during wet years (see Jury and Lindesay, 1991). In contrast, during dry years, the cloud bands migrate eastwards and locate instead over Madagascar with a concomitant eastward shift of the band of maximum precipitation away from the subcontinent (Harrison, 1986; Tyson, 1986; Barclay et al., 1993;

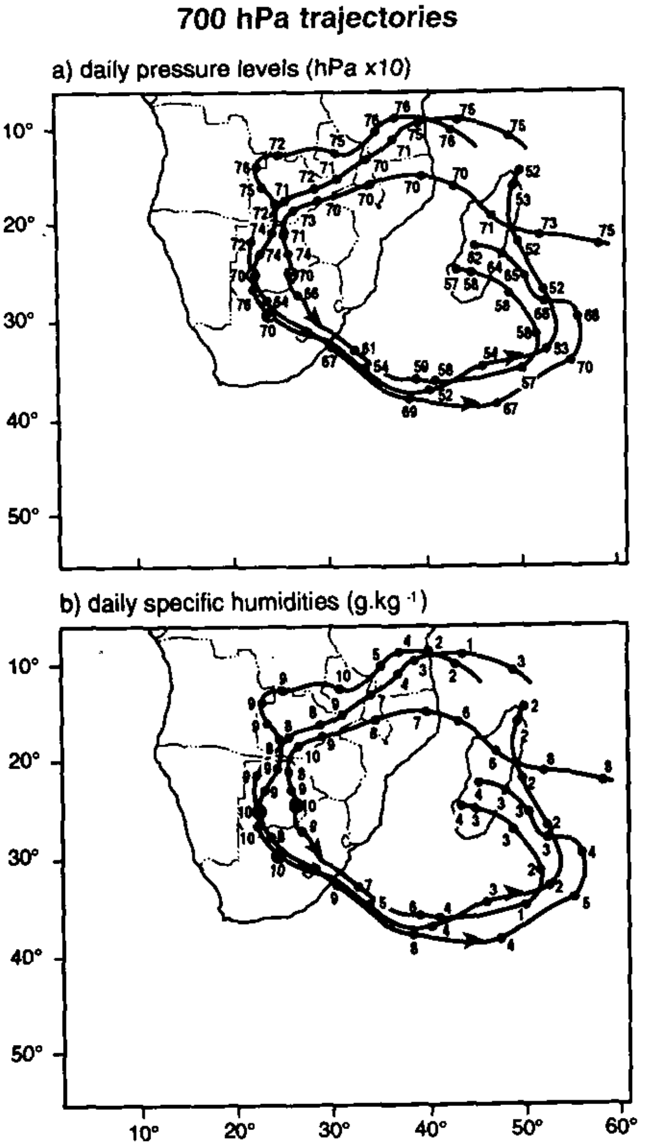


Figure 5
Backward and forward 700 hPa trajectories starting from selected points over South Africa (designated by heavy dots) starting on 23 January 1981 to show daily (a) pressure levels (hPa x 10) and (b) specific humidities (g·kg^{-1})

