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Project Leader

Dugdale, G

Organisation

Department of Meteorology
University of Reading
2 Earley Gate
Whiteknights
Reading
RG6 2AU

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DFID Natural Resources Systems Programme

NRSP, HTSPE, Thamesfield House
Boundary Way, Hemel Hempstead, HP2 7SR
United Kingdom

t: +44 (0) 1442 202447
f: +44 (0) 1442 219886
e: nrsp@htspe.com
w: www.nrsp.org.uk

IDENTIFICATION AND MONITORING OF AFRICAN WEATHER REGIMES

G Dugdale

NRI Extra Mural Contract X0256
Phase II
November 1994 to March 1995

This report, written by G. Dugdale, contains the results of data extractions, analysis and research by C P Browne, S Holmes, V D McDougall, M Saunby, C Thorncroft & V A Thorne and the author. We are indebted to The European Centre for Medium-range Weather Forecasting for the use of their facilities and data and wish to acknowledge the invaluable annotated bibliography of literature prepared for the project by M R Tucker of the Natural Resources Institute

Author's note: The hurried reader should refer to section 6, the more interested to sections 1, 2, 5 and 6. For full details include 3 and 4

Reading, 31st May 1995
(revision 1)

TITLE

IDENTIFICATION AND MONITORING OF AFRICAN WEATHER REGIMES

(Weather typing for Africa) NRI Extra Mural Contract XO 256

1. Background

The value of meteorological information for development in Africa is well recognised. However, sparse observational networks and a poor understanding of many facets of the tropical weather have limited our ability to describe the climate or current weather and to predict coming weather for more than a day or so ahead.

The advent of meteorological satellites has improved our real-time monitoring of the weather and meteorological information derived from satellite data is contributing to aspects of agro-meteorology and hydrology. Also satellite data is used to identify storm systems and to predict their movement and development over periods of a few hours.

The enhancement of the global numerical prediction models over the last twenty years have resulted in significant improvements in the short and medium range forecasting skills in mid-latitudes. This is not reflected in the tropics where it appears that the models' representation of sub grid scale processes and of physical energy exchanges at the surface and in the atmosphere is inadequate. Some progress has been made in the seasonal sub-continental forecasts over Africa using statistical and modelling techniques to relate the coming season to sea surface temperature anomalies. However, the skill shown by these techniques is not high enough to justify their incorporation in national planning activities.

Traditional forecasting techniques over northern tropical Africa are based on associating the weather with the location relative to the position of the inter-tropical convergence zone (ITCZ). This, generally east-west, zone of high temperatures and reduced surface pressure includes the confluence of the moist south westerly air mass with the dry warmer north easterly air mass. The surface position of the ITCZ is a few degrees north of the zone of maximum convergence and storm activity. Further south one may find convection suppressed by the influence of the southern hemisphere high pressure region. Forecasting is therefore concerned with the movements of the ITCZ and the activity within it. Within the convergence zone the storm activity is modulated, on time scales of up to a few days, by orographic, diurnal and synoptic influences.

While periods of enhanced or suppressed convection lasting five to fifteen days are not an unusual feature of the weather in this region there is little skill in forecasting them. It is probable that these changes are related to persistent fluctuations in the extra-tropical circulation which may be predictable by the numerical weather prediction (NWP) models.

It is the objective of this study to associate these medium term changes in weather patterns to the sub-tropical circulation patterns.

The first phase of the project took place from December 1993 to March 1994. This was limited to a study of a three month period centred on August 1991. It was shown that there was some correspondence between rainfall as inferred from satellite studies of storm clouds and the numerical analyses of the region made by The European Centre for Medium-range Weather Forecasting (ECMWF). (See report of J R Milford dated May 1994).

This second phase of the project was designed to extend the 1991 data to cover the season from May to October and to add a second year. The year chosen was 1992. This offered several advantages. It was within a period during which no major changes had been made in the ECMWF model; it contrasted in several ways to 1991 and, being the year of the Hapex-Sahel experiment some additional data was available. The use of the Hapex-Sahel year has the further advantage that the findings of this study are more likely to be used as the basis for further research than would otherwise be the case.

This report is structured so that the methodology and the rationale behind it are discussed next; followed by a description of the data sources and the preliminary data processing. Section four describes the various analyses which were made of the data and the findings specific to each study.

Section 5 reviews the results of the individual studies and interrelates them. The final section discusses the implications of the findings for forecasting in West Africa and suggests where further effort should be made to confirm and extend the results.

Because of the lack of rainfall data and the expected poor correlation between cold clouds and rainfall over the Guinea (Conakry) region and over the southern Cameroon mountains, these areas are excluded from the discussions.

References to the scientific literature have been avoided in this report as many of the readers may not have easy access to them. Instead the report is intended to be self contained. However, it does rely heavily on the literature survey made by Dr M Tucker.

2. Methodology

2.1 *General*

The overall objective of this study is to identify means of improving weather forecasting over tropical West Africa on time scales of five days or more. Within this region weather forecasting is essentially rainfall forecasting and this in turn is, except for a few locations at specific seasons, the forecasting of thunderstorms. Accepting that current NWP models have little skill in rainfall prediction at the scales of interest in this region, our task is to identify any aspects of the rainfall patterns which are associated with predictable features of the large scale flow.

In the 1993/94 first phase of this study we tried to identify anomalies of the rainfall and flow patterns in the summer of 1991 from a five year mean. As we only had detailed data for three months of one season this was the preferred form of analysis. However, the use of differences from mean patterns does present some problems particularly when studying intense features of limited latitudinal or longitudinal extent such as jet streams or narrow zonal rainfall belts. This arises because the inter-annual changes in the position of the feature produce a mean pattern extended latitudinally but of lower amplitude and does not represent the actual characteristic of the feature. For this reason attention has been focused on the intra-seasonal and inter-seasonal changes using both dekadal and monthly mean patterns. In each case what will be identified is not the fine detail of the feature but those aspects which are persistent over the averaging period. The chosen periods are consistent with the time scales over which we hope to improve forecasting.

Three time/space scales of prediction are sought. The larger scale refers to such features as the timing of the onset and cessation of the wet season over most of the region and to long term displacements of the ITCZ within the season. The medium scale refers to in-season relatively wet or dry periods of the order of a dekad and on space scales which may not influence the whole region. The third, smallest scale, refers to the forecasting of the arrival of synoptic scale events up to five days ahead. Somewhat different approaches are used to try to identify the causal relationships in each case. Also brief extra studies are made of the synoptic scale features of West African weather and the changes in storm characteristics associated with wet or dry periods.

The mapped raingauge data gives an inadequate description of the rainfall and its variability on the required time and space scales. The CCD data is used to monitor storm activity. A preliminary study of the CCD/raingauge maps was made to determine the validity and shortcomings of the surrogate.

The plotted data for this study totalled some 500 maps. The problems of assimilating this amount of data are considerable. Extensive use of Hoffmuller type diagrams was made to follow the seasonal trend of those features which were expected to be relevant i.e.

1000mb	Sahelian position of $v = 0$
850mb	axis of maximum θe
700mb	position of African E. Jet
700mb	strength of African E. Jet
200mb	position of Tropical E. Jet
200mb	strength of Tropical E. Jet
CCD	N.position of dekadal 15 hour duration isohyet
CCD	S.position of dekadal 15 hour duration isohyet
CCD	Duration 6 to 10°N.
CCD	Duration 10 to 18°N.
CCD	Duration 6 to 18°N.

In each case the isopleths are drawn against longitude/time axes with the values smoothed over 5^0 of longitude. It is mainly these diagrams which will be used to illustrate the discussion in later sections.

2.2 *Large scale fluctuations*

The monthly mean analyses have been the main tools used to identify significant long term differences between the two years. Direct comparison of each of the model outputs and of the CCD imagery was made with a view to associating the changes in the weather and the tropical flow and changes in sub-tropical and tropical flow. These studies were complemented by more detailed comparisons of the more important differences.

2.3 *Medium term fluctuations (5 - 15 day)*

The approach used here was to make a detailed study of the 1992 dekadal fields. First the development of the season in each field was monitored and deviations from a smooth transition noted. Then a composite view of the development and deviations was developed. From these associations were made between the model fields and the satellite observed enhanced and suppressed storm activity and movements of the ITCZ. The 1991 data was used to test these findings.

2.4 *Short term fluctuations*

It has been recognised for several years that the ECMWF model does produce and propagate waves on the lower tropospheric easterly flow which develops over sub-Sahelian Africa during the wet season. The area of generation of these waves and their speed implies that it may be possible to predict their arrival over the western parts of the region several days ahead. Analyses of ECMWF six-hourly 850mb data were used to track the model waves in 1991, and radio-sonde data from one site was used to try to confirm their passage through Bamako. CCD data was used to try to see the storm response to wave passage.

3. Data and initial data processing

This study covers the periods May to October 1991 and May to October 1992. Four types of data have been used in the analyses:

- Selected fields from the analyses of a NWP model
- Raingauge data
- Satellite thermal infra-red data
- Limited radio-sonde data

The area covered varies with the data type. The satellite and raingauge data is generally limited to tropical Africa north of the equator, while the model data extends to mid-latitudes to permit association of tropical weather systems with mid-latitude forcing.

3.1 *Numerical model data*

The ECMWF allowed access to their archives and the use of their computing facilities to extract pertinent fields.

Based on the findings of the 1993/94 analyses of West African weather regimes and on the literature search the following fields have been printed for the 1991 and 1992 seasons:

1000mb wind vectors and meridional wind
850mb wind vectors and theta-e
700mb wind vectors and isotachs
400mb wind vectors and omega
200mb wind vectors and isotachs.

Both dekadal and monthly averages were extracted from 6 hourly model fields. The averages were on a spatial resolution of approximately 150km and covered the region 50°N to 40°S, 30°W to 50°E. The forecast fields for 24 hours ahead of the analysis time were used. This is done to allow the cloud and convection schemes to become operative. This, it is believed, gives a better representation of the atmosphere than the real-time analysis. It should be noted that the analysis itself is a composite of the forecast state of the atmosphere from six hours previously and of the current observations. The weighting given to each component depends on the density of the observations. Hence, the so-called analysis in data-sparse West Africa contains a large element of the model's characteristics. It is therefore important that no major changes in the model should be made during a period under study. This was the case.

Examples of each of the ECMWF dekadal fields are shown in figures 1(a) to 1(e) at the end of section 3.

An additional ECMWF data set was the 850mb meridional wind field on a daily basis for 1991. This was used to test the ability of the model to develop and track easterly waves.

3.2 *Raingauge data*

Some 800 Raingauges sited in Africa between 5°N to 20°N contributed to these analyses. The sources of the data are the FAO data sets, the Centre Agrhymet and the personal contacts through national meteorological services. Despite the efforts made, the coverage is sparse and sporadic. Within each season and between seasons the coverage is variable. Figures 2.a, b & c show the positions of all stations that were used, of those which contributed to a dekad with usually good coverage and of those which were common throughout the 1991 and 1992 seasons. The erratic nature of this data makes consistent analysis difficult. In general, the longer the period the less data is available and if only the common data is used the coverage becomes inadequate for meaningful analysis. Because of this all available data was used in each of the analyses made. However, this does cast doubt on the validity of comparisons between rainfall maps, particularly between individual dekads and months and the long term means. The implications of the limitations of the raingauge data are discussed in section 4.1..

The Golden Software package "Surfer" was used to produce the rainfall maps by a Kriging technique operating on the ten sites closest to each grid point.

The maps have to be interpreted with caution, especially in data-sparse areas and round the periphery of the maps where extrapolations and interpolation can produce unrealistic isohyets. Figures 3.a to c show typical dekadal, monthly, five year dekadal mean maps.

3.3 *Satellite data*

The satellite observations are all derived from the thermal infra-red (TIR) channel (10.5 - 12.5μm) of the European geostationary satellite Meteosat which is sited over 0°N, 0°E, and gives an excellent view of tropical Africa. Observations are made each 30 minutes with a spatial resolution of about 5km at the satellite sub-point.

Two products based on the TIR data have been used; the derived duration of storm clouds and a movie loop of the storms crossing the centre of the region of interest over a three month period in 1992.

A temperature threshold of -40^{0}C has been chosen to define storm clouds. This choice and the representation of rainfall by cold cloud duration (CCD) is discussed in section 4.1.. The duration of storm clouds or CCD imagery is produced by processing hourly TIR imagery. Each pixel with a radiometric count which indicates that it is colder than the threshold scores one, and all other pixels score zero. At the end of each day the sum of the twenty-four hourly binary images gives the daily CCD. These are then accumulated into the ten day or monthly CCDs. Missing lines in the satellite data are filled by the value of the pixels on adjacent lines. If more than ten lines are missing the image is considered invalid. A single missing image is accounted for by attributing the value of the preceding image. If more than one image is missing then the gap is infilled by both preceding and subsequent images. In addition to the dekadal and monthly images for the two years, five year average (1990- 1994) dekadal and monthly images were produced together with the anomaly images for each month. Examples of the range of CCD imagery are given in figure 4.a to 4.f.

Satellite imagery was also processed to give a movie-loop of the hourly thermal infrared imagery for the period August to October 1992 and of the five day running mean CCD for the same period. The area covered was approximately 6 to 23°N, 8°W to 23°E, with high resolution concentrated over around 13°N, 20°E. The screen displays of the two types of imagery are shown in figures 5.a & b.

3.4 *Radio-sonde data*

To confirm the results of the ECMWF analysis of easterly waves a daily series of radio-sonde data from Bamako for the 1991 season was acquired. Generally the quality appears adequate but some days were missing and occasional ascents appeared dubious.

3.5 *Data synthesis*

In total there are over 350 model and CCD fields. In order to highlight the most important features extensive use has been made of Hoffmuller (HM) diagrams in which isopleths of the selected feature are drawn as a function of time and either latitude or longitude. In this report the axes used are dekads within each season and the longitude with the value of the feature smoothed over 5° of longitude. The features analysed in this way are

Average CCD 10 to 18°N 1991,1992
Average CCD 6 to 10°N 1991, 1992
Average CCD 6 to 18°N 1991, 1992
Northern position of 15 hour CCD isopleth 1991, 1992
Southern position of 15 hour CCD 1991, 1992
Northern position of V=0 at 1000mb 1991, 1992
Latitude of 700mb jet 1991, 1992
Speed of 700mb jet 1991, 1992
Latitude of 200mb jet 1991, 1992
Speed of 200mb jet 1991, 1992

a) 1000mb wind and v component

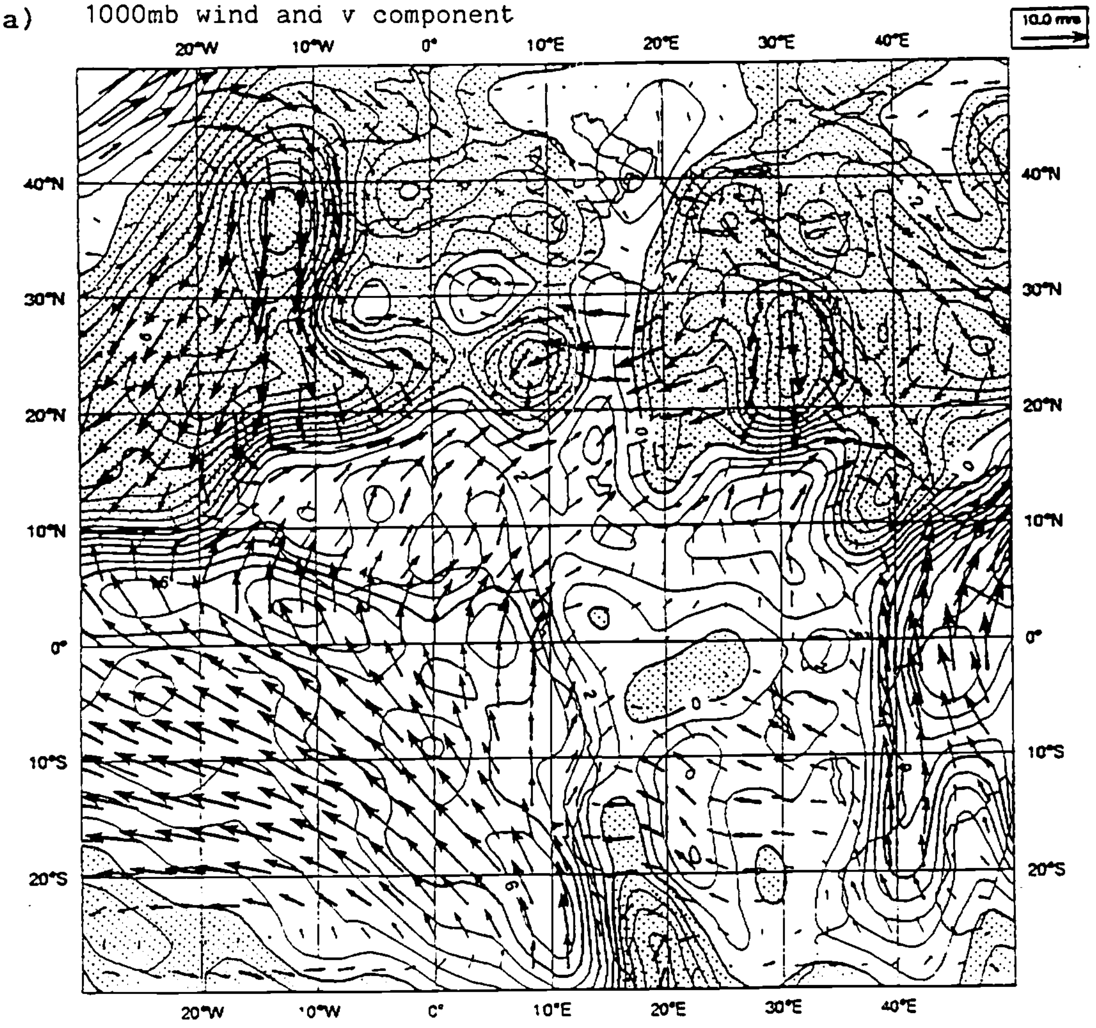
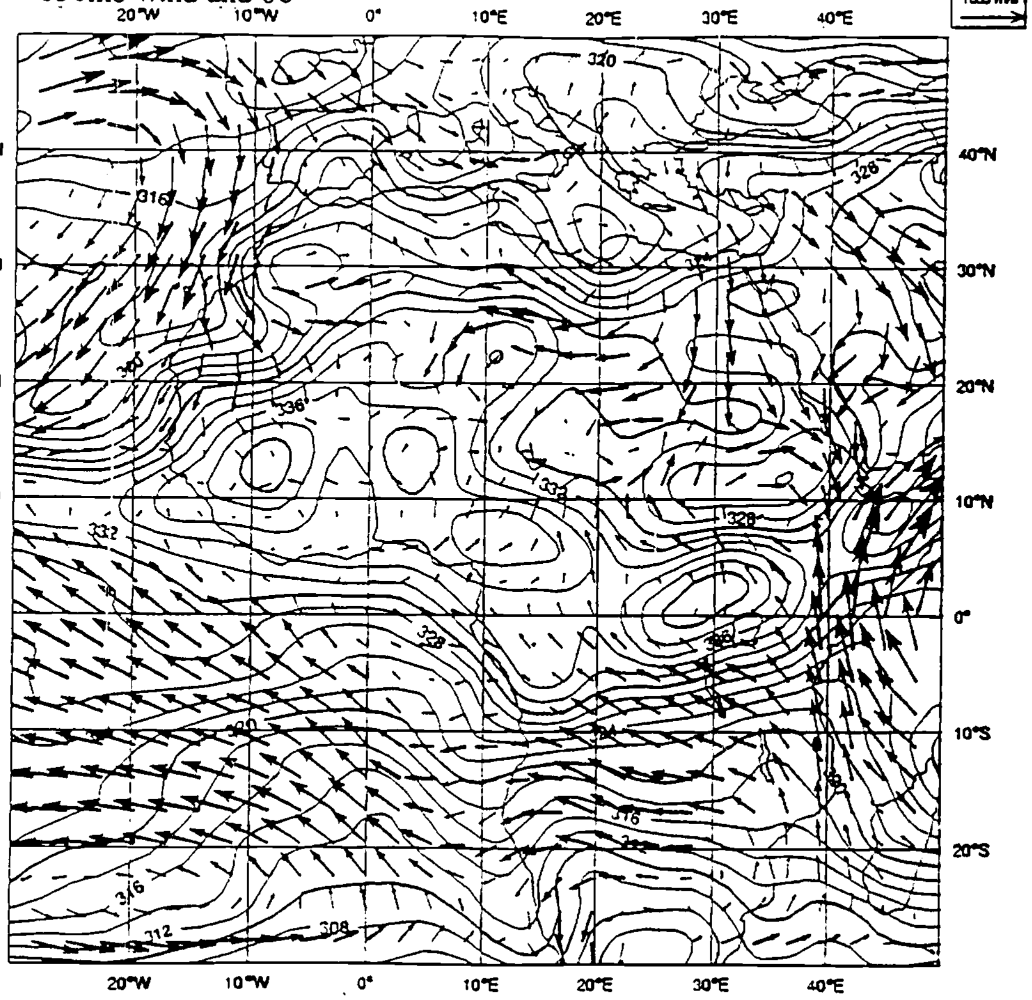


