The atmosphere, aerosols, trace gases and biogeochemical change in southern Africa: a regional integration

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Attention is focused on temperature and rainfall changes occurring over the subcontinent of southern Africa, on atmospheric circulation and transport of aerosols and trace gases in the vertical and horizontal, and on repeated recirculation of atmospheric constituents over the region. It is shown that most air, and whatever is contained therein, exits the subcontinental airspace in a major plume moving to the east over the Indian Ocean at 31°S towards Australia and New Zealand. On occasions, the plume may be discernible over Australasia. Some of the consequences of sulphur emission and transport of sulphate aerosols over the region are considered and it is shown that on occasions sulphates from South Africa may be observed in Kenya and beyond. The possible role of aerosols in diminishing and enhancing regional rainfall is examined. The contribution of atmospheric particulates in the biogeochemical cycling of nutrients in terrestrial and marine ecosystems is illustrated by showing that airborne nitrates and phosphates contribute significantly to the balancing of the papyrus nutrient budget in the Botswana wetland ecosystem of the Okavango Delta region. Future climate scenarios also are considered. It is concluded that changing regional climate is one of the major driving forces leading to biogeochemical changes in terrestrial and marine ecosystems sustaining the region.

Introduction

The atmospheric circulation over southern Africa imparts a distinctive unity to the region. Any consideration of the regional effects of global change over the subcontinent must recognize this fact. Changes in temperature and precipitation regimes in future, particularly in respect of extreme drought and flood conditions, will have profound effects. In addition, understanding biogeochemical changes occurring at present and in the future depends on appreciating the roles played by the subsidence of air associated with dominant anticyclonic flow fields, the longevity of thermodynamically stable layers on non-rain days, the persistence of haze layers that blanket vast areas, and the transport of aerosols and trace gases within the haze layer.

The variability of climate over southern Africa has been reviewed extensively.[1–3] By contrast, little has been done on the regional consequences of global change in the subcontinent. A need exists to review, collate and integrate the literature concerning the accumulation and distribution of aerosols and trace gases in the regional atmosphere and their subsequent transport within and beyond the region. In this paper such an integration is attempted for Africa south of the equator, including Kenya, but excluding the Congo. In climatological terms the southern African region extends only to the latitude of northern Zambia. However, ecological affinities suggest that inclusion of Kenya and northern Tanzania in the region is sensible; hence this has been done.

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Temperature and precipitation changes

Over much of South Africa, annual mean maximum temperatures have been rising steadily over the last few decades[4] (Fig. 1a). The same is true of mean annual temperatures over the wider southern Africa region.[5,6] Warming has been at a maximum of nearly 2°C per century over the central interior of the region. By contrast, the southern and southeastern coastal regions have cooled by nearly 1°C over the same period. The increase is associated with a concomitant increase in South African surface rock temperatures derived from borehole temperature profiles.[4] Whether this is definitely a response to global warming is as yet impossible to say. It may be.

Rainfall over the southern parts of the region as a whole has shown no large systematic linear trends during the twentieth century (Fig. 1b).[1,7] Local areas have shown weak upward and downward trends of up to 10% per century, however, except over the central tropical area of the region and western Angola, where increases appear to have been greater. Over shorter periods than the twentieth century, local trends may have been more pronounced, e.g. in the Lowveld of South Africa, Zimbabwe and Mozambique in recent years.[8] A high degree of inter-annual and inter-decadal rainfall variability characterizes the whole region.[1,9,11] Evidence exists to suggest that variability and extremes in the southern parts of southern Africa may be increasing,[8] especially in the drier western parts.[11] Between 1931 and 1990, the intensity of extreme events increased significantly over South Africa.[12]

Heavy rain events, where more than 25 mm of rain fell in 24 hours over an area of more than 20 000 km^2, increased over South Africa between 1940 and 1999, owing to an increase in such rain in one-day spells. At the same time, the incidence of such rains in spells longer than one day decreased.

Droughts are an endemic feature of the climate and are the single greatest cause of climate-induced deaths in Africa.[13] The cost of drought for all countries of the region is high; they are likewise the greatest of the climate-induced burdens imposed on national economies.

The effect of variability in Pacific Ocean sea-surface temperatures and El Niño has a direct and clearly discernible effect throughout southern Africa on the inter-annual time scale. ENSO-induced variability is a strong signal in most areas, particularly so in the southeastern parts of the subcontinent and in East Africa.[14] Over South Africa the ENSO variability is strongly modulated by the stratospheric quasi-biennial oscillation (QBO).[18] When the QBO is westerly, ENSO may account for more than 36% of rainfall variability over central South Africa; when the QBO is easterly, the variance accounted for diminishes to less than 16%. Droughts induced by El Niños and wet conditions by La Niñas are likewise a clear feature of the climate of Zimbabwe and parts of Zambia, unlike Kenya, where the opposite patterns prevail.[16] In East Africa El Niño is linked to flooding and La Niñas to droughts. Such inverse teleconnections between the rainfall over East and southern Africa have long been recognized.[17] ENSO variability manifests itself in oscillations in the range 3–7 years, peaking at around 3–4 years.

Normally during El Niño periods rainfall over Lake Victoria is 15–25% above the long-term average.[18] With the 1997/98 El Niño, the strongest in the twentieth century, the rainfall anomaly increased to 160% of normal over much of the lake's catchment.[18] Satellite radar altimetry reveals that the level of Lake Victoria rose by ~1.7 m, and that large increases in levels occurred in lakes Turkana, Tanganyika and Malawi.[21] The 1997/98 flood episode was similar to flooding in the non-El Niño year of 1961, leading to speculation that events over East Africa are modulated not only by ENSO, but also by internal variability of the Indian Ocean system.[20]

One of the most pronounced characteristics of rainfall variability in the summer rainfall region of South Africa is the strong inter-decadal variability that occurs with a quasi-periodicity in the range 16–20 years with a spectral maximum at 18.6 years.[9,21,22] The oscillation has been reported in Zimbabwe,[23] Botswana[24] and has been shown to extend over plateau areas of southern Africa at least to the latitude of northern Zambia.[25] That the dominant mode of variability in the rainfall of the summer rainfall region of southern Africa is an inter-decadal oscillation at around 16–20 years, is clear from wavelet analysis (Fig. 1c). The oscillation has also been observed in South African annual temperatures,[26] in river runoff,[27,28] sea-surface temperatures in parts of the oceans adjacent to South Africa[29] and in tree rings.[30–32] From the tree ring data it appears that the oscillation has been present for up to 600 years.[30–32] Whether or not the 16–20 year oscillation, like that of ENSO at around 3–4 years, will be modified in future by global warming remains a moot point.

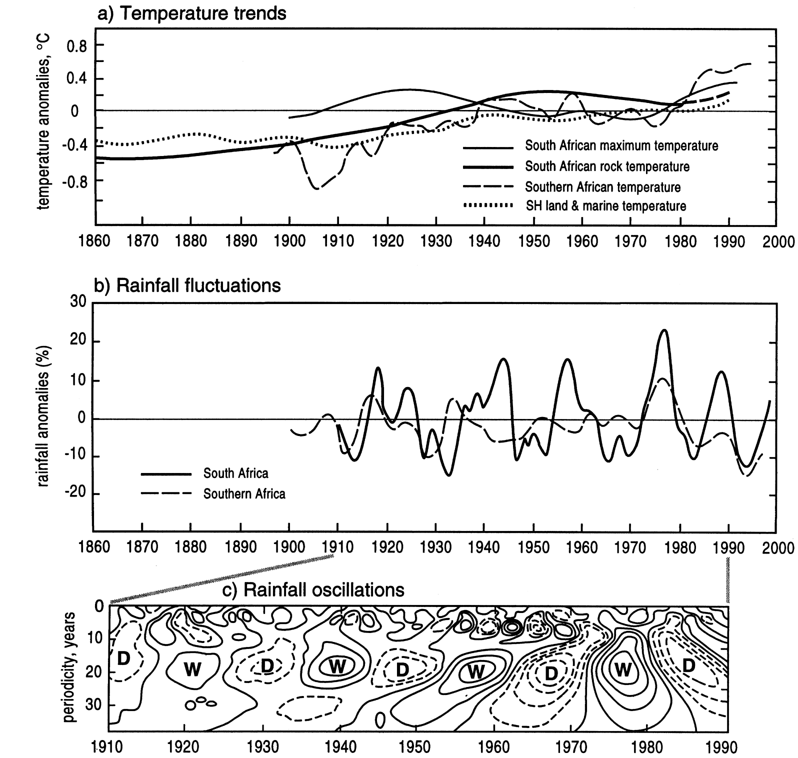

Fig. 1. Regionally averaged decadal climate variability for the summer rainfall region of southern Africa: **a**, 10-year mean maximum temperatures and surface rock temperature anomalies (°C) for South Africa[4] compared to southern African mean temperature anomalies[5] and the southern hemisphere record;[6] **b**, 5-term binomial filtered South African percentage rainfall deviations from the 1905–1990 mean[3] compared to smoothed rainfall anomalies for a wider southern African region;[5] **c**, wavelet analysis of rainfall anomalies for 12 stations in South Africa, Mozambique, Botswana, Zimbabwe, Malawi and Zambia. The dominant mode of variability is in the range 16–20 years (W indicates wet conditions; D dry).