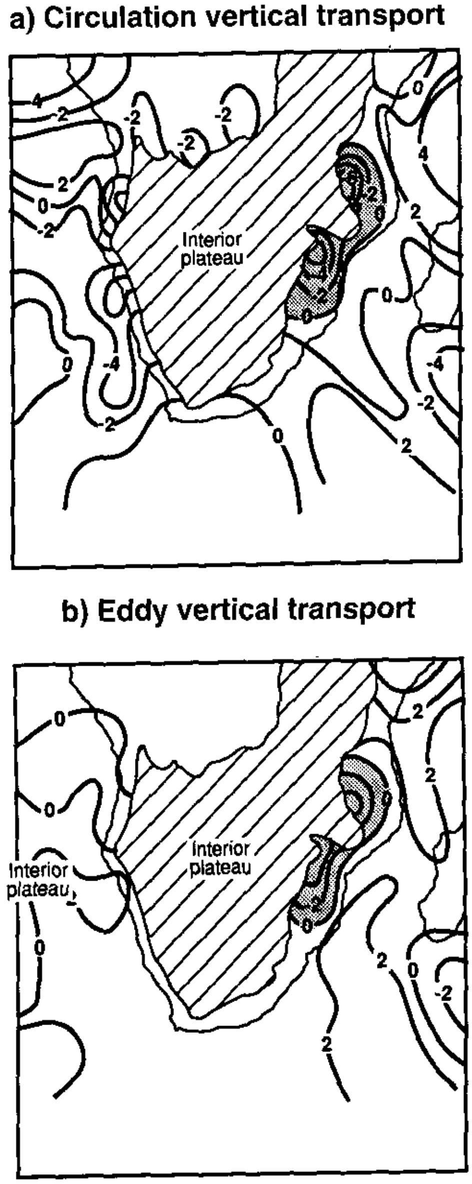


Figure 6
Circulation (a) and standing eddy (b) vertical transport of moisture from the 1000 hPa level for 15 January 1981. Units are x 100 g·kg^{-1}·pa^{-1}·s^{-1} in (a) and x 10 g·kg^{-1}·pa^{-1}·s^{-1} in (b)

Van den Heever, 1995).

A well-documented case study of a tropical-temperate trough and associated cloud bands occurring between 22 and 23 January 1981 (Van den Heever,1995) has been selected for further investigation. Research using the Regional Atmospheric Modelling System (RAMS), generated specific humidity fields at 700 hPa for the case study. An example of a moisture maximum coinciding with the position of the cloud band over South Africa is given in Fig. 1a. In order to determine the major moisture source for the cloud band, backward trajectories emanating from regions of highest specific humidity over central South Africa and Namibia have been modelled. These have then been coupled to forward trajectories from the same points of origin to allow the combined history of the airstream 10 d before reaching the points of origin and for 10 d after leaving them to be determined. Specific humidities greater than 10 g·kg^{-1} at 700 hPa were observed over central regions of South Africa on 22 January 1981. Backward trajectories for the day conform to the mean rain-day fields discussed earlier and trace back from central Southern Africa, over the northern parts of subtropical Southern Africa to an area over the tropical western Indian Ocean off the coast of East Africa (Fig. 4a). All trajectory pathways are confined to levels between 700 and 800 hPa. Specific humidities of 8 g·kg^{-1} are uniform over the ocean source region, increasing to 9-10 g·kg^{-1} over southern Zimbabwe, whereafter they increase by moisture convergence to about 10 to 11 g·kg $^{-1}$ over central South Africa (Fig. 4b). From this region gradual slantwise ascent is accompanied by desiccation as the airstream ascends out of the cloud band to an average height of about 550 hPa with an average specific humidity of about 5 g·kg^{-1} over the middle of the Indian Ocean at 70°E , 40°S

