

## The Australian monsoon, Part 2: Depressions and cyclones

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**सार** - दक्षिणी ग्रीष्मकाल के समय, ऑस्ट्रेलिया के क्षेत्र के एन.सी.ई.पी./ एन.सी.ए.आर.के पुनः विश्लेषण से यह पता चलता है कि इस क्षेत्र के अधिकांश अवदाब और चक्रवात अप्रगामी लहर में बनते और विकसित होते हैं, यह लहर धरातल समुद्र की तापीय विषमता के कारण इस अवधि के दौरान इस महाद्वीप की उत्तरी तटीय रेखा के साथ-साथ विकसित होती है। इस शोध-पत्र में अप्रगामी तरंग की संरचना और विशेषताओं के बारे में विस्तार से बताया गया है तथा आंतरिक एवं बाह्य प्रणोदनों के बारे में भी चर्चा की गई है जिसके कारण इस लहर से अवदाब और चक्रवात बनते हैं। जिन पर्यावरणीय कारकों द्वारा इस क्षेत्र के इन चक्रवातों की चाल और प्रतिवर्तन प्रभावित होने की संभावना है उनके विषय में दो अध्ययनों की सहायता से बताया गया है।

**ABSTRACT.** A study of the NCEP/NCAR Reanalysis for the Australian region during the southern summer reveals that most of the depressions and cyclones over the region form and develop in a stationary wave that develops along the continent's northern coastline during this period due to land-sea thermal contrast. The structure and properties of the stationary wave are brought out in detail and internal and external forcings that lead to its development into depressions and cyclones are discussed. Environmental factors that appear to influence the movement and recurvature of cyclones over the region are discussed with two case studies.

**Key words** – Australian monsoon disturbances, Depressions and cyclones in Australia, Tropical cyclones in Australian region.

### 1. Introduction

The mean monsoon circulation over Australia and surrounding oceans during the southern summer, described in Part 1 of this study (Saha and Saha, 1999), is often perturbed by the formation of depressions and cyclones. As is well-known, these disturbances are synoptic-scale low pressure systems which have cyclonic circulations around the center with maximum tangential velocity near the center of at least 17 m/s in depressions and 24 m/s or more in cyclones, as per existing official terminology in India and Australia (e.g., Rao, 1976; Bureau of Meteorology, 1956, 1978). Because of their great importance in the context of the continent's weather and climate, human safety and potential for destruction of life and property, they have received special attention of meteorologists from very early times.

Several studies (Bureau of Meteorology, 1956, 1978; Gray, 1968; Falls, 1970; Davidson *et al.*, 1983, 1984; McBride, 1981; McBride and Zehr, 1981; McBride and

Keenan, 1982; Holland, 1983; Holland, 1984 a,b,c; Holland and Merrill, 1984; Love and Garden, 1984; Love, 1985a,b; McBride and Holland, 1989) have addressed the problems of their genesis, development and movement. As a result of these studies, it is now known that:

- (i) Most of the disturbances originate in the monsoon trough or shear zones over warm ocean surface close to the coast of northern Australia including the Gulf of Carpentaria and a wide strip of the southwest Pacific ocean, extending eastsoutheastward from the Coral Sea region, which is popularly known as the South Pacific Convergence Zone (SPCZ).
- (ii) In terms of cyclone days, the highest frequency of occurrence of tropical storms is in the Gulf of Carpentaria with secondary maxima in the Coral Sea region and the areas off the coast of northwestern Australia where the ocean surfaces are very warm (Holland, 1984a).

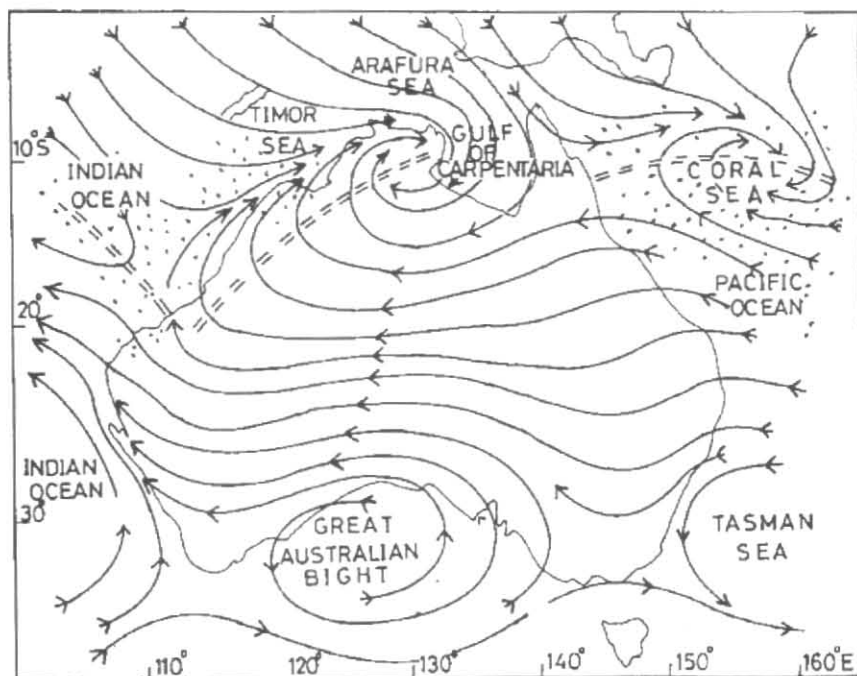


Fig.1. Mean surface air flow over Australia and surrounding areas during February, showing the approximate location of the monsoon trough (thick double-dashed line) and depressions and cyclones (dots)

