Numerical simulation of tropical-temperate troughs over southern Africa using the CSU RAMS model

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Tropical-temperate troughs and their associated cloud bands have been modelled over southern Africa using the Regional Atmospheric Modeling System (RAMS). The correspondence between simulated fields and observational data for both the dry (1980) and the wet (1981) late summer case studies has been examined. Model simulations reveal that the tropical-temperate troughs form when an upper westerly wave coincides with an easterly wave or depression in lower levels. These systems occur preferentially over southern Africa (Madagascar) during wet (dry) southern African summers and are a major conduit for the poleward transfer of tropical moisture and energy.

Cloud bands and their attendant synoptic systems have been found to exist in various parts of the world and have been studied in Australia,[1,2] South America,[3,4] the north Pacific Ocean,[5] and southern Africa.[6–9] Cloud bands or tropical-temperate troughs that form in preferred locations of the southern hemisphere have numerous characteristics in common. They all contribute significantly to the regional rainfall and variations in their position and frequency affect the rainfall distribution over the region. All cloud bands are found to link temperate (south of 35°S) and tropical circulation regimes and appear to facilitate the transport of energy, moisture and momentum from the tropics (north of ~20°S) to the mid-latitudes. All form eastward of upper air semi-stationary long waves in the atmosphere.

Tropical-temperate troughs over southern Africa have recently been investigated.[6–11] These systems form when a tropical disturbance, such as an easterly low or wave at the surface, occurs in conjunction with a westerly wave or low in the upper atmosphere. Under such conditions, an elongated trough extends in a northwest-southeast direction across the subcontinent and the southwest Indian Ocean.[7,10] Surface convection and upper air divergence result in ideal conditions for strong vertical uplift and the formation of cloud bands. Tropical-temperate troughs, including cut-off lows, which develop characteristically in conjunction with the south-eastward transport of warm tropical air associated with tropical-temperate troughs,[12] contribute up to 30 per cent of the October and December rainfall and 60 per cent of January precipitation. Their contribution to the total annual rainfall is approximately 40 per cent, making them one of the most important contributors to summer rainfall over the central interior of South Africa.[6] Other systems affecting the subcontinent do not individually contribute more than 14 per cent.[7]

As tropical-temperate troughs extend from the tropics to the mid-latitudes and often occur over the ocean, research into these important rain-producing systems has been hampered by the scarcity of data over the African subcontinent and adjacent oceans. Numerous observations and hypotheses regarding the large-scale circulation controls and the kinematic characteristics of tropical-temperate troughs over southern Africa have been made in the past. In order to substantiate these hypotheses, the Colorado State University Regional Atmospheric Modeling System (RAMS) is used to model the occurrence and consequences of tropical-temperate troughs over southern Africa.

The Regional Atmospheric Modeling System[13–15] was developed at Colorado State University by combining a non-hydrostatic cloud model[16] and two hydrostatic mesoscale models.[13,17] RAMS is a modular, flexible and general modelling system. It has been used successfully to simulate a variety of atmospheric systems ranging from one hundred metres in scale to thousands of kilometres in extent.[18] These simulations include the interaction between deep sea breezes and deep convection over south Florida,[19] orographic cloud systems:[20] and squall line structures.[21]

All model simulations were performed in three dimensions. The vertical co-ordinate system used is the terrain-following σ_z system. The width and number of vertical levels are specified by the user. As tropical-temperate troughs are generally thousands of kilometres long, but comprise numerous cloud clusters that rely on smaller-scale processes, it is necessary to incorporate the entire system in a large domain model, while a fine resolution is necessary to simulate the smaller-scale cloud processes. The nesting option was used where the nested and coarse grid resolutions were 55 and 120 kilometres, respectively. The domain of the coarse grid was approximately 0–50°S, 10–80°E, and the domain for the fine grid was approximately 15–40°S, 20–60°E.

Both control runs included the modified Kuo parameterisation scheme, but did not include any resolvable microphysics. The convective precipitation rate is the rate of precipitation computed by the convective parameterisation scheme and indicates only the precipitation obtained from deep convection. Precipitation resulting from other processes, such as those involved with stratiform type clouds, is not simulated. As the convective precipitation is simply a picture of what is occurring at a specific moment, comparing the regions of convective precipitation with satellite images or synoptic charts does not always yield a close correspondence. Nevertheless, the convective precipitation rate is indicative of regions of deep convection along the cloud bands and other grid regions and is an important variable to examine, even though it does not give a complete picture of total rainfall.

A loam soil and tall grass were specified for the soil and vegetation types over the entire domain and the surface roughness was set at 10 centimetres. Ten soil levels, constituting a soil depth of 50 centimetres, were employed. Historical monthly mean sea-surface temperatures for January were specified for the sea-surface parameterisation.

The model was variably initialised.[15] In this scheme the model is provided with 3-dimensional atmospheric fields, obtained from surface and radiosonde data sets, at the initial time-step. These variables are then interpolated vertically to the isentropic levels, which are produced at 12-hour intervals.

