ATMOSPHERIC MOISTURE TRANSPORT AND SOURCES FOR SOUTHERN AFRICA

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Report to the Water Research Commission on the Project

"*The Climatology of water vapour sources, sinks, and transport in southern Africa*"

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EXECUTIVE SUMMARY

The project on moisture transport, sources and sinks, seeks to investigate the underlying dimension of atmospheric moisture on which the South African rainfall is inherently dependent. This aspect of the South African climate system has been under-investigated, with past work providing some insight, yet at times contradictory interpretations. This project thus focuses on clarifying the issues involved in order to better understand the implications for rainfall in the context of climate variability and possible implications of climate change. At the same time, the results provide a foundation for further research avenues. The original project objectives, as proposed, were as follows:

- To develop trajectory transport models with the inclusion of diffusion and precipitation in the transport of moisture
- Develop long-term climatology of atmospheric water transport for different regions of southern Africa
- Analysis of moisture sources, sinks, and relevance to controls on precipitation
- Evaluate moisture transport in global models
- Analysis of transport characteristics in regional models with relevance to climate change and seasonal forecasting

These objectives have been achieved, and in many respects, exceeded.

The research follows two complementary pathways, adapting the research agenda in light of the evolving results and findings. Firstly, a trajectory model is developed and then applied to investigate the time-evolving transport paths of the atmospheric moisture, and the related sources of moisture. The trajectory model takes advantage of low cost computing infrastructure, and is developed to specifically address large-volume trajectory calculations. From this is developed a 20-year climatology of moisture transport for southern Africa that is then examined in terms of seasonal and sub-seasonal attributes. Secondly, the large-scale seasonal mean moisture dynamics are examined to identify key source regions of moisture contribution to the atmosphere. Both approaches develop different insights into the climate system, yet complement and support one another.

Overall, the results lead to a number of key conclusions:

a) For summer rainfall over the sub-continent, and particularly for the key economic agricultural region of the South African interior, at the seasonal time frame there is a significant moisture transport pathway from the east (elevated over the ocean) with a dominant source of moisture from east of Madagascar.
b) The ocean regions to the southeast of the continent, in particular over the Agulhas gyre, are a strong source of moisture for the atmosphere. However, there is some question over how much of this moisture makes direct or indirect contributions to continental rainfall.
c) There are clear indications that local continental feedbacks may be of significant importance in modulating intra-seasonal variability of rainfall.
d) Intra-seasonal atmospheric moisture content over the continent does not show large variability, suggesting the dynamics of circulation processes may have a greater role in modulating rainfall than the moisture transport itself.

e) Spatially extensive heavy rainfall events appear to have moisture transport pathways and mean atmospheric moisture contents that are not dissimilar to the seasonal means, again suggesting that other dynamic processes may be more important.
f) Climate change implications for moisture transport remain uncertain due to issues of skill in the GCMs used to project future climate regimes. However, current consensus is that significant changes are indeed expected, with a tentative inference for wetter conditions on the eastern margins of South Africa, and drier conditions to the west.

These results suggest, in particular, three main research avenues in need of further investigation. Firstly, to distinguish the relative roles of the identified large scale sources of moisture to the atmosphere (particularly the Agulhas gyre) on a seasonal basis. This work would require the application of regional climate models to better address the regional scale process controls.

Second is the question of identifying the role of local land-surface feedbacks and moisture recycling in the intra-seasonal time frame. There are suggestions that these may be of significant importance but it remains unclear whether their role is dominant in modulating individual events, or how these impact the seasonal mean, such as by playing a role in determining onset of summer rains, or influencing the intensity of extensive heavy rainfall.

Third, it remains unclear as to how credible global climate models are in representing the foundational moisture transport processes, and consequently their ability to credibly simulate projections of future climate. This requires new methodological approaches to determining model skill at time and space scales of relevance to the continental hydrology.

In terms of building capacity, the project has developed a new trajectory model that may be readily applied in a wide variety of contexts, and has already been adopted as part of other post-graduate thesis work. Linkages with the SA Weather Service have improved with increased collaboration as a direct consequence of this project. In addition, a core group of scientists and students has been developed who are increasingly addressing the key question of regional hydrology in the context of a coupled ocean, land, and atmospheric system, reflecting complex feedbacks and coupling mechanisms, and which necessitates a coupled systems approach. A number of post-graduate projects have evolved from this that will, in part, address the key questions outlined above.

The primary recommendation to come from this project is for continued support of complementary climate research activities, focused on coupled climate system dynamics, and in particular through the use of climate models. Key to this is developing a sustainable research thrust that builds on accomplished work to support an understanding of the collective aspects of the climate system, the consequent impact on surface hydrology, and ultimately, the relevance to society.

Overall the project has successfully met and exceeded the original objectives, and represents a significant advance in our understanding of this key component of the climate system.

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1. Introduction

It has long been recognized that water vapour flux is fundamental to the global hydrological cycle and that fluctuations in this flux can relate directly to droughts and floods (Rosen et al., 1979). Most of southern Africa is semi-arid and the moisture that contributes to precipitation in the region must be largely imported from elsewhere (D'Abreton and Lindesay, 1993). Potential sources of this water vapour have been identified as the southwest Indian Ocean (Lindesay and Jury, 1991; Levey and Jury, 1996), South Atlantic Ocean (Taljaard, 1986) and the tropical areas of continental Africa (D'Abreton and Lindesay, 1993). More recently, attention has been given to the influence of the Agulhas current on summer rainfall along the southeast coast of South Africa (Jury et al., 1993; Mason, 1995) and over the sub-continent as a whole (Reason, 2001). This narrow southward-flowing current hugs the east coast of South Africa as far south as Cape Agulhas before dissipating into eddies. A quantification of the importance of this warm current as a direct supply of moisture to the interior of southern Africa is still a matter of debate. However, significant positive correlations between SST anomalies in this region and summer rainfall have been established (Mason, 1995).

Following the studies already undertaken above, it is apparent that there remains much uncertainty around the processes and characteristics of moisture transport, the variability, relationships to extreme events, and how climate change may impact on the system. All of these raise uncertainty over the response of the hydrological system to the variable climate forcing, and mitigates against long-term planning and policy development. In particular, only recently have new investigations begun on the role of local forcing in the regional climate variability – work that is highlighting feedback mechanisms that have a significant impact on the regional hydrological response. Consequently, the following objectives were identified for this work:

- To develop trajectory transport models with the inclusion of diffusion and precipitation in the transport of moisture
- Develop long-term climatology of atmospheric water transport for different regions of southern Africa
- Analysis of moisture sources, sinks, and relevance to controls on precipitation
- Evaluate moisture transport in global models

- Analysis of transport characteristics in regional models with relevance to climate change and seasonal forecasting

The work of this project thus forms a backdrop for these more regionally focused investigations, and allows one to begin to apportion relative importance of different mechanisms controlling the climate system. This understanding forms an essential component to advancing our understanding and enabling the research to address the more immediate questions of impacts and surface hydrological response to climate change and variability. At one level these studies are, however, preliminary. Ultimately, understanding the dynamics of the complexities of the large scale and local scale coupled systems will require significant further investigation with appropriate tools, for example, using regional climate models[1].

Nonetheless, such investigations, and the associated assessment of the consequences for water resources and management, needs to be placed in the context of the baseline climate system. This project thus seeks to serve this objective by targeting questions of the long-range transport, the role of the large-scale dynamics, and the relation of the circulation to spatially extensive heavy rainfall. The approach to these issues has been twofold. First the full climatology of the atmospheric moisture transport trajectories in the atmosphere is assessed. This includes consideration of not only the pathways of transport, but also the proportional contribution to moisture content by regions along the pathway of the trajectories. The trajectories are calculated over 20-years, and provide a climatology of the mean transport and source regions. This is then further extended to consider the transport under key events of spatially extensive heavy rainfall.

The relationship of moisture flux to spatially extensive heavy rainfall is further extended to consider the mean flow patterns associated with the different characteristic events. These outline areas of commonality between precipitation events, and regions of marked dissimilarity. The potential consequences of climate change on these features are examined using a GCM simulation of future climate.

[1] A good start on this has been made in the WRC project on climate modeling, where the regional climate dynamics in response to perturbations in the soil and land surface are being investigated.

Following the transport analysis, the role of synoptic scale circulation has been principally addressed through an examination of the underlying synoptic scale features of the atmosphere. This approach uses the velocity potential fields to assess moisture sources and sinks, although recognizing that the identification of a source, coupled with a view of the static circulation field, does not necessarily imply that the source is a direct contributor to the continental rainfall – a source is merely, in this context, a source for the atmosphere with no regional destination implied. Nonetheless this does give indication of the relative role of sources in relation to the large scale circulation systems. In particular, and examination of the differences of wet and dry years, using Self Organizing Map (SOM) analysis of the daily circulation events, illustrates the distinctive moisture flux differences between years.

The two approaches to evaluating moisture transport provide complementary views of the atmospheric processes, and afford valuable insight that underpins further research. In particular this complements the growing research activities with climate models to investigate climate system sensitivities in the context of climate variability and change.

The strong regional differentiation of the climate system and the complexity of secondary attributes of the moisture transport over southern Africa are such that the volume of a data precludes detailed examination of all aspects. Consequently this report focuses on the summer rainfall of the central interior, in that this region is of key economic and societal importance. The full data set of all trajectory work, along with the multi-GCM data comprises many gigabytes of data and is available on request, and at the same time contributes to other ongoing research addressing the issues of extreme events, intra-seasonal variability, and uncertainty in climate model simulations.

This report considers first the methodological developments for the trajectory analysis, following which the principal results and conclusions of the different analyses are examined. The final section draws together conclusions from different aspects of the work, and suggests key questions for further work.

2. Trajectory model

The trajectory model is used to track the pathway of "air parcels", or points, along with the associated moisture content in the atmosphere under the influence of the 3-dimensional wind fields. The model based on simple kinematic principles, utilizing the wind components on the horizontal and vertical to determine the 3-dimensional pathway through the atmosphere such as would be followed by a neutral density point in the atmosphere (ignoring diffusion and turbulence). This is a common approach to trajectory analysis, with numerous software options available. In practice a starting point is defined, typically at some level in the atmosphere for some geographic location. The point location would then be moved according to the prevailing atmospheric motion in the horizontal and vertical. In this manner the point is traced in 3-dimensions over a period of time, thus determining the transport pathway.

In practice, however, the matter becomes somewhat more complicated, and due cognizance needs to be given to a range of factors, each of which may induce error. Amongst others, these include:

- the time and space resolution of the observational wind data,
- the coordinate system used in the horizontal and vertical,
- interpolation methods,
- the time step over which motion is calculated,
- and the accounting for strong curvature in the flow.

A number of existing models were investigated for possible application, and three options in particular were targeted; an existing model developed at the University of the Witwatersrand, the HYSPLIT4 model[2], and the FLEXTRA[3] and FLEXPART[4] models. The FLEXTRA code in particular had a number of very sophisticated features to its credit. However, each of these models have constraints in terms of this projects objectives, which for any one model generally fell into one or more of three categories:

- Poorly documented code, or code not under active maintenance/development, thus making alteration difficult.

[2] http://www.arl.noaa.gov/ss/models/hysplit.html
[3] http://www.forst.uni-muenchen.de/LST/METEOR/stohl/flextra.html
[4] http://www.forst.uni-muenchen.de/LST/METEOR/stohl/flexpart.html

- Highly specific data formats, making it necessary to reformat large volumes of existing data into appropriate formats.
- A limited capacity to handle very high volumes of trajectory calculations in one pass, and which would thus necessitate multiple executions of the code to achieve even small sets of trajectories.

To a large degree these limitations are as a result of the specific focus for which these models were developed, and not inherent shortcomings of any one model. By and large the purposes of the models are for case studies from a limited number of starting locations. Other limitations also existed in the codes, although it would largely be possible to circumvent these.

Conversely, the tasks identified in this project are computationally demanding, with the objective of tracing 7-day pathways from starting points across the entire subcontinent, starting each 6 hours, from multiple levels in the atmosphere, over a full 20 years. Consequently, a decision was made to build on existing core code developed at UCT, and maximize the computational performance by developing the model specifically for a distributed processing system, in this case a cluster of Pentium-class PCs. The code is thus developed around the MPI[5] message passing interface standard, using the MPICH software library. This allows for efficient communication between code sections running on different machines, even to the extent that different hardware platforms may be used. In practice two versions of the trajectory model were developed to investigate sensitivities to coding decisions, and the final version being a merge of the two development streams.

2.1 Model principles

While basic kinematic trajectories are, in principle, simple to implement, a number of key issues present themselves as highlighted above, and which have been evaluated in a number of studies[6]. These issues relate largely to the coordinate system used, the interpolation schemes, the time step, and for large-scale flow, whether to include parameterization of turbulence and convection. The two code development streams examined many of the choices for implementation, and for a number of cases, under

[5] http://www-unix.mcs.anl.gov/mpi/mpich/
[6] See, for example, http://www.forst.uni-muenchen.de/LST/METEOR/stohl/flextra.html#TI

large-scale flow, the choice led to only small differences. Following this clarification, a final version was developed which has the characteristics as outlined below.

The vertical coordinate system selected for the model is the sigma coordinate, where the level in the atmosphere is expressed as a function of the ratio between the pressure at a given point in the atmosphere and the surface pressure. Sigma levels are terrain following, flattening as one rises in the atmosphere, and parallel to pressure surfaces at the top of the atmosphere. This has a particular advantage over working on pressure surfaces as one does not have to deal with the intersection of a pressure level by the topography. In all 12 levels in the vertical are used. The inter-level spacing is closest in the lower levels in order to resolve the more complex lower atmospheric features, and becomes further apart higher up in the atmosphere.

A number of different interpolation schemes were tested for both the horizontal and vertical dimensions, of varying complexity and computational efficiency. The more complex schemes (bicubic splines, polynomials, etc) made little difference to the results, and due to their greater computational demand, were not used. In the final version simple linear interpolation is used in the horizontal, and since a vertical pressure coordinate system is used, a log-based interpolation is applied in the vertical.

Different time steps were evaluated, ranging from 12 hours down to 10 minutes. It was found that little difference in the results occurred for time steps ranging from 10 minutes to a few hours, with the differences progressively increasing from then on. As a compromise a time step of one hour was selected, based on the guideline that in one hour most trajectories would not traverse more than half a grid cell of the atmospheric forcing data. Using this approach a given point in the atmosphere may be projected forward or backward in time based on the 3-dimensional wind field.

The simplest approach to projecting a trajectory is to calculate the tangential path based on the instantaneous wind components. However, an adjustment is necessary to resolve a problem experienced under strong curved flow. In using discrete step-wise approximation of the trajectories, in effect one calculates tangential flow at each time step and consequently induces a lower curvature flow than the actual kinematic fields would indicate. This is only of noticeable effect under strongly curved consistent flow regimes, and in terms of the long-term climatology appears to have a relatively small impact. Nonetheless, a simple correction may be implemented whereby for each time step the 3-D wind-field at the initial projected position based on tangential projections is averaged with the starting point values. These average values are then used to recalculate a new projected position based on the mean 3D wind components experienced over the span of the model time step. This corrects for any identifiable error in final trajectory curvature and allows for a longer time step to be employed with minimal degradation in performance. Without this correction the consequence is such that in curved flow fields the calculated pathway spirals outward (around a high pressure system) or inwards (under low pressure systems) to an anomalous degree. While the correction is somewhat crude, the adjustment works well in practice, and results in any resultant error being negligible for the time step used.

An additional refinement is the introduction of a stochastic perturbation of the horizontal positioning for the starting location of each trajectory. Whereas most trajectory models start each trajectory from a fixed point arranged in a regular grid, we now explicitly treat the grid as composed of *cells*, and each trajectory starts from a random position within each grid cell. The motivation underlying this is to avoid potential bias in the trajectory results where the trajectory may be sensitive to local variation within the cell due to, for example, topography.

Calculation of the trajectories reflects the primary task of the model, and these become the basis by which the moisture content of the air may also be traced. Initially only the absolute values of moisture were recorded (as specific humidity). However, in seeking to ascribe sources of moisture it becomes necessary to account for proportional contribution by regions to the absolute magnitude of moisture at any given moment. This refinement to the trajectory calculations is described later in its own section.

Trajectory positions are saved only every four hours to maintain a manageable data size. Trajectories are calculated both forward and backward in time for a user-defined number of days (set to 7 days) from starting points on each sigma level in the vertical, and on a 1º grid in the horizontal for all locations over the land for the continent south of 20ºS. With these parameters ~1.8 Gigabytes of binary format trajectory data are generated for each year.

2.2 Software configuration

The software has been specifically written to use simple formats for both the input and output files, and uses an easy text file of parameters for the configuration. The principle underlying this approach is to create a robust suite of software that is easily implemented by other researchers. The input files are basic multivariate binary files as used by the GrADS[7] visualization program. This format is widely used in the atmospheric science community and easy to generate. The trajectory output data is a simple header format binary file and post-processing utilities have been written to convert this to volumetric densities of trajectories for a selected starting location, or to extract individual trajectories.

The trajectory program itself is configured via a simple text file that provides all the parameters for a given run. The text box in Appendix 1 shows a sample configuration file.

2.3 Source data

The source data used in the development of the climatology is the NCEP[8] re-analysis (Kalnay et al., 1996) data spanning 1958 to the present. While these are not "observations", they are about as close as one can get. In effect the data represent a global climate model solution for the dynamical state of the atmosphere, constrained by available observations from the surface, radiosondes, and satellites. A number of similar data sets exist; however, the NCEP data has the attractive advantage of being free. As reanalysis data are a global solution constrained by available observations, it follows that there is a degree of dependency on the observations, and hence prior to 1979 (the advent of good satellite data) there are notable problems in all reanalysis data sets in the southern hemisphere due to the paucity of data. Tennant (2002) in particular documents problems with the reanalysis data over southern Africa, demonstrating a notable discontinuity in the data characteristics around 1979. Consequently, for the trajectory analysis only data after 1979 are used.

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[7] http://grads.iges.org/grads/

[8] See http://www.cdc.noaa.gov/cdc/reanalysis/reanalysis.shtml for free access.

The NCEP data are on a 2.5º degree latitude/longitude grid, and available on 12 levels (including the surface) at a 6-hour interval. All levels up to 100hPa are used in the trajectory analysis, with 100hPa being deemed the top of the atmosphere for these purposes (flow being essentially laminar at these levels). A spatial domain stretching from 30W to 75E, and 65S to 10N is used, encompassing the ocean basins around the continent. Trajectories that leave this domain are deemed lost to the analysis.

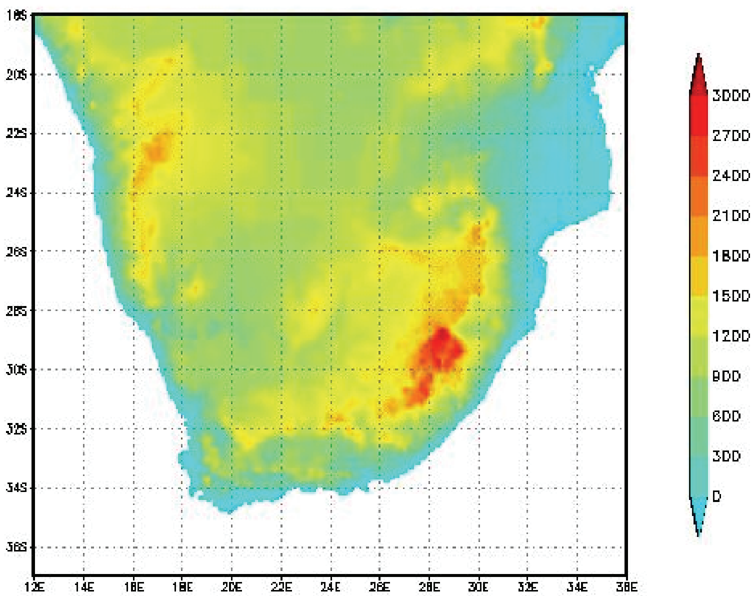
The surface boundary is defined by a smoothed topographical surface proportional to the atmospheric grid resolution. The source data for the topography is a global 5' digital elevation model. From this data set a sub-field matching the atmospheric domain is extracted, and smoothed with a spatial window of the same size as an atmospheric grid cell, in this case 2.5º by 2.5º. Figure 1a ,b shows the source topography and the smoothed field.

In summary, the forcing fields required for the trajectory model include the topography, and atmospheric 3-dimensional fields at 6 hour intervals of:

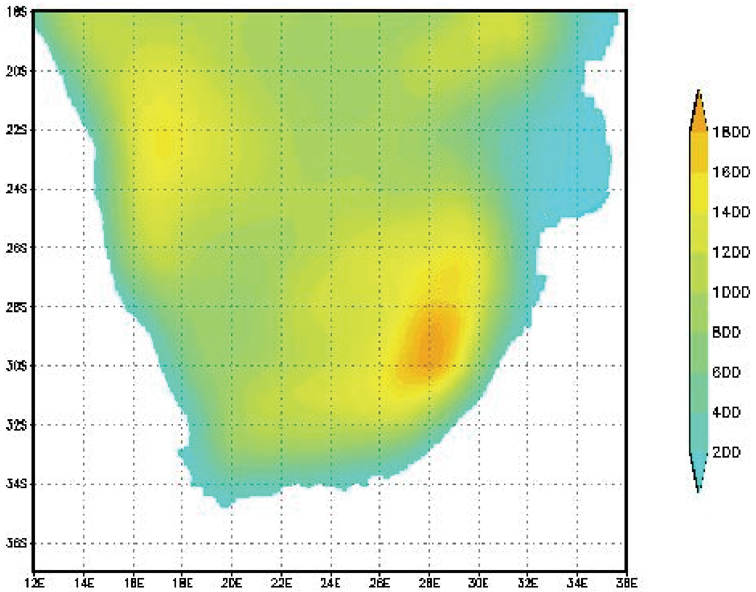
- Surface pressure
- Surface u and v winds, and vertical motion (at 10m)
- Surface specific humidity (at 2m)
- Specific humidity, u and v winds, and vertical motion on all pressure levels in the vertical.

2.4 Hardware infrastructure

As noted earlier, running the model is computationally demanding. On the configuration as noted in the example above, approximately 1200 valid trajectory starting points exist over the continent. To accommodate this task, a cluster of PC-level computers is used, linked on a high-speed network to a "master" machine that provides file-serving duties to the slave PCs. Each of the PC's runs Linux configured for SMP processing. Under this configuration the system can handle ~1 year of trajectories per day including the pre and post-processing phases.



(a)



(b)

Figure 1: Topography on a 5’ grid (a), and smoothed (b) with a 2.5º spatial filter.

3. Trajectory Climatology

Due to the concerns with the NCEP forcing data prior to 1979, the climatology has been calculated for the period 1980 to 1999. For the trajectories a 1° grid of starting locations is defined on the vertical sigma levels of 0.995, 0.95, 0.9, 0.85, 0.8, 0.7 and 0.5. This effectively covers the vertical differentiation in the lower half of the troposphere. The upper levels are not included here as they display very similar trajectories to the 0.5-sigma level, and in any case, contain minimal moisture. The model was run for all months of the year, calculating a set of 7-day trajectories beginning every 6 hours, in both the forward and backward directions.

The data volume and complexity precludes full examination of all trajectory characteristics in this report. The climatology developed is instead presented first as a series of examples of relevant analyses that may be undertaken. Following this the focus shifts to specific issues of relevance to the understanding of moisture transport over southern Africa for the summer regions. The 20-year climatology data remains the subject of other ongoing work in other project activities.

3.1 Issues of visualization

The baseline climatology is established for the period 1980-1999. Initial evaluation of the derived trajectories shows good agreement with the general understanding of the synoptic scale circulation features. For example, Figure 2 shows the 7-day back trajectories for one month from a starting point over central South Africa at the sigma level of 0.995 (boundary layer). The principal transport pathways are clearly evidenced as flow from the southwest in the mid-latitude westerly wind belt, flow from the east warmer Indian ocean, and secondary, less frequent flow from the south east and north west. Being a plan view this naturally does not indicate the changes in the vertical dimension. Figure 3 shows a series of trajectories, plotted as the vertical dimension (exaggerated) against longitude. The figure clearly shows a range of complex vertical pathways, in large part driven (in this example) by the passage of mid-latitude low pressure systems.

Such “spaghetti” plots, however, are problematic as a means of visualizing the climatology. For example, Figure 4 shows a full 20-year set of trajectories, and clearly, apart from outlining the dominant regions of flow, little of useful detail can be seen. A number of vizualization approaches may be adopted, all with relative advantages and disadvantages. For example, full 3-dimensional isosurfaces of trajectory density may be generated. However, for most purposes simple plan view and cross sections of fields derived from the raw trajectories serve the purposes of this report best. Consequently, the balance of trajectory results reported here uses simple 2-dimensional plots of vertical cross sections and plan views.

3.2 Regionalization

One of the first questions that may be asked of the climatology is, which regions of South Africa are subject to air parcels sharing common transport pathways – in effect identifying trajectory starting point regions of relative cohesive trajectory characteristics. Recognizing that boundaries between regions are gradational, the task is to some degree artificial, requiring one to place hard boundaries on what is, in essence, a continuum. An algorithmic solution is problematic, notably due to the fact that the relevance of separation between any two trajectories is a complex function of a number of factors including the distance from the point of origin or destination, distance from preferred pathways, the velocity of the trajectory, etc. Consequently, distal regions of the trajectory have undue influence on quantitative measures of similarity.