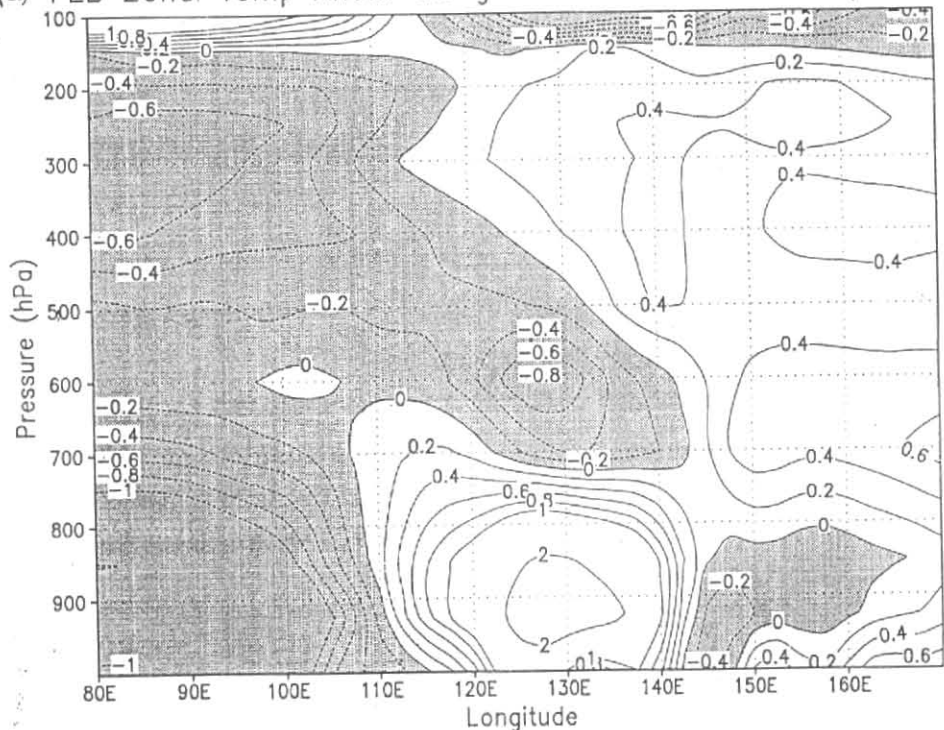
- (iii) Monsoon depressions and cyclones undergo little structural change on being transformed from one to the other, despite the fact that they differ greatly in intensity and strength from each other.
- (iv) After formation, the disturbances generally move westward or southwestward, although a large proportion of them, especially over the SW Pacific region, change course and recurve towards the south, or southeast, or even east, after development into tropical cyclones or severe tropical cyclones.
- (v) Their development often follows cold surges from the South China Sea in the north and the west Australian coast in the southwest at lower levels, and an interaction with subtropical jets at upper levels. Needless to state, these findings have contributed much to our knowledge and understanding of these disturbances. However, despite remarkable progress made, some uncertainties still remain in a few areas which call for further study. Some of these are addressed in the present study, using a dataset from NCEP/NCAR Reanalysis (Kalnay *et al.*, 1996).

The layout of Part 2 of the paper is as follows: Section 2 introduces the monsoon trough over Australia as part of a stationary wave over the region and gives details of its structure and properties. Section 3 discusses the mechanism of formation of an initial or starter vortex or depression in the monsoon stationary wave. Section 4 discusses the development of a tropical cyclone and a possible mechanism for the formation of the cyclone eye. Section 5 discusses the movement of a cyclone and presents the results of two case studies which highlight the effect of interaction of the cyclone with the environment. The findings are summarized in Section 6.

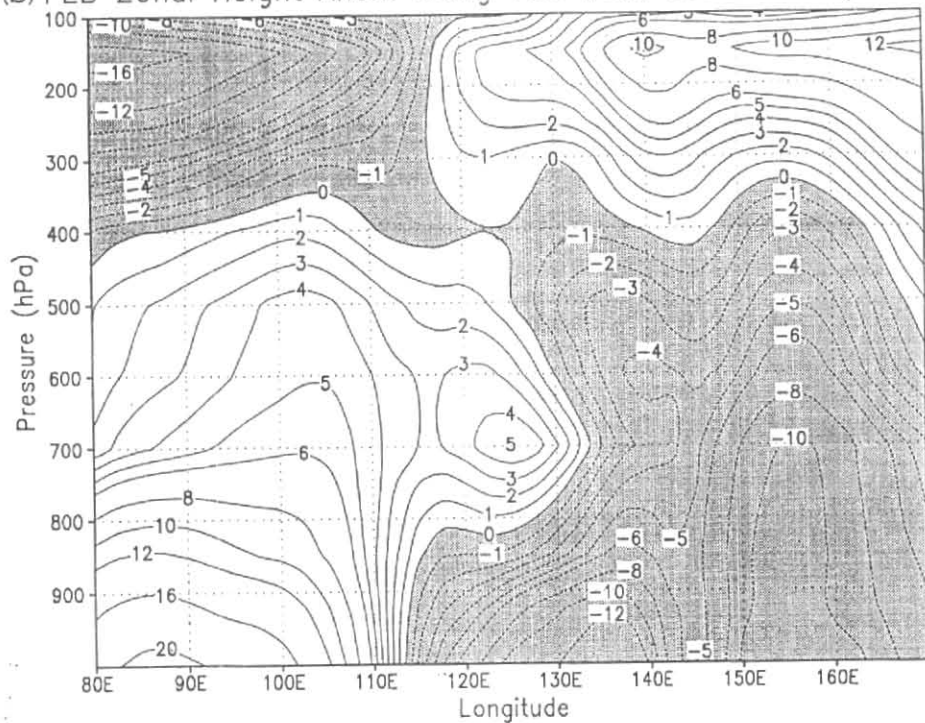
## 2. The monsoon stationary wave: its structure and properties

In the monsoon region of Australia, the tradewinds of the two hemispheres do not appear to meet directly as they do over the open oceans. Instead, they meet the heat low circulation over the continent which separates them and which they interact with along the continent's northern and southern boundaries. Due to the uneven distribution of land and sea along the northern boundary, however, the interaction between the heat low circulation

(a) FEB Zonal Temp Anom along 15S from Reanal Clim (79-96)

