Tellus (1983), *35A*, 189–197

Satellite observations of the southern hemisphere monsoon during Winter MONEX

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(Manuscript received May 7; in final form September 13, 1982)

ABSTRACT

Time–longitude strips of infrared GMS satellite imagery have been used to study the southern hemisphere summer monsoon during Winter MONEX. This representation reveals a sudden monsoon onset in late December characterized by a transition to spatially organized convection. Active and break regions of the monsoon show a strong coherence in time but are very longitudinally dependent. The latitudinal dependence, on the other hand, is quite weak. The dominant spatial scale over which changes in convection take place is of order 35 degrees longitude by 15 degrees latitude. These synoptic scale convective regions can move in either the eastward or westward direction. Typical phase speeds of movement range between 3 and 8 degrees longitude per day. Tropical cyclones in the region are revealed to be embedded in the large-scale monsoon circulation.

1. Introduction

This study was originally motivated by a consideration of the role of lower tropospheric easterly waves in the forcing of tropical convection north of Australia. The literature pertaining to the northern hemisphere contains much information on the importance of these westward propagating perturbations in the wind field for the modulation and enhancement of tropical cumulonimbus activity (e.g. Riehl, 1945, 1954; Chang, 1970; Frank, 1969, 1975; Reed and Recker, 1971; Reed et al., 1977; McBride and Gray, 1980).

The simplest means of demonstrating the existence of the waves is by the use of longitude–time sections constructed from successive daily satellite photographs cut into thin zonal strips. The use of this technique by Chang (1970) and Reed and Recker (1971) for the 5–10° N and 10–15° N latitude strips over the North West Pacific Ocean during July–September revealed a diagonally striped pattern made up of a regular sequence of cloud clusters propagating westward at a speed of approximately 7° longitude per day at a frequency of one every 4–5 days.

There has been much discussion among southern hemisphere tropical forecasters as to the existence or frequency of similar disturbances in their region. Beginning with the southern hemisphere summer of 1978–79, full-earth disc infrared satellite images have been operationally available in the Australian Bureau of Meteorology from the Japanese Meteorological Agency geostationary satellite, GMS-1. Accordingly it was decided to use these images to construct time–longitude sections for the southern hemisphere tropics. These are shown in Fig. 1 for the period December, 1978–March, 1979 for the four latitude belts 0–5, 5–10, 10–15 and 15–20° S. The time resolution is once per day at 00 GMT (approximately 09 local time). Imagery at this time of day is little affected by diurnal enhancement of convection due to solar heating of land.

There is no indication in the figure of the characteristic pattern described above associated with a series of westward propagating easterly waves. However, from a visual inspection of the figure a number of other inferences can immediately be made on the large-scale organization of tropical convection in the region. It is con-