Initial work has focused on the application of Self Organizing Maps (SOMs), with reasonable success (Hewitson and Crane 2002; Crane and Hewitson, 2003). To consider similarity of trajectories, a vector of similarities measures characterizing each grid cell against all other cells is constructed using the standardized mean absolute error between the 3-dimensional coordinates of any two trajectories. In this manner the trajectory information is transformed so that each grid location is located at some position in "similarity space". The vectors represent a significant data reduction, and are then used as the basis to identify groupings of grid cells with similar characteristics.

The SOM approach endeavors to identify archetype patterns in a multidimensional data set, analogous in some ways to cluster analysis. Full details of SOMs may be found in Hewitson and Crane (2002), and the approach is considered a robust technique to finding commonalities within data. In effect a SOM determines a subset of vectors in the data space such that the vectors represent archetypes that span the variation within the data space. Each grid cell may then be identified with a SOM vector that is most similar, and thus grouped. In undertaking this process on the similarity vectors derived from the trajectories for a given layer, it is important to recognize that trajectories starting at different levels may lead to different regionalizations. Two contrasting regionalizations are represented here. Figure 3 shows the regionalization of trajectories for December-January-February from the 0.995 sigma level, and Figure 4 for the 0.5 Sigma level. The regionalization most notably indicates regional groups characterized by a north-south elongation in comparison to the west east dimension. This reflects principally the nature of the climate gradients across the continent that are greatest in the west-east axis, and supports the conclusion that the regional climate gradients are most directly a consequence of the atmospheric forcing.

3.3 General climatology trajectory characteristics

Maintaining a focus on the summer rainfall region of the central interior, this section focuses on the general characteristics of transport to region 14 of figure 5a. Figures 6-14 show a series of representations of the information expressed by the trajectories as follows:

a) Figure 6: Spatial frequency of trajectories in space: reflecting the mean percentage of time that a region is traversed by trajectories terminating within the boundary layer over the region in question.
b) Figure 7: The mean velocity and direction of the air along the trajectory pathway.
c) Figure 8 & 9: The mean change in the u and v velocity over 6 hours along the trajectory pathway. Positive values here indicate acceleration, and negative values indicate deceleration. Consequently, where the trajectory is near the surface this would be indicative of subsidence (dry) conditions in the atmosphere. In general the figure clearly outlines regions of the South Atlantic convergence zone, and the zone of mid-latitude disturbances. However, as this is in part dependant on the level in the atmosphere, this figure needs to be interpreted in conjunction with the mean level of the trajectory, complemented by the mean vertical motion (next two figures).
d) Figure 10: Mean sigma level of the trajectory. This indicates that on average, air terminating in the boundary layer over Gauteng is, for the most part, transported at an elevated level above the boundary layer over the oceanic regions.

e) Figure 11: Mean vertical motion (change in sigma level per 6 hours), indicating in general the propensity for uplift along topographical features, and of particular interest, decent over the coastal ocean regions along the Agulhas current.
f) Figure 12: Mean specific humidity along the trajectory pathway. Not surprisingly, this shows elevated moisture content toward lower latitudes, and especially over the warm west-Indian ocean regions.
g) Figure 13: Mean change in specific humidity. This figure provides the first suggestion of moisture sources for air reaching Gauteng. Of note are the strong positive values along the eastern slopes of topographical forcing, indicating a degree of vertical moisture convergence of the lower atmospheric levels into the trajectory pathway.
h) Figure 14: Average transport times in number of days. Of special note here are relatively long times taken for air transport from the coast to the interior – of the order of 2-3 days or more. This suggests that local land surface fluxes during this period may be of significance in determining the final moisture level in the air, and raises questions over the relative importance of local scale feedbacks.

These figures represent the climatology of transport for one (important) region of South Africa. Similar analyses may be undertaken for all regions, and form part of other ongoing modeling work in researching extreme events, and in particular the role of local land surface feedbacks.

3.4 Seasonal stratification

Stratifying the trajectories by season allows one to investigate the transport under different seasonal modes. In this case, a key issue is which criteria to adopt for identifying the seasonal modes. As a key focus of this project relates to water resources, the daily spatial pattern and amplitude of rainfall are of necessity of principal importance. Hence, stratifying one season from another requires consideration of the daily events that go into making up the seasonal average. Seasonal means from different years may well appear similar, yet be a response to widely differing histograms of daily events. Consequently, in assessing the composite characteristics of one season's trajectories it is important to differentiate correctly one seasonal mode from another.

Differentiation of the seasons is accomplished by examining the daily rainfall patterns over southern Africa. Rainfall is used as the primary discriminator of daily events as, while the circulation is the forcing factor, the principal interest is the response – especially in terms of water availability. The analysis of the daily rainfall patterns is undertaken with the aid of SOMs. Using gridded (0.25°) precipitation data, derived from the full CCWR station data record over South Africa, Namibia, and Botswana, the SOM is applied to identify generalized characteristic spatial patterns of rainfall (Figure 15). Note that the diagonals of the matrix represent opposing modes.

Having derived characteristic patterns, the average climatological frequency of daily events on each SOM node (figure 15) may be determined (Figure 16a), as well as the frequency distribution for any given season (Figure 16b). The frequency map across the SOM nodes of all rainfall patterns in a season (such are figure 16b) then characterizes that season – in effect the SOM provides a 2-dimensional histogram of the rainfall characteristics.

Taking each season's two-dimensional histogram, these characteristic patterns for each season may in turn be grouped to identify characteristic seasons. This is accomplished again with a SOM, in this case using the SOM to group the histograms and find characteristically similar seasons as represented by their frequency distribution of daily precipitation events. This SOM-determined distribution of characteristic seasons (modes) is shown in Figure 17, where the number on each node is the number of years characterized by that nodes frequency pattern. Considering node [0,0] of this SOM (lower left corner), it is apparent that the frequency pattern shows a dominance of events characterized by rainfall patterns found on the top left of the precipitation SOM (see figure 16). The nodes in this area of the precipitation SOM represent extensive rainfall over the north eastern quadrant of South Africa.

Using this stratification of seasons, the differential of the seasonal set of trajectories for two years may be evaluated – the differences now identified as true reflections of the daily events that go to make the season characteristics. In this case two Januaries are identified, one as dry (1996), one wet (1997), with their frequency distributions shown in Figures 18a,b.

Using these two seasons as exemplars, Figures 19-30 show characteristics of the trajectory transport differences. Considering the mean frequency of passage of trajectories the two years, there are some noted dissimilarities in the mean transport (Figure 19,20), shown more clearly in Figure 21 which is the anomaly of wet – dry years (Figure 19 – 20). The key feature of note is that the differences are principally reflected in an anomalous shift in wet years toward increased transport from due east – characterized by warmer seas surface temperatures and, by inference, more moisture.

Figures 22-30 show, in more detail, the additional aspects of the differences in seasonal trajectory characteristics. In all cases there are identifiable differences, although for the most part these are relatively small. Nonetheless, it is notable that while specific humidity, sigma levels, trajectory velocity, and travel time away from source show nominal difference, the primary distinction appears to be merely the spatial pattern of trajectories as indicated in the frequency anomaly map in Figure 21.

The results suggest that the role of the time-varying characteristics of moisture source as a primary determinant of summer rainfall may not be as strong as previously supposed. Rather, the frequency of preferential transport patterns during the season is an overriding factor, independent of the given state of moisture sources. This supports the indications from other WRC modeling work, in that the large-scale circulation establishes the general state for summer convective precipitation, the intensity and frequency of which is then modulated by synoptic processes such as tropical temperate troughs (TTT) and local feedback processes. Under this interpretation, the influence of the regional oceanic SSTs on continental precipitation is primarily through the modification of synoptic scale circulation, as opposed to being through modification of moisture sources.

This is a key result, as it implies that climate variability and long term change are principally a function of the large-scale dynamics rather than significant variation in moisture transport. While it is recognized that on an event scale basis, especially for coastal precipitation, local moisture sources and transport may be important, nonetheless for seasonal time frames the baseline moisture transport appears to be a necessary condition for precipitation of relative stability from year to year, but the criteria to translate this to actual rainfall is inherent in the circulation dynamics and other local processes.

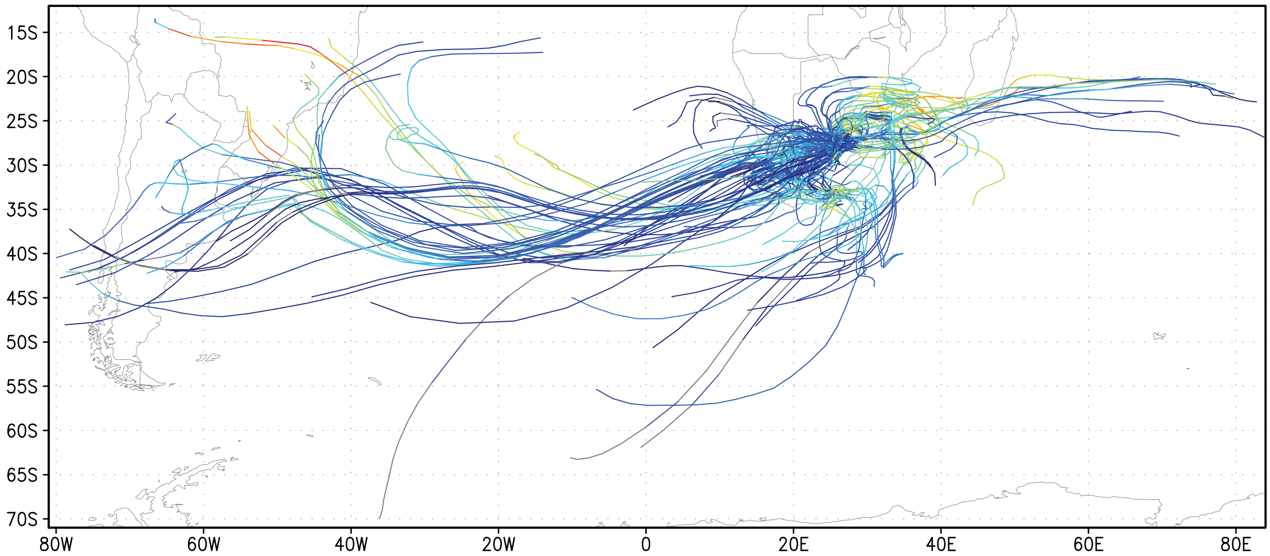


Figure 2: All 7-day trajectories for one month (January) staring from sigma level 0.95 over central South Africa (Yellow/red indicative of higher moisture content).

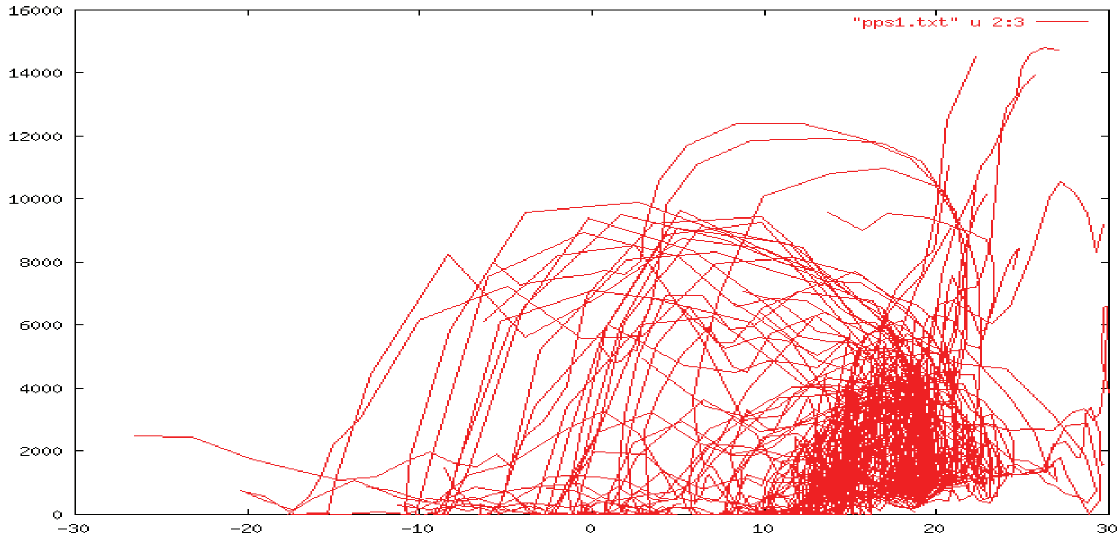


Figure 3: Example of the vertical pathways followed by 1 month of 7-day back trajectories terminating over central South Africa at sigma level 0.95.

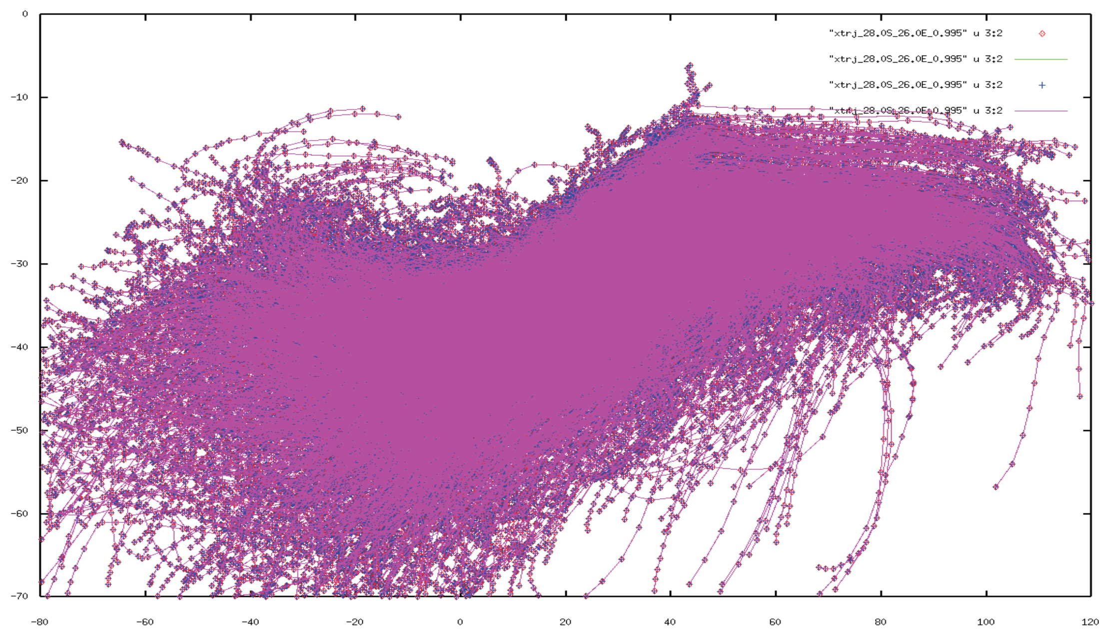
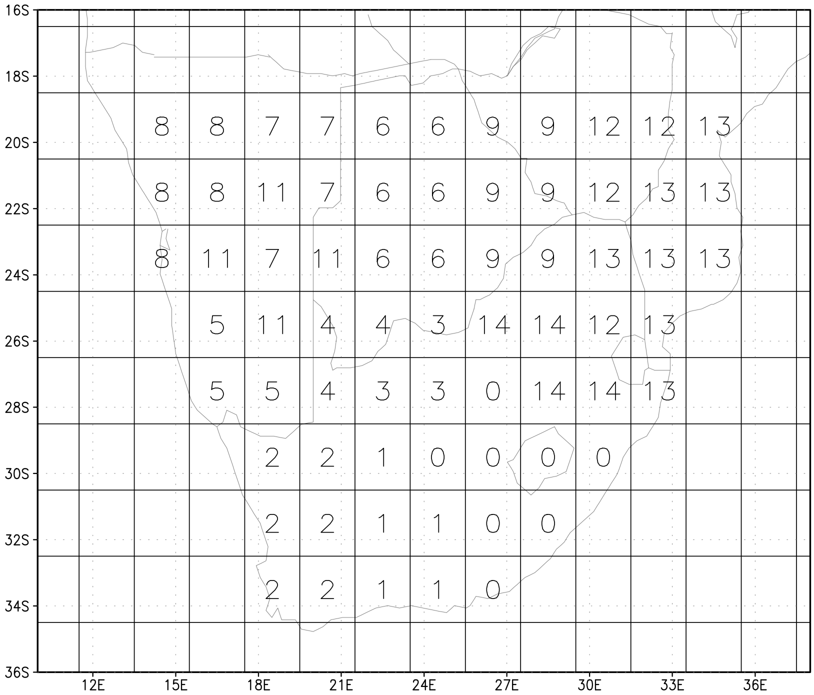
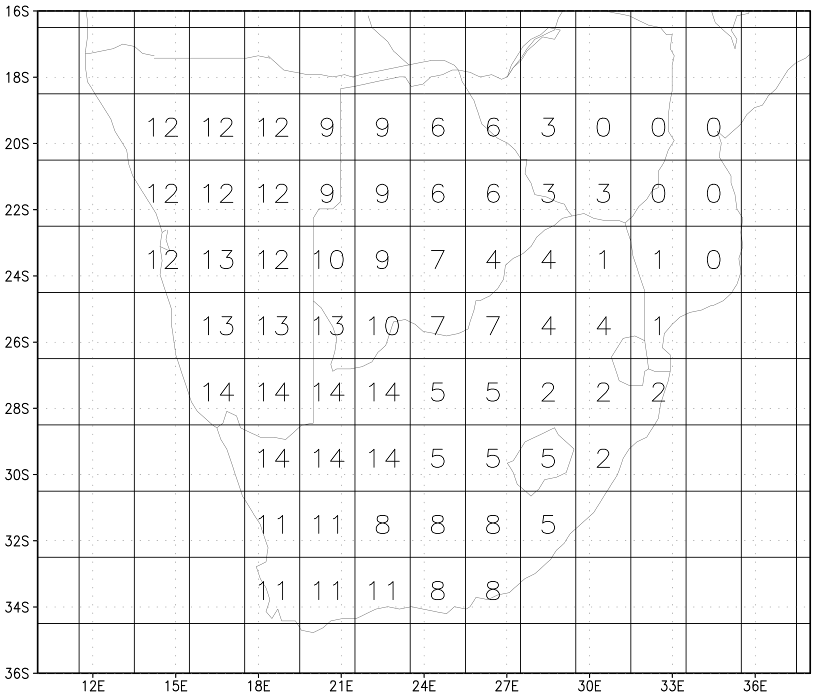


Figure 4: The full set of 7-day back trajectories over 20 years for 4 adjacent starting points over central South Africa, illustrating the challenges faced in analysing the climatological aspects of the trajectory data.



(a)



(b)

Figure 5: Regionalization based on back trajectories from sigma 0.95 (a) and sigma 0.5 (b). The number in each grid cell is a group number. Hence all cells with the same number have been identified as belonging to the same group.

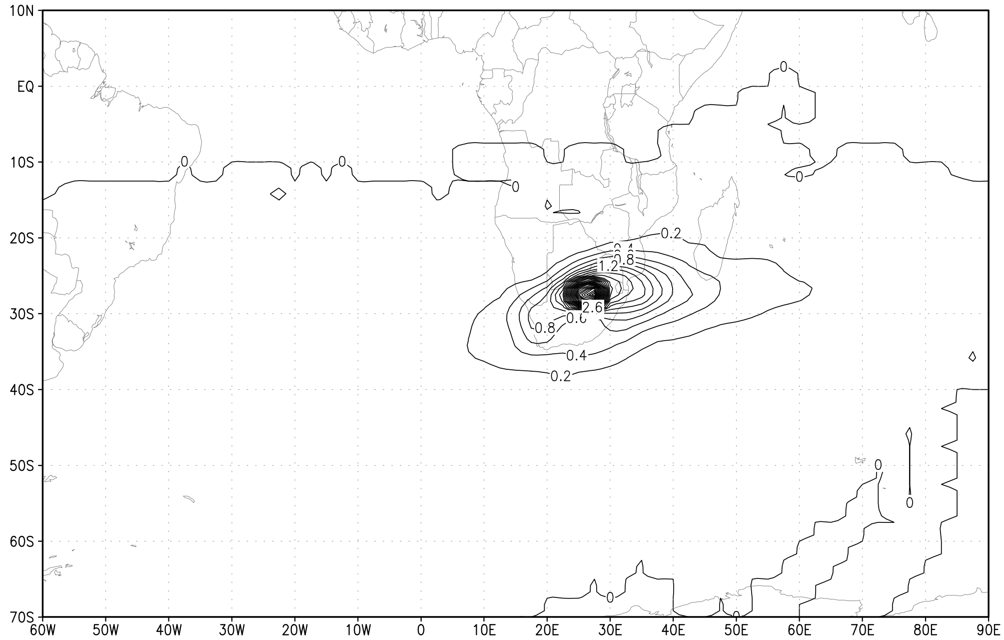


Figure 6: Frequency (%) of passage through domain by back trajectories from sigma 0.95 at 27°S, 27°E (20-year average).

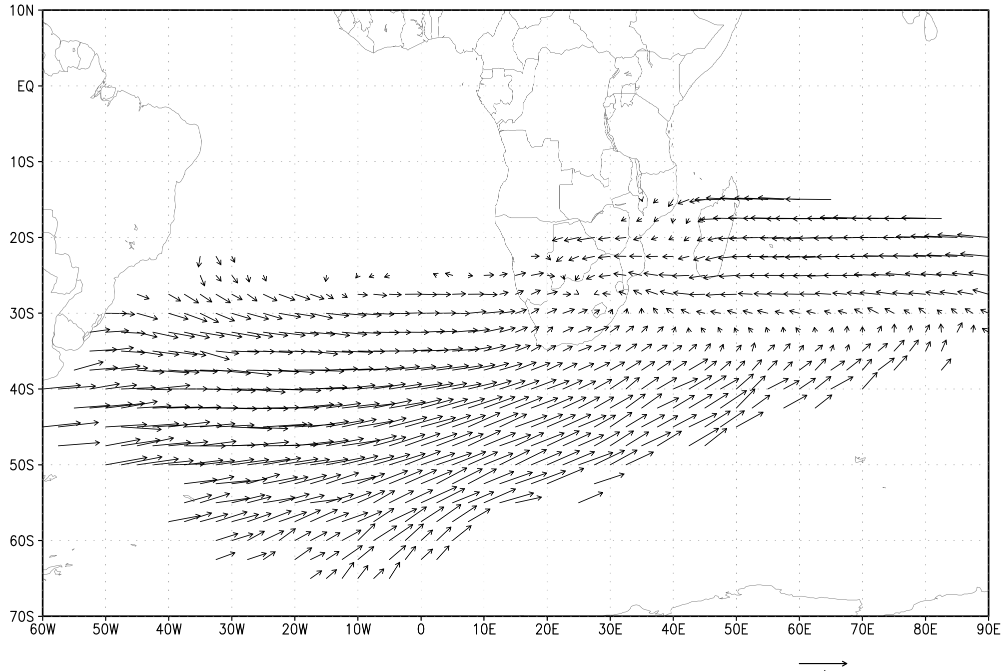


Figure 7: Mean velocity (m/s) along trajectory (20 year average)

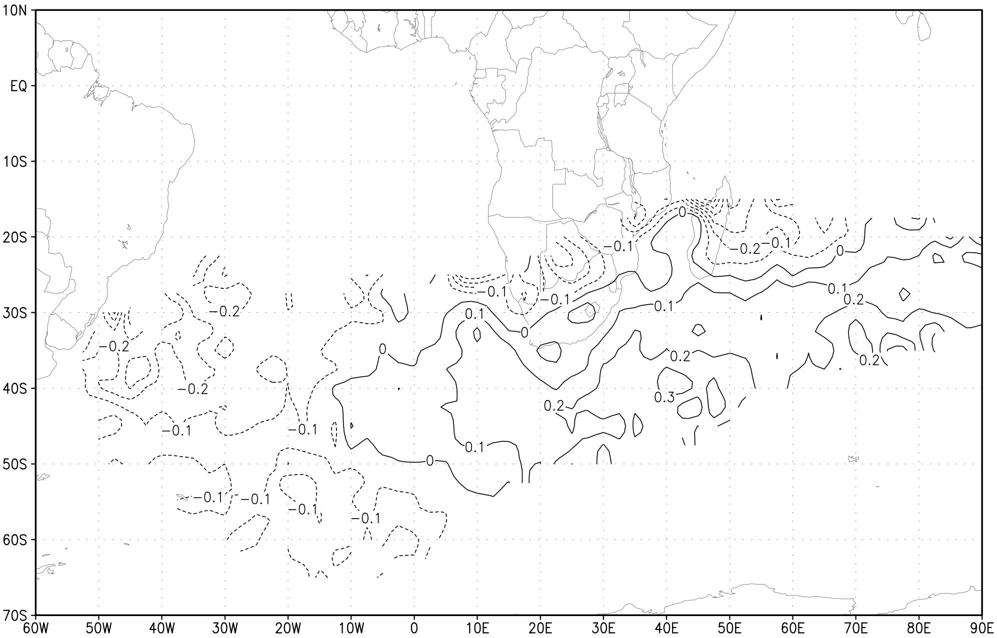


Figure 8: Δ u wind velocity (m/s per 6 hours) along trajectory (20 year average).