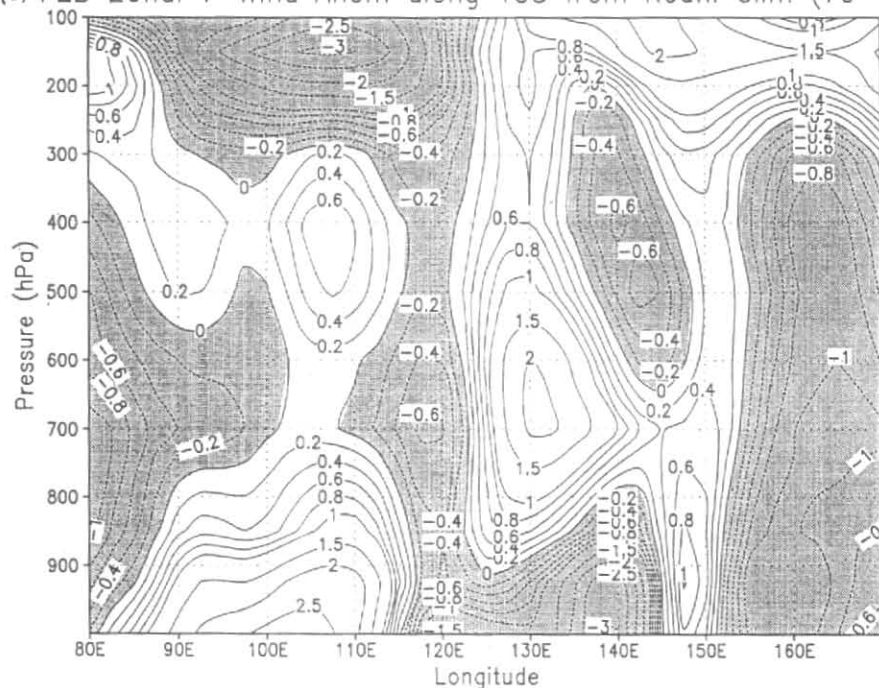


(b) FEB Zonal Height Anom along 15S from Reanal Clim (79-96)



Figs.2 (a&b). Vertical distributions of zonal anomalies of: (a) Temperature (°C), (b) Geopotential (m), along 15° S

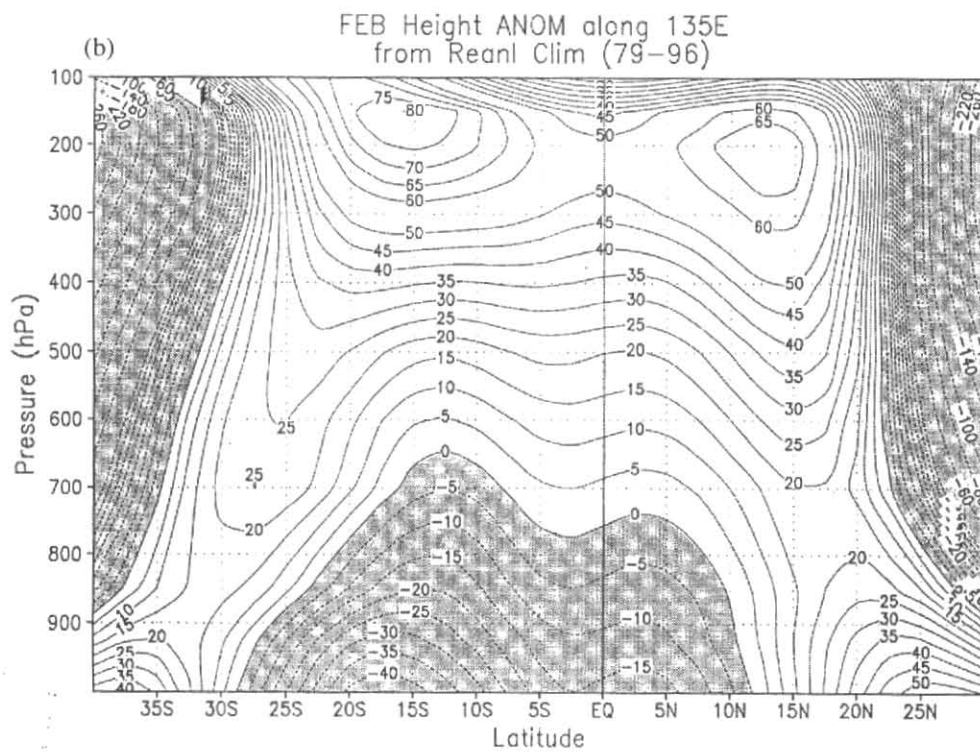
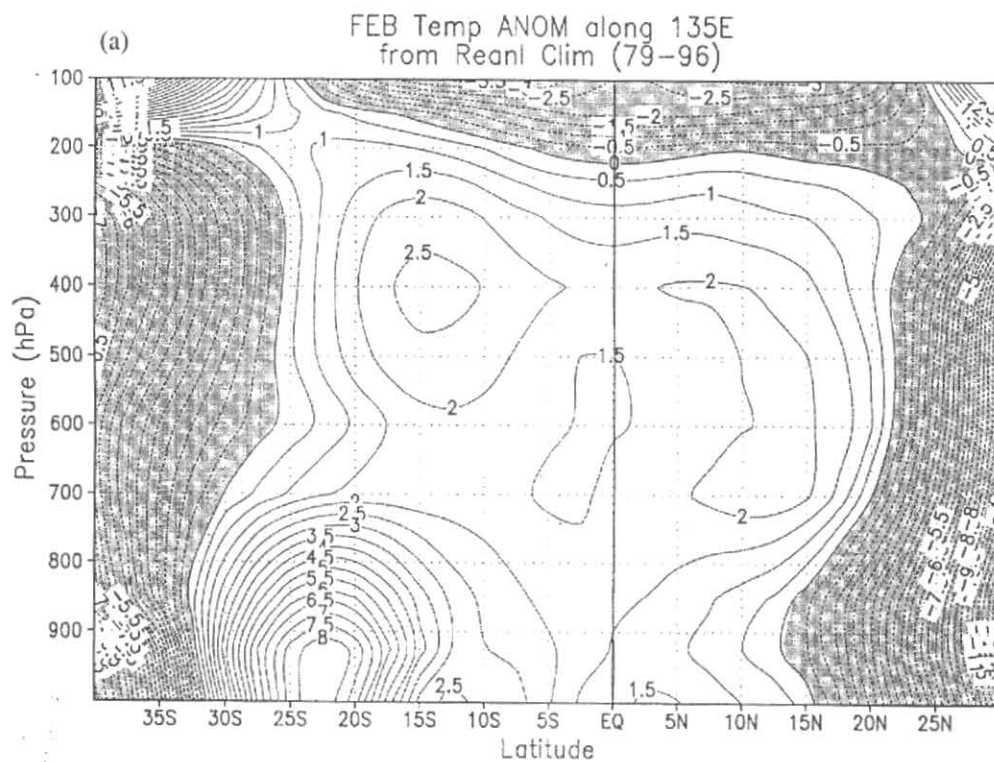
(c) FEB Zonal V-Wind Anom along 15S from Reanal Clim (79-96)