Most of the data sets used with RAMS were obtained from the National Center for Atmospheric Research (NCAR), in Boulder, Colorado. These include the European Centre for Medium Range Weather Forecasts (ECMWF) III-b Global Analysis Data Set and the National Meteorological Center (NMC) observational and surface data and radiosonde sets. Visual images of the tropical-temperate trough case studies were obtained from the National Oceanic and Atmospheric Administration Environmental Data and Information Services' TIROS-N and NOAA6 polar orbiting satellite imagery (NOAA, 1980, 1981). Radiosonde data were supplied by the South African Weather Bureau (SAWB) and monthly mean sea-surface temperature data were obtained from the Meteorological Office Historical Sea Surface Temperature (MOHSST) data set. All of the RAMS simulations were performed on the Cray YMP supercomputer at the SAWB.

Contrasts between wet and dry conditions

In order to determine whether the RAMS model output is representative, to some degree, of reality, the output needs to be compared with actual data. Two cases have been chosen for detailed study, one during a wet year (22–24 January 1981) and one during a dry year (6–8 January 1980).

The wet case study: 22–24 January 1981

A tropical low over northern Namibia, a trough orientated in a northwest to southeast direction across the central interior of South Africa, a cold front approaching the subcontinent from the south-west and the South Atlantic and South Indian anticyclones were prominent surface level features at 12:00 UT on 22 January 1981 (Day 1) (Fig. 1*a*). The 500 hPa geopotential height field for 22 January 1981 is characterised by a large amplitude, short wavelength wave to the southwest of the subcontinent (Fig. 1*d*). These features are reflected in the cloud analysis based on the satellite image for the corresponding day (Fig. 3*a*). Tropical cloud associated with the surface trough covered the western and central interior of the subcontinent.

On 23 January the trough across the subcontinent had intensified (Fig. 1*b*). The temperate link between the interior trough and the cold front to the south of the subcontinent had formed and the tropical-temperate trough had reached the mature stage of its development. This was reflected in the associated cloud band (Fig. 3*b*). The westerly wave had increased in amplitude such that its trough axis was situated over the western regions of southern Africa (Fig. 1*e*). In accordance with theory, divergence in the upper westerly wave overlays convergence in the surface trough, thus promoting ideal conditions for convection along the cloud band.

The tropical-temperate trough had partially dissipated by 24 January 1981, despite the continued presence of the interior trough (Fig. 1*c*). The cold front had progressed eastward, thereby breaking the tropical-temperate link. The westerly wave had shifted slightly eastwards by 24 January 1981 (Fig. 1*f*). Some cloud cover was still present over southern Africa and to the south of the subcontinent (Fig. 3*c*). The cloud band started to regenerate by the night of 24 January (not shown). Full dissipation of the cloud band occurred on 27 January 1981. It should be noted that the speed of the trough was much slower than expected for such a short wavelength perturbation. This may be the result of the presence of a persistent, deep anticyclone over the south Indian Ocean impeding the eastward displacement of the trough (see Figs 1, 4).

The dry case study: 6–8 January 1980.

An extensive frontal system to the southeast of the subcontinent, an anticyclonic ridge behind the system, the South Indian Anticyclone centred to the southeast of Madagascar and two regions of low pressure over central southern Africa were all significant features at the surface on 6 January 1980 (Fig. 2*a*). The frontal system to the southeast constituted the temperate section of the tropical-temperate trough and heavy cloud cover occurred in association with this system (Fig. 3*d*). At the 500 hPa level, the geopotential height fields are characterised by two waves: one to the southwest of the subcontinent, and the other between South Africa and Madagascar (Fig. 2*e*).