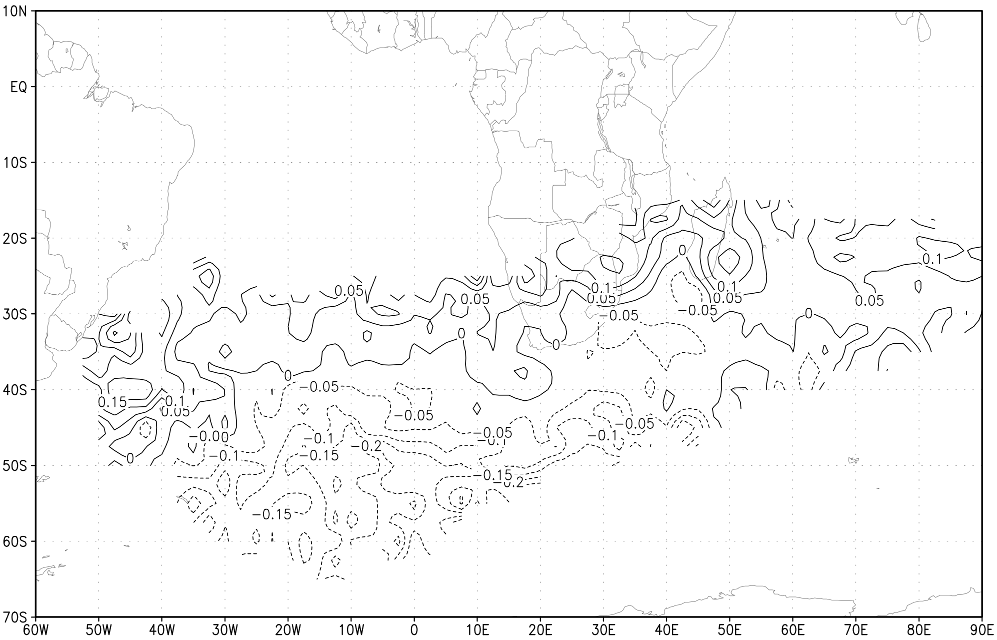


Figure 9: Δv wind (m/s per 6 hours) along trajectory (20 year average).

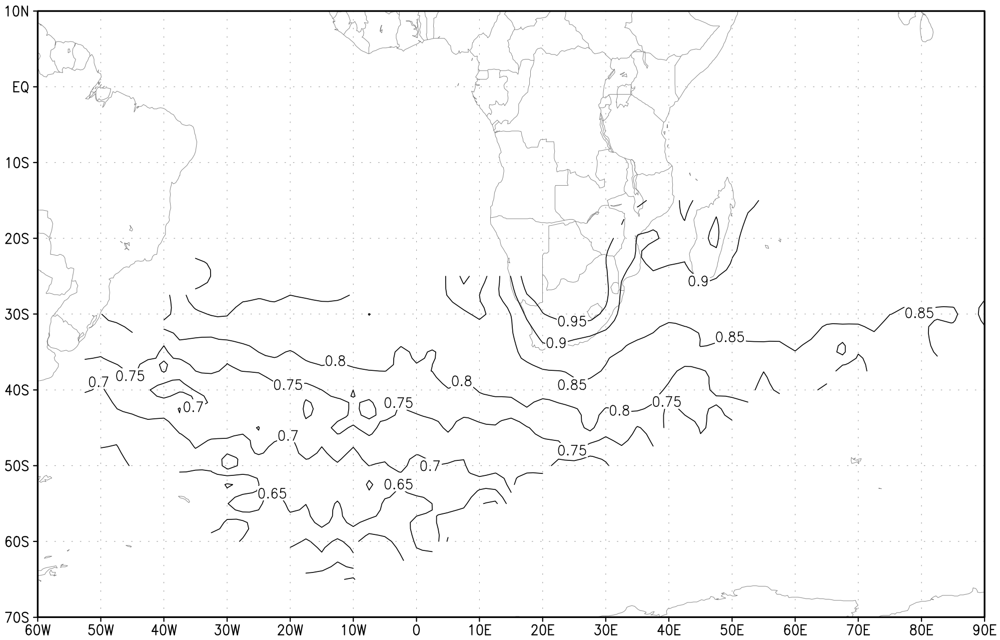


Figure 10: Mean sigma level along trajectory (20 year average).

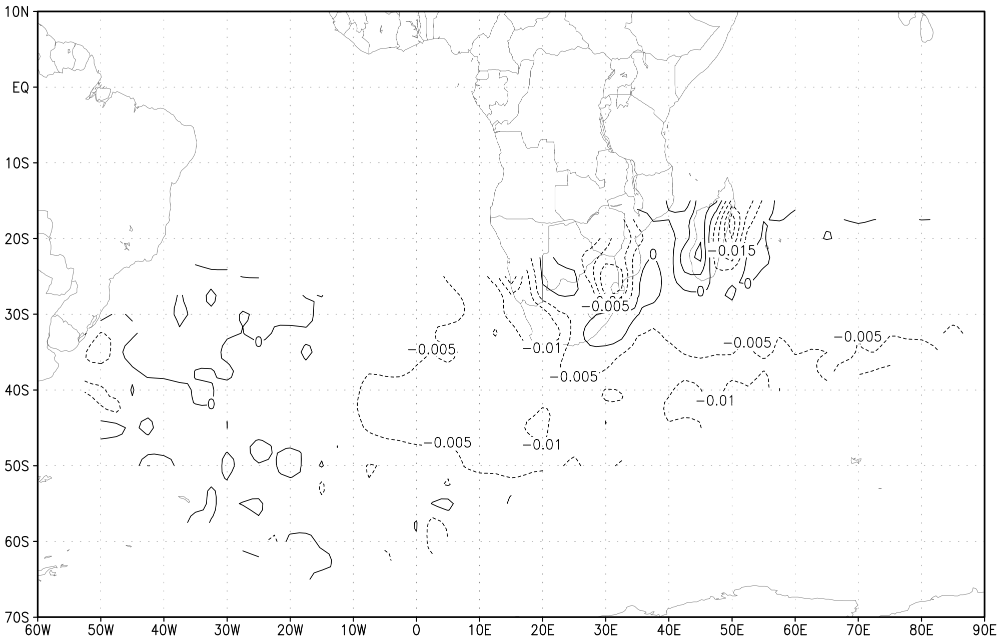


Figure 11: Mean change (per 6 hours) in sigma level along trajectory (20 year average).

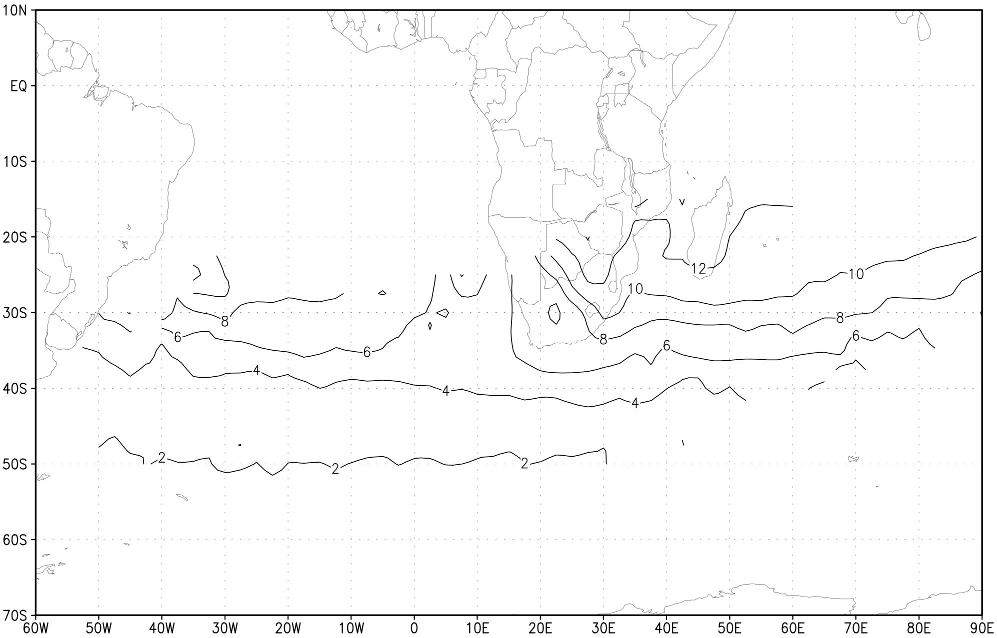


Figure 12: Mean specific humidity (g/kg) along trajectory (20 year average).

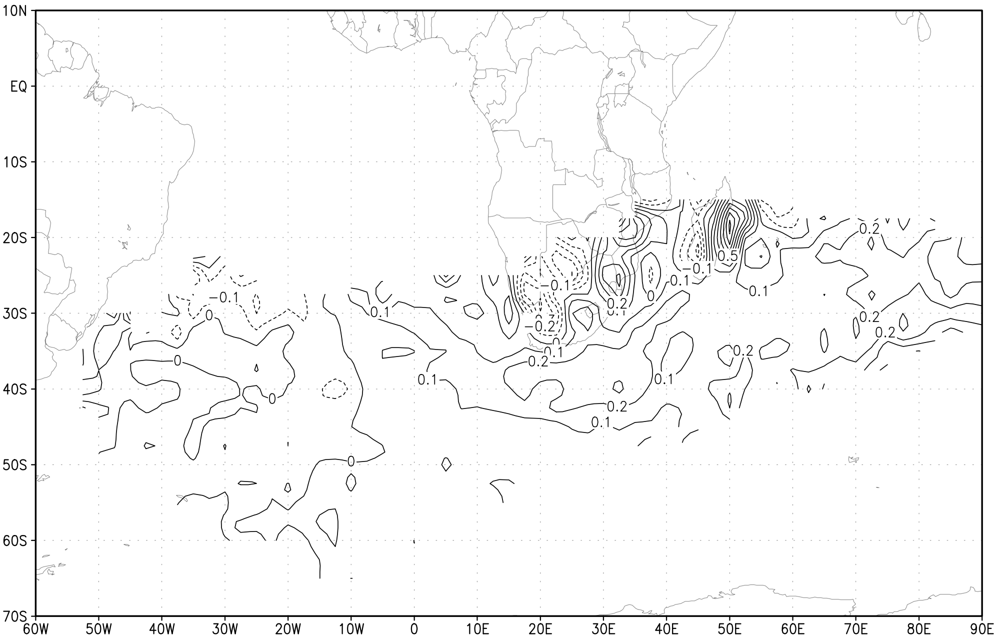


Figure 13: Mean change (g/kg per 6 hours) in specific humidity along trajectory (20 year average).

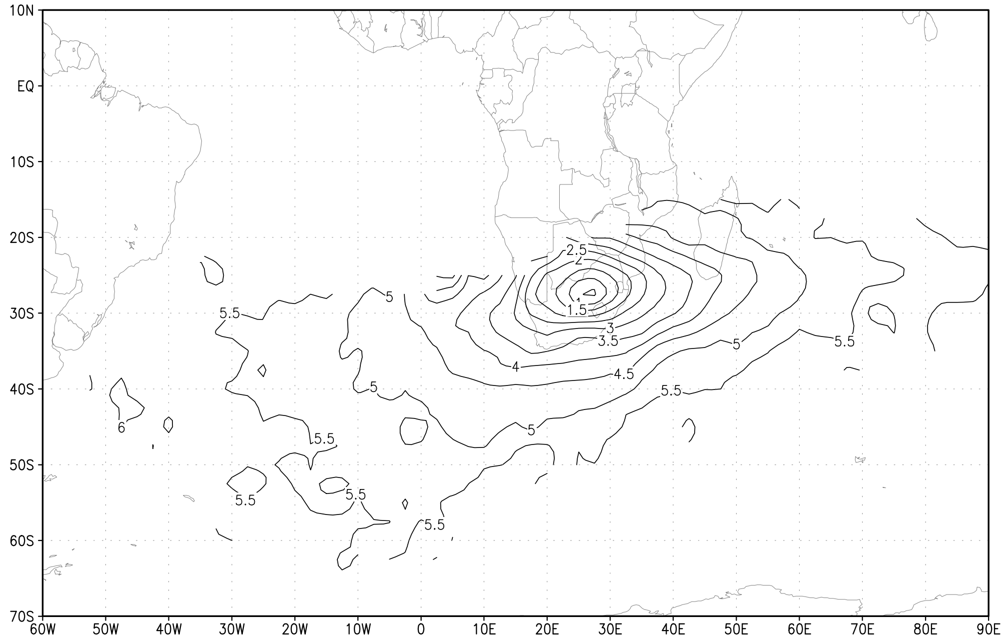


Figure 14: Time taken (in days) to travel from source (20-year average).

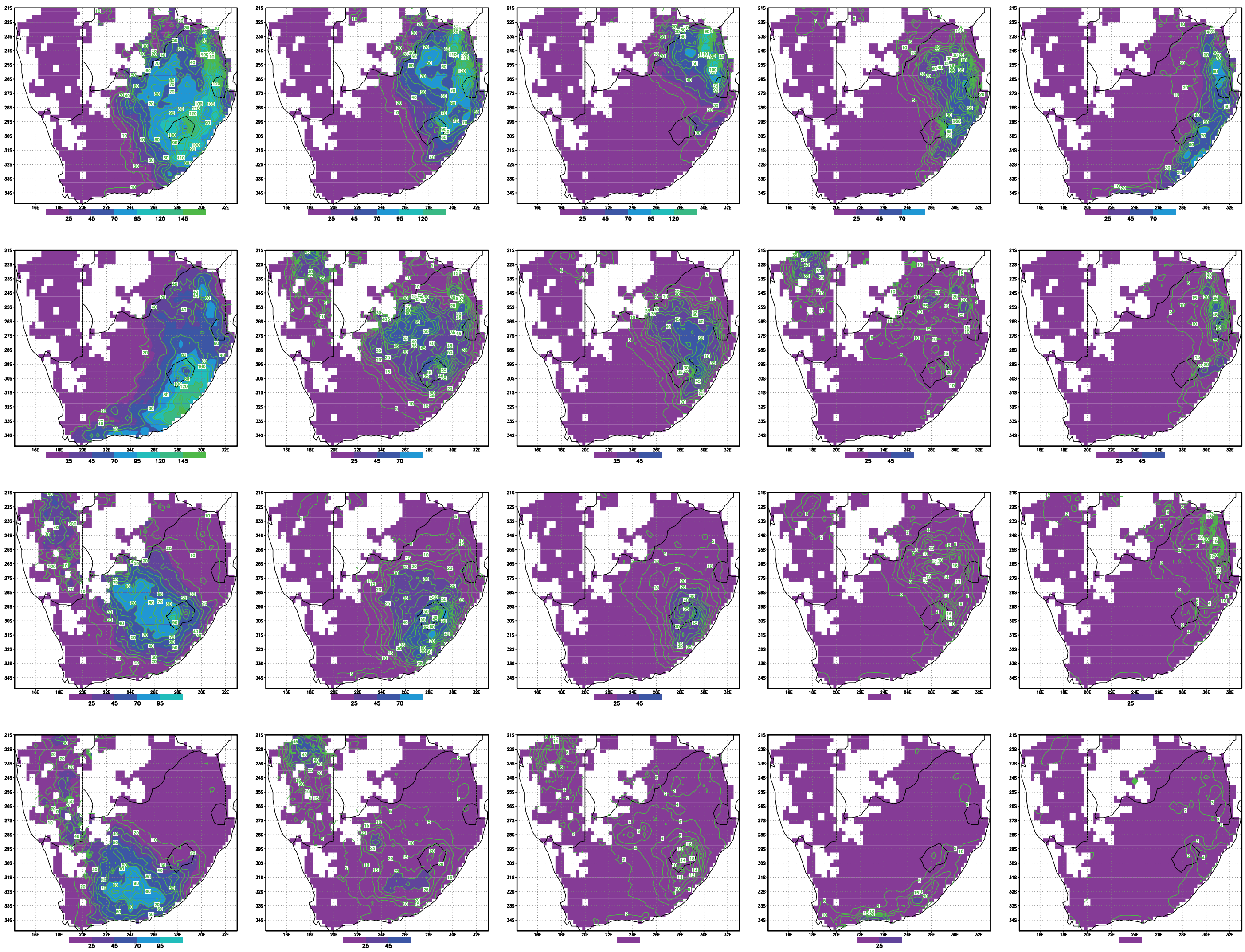
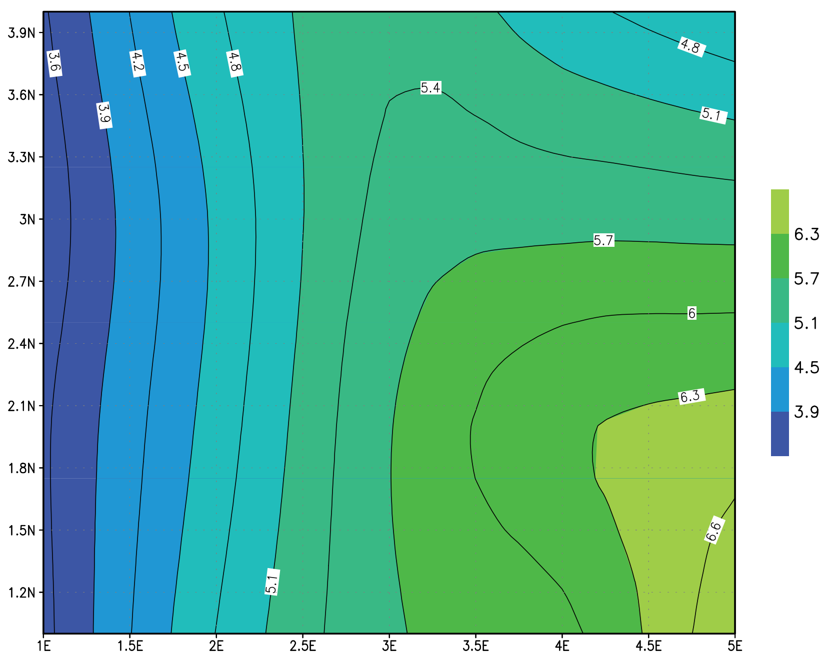
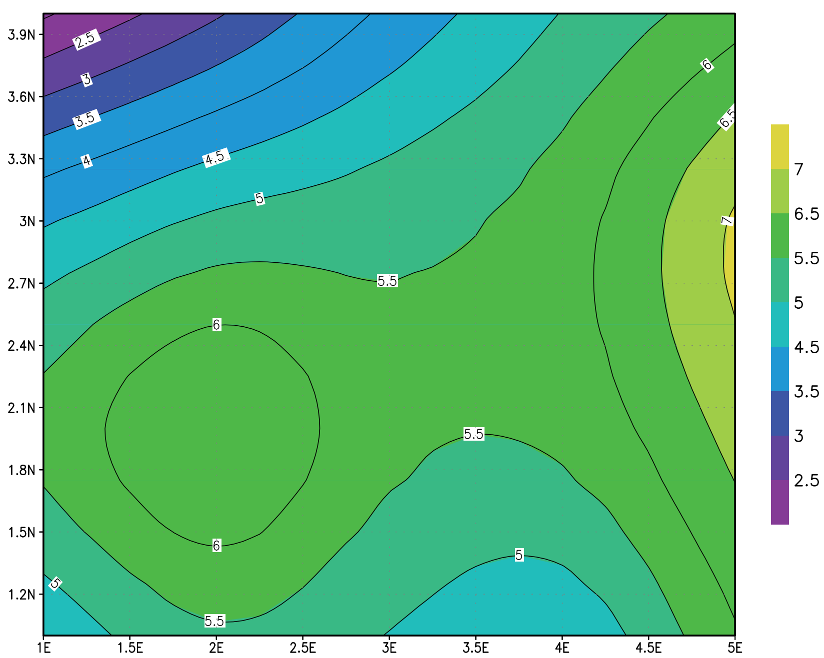


Figure 15: Characteristic daily precipitation patterns for December-January-February identified by the SOM from the precipitation record of 1950-1999. Each pattern represents a SOM node – archetypes that collectively span the data space.



(a)



(b)

Figure 16: Average frequency (%) of occurrence (a) of generalized DJF daily precipitation events (20 year average). Contours plotted as frequencies of occurrence on each node of the SOM map in figure 5, and an **e**xample (b) of the frequency distribution across SOM map for an individual month (January 1987).

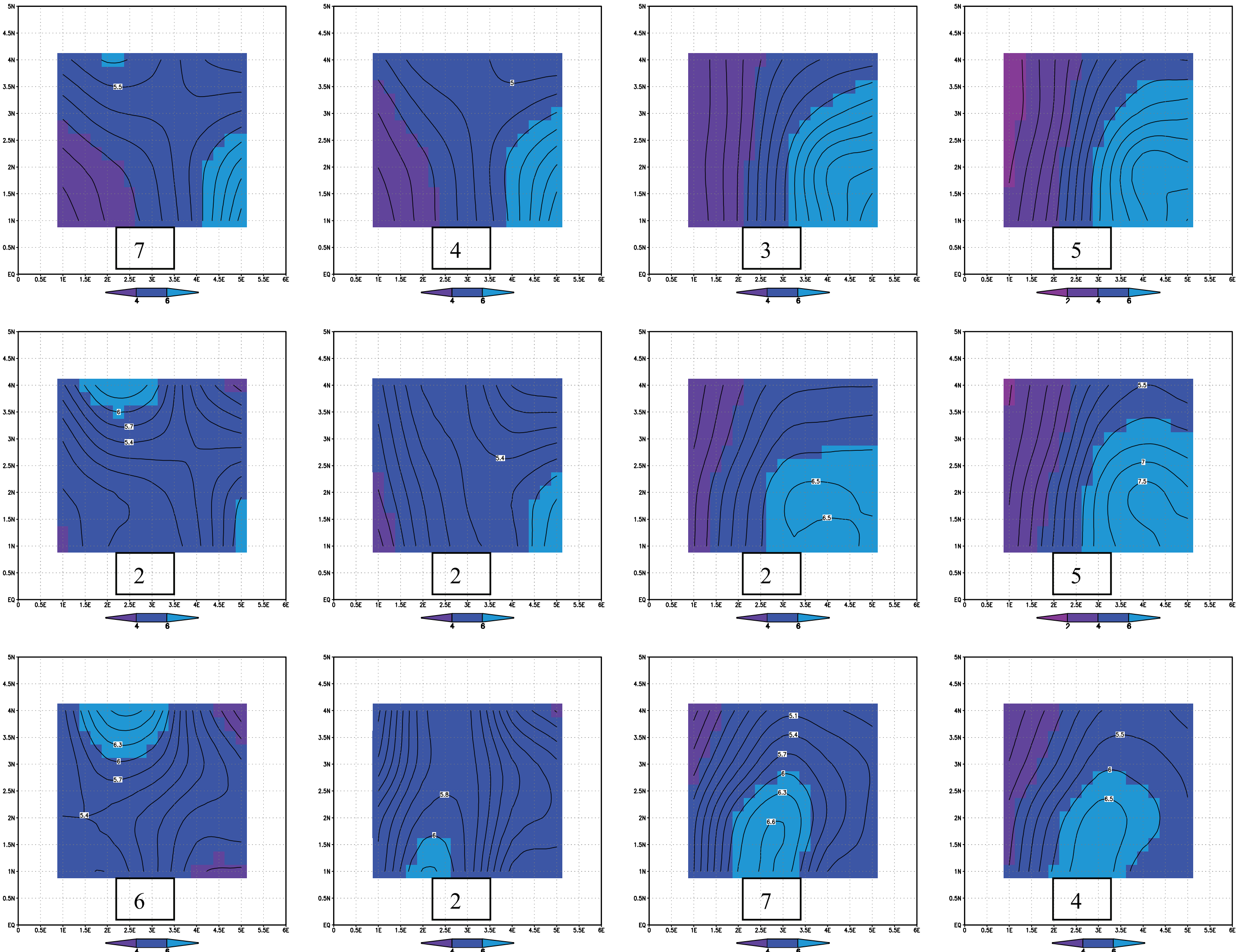
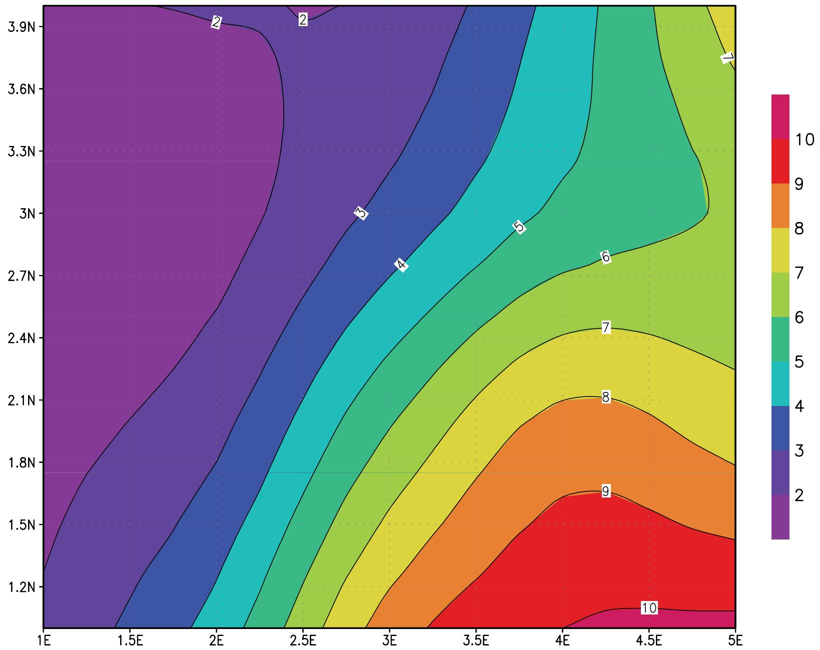
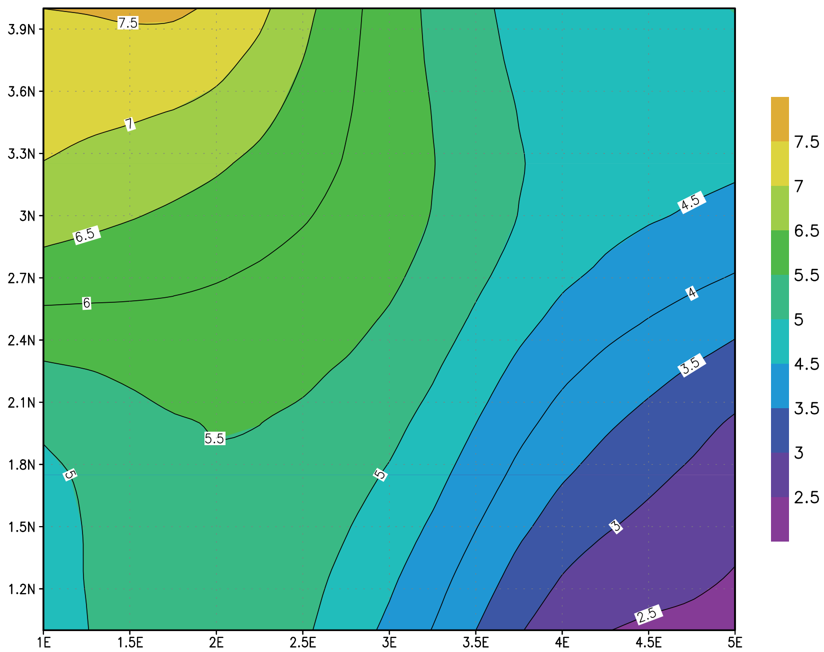


Figure 17: Arch-types of DJF frequency distribution across SOM of Figure 16, derived through a SOM analysis of DJF seasonal frequency distribution for each DJF season from 1950-1999. Figures in each box refer to the number of years between 1950-1999 where the DJF season is characterized by that typical frequency distribution.