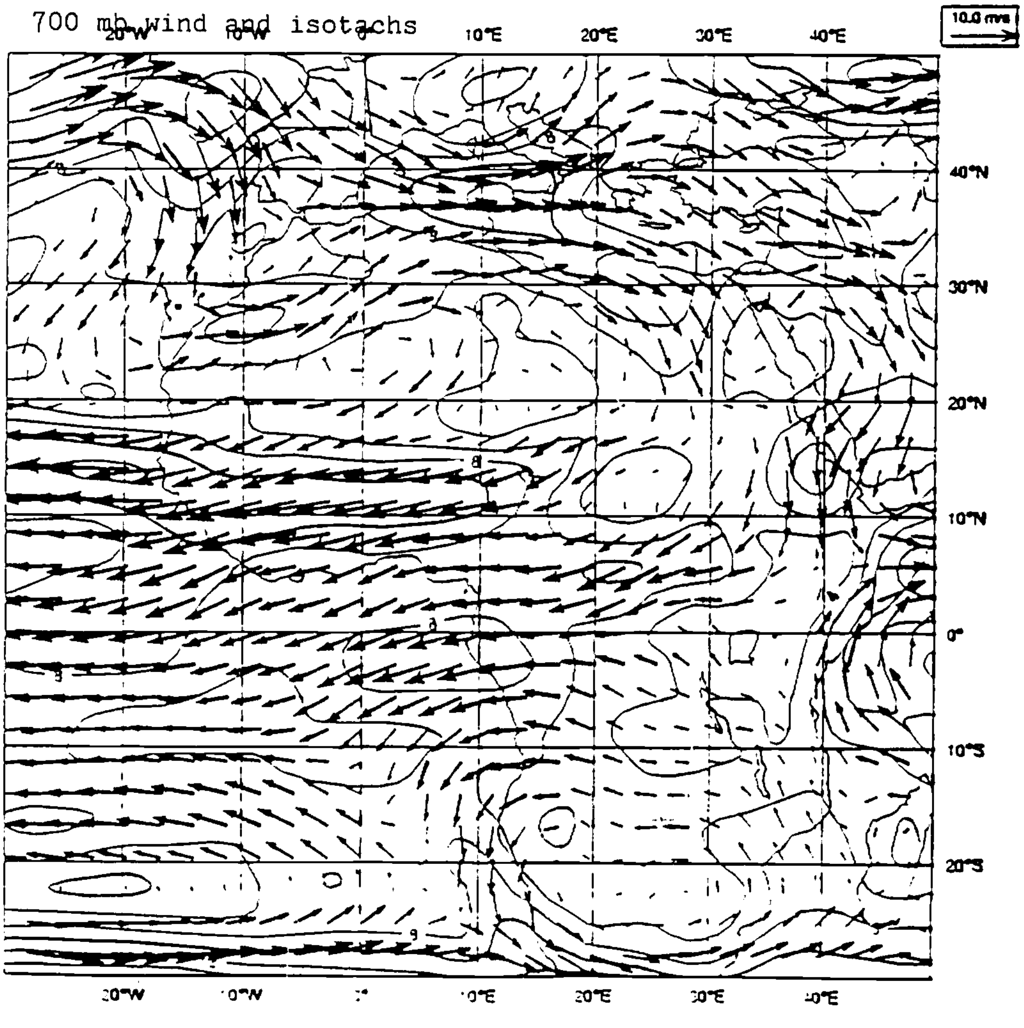
Figure 1: Examples of ECMWF fields

a) July 1-10, 1992, 1000mb, wind vectors and meridional wind component (v)
b) July 1-10, 1992, 850mb, wind vectors and theta-e
c) July 1-10, 1992, 700mb, wind vectors and isotachs
d) July 1-10, 1992, 400mb, wind vectors and vertical motion (omega)
e) July 1-10, 1992, 200mb, wind vectors and isotachs.

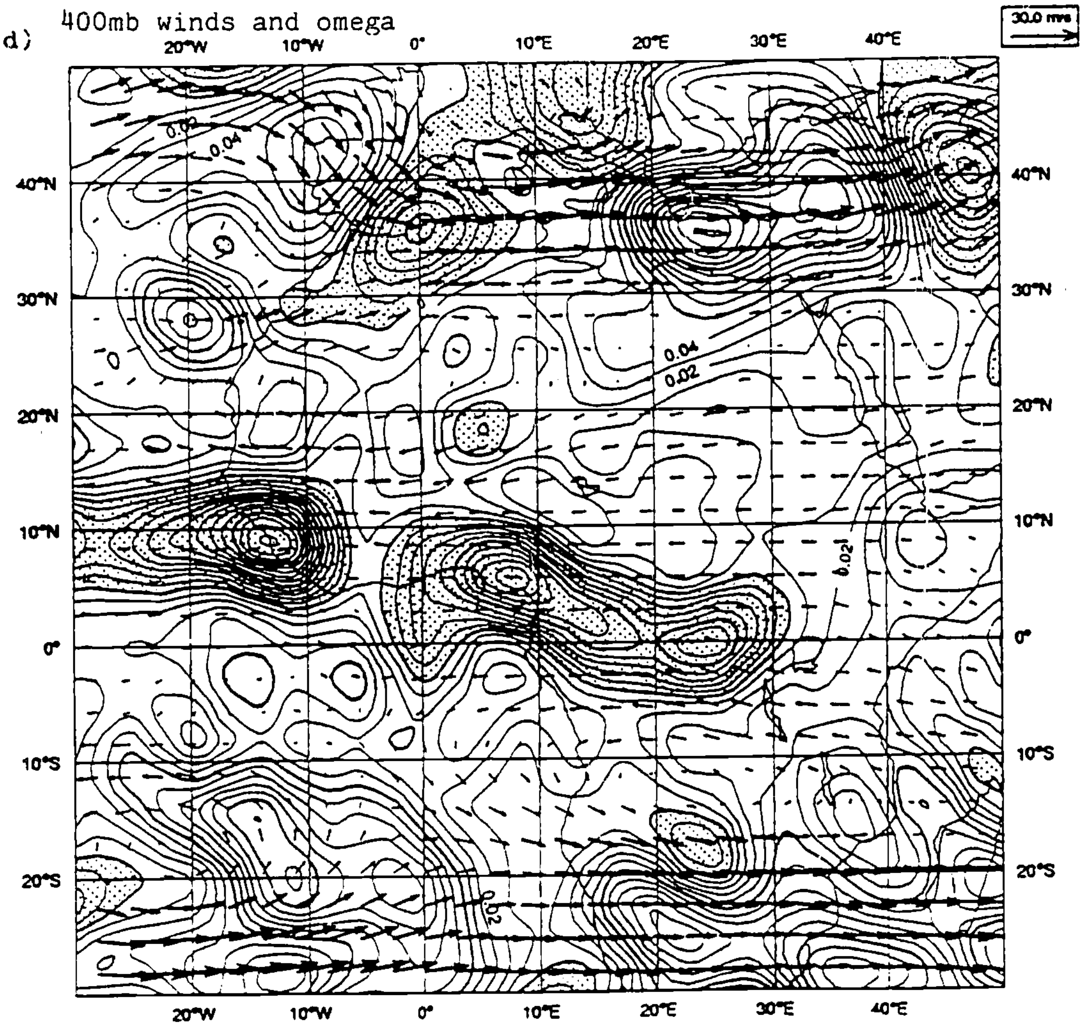
b) 850mb wind and θe



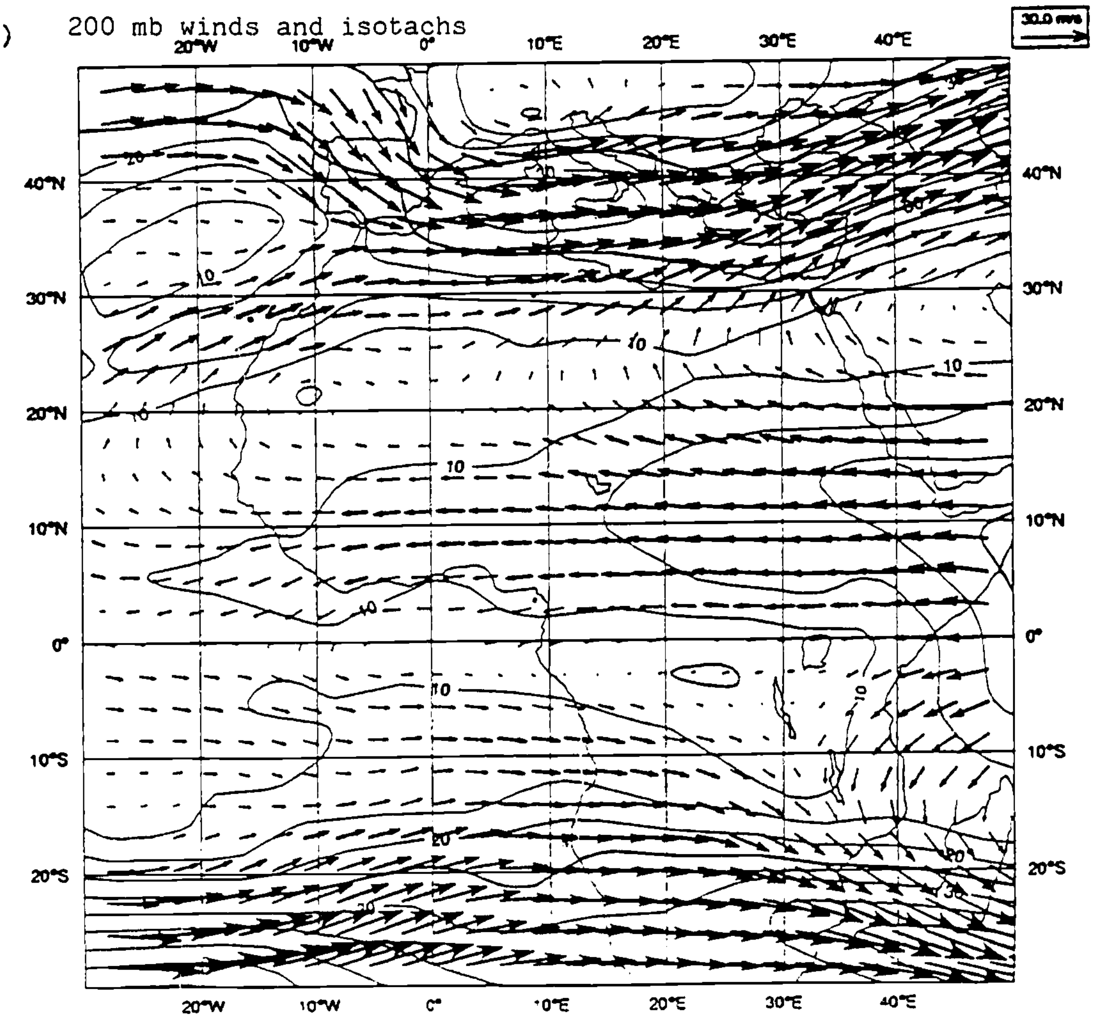
c) 700 mb wind and isotachs



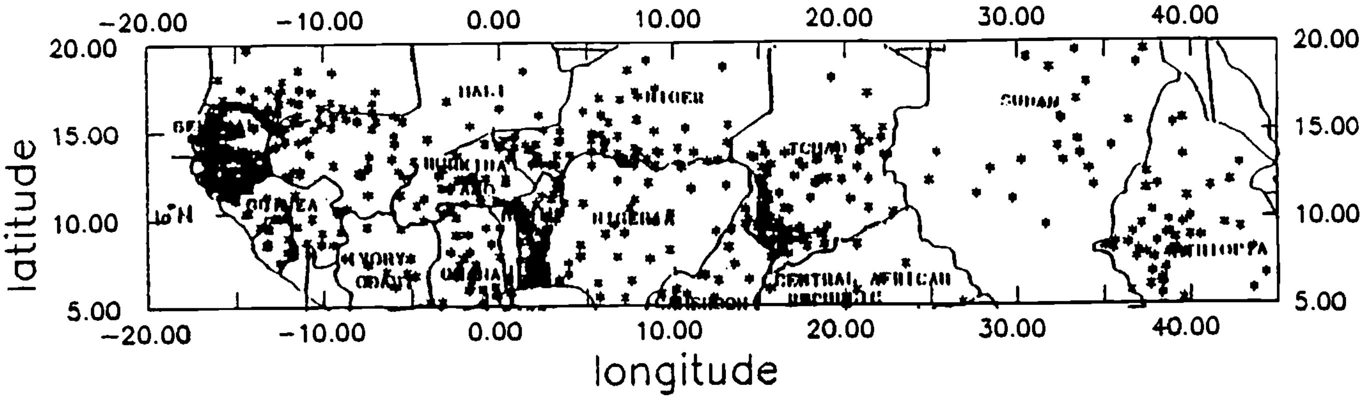
d) 400mb winds and omega



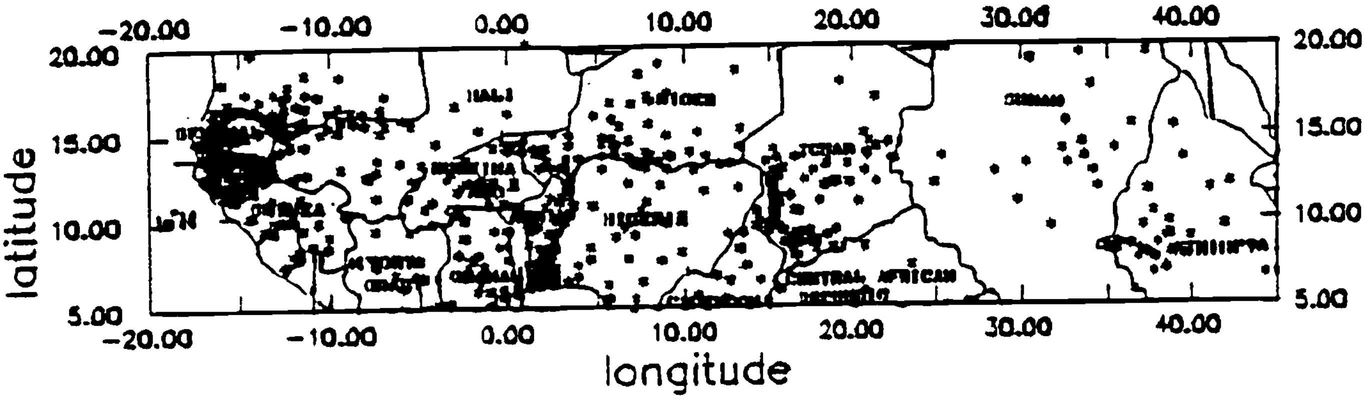
e) 200 mb winds and isotachs



All gauge stations 1991 & 1992 - 809



b) Gauge stations used July2 1991 - 700



c) Gauges available all dekads 1991 & 1992 - 169

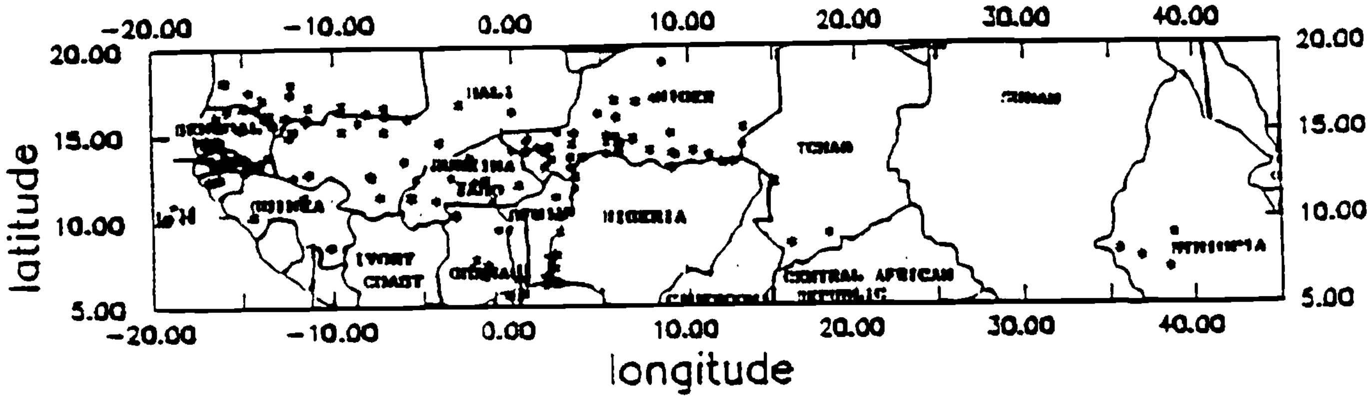
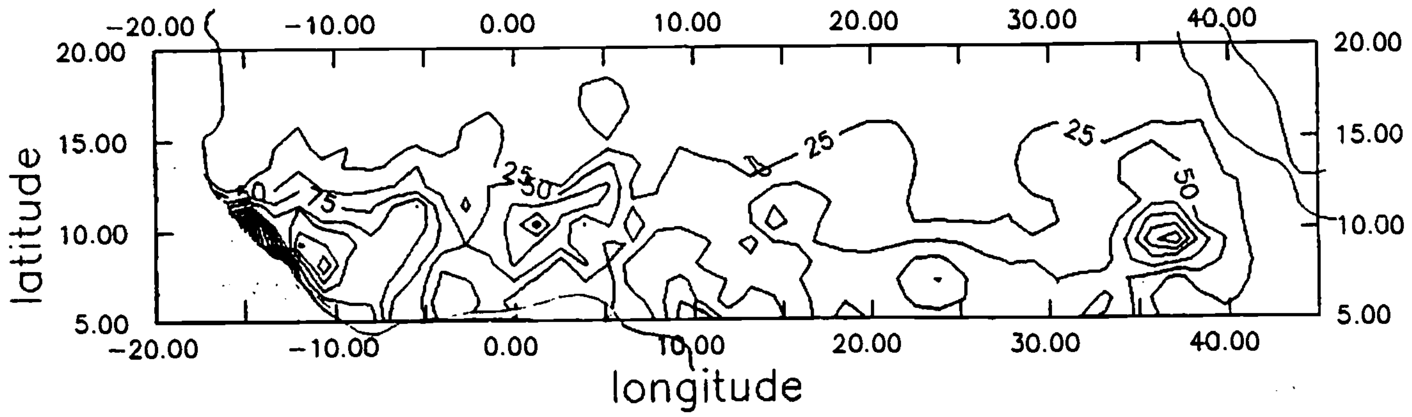
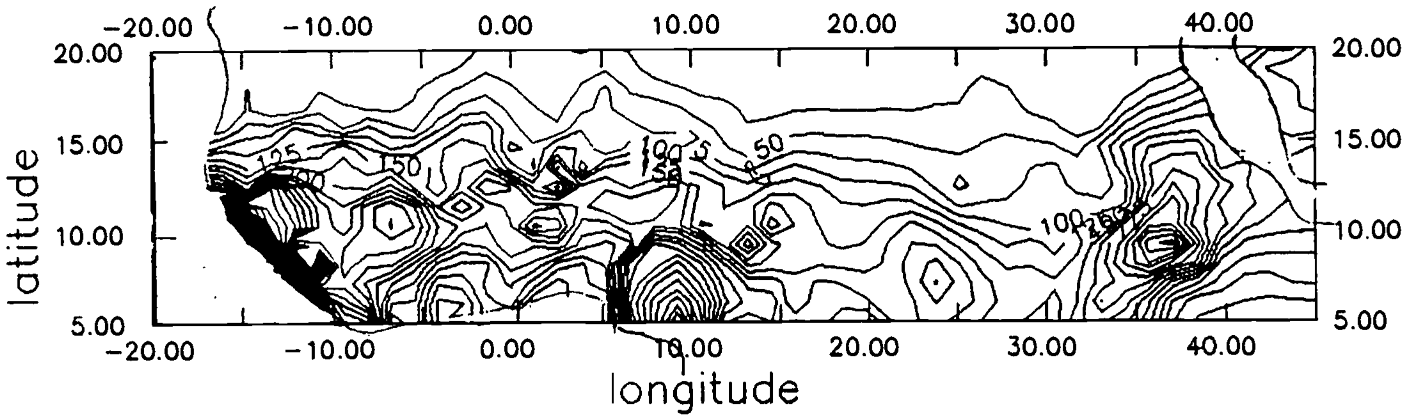