Fig.2(c). Vertical distributions of zonal anomalies of Meridional component of the wind ( $\text{ms}^{-1}$ ), along  $15^\circ\text{S}$ 

and the northern-hemispheric tradewinds, which after crossing the equator turn into a cool northwesterly wind, appears to produce a stationary wave along the northern Australian coastline and over the neighbouring oceanic area. The trough of the stationary wave forms between the warm air from the land diverging out to sea, and the cool air from the sea to its east converging onto the land. This is shown schematically in Fig.1 which indicates the approximate locations of the troughs and ridges of the stationary wave in the field of surface air flow during the Australian summer. The approximate locations of initial formation of depressions and cyclones over this region of northern Australia and neighbouring seas and oceans, as reported by several workers (Holland, 1984a), are marked by small dots in Fig.1.

Since the trough at surface is oriented in an approximately NE-SW direction, one can get an idea of its structure in space from projections onto zonal and meridional planes. Figs. 2 (a-c) show how the structure of the stationary wave varies in a zonal-vertical section along  $15^\circ\text{S}$  which intersects the troughline at about  $135^\circ\text{E}$ , in the fields of zonal anomalies of temperature, geopotential height and the meridional component of the wind respectively. While Figs.2(a&b) appear to bring out the alternate sectors of warm and cold anomalies relative to

the locations of the troughs and ridges of the stationary wave, the zonal anomaly of the meridional component of the wind Fig. 2(c) shows the alternate sectors of southerlies and northerlies, the dividing zones between them identifying the approximate locations of the troughs and ridges of the stationary wave. In Fig. 2(c), one can identify the presence of the main monsoon trough between about  $125^\circ\text{E}$  and  $140^\circ\text{E}$  over northern Australia, and a second near  $150^\circ\text{E}$  in the Coral Sea region. It is the main monsoon trough which will concern us mostly in the present study. It appears to tilt zonally with height, eastward between about 900 hPa and 700 hPa and westward between about 650 and 300 hPa. This differential tilt of the monsoon trough between the lower and the upper troposphere over Australia appears to be very similar to that found by Saha and Saha (1996) over India and would appear to be very significant in the context of the formation, development and movement of disturbances over this region, as would be pointed out in subsequent sections. The meridional structure of the trough is presented in Figs.3(a-c) which show the meridional anomaly (deviation from the meridional mean) of the same elements as in Figs.2(a-c) in a meridional section along  $135^\circ\text{E}$ . Fig.3(a) shows a strong warm anomaly over mainland Australia extending vertically to about 700 hPa, with the warmest anomaly being at the