(a)



(b)

Figure 18: Histogram (a) for 1996 (dry year) frequency distribution of daily events (based on SOM characterization in figure 15). This distribution maps to node 3,1 in the SOM mapping in figure 17. Histogram (b) for 1997 (wet year). This distribution maps to node 0,0 in the SOM mapping in figure 17.

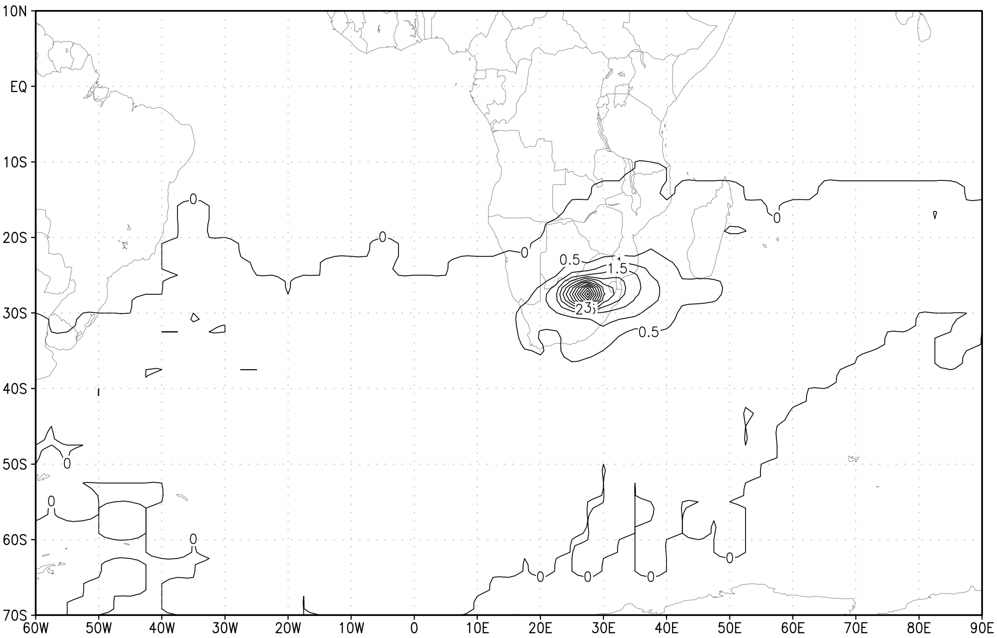


Figure 19: January 1996 frequency (%) of the passage of back trajectories through the domain originating from sigma 0.95 at 27°S, 27°E. 1996 was a characteristic dry year.

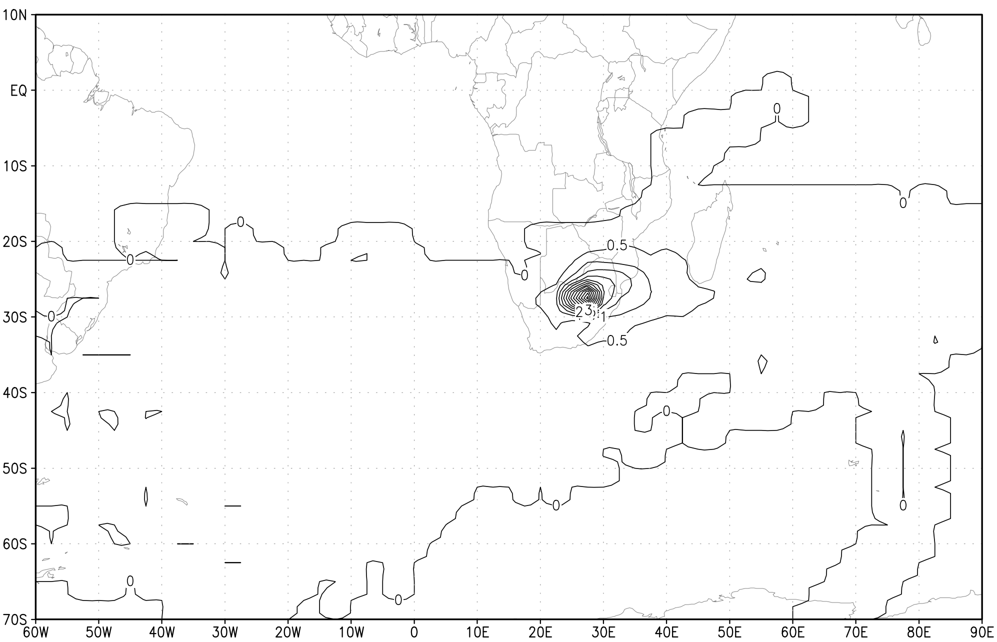


Figure 20: January 1997 frequency (%) of the passage of back trajectories through the domain originating from sigma 0.95 at 27°S, 27°E. 1997 was a characteristic wet year.

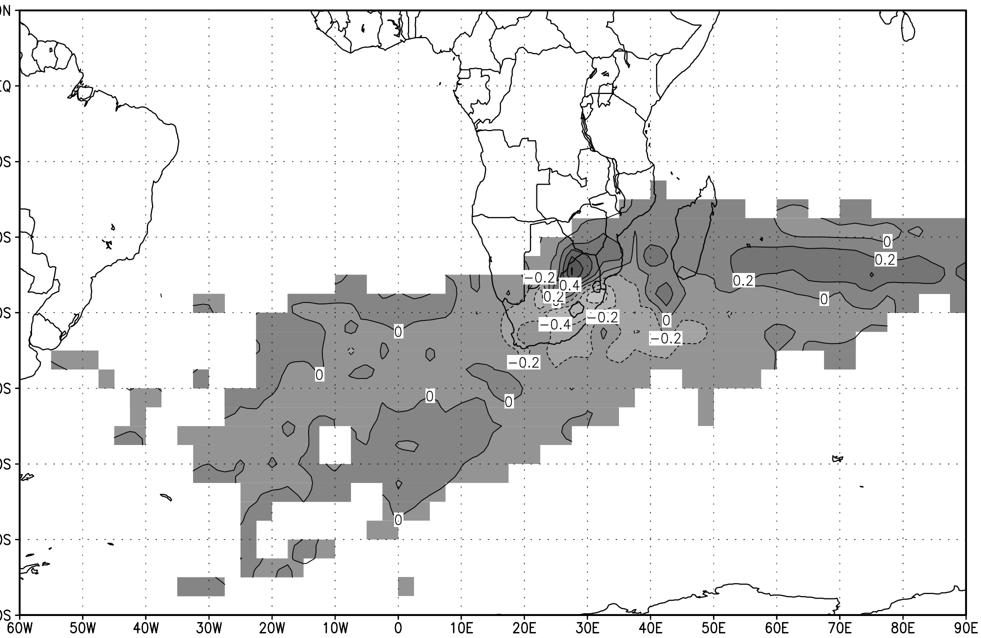


Figure 21: Difference in frequency (%) of passage of trajectories: January 1997 – January 1996.

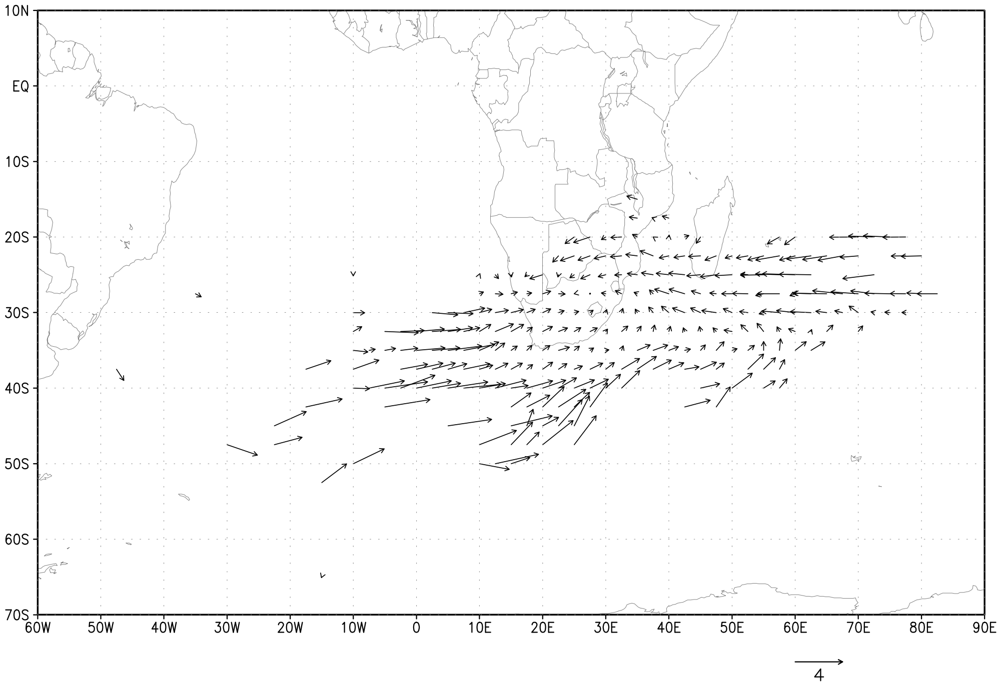


Figure 22: Mean velocity (m/s) along trajectory: January 1996.

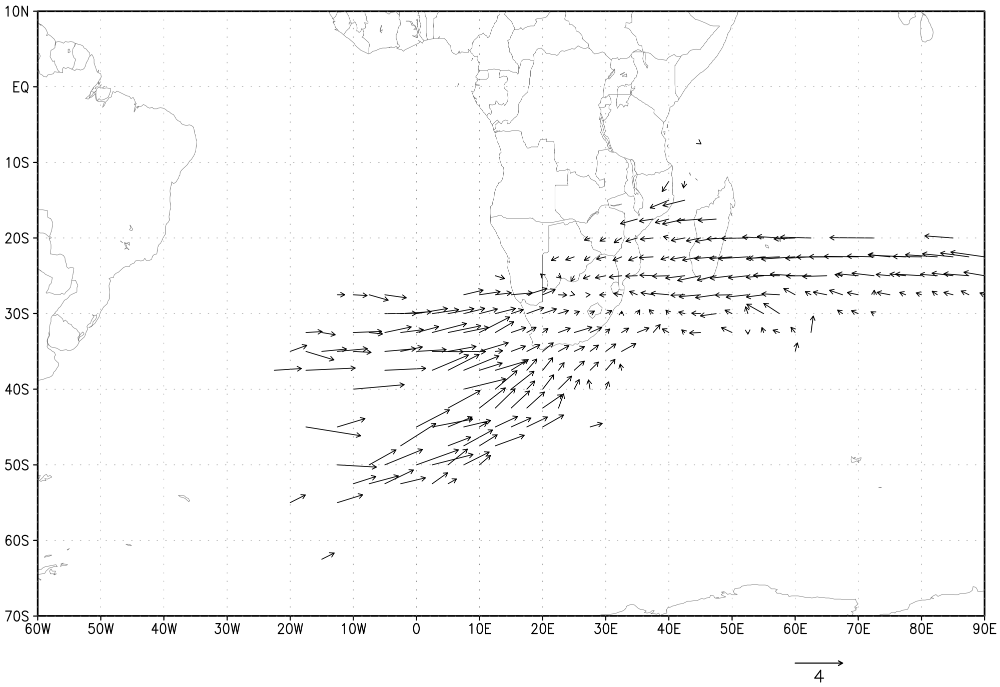


Figure 23: Mean velocity (m/s) along trajectory: January 1997.

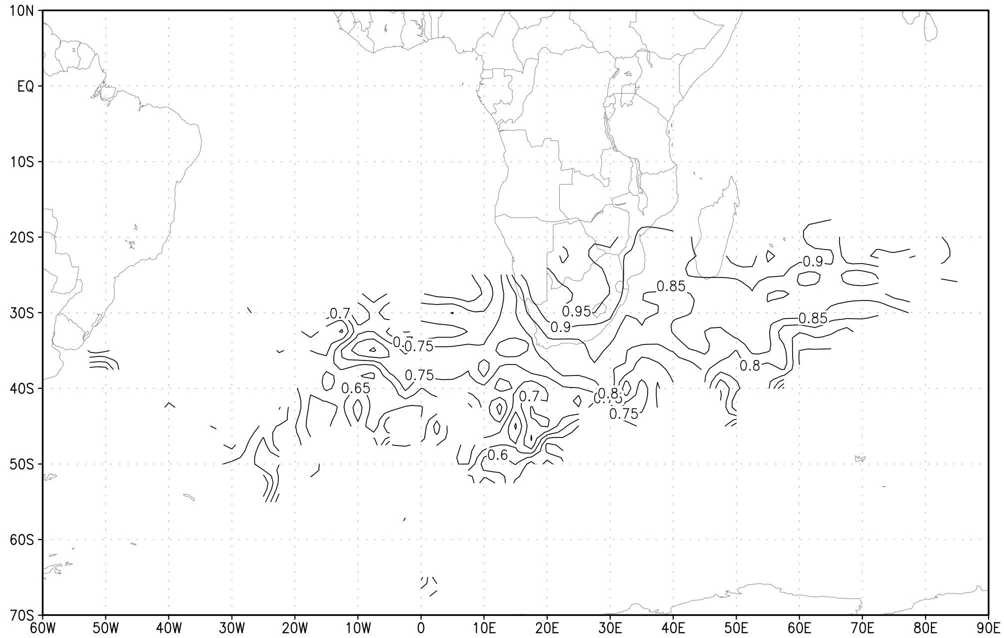


Figure 24: Mean sigma level along trajectory: January 1996.

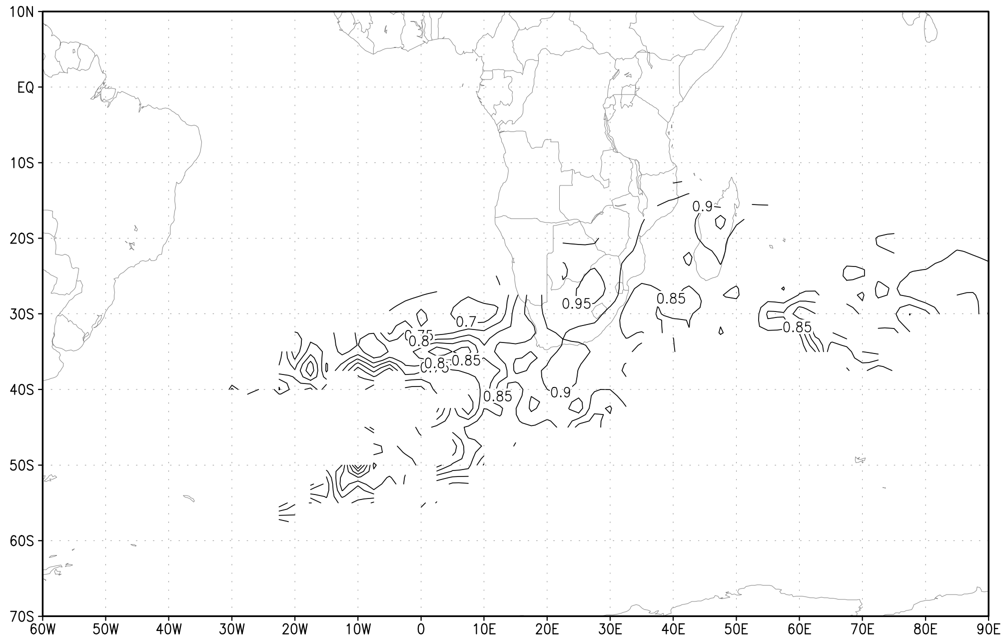


Figure 25: Mean sigma level along trajectory: January 1997.

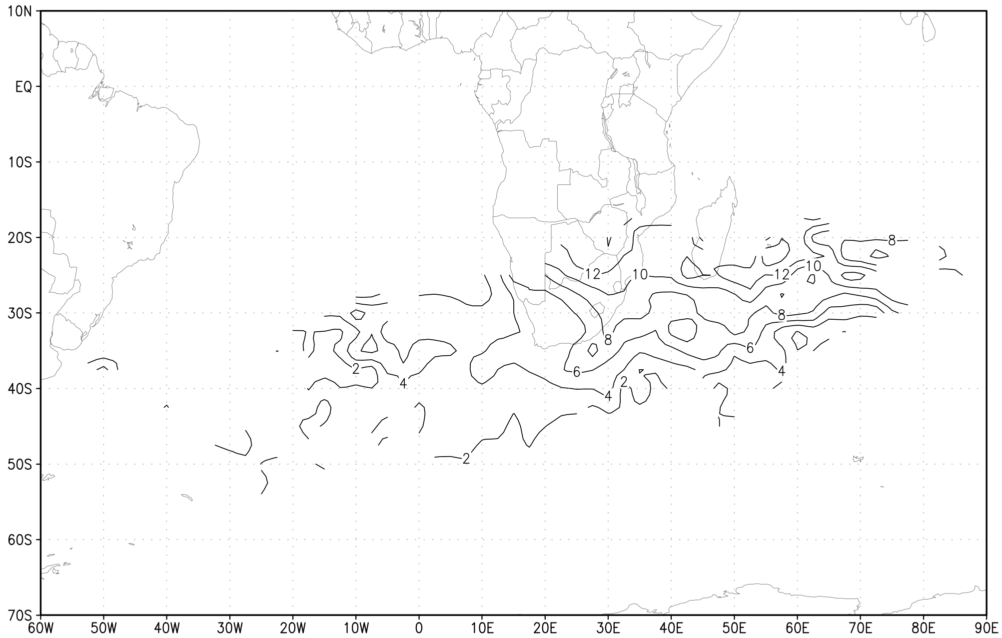


Figure 26: Mean specific humidity (g/kg) along trajectory: January 1996.

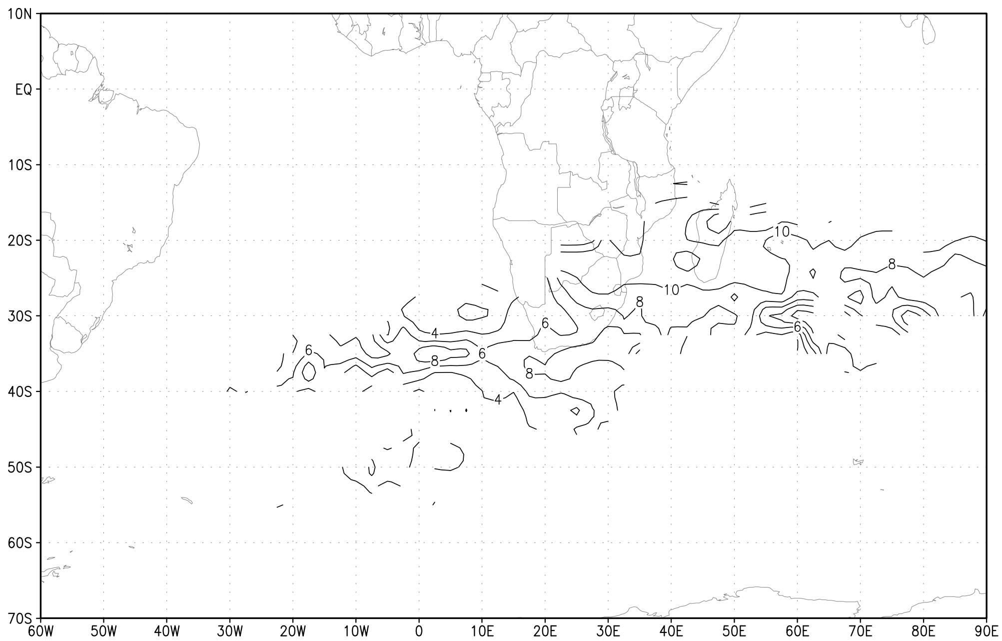


Figure 27: Mean specific humidity (g/kg) along trajectory: January 1997.

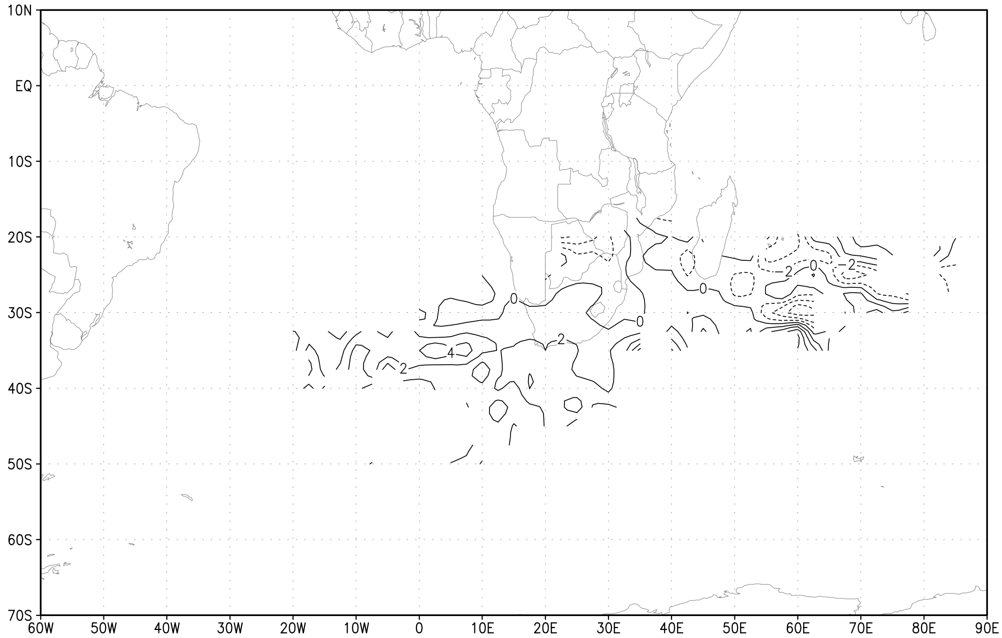


Figure 28: Difference in mean specific humidity (g/kg) along trajectory: January 1997 – January 1996.

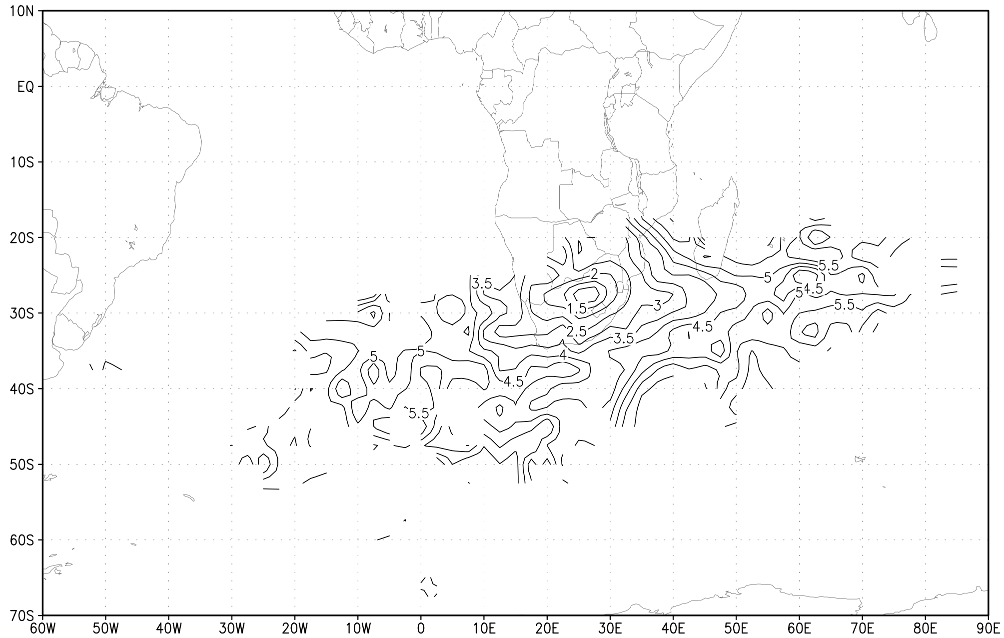


Figure 29: Time taken (in days) to travel from source: January 1996.