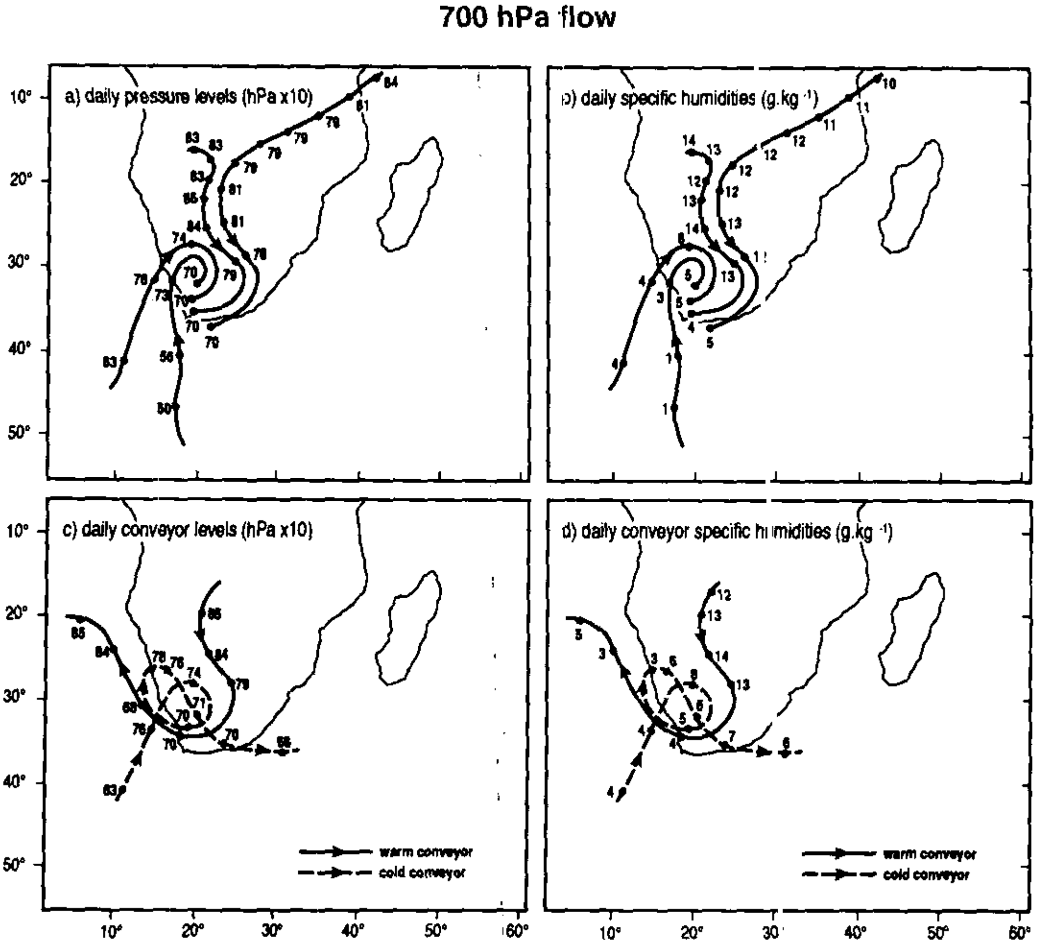


Figure 7

700 hPa back trajectories from selected points in the Western Cape for the cut-off low on 25 January 1981 to show daily (a) pressure levels (hPa x 10) and (b) specific humidities (g·kg^{-1}). Coupled back and forward trajectories in (c) and (d) give levels and specific humidities on warm, tropical and cold, temperate conveyors into and through the cut-off low.

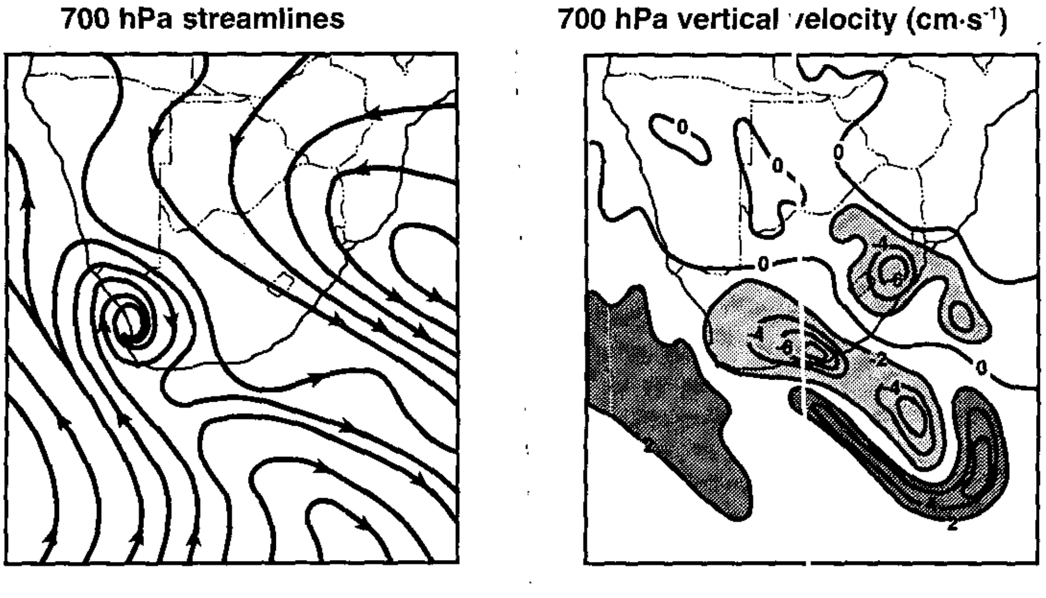


Figure 8

RAMS model (a) streamlines and (b) vertical velocities (cm·s^{-1}) for 12:00 UT on 24 January 1981 (after Van den Heever, 1995). Light shading indicates ascending motion and dark shading, descent.