Figs. 3(a & b). Same as Fig. 2, except for meridional anomalies along 135° E

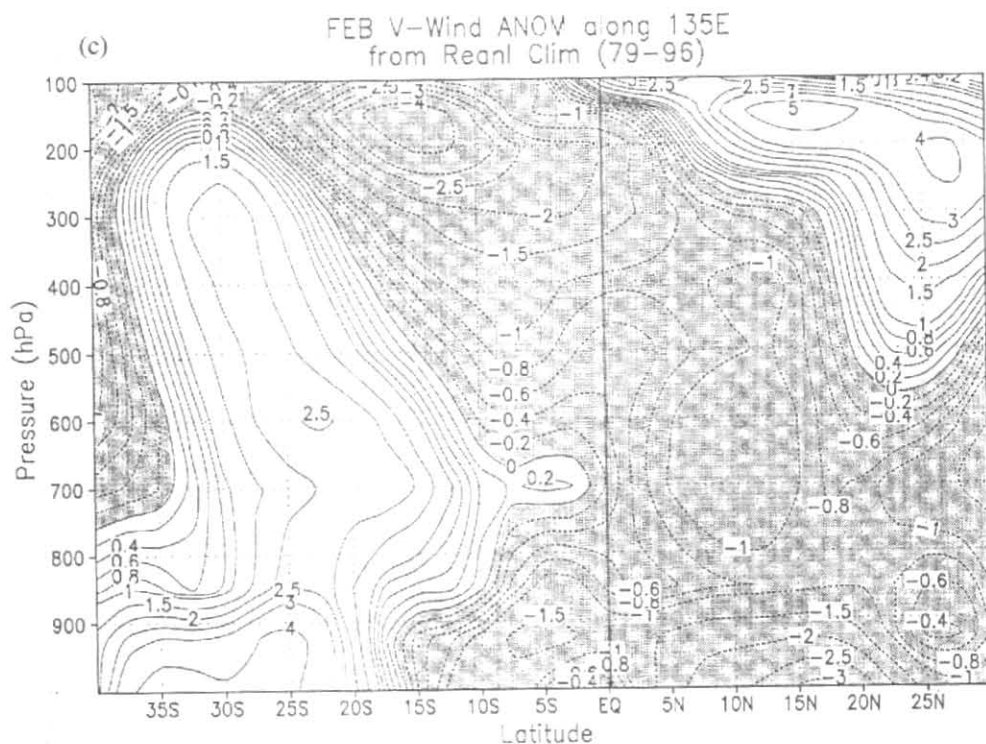


Fig.3(c). Same as Fig.2, except for meridional anomalies along 135° E

land surface between about 20°S and 25°S. The temperature generally decreases northward, though there appears to be a slightly warm area just north of the equator. The coldest anomaly in the lower troposphere appears north of about 15° N. A warm anomaly appears in the middle and upper troposphere of both the hemispheres, that in the southern hemisphere between about 5° S and 20° S and the northern hemisphere between about 5° N and 15° N. In Fig. 3(b), the 'heat low' over Australia stands out in the vertical with its associated trough axis tilting equatorward up to a height of about 650 hPa. A feeble trough of low pressure appears between the equator and about 5° N. Fig. 3(c) testifies that cold aircurrents from the northern hemisphere, after crossing the equator, converge at the monsoon trough zone over northern Australia and adjacent ocean areas. The mean meridional circulation along 135° E, deduced from Reanalysis data (see also Part 1), is presented in Fig.4. It reveals the existence of two Hadley cells, one in each hemisphere. It also shows clearly how the Hadley circulation cell of the Southern Hemisphere is lifted by the monsoon circulation over Australia in the lower troposphere.

In the sections that follow, we try to show that the basic structure of the monsoon stationary wave, as outlined above, remains largely unaltered or undergoes

minor re-organization only, as the wave develops into a low or depression, prior to its development into a mature tropical cyclone.

### 3. Formation of a depression- the starter mechanism

Since the main source of energy for a tropical cyclone is the latent heat of condensation of water vapour and the tropical atmosphere is basically conditionally unstable with the tradewind belt moisture usually confined to the very low levels of the atmosphere, a mechanism is required to lift the low-level moisture to levels well above the condensation level to start the cyclone development process. The formation of a depression in the monsoon stationary wave is thus a necessary first step to start this process. It envisages a fall of pressure in the monsoon trough zone by at least 5 to 10 millibars and can occur by increased low-level convergence and upper-level divergence. Just how these can occur is suggested in Fig.5(a) which presents an idealized view of the vertical circulations associated with the troughs and ridges of the stationary wave along latitude about 15° S, deduced from Reanalysis [Fig. 2(b)]. It shows clockwise vertical circulations associated with both the eastward-tilting lower segment and the westward-tilting upper segment of the monsoon trough and anticlockwise circulations