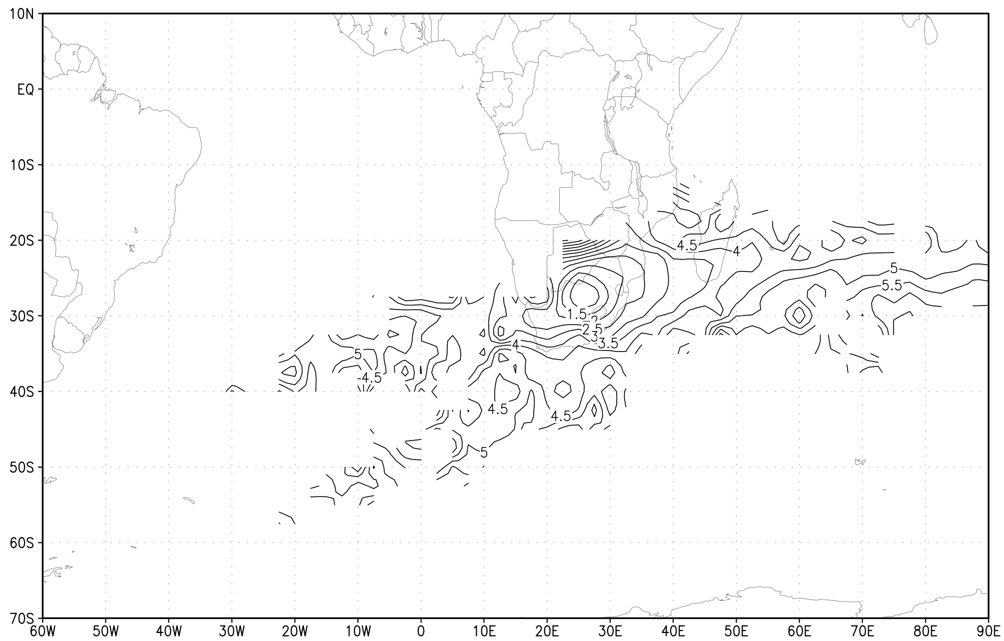


Figure 30: Time taken (in days) to travel from source: January 1997.

4. Proportional contribution of moisture

Proportional contribution is an approach adopted to ascertain to what degree a region along the trajectory pathway contributes to the final moisture content at the target location (origin of trajectory). Identifying transport pathways is, in effect, only part of the issue, and it is as important to quantify the seasonal contribution of moisture by each region traversed by the air.

For back trajectories we determine this by tracing the moisture content along a trajectory through time from the starting point. As every decrease in moisture content is encountered, we maintaining this value as representing an absolute maximum that any regions yet to be traversed could contribute to the air parcel at the starting point of the trajectory. Reversing the process, conceptually one may consider this from the view of traveling along the trajectory starting at the most distal point from the origin of the trajectory. Working forward in time one may consider the air parcel to have a moisture content of X, and traversing a spatial location may contribute an additional Y units of moisture. If at a further stage along the trajectory the moisture content of the air is reduced (perhaps from rainfall or moisture divergence) to a value of X or below X, then the contribution Y may be considered to have had zero contribution to the final value.

In this manner, the spatial relevance may be evaluated in terms of value to the moisture available for precipitation at a given region. This in itself is an improvement over the specific humidity flux approach already considered in the previous chapter. Figure 31 shows, as an example, a north-south latitudinally integrated and west-east longitudinally integrated vertical cross section of proportional contribution of moisture based on 20 years of back trajectories from sigma 0.95 centered on the summer interior rainfall region. The most notable aspect demonstrated in this figure is the dominant eastern source for moisture (a), and that this is transported in a relatively stable core from the east (b).

However, while this provides greater insight, as with earlier work the approach may be considerably enhanced by first stratifying trajectories in relation to whether precipitation occurred, and in fact by the spatial characteristics of the precipitation.

4.1 Stratifying data by precipitation

In much the same way as precipitation days were used as a basis for characterizing seasons in the previous chapter, one may use the same SOM results to select individual precipitation events – independent of a season's total characteristic. The same SOM of the previous chapter is used here, representing characteristic daily gridded rainfall for all days from 1950 – 1999 (Figure 15). In this approach, stratification of all daily data according to which characteristic daily pattern they match allows one to select trajectories according to the resultant precipitation event. For example, one may select all days that match the characteristic pattern of precipitation from the lower left SOM node (rainfall over the south central interior extending into Namibia). The trajectories terminating in the center of this rainfall region for all these days can then be extracted and the proportional contribution of moisture sources examined.

For this report, we examine moisture transport for days matching the nodes associated with the corners of the precipitation SOM (figure 15). The nodes associated with the corners are selected, as they are analogous to the opposing modes of the first two eigenvectors of the precipitation data. The specific nodes selected from the SOM in Figure 15 are (x,y coordinates indexed from 0,0 in lower left corner):

- lower left {0,0 0,1 1,0}
- upper left {0,2 0,3 1,3}
- lower right {3,0 4,0}
- upper right {3,3 4,3 4,2}

Each corner selection of nodes accounts for ~15% of DJF days between 1950 and 1999, with the total number of days accounted for by this set of nodes totaling ~65% of all days.

Considering first the vertically integrated frequency of passage of trajectories for air arriving in a column centered on central summer rainfall region of South Africa, Figure 32 shows the dominant frequency of trajectories from different characteristic precipitation events. For relatively dry days, and for days with coastal rainfall (right hand side panels), the source air for the central region has a clear dominant western source. From figure 33, which shows the proportional contribution of moisture for these conditions, the moisture that does arrive over the central regions is nominally biased to the west, but still has strong contributions from the east, notwithstanding the frequency bias to western sources.

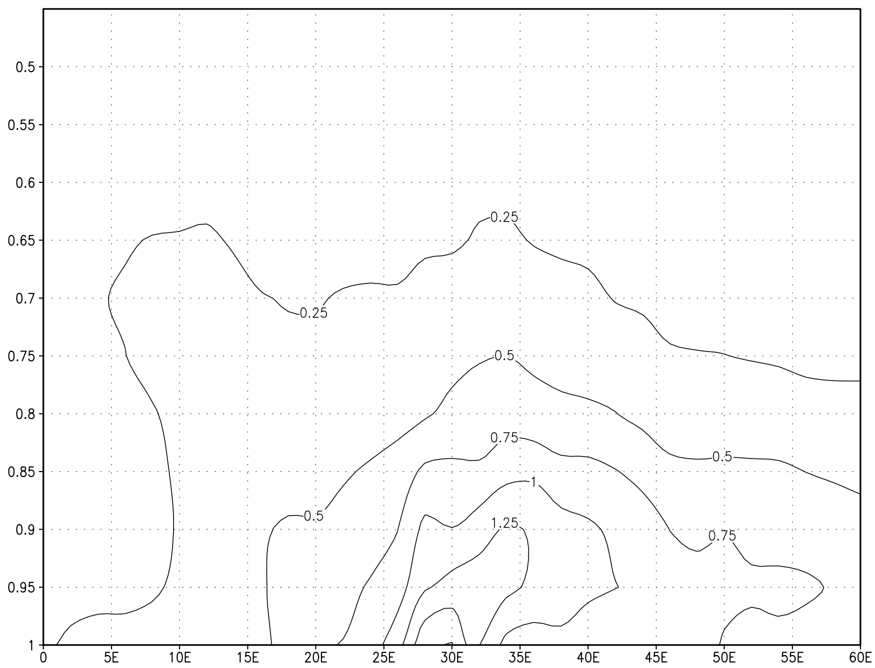
For those days where significant rain is experienced over the central interior and northeastern regions (left hand side panels in figures 32 and 33), the frequency of air transport is nominally equally split between western and eastern sources. However, in terms of proportional contribution (figure 33) of moisture, the sources are clearly biased toward the east in the south Indian ocean.

If one switches focus to northeastern South Africa as a target region for moisture transport (Figures 34 and 35), then the same interpretations hold as for the central region, only more strongly so. Investigating this further, one may calculate vertical cross-sections for the very wet (top left corner of figure 15) and very dry (bottom right corner for figure 15). These are shown in Figure 36 (west-east cross section, latitudinally averaged) and Figure 37 (north-south cross section, longitudinally averaged).

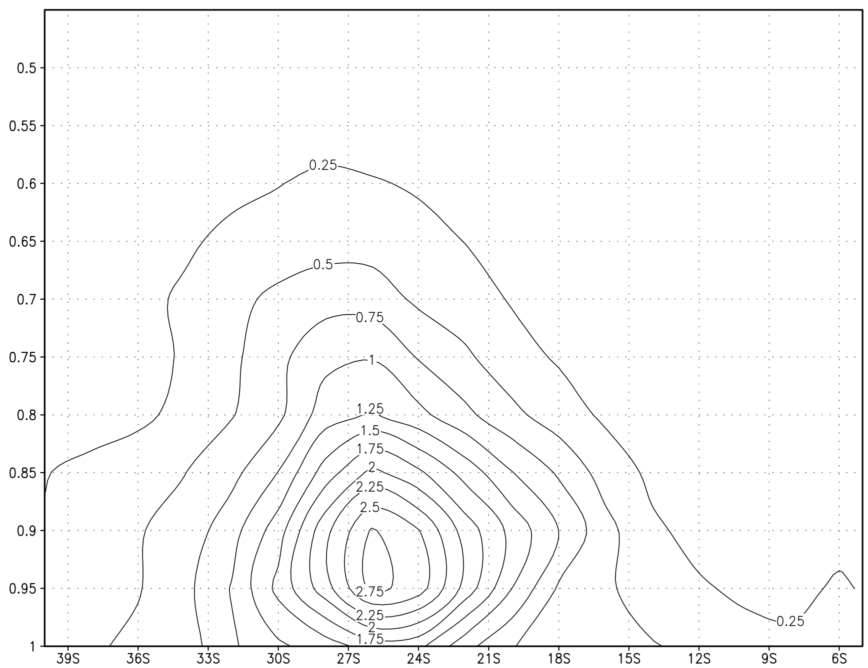
Considering first the west-east cross section (Figure 36) it is apparent that the wet case days receive more moisture from elevated levels and from further east than do dry days. Surface flux contributions to the moisture are greater only east of ~42ºE (see anomaly pattern in lower panel). In north-south cross section (Figure 37) the moisture source is latitudinally constrained, and it is clear again that the wet case days receive greater moisture from elevated sources. The core of the positive anomaly moisture contribution (lower panel) centers on sigma levels 0.8 - 0.9, and displays a notable northward shift (centered on ~23ºS) in source region compared to the dry case days.

This information holds a number of implications for understanding moisture contribution to South Africa rainfall, and raises issues of, among others:

- What controls the vertical structure of moisture transport?
- To what degree is the moisture transport and spatial structure influenced by near-coastal SSTs versus SSTs further east (~42ºE and further)?
- What are the climate change implications for this moisture transport in terms of firstly, SST change, and secondly, circulation change?



(a)



(b)

Figure 31: Example of the 20-year mean DJF proportional contribution of moisture and frequency of passage for air arriving over north eastern SA in west-east longitudinally integrated (a) and north-south latidudinally integrated (b) cross sections. Values are displayed as the square root of the specific humidity contribution due to the rapid decay away from the target region as the trajectories spread in space.

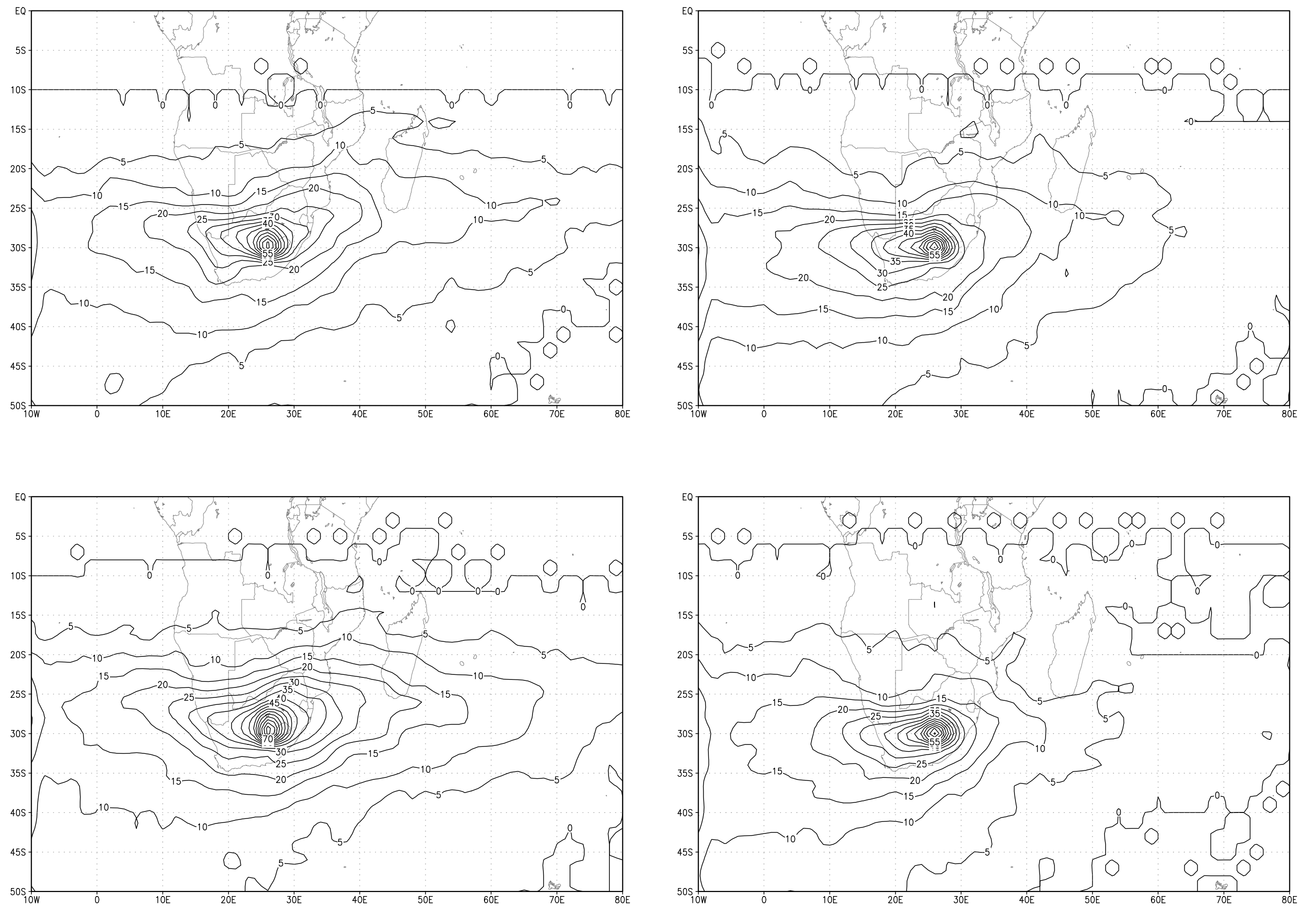


Figure 32: Vertically integrated frequency of passage (%) of trajectories terminating in central South Africa. The four maps correspond to the mean of all days falling on the corner nodes of the precipitation SOM (figure 15).

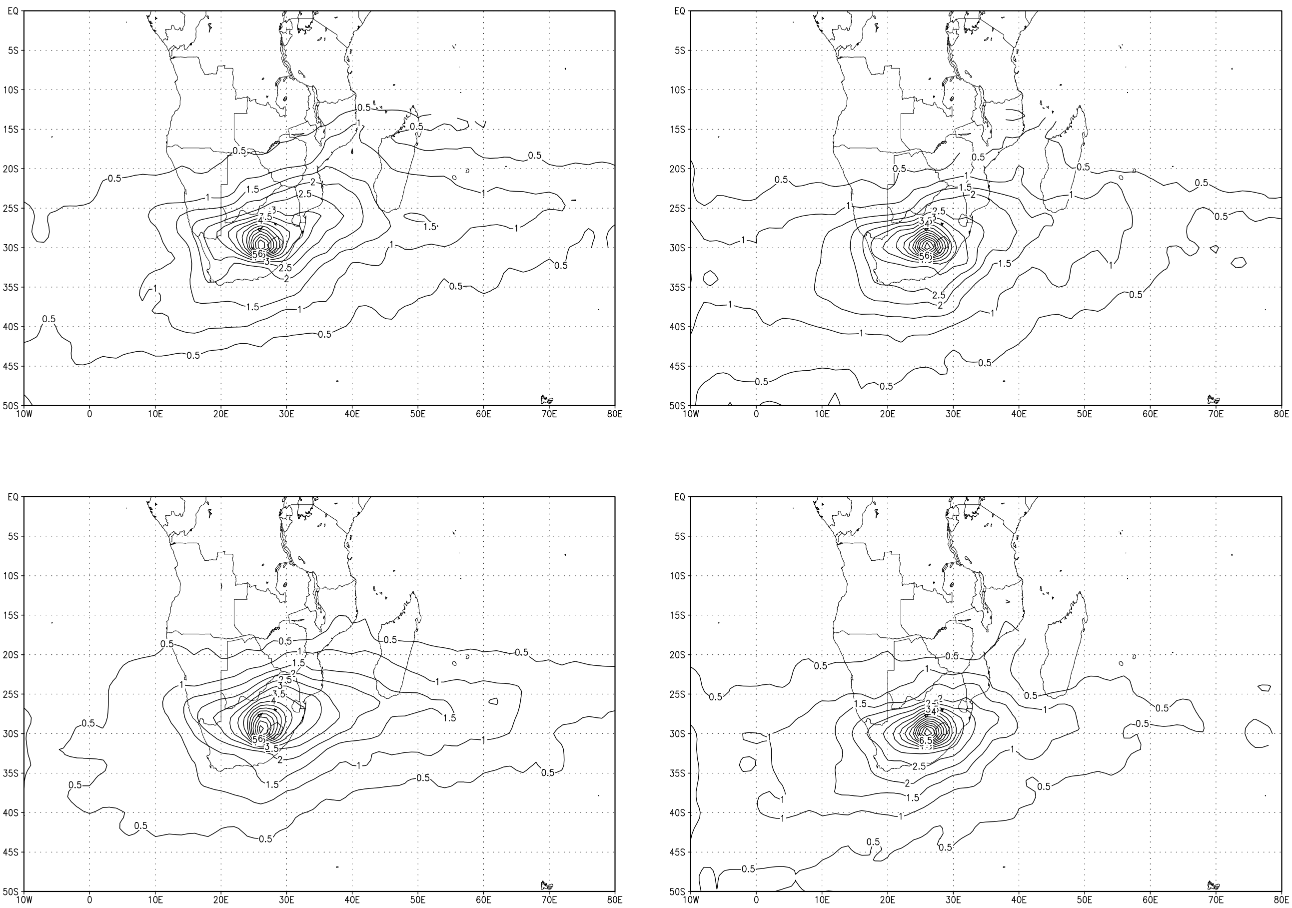


Figure 33: Vertically integrated proportional contribution of moisture to trajectories terminating in central South Africa. The four maps correspond to the mean of all days falling on the corner nodes of the precipitation SOM (figure 15).

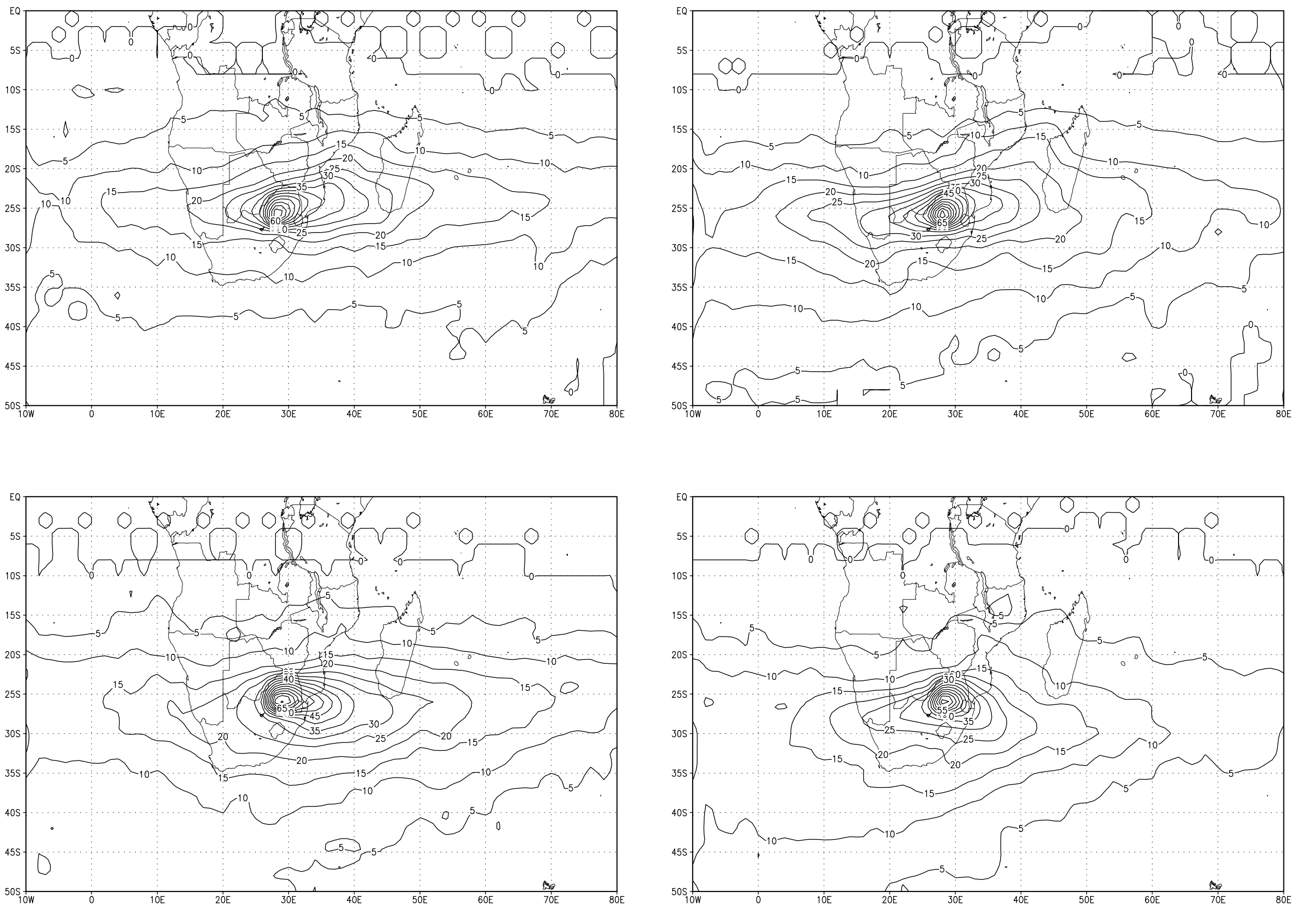


Figure 34: Vertically integrated frequency of passage of trajectories terminating in north eastern South Africa. The four maps correspond to the mean of all days falling on the corner nodes of the precipitation SOM (figure 15).

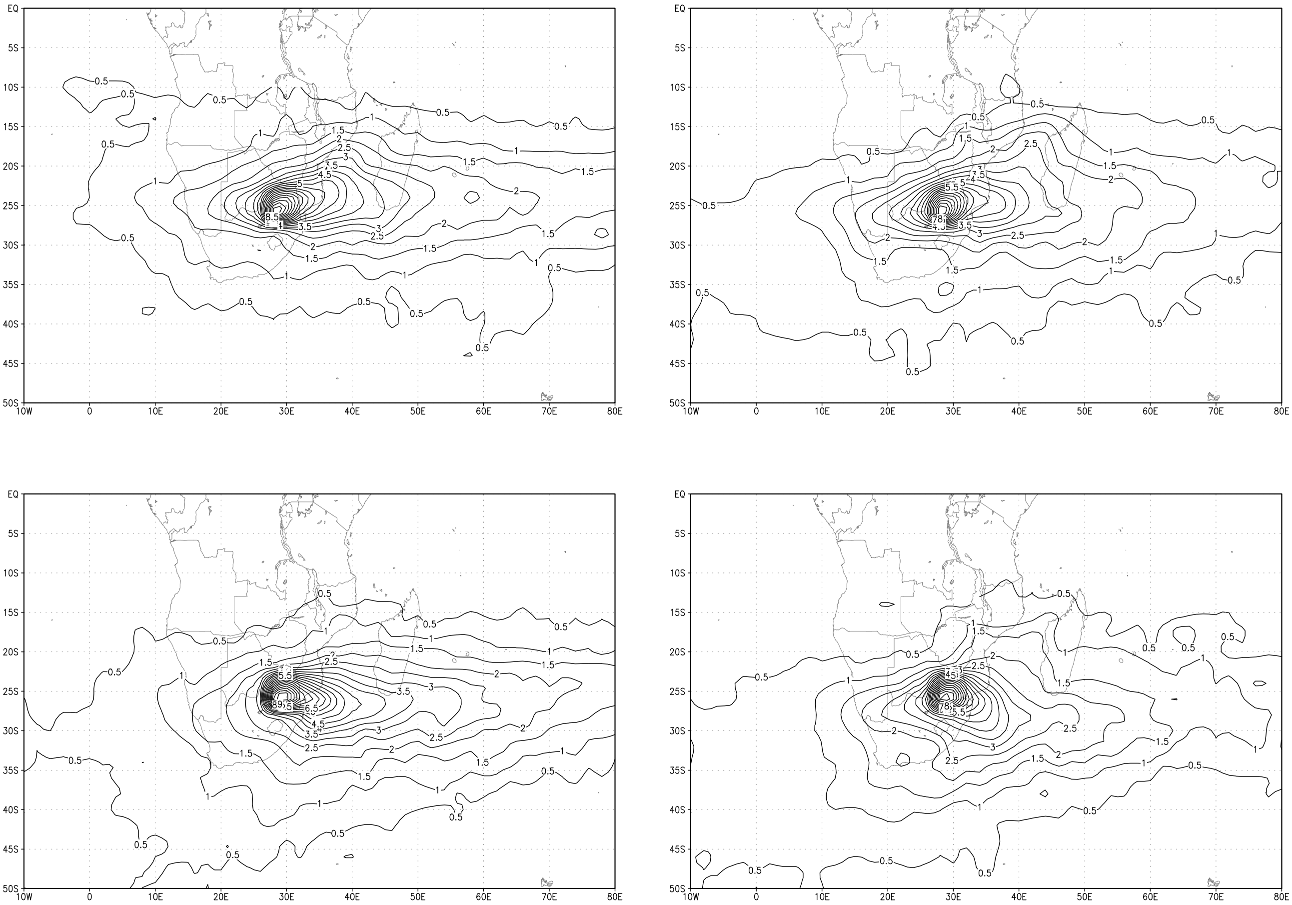


Figure 35: Vertically integrated proportional contribution of moisture to trajectories terminating in northeastern South Africa. The four maps correspond to the mean of all days falling on the corner nodes of the precipitation SOM (figure 15).