The decadal-scale variability in southern African rainfall is clearly linked to changes in circulation patterns.[1] Circulation variability not only modulates rainfall, but also controls regional patterns of horizontal atmospheric transport of aerosols and trace gases. Like changes in rainfall, changes in transport of aerosols and trace gases may have important regional consequences.

Circulation and transport

Southern Africa is dominated by the subsidence limb of the southern Hadley cell of the general circulation of the atmosphere, particularly in winter (Fig. 2a).[33] The mean circulation over the subcontinent is anticyclonic throughout the troposphere for most of the year.[34,37] The July circulation at the 850-hPa level in the atmosphere (~1.5 km, approximately the mean height of the inland southern African plateau) illustrates the point (Fig. 2b). Anticyclonic airflow is common throughout the year in subtropical latitudes.[35] Circulation changes associated with the Inter-Tropical Convergence Zone (ITCZ) affect northern tropical and equatorial areas, but even at such times and in such regions, anticyclonic curvature in the windfield is common.[38–40] The variation in anticyclonic airflow in the subtropics is illustrated by conditions obtaining over northern South Africa[35] (Fig. 2c). The subsidence associated with such flow is ubiquitous and blankets the whole of southern Africa in winter (Fig. 2d).[36]

The dominance of anticyclonic curvature in the windfield and its controlling effect on horizontal transport patterns is evident throughout the region, except in the near-equatorial tropics where ITCZ effects are more important. The integrated 700–500 hPa climatology for March illustrates the degree to which transport to Kenya at the equinoxes is a function of both northern and southern hemisphere circulation forcing (Fig. 3a).[41] Transport to Kenya from the Mozambique Channel area reaches a maximum in May (67%) in contrast to January, when it rarely if ever occurs. At all times of the year transport from Kenya takes place in the tropical easterlies along an equatorial duct towards the Atlantic Ocean. In contrast, from Zambia south to the southern extremity of the region, transport is dominated by the semi-permanent subtropical high-pressure systems associated with the southern Hadley cell over Africa. This is illustrated by regional transport patterns originating from the Highveld of South Africa[42] (Fig. 3b) and from Mozambique, Malawi, Zambia and Zimbabwe[43,44] (Fig. 3c). Given the anticyclonic forcing of transport pathways over southern Africa, it is not surprising that the major outflow duct for aerosols and trace gases from the subcontinent south of Zambia is to the Indian Ocean over South Africa[36] (Fig. 3d). The locus of the mean annual plume is at 31°S over southern Lesotho. More than 75% of all air circulating over South Africa and countries adjacent to the north, and material within, exits the subcontinent at this point.[42,45]

The prevalence of subsidence in the atmosphere over southern Africa on most no-rain days results in the formation of

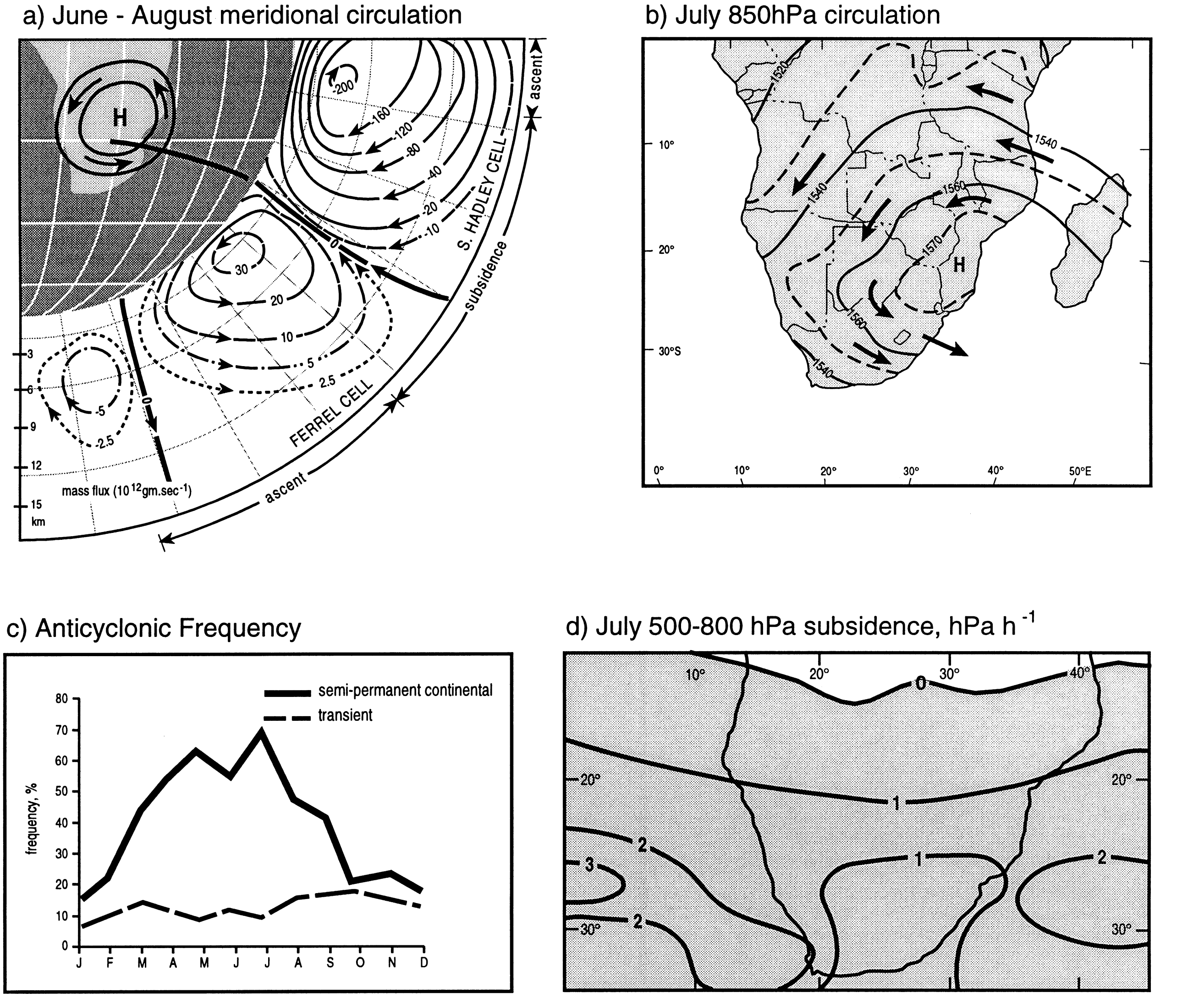

Fig. 2. a, The June–August meridional circulation of the southern hemisphere;[33] **b**, July 850-hPa surface (gpm) over southern Africa;[34] **c**, annual percentage frequency of semi-permanent subtropical highs and transient ridging anticyclones over South Africa, 1988–1992;[35] **d**, July 500–850 hPa subsidence over southern Africa (hPa h^{-1}).[36]

absolutely stable layers in which the observed lapse rate of temperature is less than the saturated adiabatic lapse rate. These layers are sufficiently stable to inhibit the vertical transport of aerosols and trace gases. The point must be stressed that inversions of temperature are not needed for this to happen. If inversions do occur, they are even more stable and inhibiting of vertical transport than the absolutely stable layers defined by the given criterion. The stable layers form preferentially at levels around ~700 (~3.5 km altitude), ~500 (4–6 km) and ~300 hPa (~8–9 km) over the interior plateau.[49] Over the region between the coast and escarpment, a further layer at around the 850-hPa level (~1.5 km) is present (Fig. 4a). All three layers trap material below. The ~500-hPa layer is the most persistent. On occasions it may prevail without disruption, while oscillating in height about its mean level, for more than 40 days over South Africa in winter and early spring.[35] The ~700- and ~850-hPa layers tend to be less persistent and are disrupted approximately weekly by the passage of frontal disturbances[53] over the central and southern areas of the region. This promotes vertical mixing of aerosols and trace gases to the ~500-hPa level. It is the stable layer at this level that exerts the most visible effect, since it usually marks the top of the southern African haze layer at altitudes between 4 and 6 km. The haze layer may cover the entire southern African region and extend over more than 30° of latitude.[35,36] An example of such a layer extending from South Africa to northern Zambia[47] is given in Fig. 4b, together with measures of the aerosol loading within the haze layer.[48] On this occasion the ~500 hPa layer clearly controlled the accumulation of aerosols in the vertical. Similar findings have been reported.[54–56] Hydrocarbon trace gases likewise become concentrated below the layer[56,57] (Fig. 4c). Measurements made at a high-altitude site on the top of the 3000-metre Ben Macdhui mountain on the southeastern edge of the Lesotho massif effectively sample mean maximum outflow within the haze layer in the transport plume to the Indian Ocean over South Africa.[45] They reveal that in the coarse aerosol fraction 85% of the particulate matter being transported out to sea is aeolian, surface-derived, mineral dust (Fig. 4d). The second largest contribution to total plume loading is industrially derived sulphur at 13%. By contrast, in the fine fraction, industrial sulphur constitutes 59%, aeolian dust 36% and particulates from biomass burning only 6%.[52] South of around 20°S, biomass burning produces only a small fraction of the aerosol loading of the lower troposphere over southern Africa.[85] North of 20°S the amount of burning is much greater[59] and biomass burning products constitute a higher proportion of the aerosol loading. Aeolian dust loading in the haze layer is at a maximum in the dry winter over most of southern Africa. The sulphur being transported, as a patchy coating of precipitated sulphur products on small dust nuclei, is at a maximum in warmer, moister summer air when oxidation of SO_x is at its maximum.[58]