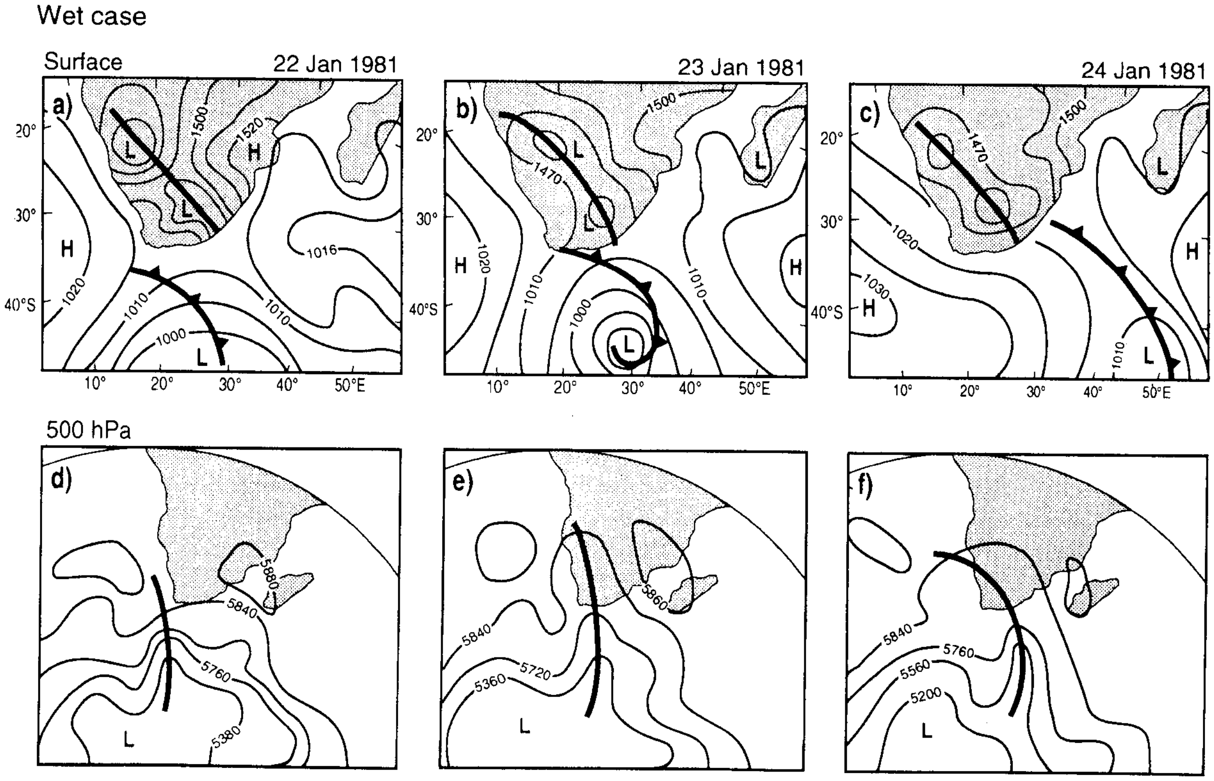

Fig. 1. Synoptic charts and 500-hPa geopotential height fields at 12:00 UT for (*a*) 22 January, (*b*) 23 January and (*c*) 24 January 1981.

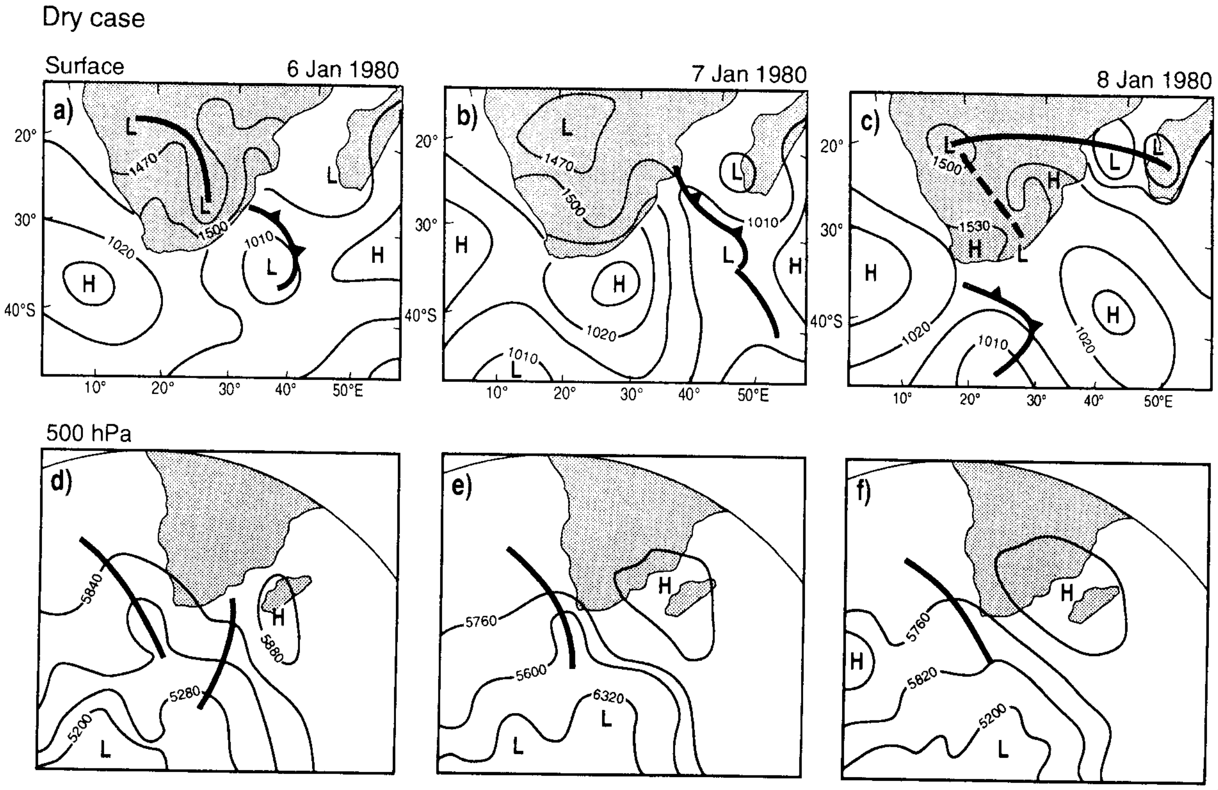

Fig. 2. Synoptic charts and 500-hPa geopotential height fields at 12:00 UT for (*a*) 6 January, (*b*) 7 January and (*c*) 8 January 1980.