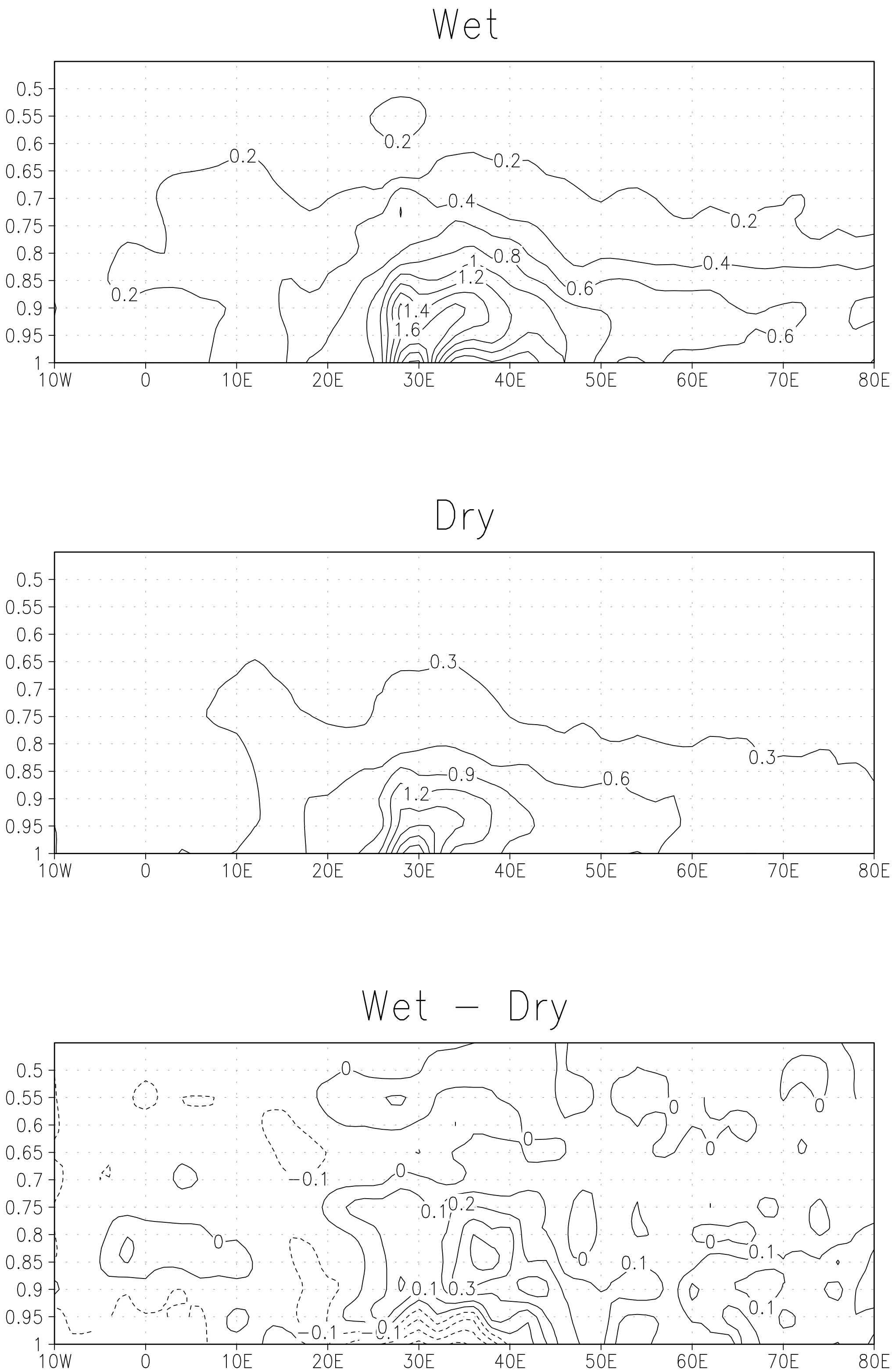


Figure 36: West-east cross section of proportional contribution to moisture arriving over the north eastern South Africa. The top panel is for wet days (top left node of the precipitation SOM in figure 15). The centre panel is for dry days (lower right node of the precipitation SOM in figure 15). The lower panel is the wet case minus the dry case.

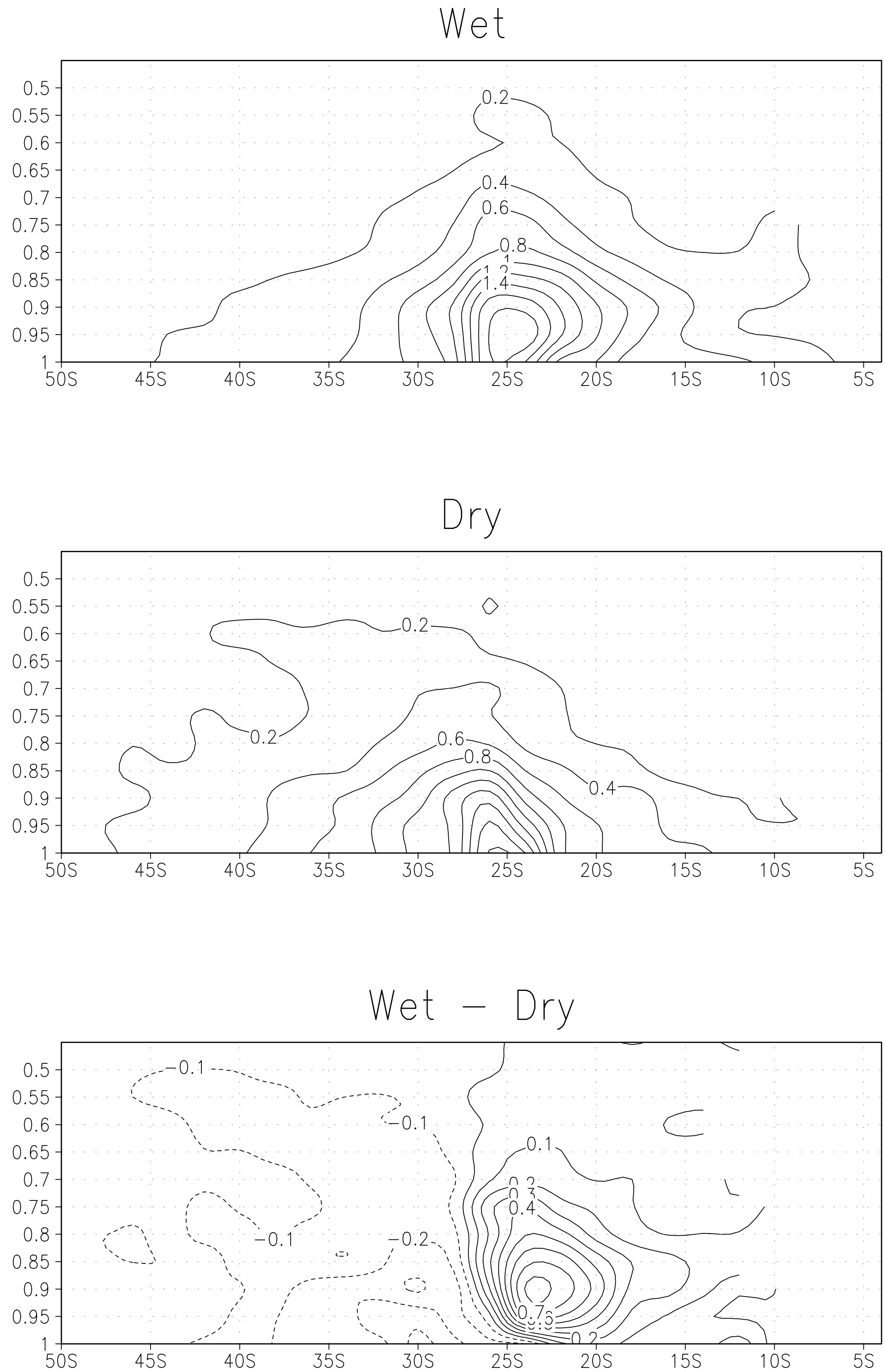


Figure 37: North-south cross section of proportional contribution to moisture arriving over the north eastern South Africa. The top panel is for wet days (top left node of the precipitation SOM in figure 15). The centre panel is for dry days (lower right node of the precipitation SOM in figure 15). The lower panel is the wet case minus the dry case.

5. Spatially extensive heavy rainfall

The interest shown in extreme events, including those related to precipitation, has been receiving growing attention in the recent years. This comes as a result of understanding that changes in the mean of variables has a large influence on the extremes of these same variables (Katz and Brown, 1992; Mearns et al., 1984). In fact, changes in the extremes can be disproportionate (Meehl et al., 2000; Groisman et al., 1999) to the changes seen in the means and often have more impact on both society and the environment.

To investigate some of these issues in the context of the long-term climatology of moisture transport, this section focuses on what is defined here as spatially extensive heavy precipitation events in South Africa. While not an "extreme event" as may be commonly understood, this takes a broader view and focuses on heavy rainfall (>90th percentile for each location) that is spatially extensive – in effect focusing on precipitation events that have regional impact and lie within the top 10% of events experienced by any one location. This explores, in addition, the possible spatial patterns that exists within such events, and considers the non-local sources of moisture. In order to do this, the study first identifies suitable days that maybe classified as both having high precipitation as well as affecting a large area.

The selection process of appropriate days uses the gridded version of the CCWR daily station rainfall (see chapter 3). Using a minimum precipitation threshold set at the 90th percentile for each grid cell, the spatial extensiveness of the events are identified by selecting only events in which 800 or more cells in the domain (~25% of the area) satisfied the first criterion. Once all days meeting these criteria are selected, archetype representations are determined using, once again, SOMs to categorize the days. As evidenced in the earlier application, one of the advantages of using the SOM method over the more traditional cluster analysis is that it enables the visualization of the relationships between the nodes (Hewitson and Crane, 2002), and is particularly helpful here to visually establish the nature of spatially extensive rainfall events – with the principal modes identified by the corner nodes, and more transitional states placed between these nodes.

In all 459 days are identified in this process between 1959 and 1997. These are classified into 12 archetypes by the SOM, and are displayed in Figure 38. The SOM results show that the areas with the most significant events are, as expected, in the eastern and northeastern sectors of the country. A distinct pattern across the interior of the country with a northwest-southeast axis (nodes [0 0], [1 0] and [1 1]) can also clearly be seen in this diagram. This pattern closely resembles that of the tropical-temperate troughs that are known to occur in this region during the summer season. It is also known that these systems are responsible for a large portion of the summer rainfall over the region (Harrison, 1984; Lindesay, 1998).

Examining the frequency distribution of the events among the SOM nodes showed that the node [2 2] has the highest number of events mapped to it, whilst node [1 0] has the least. The distribution of the events in general however appears to be dispersed more evenly. The frequency also seems indicate that events occurring in the northern, northeastern and eastern parts of the country are more frequent (e.g nodes [2 0], [2 2] and [2 3]). Thus the classification shows not only the actual amount of rainfall in these regions to be the highest, but the frequency of events in these same regions are also the highest.

Examining this further in terms of the summer season, the frequency of occurrence of different events shows distinct sub-seasonal differences. Figure 39 shows that SOM nodes [2 2], [0 3] [1 3] and [2 3] are dominated by events that occur in mid and late summer during January and February. These four nodes all fall in the lower part of the SOM map. SOM nodes [0 0], [1 0][2 0] and [2 1] are seen to be dominated by February events. These four nodes form the opposite end of the SOM map from the previous category. Walawege and Hewitson (2003) take this analysis significantly further, particularly with regard to the temporal characteristics, but this material work goes beyond the focus of this report.

Sample events from three of the SOM nodes ([0 0], [2 0] and [2 3]) are further considered in a preliminary manner in terms of the trajectories associated with them to examine the possible non-local moisture sources for the extreme precipitation events. Back-trajectories from starting locations for a number of extreme event days corresponding to the selected SOM nodes were carried out. The results indicated that air masses to these locations originated from three possible regions; the tropical Atlantic Ocean, the south Atlantic (of lesser importance) and the tropical south Indian Oceans (examples of these trajectories are provided in Figure 40). Of these locations, much of the moisture for the events was transported from the south Indian Ocean. Although similar findings have been presented in the past, the present investigation showed that this possible source of moisture to be further south that previously thought. The results showed that an area in the south Indian Ocean, east of Madagascar (~20º-35ºS and 45º-60ºE) to be the possible source of moisture for these particular events. Examples of these were seen for events in all three SOM nodes examined. This finding was also confirmed through the examination of individual case events. Latent heat fluxes (from the NCEP reanalysis data, not shown) for the same time periods in the area also indicate high values, corresponding to possible high evaporation of moisture from the warmer ocean surface.

In general, these results suggest that the spatially extensive heavy rainfall events display similar transport characteristics to the general seasonal climatology. In particular, there appears to be no clear, unique attribute to the transport underlying these events, in turn signifying that the nature of these events is perhaps related more to the circulation dynamics driving the precipitation processes and other possible local feedback mechanisms, than any clear anomalous large scale moisture transport signal. Seasonally, there is a bias toward late season occurrence of these events, which in the light of the previous point raises a question of whether the late season bias is a function of sub-seasonal changes in the large scale dynamic, or whether this is a reflection of changing land surface characteristics through the season, leading to more active local feedback mechanisms. Overall, the indication that the moisture transport is not the primary causal factor behind the spatially extensive heavy rainfall events is a critical development in understanding where the focus for further research should be placed. However, further work to further justify this conclusion is needed.

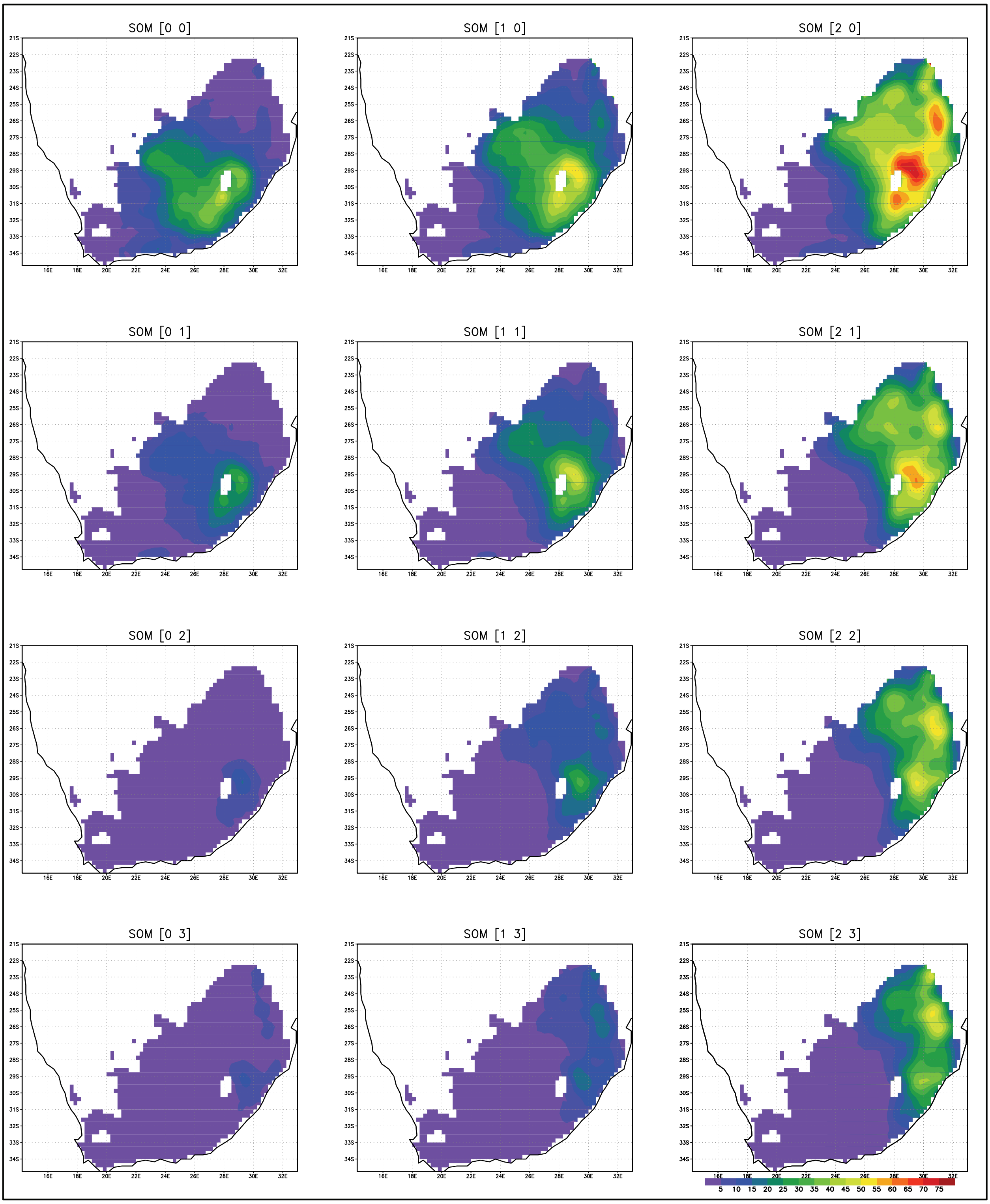


Figure 38: Spatially extensive heavy rainfall archetypes identified from the summer (DJF) months between 1950-1999.

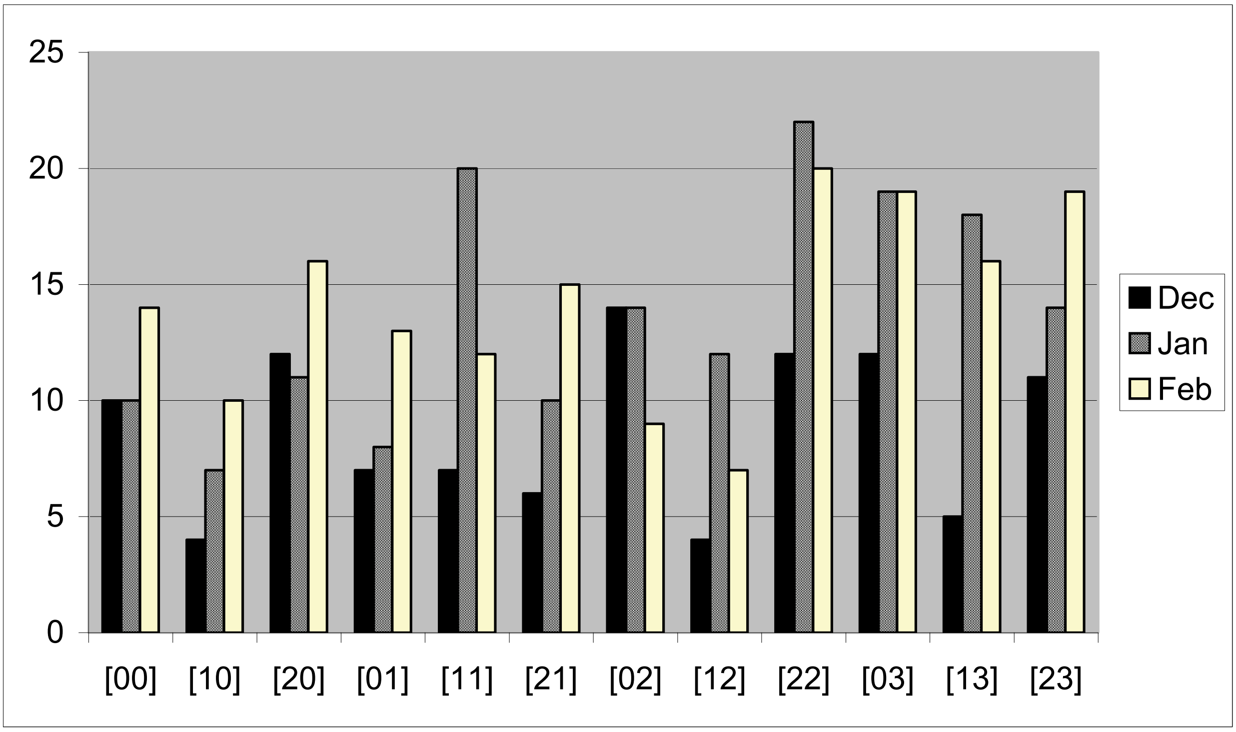


Figure 39: Frequency distribution by month of events mapped to the SOM nodes.

Figure 40: Example trajectories calculated for events mapped to SOM node [0,0].

6. Large Scale Moisture flux characteristics

Moisture is a necessary but not a sufficient condition for rainfall. However, the presence of moisture and the transport thereof does provide insight into climate variability, and it is the large-scale circulation dynamics that are the fundamental determinant of these aspects. Global-scale, climatological moisture sources and sinks may be identified through velocity potential fields of moisture flux integrated from the surface to 700hPa (Fig. 41). The analysis of these fields provides a *static* snapshot view of the role of circulation, and the actual pathway followed by the moisture over a period of days may be notably different to that which may be indicated by a static circulation pattern. Nonetheless, the analysis of the circulation fields provides significant insight into the large-scale controls.

From Figure 41 it is apparent that during the DJF season major moisture sources are the North and South Atlantic and Eastern Pacific Oceans. The subtropical Indian Ocean also acts as a moisture source, but on a much smaller scale when compared globally. The major sinks of moisture are the Western Pacific Ocean and maritime continent and the mid-latitudes. There are significant changes to these patterns of moisture sources and sinks between wet and dry DJF years in the summer rainfall area of South Africa (Fig. 41b). First, the ENSO signal is clear where there is an eastward shift in the convergence of moisture during dry years. Closer to Africa we see the northeastward shift of the South Indian Convergence Zone (SICZ). This shift and its impact on rainfall variability in southern Africa has already been documented (Mason and Jury, 1997; Cook, 2001). Although ENSO appears to be a common factor during dry years in South Africa, each event is distinct. This is clearly seen in the anomalies of divergent moisture flux during the 1982/83 and 1997/1998 ENSO events (Fig. 41c+d). Over the Pacific basin anomalies are similar, but elsewhere quite different. Slingo and Annamalai (2000) attributed the unconventional response of the Indian Monsoon to the 1997/98 ENSO event to local Hadley circulation which tended to override the effects of a shift in the Walker Cell.

In terms of African climate variability, it seems that shifts in the Walker Cells in this region are not as dominant as in the Pacific basin (Fig. 42). The Walker Cells in this instance are determined from seasonal average divergent component of moisture flux for a latitude band from 5^{o}N to 15^{o}S. Areas of convergence around 140^{o}E and divergence around 100^{o}W can be deduced from the figure. Shifts in the convergence zone around 140^{o}E, related to shifts in the Walker Cell over the Pacific Ocean, correlate well with South African summer rainfall. Eastward shifts of the convergence zone, typically during ENSO events, generally correspond to dry years (lowest quintile). However, two interesting features emerge. First, not all dry summers in southern Africa relate to ENSO, and second, longitudinal shifts in the Walker Cells between 60^{o}W and 60^{o}E are relatively insignificant. Walker cells are useful in understanding climate variability over the Pacific Ocean but the latter point above raises questions about using these to explain the atmospheric response over Africa to ENSO events. This supports the notion that other mechanisms must exist whereby the ENSO signal is linked to southern Africa climate.

As with the Indian monsoon, the Hadley circulation does seem to be linked to wet and dry years in South Africa. This can be seen in the meridional transport of moisture (Fig. 43). In the tropics moisture is transported towards the ITCZ by the trade winds. Here dry years are associated with a stronger zonally-averaged northern Hadley Cell as demonstrated by enhanced southward moisture transport north of the ITCZ in DJF. Over the African longitudes greatly enhanced meridional moisture transport into the mid-latitudes and tropics away from southern Africa are characteristic of dry years. In this instance the meridional transport of moisture is more than doubled in magnitude between wet and dry years. These differences are probably related to stronger southeasterly trades and enhanced baroclinic activity in the mid-latitudes. This contradicts to some degree the notion that tropical-temperate-troughs, the major summer rainfall system, are a dominant conduit for moisture (and momentum) from the tropics into the mid-latitudes (Harrison, 1984; Tyson and Preston-Whyte, 2000).