Annual mass fluxes of aerosols being transported over southern Africa may be estimated from trajectory-swarm determination of the volume of air being transported in mean plumes[45] and from measurements of background ambient aerosol loading.[43,55,60–64] The annual fluxes are large (Fig. 5a).[45] Over the central subcontinent, 12 Mt yr^{-1} is transported over Zimbabwe and Botswana in the direction of the Atlantic Ocean. Over Botswana and Namibia the transport field diverges into a major plume recurving to the south with a minor plume moving westward. By the time the latter exits the continent to the ocean off Namibia, the flux has increased to 29 Mt yr^{-1}. Recurving anticyclonically towards the east and the Indian Ocean at 30–32°S, the flux in the main transport plume has reached ~39 Mt yr^{-1} over central South Africa. By the time the plume has reached 35°E off the southeast coast of South Africa, the flux is estimated at ~45 Mt yr^{-1}. The estimated mass fluxes out of southern Africa do not take into account possible wet and dry deposition once air has exited South African airspace. They appear to be about half those reported for transport westward out of the Sahara from northern Africa.[68,69]

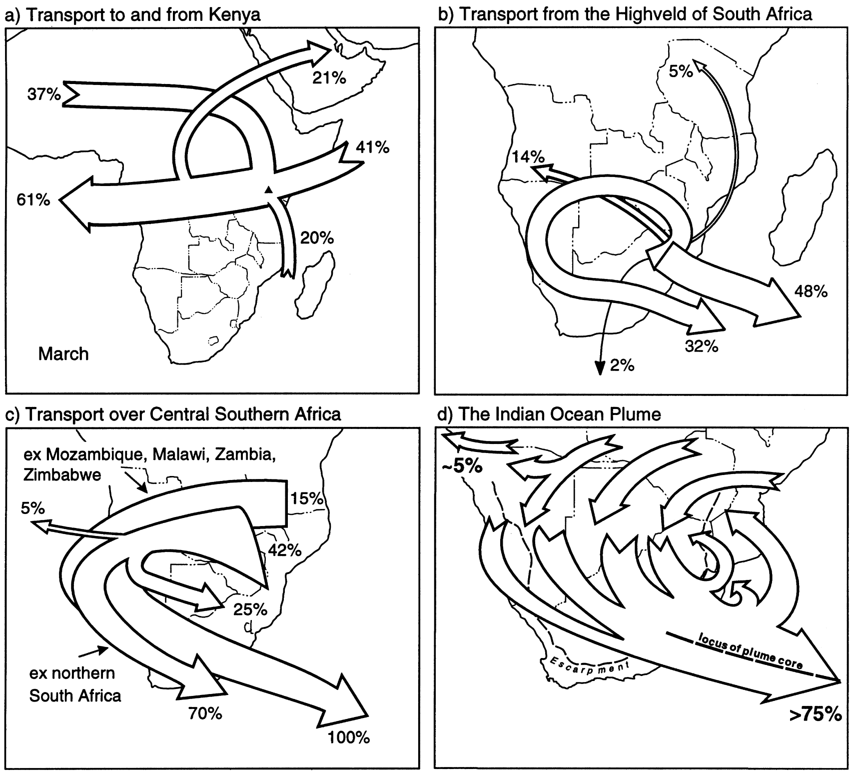

Fig. 3. Aerosol and trace gas horizontal transport patterns over southern Africa: **a**, integrated March 700–500 hPa transport to and from Mount Kenya for the period 1991–93;[41] **b**, transport from the South African Highveld, 1990–94;[42] **c**, transport from Mozambique, Malawi, Zambia and Zimbabwe during SAFARI-92;[43] **d**, schematic depiction of mean annual transport over the subcontinent.[36] Percentages at the start of arrows indicate transport to, those at the end of arrows transport from, a point of origin.

The air transport in the plume from South Africa that moves towards Australasia has been modelled empirically by kinematic trajectory analysis (Fig. 5b).[65] Transport of CO_2 from southern Africa has been simulated using GCM chemical transport models (Fig. 5c).[66] Satellite observations of dust transport from South Africa to Australia have been made (Fig. 5d).[67] The plume is a major feature of the southern hemisphere and effects large-scale inter-regional transfers of aerosols and trace gases. It indicates clearly the influence of continentally derived air from Africa on the surrounding region. In addition to transporting carbon dioxide, the plume carries tropospheric ozone far over the Indian Ocean, particularly in spring.[70,71] Moody *et al.*[72] demonstrate, from Global Chemistry Project analyses of rainfall samples collected over the period 1980–1987 on Amsterdam Island, approximately midway between South Africa and Australia at about 38°S, 78°E, that radon, and non-sea salt sulphates and nitrates may be transported to the island from southern Africa and Madagascar, a distance exceeding 5000 km, in as few as three days on occasions. With anticyclonic systems prevailing over South Africa, the average time of transport to Amsterdam Island is around six days.[35,45]

Recirculation

A striking feature of the transport of aerosols and trace gases over southern Africa is the degree of recirculation that takes place. This occurs when air, and the contents therein, is not transported directly across or out of the airspace over the subcontinent, but instead is entrained by prevailing airflow to be recycled before exiting the region. An example of air trapped between the ~700 and ~500-hPa stable discontinuities over southern Africa and recirculating in the enclosed space for more than three weeks is given in Fig. 6a. A 7-year climatology reveals that approximately 44% of all air circulating over southern Africa on fine (no-rain) days was recirculated on a subcontinental scale at least once (Fig. 5a).[74] The annual flux of aerosols being recirculated to the west over northern South Africa and southern Zimbabwe is estimated at around 11.5 Mt yr^{-1}; that being recirculated to the east over South Africa at around 32° S 17.3 Mt yr^{-1}. Recirculation occurs at a variety of temporal and spatial scales extending from hours to weeks and from tens to thousands of kilometres. Most often it is confined to the troposphere below ~500 hPa.

Whatever the form of transport, direct or recirculated, it usually involves trans-boundary movement of air over southern Africa. Examples have been reported of air originating at the Victoria Falls, being transported over southern Angola and Namibia, recurving to the east over South Africa, being transported to the north over the Madagascar region, recurving to the west over Mozambique, moving across Malawi and thence back to the Zimbabwe/Zambia border region again.[35] A 1990–94 climatology revealed that air moving from the industrial heartland of South Africa recirculated over Mozambique, Zimbabwe and Botswana before recurving back over South Africa (Fig. 6b).[73] Such recirculating air carried aerosols and trace gases. It is estimated that more than 30% of all material transported over Mozambique and Botswana has recirculated from South Africa.[75] Up to 30% of air reaching Zimbabwe has likewise passed over South Africa before reaching the country from the east. That passing over Zambia and Angola from the same source is up to 15% and that getting to Tanzania and Kenya 5% or less per annum.