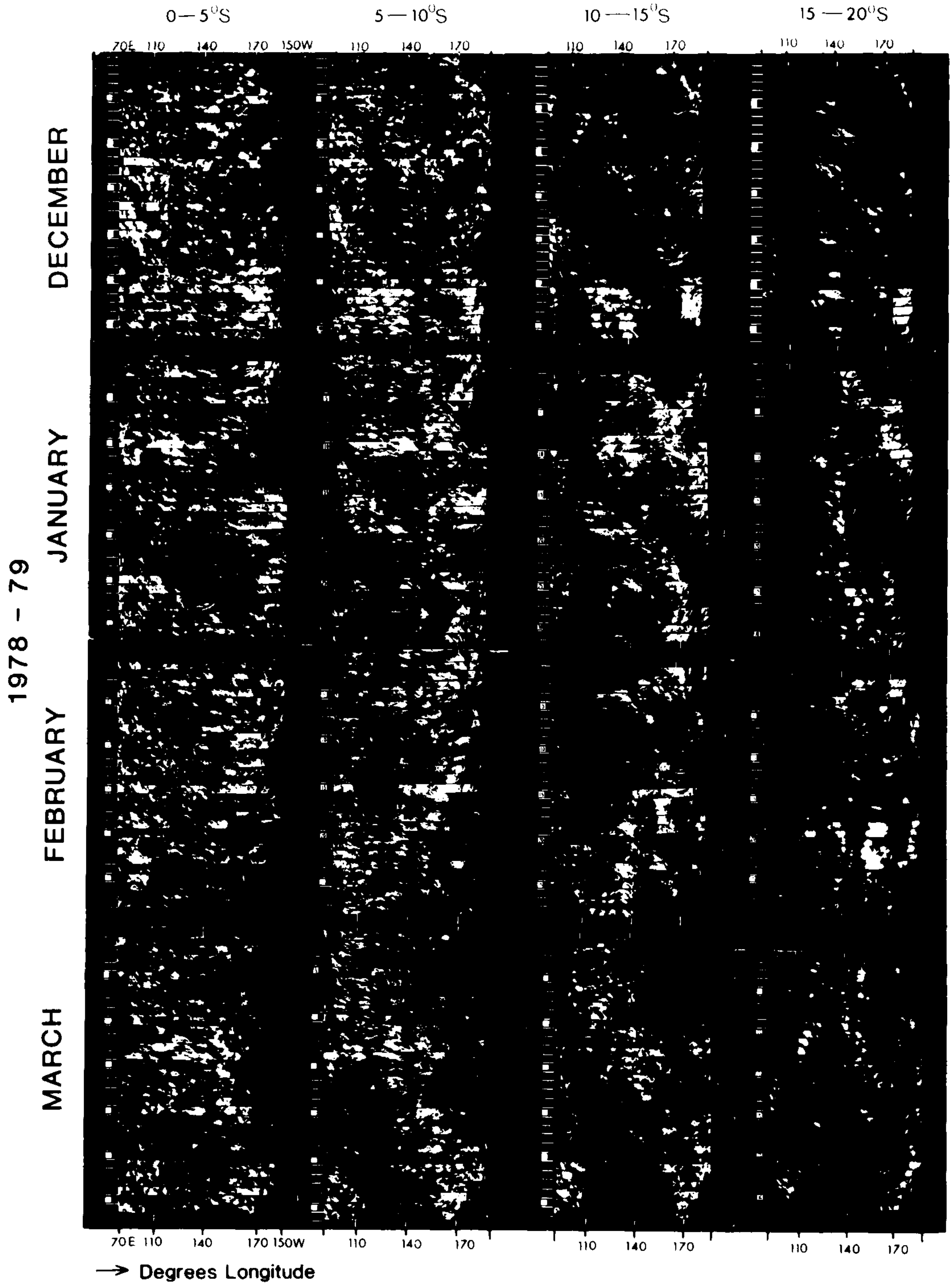

Fig. 1. Time–longitude representation of Geostationary Meteorological Satellite (GMS) infrared imagery for the latitude intervals of 0–5, 5–10, 10–15 and 15–20° S for the Southern Hemisphere summer of 1978–79.

sidered that these are of sufficient importance to warrant publication in this short note prior to an extensive analysis.

2. The southern hemisphere summer monsoon

The Japanese geostationary satellite is located above the equator at 140° E. The base chart in Fig. 2 shows the southern portion of the area covered by the resultant full-disc image. The heavily outlined region delineates the area of the time–longitude strips shown in this paper (Fig. 1). The period spanned by the satellite strips of Fig. 1 includes the field phase of the International Monsoon Experiment, Winter MONEX, which extended from December 1, 1978 to March 5, 1979. The focus of field experiment activity during Winter MONEX was concentrated in the South China Sea north of Borneo, as indicated on Fig. 2. A major component of the surrounding large-scale flow during the experiment, however, was the southern hemisphere monsoon circulation. The geographical extent of the southern hemisphere monsoon can be defined as the extent of near-equatorial upper-level easterlies and low-level westerlies. This has been determined from the climatological wind charts of Sadler (1975) and Atkinson and Sadler (1970). Accordingly, the extent of the monsoon circulation is represented on Fig. 2 by the dashed line which is the climatological position at the gradient level (approximately 900 mb) of the monsoon shear line separating trade wind easterlies from equatorial westerlies. At upper levels, the circulation is bounded by the 200 mb ridge line (the dotted line on Fig. 2) which separates mid-latitude westerlies from low-latitude easterlies. The locations of both lines show that the area of the time–longitude strips of Fig. 1 is essentially that of the southern hemisphere monsoon, and consequently the figure will be interpreted in that context.