Figure 2: a) Sites of all raingauges which contributed to the total rainfall data set.
b) Sites of raingauges which were available for a selected good dekad.
c) Sites of raingauges which were available for throughout the two years.

a) Gauge Rainfall in mm July1 1992



b) Monthly Gauge Rainfall in mm July 1992



c) Mean Monthly Gauge Rainfall July 1990-94

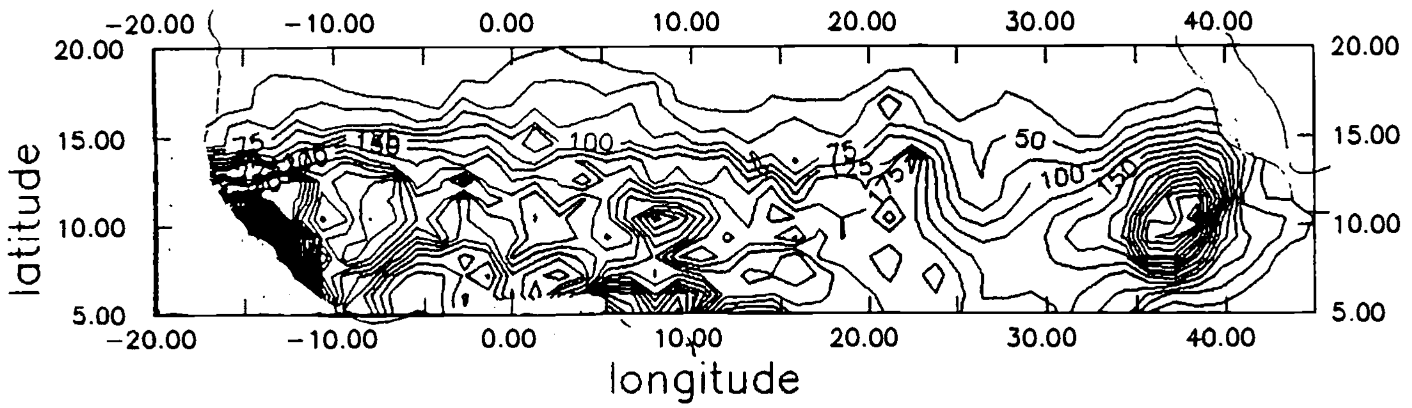


Figure 3: a) Dekadal rainfall isohyets, July 1-10, 1992.
b) Monthly rainfall isohyets, July, 1992.
c) Five year average rainfall, July 1990-1994.

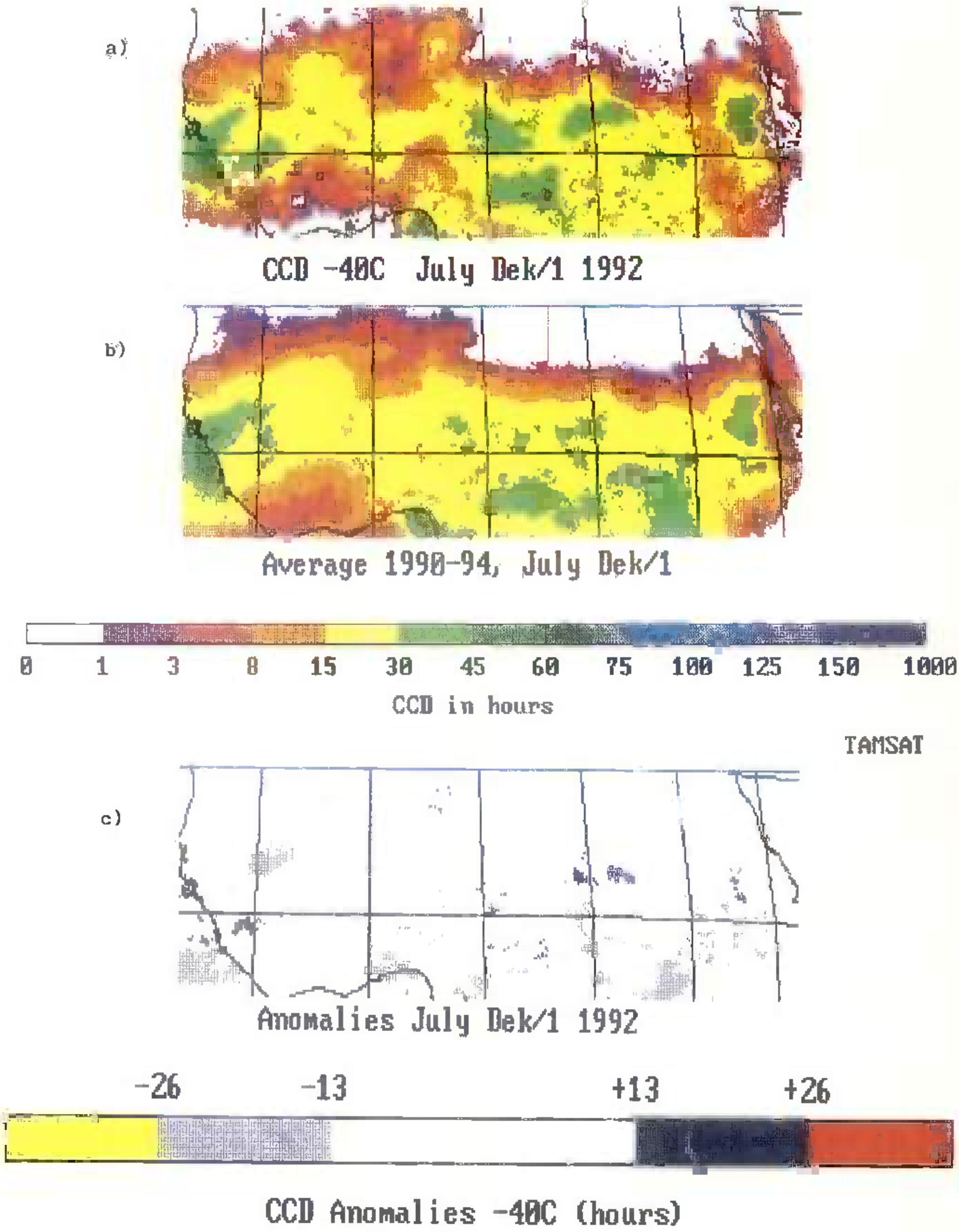


Figure 4:

a) Dekadal Cold Cloud Duration (CCD), 1-10 July 1992
b) Five year average dekadal CCD, July 1-10, 1990-1994
c) Dekadal CCD anomaly, July 1-10, 1992

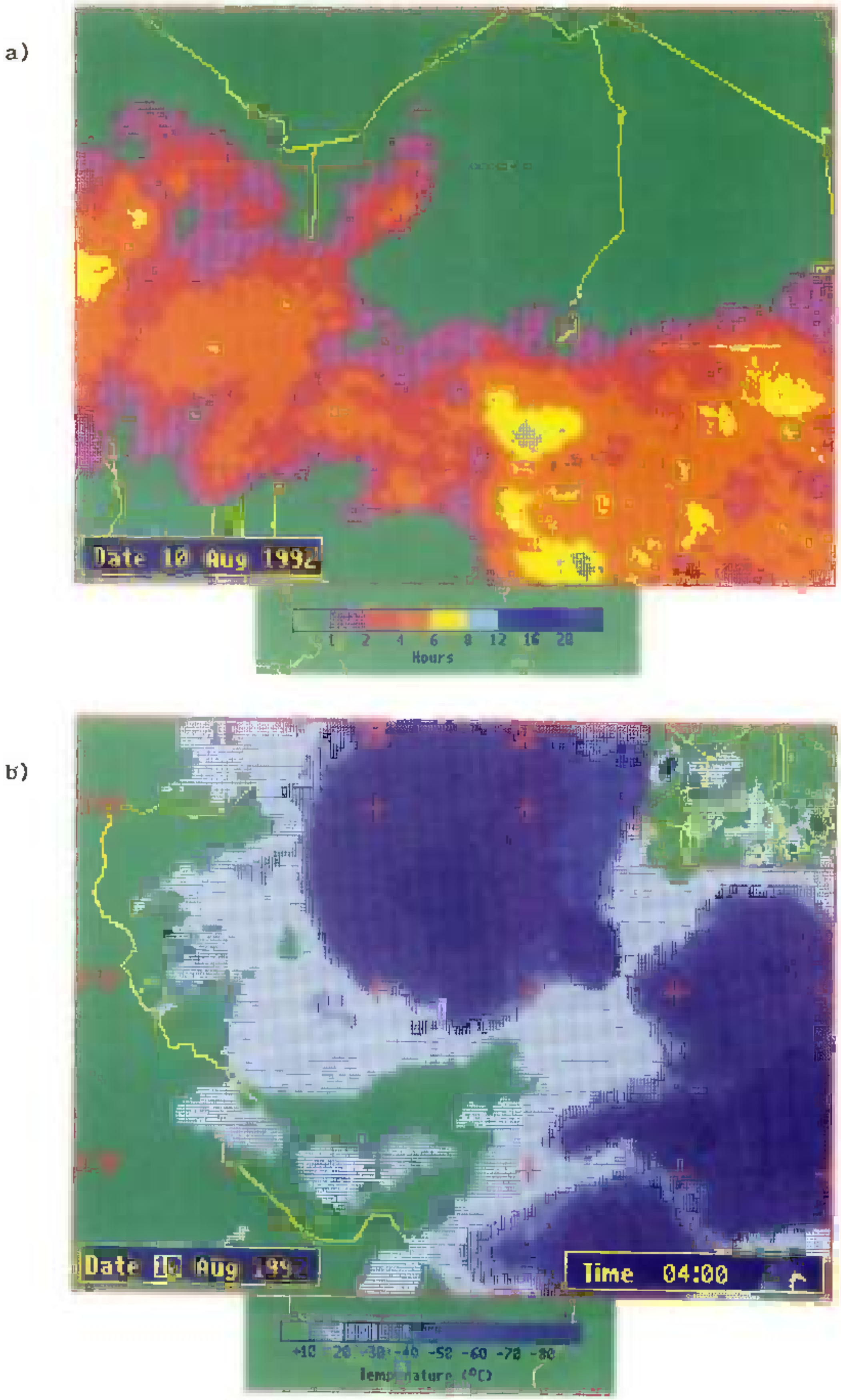


Figure 5:

a) A screen display from the film loop of five day running mean cold cloud duration

b) A screen display from the film loop of hourly thermal infra-red imagery

4. Analysis of data

This section consists of 4 parts, the use of CCD to represent rainfall, the analysis of interannual differences, the changes in dekadal patterns and studies of shorter time scale weather fluctuations.

4.1 *The use of CCD data to represent rainfall*

As mentioned in section 2.2 and illustrated in figure 3.a, b & c the coverage of raingauge data is poor over much of the region. There are insufficient sites from which data is available throughout the period of study to allow meaningful isohyetal maps to be drawn. For this reason all available gauge data was used for dekadal and monthly analysis. The inconsistency of the data source prevents these maps being used for inter-dekad or inter-monthly comparisons. They are, however, useful when used in conjunction with the maps of the positions of the contributing gauge sites for comparison with the corresponding CCD imagery.

In this study a temperature threshold of -40°C has been used to define storm clouds. Many years experience in using cold cloud thresholding as a rainfall estimation technique has shown that a single threshold cannot discriminate between active and inactive cloud throughout the season over the whole region of interest. Further, the average rainfall rate from a properly identified active storm varies according to the region and part of the season in which the storm occurs. However, when considering large space and time scales the duration of cold cloud at different thresholds is strongly correlated. Hence, while the quantitative relationship between cold cloud duration and rainfall varies over the region, the relative local distribution of rainfall in space or time can be represented by a single threshold. The validity of this has been checked using the 1992 dekadal rainfall and cold cloud duration maps and derived products. Examination of the 1991 CCD and rainfall anomaly maps shows this to be true for large anomalies but small anomalies are frequently in the opposite sense in the two data sets. This confirms that our studies should concentrate on the largest intra-seasonal and inter-seasonal changes in weather.

4.2 *Inter-annual comparisons of monthly average data*

Most of the analyses in this section are based on the monthly data for 1991 and 1992. As this contains some 72 diagrams and charts they are not reproduced in the report. However, most of the deductions can be seen in the HM diagrams at the end of section 4 which indicate the dekadal march of the most important features.

4.2.1 *Cold cloud duration, Inter-annual.*

These comparisons are based directly on visual examination of the monthly mean dekadal CCD for 1991 and 1992 using the corresponding five year, (1990-1994), average as a background. This data is reproduced as figure 6.

The 1991 season started with a northwards extension of about three degrees of the rainy area between 0 and 10°E compared to either 1992 or to the normal with significantly more rain down to the coast at the same longitudes. The Jos plateau area was exceptionally stormy in the second and third dekads. By June the northern extent of the storms was, in both years, similar to normal but a relatively dry area was developing along the coast from 0 to 10°W. This feature continued throughout July and August resulting in an unusual extension of the short dry season along a 2 or 3° wide coastal strip from 5°E to 10°W. August saw enhanced stormy activity between 10 and 20°E south of 15°N in 1992. The September retreat of the ITCZ was similar on a monthly scale in both years, but in October 1992 the ITCZ had become discontinuous across 5°E to 10°W while in 1991 it was maintained as a weak feature at about 10°N.

The main long term (generally >15 day) differences between the seasons are

a) enhanced convection between 0 & 10°E at the start of the 1991 season,
b) long dry season in coastal areas in 1992,
c) reduced activity between 5°E & 10°W in October of 1992.

Other more detailed differences of these persistent changes will emerge from the study of dekadal data.

4.2.2 *1000mb wind, interannual.*

The model uses a vertical co-ordinate of pressure relative to the surface pressure (sigma co-ordinates). When converting the wind values from sigma to pressure surfaces the sigma = 1 values are used at any pressure surface which is greater than the actual pressure at the earth's surface. Hence, as most of this region is above the 1000mb level the 1000mb chart generally represents ground surface winds. Other fields than winds are extrapolated using, in each case, what is considered the most appropriate routine.

The major differences in the 1000mb winds in the two years are a stronger northerly flow into the ITCZ in 1992 early in the season. Through mid season the moist southerly feed in 1992 penetrated further north to the west of the meridian and less far north east of the meridian than in 1991. The late season surface flow differed little between two years.

4.2.3 *850mb wind and static stability, interannual.*

The northern sub-tropical flow in May was quite different between years with a stronger northerly flow down the west coast in 1991 and troughing in the sub-tropical easterlies at 15°N. Through June and July interannual differences were small but in

August 1992 strong westerlies developed at mid latitudes with a moderate circulation round the Azores high. At the same time southern hemisphere flow was similar in the two years but in 1991 the recurvature across the equator was more marked and resulted in stronger westerlies to 10°N. These were associated with a northern displacement and increase in the maximum of theta-e. In September the major difference was the stronger flow round the sub tropical anticyclones in 1991 giving stronger easterlies across the region than in 1992. In October 1991 the airflow from the eastern Mediterranean was stronger and penetrated to the west coast of Africa.

4.2.4 *700mb wind, interannual.*

At 700mb the background circulation in the wet season is westerly in the mid-latitudes of both northern and southern hemispheres. Anticyclonic circulations in the south Atlantic, over South Africa, and over the Sahara feed into a generally easterly flow in the tropics. The position of these semi-permanent anticyclones fluctuate in response to high latitude influences.

The 700mb wind is regarded as an important feature of the West African climate. A jet (the African easterly jet, AEJ) develops during the wet season and its position and strength are believed to be important in determining the storm development and storm tracks. Baroclinic waves develop on this mid-tropospheric jet. These are one of the modulating influences on storm activity and will be described briefly in section 4. 4
The southern hemisphere 700mb winds were similar in the two years in May but the northern and Saharan circulations were quite different. In 1991 there was a trough in the European westerlies at about 10°W with circulation round the Saharan high at 25°E giving east winds across most of Africa between about 20°N and 10°S. In 1992 the trough in the westerlies was further west and there were two centres to the Saharan high. This resulted in a north easterly flow at about 10°N into most of West Africa, and a southwards displacement of the developing AEJ relative to 1991.

By June the average flows in the two years were more similar with the Saharan circulation drawing Mediterranean air southwards into West Africa between 20°E and 10°W. The jet continued to develop west of 10°E; its 1992 position was a degree or so south of the 1991. The mean July circulations were more different with a stronger northern hemisphere mid latitude feed from the central Mediterranean into the West African flow in 1991.

The flow patterns generally remained similar for the rest of the season. The persistent difference between the years were in the May interactions with the mid latitudes and slight differences in the AEJ; this being stronger in the early season in 1992 and in the late season in 1991. Its axis was one or two degrees further north in 1991 than in 1992.

4.2.5 *400mb wind and vertical motion (omega), interannual.*

The 400mb level being close to the level of minimum divergence shows well the vertical motion field. The analysis of this data is to confirm, or otherwise, the model's ability to correctly position the convective activity. Clearly the semi-permanent convective centres off the coast of Guinea, over the Cameroon highlands and the Jos plateau will dominate the patterns. What we seek is an agreement between the CCD and omega fields on the more subtle features which may change slowly and differ from year to year.

The May charts agree well with the CCD imagery in that the unusual northern extension of the rain area between 0° and 10°E in 1991 is captured. At the same time the southern extent sub-tropical westerly flow is displaced some 4°N. By July the vertical motion plots pick up the start of the coastal dry period in 1992; the area of ascent being some 3°N of its 1991 position. This feature is continued through August. Both CCD and Omega show that in October 1992 the region around the meridian was drier than in 1991.

One surprising aspect of the omega field which is probably incorrect is the absence of significant ascent over the Ethiopian highlands for much of the 1992 season.