That long-distance transport of aerosols takes place over the southern African region is not in doubt. Sulphur emitted into air recirculating over Zimbabwe, Botswana. Namibia and South Africa has been observed to circulate over Madagascar before

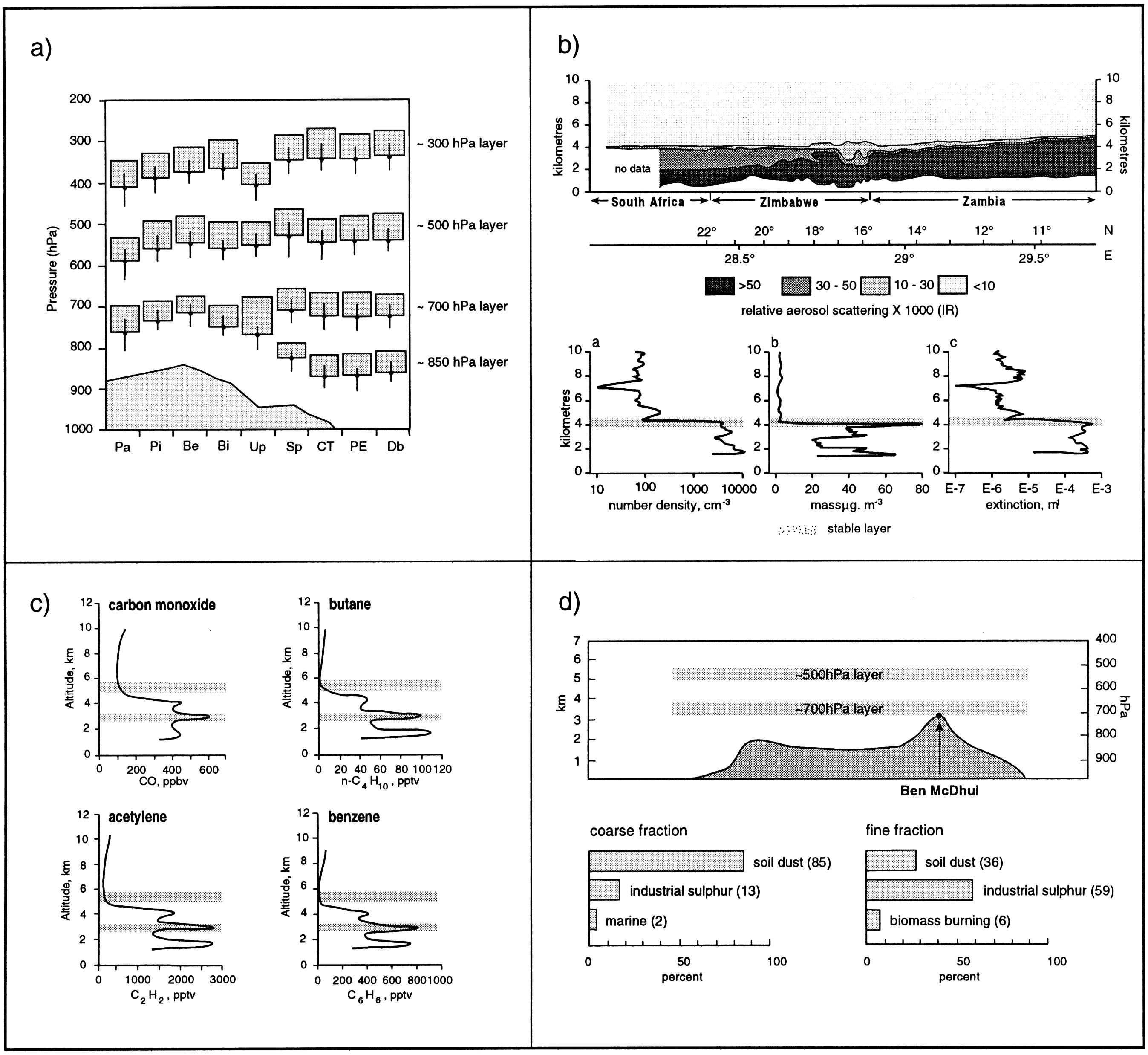

Fig. 4. Atmospheric stability and the haze layer over southern Africa: **a**, mean heights and depths of absolutely stable layers (where the observed lapse rate is less than the saturated adiabatic lapse rate) over South Africa, with standard deviations of base heights;[46] **b**, aerosol concentrations in the haze layer observed in a transect from Johannesburg, South Africa, to northern Zambia on 6 October 1996 as indicated by relative aerosol scattering,[47] vertical profiles of aerosol number density, mass and extinction in and above the layer.[48] The top of the haze layer is capped by absolutely stable discontinuities;[49,50] **c**, vertical profiles of hydrocarbon trace gases over southern Africa, October 1992.[51] The climatological heights of the ~700 and ~500-hPa absolutely stable layers[46] are shown; **d**, the location of the high-altitude, remote, background-aerosol Ben MacDhui site in relation to the ~700 and ~500 hPa absolutely stable layers over South Africa and annual source apportionment of coarse and fine-fraction aerosols at Ben MacDhui.[22,52]

being recirculated inland to be recorded at high levels (4220 m) on Mount Kenya (Fig. 6c).[41] In the example cited, sulphur was trapped within the air below the ~500-hPa stable layer, transport was at the level of the layer and transit time from South Africa to Kenya was around five days. After passing Mount Kenya, the diluted transport plume moved onward towards India. Climatological studies of transport from the industrial areas of the Highveld of South Africa reveal that such flow to Kenya may occur on about 5% of occasions in a year.[73,75]

Over the southern part of southern Africa, the integrated 850–500 hPa easterly component of both direct and recirculated aerosol transport is estimated at around 29 Mt yr^{-1} at 10° E off the west coast of South Africa and Namibia (Fig. 6d).[45] The locus of the plume is at 18°S at a mean height of around 800 hPa, i.e. below the level of the ~700-hPa stable layer. The mean time of transit to reach 10°E from the central continent is 7.5 days. Of the total amount transported to the west, 24 Mt yr^{-1} is deposited in the sea between the coast and the Greenwich Meridian to the west. By contrast, the integrated 850–500-hPa offshore transport over the east coast of South Africa is about 45 Mt yr^{-1} at 35° E. The locus of the plume is at latitude 31°S with a mean height of about 750 hPa (again below the ~700-hPa stable layer). The transit time from the central interior to 35°E is 3.5 days. Only 4 Mt yr^{-1} is estimated to be deposited between 40° and 50°E. Most deposition consequent upon trajectories going to surface appears to occur over the central Indian Ocean at around 70°E.[75]

Sulphur deposition

Inventories of SO_2 emissions over southern Africa are available.[76] Two main areas dominate the emission field: the South

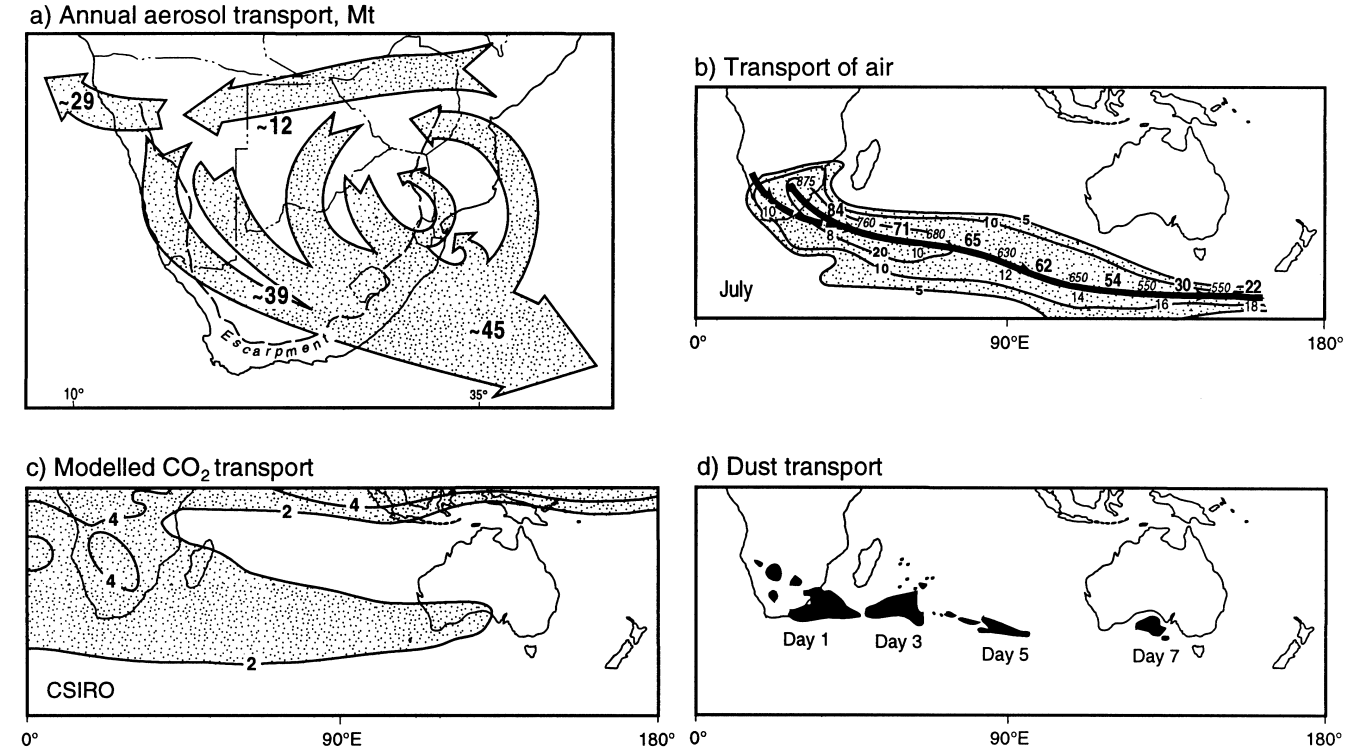

Fig. 5. Transport plumes exiting South Africa to the Indian Ocean and beyond: **a**, annual mass fluxes of aerosols (Mt yr^{-1}); **b**, vertically-integrated 850–800 hPa westerly component, zonal July transport of air across the Indian Ocean from the Highveld of South Africa. Contours give the percentage number of air parcels originating between 850 and 800 hPa. The heavy solid lines indicate maximum frequency pathways; solid lines denote direct transport; broken lines indicate recirculated transport. Along maximum frequency pathways bold numbers denote total percentage plume transport across the meridian, italic numbers indicate geopotential heights and roman numbers times of transport in days;[65] **c**, simulated CO_2 transport across the Indian Ocean as modelled by the CSIRO model (peak-to-peak amplitudes are given in ppmv at 500 hPa);[66] **d**, a 7-day variation of UV-absorbing aerosols as observed from Nimbus-7/TOMS data.[67]

African Highveld and the Zambian/Congo Copperbelt. Of these, the South African is the greater. The regional Swedish MATCH model[77] has been used recently to model both wet and dry sulphur deposition over the southern African region.[76] Given that rain falls on so few days per year (around 20% of days for most areas), only dry deposition is illustrated (Fig. 7a). Annual dry deposition covers most of the subcontinent, with highest rates of deposition occurring around the major emission areas. The Indian Ocean plume is discernible. The percentage contribution by South African emissions to total annual sulphur deposition is greatest over South Africa and adjacent regions (Fig. 7b) and constitutes over 70% of the sulphur in the Indian Ocean plume.