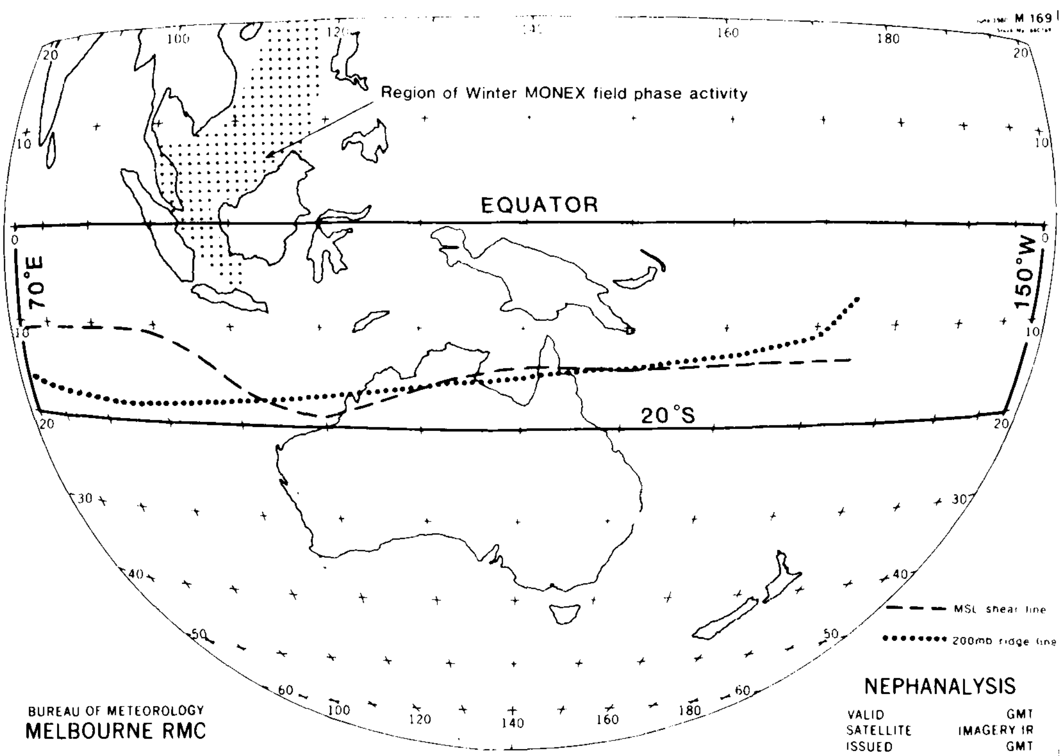

Fig. 2. Base chart showing the southern portion of the area covered by the full disc image of the GMS satellite. The heavily outlined region delineates the area of the time–longitude strips shown in Fig. 1. Also shown are the climatological locations of the low-level monsoon shear line (dashed) and the upper-level subtropical ridge (dots).