4.2.6 *200mb wind, interannual.*

The main tropical feature of this level is the tropical easterly jet TEJ. This originates over the Tibetan plateau in summer and weakens as it approaches Africa. Most references remark on its re-enforcement as it crosses Africa. This jet is usually situated a few degrees to the south of both the AEJ and of the zone of maximum convection.

In May the TEJ is not established but in 1991 an anticyclonic circulation was developing at about 15°N, 10°E causing the sub-tropical westerlies to circulate and give a light easterly flow between 10°N and 0°N west of 10°E. By June the TEJ was apparent in each year extending to about 30°E and centred at about 10°N. Light easterlies continued across West Africa aided in 1992 by a Saharan circulation similar to that of May 1991. In July the eastern part of the TEJ appeared at about 14°N but the developing jet further west of the meridian was ten degrees further south. This persisted through August with the western part now of similar strength to the eastern. Both sectors of the jet weakened significantly in September each year, but more rapidly in 1991 than in 1992 when average speeds above 10ms^{-1} were sustained. By October only the coastal areas of West Africa had easterly winds.

Detailed study of the 200mb winds does indicate that the development of the TEJ over West Africa is perhaps not only an extension of the more eastern jet. As it develops a split jet occurs with the western sector well south of the eastern and becoming stronger than the eastern. Only as the western part decays does the east resume its position.

4.2.7 *Summary of interannual differences*

Both the CCD and the 400mb omega fields identified enhanced convection in May between 0 and 10°E, in 1991 and a short dry season in 1992 over coastal areas of unusual duration and extent followed by a dry late season in the area around the meridian. These areas of agreement at the largest scale indicate that the model is able to reproduce the coarse features of the interseasonal differences as well as the longer term climatology.

In the wind fields conventional forecasting techniques suggest that changes in the TEJ and AEJ and in the 850mb southerly flow should be associated with differences in weather types. The Hoffmuller diagrams (figs 15, 16) show the TEJ developed earlier in 1991 and was, early in the season, further north than in 1992. By mid season in 1992 it was slightly weaker than in 1991 and positioned a degree or so further north. At the end of the season the 1992 jet retreated southwards and decayed more rapidly than in 1991.

The AEJ (from figs 13, 14) showed a larger amplitude of both position and speed in 1991 than 1992 with greater inflow of Mediterranean air in the 1991 mid season. At this time the jet was reduced in speed to below $8ms^{-1}$ and locally to $6ms^{-1}$. During the May 1991 period of enhanced convection there was deep troughing west of 10°E with strong northerly flow from western Europe into Africa.

The May 1991 northwards extension of the storm area also coincided with an influx of air of southerly origin at 850mb which extended 5° further north than in 1992. The corresponding northern hemisphere difference was the strong northern flow between 20°W and 10°E. The extended short dry season of 1992 was marked by light 850mb winds in 1992 whereas in 1991 westerlies of about $6ms^{-1}$ prevailed.

4.3 *Inter-dekadal changes in model and CCD patterns*

In this section a fairly detailed analysis of all the 1992 fields is made in an attempt to associate inter-dekadal changes in storm activity to changes in flow patterns. The 1991 data is then used to test these findings. Most of the features described can be identified on the HM diagrams which are reproduced at the end of the section, though the full detailed fields, examples of which are given at the end of section 3, were also used in the study.

4.3.1 *The 1992 cold cloud duration (dekadal)*

Figures 7b, 8, 9, and 10 illustrate the analysis made below in which the major inter-dekadal fluctuations are noted and may broadly be classed as representing either changes in the position of the ITCZ or changes in its activity.

The early season saw strong fluctuations in the dekadal storm activity with a significant increase across the region from 6 to 12°N in the second dekad of May. In the third dekad it was very stormy west of 10°W extending to 13°N but activity reduced further east. A general decline in activity continued through June but by the end of the month a weak ITCZ had formed centred on about 11°N in the west to 15°N at 10°E then extended eastwards at about 10°N. July saw a fairly steady northwards movement of the ITCZ of about 3° with some modulation of the storms which varied longitudinally. The third dekad was particularly active west of the 0° meridian with reduced activity to the east. In August the enhancement in the 0° - 10°W region continued through the first dekad with other areas relatively quiet. The second dekad of August was generally settled west of 10°E with widespread enhanced activity further east. The last dekad of the month showed the best continuously active ITCZ across the region with almost all longitudes having in excess of 30 hours CCD. A sudden movement of 3 or 4° southwards of the ITCZ occured between late August and early September with a significant reduction in activity, particularly between 10°W and 5°E. Through the rest of September a southwards movement of the ITCZ and a general decline in storm duration took place. During the last dekad of September and throughout October extended storm duration was confined to the orographically favoured areas.

Another feature which can be observed in the HM CCD plots (figure 8.a, b) are smaller scale fluctuations in the position of the ITCZ which are manifested as increases (decreases) to one side of the 10°N latitude with corresponding decreases (increases) on the other. In late July and early August 1992 one such incident occurred between 10°E and 10°W with a northwards surge of the ITCZ. The late August increase in storms east of 10°E was accompanied by a southwards movement of the centre line of activity in this region buth further to the west there was a short-lived northwards movement of the ITCZ.

The dekadal imagery confirmed the extended coastal dry period remarked on in the inter-annual comparison. Some areas had no cold cloud for seven dekads.

In summary the major features shown by the 1992 CCD imagery were:

- the active period in mid-May continuing into late May in the west,
- a fairly quiet June with the development of an arc shaped ITCZ in the last dekad
- steady northwards movement of the ITCZ in July
- increased activity 0 - 10°W in late July and early August
- unusually well developed ITCZ in late August
- marked changes in position of the ITCZ in late August
- steady decline and southwards movement of the ITCZ in September and October.

4.3.2 *The 1000mb wind and meridional speed fields, 1992 dekadal.*

The flow of the NE and SW monsoon air streams into the ITCZ may indicate areas of increased convergence. The position of the confluence line (V=0) is an indicator of the surface position of the ITCZ (fig.11).

The background larger scale 1000mb wind pattern is a northerly flow round the Azores high over north west Africa, a generally north easterly flow into tropical Africa east of the meridian drawing in some eastern Mediterranean air and, from the south, a flow generally curving westwards on crossing the equator.

Dekadal evolution.

West of 10°E the latitude of the V=0 progressed fairly steadily northwards throughout May, June and July from about 13 to 20°N with a northwards extension to 23°N in late July between 0 and 10°W. Between 10 to 20°E the southern component reached 18 to 20°N through most of this period. By late August the V=0 penetrated to 24°N to the west of 0° meridian and 20°N east of the meridian, having only been at 16° N east of the meridian in mid-August. The norther extension west of the meridian continued into early September after when there was a general southwards movement to 12/14°N by late October.

There is coincidence of the late July early August rain (0-10°W) with the local northern extension of V=0 and an associated, slightly increased flow from the south. There is little information in the flow at this level to account for the widespread strong activity in late August though there is some increase in the southerly flow south of 10°N and a corresponding northwards movement of the V=0 isotach west of 1°E.

4.3.3 *The 850mb wind and stability fields, 1992 dekadal.*

The major flow regimes are similar at 850mb to those at 1000mb described in the previous section. There is however much variability in this field particularly the trans-Saharan flow and significant input of south easterlies from the southern Indian Ocean to eastern Africa. The stability of the air mass is indicated by its theta-e value. The latitude of the maximum theta-e values throuthout the season are shown in figure 12.

In early May the confluence between the air of southerly and northerly origin was between 8 and 10°N with the main sources of the northerly air in the eastern Atlantic and eastern Mediterranean. During the month the confluence moved northwards about two degrees. In the second dekad there was a strong feed of air from the mid and eastern Mediterranean into west and east Africa respectively. At the same time the area of maximum θe moved northwards but the actual maximum θe values declined. In June the θe pattern (see fig 12) conformed with the arc shape observed in the CCD. Although there were significant changes in the 850mb flow during the month there was not a strong corresponding signal in the CCD.

Throughout July and early August there was little change in the 850mb circulation in those parts of the southern hemisphere or eastern Atlantic included in our study, but late in July and early August, and again at the end of August, strengthening westerlies entered West Africa at about 10°N. In mid August, coinciding increased CCD the theta-e values reached a season's maximum east of the meridian. However, the westward extension of high CCD at the end of the month did not appear in the theta-e field.

4.3.4 *The 700mb wind field, 1992, dekadal.*

The opportunity will be taken here to describe the general seasonal characteristics of the African Easterly Jet (AEJ) which are not well documented. Also there is conflicting evidence concerning its role in modulating the weather. It has been ascerted that a weak jet is associated with seasons of high rainfall. This may be partly a causal influence but it is also seen that the jet usually weakens as it moves north and its movements are related to those of the ITCZ. It could therefore be that both the weaker jet and enhanced rainfall are symptoms of a more northern covergence zone. The jet is also important in being a necessary condition for the formation of the meso-scale convective systems known as West African line squalls which are responsible for much of the West African rainfall. However, what the critical wind sheer is for the formation of these storms is not clear. An additional impact of the jet is the easterly waves which develop on it. These will be discussed in the section 4.4.

A summary of the AEJ's characteristics in 1992 follows and can be seen in figures 13 and 14. Over West Africa the jet strengthens and moves from the coast to about 10°N in May and June reaching some 14 ms^{-1} at the end of June. During the next two months it continues northwards but decreases in strength to 10 ms^{-1} at around 14°N. Its retreat is more rapid, reaching 8°N by the end of October, passing through a maximum speed of about 14 ms^{-1} again at around 11°N. Next, the seasonal trend of the whole 700mb wind pattern is discussed.

The 700mb flow is generally easterly to the south of the axis of the Saharan high. The axis itself moving seasonally from about 16°N in May to 30°N in August then returning southwards. On this axis the positions of the anticyclonic centres vary in an east west direction under the influence of troughs in the northern latitude flow. This gives rise to fluctuations in the sources of the mid-tropospheric air mass over our region. These fluctuations appear to be associated with West African weather changes in 1992. In mid-May an anticyclonic circulation developed at about 12°W drawing northern air into the tropical easterlies to the west of the meridian. This anticyclonic centre displaces slowly east until by mid-June eastern Mediterranean air was being fed into the tropical easterlies to the east of 25°E. the next northerly intrusion occurred in late June between 0 and 10°E and persisted through the first dekad of July. In late July another northerly intrusion occurred near the west coast and persisted with an eastwards extension into mid-August. At the end of August this intrusion was penetrating south of 20°N across much of West Africa. Through September and October the pattern had changed; the feed into the tropical easterlies coming mainly from a circulation over Arabia.

There does appear to be evidence of the location and timing of increased CCD being associated to some extent with the northern air intrusions.

4.3.5 *The 400mb vertical motion field, dekadal*

This section looks at the agreement between the location of enhanced CCD and the 400mb omega field. Orographically favoured areas are discounted.

The high CCD in mid and late May is shown as high omega values in the 400mb charts, but the persistence in the omega field is longer than in the CCD. Through mid-June and early July both fields are suppressed with a slight revival in mid-July. Throughout August convection in both sets of data is enhanced west of 10°E and suppressed from 0 to 10°W. However, the northern displacement of the maximum in the omega field is not seen in the CCD. The late August almost continuous ITCZ is also common to both fields followed by the September split and decrease in activity.

In general there is good qualitative agreement between the fields regarding changes in position and strength of the convection, but it is unlikely that a qualitative analysis would show good correlation.

4.3.6 *The 200mb wind field, dekadal*

The main feature of interest here is the TEJ; its seasonal march and the fluctuations within this. The relevant HM diagrams are figures 15 and 16. Through May the tropical 200mb flow is light and the TEJ only makes its appearance at about 40°E, 8°N in mid-June. By early July the jet has extended across Africa from about 13°N in the east to 8°N in the west. During the second dekad of July the western part of the jet appears to develop independently of the east. By mid-August it achieves a similar speed of 20 ms^{-1} with a tight core at about 4°N, some 10°S of the eastern branch of the jet. In late August as the ITCZ develops its longitudinal structure and the TEJ moves rapidly north to lie two or three degrees south of the ITCZ. Thereafter the jet slowly declines in strength and returns to 4°N by mid-September, when its identity as a jet is lost.

It may be significant that the western jet developed further south and east in 1992 than in 1991. In 1992 the CCD maximum at 10 to 25°E was much stronger than in 1991 and the AEJ was also several degrees further south than in 1991.

4.3.7 *Summary of dekadal charateristics of 1992.*

The features of the CCD were, as summarised in section 4.3.1:

- active mid-May continuing to late May in the west,
- generally subdued June,
- increased activity 0-10°W in late July and early August,
- an unusually well marked ITCZ in late August.

The first field to look for consistency between the satellite and model data is the 400mb vertical motion (omega) field as this provides the integral of the model's physical and dynamical representation of the atmosphere. Generally agreement between the maxima and between the trends in the CCD and omega fields is good. However, qualitatively the correspondence is not convincing. The implication is that some important features contributing to omega are not properly represented. However, the agreement is good enough to encourage the cautious use of this field.

At the lower levels of 1000 and 850mb occasions of strong northwards movement of the 1000mb V=0 and 850mb theta-e maxima were associated with high CCD. Also the modulations in the strength of the theta-e showed some correlation with the CCD fluctuations on the longer time scales. The occasions of strengthening of the recurving southerly stream to westerlies flowing into West Africa also were associated with increased CCD and a northwards movement of the ITCZ in the west of the region.

At 700mb the position of the jet moves in phase with the ITCZ but minor changes do not appear to correlate with the storm activity on the ten day scale. At this level it is the slowly changing influx of northern air into the easterly flow which appears to modulate the weather. When this occurred in the west or in the east, storm activity tended to increase in these regions; but when the inflow was widespread the influence appeared to be mainly in the east of the region.

The position and strength of the 200mb TEJ over West Africa appears to be strongly linked to the overall storm activity; whether this is cause or effect is unclear.

4.3.8 *The dekadal fields for the 1991 season*

Here we are looking for confirmation or otherwise of the associations between the model fields and the CCD which were established in the 1992 study. First an analysis of the CCD field is given followed by the association of the model data with the significant fluctuations of the CCD.

4.3.8.1. *Cold Cloud Duration fluctuations 1991*

Attention is concentrated on significant inter-dekadal changes in the storm activity and position (figures 7,8,9 & 10).

The first abnormality of the 1991 season was the extension of the storm area to 20°N in the 0 to 10°E region in the second and third dekads of May. This was accompanied by widespread high CCD values further south, making May the cloudiest month in some regions. Early June data is missing. Mid-July saw an overall increase of CCD in the west with a small southwards shift of the ITCZ. A reduction in the hours of CCD in the east and increase in the west in late July was accompanied by a northwards movement of the ITCZ. August saw an increase in activity east of the meridian and a temporary increase in mid-month between 0 and 10°W. By late August the line of maximum activity was fairly continuous and centred on about 12°N. The decline of the season was quite smooth except for a local increase of storms between 10 and 30°E in mid and late September as the ITCZ moved south.

The features we seek to characterise are:

- strong activity in late May with northwards extension of rain between 0 and 10°E,
- fluctuation of east west distribution of activity in July,
- increases in activity east of meridian throughout August,
- increased activity mid-August 0 to 10°W,
- stormy period 10 to 30°E, 5 to 10°N in September

4.3.8.2 *The vertical velocity field, 1991.*

The 400mb vertical motion field reflected the May northward extension of convection but did not capture the increased activity south of 15°N. The main features of the August CCD also appear in the 400mb omega field but the latitude of maximum vertical velocity is displaced about 2° southwards. The September rain surge between 10 and 20°E was recognised but displaced, again somewhat southwards, in the omega field.

4.3.8.3 *Low and mid level flow, dekadal, 1991*

The May enhanced and extended rainfall coincided with a strengthening southerly flow at 1000mb which extended to 18°N, 0° where it was in confluence with both northerly and north-easterly streams. This was not marked in 850mb flow but a maximum theta-e coincided with the northward extension of rainfall. In late July and early August the strengthening westerly flow into west Africa accompanied the slight increase in convection between 0 and 10°W which was sustained through August but collapsed in early September. The high CCD in September in the south west of the region coincided with increased flow into this area of south easterly air from the Indian Ocean and northern air from the Red Sea at 850 and 700mb levels. This is a symptom of the seasonal and geographic changes in the nature of the ITCZ.

At 700mb the main changes relate to the development and movement of the AEJ and the fluctuations in the sub-tropical circulations feeding into the tropical easterlies. The May weather anomaly is associated with northern flow at 700mb between two sub-tropical anticyclonic centres. The 1991 fluctuations in the sub-tropical circulations were less marked than in 1992 but again a northerly air intrusion in mid and late August around the meridian coincided with increased convection in the 0 to 10°W region. This was also accompanied by troughing in the TEJ in this area.

4.3.8.4 *The 200mb flow, dekadal, 1991.*

As in 1992 the 200mb wind charts show little inter-dekadal fluctuation, and so linkages to the CCD fluctuations on these time scales is observed. However, the inter-annual differences in the 200mb fields are greater than in most of the other levels and this needs more study.

4.4 *Studies of easterly waves and the manifestation of wet and dry periods.*

As mentioned in the introduction, the existence of westward propagating waves on the easterly jet has been well documented and the ability of the NWP models to initiate and propagate them has been demonstrated. Studies have been made to evaluate the possibility of forecasting these waves several days ahead, into how well the model represents reality and how the waves modulate the weather.

Typically waves have a wavelength of about 2500km and propagate at about 7 ms^{-1}. They can be identified at most levels in the troposphere but are strongest at the 700mb jet level.

4.4.1 *Modelled easterly waves*

The meridional component of the 850mb flow has been extracted from the ECMWF data. Grid point values at three latitudes (12.6, 15.3 and 18.1°N) have been averaged and Hoffmuller plots drawn of both the positive and negative components. These are reproduced in figures 17. The continuity of the waves in these diagrams is remarkable and it is clear that this allows forecasting several days ahead after their first identification. The mean characteristics of the depicted waves are:

	Number	Wavelength km	Phase speed (ms^{-1})	Period (days)
July +V	6	2900	12	4.4
July -V	6	3400	12	4.5
August +V	5	3300	9	6.5
August -V	5	2700	9	5.0

Clearly the differences in measured wavelength and periods of the same waves arise from the analysis technique used.

In the east the waves appear to be poorly resolved which reduces the forecasting lead time for West Africa. Much of the eastern difficulty arises from the distortion of the wind field by the orography. If differences from the local average mean meridional flow were taken it may be possible to better identify the waves nearer their source. Nevertheless this illustration does appear to promise some forecasting potential.

4.4.2 *Observations of easterly waves at a single station*

Two studies of time series single station radiosonde data have been made to try to identify the passage of easterly waves. One using Dakar (14.8°N, 17.0°W) data for June, July, August and September 1991, the second using Bamako (12.8°N, 8.0°W) data for July, August and September 1991.

An example of the Bamako study, based on 850mb data is given in figure 18.

From this data set the maxima of meridional wind at Bamako appear as follows

July 4, 7-9, 11, 16, 22, 26?, 30
August 6, 9, 13, 18/20, 26/29
September 3, 7, 14, 22, 27

In the Dakar study trough passages were identified on

June 4, 8, 15 (no data after 18th)
July 4, 13 (no data 14 to 31)
August 9, 14, 17?, 21, 28/31 (sparse data 1 to 8)
September 5/6, 10, 15 (no data from 15)

These are based on the fluctuation of the meridional wind component at 850 and 700mb.