Daily fields of velocity potential of moisture flux, integrated from the surface to 700hPa, for all DJF days were submitted to a SOM analysis. The frequency of the various archetypes (nodes) for dry and wet years were compared. Overall, a general distinction in the frequencies between wet and dry years was not found. Such clear distinctions have been found for vertical-mean and shear wind components (Tennant and Reason, 2003). However, two scenarios do emerge that can be considered characteristic of dry and wet years (Fig. 44). Scenario A, mostly associated with dry years, shows the South Atlantic Ocean and to a lesser degree the tropical Indian Ocean as a moisture source. The important feature here is the overall eastward gradient of divergent moisture flux into what resembles a northeastward displaced SICZ. Scenario B, mostly associated with wet years, shows a larger area of moisture source in the tropical Indian Ocean and south of that in the Southern Ocean. The difference between this scenario and scenario A is the general westward gradient of divergent moisture flux (as marked by white arrows in figure 4). The tropical Indian Ocean moisture source, at first glance, appears to supply moisture to South Africa. However, this moisture source lies to the north of the SICZ and probably is predominantly a feeder of the main axis of the SICZ and not for South Africa, which lies south of the SICZ. Twice-daily vectors of moisture flux, vertically integrated from the surface to 700 hPa, over the southern Africa area from the Greenwich meridian to 60^{o}E and 45^{o}S to the equator that were submitted to a SOM analysis also show the major source of moisture to be the Agulhas Current and Indian Ocean south of 25^{o}S (Fig. 45).

Nonetheless, while the findings from the SOM analysis of moisture flux suggest that the Agulhas gyre region remains a major source of water vapour, to what extent this moisture is a direct contributor to individual continental rainfall events remains somewhat unclear, as mean circulation patterns do not disclose the dynamic nature of transport with the daily passage if different synoptic systems. Notable is that during major spatially extensive rainfall events of tropical temperate troughs the mean flow over the Agulhas gyre is away from the continent. Further, for the interior of the country, as indicated by the trajectory analysis, there is typically an ~3 day travel time from the coast.

Nonetheless, the identified moisture source will, naturally, be of importance in that the dynamics of the atmospheric circulation are perturbed. Further, the moisture sourced from this region will be advected by transport from the east around the Indian Ocean anticyclone and enter the region of moisture source identified from the trajectory analysis. In addition, Reason (2001) supports this by showing that above normal SSTs south of Madagascar lead to enhanced evaporation, and that these are significantly correlated with summer rainfall over eastern South Africa.

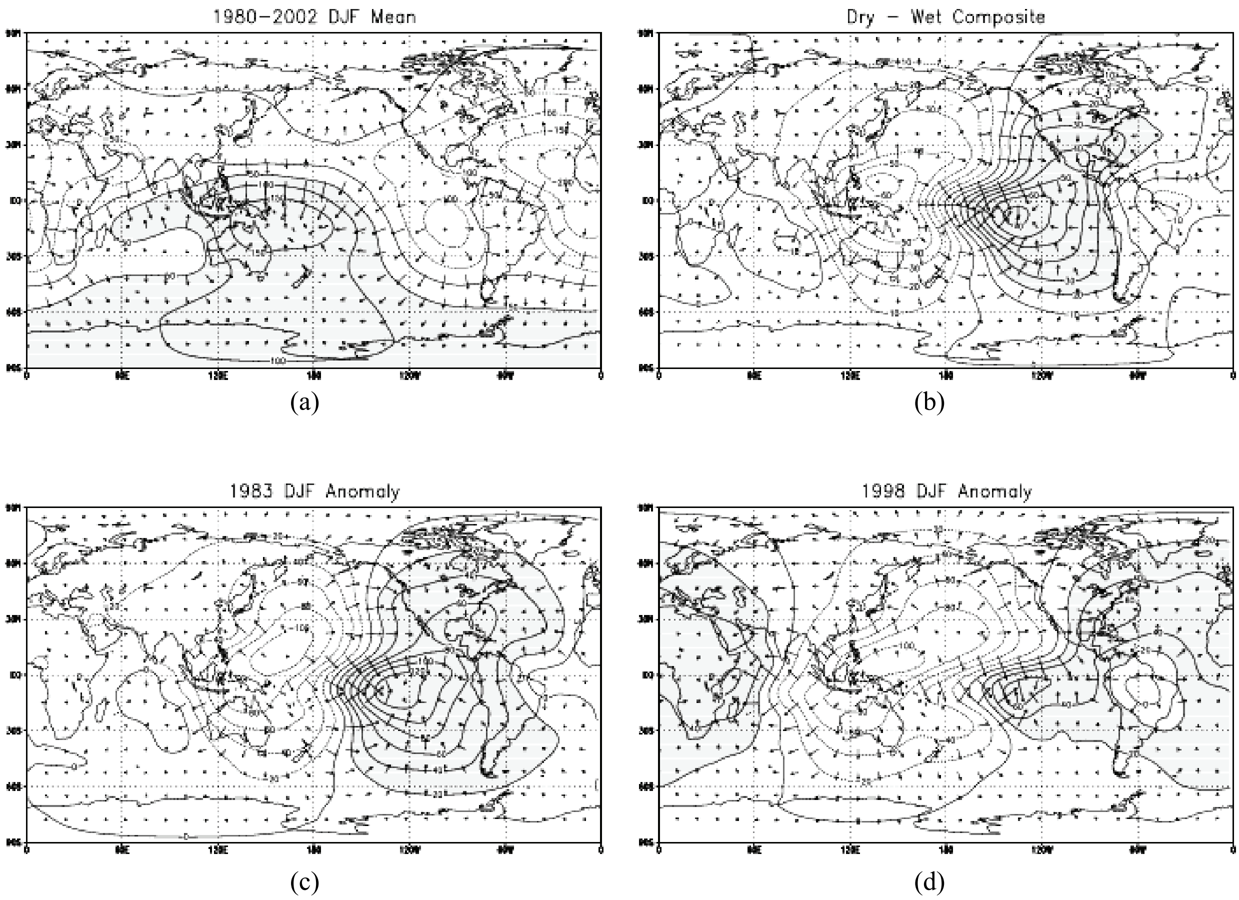


Figure 41: Velocity potential and vectors of divergent moisture flux integrated from the surface to 700 hPa. Shaded areas indicate convergence of moisture, dashed lines divergence of moisture.

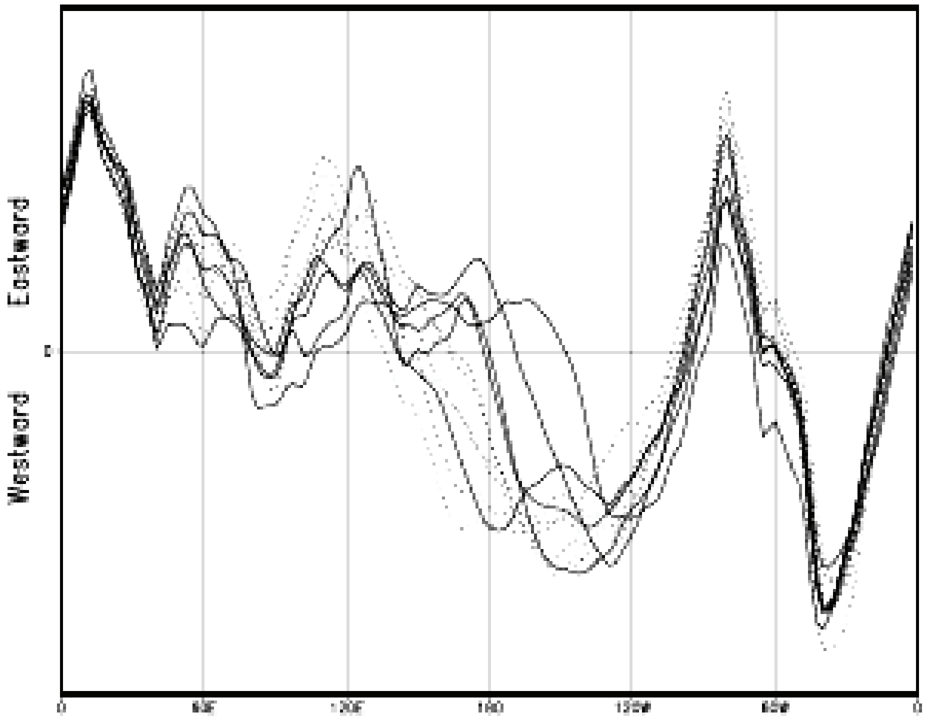


Figure 42: Zonal divergent moisture flux in the layer from the surface to 700hPa, averaged from 5N to 15S for wet (solid) and dry (dotted) years in central South Africa.

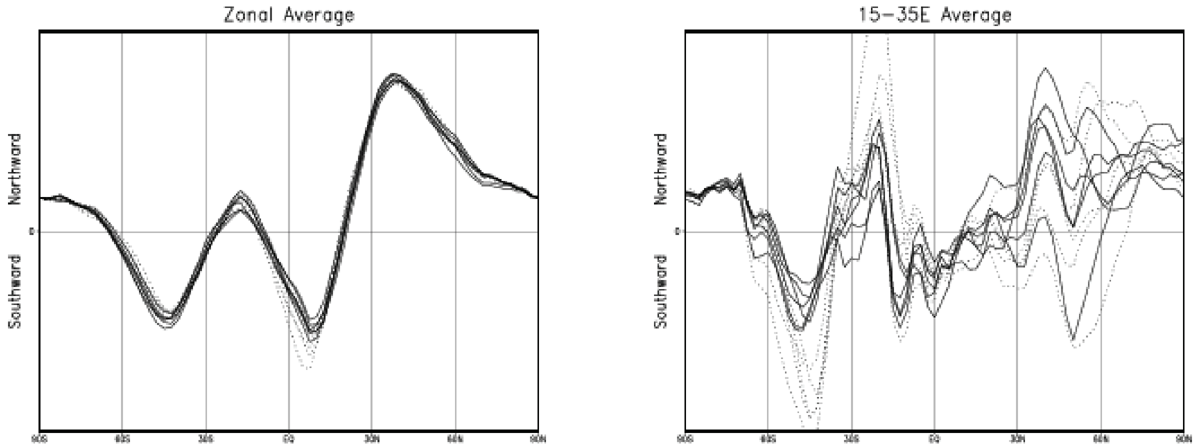


Figure 43: Meridional transport of moisture, zonal average (left) and 15 to 30E (right), for dry (dotted) and wet (solid) years as in figure 42.

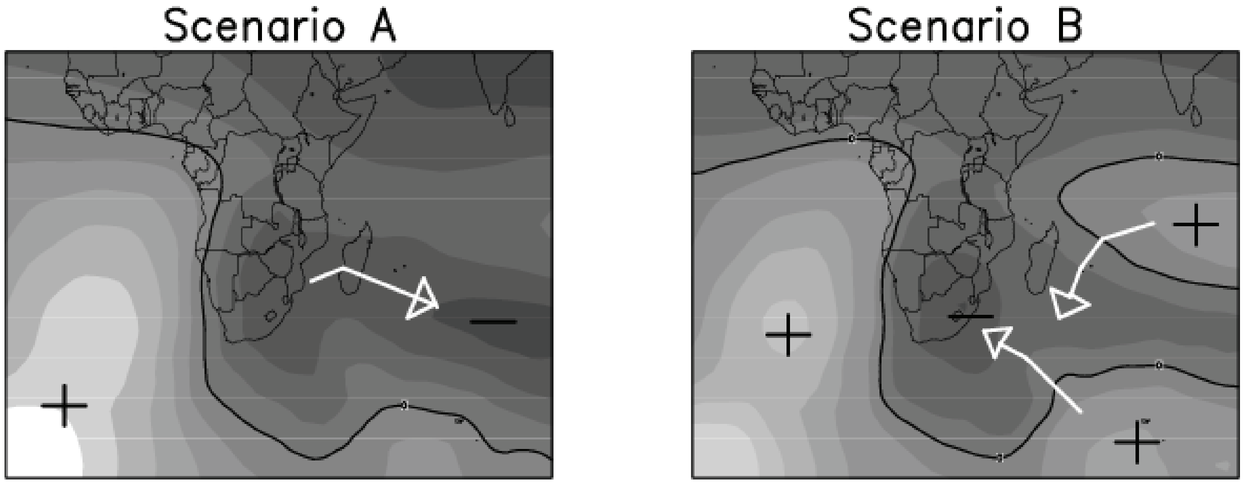
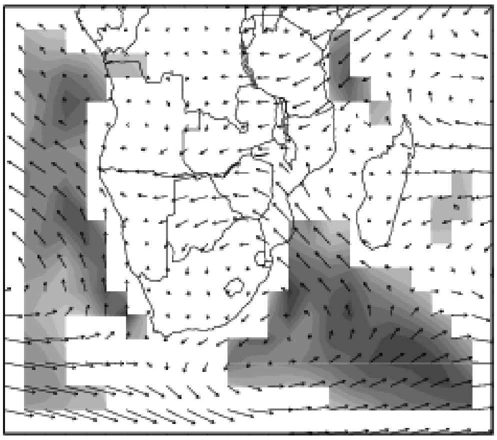


Figure 44: Selected archetypes of daily moisture flux velocity potential, indicating moisture sources (+) and sinks (-). Divergent moisture transport indicated by white arrows.



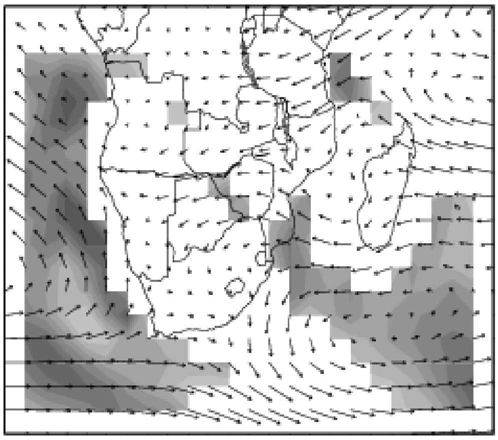


Figure 45: Selected archetypes of daily moisture flux with areas of divergence shaded, showing possible sources of moisture for those synoptic systems advecting moisture into the interior of South Africa.

7. Future climates

Considering what the future may hold is, in one respect, simple. Numerous GCM simulations exist for future climate, based on a wide range of greenhouse gas emission scenarios[9]. However, what is not commonly recognized is the range of uncertainties associated with such simulation data, and in particular the necessity for users to undertake rigorous evaluation of the skill of any GCM to simulate the atmospheric dynamics for the region in question. Downscaling is commonly viewed as one approach to deriving skillful regional scale information, yet even here there are notable assumptions and caveats that often increase uncertainty (Hewitson and Crane, 2003). Consequently the approach adopted in this report is to assess climate change impacts on large-scale circulation features related to the moisture transport, as the local-scale skill (grid cell resolution) of GCMs is poor and any conclusions drawn are thus of questionable value without rigorous evaluation *on the time and space scales of application* – an aspect only now beginning to be recognized in the community (Hewitson and Crane, 2003).

7.1 Large scale moisture characteristics

Following the approach of the last chapter, and looking ahead to future climates in a somewhat preliminary fashion, we first consider the 30-year periods of GCM simulation output for present and future climates under the A2-emissions[10] scenario (a rapid increase in atmospheric carbon dioxide) using the ECHAM4 GCM. This GCM is chosen here out of a range of available models due to initial evaluation (as part of other work) that indicates this model as more credible for the southern Africa domain. As shown in Figure 46 the model simulates present moisture sources and sinks reasonably accurately at a global scale but has positive biases of moisture sinks over southern Africa, tropical Indian Ocean and east of the maritime continent near the dateline. For the future climate, the model suggests increases in moisture convergence over the maritime continent, South Atlantic Convergence Zone and South Indian Convergence Zone. However, in order to place any confidence in these projections of future climate, one would need to determine the source of the errors in the present climate and ensure that the model is not simply exacerbating these errors under conditions of increased levels of carbon dioxide in the atmosphere.

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[9] For example, see the range of results available from the IPCC DDC at http://ipcc-ddc.cru.uea.ac.uk/
[10] See the SRES report from http://sres.ciesin.org/

7.2 Mean circulation changes

Taking a closer view at the synoptic scale mean circulation patterns, and the associated changes predicted by the GCMs, some suggestion of future changes may be obtained. Evaluation of GCM predictions are typically undertaken in terms of time-space averages – implicitly averaging out (some) noise and error in the GCM and considering scales more associated with the skill scale of the model. However, simply averaging seasonal values can obscure important information in relation to the hydrological cycle, and in particular, precipitation events. Consequently, we first examine here, using the historical data of the NCEP reanalysis, the time-mean fields relevant to moisture flux for important precipitation events. Following this the GCM future climate anomaly may be considered in terms of whether these indicate changes that modulate the features identified from the historical data.

To identify time-mean fields related to relevant rainfall events we stratify the data by the spatially extensive heavy rainfall identified in Chapter 4, and select all days related to the key corner nodes of the SOM in Figure 38. For all days on a given node the mean wind field and horizontal moisture flux are derived for the 925hPa, 850hPa, and 700hPa levels. The levels around 850hPa have already been identified in the trajectory analysis as being of particular relevance, and hence this level will be principally focused on.

Figure 34 shows the mean horizontal wind, and Figure 48 the mean horizontal moisture flux as vectors for all four SOM nodes. By plotting the vectors for all four nodes (precipitation modes) onto one map one can readily assess the degree of commonality in the atmospheric circulation for each of the 4 identified precipitation modes of the SOM. From this is can be seen that the in the lower levels (925 and 850hPa) the most notable difference between the different precipitation states identified by the SOM relate to an axis aligned with the classic tropical temperate trough situation – in effect indicating the dependency by some of the precipitation states on such trough events versus other dynamic controls. By contrast, at more elevated levels (700hPa) the major distinction between states lies more in the lower latitudes.

However, considering the moisture flux component (Figure 48), the same conclusions may be made about the lower levels, while at the 700hPa level the differences are small.

Consequently, while the dynamics of the circulation at the 700hPa may be important in enhancing or suppressing precipitation activity, it appears to have a smaller role to play in direct moisture feed to the summer rainfall region.

Considering the above in the light of the very similar mean specific humidity under each characteristic event (figure 49a), this suggests that during the summer months, once the moisture is established over the continent, the variability of the moisture feed is perhaps less important than the circulation dynamics that enhance or suppress convection through subsidence or instability in the atmosphere. If one expresses the moisture state for each node as an anomaly from the mean of all days identified as spatially extensive heavy rainfall (figure 49b), it is more readily apparent that the differences are of the order of only a few percent, reaching in places to ~10%. Of note is the anomaly for node [3,0] centered over the Agulhas gyre and ocean to the south east of the continent, and characterized by days of extensive rainfall over much of the summer rainfall domain. These are the most frequent of the identified events, and relate largely to the occurrence of tropical temperate troughs that are the leading contributor to summer rainfall totals. The positive specific humidity anomaly under such circumstances is, however, associated with flow *away* from the continent, and as discussed earlier raises some question as to the direct contribution of moisture from this region to the overall summer rainfall totals over the continent.

Turning to the projected future climate, as simulated by the ECHAM model, the 850hPa moisture flux anomaly (Figure 50) displays a pattern that has some notable similarities to the mean flux pattern of those days used in the SOM analysis, and represented in Figure 49. The key similarity relates to anomalous southward flux along the east cost margins, along with an anomalous westward flux along the south coast regions. However, by contrast, the ECHAM model also shows an anomalous eastward flux at lower latitudes over the continent. The pattern is conducive to increased precipitation along the east coast, although suggest a drier western half of the subcontinent. Interestingly, the future climate precipitation anomaly from the ECHAM model, while perhaps one of the less reliable variables from a GCM, supports this conclusion. Figure 51 shows the projected precipitation anomaly as a spline surface over the sub-continent (from Hewitson, 2003). This agreement does suggest that the models projection of future climate precipitation change is consistent with the underlying circulation dynamics of the region.

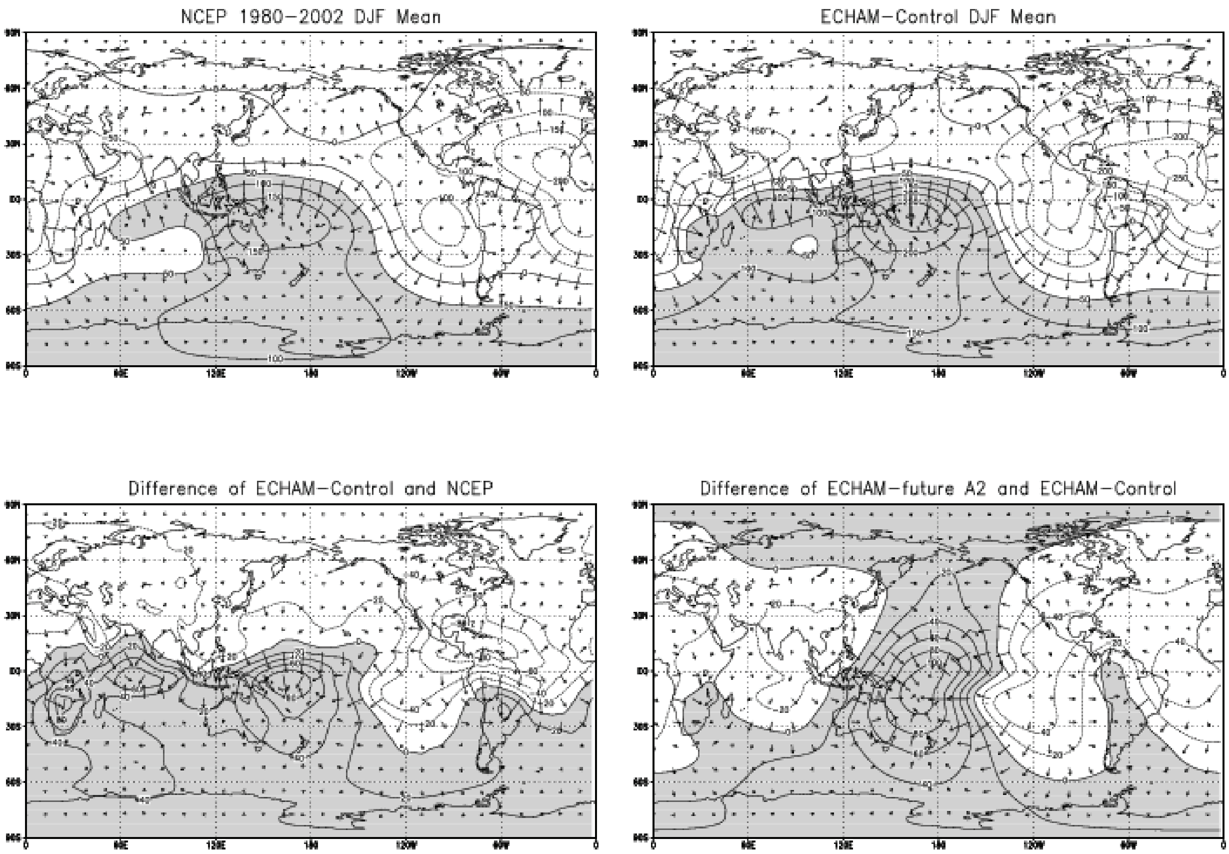
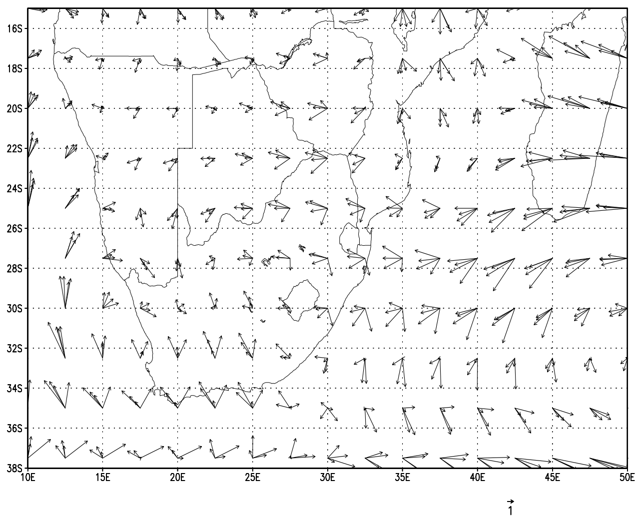
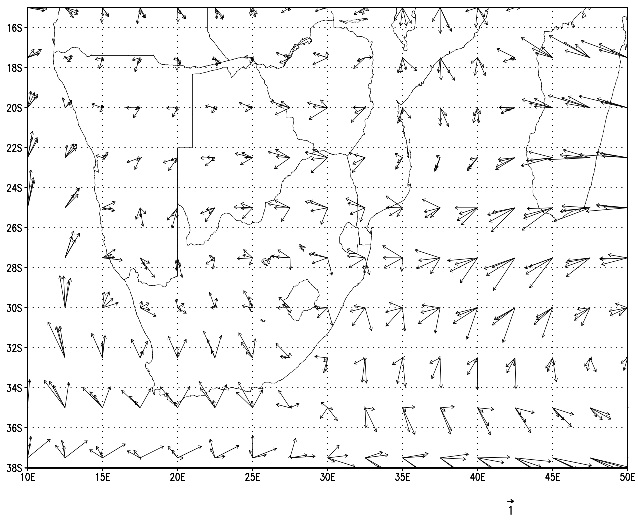


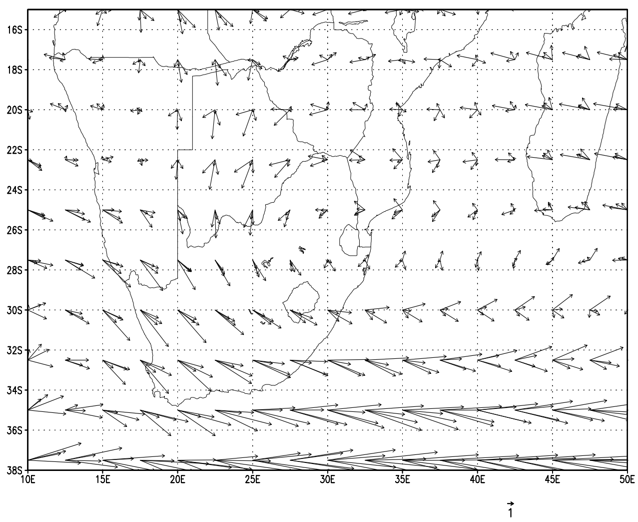
Figure 46: Velocity potential and vectors of divergent moisture flux integrated from 1000 hPa to 700 hPa for NCEP and the ECHAM4 model for current and future climates. Shaded areas indicate convergence of moisture, dashed lines divergence of moisture.