By 7 January 1980, the cold front had progressed eastward and was aligned with the trough extending from over central Mozambique to southern Madagascar, so forming the tropical-temperate link (Fig. 2*b*). The upper level westerly wave was situated off the west coast of southern Africa (Fig. 2*e*). The tropical-temperate trough was now well developed and extensive cloud cover extended southeastwards over the Mozambique Channel and the eastern regions of southern Africa (Fig. 3*e*)

The tropical-temperate trough had started to dissipate by 8 January 1980, due to the breaking of the tropical-temperate link. The leading cold front was located to the east of Madagascar, making any connection with the tropical low over northern Mozambique impossible (Fig. 2*c*). The high pressure cell, which enhanced the eastward movement of the cold front, resulted in a south-easterly airflow over the southern Mozambique Channel (Fig. 2*c*). The westerly wave was still situated off the west coast of southern Africa (Fig. 2*e*). Dissipation of the tropical-temperate trough was associated with a reduction in the tropical cloud

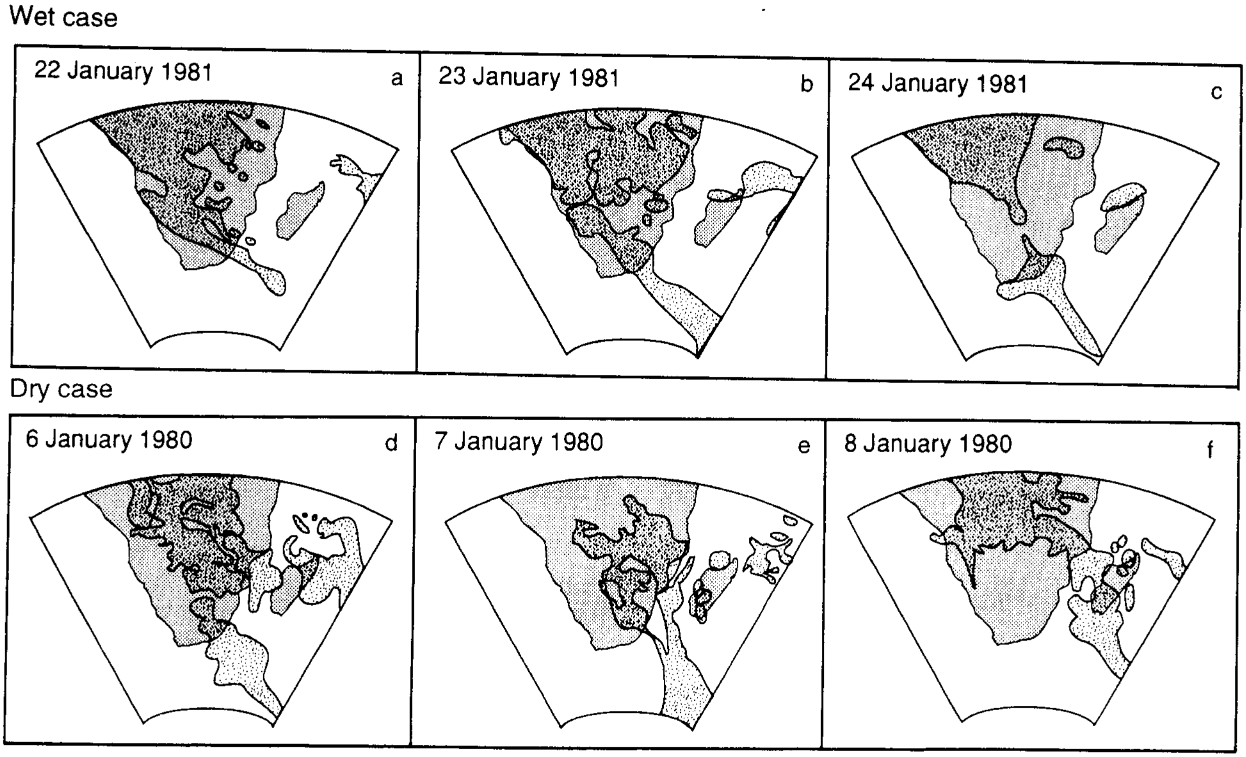

Fig. 3. Cloud cover based on satellite imagery for (*a*) 22 January, (*b*) 23 January, (*c*) 24 January 1981, (*d*) 6 January, (*e*) 7 January and (*f*) 8 January 1980.