The maximum meridional winds corresponding to the passages are:

June 1991 6,10,16 (no data after 18 June)
July 1991 5,13 (no data after 14 July)
Aug. 1991 9,15,21 (sparse data up to 13 Aug.)
Sept.1991 2,7,11,16(no data after 17 Sept)

Comparisons of the Bamako and Senegal data does show continuity with waves passing through Dakar 2 days (± 1 day) after Bamako. This agrees quite well with the typical phase speed of 5° of longitude per day. Greater accuracy cannot be expected from daily unsmoothed data.

The passage of the observed waves through Bamako and Dakar in July and August, superimposed as black circles on the model analysis in figures 17b and d, show good agreement between the two data sets and analysis techniques in July with less correlation in August.

The remaining question of relating the waves to the weather is considered next.

4.4.3 *Relating easterly waves to the weather patterns and the manifestation of wet periods.*

The ability to forecast the passage of easterly waves several days ahead is not useful if we cannot associate weather with their passage. Similarly the differences in storm characteristics in wet and relatively dry periods is important to many of the users of the forecasts. Small studies have been made to answer these questions.

4.4.3.1 *Easterly waves and rainfall*

Attempts to correlate Dakar rainfall with the passage of easterly waves as observed in the local radiosonde data were unsuccessful. When the average rainfall for the whole country, obtained from the gauge measurements, was used the correlation improved but was still inadequate to use directly as a forecasting tool. Three reasons for this were postulated; the gauges may not represent the area average rainfall, the modulation of the rainfall by the waves may be only one of several influences, and the effects may be masked by the passage of line squalls through the waves. A daily time series of the fraction of gauges in the country receiving more than 2mm of rain plotted together with the passages of the wave ridges and troughs was revealing. Figure 19 shows that the waves are influencing the rain pattern and that the maxima and minima correspond to the trough and ridge passage. The background rainfall pattern however is controlled by other, probably larger scale influences.

This type of analysis needs to be extended to determine the quantitative relationship and to ascertain the influence of the waves further east where they are weaker.

4.4.3.2 *Storm characteristics in convective and suppressed periods*

Two film loops covering the period August to October 1992 were studied to try to associate storm characteristics with periods of high and low activity. The two types of data were daily, five-day running mean CCD images and hourly thermal infra-red images. The largest area covered was about 6 to 23°N, 8°W to 23°E with higher resolution over south-west Niger. Figures 5a and 5b show the two types of screen images.

An objective scheme was adopted to classify wet and dry periods. The area was divided into nine regions and the running mean CCD noted in each daily. The outstanding wet periods were 14 to 19 August in the south-east region and 15 to 18 August in the east-central region, a relatively dry period lasted from 28 August to 1 September.

The hourly thermal infra-red images were reviewed to identify the differences in storm developments throughout the three months. Each region was classified on a four point temperature scale and on coverage. Cloud morphology was noted. In the two wet periods storms developed against a general background of sub-zero cold clouds, the developments seldom reached temperatures lower than -70°C. They frequently amalgamated into large clusters which were slow moving and persisted over several days. This description of the satellite observed storms is familiar to experienced synopticians as typical of the storms and rain within slow moving 850mb vortices which occur south of troughs in the mid-tropospheric easterlies. Dry period storms were mainly local developments in otherwise fairly clear skies. These often reached temperatures below -80°C but their lifetimes were generally less than a day. Transient storms, propagating line squalls, occurred with both weather regimes.

On viewing the whole sequence massive sudden storm growth was observed at approximately ten day intervals. Storms expanded from a few hundred kilometres diameter to over a thousand in a few hours. Similar but less spectacular events were seen at many of the intervening five day intervals. It is tempting to ascribe these events to the passage of a squall line through the trough region of a wave. This needs to be investigated.

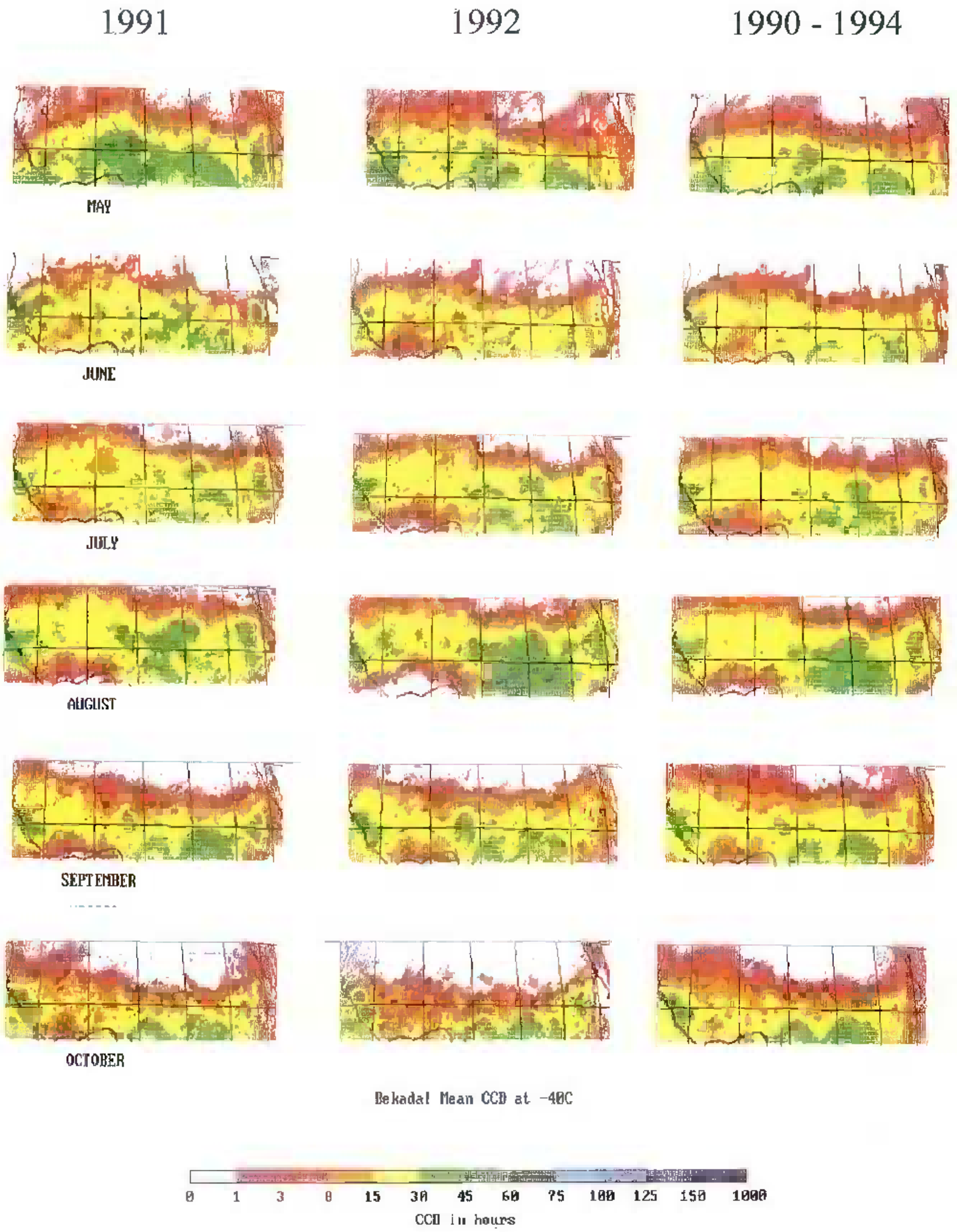
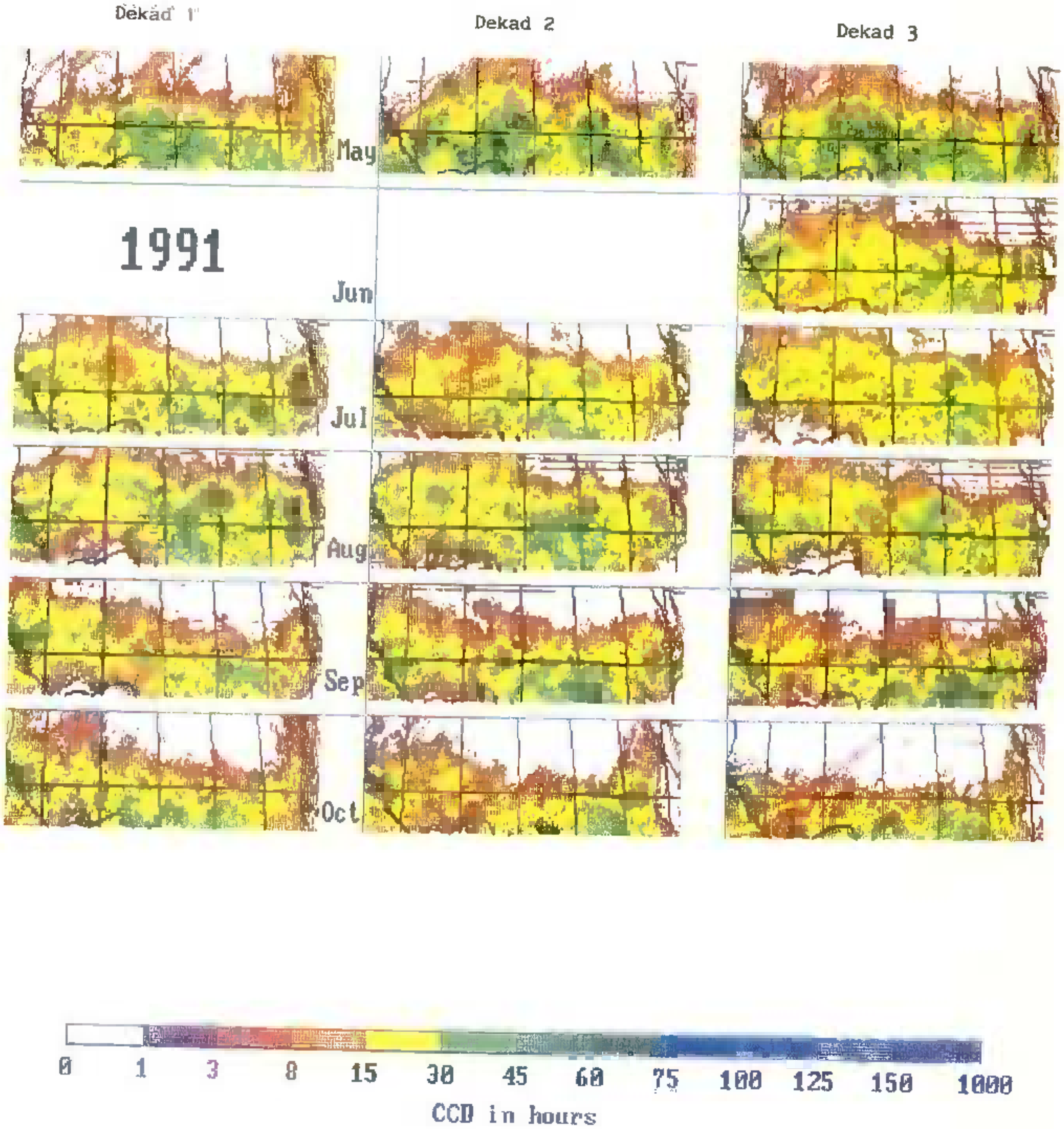


Figure 6:
Monthly mean dekadal cold cloud duration, May to October, 1991, 1992 and five year mean.



TAMSAT

Figure 7a:
Dekadal CCD 1991

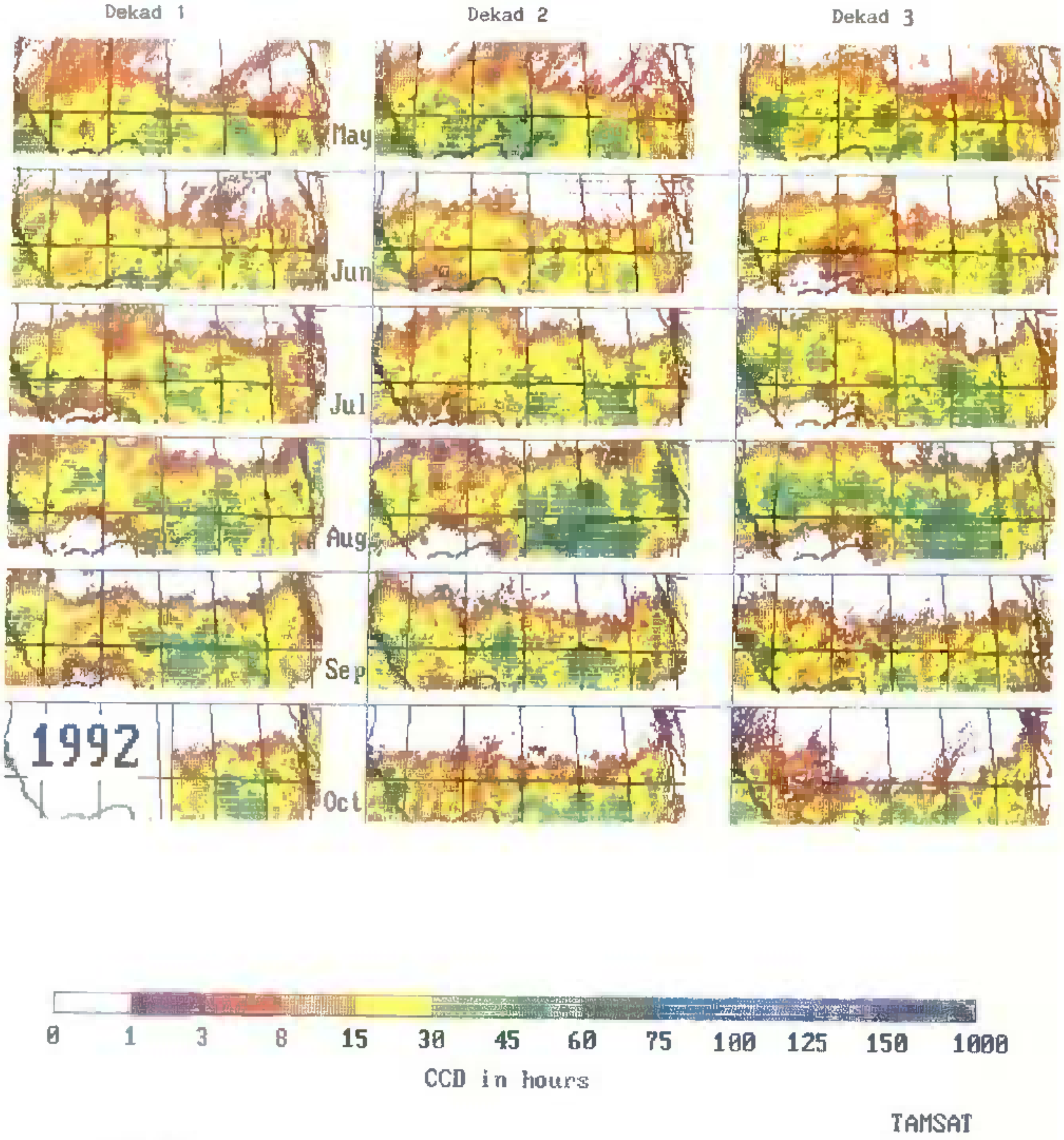
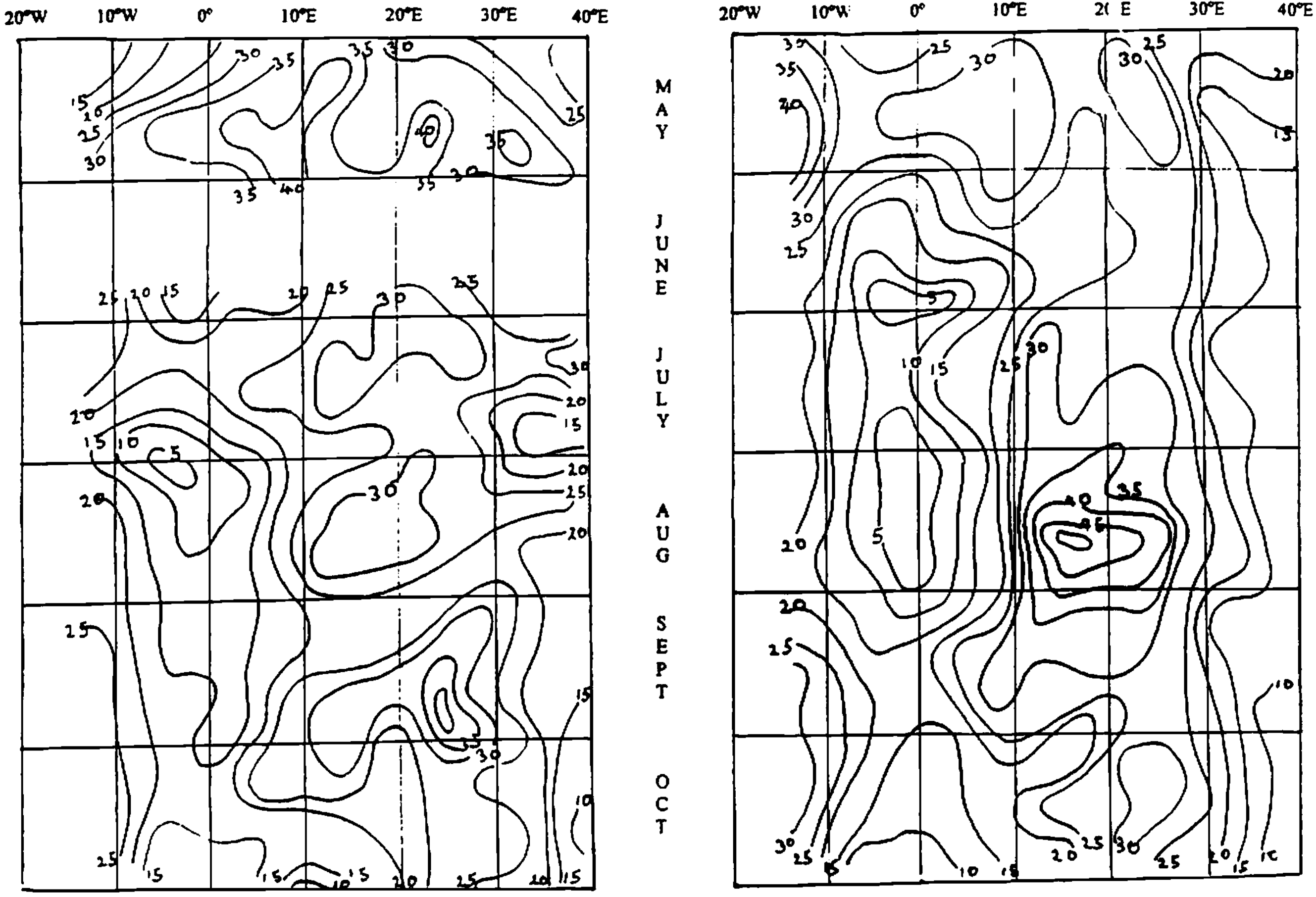


Figure 7b:
Dekadal CCD 1992

8.a)



1991

1992

Figure 8:

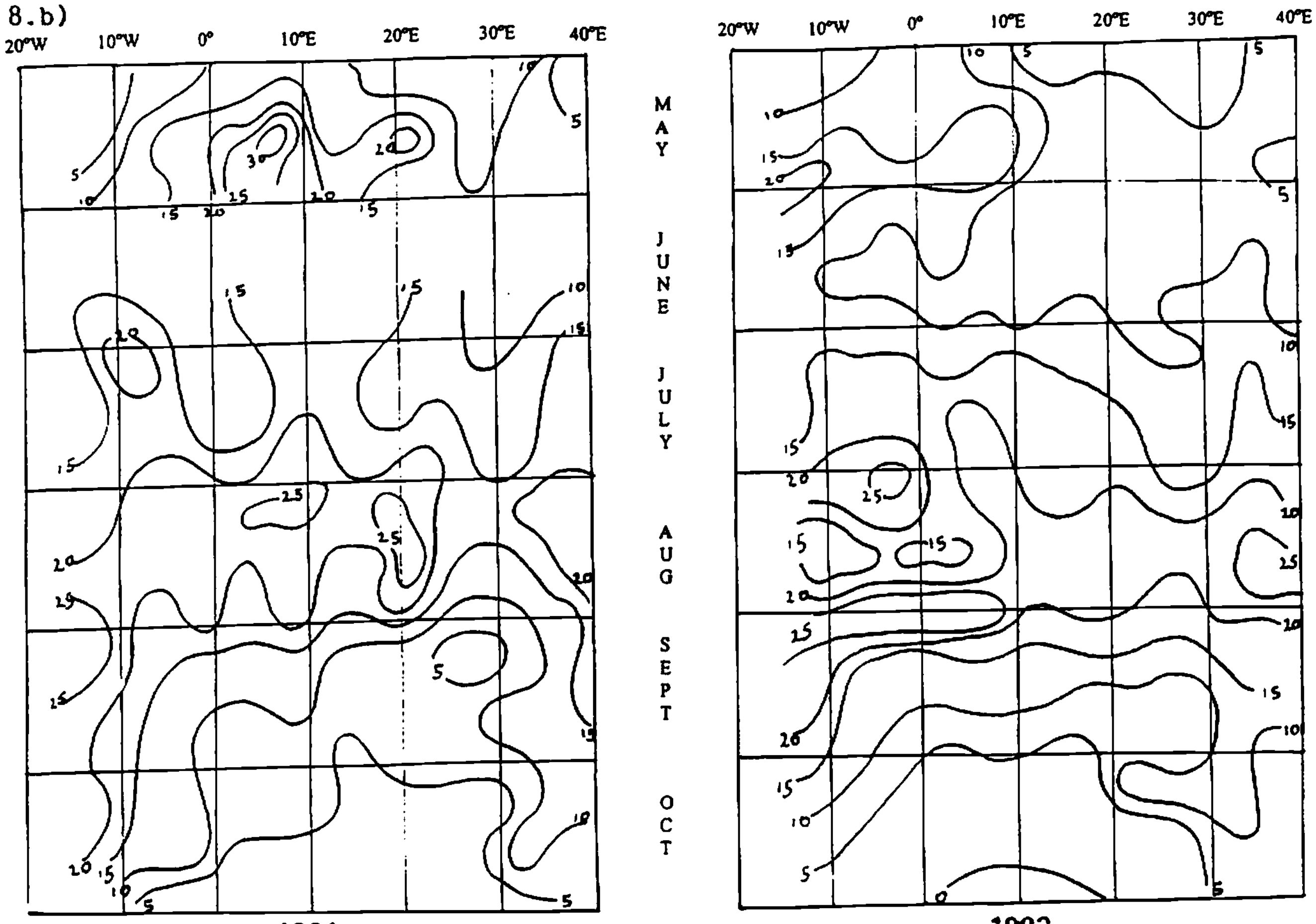
The seasonal development of cold cloud duration

a) Between 6°N and 10°N, 1991, 1992

b) Between 10°N and 18°N, 1991, 1992

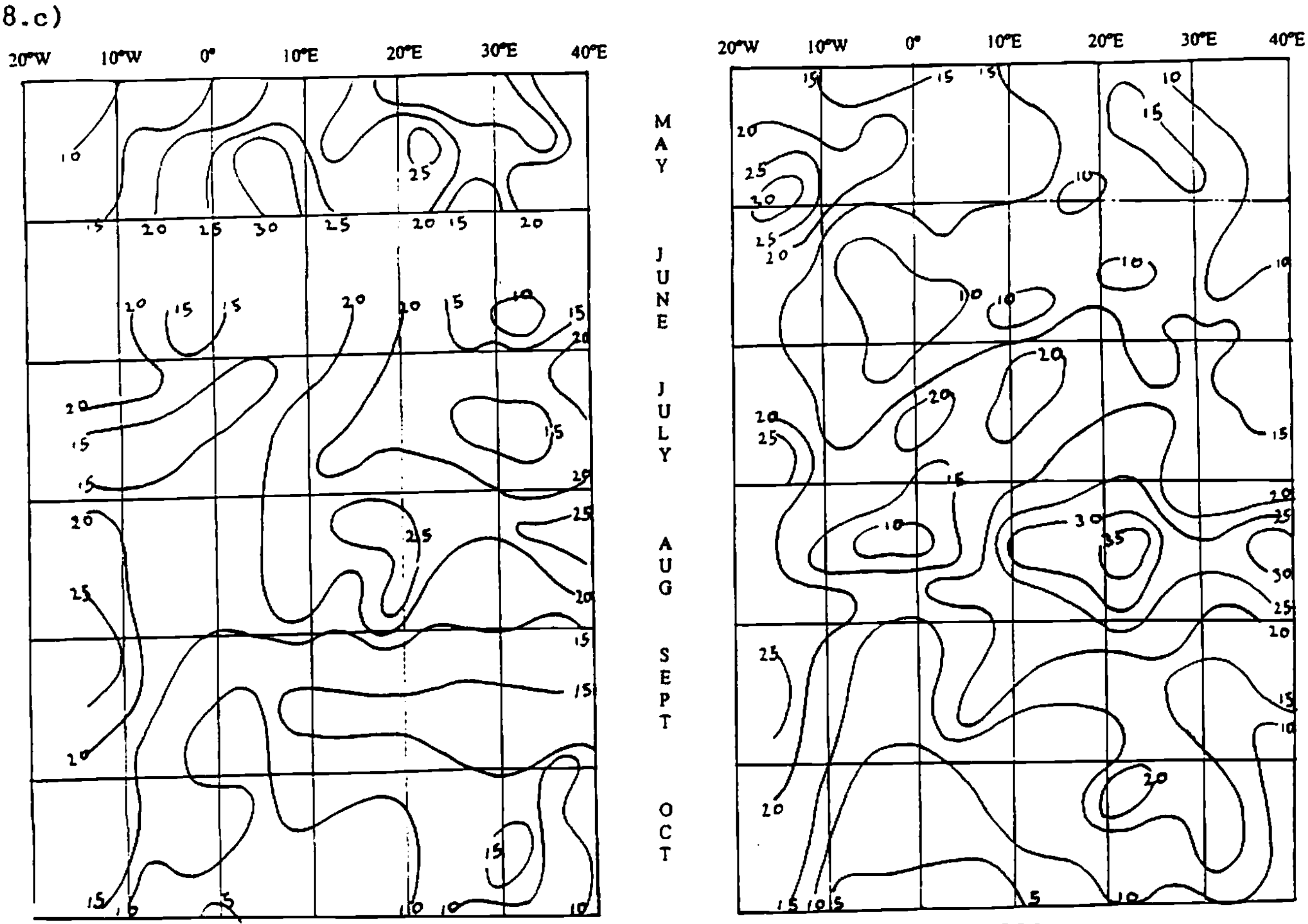
c) Between 6°N and 18°N, 1991, 1992

8.b)



1991 1992

8.c)



1991 1992

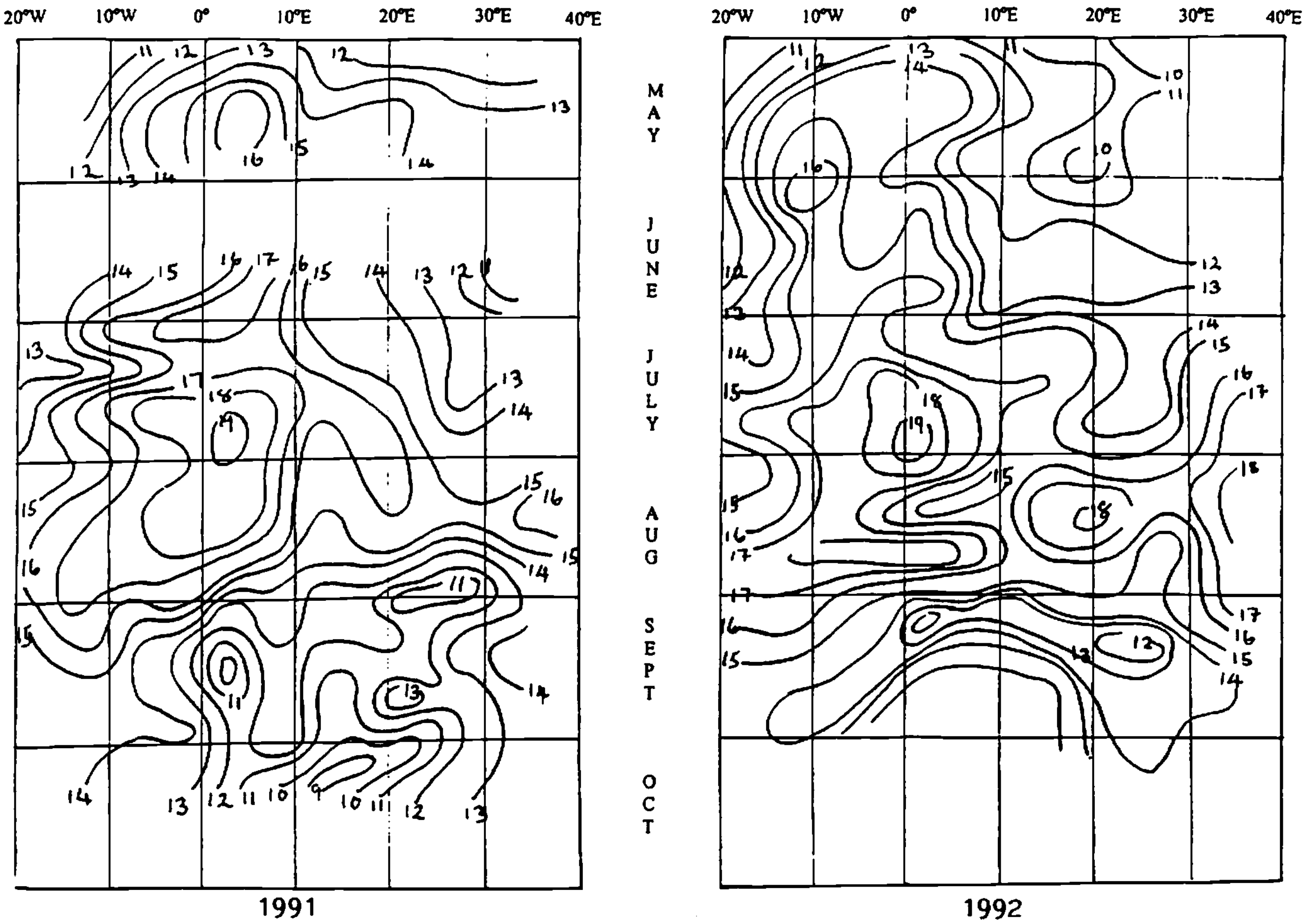


Figure 9: The latitude (°N) of the northern ITCZ 15 hour CCD 1991, 1992.

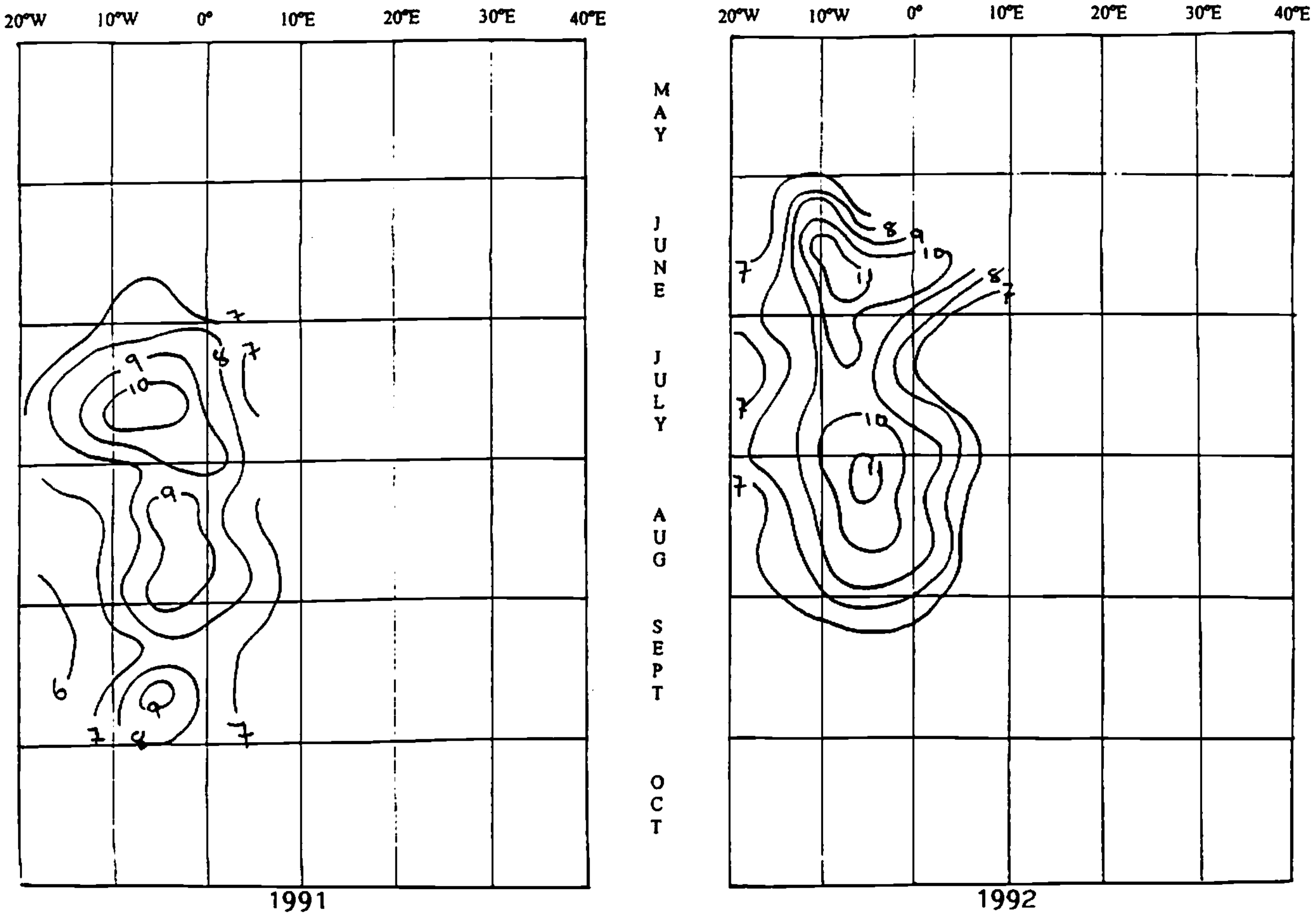


Figure 10: The latitude (°N) of the southern ITCZ 15 hour CCD isopleth 1991, 1992