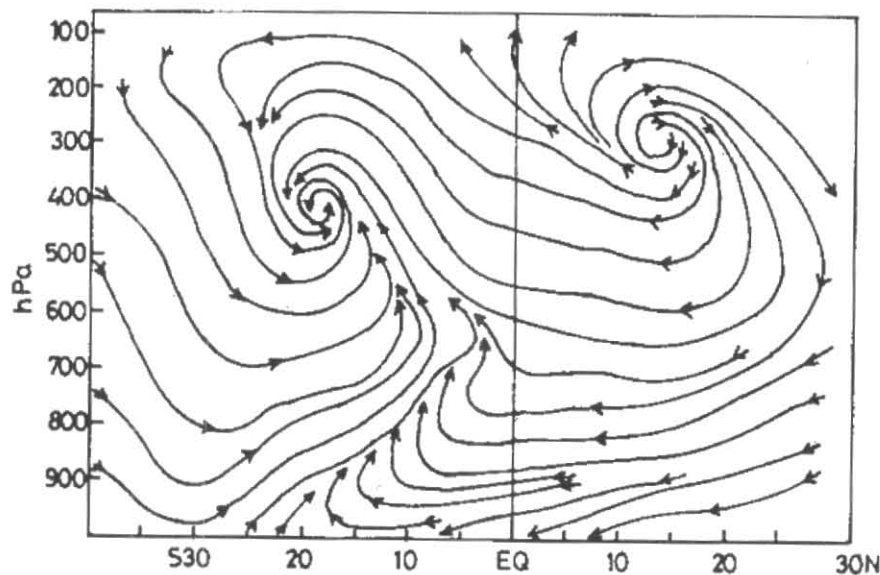


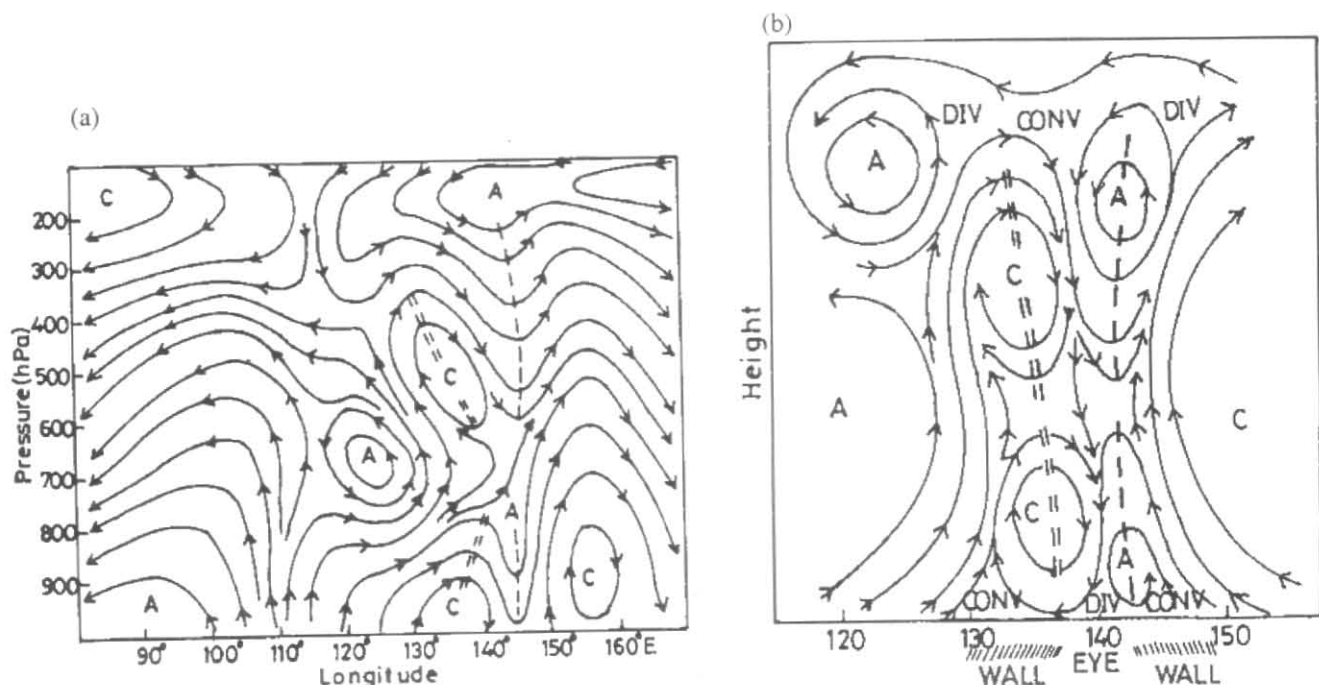
Fig.4. Meridional-vertical circulation (constructed from computed  $v$  and  $\omega$  values) along  $135^\circ$  E, showing the Hadley circulation cells of the two hemispheres relative to the monsoon trough zone over Australia

associated with the ridges of the stationary wave. In the Australian region, several mechanisms may be at work to lift the low-level tradewind moisture to higher levels, such as boundary layer convergence due to friction, also known as Ekman pumping (Charney and Eliassen, 1964), and/or barotropic or baroclinic instability of the flow. However, a study by Davidson *et al.* (1983) concludes that the barotropic mechanism may not make any significant contribution to the development of any deep convection over the region. There is a strong suggestion in Fig. 5(a) that the monsoon stationary wave has a built-in baroclinic mechanism to lift the moist monsoon air *via* a vertical overturning represented by the circulation cell associated with the lower segment of the monsoon trough. The process may be visualized as follows: An increase in low-level absolute vorticity in the monsoon trough zone by the convergence of the cold NWly air from the equatorial latitudes and the relatively warm S/SWly air from the 'heat low' circulation over Australia (see Fig.1) would produce strong upward motion which would lift low-level moisture to higher levels. However, it would appear from Fig. 5(a) that initially, at the depression stage, the moist air at the lower segment of the monsoon trough zone is lifted to a height of about 700 hPa only, since its further rise is prevented by a wedge of cold high in midtroposphere and a stable warm layer above. However, cool moist air from further west of the lower segment of the monsoon trough can rise to a level of about 300 hPa to the west of the upper segment of the trough and descend strongly over the lower segment of the trough zone. It is likely that it is this strong descent that by adiabatic

warming stabilizes the upper troposphere and thereby limits further growth. In any case, the clockwise vertical circulations associated with the monsoon trough appear to act as an effective baroclinic mechanism to lift the low-level moisture to, at least, the mid-tropospheric levels. The limitation of the cyclonic circulation to mid-tropospheric levels in monsoon depressions appears to be well borne out by observations over several parts of the tropics.

#### 4. Development of a tropical cyclone

It is a fact of observation that out of the several hundreds of tropical depressions that form over the tropics every year, only a small fraction manages to develop into tropical cyclones and that of the latter only about 50% or so develop an eye at the center. Much has been known regarding the structure and behaviour of tropical cyclones over several parts of the globe including the Australian region during the last several decades through studies using special observations from research aircraft probes, satellite-borne sensors, ground-based instruments and composited data analysis (*e.g.*, Malkus and Riehl, 1960; Black and Anthes, 1971; Gray and Shea, 1973; Hawkins and Imbembo, 1976; Frank, 1977; Gray, 1968, 1979; Sheets, 1980; Holland, 1984a,b,c) and theoretical and numerical simulation studies (for a review, see Anthes, 1982) have thrown light on several aspects of these disturbances. However, we still do not know clearly about some aspects of the development and movement of these systems, especially the mechanism that leads to the formation of the eye and the manner and consequences of



Figs. 5(a&b). Structure of the zonal-vertical circulation along 15° S, showing the cyclonic (C) and anticyclonic (A) circulation cells associated with: (a) Monsoon Stationary Wave Trough or Depression, (b) Tropical Cyclone. Double-dashed indicate Trough; Single-dashed Ridge

their interaction with the environment. As is well-known, in an axi-symmetric cyclone, the eye is characterized by subsidence, extremely low pressure and high temperature with little or no clouding or precipitation within a radius of about 20-30 km from the center and is surrounded by a wall of hurricane-force tangential winds, strong rising air currents and torrential precipitation extending to a radius of about 300 km from the center. Several spiraling cloud or rain bands are observed to be drawn into the cyclone circulation from great distances in the environment and converge at the cyclone. Regarding the formation of the eye, Anthes (1982) writes: 'As tropical storm intensifies, air rises in vigorous thunderstorms and tends to spread out horizontally near the tropopause or in the lower troposphere. As the air spreads out aloft, a positive perturbation pressure at high levels is produced, which accelerates a downward motion next to convection. With the inducement of subsidence, air warms by compression and a positive buoyancy (warm eye) is generated. Eventually, this buoyancy term grows to balance the perturbation pressure gradient term and the downward vertical acceleration decreases. At this point the interior of the storm may reach a steady state, with little or no vertical motion in the eye'. Qualitatively, it appears to us that in the Australian region, the mechanism envisaged above may, *mutatis mutandis*, be inherent in the structure of the monsoon stationary wave or depression and its associated circulation, presented in Fig.5(a), provided that the main stumbling block to further