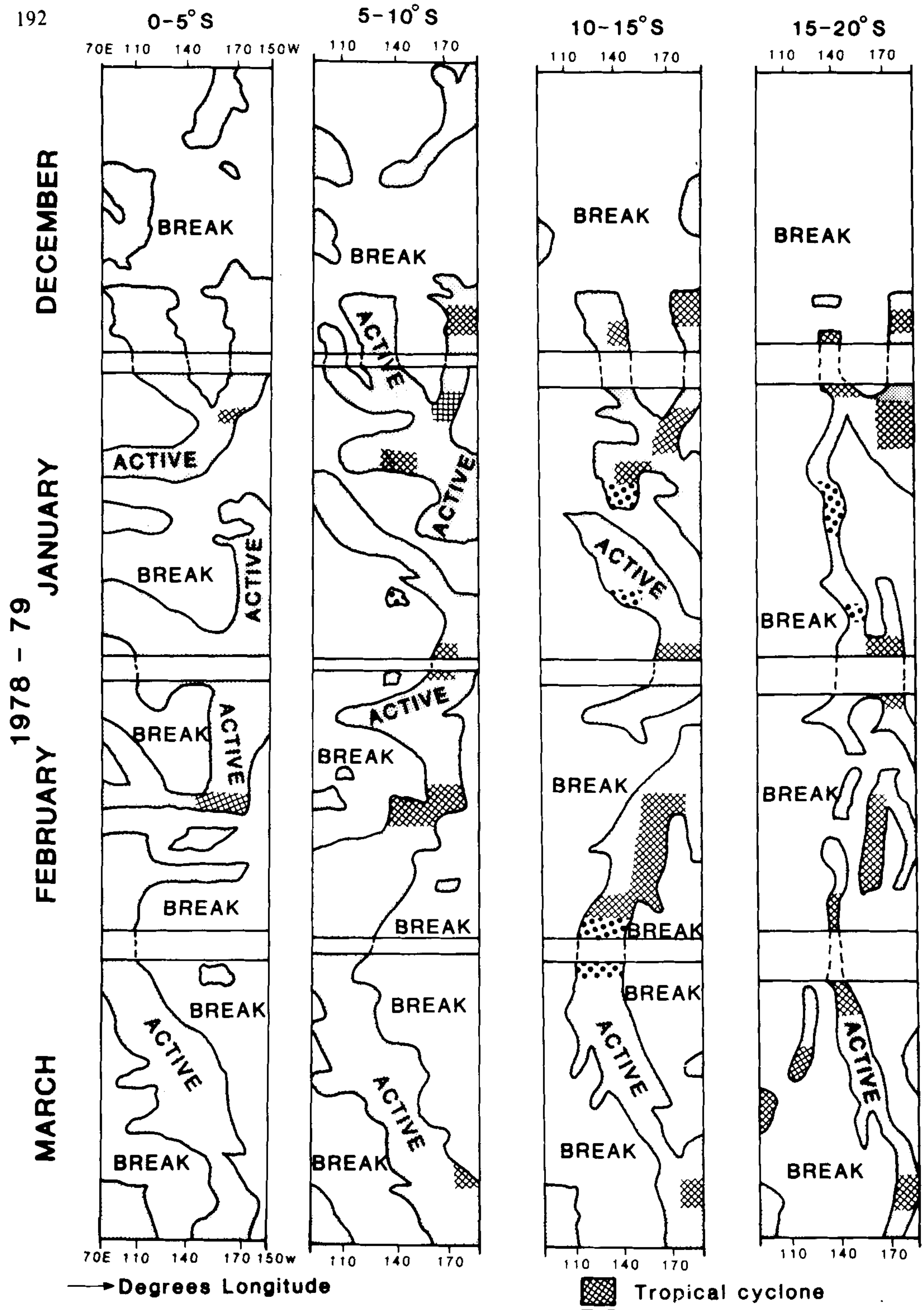

Fig. 3. Schematic representation of the main bands of cloudiness depicted in Fig. 1.

Fig. 3 shows a schematic representation of the main movements of upper level cloud. The figure is on the same scale as Fig. 1 and was constructed by overlaying tracing paper on that figure. The shaded regions on Fig. 3 represent the upper-level cloud (which is white coloured on Fig. 1). Experience with the GMS-1 photographic infrared imagery has shown that these clouds all have tops higher than the 300 mb level. They are entirely convective in origin, and on the basis of synoptic and observational experience will here be interpreted synonymously with areas of upward vertical motion or rainfall. The cross-hatched areas of Fig. 3 represent the cloudiness that can be associated with tropical cyclones (hurricanes or typhoons). The dotted regions are cloudiness associated with monsoon depressions, which are here defined as synoptic scale low-pressure systems located over land within the monsoon trough and with maximum intensity near the 700 mb level.

Inspection of Figs. 1 and 3 leads to the following conclusions on the large-scale organization of convection during the 1978–1979 southern hemisphere monsoon. They are presented below in a concise form. Certain of them will be expanded upon in the subsequent section.

(a) A marked onset of the monsoon can be seen in the sudden transition to spatially organized convection on December 26. This onset date corresponds well with dates determined by more traditionally used objective criteria based on westerly wind strength and area-averaged rainfall.

(b) The zone of maximum cloudiness lies in the 0–5° and 5–10° S latitude bands, as has been observed earlier by Kornfield and Hasler (1969), Zangvil (1975) and Murakami (1980). It is noteworthy that this is equatorward of the climatological position of the low level monsoon shear line during January–February. Thus the cloud exists predominantly in low-level westerly flow.

(c) Interpreting the major movements or bands of convective and suppressed conditions in terms of the traditional monsoon terminology of *active* and *break* phases, these phases have a strong longitudinal dependence.

(d) Conversely, the obvious correlations apparent in the figures between cloudiness bands in adjoining latitudinal strips demonstrate that the latitudinal dependence of active and break phases is quite weak. Thus a convective or active monsoon period over Darwin (for example) is not associated with the equatorial cloud zone moving southwards but rather with a longitudinally localized enhancement of convection at all latitudes between 0 and 20° S.