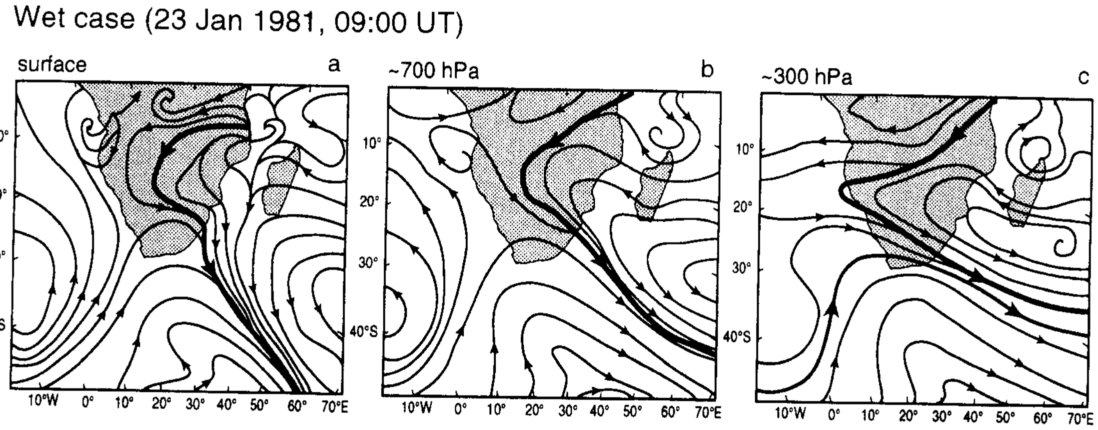

Fig. 4. Simulated streamlines at 09:00 UT for 23 January 1981 for (*a*) surface, (*b*) 700 hPa and (*c*) 300-hPa pressure levels.

cover. Remnants of the cloud band were present over the oceanic regions southeast of Madagascar, and were largely associated with the eastward-progressing cold front (Fig. 3*e*).

Control runs for the wet and dry case studies

The characteristics of tropical-temperate troughs that develop during wet and dry periods have been found to differ significantly.[7,9,10] The eastward shift of tropical-temperate troughs from their position over the subcontinent during wet summers, to over the Mozambique Channel and Madagascar during dry summers, has a significant effect on southern African rainfall. Changes in wind flow, atmospheric moisture and rainfall over southern Africa are associated with the variation in the locations of tropical-temperate troughs in wet and dry conditions. In this paper, RAMS is used to investigate the characteristics of meso-scale systems at resolutions greater than those of present observational data sets. The first objective in attempting to investigate wet- and dry-year tropical-temperate trough characteristics using the meso-scale model is to establish a suitable control run. The simulated results will be compared with the satellite imagery and with the movement and the development of the systems as illustrated by the synoptic charts presented above. Four data fields have been selected to compare simulated with observational data. These are streamlines, pressure, vertical velocity and convective precipitation rate.

Streamlines

At 09:00 UT on 23 January 1981, 21 hours into the simulation period for the wet case study, a tropical low is evident over northern Namibia at the surface (Fig. 4*a*). An interior trough extending in a northwest to southeast direction from the tropical low over Namibia is clearly visible in the surface streamlines over South Africa. The trough is also evident at the 700 hPa with the extension of the westerly wave over the interior (Fig. 4*a*). North-easterly flow from eastern tropical Africa and the adjacent oceanic regions, which has been found to be important in transporting moisture over southern Africa,[11,22,23] is clearly obvious in the modelled surface and 700 hPa streamlines (Fig. 4*a*, 4*b*). The simulated South Atlantic and South Indian anticyclones and the westerly wave throughout the troposphere correspond closely with the observed circulation fields (Figs 1*b*, 1*e*, 4*a*, 4*b*). Furthermore, the formation of a closed cell of cyclonic circulation in the modelled westerly flow at the lower levels closely matches that of the synoptic chart and 700 hPa pressure fields (Figs 1*b*, 4*a*, 4*b*).

The surface trough associated with the cold front to the south of Madagascar and the ridging of the high pressure cell from the South Atlantic Anticyclone are clearly simulated by the model at 12:00 UT for the dry case on 7 January 1980 (Fig. 5*a*). A trough is evident over the Mozambique Channel and forms the link between the tropical low over Malawi and the westerly wave. The feature is only partially evident on the synoptic chart (Figs 2*b*, 5*a*). North-easterly flow occurs into the region of the tropical low from over tropical Africa and the oceanic region to the northwest of Madagascar. The modelled centres of both the South Atlantic and South Indian anticyclones agree closely with those indicated on the synoptic chart (Fig. 2*b*). Given that the simulated and observed levels do not coincide, the circulation features evident in the 500-hPa upper air charts are in general agreement (Figs 2*e*, 5*c*). However, the 300-hPa streamlines suggest the trough axis is located over South Africa, while the analysed 500-hPa trough axis occurs to the west of the subcontinent

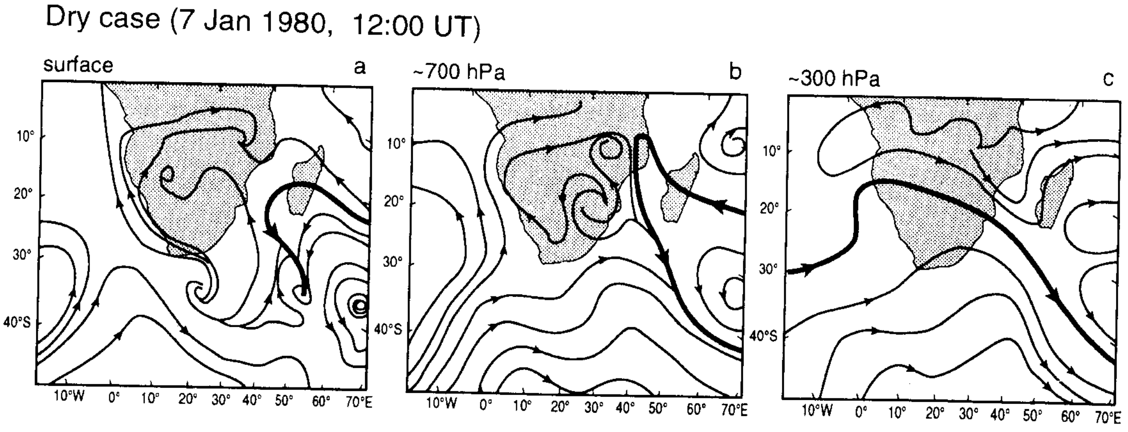

Fig. 5. Simulated streamlines at 12:00 UT for 7 January 1980 for (*a*) surface, (*b*) 700 hPa and (*c*) 300-hPa pressure levels.