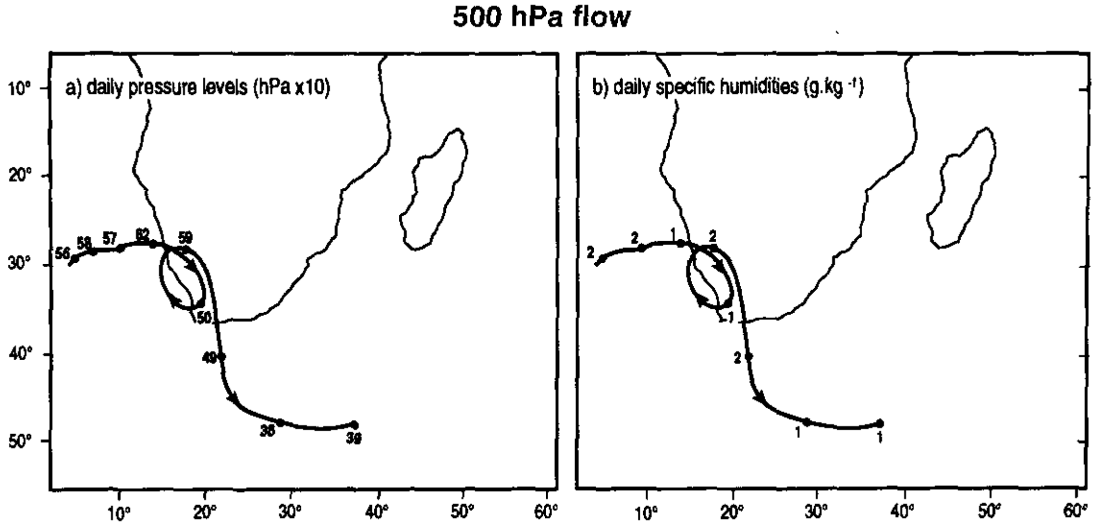


Figure 9
500 hPa back trajectories into and forward trajectories out of the centre of the cut-off low (designated by a heavy dot) on 25 January 1981 to show daily (a) pressure levels (hPa x 10) and (b) specific humidities (g·kg^{-1})

(Figs. 3a and b).

The trajectory fields and moisture pathways on the following day, 23 January 1981, are similar to those of the previous day. The transport of moisture from the tropical Indian Ocean is again at a nearly constant height of 750 to 700 hPa and slantwise ascent again occurs in the cloud band over the south-east coast of South Africa and the adjacent Indian Ocean to a level of about 550 hPa at 35°S to the south of Madagascar (Fig. 5). The major difference on the second day of rain over much of South Africa is that once ascended to a position south of Madagascar, the 700 hPa cloud-band airstream recurved anticyclonically back towards Africa, tending towards subsidence as it did so. Nearly two weeks after having passed over Botswana it was back over the northern Mozambique Channel in the tropical Indian Ocean. Initiation of the recirculation appears to mark the onset of cloud-band dissipation and supports earlier suggestions that such dissipation occurs with an eastward movement of the westerly wave trough and the weakening of the poleward flow (D'Abreton, 1993; Van den Heever, 1995).