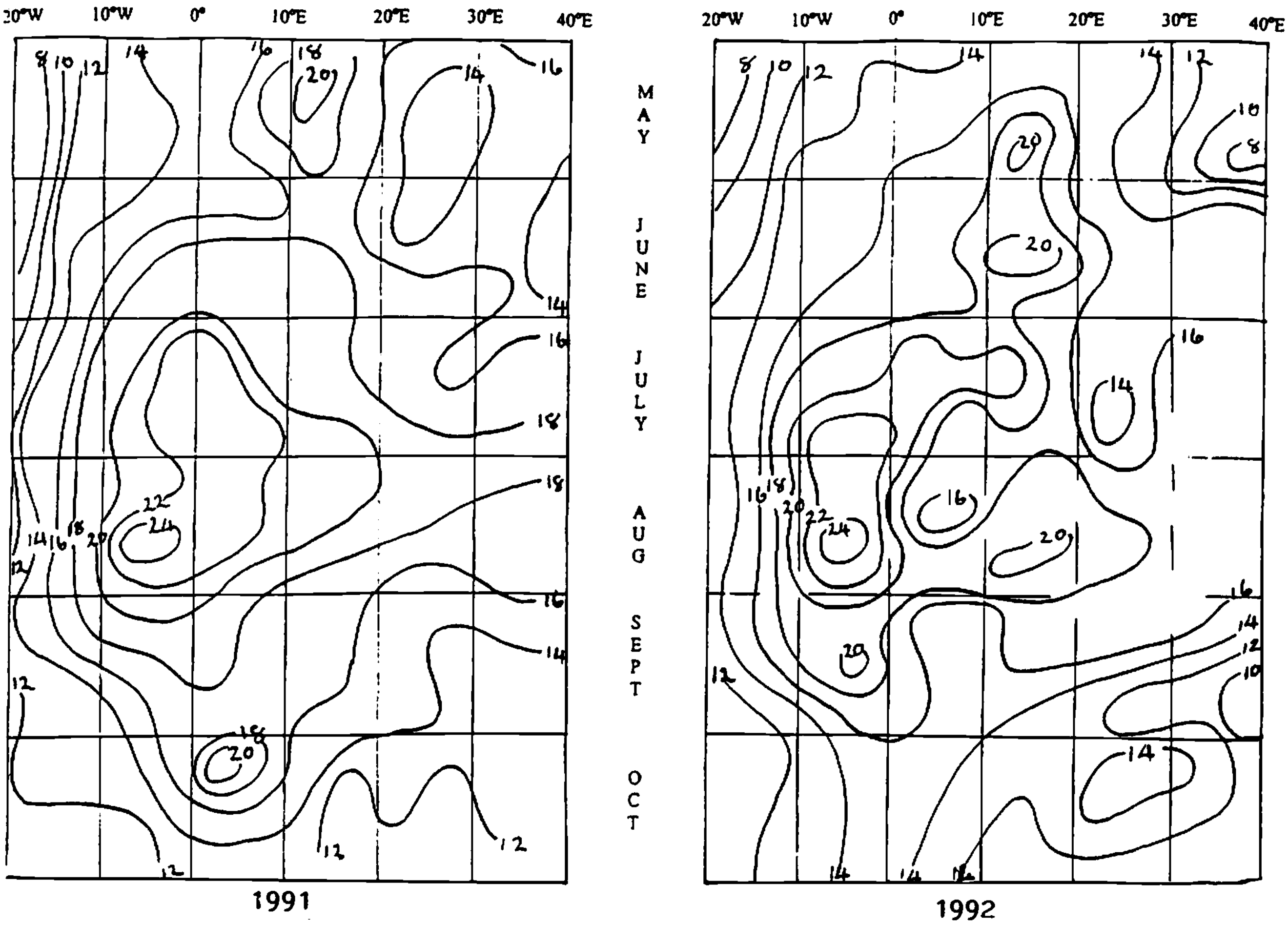


Figure 11: The latitude of the 1000mb zero meridional wind 1991, 1992

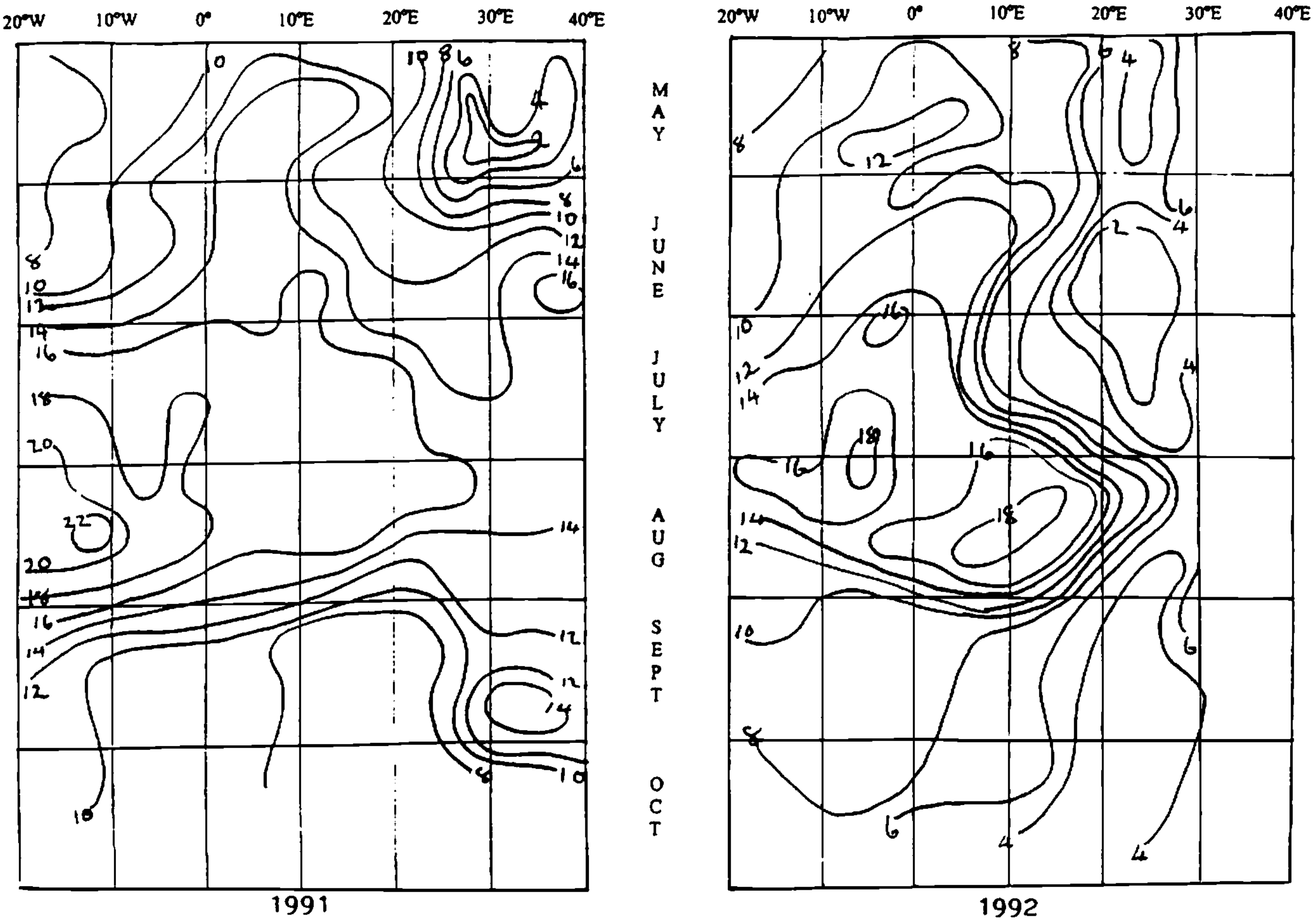


Figure 12: Latitude of the maximum value of θe at 850mb

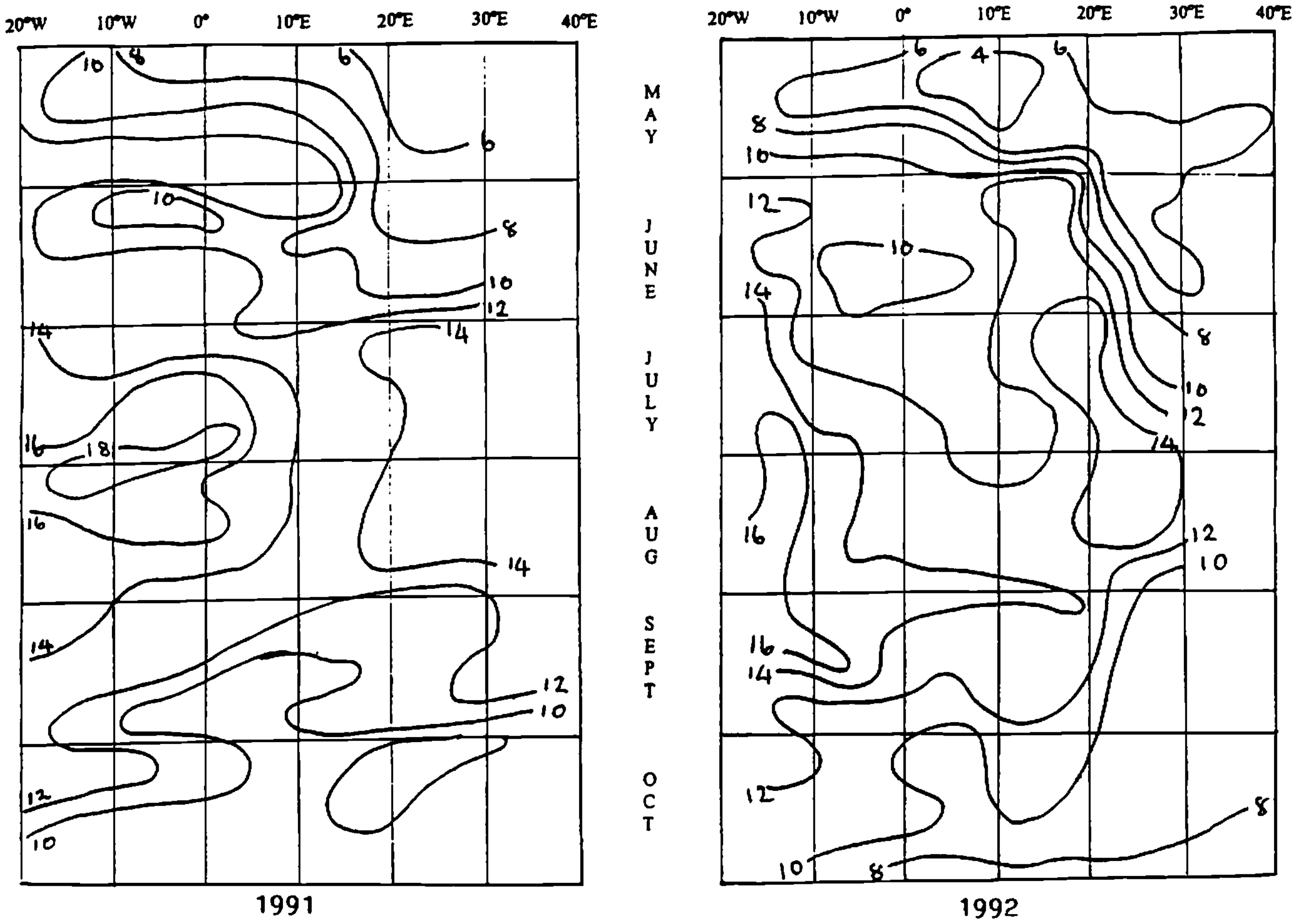


Figure 13: The latitude (°N) of the 700mb African Easterly Jet 1991, 1992

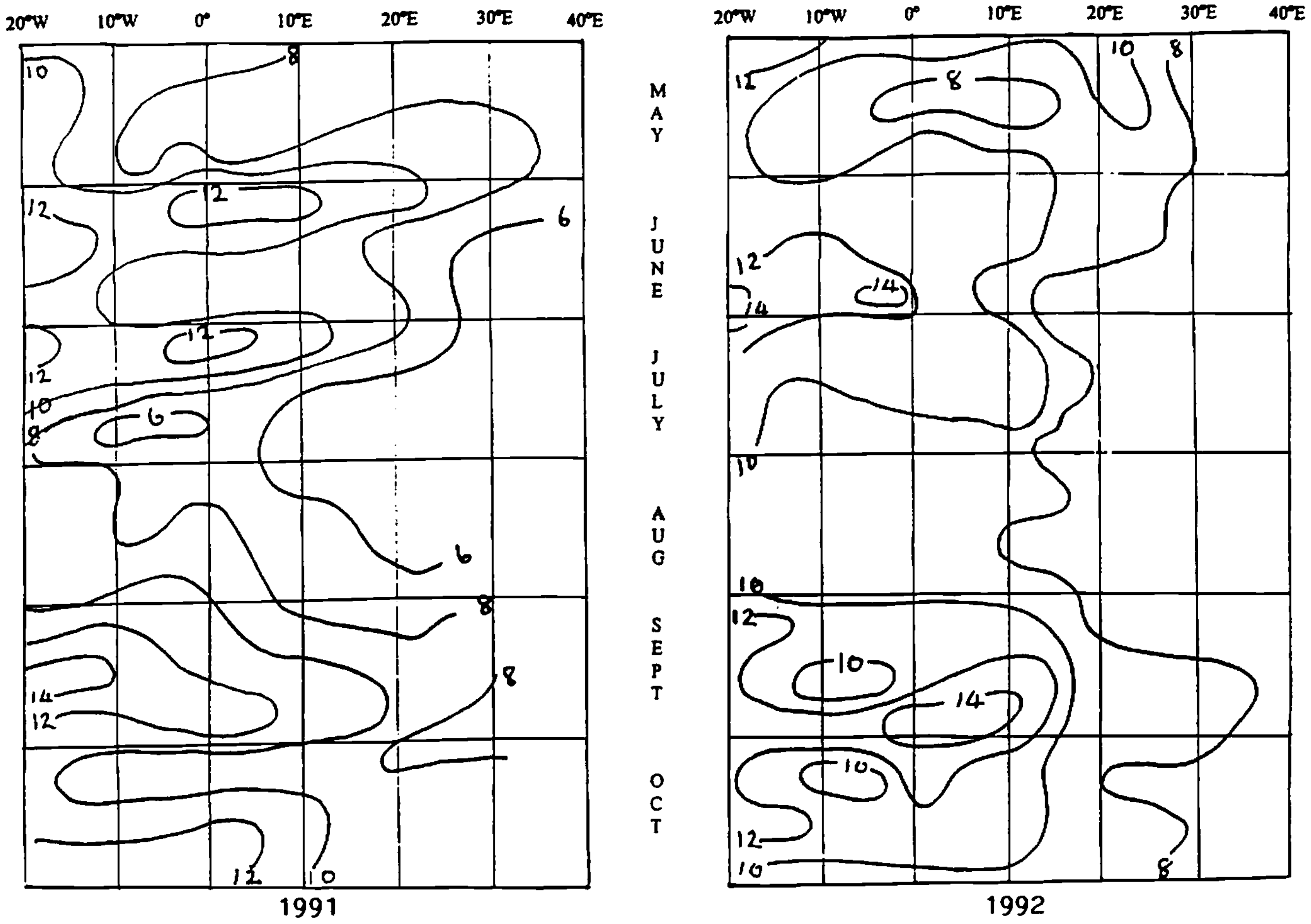


Figure 14: The speed (ms^{-1}) of the 700mb African Easterly Jet 1991, 1992

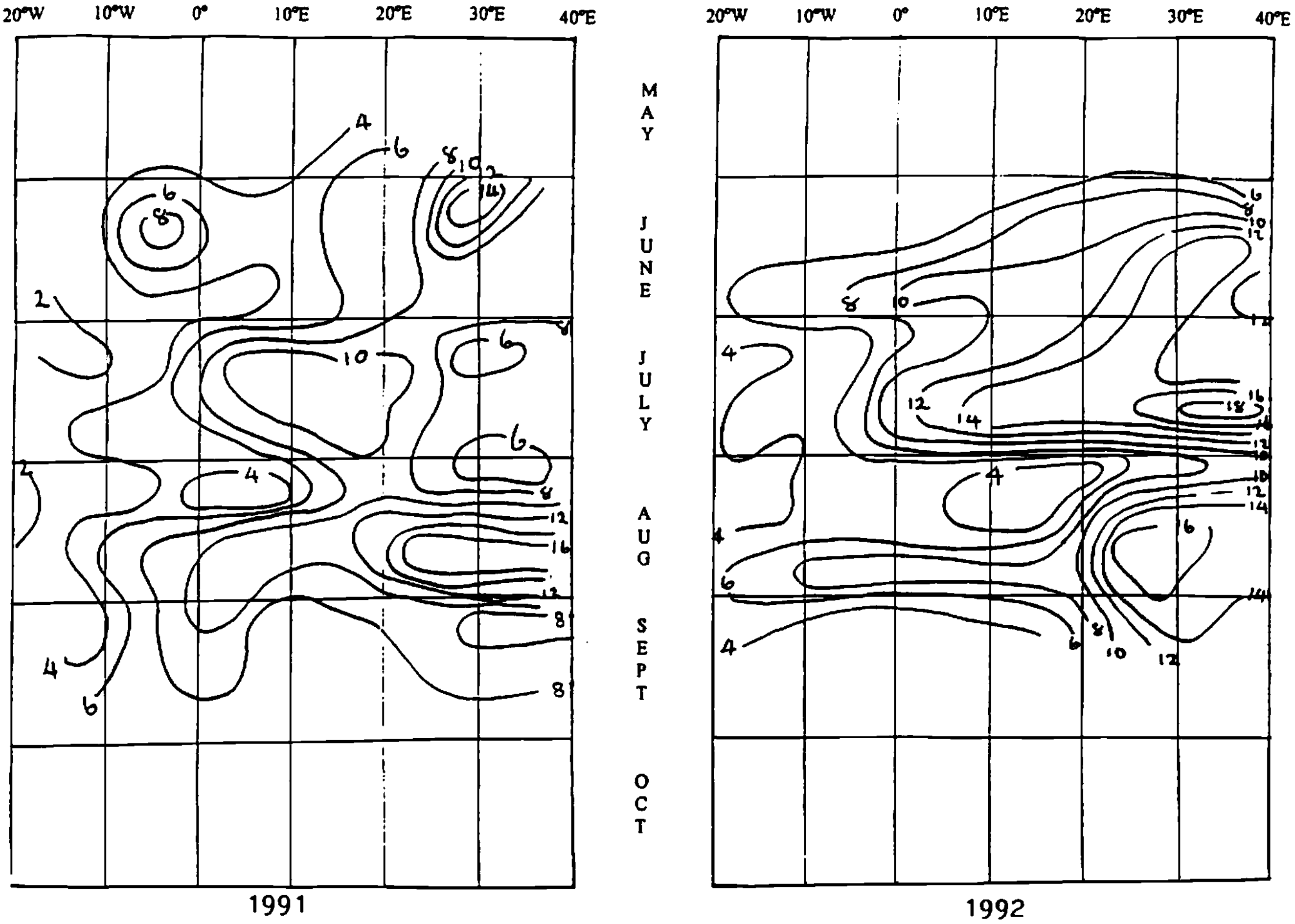


Figure 15: The latitude (°N) of the 200mb Tropical Easterly Jet, 1991, 1992

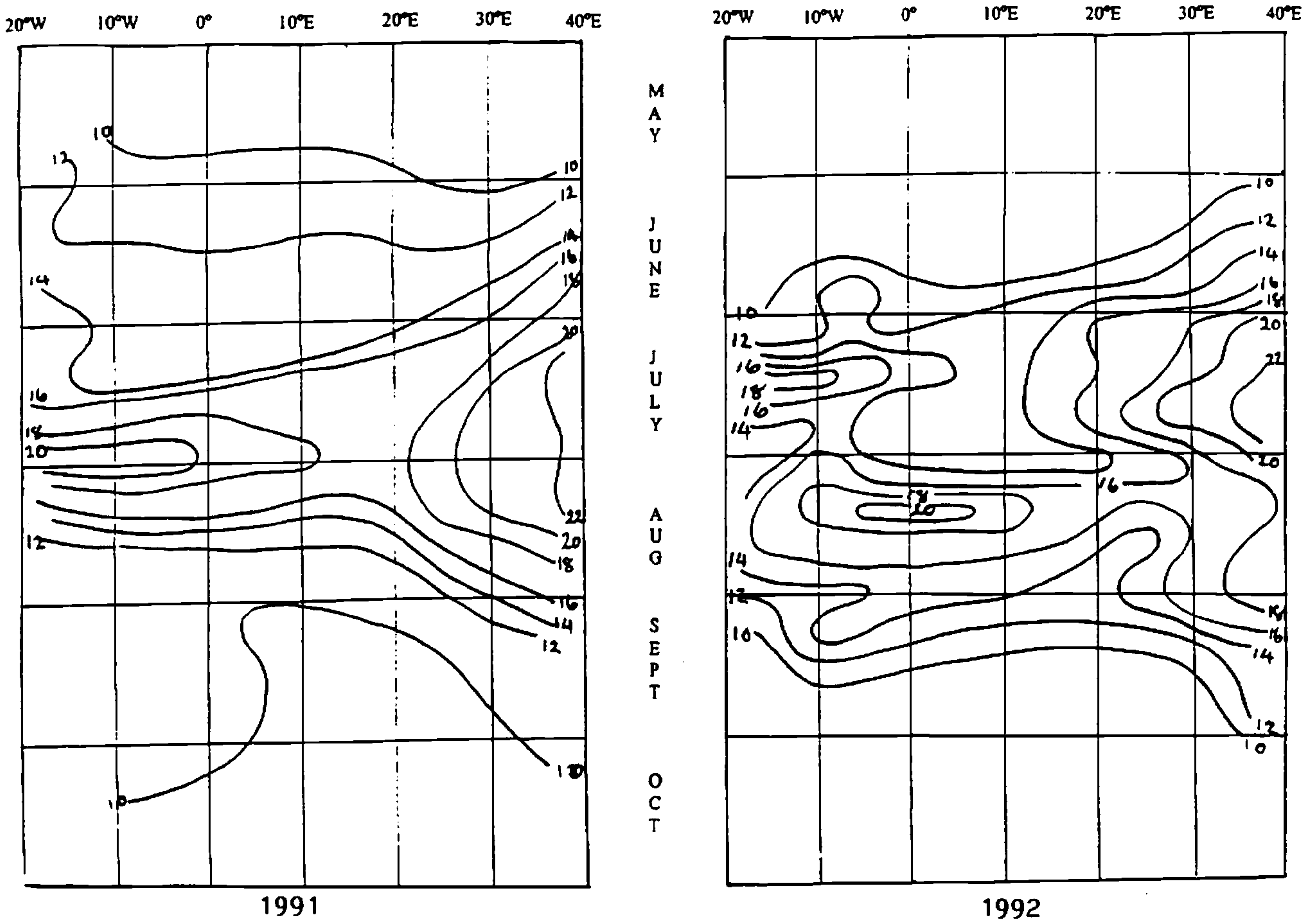


Figure 16: The speed (ms^{-1}) of the 200mb Tropical Easterly Jet 1991, 1992

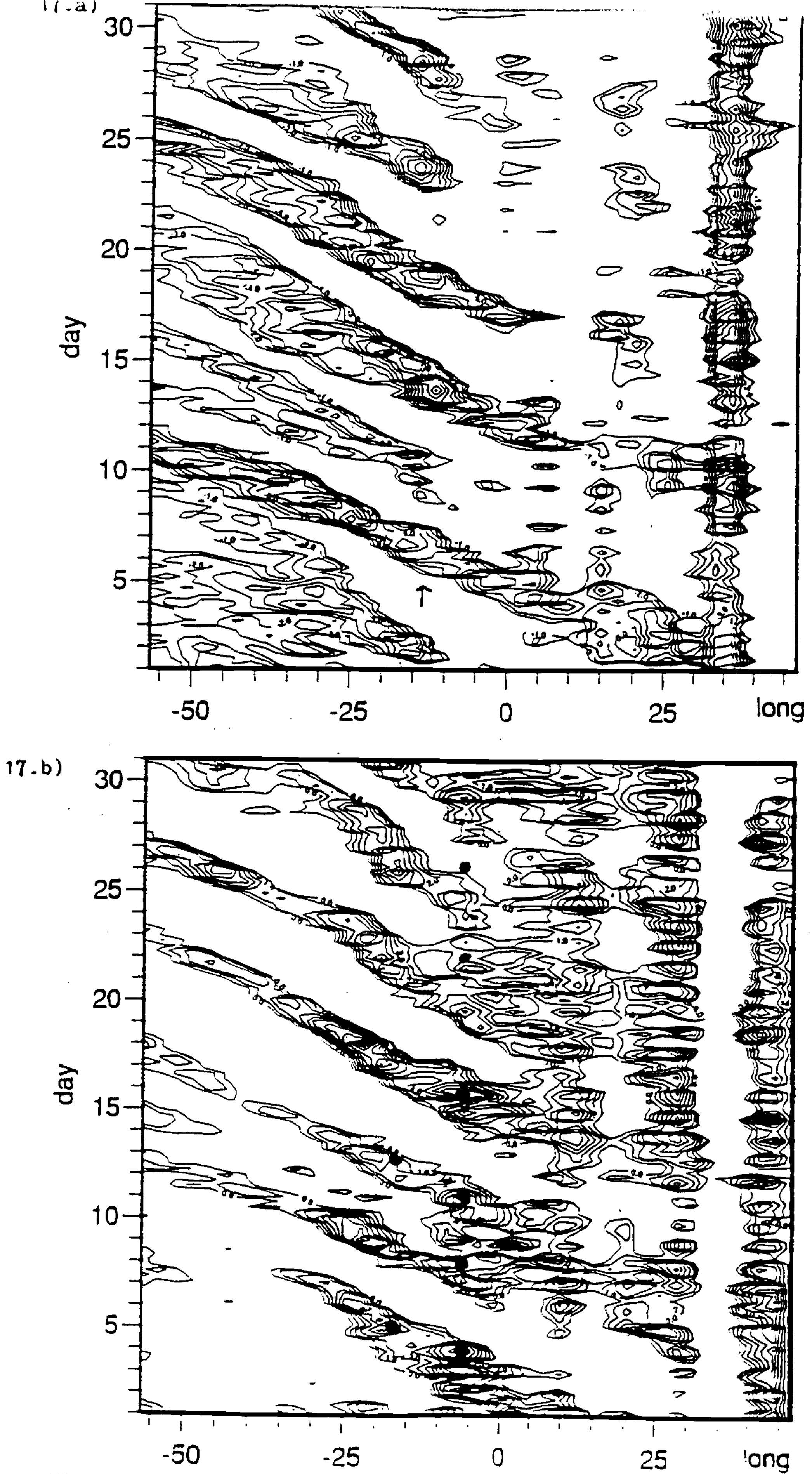
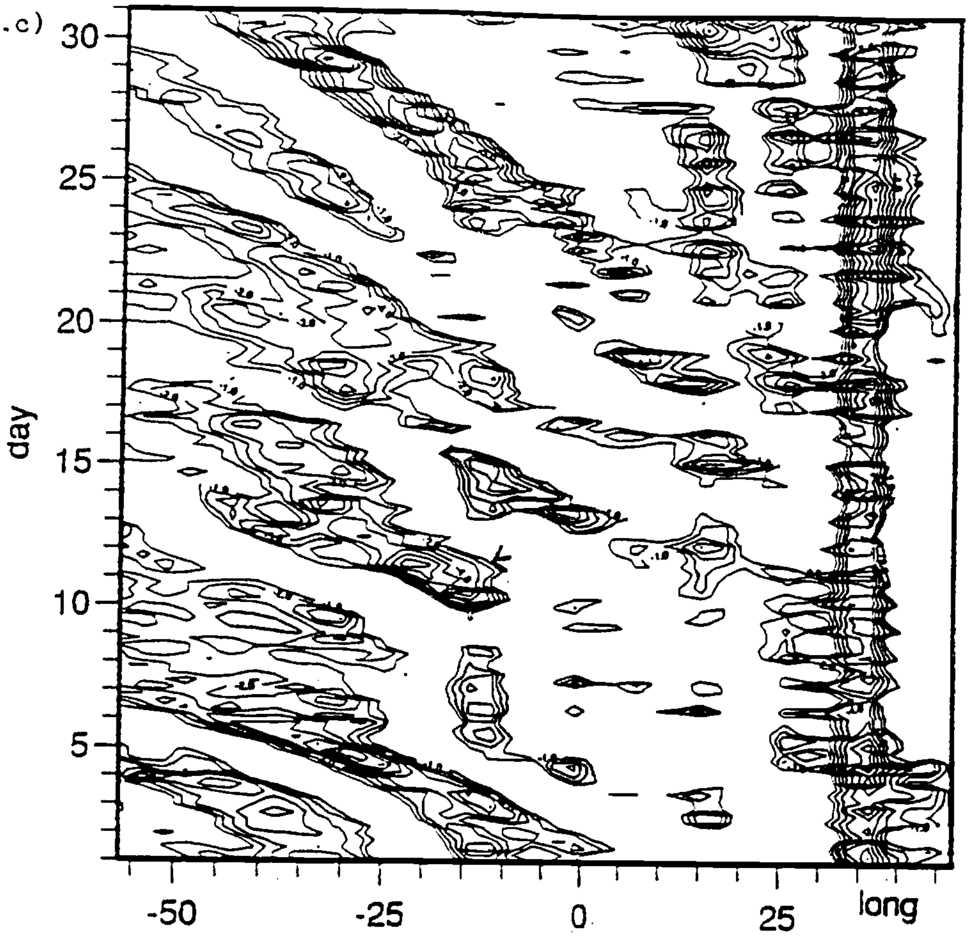


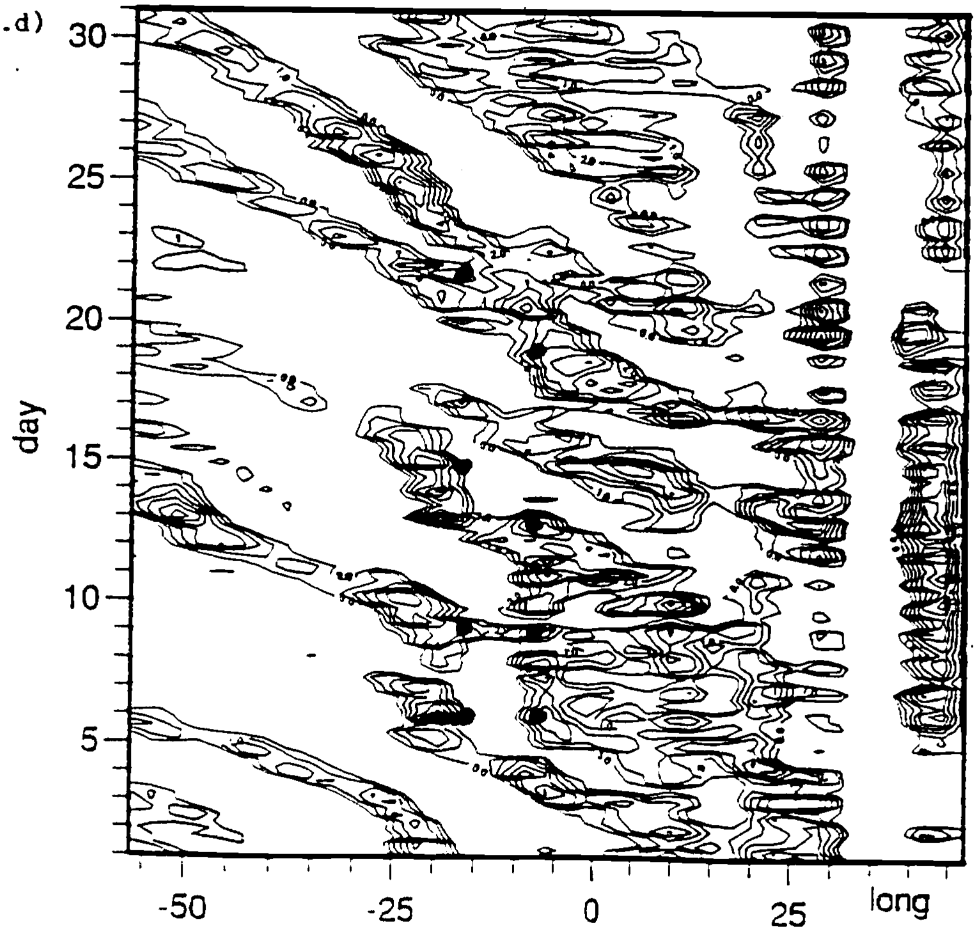
Figure 17: The modelled average meridional 850mb wind component, 1991, between 12°N and 18°N.

a) Northerly, July
b) Southerly, July
c) Northerly, August
d) Southerly, August
(after C.P. Browne)

17.c)


30
25
20
15
10
5
day
-50
-25
0
25
long

17.d)


30
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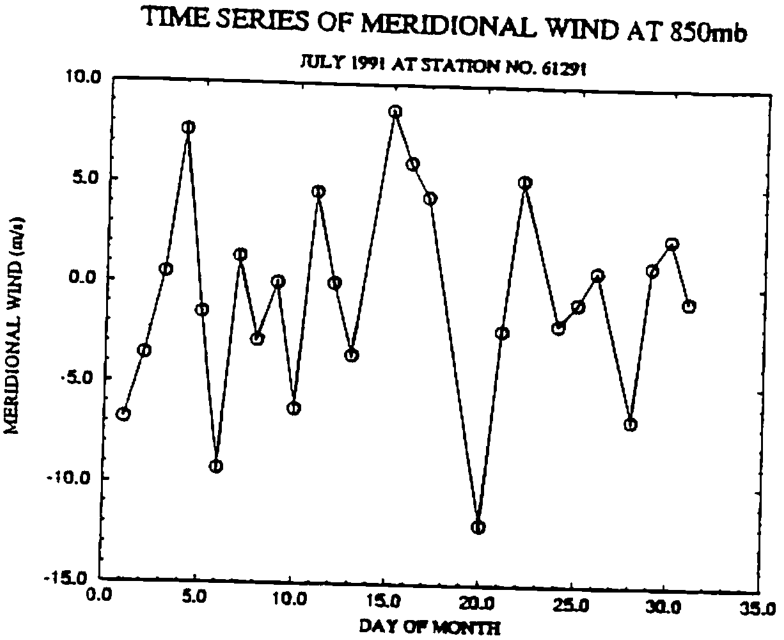

Figure 18: The observed meridional wind at 850mb in July 1991 at Bamako, 12.°N, 8.0°W (after S. Holmes).

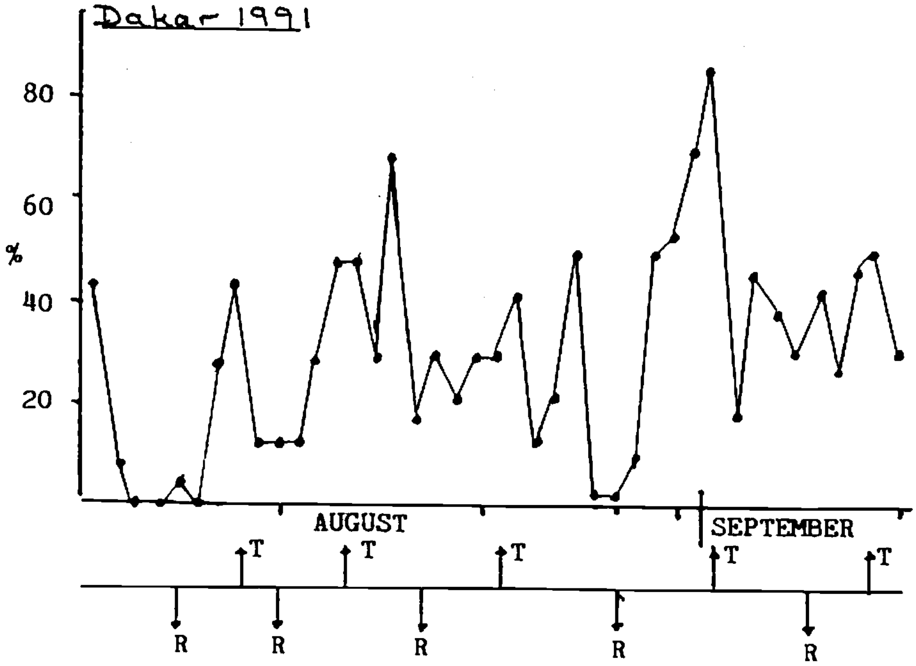

Figure 19: Percentage of raingauge sites (from 25) reporting more than 2mm rainfall with passage of easterly wave troughs and ridges.

5. Summary of findings

5.1 *Interannual differences*

On the longest time scales interannual differences which extended over two dekads or more were:

- a northwards projection of the rain area between 0 and 10°E in May 1991
- a long coastal "short dry season" in 1992,
- fairly light rains towards the end of the 1992 season from about 10°E to 10°W.

These differences were shown in both the CCD and omega fields. Features of the tropical and sub-tropical flow associated with these interannual differences were:

- the May 1991 northwards extension of rain preceded the development of the TEJ and the early stages of the AEJ development. At 850mb the rain appears to be associated with a north westwards displacement of the Azores anticyclone together with enhanced cross equatorial curvature and northwards penetration of the flow from the south. This circulation is encouraged by the 700mb anticyclone at 20°N, 15°E in 1991 and deep trough in the mid latitude circulation extending to 20°N west of the 0° meridian.
- The coastal dry season of several weeks in 1992 coincides with weak south westerly 850mb flow in 1992 compared to 1991. During this period the 700mb flow patterns in the coastal regions were similar but the AEJ was stronger by 2ms^{-1} on average and displaced southwards. The 200mb flows differed only slightly.
- The generally drier end to the season in 1992 is not marked by any major differences in the 1000mb winds but increased wind shear between 1000 and 850mb is noticeable in 1991 with the AEJ also stronger for most of the period.

5.2 *Dekadal scales*

The main dekadal differences which were identified within the 1992 season were:

- active mid-May extending into late May in the west.
- increased activity 0-10 W in late July and early August.
- a well developed ITCZ in late August,
- marked fluctuations in ITCZ latitude in late August,
- smooth northward progression of the ITCZ in July and retreat in September and October.

These, CCD derived, characteristics are confirmed by the 400mb omega fields from the ECMWF model. The related features of other fields are:

- increased activity,
  when the southerlies strengthen and veer,
  with sudden northwards displacement of the 1000mb v=0,
  with sudden northward movement of the 850mb θe maximum,

with northerly inflow into the tropical mid tropospheric easterlies, (the source of the inflow influencing the region of enhanced convection).

- The TEJ strengthening with strong convective activity and taking a position a few degrees south of the activity.
- The AEJ is usually a few degrees south of the northern extent of convection and more stable in its position than the convection. The strength of the jet reduces significantly as its axis moves north.

The 1991 season offered some noteworthy differences from 1992:

- rainfall to 20°N in May,
- a very short break in the rains,
- strong east west contrasts in convection through July and August,
- vigorous ITCZ between 10 and 30°E in September.

The unusual May rains confirmed the importance of a strong southerly flow for enhanced activity but in this case it was in confluence with both north-easterly and north-westerly (moist?) air. Also the increased convection in the west in July/August was associated with the south wind recurving to westerly. However on this occasion the northern 700mb flow was from the central Mediterranean and exceptionally strong. The late season heavy rain in the south-east had its origin in air flows from the Indian ocean and Arabia; a feature of the changing season.

5.3 *African easterly waves*

It has been shown that simple techniques can be used to identify these waves in radiosonde data or in model outputs. The models generate and track the waves in a realistic manner and over the small sample studied the model agrees with observations. The lifetime of the waves is such that their position can be predicted several days ahead. It has been further shown that, at least in the west, they have a significant modulating effect on the rainfall. Characteristics of the storms in wet and dry periods have been identified. The dry periods tend to have localised short lived storms while in the wet periods the storms tend to form within a generally cloudy background, be slow moving and merge into large clusters. Another hint was obtained in the same study that the waves may be modulating the squall lines which pass through them giving rise to the very large storms which are observed in the satellite imagery. (Note, squall lines move at twice the speed of the waves.)