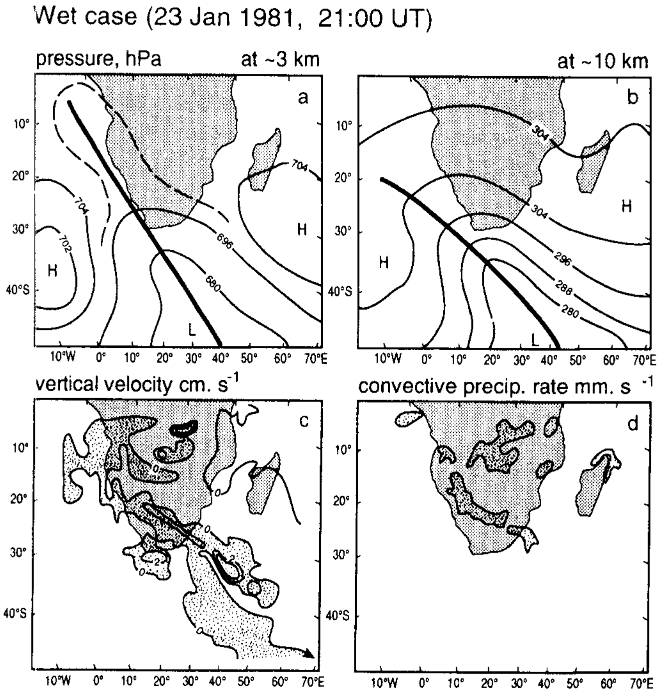

Fig. 6. Simulated pressure fields at (*a*) 3 km, (*b*) 10 km, vertical velocity fields at 700 hPa (*c*), and convective precipitation rate (*d*) at 21:00 UT on 23 January 1981. Units are hPa in (*a*) and (*b*), cm s^{-1} in (*c*) and mm s^{-1} in (*d*). Shading in (*c*) indicates upward motion.

(Figs 2, 5*c*). This dichotomy may be due to the subjectivity inherent in the hand-drawn 500-hPa chart.

Lower level convergence occurs along the modelled tropical-temperate trough when fully developed. Divergence on the leading edge of the upper westerly wave is associated with the low level convergence and promotes strong uplift in the region of the tropical-temperate trough (Figs 5*a*, 5*c*). The model shows that pole-ward flow does not occur along the entire tropical-temperate trough at the surface level, unlike that at the 700 and 300-hPa levels. Simulated easterly flow over Madagascar around the South Indian Anticyclone also contributes to the pole-ward flow along the tropical temperate trough.

Pressure, vertical velocity and convective precipitation

During the mature stage of the tropical-temperate trough development on 23 January 1981, the temperate link between the westerly wave and the interior trough is evident (Fig. 6*a*). The westward tilt of the westerly wave with height, typical of bareclinic systems, is also clearly obvious (Figs 6*a*, 6*b*). The simulated pressure fields at 3 km and 10 km approximate in general the observational data at 850 and 500 hPa (Figs 6*a*, 6*b*, 1*b*, 1*e*), but not in all respects.

The vertical velocity field at 21:00 on 23 January 1981 is characterised by strong vertical uplift along the entire tropical-temperate trough system to approximately 40°S (Fig. 6*c*). The area of uplift over the ocean did not extend as far poleward as the cloud band evident in the satellite imagery (Fig. 3*b*). The synoptic chart for 23 January reveals that the centre of the low pressure cell associated with the cold front is situated at approximately 43°S (Fig. 1*b*). Strong vertical uplift is not likely to be found south of this position.

The simulated convective precipitation rate over southern Africa and adjacent oceans at 21:00 UT on 23 January is illustrated in Fig. 6*d*. Convective precipitation is evident along the fully developed trough. The band structure of the tropical-temperate trough is clearly obvious. The confinement of the convective precipitation to north of approximately 35°S is in keeping with the southerly extent of the region of vertical uplift. Some convective activity is observed over the tropics and is related to the presence of tropical cloud clusters (Fig. 3*b*).