Use of the Hadley Centre CM2 coupled ocean–atmosphere climate model[78] allows an estimate to be made of the extent to which the sulphate aerosol loading over southern Africa is currently inducing an anthropogenic climatic change. By comparing the modelled climate using greenhouse gas and combined greenhouse gas and aerosol forcing, the aerosol effect may be isolated (Fig. 7c). On the basis of the current state of knowledge, and subject to the uncertainties known to be associated with current models,[6] it appears that sulphate aerosols cause cooling in excess of 1°C over most of the subcontinent in early winter. During the rest of the year sulphate-induced cooling is much less.[78]

Some consequences of aerosols in the atmosphere

The role of aerosols in global change modelling has received much attention in the last few years.[6,79–81] The manner in which aerosols may affect climate both directly and indirectly has been reviewed[82,83] and their effects in mitigating the effects of global warming have been considered.[6,84–87] The incorporation of aerosols into GCMs results in greater regional variability of simulated temperatures and precipitation.[6,87] The degree of uncertainty associated with GCM simulations for southern Africa has been assessed[88,89] and in the case of precipitation is considerable. Since it is unlikely that the uncertainties relating to rainfall simulation will be eliminated in the foreseeable future, an attempt has been made to use a simple basin hydrological model to assess the integrated effects of aerosols on regional precipitation patterns in southern Africa.

Aerosols and precipitation

The hydrology of Lake Tanganyika and its catchment basin system has been modelled and the sensitivity of modelled precipitation to changes in atmospheric transmissivity has been assessed.[43] Considering only the effects of changing aerosol loadings on solar transmissivity and the solar radiation balance, and the feedback of these alterations on the basin hydrology, has enabled indirect estimates of the effects of transmissivity on rainfall to be made. It appears that the model is more sensitive to changes in atmospheric transmissivity than to changes in surface area of the lake, temperature, albedo or Bowen ratio. The model suggests that a 10% decrease in atmospheric transmissivity over the region of Lake Tanganyika might produce a 15% diminution in rainfall. Such a change in transmissivity falls within the range of inter-annual variability observed within the second half of the twentieth century in southern Africa. Modified transmissivity of this order may become more common in future should the climate become drier.

Qualitatively, the results from the simple model are in agreement with those of the aerosol-incorporated GCM simulations for southern Africa. The findings for Lake Tanganyika are likely to be a good indication of the kinds of precipitation effects

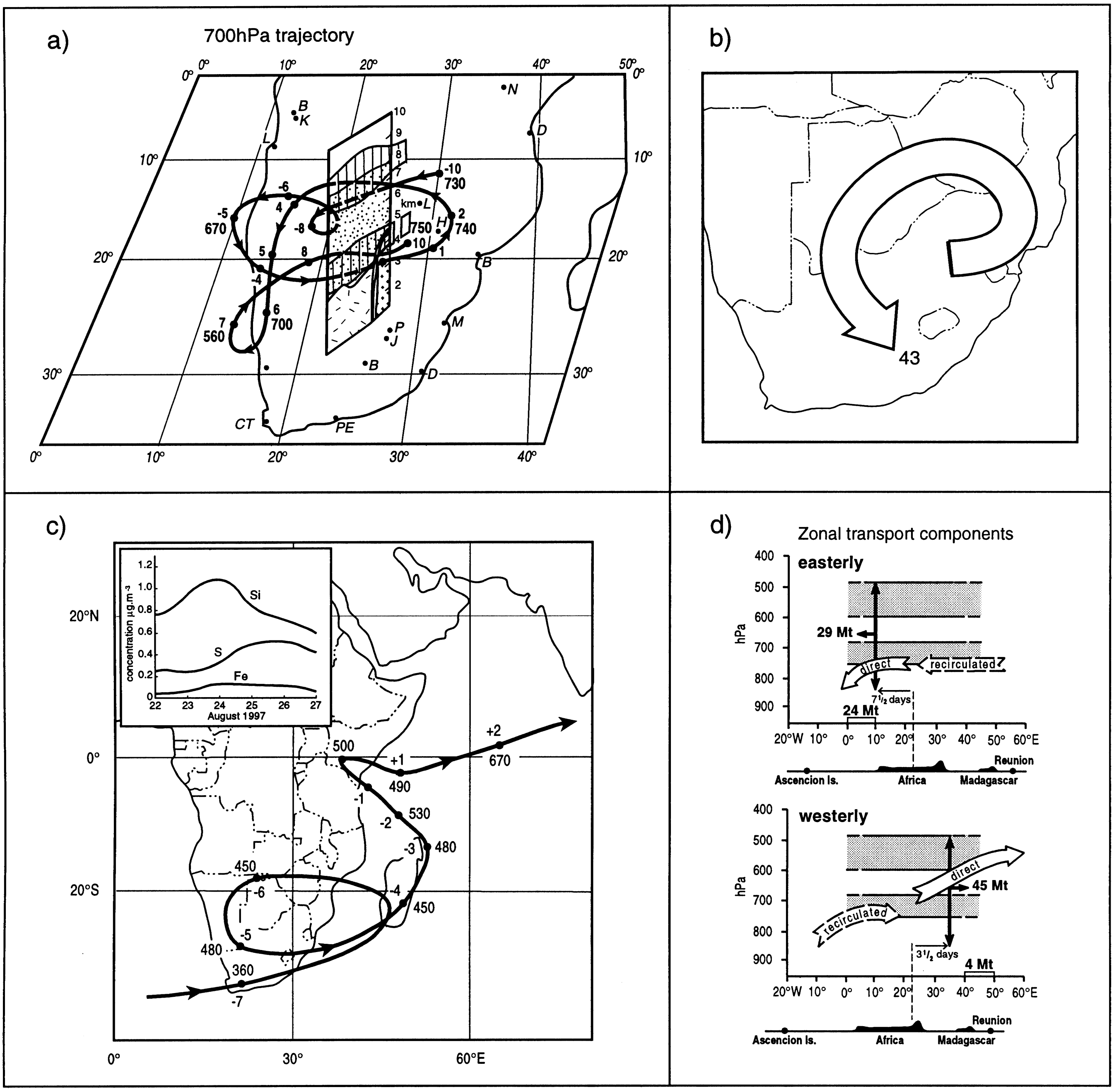

Fig. 6. Recirculation of aerosols over southern Africa: **a**, 700-hPa kinematic trajectories over a 20-day period to show recirculation trapped between the ~700 and ~500 hPa stable layers over South Africa, 3 October 1992 (days of travel and daily geopotential heights are shown along the trajectory);[36,47] **b**, percentage mean transport between 800 and 700 hPa from the South African Highveld, 1995–98;[73] **c**, transport of silicon, sulphur and iron from southern Africa to Mount Kenya and beyond, August 1997 (the height of the transport plume (hPa) is given at specified times (days)); **d**, mean annual vertically integrated 850–500 hPa zonal transport of aerosols (Mt yr^{-1}) over the east and west coasts of South Africa in relation to annual mean positions of the semi-permanent, absolutely stable layers.

changing aerosol loadings had in the past and may have in future over a much wider region of Africa.