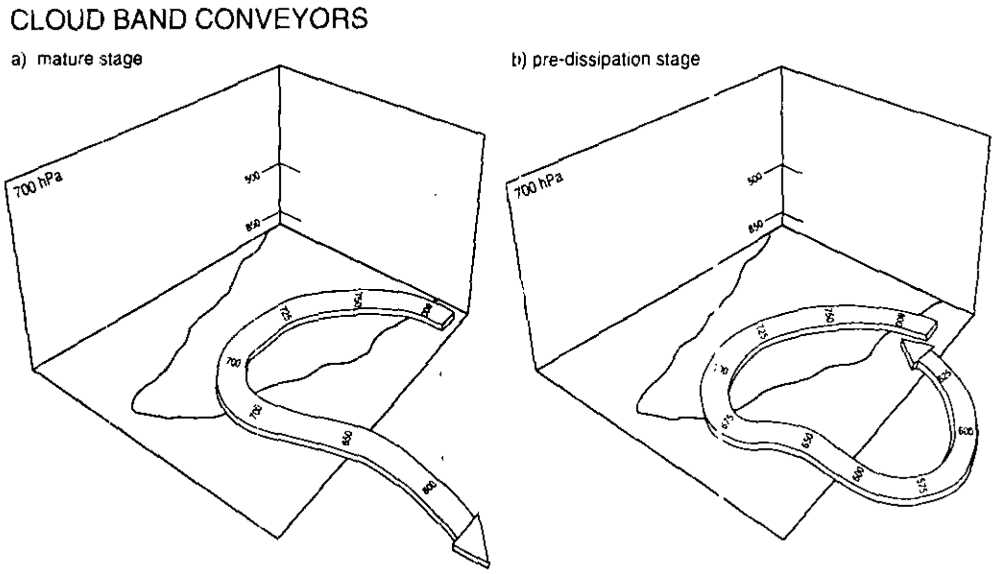
The question of how the vapour content of the airstream increases as it moves from the ocean north of Madagascar over the east coast of Africa is best answered by examining surface circulation and standing eddy vertical water vapour transport fields at 1 000 hPa, i.e. at levels below the Great Escarpment of the interior plateau of Southern Africa (Fig. 6). Circulation transport is that effected by the mean motion; standing eddy transport describes transport associated with the semi-permanent features of the atmosphere. Such fields have been determined for the day the air was crossing the east African coast (15 January) *en route* to precipitating over central South Africa on 22 January. Both circulation and standing eddy upward vertical water vapour transport is evident over southern Tanzania and northern Mozambique to provide for the increase in observed specific humidities along the moisture trajectories. This transport may be associated with disturbances along the Inter-Tropical Convergence prevalent over the northern parts of Southern Africa during summer. That the confluence of the north-east monsoon over the East African coastal area is a source of water vapour in mid-summer is supported by earlier work on vertically-integrated 850 to 700 hPa moisture divergence over Southern Africa (D'Abreton, 1993; D'Abreton and Lindesay, 1993; D'Abreton and Tyson, 1995).

A case study of a cut-off low pressure system

Cut-off low pressure systems are cold-cored baroclinic depressions associated with strong convergence and vertical motion. They are responsible for many of the flood-producing episodes over South Africa (Taljaard, 1985). On 25 January 1981, a cut-off low pressure system over the south-western interior of South Africa resulted in excess of 180 mm being recorded in the so-called Laingsburg storm over a normally semi-arid region during a 24-h period (Estie, 1981). Trajectory modelling of the moisture supply into the storm at the 700 hPa level has been undertaken. Aspects of the dynamics of the system are thereby illustrated as well.

The 700 hPa backward trajectories determined for several points around the core of the cut-off low reveal two diametrically-opposed conveyors feeding the low (Fig. 7). The warm conveyor of tropical origin has two sources of moisture. The first stream originates over Tanzania and the equatorial Indian Ocean off Kenya (Fig. 7a) and has a potential temperature of 32 to 37°C and specific humidities of 10-12 g·kg^{-1} (Fig. 7b). A second tropical stream originates over Angola with specific humidities of 13 to 14 g·kg^{-1} and a potential temperature of about 37°C. The confluence of the streams occurs over southern Zambia and both ascend by slow slantwise convection from northern Botswana into the low over South Africa.