(a)

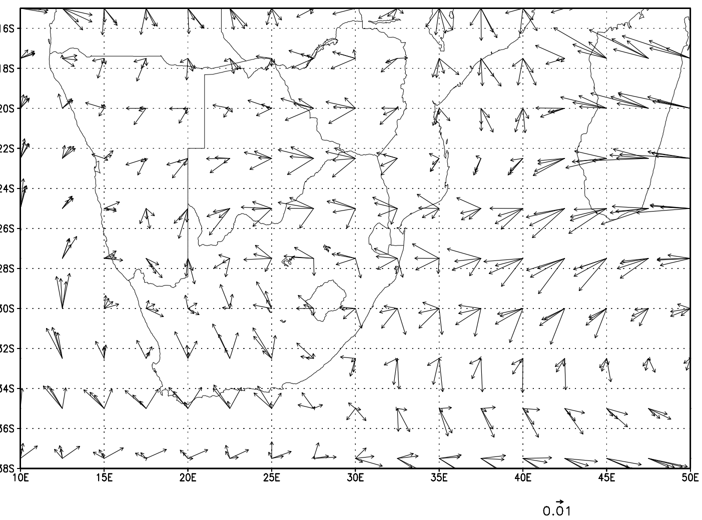


(b)

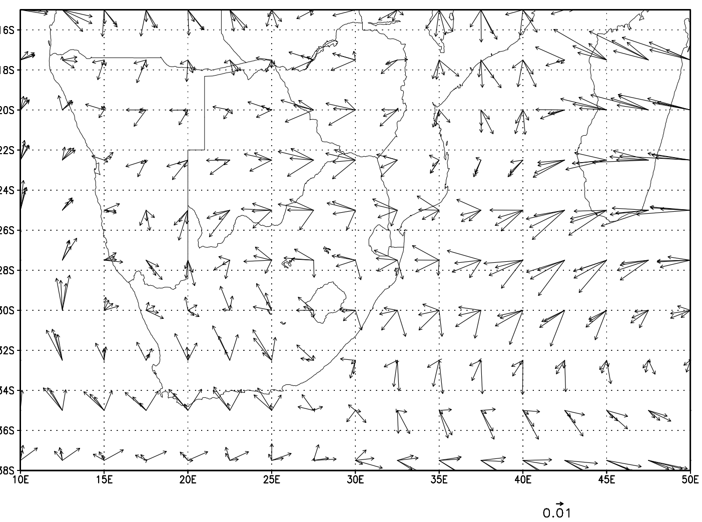


(c)

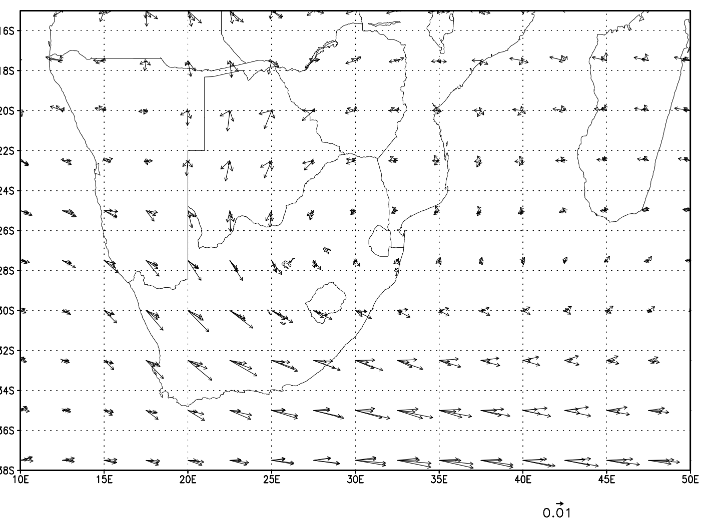
Figure 47: Wind vectors for corner nodes of the SOM in figure 38 for 925hPa (a), 850 hPa (b), and 700hPa (c).



(a)

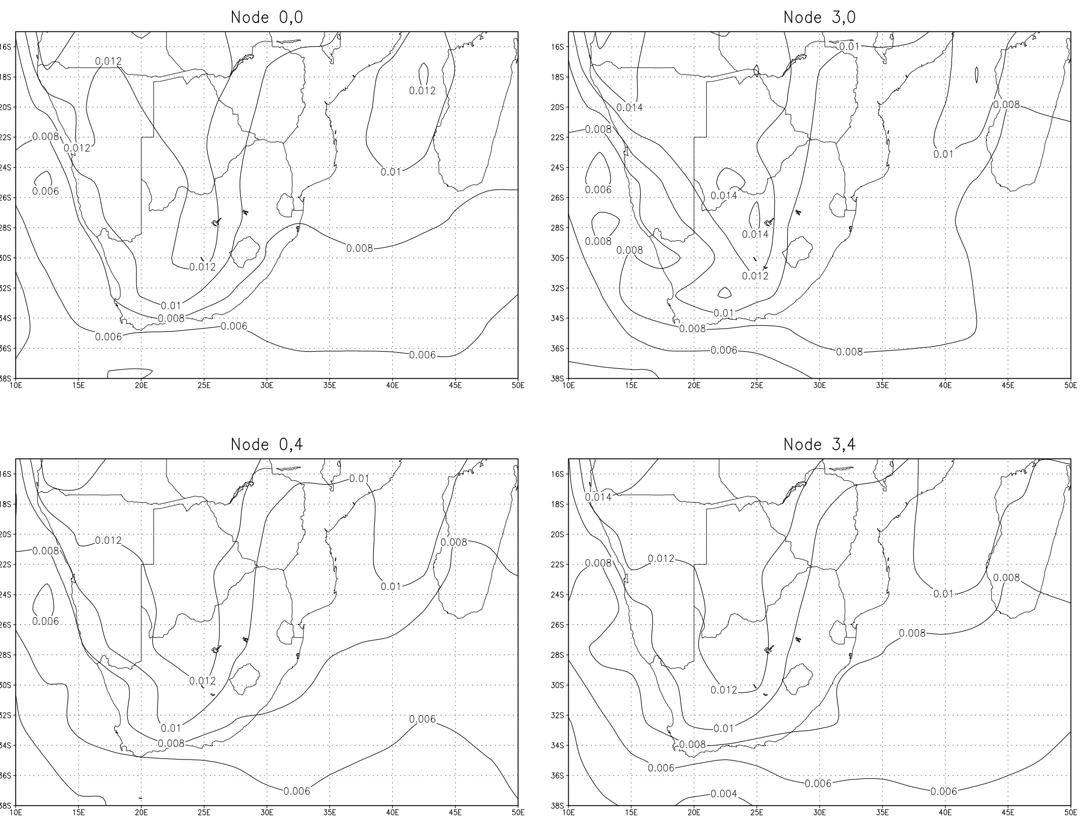


(b)

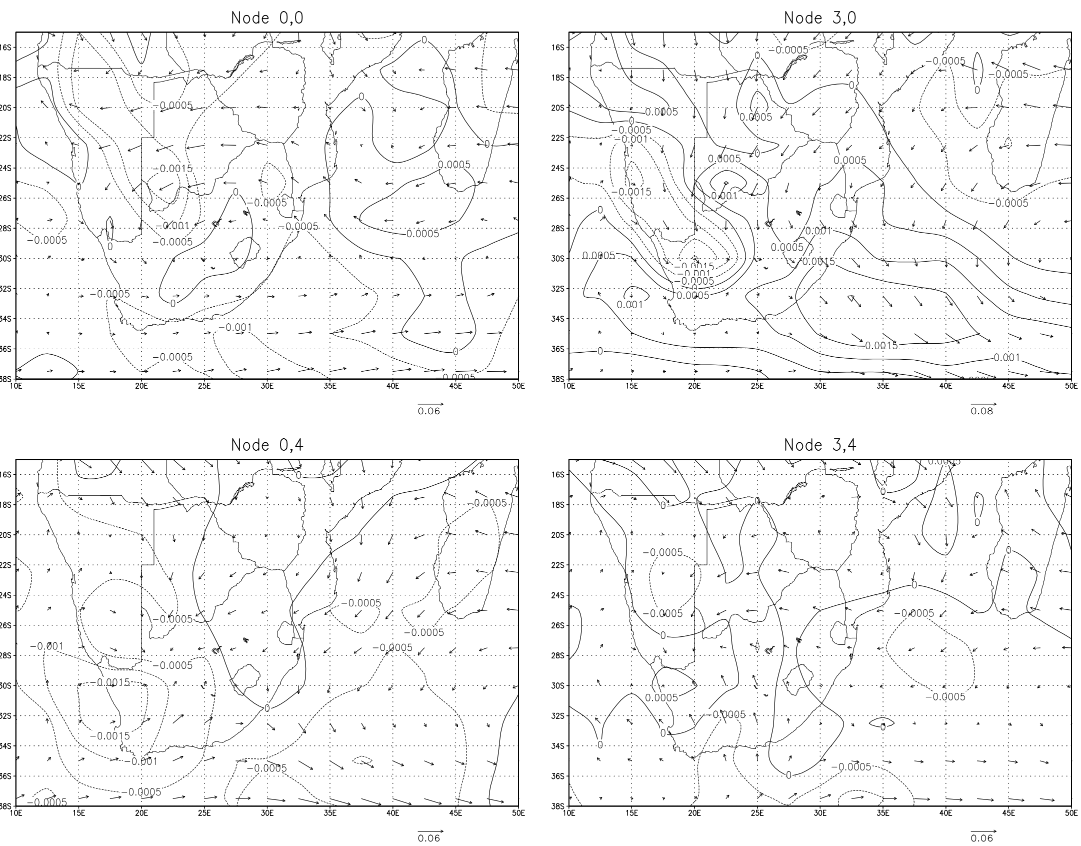


(c)

Figure 48: Horizontal moisture flux for corner nodes of the SOM in figure 38 for 925hPa (a), 850 hPa (b), and 700hPa (c).



(a)



(b)

Figure 49: Mean specific humidity (a) at 850hPa for the four corner nodes of the SOM in Figure 38, and the anomaly from the mean of all days on all SOM nodes (b).

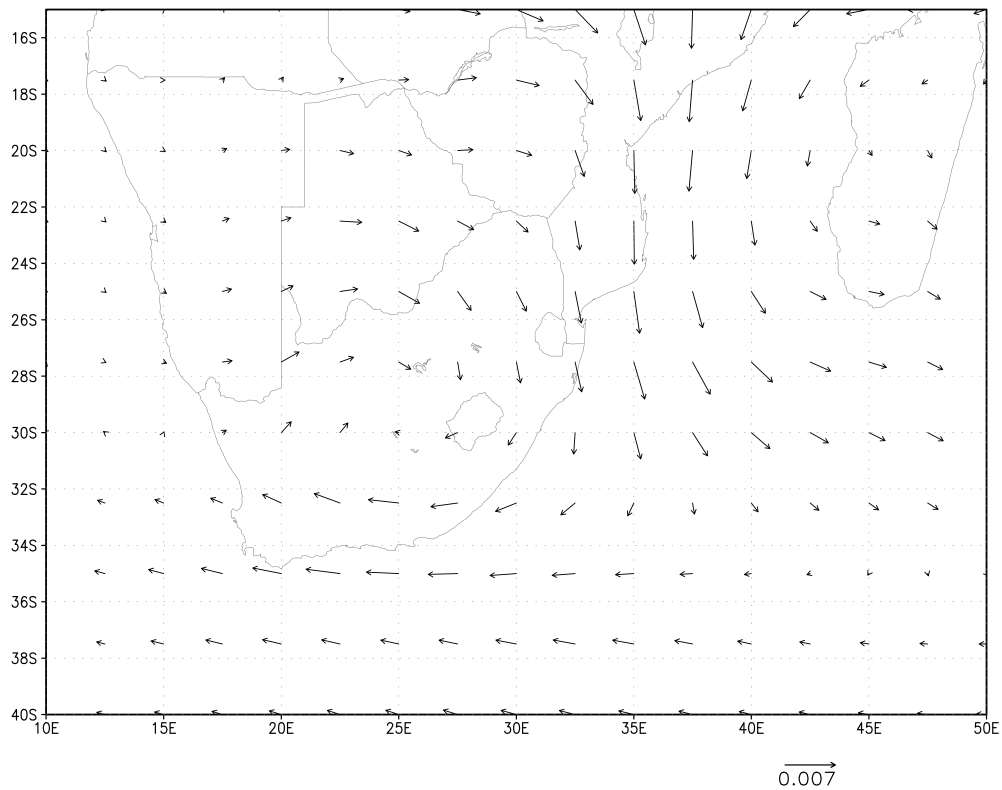


Figure 50: Average 850hPa horizontal moisture flux anomaly for December-January-February as simulated by the ECHAM model. Anomaly derived by differencing the 30-year mean of the simulated future climate from the 30-year mean of the simulated current climate.

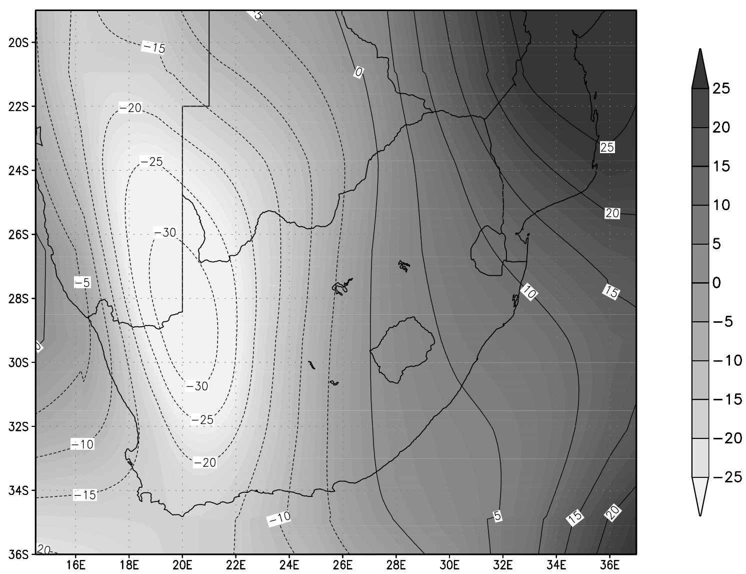


Figure 51: The projected change of DJF precipitation (%) derived from the current and future climate means of the ECHAM4 GCM. Dashed lines are negative.

8. Summary and conclusions

The analysis of moisture transport, sources and sinks, and the relation to southern Africa climate has followed two separate, but complementary avenues. On the one hand, an investigation from an explicitly temporal view through the development of trajectories and examining the transport pathways. On the other hand, an approach examining the large-scale mean state of the atmosphere field provides an inherently (static) spatial view of the processes. Each approach has it's own respective strengths and weaknesses, yet lead to similar results, and in doing so, provides a stronger foundation of evidence for the conclusions drawn.

8.1 Key findings

While the preceding chapters address disparate issues with a variety of methods, a number of coherent conclusions may be drawn:

g) For summer rainfall over the sub-continent, particularly the key economic agricultural region of the South African interior, there is a significant moisture transport pathway from the east, with a notable source of moisture from east of Madagascar. This is in contrast to earlier understanding of the importance of the region to the north of Madagascar.

h) The ocean regions to the southeast of the continent, in particular over the Agulhas region, are a strong source of moisture for the atmosphere. However, there is some question over how much of this moisture makes a direct contribution to continental rainfall, or whether this moisture is circulated around the South Indian High Pressure system to contribute the moisture transport mechanism identified by the trajectory analysis.

i) The preceding point, coupled with the understanding of the time required to traverse the distance from the coast to the central summer rainfall area of South Africa, suggests that local forcing and feedbacks may be of significant importance in modulating intra-seasonal variability.

j) One of the difficulties in moisture analyses is to relate actual moisture transport and regional sources and sinks of moisture, the latter being highly sensitive to the divergent circulation of the GCM. Intra-seasonal atmospheric moisture content over the continent does not show large variability, suggesting the dynamic of circulation processes may have a greater role in modulating rainfall than the moisture transport itself.

k) Spatially extensive heavy rainfall events appear to have moisture transport pathways and mean atmospheric moisture content that is not dissimilar to the seasonal means. This supports the earlier proposition that moisture variability is not itself the primary factor differentiating one precipitation event from another, and that other dynamic processes may be more important.

l) From the trajectory analysis, wet seasons are characterized by greater moisture transport at lower latitudes, with more distal source regions. Following this, it is apparent that a wet season would result in increased soil moisture and continental surface latent heat fluxes. The extent to which this augments a wet seasons rainfall remains unclear, and particular, whether this plays a role in the propensity for spatially extensive heavy rainfall events to occur more frequently in the latter half of summer.

m) Climate change implications for moisture transport are, at this point, still uncertain due to issues of skill in the GCMs and the necessity to evaluate GCMs at the time and space scales of relevant to the research question. However, current consensus is that significant changes are indeed expected, with a tentative inference for wetter conditions on the eastern (coastal?) margins of South Africa, and drier conditions to the west.

6.2 Recommendations, and future directions.

The above work clearly advances our understanding of the moisture-related issues within the coupled climate system of southern Africa. However, the work also raises as many new questions, and highlights a number of distinct research avenues of significance, some of which are being addressed in other work, and some of which are in need of new research initiatives. From this we may suggest a number of key questions in need of further work.

a) There is a clear need to distinguish the relative roles of large scale sources of moisture to the atmosphere (particularly over the Agulhas region) on a seasonal basis, how these may be direct contributors to the moisture content over the continent, whether these have an indirect role in the moisture feed, and how these modulate cumulus convection properties. This work requires additional work using regional climate models to better address the regional scale process controls.

b) Related to this is the question of to what degree the near-coastal ocean surface fluxes have a direct modulation of the continental interior, especially in light of the trajectory analysis indicating the importance of elevated transport over the ocean to the continental interior.

c) A further question of growing importance is that of identifying the role of local land-surface feedbacks and moisture recycling in the intra-seasonal time frame. There are suggestions that these may be of significant importance but it remains unclear whether their role is dominant in modulating individual events, or how these impacts the seasonal mean. Specific within this issue are questions of:
    - How do antecedent land surface conditions affect the timing and onset of seasonal rain?

- To what degree does local feedback enhance or suppress precipitation processes established by the large-scale circulation (for example, tropical temperate troughs)?
- Intimately coupled to the prior two issues is the question of what is the magnitude of local moisture re-circulation over the continental interior?

d) For many sectors (especially hydrology) the key vulnerability to the climate is on short time scales – that of weather events – whereas much of the work in this project focuses on the climatological aspects. Consequently there is an important need to use this work as a starting point to investigating the sensitivity of individual weather events and extremes to the variability and characteristics of the long-range moisture transport. This is also of key importance for understanding the future climate projections and the probable impact on the climate of South Africa.

e) How credible are GCMs in representing the foundational moisture transport processes, and how is skill in these terms determined for GCMs? Following this comes the question of what is acceptable error in a GCM. Methodologically it is simple to derive a climate change projection, yet without quantifying the uncertainty behind this, it becomes relatively valueless.

f) Assuming the GCM skill is assessed as credible, what are the changes in moisture content and circulation dynamics related to precipitation projected for the medium and long-term future. This is a foundational issue if downscaling procedures are to be used for deriving more local scale projections of climate change.

These questions are non-trivial, and require concerted research activities that are complementary, and build over time in a synergistic fashion to address the overall understanding of the complex coupled climate system. We suggest here that this is not possible without adopting a climate modeling approach. This, however, is predicated on appropriate computational resources and a sustainable skill base of researchers working in a collaborative approach. At present, research within South Africa is somewhat fragmented in it's approach to addressing these large questions of importance to understanding the foundational principles of the climate system, and the consequent impact on society. There exists then a need for "big-science", an investment in team research to undertake these tasks.

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Appendix 1: Sample configuration file for the trajectory model.

```
# Trajectory config file
# directory to use for temporary files
TDIR /tmp
# directory for results
RDIR /big/traj/res80
# atmospheric forcing data file details
DATAFILE /big/traj/data/80.dat
# start date of data as yyyymmddhh
STARTDATE  1980010100
# topography details
TOPOFILE /big/traj/topo/smtopo.dat
TOPO_NLON       1261
TOPO_NLAT       901
TOPO_LON_START  -30.0
TOPO_LON_INC    0.0833333333333333333333333333
TOPO_LAT_START  -65.0
TOPO_LAT_INC    0.0833333333333333333333333333
# data dimensions
# number of height levels = geopotential height levels + 1 for sfc
NLEV      12
NLON      43
NLAT      31
# pressure values for levels -- NLEV-1 numbers, ordered from bottom to top
PRESS_LEV 1000 925 850 700 600 500 400 300 200 150 100
# data grid details
LON_START  -30.0
LON_INC    2.5
LAT_START  -65.0
LAT_INC    2.5
# Number of time obs to use for forward and backward trajectory, beyond the starting time slice.
# eg: a 24 hour trajectory on 6 hourly data will be 3.  0Z is the start slice, plus need 6Z,
# 12Z, 18Z, 24Z.  Calculate from : (hours into future / obs interval)
NTFWD        21
NTBWD        21
# time increment of input data observations in seconds
OBS_TINC  21600
# time interval at which to save trajectories in seconds -- must be >= 3600
SAVE_TINC  14400
# trajectory parcel details
# longitude of westernmost pp starting point
PLON_START  15
# longitude increment of pp's
PLON_INC    1.0
# number of pp starting points eastward
NPP_LON     20
# latitude of southernmost pp starting point
PLAT_START  -35
# latitude increment of pp's
PLAT_INC    1.0
# number of pp's starting points northward
NPP_LAT     15
# top-most pressure level for pp
PZ_TOP      100
# number of pp's vertically and on which SIGMA levels
NPP_Z       12
PSIGMA 0.995 0.93 0.89 0.84 0.78 0.7 0.6 0.5 0.4 0.3 0.2 0.1
# model time step in seconds for pp position calculations
# *** Must be an integer divisor of SAVE_TINC
PP_TINC    3600
```

Appendix 2: Summary of technology transfer and capacity building

Technology transfer:

This work has had direct contributions into two other multi-institutional projects. The first is WRC funded and focuses on continued modeling work on understanding the climate system dynamics through the application of climate models. This project is collaborative with the University of Pretoria and the South African Weather Service. The second is funded by the Dept. Arts, Culture, Science and Technology, and focuses on seasonal forecasting. This latter project involves researchers at 5 institutions around South Africa and two institutions overseas, and has directly benefited from the capacity developed in this project.

Physical Capacity:

The infrastructure developed through this project has been co-funded with other projects funded by the NRF, other WRC projects, and the DACST Innovation Fund project on seasonal forecasting, together sustaining a computational infrastructure capable of handling the research tasks, and also supporting other climate related research. At present the infrastructure consists of (collectively from all funding sources):

- 16 CPU PC computer cluster
- 6 CPU PC cluster
- 8 CPU Alpha ES40 computational server
- Data storage to 9 TerraBytes

In addition are tape storage services and older computer systems no longer meeting the computational demands.

Human capacity (participants/contributors to project):

Name	*Institution*	*Gender*
Chris Jack	UCT	Male
Ruwani Walawege	UCT	Female
Jeremy Main	UCT	Male
Celia Cook	UCT	Female
Lawrence Ngorora	UCT	Male
Chris Reason	UCT	Male
Bruce Hewitson	UCT	Male
Warren Tennant	SA Weather Service	Male

Publications drawing on this project (already submitted, in press, or published)

Hewitson, B.C., and Crane, R.G., (2003): Global climate change: Questions of downscaled climate scenarios for impact assessment, submitted to *Bulletin of the American Meteorological Society.*

Hewitson, B.C., and Crane, R.G., (2003): Gridded area average precipitation via conditional interpolation, in revision for *Journal of Climate.*

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Appendix 3: Data archiving and access.

All data sets used and generated in this work are archived on the CSAG computer system at UCT. The data sets are in binary format and require appropriate software (free) for visualization. Further, the data sets are large, in some cases in excess of 2 Gbytes per file, and are thus only accessible through a logon on the CSAG system, or distributed on DVD discs.

Other related WRC reports available:

The South African fog water collection project

J Olivier and J van Heerden

The objective of this project was to assess the amount and quality of fog water available in relation to needs of rural communities in various parts of South Africa. Spatial and temporal characteristics of fog occurrence were deduced from measurements made along the West Coast and in the mountainous and escarpment regions of the Northern Province and Mpumalanga. Pilot fog collectors in the form of either 1 m^2 or 3.6 m^2 screens were installed and tested at several sites in each of these areas. Both area characteristics and site characteristics conducive to high fog-water yields were identified. At the better escarpment sites with altitudes well in excess of 1 000 m, average daily water yield over all seasons was between 10 and 20 ℓ/m^2 of collector surface, with even the dry winter months having average daily yields of approximately 2.5 ℓ/m^2. Yields along the West Coast were considerably lower but nevertheless comparable to those obtained in a successful fog-water supply project in Chile. Water-poor communities in the Northern Province who might be potential beneficiaries of fog-water collection schemes were identified and a fog-water collection unit for potential large-scale implementation was provisionally designed.

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