Another way in which aerosols may affect rainfall is by modifying the microphysical processes regulating condensation and precipitation formation in warm clouds. South African cloud-seeding experiments demonstrated that the convective clouds of the region are very sensitive to the size and chemistry of aerosols in the atmospheric boundary layer.[90,91] Aerosols derived from the crust of the earth and biomass burning, as well as sulphates and elemental material from industrial sources, frequently remain in the haze layer for periods of a week, and on occasions for as long as three, while they recirculate anticyclonically over South Africa before offshore export occurs.[74] Particles surviving this long in the lower layers of the atmosphere typically have diameters less than 2 μm. An excess of such small particles will enhance the growth of small droplets in clouds at the expense of large ones, thus inhibiting the development of cumulus clouds in which the coalescence process and rainfall production are optimized. The consequence may be a diminution of regional rainfall.[90–92] This question is currently being investigated in the Aerosol Recirculation and Rainfall Experiment (ARREX).[93]

Nutrient recirculation

Recirculation of aerosols in the atmosphere over southern Africa includes particulate nutrients as well. Deposition of such nutrients and their subsequent recycling back into the atmo-

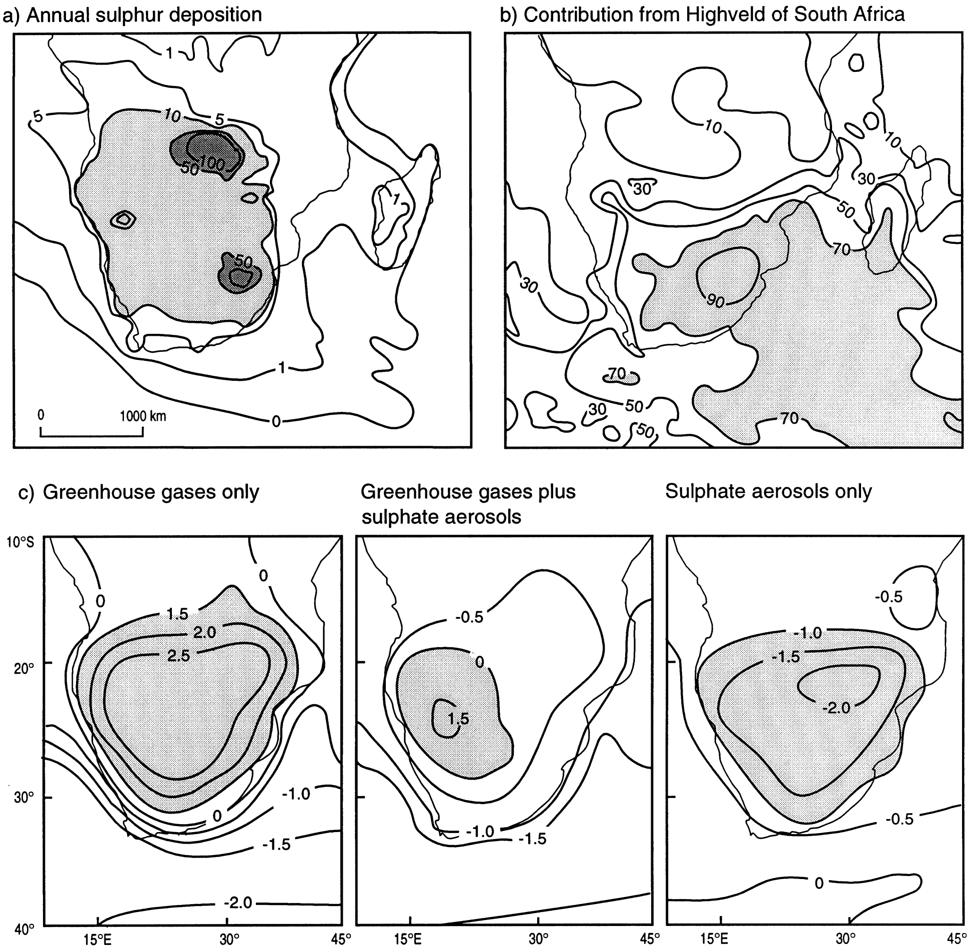

Fig. 7. **a**, Annual sulphur deposition over southern Africa;[76] **b**, the percentage contribution from the South African Highveld alone,[76] together with (**c**) Hadley Centre CM2 coupled ocean-atmosphere climate model estimations of sulphate aerosol cooling of the atmosphere with a doubling of greenhouse gases.[78]

sphere as dust, biomass burning products and industrial pollutants has considerable biogeochemical significance for both terrestrial and marine ecosystems. It is interesting to consider the effect of aerosol deposition from the atmosphere on the biogeochemistry of a wetland ecosystem in southern Africa. The Okavango Delta, with an annually flooded area of up to 12 000 km^2, is the largest wetland ecosystem in the subcontinent. The delta is in a semi-arid region (annual rainfall ~500 mm) where annual evaporation exceeds precipitation by a factor of three; in an extreme dry year the annual net radiation is capable of evaporating around 10 times the yearly rainfall.[1] The water of the delta is supplied by the Okavango River, which rises in subtropical central Angola. The rainy season in the catchment is January–March. Peak discharge into the delta at its head occurs in April; it takes a further five months for the water to traverse the 250 km from head to toe. The base flow in the river sustains at maximum 4000 km^2 of permanent swamp; the annual flood seasonally inundates up to a further 8000 km^2. Only 1.5% of the river inflow leaves the delta. The maximum aerial extent of flooding occurs in winter (July–August), when aerosol loading and deposition are at their greatest.[58]

The annual sediment load carried by the river into the Okavango Delta is around 620 000 tonnes.[94] The estimated atmospheric deposition from anticyclonic systems alone (which occur with a maximum frequency of ~80% in winter and ~25% in summer) is estimated at around 250 000 tonnes, i.e. ~40% of the river load.[95] The delta is a hyper-oligotropic system.[99] Much of the catchment area is covered with Kalahari sand with a low inherent nutrient status. The general absence of chemical weathering in this environment results in a low dissolved solids load in the water of the river, most of which consists of silica and calcium and magnesium bicarbonates.[97] Nutrient species occur at low concentrations: nitrogen (as nitrate or ammonium ions) is typically 0.08 ppm, phosphorus 0.04 ppm and potassium 2.9 ppm.[96] Atmospheric aerosol deposition under anticyclonic conditions is estimated at 0.57 kg ha^{-1} d^{-1} over the delta as a whole.[95] In the delta's distributary channels, water supplies 90% of the nitrate and phosphate needs of plants. However, in low productivity areas beyond the edges of the channels (which constitute 90% of the area of the delta) aerosols supply up to 52% of phosphates and 30% of nitrates (but only around 10% of potassium needs). The hitherto not-considered atmospheric contribution to nutrient cycling and the nutrient budget of the wetland ecosystem is substantial. The implications for other ecosystems, both terrestrial and marine, is significant. For instance, nutrient cycling in the Benguela upwelling system off the west coast of Namibia and South Africa will have to be re-evaluated in this light.

Iron fertilization of the Indian Ocean

The extent to which atmospheric transport of aeolian dust maintains or enhances ocean productivity and the ocean carbon cycle is a matter of significance. Iron is known to be an essential ingredient for phytoplankton to flourish even in regions of the world oceans where nutrients are abundantly available at the surface through upwelling.[98] Areas where phytoplankton

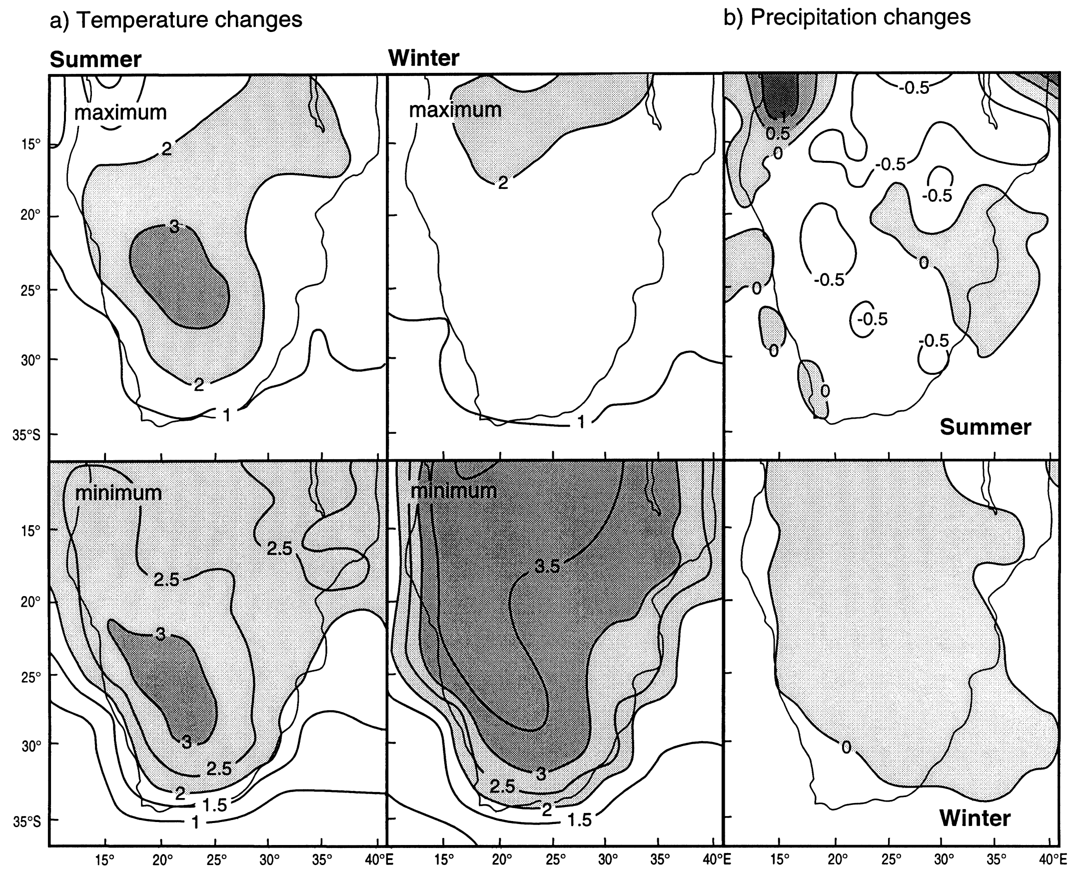

Fig. 8. HadCM2 model simulations for southern Africa, assuming combined greenhouse gas and sulphate aerosol forcing with a transient increase in carbon dioxide until doubling in 2030–2059: **a**, summer and winter maximum and minimum temperature increases (°C).[78] Shaded areas indicate degree of warming; **b**, summer and winter daily precipitation changes (mm d^{-1}) over southern Africa.[99] Shading indicates drier conditions.