At 21:00 UT on 7 January, the modelled convective precipitation rate over tropical Africa (Fig. 7*d*) closely coincides with the well-developed tropical cloud clusters evident in the cloud analysis of the satellite imagery (Fig. 3*e*), and occurs along most of the mature tropical-temperate trough from the tropical low over the Mozambique Channel to about 35°S (Fig. 7*d*). Convective activity also coincides with the fields of vertical velocity in this case, and is reflected by the cloud cover evident in the satellite imagery for 7 January (Figs 7*c*, 7*d*, 3*e*). Southern Africa is relatively dry during this time (Fig. 7*d*). The simulated pressure fields at the 700 and 300-hPa levels for the 7 January 1980 case study agree in general with those of the observed upper air charts. The tropical temperate trough had reached its mature stage of development at 21:00 (Fig. 7*a*, 7*b*), and the westerly wave at 700 hPa was situated off the east coast of southern Africa, tilting slightly westward with height.

Higher resolution sensitivity

All of the control simulations discussed so far were performed using a coarse grid resolution of 80 kilometres. At such a resolution, the meso-scale circulations associated with the tropical-temperate troughs are somewhat crudely resolved. A grid resolution of 50 kilometres is used to determine the effects of finer resolution on the circulation. The spatial extent of the filler grid is necessarily smaller than the coarse grid, due to computer limitations. Apart from changing the grid resolution, no other changes were made to the model setup. Differences between the coarse control run and the finer resolution sensitivity test can therefore be attributed either to the change in the grid resolution or to the change in position of the lateral boundaries in relation to the tropical-temperate trough system.

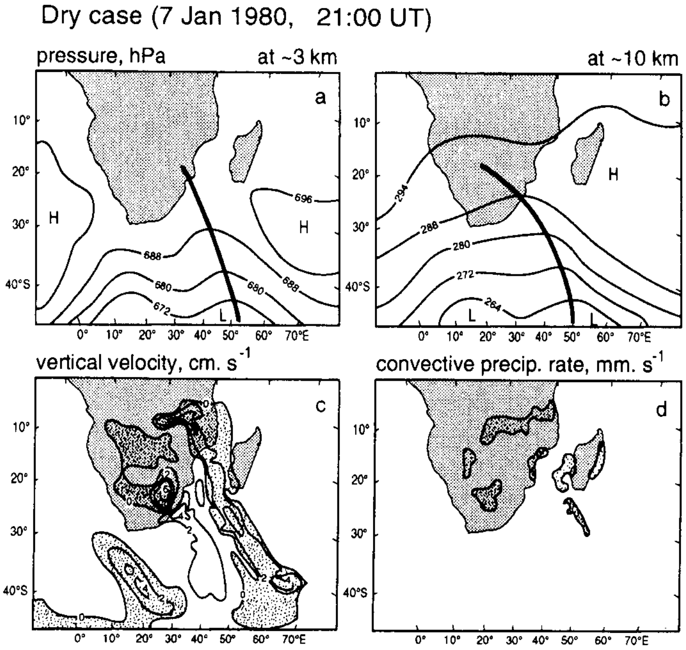

Fig. 7. Simulated pressure fields at (*a*) 3 km, (*b*) 10 km, vertical velocity fields at 700 hPa (*c*), and convective precipitation rate (*d*) at 21:00 UT on 7 January 1980. Units are hPa in (*a*) and (*b*), cm s^{-1} in (*c*) and mm s^{-1} in (*d*). Shading in (*c*) indicates upward motion.

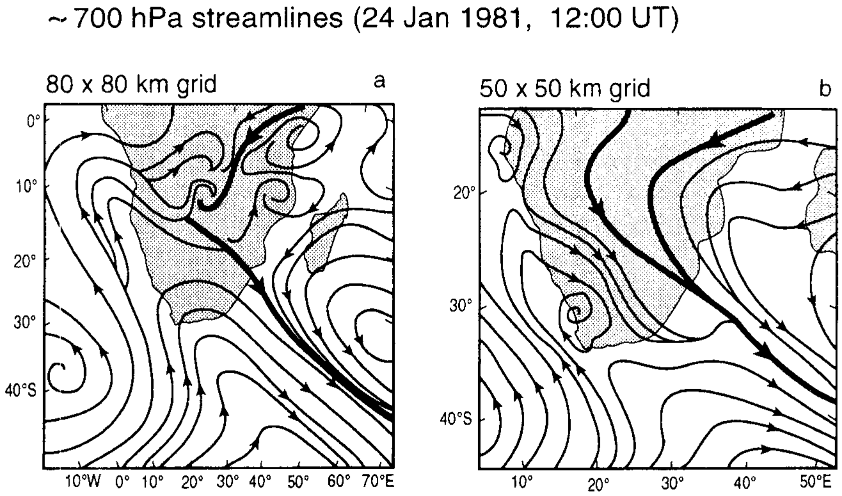

Fig. 8. Simulated streamlines at the 700-hPa level at 12:00 UT on 24 January 1981 for (*a*) the coarse resolution (80 × 80-km grid) and (*b*) for a finer resolution (50 × 50-km grid) sensitivity test.