(e) The spatial scale over which changes in convection take place is of order 35 degrees longitude by 15 degrees latitude. The cloud cluster scale (approximately 10 degrees by 10 degrees) is also present, but is embedded within the larger scale monsoon cloudiness outlined by the shading in Fig. 3.

(f) The major bands of cloudiness depicted in the figures have a slow spread of movement. The dominant impression gained from the figures is a sloshing back and forwards across the strip, rather than of any favoured direction of propagation. There is no indication of the characteristic pattern associated with a series of westward propagating "easterly waves", as has been documented by several authors for the North West Pacific (e.g. Chang, 1970, Reed and Recker, 1971).

(g) The cloudiness associated with tropical cyclones is marked by the hatched regions on Fig. 3. The longitude–time representation reveals a close relationship between the cyclones and the monsoon circulation. The cyclones are generated within the broad bands of monsoon cloudiness and tend to remain embedded within these bands throughout their lifetime.

3. Discussion

A surprising aspect of Fig. 1 is the suddenness or very marked nature of the transition from scattered random convection in early and mid December to spatially organized convection from 26 December onwards. The subjective impression gained from visual inspection of daily satellite photos for other years is that such a well-defined transition is a common feature but is not always the case. A more definite statement on interannual variability must await the construction of time–longitude strips for a number of years.

That the onset of large-scale organized convection corresponds to the onset of the monsoon can be verified by reference to other criteria for monsoon onset. The monsoonal nature of the summer circulation north of Australia was first demonstrated quantitatively by Troup (1961). He demonstrated that in the region of Darwin

(12°26′S, 130°52′E) organized rain events in the peak of the wet season are accompanied by spells of moderate strength westerly winds at low levels. Using observed rainfall at six stations close to Darwin he defined monsoon onset as the beginning of the first objectively defined rainfall event. He demonstrated that the onset defined in this manner corresponds to a marked large-scale change in the atmospheric circulation. In the years studied, the change was preceded by a sudden increase in the 200 mb level easterlies at Cocos Island (12°05′S, 96°53′E) and was accompanied by a marked increase in both low-level westerlies and upper-level easterlies at Darwin. Radok and Grant (1957) and Radok (1971) showed that the onset of the southern hemisphere monsoon is accompanied by a sudden shift southward of the southern hemisphere subtropical jet stream.

Table 1 shows the dates on which each of these large scale atmospheric changes took place during the 1978–79 season. The table leaves no doubt that the change to organized convection seen on the time longitude strips is related to the onset of the monsoon as defined by traditionally-used quantitative criteria.

The strong longitudinal dependence of the active and break regions of monsoon activity shown in Figs. 1 and 3 has to the author's knowledge not been previously commented on in the literature. Inspection of the figures reveals that if a restricted longitudinal band, say 20° wide, is considered in isolation, its time series of cloudiness has the character of alternate sequences of enhanced (active) and suppressed (break) convective activity. Looking at a wider longitudinal span, however, at the time of monsoon onset in late December a number of major bands of convection are established. These bands gradually move backwards and forwards across the domain, but on any given date through the season they are present at some longitude. Thus on any date there exists some longitude at which the monsoon is active.

Despite this there are fluctuations in intensity and amount of cloudiness throughout the season, and the question that immediately arises is whether these correspond to changes in the overall large scale atmospheric structure. Some indication of this can be obtained from an inspection of Fig. 4 (taken from Murakami and Sumi, 1981). This figure shows a time–longitude section at 10° S of the

Table 1. *Dates on which large scale changes in the atmosphere occurred in association with the onset of the southern hemisphere monsoon*

Signatures of monsoon onset	Date during 1978–79 season
A: Antecedent condition	
Intensification of upper level easterlies at Cocos Is. (Troup, 1961)	18 December
B: Onset definitions	
Low level westerly wind increase at Darwin (Troup, 1961)	24 December
Upper level easterly wind increase at Darwin (Troup, 1961)	28 December
Areal averaged rainfall spell at Darwin (Troup, 1961)	7 January
Southward shift of southern hemisphere subtropical jet stream (Radok and Grant, 1957; Radok, 1971)	28 December
Time–longitude satellite observations (this study)	26 December