The cold conveyor originates to the south-west of Cape Town around latitude 45°S at about the 550 to 600 hPa level (Fig. 7a) with a potential temperature of about 22° to 26°C and specific humidities of about 4 g·kg^{-1} (Fig. 7b). Over a distance of about 3 000 km, dry air descends along the cold conveyor from the middle troposphere to the 700 hPa level over the Laingsburg area, where the heaviest rainfalls were recorded. The increase in water vapour content of the cold conveyor as it crosses the west coast is the result of moisture convergence with tropical air of higher



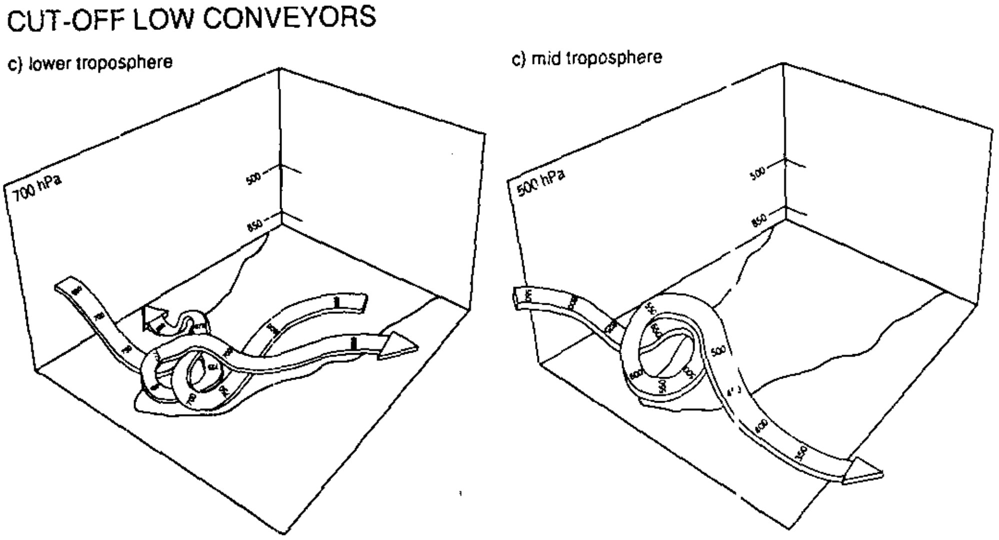


Figure10

Schematic models to show the warm, moist 700 hPa conveyor feeding (a) mature and (b) immediately pre-dissipation stage tropical temperate troughs and cloud bands and to show (a) the interaction of the tropical warm, moist and temperate cool, dry 700 hPa conveyors in cut-off lows over Southern Africa and (b) the absence of such conveyors at the 500 hPa level. Approximate pressure levels are indicated along the conveyors.

specific humidity. The most important source of moisture for the mid-latitude cut-off low pressure system is the tropical warm conveyor. The amount coming from elsewhere is negligible.

As the warm conveyor spirals towards the centre of the cut-off low, it ascends over the cold air descending in the cold conveyor (Fig. 7a and b). The average rate of ascent in the conveyor as the moist air moves south is the order of 55 hPa per day over about 4 d. A maximum height of about 680 hPa is reached north-west of Cape Town as the warm conveyor ascends through the centre of the storm before subsiding abruptly as it passes into the region of the Atlantic high-pressure cell off the west coast. The pathway of the cold conveyor is more complicated than that of its tropical warm counterpart. The air in the cold conveyor descends from mid-tropospheric levels into the cyclonic vortex from the south-west. Thereafter, it begins to ascend as it spirals cyclonically upwards on the eastern side of the system. It then subsides again on the western side with further cyclonic rotation before ascending with continued cyclonic motion for a second time as it again passes through the eastern side of the cell. Finally, the conveyor rises by slantwise ascent toward the east before becoming entrained in the westerlies over the Indian Ocean.

The Laingsburg storm has been modelled using RAMS (Van den Heever, 1995). Model streamlines at 700 hPa show the cyclonic vortex to be located to the north-west of Cape Town (Fig. 8a). More importantly, the model is able to replicate the asymmetry in the vertical velocity field to the east and west of the system (Fig. 8b). The meso-scale atmospheric circulation model and the trajectory model both show ascent to the east of the cut-off low and descent to the west in the lower troposphere. At the 500hPa level, while the vortex of the low is still clearly evident, the trajectory model shows that the twin conveyor system is absent (Fig. 9). Instead, cold dry air is entrained into the system from the west and exits to the east in just over a day.