6. Suggestions for developing forecasting tools and for further studies

Most meteorological services in Africa now have ready access to the analysis and forecast products from the global numerical prediction models either through the Meteorological Data Dissemination (MDD) system or through the Global Telecommunications System (GTS) of the World Meteorological Organisation. This project has been aimed at improving the forecasting of West Africa weather by harnessing the predictive capability of the models for the larger features of the extratropical flow. The study has sought to establish which features of the tropical circulation are associated with the mesoscale convective systems that produce most of the West African rainfall and how these tropical features relate to the extra-tropical situation. As the observational network in Africa has deteriorated increasing reliance is placed on the products of the NWP models. It is therefore important to confirm that the traditional forecasting indicators are still applicable when working with model outputs.

This study has revealed or confirmed several important aspects of the atmospheric circulation which influence the development of the West African wet season and of the variations of the weather within the season. It is encouraging that there is usually good agreement between the NWP model fields, radiosonde observations and satellite derived convection indicators. This gives some confidence in using the model fields, analyses and forecasts, as a basis for medium range forecasting in the region. Despite the models' rainfall fields being unrealistic in the continental tropics the 400mb omega fields, which integrate many of the models' features, are in general agreement with the CCD over West Africa. However, there are occasions when the omega analyses do differ significantly from the observations so the use of forecasts of omega may not yet be advisable.

Features of the low level flow have been identified which are associated with enhanced convection on scales of ten days or more. Strong recurvature of the southern hemisphere flow on crossing the equator so that they enter West Africa from the west increases rainfall south of 10°N. The northern inflow at 700mb is also important. Flow down the west coast enhances convection to the west of the meridian and from the central or eastern Mediterranean has more effect on the eastern part of the region. These northern 700mb flows are controlled by the slowly changing positions of the sub-tropical anticyclones and by the passage of large mid- latitude troughs. The model analyses of the southern Atlantic troposphere are lacking in features which change on ten or twenty-day time scales. While less variation may be expected in the south than in the north, one suspects that the uniformity of the fields may be due to the sparsity of data causing the model to produce climatology.

The precise role of the mid tropospheric African easterly jet is not clear. Its seasonal characteristics have been described in section 4 but what its precise relationship to the higher level tropical easterly jet and what are the controlling roles of the jet on the formation of squall lines are not clear. This topic is a good candidate for mesoscale numerical model experiments where the influence of different factors may be determined.

It is observed that convection usually extends four or five degrees north of the 700mb jet position. However the small scale fluctuations in the position of the jet have a longer time constant than those of the convection. This offers the possibility of deciding whether shifts in the latitude of convection are short term fluctuations or trends.

It is disappointing that we have been unable to link the extended break in the rains in West African coastal areas in 1992 to extra-tropical influences. This persistent feature was marked by light southerly winds north of the equator but significant differences in the southern hemisphere flow was not observed. As this feature was also observed in the model 400mb omega field it should be amenable to model experiments.

Study of the easterly waves on the 850 and 700mb flows proved profitable and should be pursued further by meteorologists in West Africa. The Hoffmuller type analysis should be extended to a longer data set and the input data filtered to remove orographic effects. The use of 700mb data may also aid the early identification of the waves in the east so increasing the lead time of forecasts for areas to the west. Single station analysis of selected radiosonde station data can also be used to identify and predict future wave positions. The ECMWF model appears to give good positioning of the waves and the forecasting capability needs to be tested. It has been demonstrated that the waves do modulate precipitation over the western part of the region. This needs to be extended to other regions where the waves are less strong and the nature of the influence to be established. Hints about the links between waves and storm development and structure came from the study of storm film loops which indicated strong interaction between waves and squall lines which pass through them.

Effort has been concentrated on the real time fields rather than the modelled forecast fields so the predictive capability of the models for the relevant fields needs testing.

A particular shortcoming of this study is that none of the findings have been rigorously tested or placed on a quantitative basis. Nevertheless several important results have been obtained which are able to hint where forecasters should to look to improve their skills. Also several specific areas are noted where further focused studies may be expected to yield useful results.

As with any broad ranging short term research more questions are raised than answered. Perhaps we have learned the right questions!