blooms occur regularly in the oceans act as effective sinks of CO_2.[99,100] Controlled experiments have revealed the extent to which, over small areas of the ocean and short periods, iron fertilization of the surface significantly affects the growth of phytoplankton in waters where iron is otherwise a limiting nutrient.[100] Over longer time scales the increased photosynthesis in an iron-enriched marine region serves as a biological CO_2 pump.[99,100]

As part of the Joint Global Ocean Flux Study (JGOFS), extensive data on ocean–atmosphere CO_2 fluxes have been collected from around the world. Key areas where the oceans act either as sources or sinks of atmospheric CO_2 have been identified.[101] The South Indian Ocean between South Africa and Australia has been identified as a major sink region. Both observations[65,68] and modelling[66] revealed that the aerosol plume from southern Africa crosses, and completely covers, the area of carbon sink.[102] 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 in the mean windfield on the western margin of the South Indian Anticyclone.[103] As air is transported towards the centre of the South Indian Anticyclone in the vicinity of 70°E, it tends to subside. On occasions, when subsidence is particularly strong, air parcels may descend to the surface. Both case studies and mean climatologies show this to be the case.

From measurements made at Ben Macdhui on the edge of the Lesotho massif, it was possible to determine mid-tropospheric mass fluxes of iron-bearing aerosols as they are transported over the Indian Ocean. Deposition of aerosols takes place either by rain-out in wet deposition or by dry deposition. The latter can occur either as dust fallout from an elevated plume or by trajectories of air parcels being forced to the surface by atmospheric subsidence. If only the latter form of dry deposition is considered, then daily case studies suggest that as much as 0.89 $\mu g\ m^{-3}$ of elemental iron may be deposited between 60° and 85°E.[75] Over long periods, as evidenced in a 5-year climatology, on average 13% of trajectories subside to the surface between 50° and 70°E. Given that iron constitutes 0.7% of the fine-aerosol loading at Ben Macdhui, and that high-iron transport episodes occur about every 11 days on average,[75] it appears that the mean daily deposition of iron into the sea in the central South Indian Ocean, following a peak-concentration episode over eastern South Africa, is around 0.99 $\mu g\ m^{-3}$. Such peak concentrations occur on around 33 days in a year. Given that the average duration of an episode centred on the peak is three days, the number of days a year in which iron fertilization may be significant appears to be around 100.

In an equatorial Pacific Ocean iron enrichment experiment, a region of 64 km^2 was enriched with ferrous sulphate to a final concentration of 2 nM (0.11 $\mu g\ m^{-3}$) of iron, which was sustained for several days by further enrichment.[99,100,106] A significant bloom of phytoplankton took place in the patch. The estimated mean concentration of 0.99 $\mu g\ m^{-3}$ deposited over the South Indian Ocean from the southern African aerosol plume is the same order of magnitude. Not all the iron in the plume is likely to be in soluble form. What is will be available for phytoplankton enrichment.

Strong evidence exists to suggest that aeolian transport of aerosols from South Africa, and atmospheric iron fertilization of marine biota, support enhanced biological productivity and the South Indian Ocean carbon sink in the central ocean between South Africa and Australia. Inter-regional nutrient transfer over

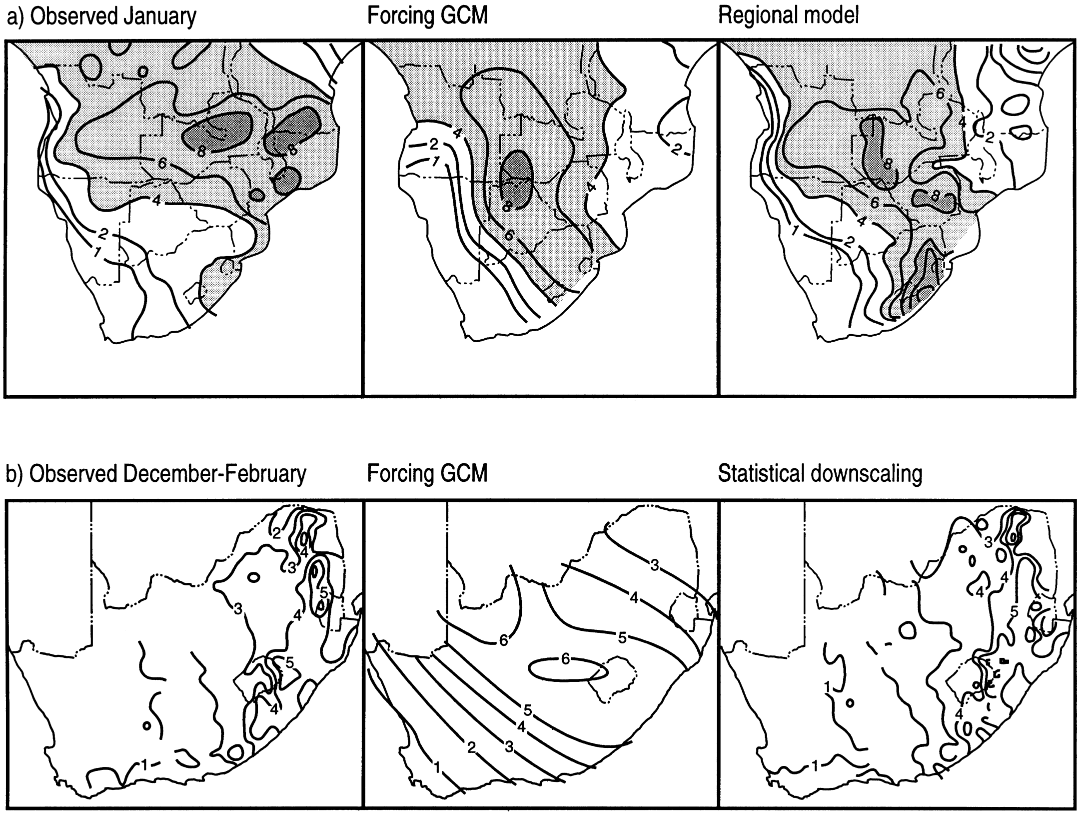

Fig. 9. Regional downscaling of GCM predictions; **a**, for January rainfall (mm d^{-1}) using the CSIRO9 model as the forcing GCM and the DARLAM mesoscale model as the nested regional model;[100] **b**, for December–February using the NCAR Genesis model as the forcing GCM and artificial neural networks for statistical downscaling.[101]

distances exceeding 5000 km have been established and links have been demonstrated between continental, terrestrial ecosystems and their remote marine equivalents.

Possible future conditions

Of a variety of mixed-layer and coupled ocean-atmosphere GCMs that have been compared for use over southern Africa,[88,89,103] the Hadley cell climate model incorporating the effect of sulphate aerosols is currently considered the best for use in the region.[78] For subcontinental Africa south of the equator, it is used without downscaling (Fig. 8). The model suggests that with a steady increase in greenhouse gases and sulphate aerosols by mid-twenty-first century, temperatures are likely to rise throughout the region and by up to 3°C over central southern Africa. Greatest increases are likely to be in winter minimum temperatures. In assessing the consequences of such changes, it must be remembered that, despite recent advances in modelling techniques, considerable uncertainty is still associated with such simulations.[6] The uncertainty increases in the case of simulations of precipitation. Here it is estimated that summer rainfall may decrease over most of southern Africa in summer except in low-lying, northern equatorial areas. Winter rainfall is thought to be likely to increase slightly, except in the southwestern winter rainfall region of South Africa, where a decrease is possible. The increase in winter precipitation posited for most of southern Africa is of no practical significance, since little or no rain falls in winter in most parts of the summer rainfall region. Even a threefold increase in an area receiving less that 10 mm on average in winter will be of no meaningful consequence.