Conclusions

Water vapour transport over Southern Africa has been examined using a Lagrangian trajectory model applied to ECMWF data stratified into two samples, one characterising rain days, the other non-rain days in the mid-summer month of January. The model is successful in the identification of major moisture streams feeding tropical-temperate troughs, despite the limitation inherent in the model imposed by the assumption that water vapour is a passive tracer. Large-scale convergence and divergence along trajectory pathways is modelled successfully.

In general, mid-summer, January rain-day conditions over the PWV and Gauteng are characterised by northerly transport in the lower troposphere, at about the 700 hPa level, of moist air from tropical east Africa and adjacent Indian Ocean south of the equator. By contrast, no-rain days over the PWV are characterised by south-westerly transport of dry subsiding air from the direction of Gough Island in the South Atlantic Ocean.

In the cases of rainfall events occurring with tropical-temperate troughs and associated cloud bands, a northerly flux of moist, tropical air takes place in a well-defined warm conveyor that recurves anticyclonically across Southern Africa. Water vapour source regions appear to be the western tropical Indian Ocean and adjacent continental regions. The model shows the warm conveyor transporting moist air to the south-west before undergoing south-easterly slantwise ascent over South Africa and the south-west Indian Ocean within the cloud band during the mature stage of the system (Fig. 10a). In later stages, as the cloud band begins to dissipate, the conveyor recurves anticyclonically as it begins to recirculate back towards Africa (Fig. 10b). Such recirculation commonly characterises fine-weather conditions and is a major feature of aerosol and trace gas transport patterns over Southern Africa (Tyson et al., 1996a; Garstang et al., 1996; Tyson et al., 1996b).

In contrast to the relatively simple structure of the conveyor system associated with tropical-temperate cloud bands, that of cut-off lows appears to be more complicated (Fig. 10c). In such cases the warm, moist conveyor appears to originate in the tropics over central Africa and adjacent Indian Ocean south of the equator. Over a period of several days the moisture is conveyed south towards South Africa in a stream in which the moisture content increases slightly due to flux convergence. Slantwise ascent occurs as the conveyor enters the region of cyclonic vorticity and begins to rotate clockwise into the vortex of the cut-off low. The structure of the warm conveyor, unlike its cold counterpart, is relatively uncomplicated. It ascends to about the 675 hPa level losing moisture through precipitation before subsiding rapidly as it moves over the Atlantic Ocean off the west coast.

The cold conveyor originates at mid-tropospheric levels to the south-west of Cape Town and cold dry air descends over several days before beginning the cyclonic spiral into the cut-off low. In descending into the vortex, the cold air forms the wedge over which the warm conveyor rises with slantwise convection, realises its thermal instability and precipitates. The cold conveyor then rises in an upward spiral to ascend over the warm conveyor before becoming entrained into the mid-level westerlies above the 650 hPa level.

It needs to be emphasised that a model of a cut-off low, such as the one proposed here, is not a statement of the structure at a given instant in time. Instead, it is one which portrays the history of the circulation into the system over a period of up to nearly a week. The structure of the interacting warm and cold conveyors is not dissimilar to that advanced by Browning (1985) for northern hemisphere cyclonic storms and transposed for southern hemisphere conditions by Preston-Whyte and Tyson (1989), but is more complicated in respect of the history of the downward spiralling cold conveyor, which contributes most to the total vorticity of the system.

Previously, Lagrangian modelling has been used for determining mass transports of aerosols and trace gases over Southern Africa. In this paper, similar modelling of water vapour transport has been shown to be useful in the determination of the structure of rain-bearing systems over Southern Africa. The modelling allows significant differences between rain and no-rain situations to be determined and offers a powerful means of further investigating the changing nature of atmospheric circulation systems during wet and dry spells over the region.

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