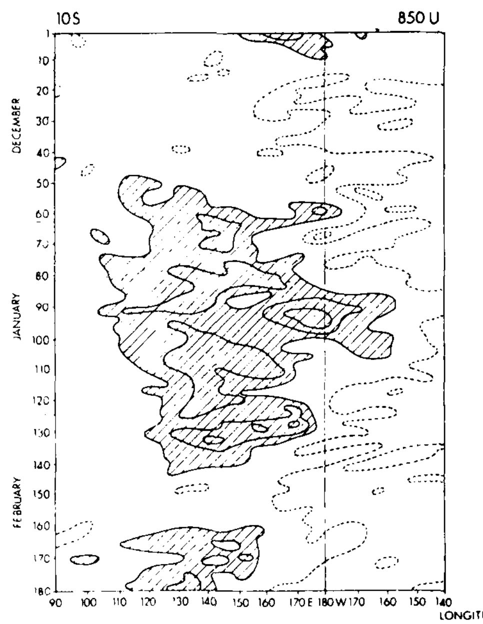

Fig. 4. Longitude–time (twice-daily, i = 1 to 180) sections of the zonal wind (m s^{-1} unit) along 10° S at 850 mb for the period December, 1978 to February, 1979. Full (dashed) lines represent positive (negative) intervals of 5 units (no zero line). Hatching denotes regions of greater than +5 units. Figure taken from Murakami and Sumi (1981).

zonal component of the wind at the 850 mb level. The general association between monsoon activity and low-level westerly wind demonstrated by Troup (1961) is apparent in the figure. The onset of organized convection in late December seen in Fig. 1 coincides with an onset of a wide band of westerlies in Fig. 4. Also the "break" in the westerlies lasting for about 6 days from 10 to 15 February in Fig. 4 occurs during a period of relative minimum of cloudiness in Fig. 1. The cloudiness–westerly wind association is only a weak one, however, as the zonal wind field in Fig. 4 shows no features corresponding to the major bands of cloudiness in Fig. 1. Also the relative minimum in the cloud field extends from 26 January to approximately 15 February; thus it is established 15 days earlier than the "break" in the westerlies.

The major bands of cloudiness depicted in Figs. 1 and 3 have both eastward and westward propagating components. Looking particularly at the 5–10° S and 10–15° S latitude strips, three major eastward movements can be seen. The first takes place from 26 December to mid-January at a phase speed of approximately 3 degrees longitude per day, the second from mid-January to the end of January at approximately 5 degrees per day, and the third throughout the month of March at 4 degrees per day. In addition, three major westward movements can be seen: 1 to 12 January at 5 deg day^{-1}; late January to early February at 8 deg day^{-1}; early February to the end of February at 4 deg day^{-1}. Based on discussions in the papers by Wallace (1971), Madden and Julian (1971) and in particular Wallace and Chang (1972), it is likely that these eastward and westward propagating cloud movements can be interpreted in terms of the Kelvin wave (eastward) and low-order Rossby wave (westward) solutions of the Laplace Tidal Equations, but such an interpretation would require a detailed analysis of the pressure and wind fields. Some analysis of one of the eastward movements in Fig. 1 has been performed by Williams (1979).

It is further noted that the westward movement from 1 to 12 January finishes at the longitude of the beginning of the eastward movement from mid January to the end of January. This in turn finishes at the beginning longitude of the westward movement through February, which in turn ends at the beginning of the eastward movement through March. Thus over the 3-month period, January to March, there is a semi-continuous movement of cloud backward and forward across the strip with a periodicity of 45 days. This is possibly related to the 40–50 day global scale oscillation documented by Madden and Julian (1972) to exist in tropical surface pressure and upper and lower tropospheric zonal wind fields.

It is important to emphasize that the westward moving cloud zones in Fig. 1 are of a different nature to the easterly waves seen in the cloud composites of Chang (1970) and Reed and Recker (1971). The major differences are in the horizontal scale of the cloudiness (35 degrees longitude here versus less than 10 degrees in the North Pacific) and in the frequency of the eastward moving cloud zones (3 in four months here versus one every 4–5 days in the North Pacific). As stated in the introduction, the original impetus for this study was to search for the North Pacific-type 4–5 day easterly waves in the Australian region. Fig. 1 shows that they did not occur in this region during the 1978–79 southern hemisphere summer. In retrospect, this is not surprising for the low-level wind flow is of a monsoon shear line nature or easterly-westerly transition region rather than being a trade wind easterly flow. The climatological location of the low-level monsoon shear line is marked by the dashed line on Fig. 2. The shear line finishes near the date line so that further east in the South Central Pacific the flow at low latitudes is trade wind easterly. Inspection of NOAA digital mosaic satellite pictures plus correspondence with New Zealand meteorologists indicates that at times the 4–5 day easterly waves are present in this trade wind region.