For practical purposes, estimations of possible future conditions are of little use unless they can be downscaled to small regions or local areas. Such downscaling has been undertaken. South African examples illustrate the approaches used. The regional, limited-area DARLAM model nested in and forced by a GCM gives a precipitation field in greater detail than that of the forcing GCM and one that much more closely resembles observed conditions (Fig. 9a).[104] However, the model is not able to estimate the number of rain days or rainfall totals correctly in high-altitude escarpment areas. Likewise, downscaling using neural networks that link rainfall to circulation types derived from the forcing GCM provides a more realistic accounting of rainfall over South Africa (Fig. 9b).[105]

Conclusions

Circulation of the atmosphere does much to give southern Africa its regional unity. Subsidence of air in the semi-permanent subtropical anticyclones associated with the southern Hadley cell of the general circulation over Africa imposes a considerable degree of similarity on the climates of the subcontinent. This is so from South Africa to northern Zambia. In the southwestern Cape of South Africa and the Congo this is not the case, but even in Kenya at certain times of year similarities with conditions prevailing to the south are present in the atmospheric stability and air transport regimes. It is these regimes that prevail on fine weather, non-rain days (which constitute the majority of days throughout the region) that are so similar over large areas.

Aircraft and space shuttle observations reveal that the haze layer beneath the mid-tropospheric atmospheric stability discontinuity at around the 500-hPa level is a feature of subcontinental extent, particularly during the dry-season half of the year. At these times the stable layer has been known to prevail for over 40 days without disruption over South Africa. A considerable scientific surprise is the realization that such stable conditions are common in the summer rainy season on no-rain days. The aerosol composition of the layer is established and has been characterized. Likewise, important first steps have been taken to establish the nature of the trace gas loading of the haze layer. North of ~20°S biomass burning is a significant source of aerosols and trace gases. To the south this is not so, even in the main biomass burning season. Instead, aeolian mineral dust from the surface appears to be the main constituent of the haze layer, except in the fine fraction where industrial sulphur products predominate. A surprise has been to find that the sulphur is transported as a patchy coating on small mineral dust nuclei. Such transport may be over considerable distances. Sulphur traced back to South Africa has been measured near the top of Mount Kenya.

Over a large part of southern Africa, extending from the latitude of northern Zambia to South Africa, the major feature of the horizontal transport field is a large anticyclonic vortex, within which aerosols and trace gases accumulate and circulate slowly. Relatively little airborne material is transported to the west and to the Atlantic Ocean. What is so transported tends to be deposited within a comparatively short distance of the shore. By far the largest fraction of aerosols and trace gases transported offshore is to the east over the Indian Ocean in a plume several kilometres thick and often over a thousand wide. The plume is almost always constrained in the vertical by the ~500-hPa stable layer. On occasions, the dust in the plume reaches Australasia. Models reveal the extent to which CO_2 and other trace gases are transported out of southern Africa in the Indian Ocean plume. A significant surprise arising out of the transport research conducted over the last few years is the extent to which recirculation occurs.

Recirculation is a major feature of the transport of aerosols and trace gases over southern Africa. Various studies conducted over different periods show that recirculation, on scales ranging from tens to thousands of kilometres, occurs on average over 40% of the time. The implications for the accumulation and transport for material in the atmosphere are considerable. Over the central areas of the subcontinent, first estimates suggest that around 40 Mt yr^{-1} of aerosols is transported eastward in the plume trapped below the ~500-hPa stable layer. The primary constituents of the plume are aeolian dust and industrial sulphur products, the latter being carried as a precipitate on fine dust nuclei. Other important trace constituent elements include nitrogen and phosphorus. As nitrates and phosphates, these constitute important nutrients that are transported from one region to another. When deposited, in either wet or dry deposition, they constitute important additional components of the biogeochemical cycle, sustaining both terrestrial and marine ecosystems. Their effect, hitherto unsuspected or ignored, must be taken into account.

Sulphur emissions over southern Africa are high over industrial and mining areas of the subcontinent. Concentrations increase in the atmosphere owing to trapping beneath the ~700- and ~500-hPa stable layers and widespread dispersion is brought about by recirculation. Modelling reveals that deposition occurs over wide areas of the subcontinent and out into the Indian Ocean in the plume exiting South Africa to the east. Climate models further reveal that the direct and indirect effects of the sulphate aerosols over the region act to cool the atmosphere by more than 1°C in many areas. This is insufficient to halt the warming trend evident over the region and which is likely to continue in the future.

Climate models suggest that by about 2050 maximum temperatures will have risen by more than 2°C in many places. Increases exceeding 3°C are likely in the case of minimum temperatures in early winter, when the warming tendency is most evident. The changes in temperature appear to be likely to be accompanied by decreases in summer rainfall over most areas of the summer rainfall region. It must be realized that, notwithstanding recent improvements in climate models, considerable uncertainty still attaches to their use, particularly in respect of future precipitation simulations. In addition, the simulations do not constitute firm predictions, but only possible scenarios of what may happen.

Any integration and synthesis of the effects global change may have in southern Africa must recognize the importance of changing climate as a major driving force leading to biogeochemical changes in the terrestrial and marine ecosystems sustaining the region. It is not the only driver. In many cases socio-economic factors may play a more important role. In some, the socio-economic drivers of change may happen irrespective of climate change; in many instances they will be modulated by it. Whichever way one looks at the regional aspects of global change, climate remains of fundamental importance.

This paper is a contribution to the IGBP-WCRP-IHDP START regional synthesis of the effect global change is likely to have on the southern African region. The authors wish to acknowledge START support for many aspects of the work. Figures were prepared by Wendy Job.

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106. Note added in proof. Another iron fertilization experiment has recently been reported, which extends our understanding of the relationship between iron supply, marine plankton and atmospheric carbon dioxide. The experiment was conducted in the Southern Ocean south of Tasmania, at approximately 61°S, 140°E, with similar results to those recorded in the equatorial Pacific Ocean. See: Boyd P.W. *et al.* (2000). A mesoscale phytoplankton bloom in the polar Southern Ocean stimulated by iron fertilization. *Nature* **407**, 695–702.

Editorial footnote

Iron fertilization and the Indian Ocean

In the above article, Tyson and Gatebe highlight how aeolian dust can affect ocean productivity and the marine carbon cycle thousands of kilometres from its source (see page 114). It is instructive to understand why.

It has been known for a decade that iron is essential for phytoplankton growth. If it happens to be a limiting nutrient in the upper layers of the ocean, addition of the element through wind-borne particulates, or artificially by the short-term admixture of sufficient amounts of iron compounds in fertilization experiments, can boost and sustain algal growth for weeks at a time.

The phytoplankton have a key role to play in the exchange of the greenhouse gas CO_2 between the atmosphere and the surface layers of the ocean — nearly half of the photosynthesis on Earth is carried out by these tiny cellular plants. The pelagic biota convert the CO_2 to organic carbon, which forms the base of the marine food web. An agent that thereby enhances marine productivity will act as a CO_2 sink and, in sufficient quantities, potentially induce climate change. Conversely, changes in climate that modify air currents and their pollution load can be expected to alter the environmental CO_2 and the associated food web.

Iron-enrichment experiments in the equatorial Pacific Ocean in 1995 stimulated a significant phytoplankton bloom, thus acting as a short-term carbon dioxide sink. A different kind of link between iron and CO_2 flux has been established by other kinds of study. In recent years, the South Indian Ocean between South Africa and Australia was identified as a major sink region for CO_2. Modelling studies and direct observations of the atmospheric circulation and composition showed that an aerosol plume from southern Africa crosses the area of the carbon sink and probably deposits its particulate load there. The iron content of the plume is calculated to introduce into the sea at least the equivalent of the amount of the element consumed in the controlled experiment in the Pacific. The next stage in this investigation is to test the hypothesis, that the iron effects the drawdown of atmospheric CO_2 via plankton, by sampling the ocean for marine life over a period of time under different climatic conditions.

Another iron fertilization experiment, in the polar Southern Ocean, has just been reported that confirms and elaborates on the link between carbon sequestration and marine productivity.[1] In this study, over 8 tonnes of an iron compound, released some 2000 kilometres south of Hobart, Tasmania, quickly led to a trebling of plankton chlorophyll levels that were sustained over a month later in the release area. Some of the scientists involved in the investigation went so far as to propose that iron supplies to the Southern Ocean have been the driver of glacial–interglacial transitions for some 400 000 years. They came to this conclusion using data on atmospheric iron fluxes derived from the Vostok ice core.[2]

These results give oceanographers and atmospheric scientists a powerful tool to probe the mechanisms that link the biological and chemical cycles that underpin the interactions between the oceans and climate. They also suggest a relatively simple means, other than planting trees, to remove carbon dioxide from the air.

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1. Boyd P.W. *et al.* (2000). A mesoscale phytoplankton bloom in the polar South Ocean stimulated by iron fertilization. *Nature* **407**, 695–702. See also: Abraham E.R. *et al.* (2000). Importance of stirring in the development of an iron-fertilized phytoplankton bloom. *Nature* **407**, 727–730.
2. Watson A.J. *et al.* (2000). Effect of iron supply on Southern Ocean CO_2 uptake and implications for glacial atmospheric CO_2. *Nature* **407**, 730–733.