development beyond the depression stage, *i.e.*, cold air subsidence in the upper troposphere above the lower-tropospheric convection be somehow removed. Fig.5(b) shows schematically how this may happen by a re-organization of the vertical circulation cells associated with the troughs and ridges, following development. The re-organization envisaged appears to take place when excessive condensation heating near the top of the lower troposphere over a time overcomes the vertical stability of the middle troposphere. The lower-tropospheric convection is then able to penetrate the overlying barrier and carry heat to the upper troposphere. The process may be compared to the working of a pressure cooker in which the lid valve is lifted by superheated steam when the saturation vapour pressure inside exceeds a certain pre-set value. Penetrative convection on rising to the top of the troposphere meets a stable layer near the tropopause and diverges, both inward and outward. The inward-moving branch of warm air converges near the center and descends. The subsidence leads to strong adiabatic warming of the whole atmospheric column and steep fall of pressure at the surface, and hence the eye. It is likely that the descending warm air in the eye may exchange heat with the rising air in the eye-wall somewhere in the middle troposphere, as shown in Fig.5(b). In an axi-symmetric cyclone, extraordinarily high temperatures are produced in both the eye and the eye-wall compared to the distant surroundings, but the warmest temperature and the lowest pressure are always found inside the eye (Hawkins



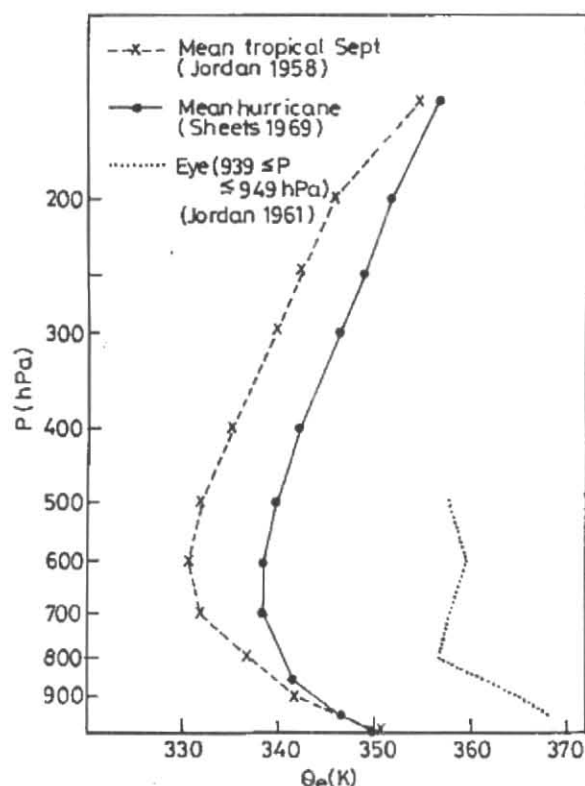


Fig. 6. Vertical profiles of equivalent potential temperature for mean tropical September sounding, mean hurricane within 100 n mi of center, and mean eye of storms with central minimum pressure between 939 hPa and 949 hPa. (taken from Anthes, 1982)

and Imbembo, 1976). This is also confirmed by actual soundings (Fig.6) which show the vertical distribution of equivalent potential temperature inside a hurricane eye as compared to that in a mean hurricane and a mean tropical atmosphere. According to Gray and Shea (1973), the temperature excess over the outer environment may be twice inside the eye than in the eye-wall. The outward-moving branch of the rising air at the top of the eye-wall also appears to play an important role in the life of the cyclone. Holland and Merrill (1984) pointed out that whenever a cyclone in the Australian region interacted with a jetstream associated with a subtropical westerly wave, there was an increased outflow from the cyclone which led to its intensification. This is not surprising considering the fact that an enhanced outflow from a warm air column caused by divergence and warm air advection should lead to a deepening of a pressure system, as given by  $\nabla^2(\partial p/\partial t)$ , where  $\partial p/\partial t$  is the pressure tendency computed from the following approximate relation derived from the simple pressure tendency equation, after neglecting the vertical velocity at the lower boundary and the slope of the isobaric surface and  $\nabla$  is the horizontal Del operator:

$$\partial p_0/\partial t = -\int_0^{p_0} [\nabla \cdot \bar{V} - (\bar{V} \cdot \nabla T)/T] \partial p \quad (1)$$

where,  $\bar{V}$  is the horizontal wind vector,

$T$  the temperature in degrees Kelvin,

$p$  the pressure,  $t$  the time and  $p_0$  the pressure at the lower boundary.

In the section that follows, we consider further application of the Eqn. (1) in dealing with the movement of tropical cyclones in the Australian region. For this purpose, we shall assume the cyclone to be in solid-body rotation, with cyclonic circulation inside and anticyclonic circulation outside interacting with the environment. Such an assumption is well supported by observations of upper-tropospheric circulation in the field of several mature tropical cyclones (Holland and Merrill, 1984; Chen and Gray, 1986; Ward and Lander, 1999).

## 5. Movement

Once formed, the movement of a cyclone is believed to be determined by its interaction with the environment. In the Australian monsoon region, the environmental flow in the upper troposphere is usually easterly and the cyclone interacting with this airstream has a tendency to move initially westward. However, if the cyclone after its development comes under the influence of a wave in the subtropical westerlies, it appears to have a tendency to recurve *via* the south to a southeasterly or easterly direction. The forces that determine the motion of a tropical cyclone embedded in an airstream with horizontal and vertical shear are not clearly known. Several methods, based mostly on climatology and persistence, and the steering method have been tried in the past to predict the movement of a cyclone in the Australian as well as other regions, but with only limited success. Even sophisticated numerical prediction models fall far short of expectations in this regard. The authors believe that in the ultimate analysis, tropical cyclones are vectored in the direction of the isallobaric gradient when in solid-body rotation they interact with the environment. In the present study, the authors tried the following kinematic relationship (Petterssen, 1956) to find an approximate direction of movement of depressions and cyclones in the Australian region:

$$\bar{C} = -\nabla(\partial p_0/\partial t)/\nabla^2 p_0 \quad (2)$$

where,  $C$  is the velocity and  $\partial p_0/\partial t$  is the pressure tendency given by Eq.(1).