Referring back to Fig. 3, the cross-hatched portions of the figure represent the cloudiness directly associated with tropical cyclones. Particularly in the 10–15 and 15–20° strips the cyclones make up a major portion of the monsoon cloudiness. This is substantiated by the results of an unpublished rainfall study performed by the author. Wet season (November–April) rainfall was analyzed for 5 seasons for 10 stations located between 9 and 21° S. Tropical cyclones contributed on average 19 per cent of the seasonal precipitation. The amounts varied from as little as 6 per cent for an inland continental station (Mt. Isa, 20°44′ S, 139°28′E) to as high as 27 per cent for a station on Australia's east coast (Townsville, 19°15′ S, 146°46′ E).

4. Concluding remarks

The time–longitude representation of the infrared satellite imagery has proven to be an extremely revealing tool for gaining an initial appreciation of the structure of the southern hemisphere summer monsoon. Features of note include very marked monsoon onset in late December and a strong time continuity in the organized convection. This latter aspect indicates that the time–longitude strips should be useful in tropical forecast offices.

The time variation of satellite-observed upper-level cloud cover has been interpreted in terms of the "active" and "break" terminology which has evolved in the context of the northern hemisphere or Indian summer monsoon. This immediately raises the question as to the extent to which features of the large-scale organization of cloud here documented are paralleled in the summer monsoon of the northern hemisphere. Relevant northern hemisphere studies are those of Murakami (1976), Yasunari (1979) and Sikka and Gadgil (1980). With the qualification that those papers used different analysis techniques to the time–longitude representation in the current paper, comparison with the current study indicates major differences between the two summer monsoons.

The current study shows that active and break phases have a strong longitudinal dependence and only a weak dependence on latitude. The above authors on the other hand demonstrate the Indian monsoon is characterized by bands of cloudiness covering a range of longitudes, and that the time variation of cloudiness at a particular longitude is governed largely by the *in situ* development and subsequent northward movement of these bands. This implies that convectively enhanced (active) and suppressed (break) phases are dependent mainly on latitude and only weakly on longitude; i.e. they are of opposite character to those in the southern hemisphere.

Being in the deep tropics, the upper-level cloud observed on the satellite strips in the current paper is convective in origin. Research on tropical convection performed in the GARP Atlantic Tropical Experiment (GATE) has been reviewed by Houze and Betts (1981). According to that research, tropical cumulonimbus clouds tend to group in mesoscale precipitation features (MPF's). The MPF contains both active cumulus cells and upper-level anvil or stratiform cloud sheets which develop from cumulonimbus cells. Analysis of radar data in GATE (Houze, 1977; Leary and Houze, 1979) and in Winter MONEX (Houze et al., 1981) shows the scale of an MPF to be typically 100 to 150 km (slightly larger than 1 degree of latitude).

The regions of upper-level cloudiness or enhanced convection seen in Fig. 1 span up to 15 degrees of latitude. Since the scale of the actual mesoscale convective elements is only of order 1 degree, this implies that the convection in the region is governed by low-level convergence spanning up to 15 degrees in the latitudinal direction. This is a very different picture to the traditional view of the Inter Tropical Convergence Zone (ITCZ) being a narrow band of convergence. Webster and Stephens (1980) present evidence that in Winter MONEX, upper-level cloud decks can extend as far as 700 km from any identifiable convective source. Even if this latter view proves correct, there is still a requirement for at least two convective sources at each longitude, rather than one narrow ITCZ.

Perhaps the most important feature revealed by the time–longitude representation is that the major changes in organized convection take place over the synoptic scale (e.g. 35 degrees longitude by 15 degrees latitude). This gives some hope for the eventual success of numerical weather prediction in the region as it seems likely that these changes could be simulated by the primitive equations driven by the appropriate heat sources and sinks over that same synoptic scale.

5. Acknowledgements

The author acknowledges several informative discussions with Drs. T. D. Keenan and P. J. Webster.

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