The most significant differences between the coarse control run and the finer resolution sensitivity tests occur at the 700-hPa level. The existence of the cut-off low pressure system, resulting in the Laingsburg flood on 24 January 1981, is obvious in the streamlines of the finer resolution simulation (Fig. 8*b*). The low is not adequately resolved by the coarse resolution of the control run (Fig. 8*a*). However, the fact that the fine resolution managed to resolve the cut-off low during the Laingsburg floods is encouraging, particularly since this system behaved in an anomalous manner for cut-off lows.[24]

In the tropics, the coarse control run appears to simulate more perturbations than does the finer resolution simulation. However, 700-hPa pressure level charts[9] do not indicate these perturbations. The north-easterly to north-westerly flow across tropical and southern Africa occurs in both the coarse control run and the finer resolution test. Despite the differences, the modelled development of the tropical-temperate troughs using the 80-km and 50-km grids show a high degree of correspondence, thereby adding credibility to the numerical model.

Discussion

RAMS appears to be a powerful tool with which to model synoptic weather systems affecting southern Africa. Modelled streamlines, pressure fields, vertical velocities and convective precipitation fields represent the observational data fairly accurately.

A tropical low, a westerly wave and a trough connecting them constituted the three main components of tropical-temperate troughs in late wet and dry years. All these components are replicated by the model. The tropical low in the wet case is situated further west (15°E) than in the dry case (30°E), when it is situated over eastern Africa, concurring with earlier work which suggested that this should be the case.[7,9] In both cases, the tropical lows are embedded within the easterly flow, which appears to enhance their development.

The model reveals that tropical-temperate trough systems form after the establishment of the link between the tropical low and the westerly wave trough. The trough over the western interior of southern Africa forms the connection during the wet case study, while the trough over the Mozambique Channel provides the link between the tropics and mid-latitudes during the dry case study. Simulations show that the influence of the westerly wave on the development of the tropical-temperate trough is evident at all tropospheric levels in both wet and dry cases. In the lower troposphere, convergence occurs to the east of the easterly wave and to the west of the temperate westerly wave. The westward tilt of the systems and the upper troposphere upper level divergence ahead of the westerly wave provide the vertical uplift at all tropospheric levels along the tropical-temperate trough. This is clearly evident in the simulated vertical velocity fields.

Previously it has been shown that the development of the tropical-temperate trough results in the organisation and enhancement of pole-ward flow along the cloud band over central and eastern southern Africa during wet seasons and over the Mozambique Channel in dry seasons over South Africa. RAMS simulations appear to confirm that pole-ward flow along mature tropical-temperate troughs is a major means of transferring moisture and energy from the tropics into temperate and high latitudes.[14,7,25,26]

The importance of north-easterly flow into the region of the tropical low is evident in both the wet and the dry simulations. During wet conditions, north-easterlies extend across the subcontinent from the eastern regions of tropical Africa and the oceanic regions to the northwest of Madagascar to the tropical low over northern Namibia, both at the surface and at the 700-hPa level. Enhanced north-easterly flow has been observed previously over southern Africa during wet summers[11,22,23,27,28] and in association with the development of wet year tropical-temperate troughs.[9] The passage of the north-easterly flow over the oceanic regions to the north of Madagascar supports the suggestion that this oceanic region is an important source of the water vapour flux over South Africa.[23] A tropical low over the Mozambique Channel, as seen in the dry case study simulation, has been linked previously to dry conditions over South Africa.[9,28] This depression and the linking trough at the surface level over the Mozambique Channel are fed by north-easterly winds which originate over the oceanic regions to the east of Madagascar.

Simulations reveal that easterly to north-easterly winds around the South Indian High contribute to the pole-ward flow along the tropical-temperate trough in both cases. During the wet case study, the South Indian High is situated closer to the subcontinent and enhances the north-easterly to north-westerly airflow over the southern African interior during the occurrence of the tropical-temperate trough. During the dry case study, the eastward shift of the South Indian High reduces its influence on the subcontinent. A similar shift between wet and dry periods has been observed previously.

The model shows that subsidence behind the upper level westerly wave over the subcontinent during the dry case results in the dry conditions occurring over most of southern Africa. During the wet case, the major convergence occurs over the eastern parts of South Africa and the associated uplift results in wet conditions over the central and eastern parts of South Africa.

In its fine resolution configuration, the model was able to simulate the cut-off low embedded to the rear of the flow fields associated with the tropical-temperate trough during January 1981.[12] This low was not resolved using the coarse grid spacing. Differences between the coarse run and the finer resolution run may be attributed to the change in grid resolution, thereby allowing for smaller-scale meteorological processes to be simulated.

Conclusions

The model has proved able to represent accurately the tropical-temperate troughs that formed during the Januaries of 1980 and 1981. Most of the simulated fields accord closely with those observed, and it would appear that RAMS is a model well suited for the investigation of synoptic and meso-scale systems over southern Africa. The model has allowed hypotheses concerning the components of the interacting systems, their positions and alignment and vertical velocity fields to be substantiated. More importantly, the use of the model has provided verification in specific cases of how the climatological locations of the tropical-temperate troughs in wet and dry conditions materially determine and account for changing surface patterns over southern Africa with time.

A foundation has been provided for the use of RAMS as a tool to study the sensitivity of southern African tropical-temperate troughs and for examining changes in various parameters during wet and dry years. In particular, the model is useful in the testing of hypotheses concerning the effects of changing sea-surface temperature and soil moisture on rainfall. A basis has also been provided for further meso-scale modelling of southern African atmospheric systems.

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