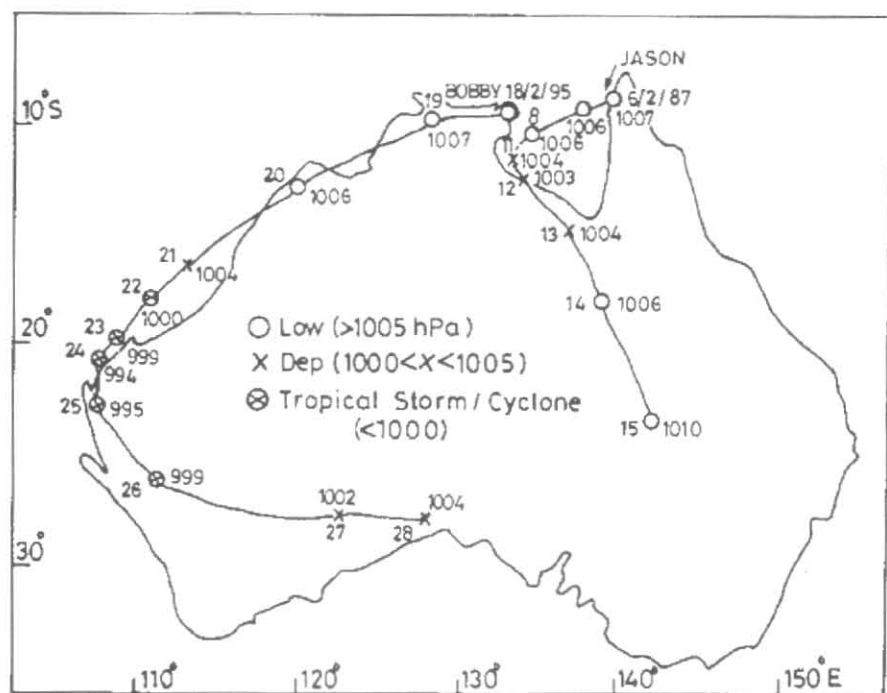


Fig.7. Diagram showing the dates, approximate locations, central pressures, intensities and tracks of the two depressions/cyclones under study, from Reanalysis

Using Eq.(1), the authors made several computations in two selected cases of tropical disturbances in the Australian region, in an attempt to test the validity of Eqn. (2), so far as the direction of motion was concerned. The movement was estimated from the gradient of the computed pressure tendency, as given by Eqn. (2). Fig.7 gives the dates, locations, central pressures, intensities and tracks of the selected disturbances, as gathered from the Reanalysis maps. The synoptic situations and the results of our computations relating to each case are briefly as follows:

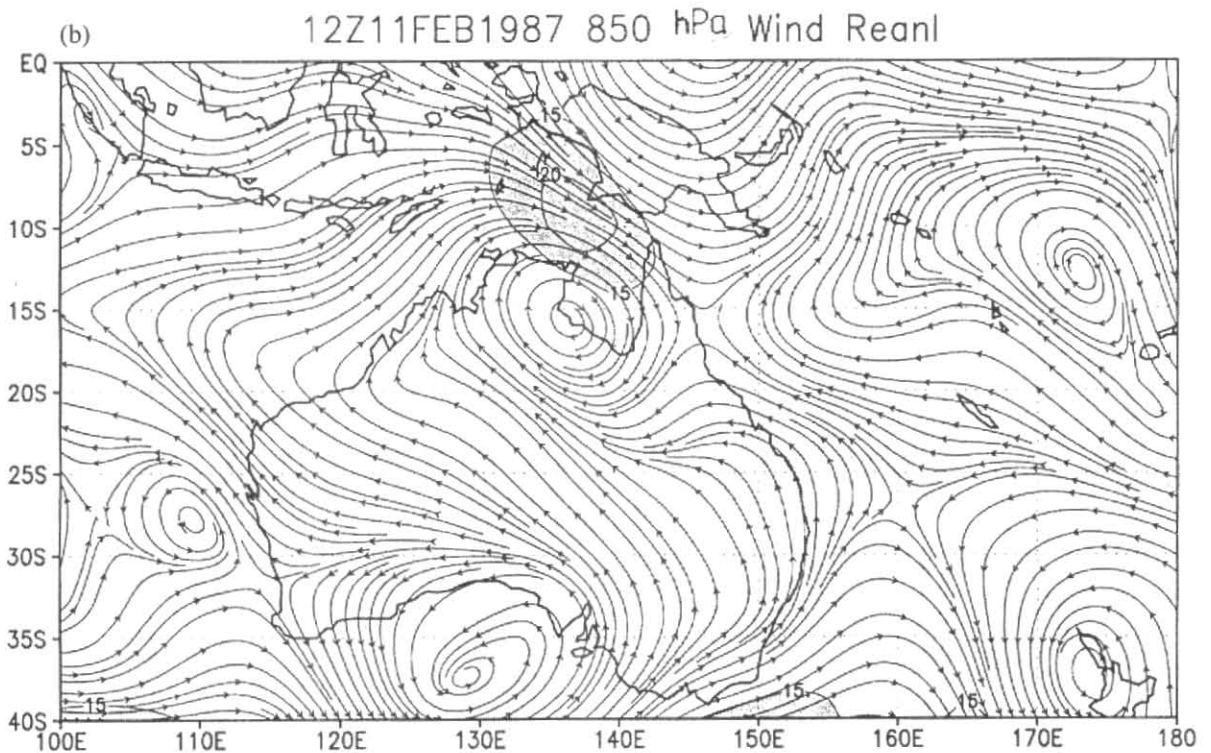
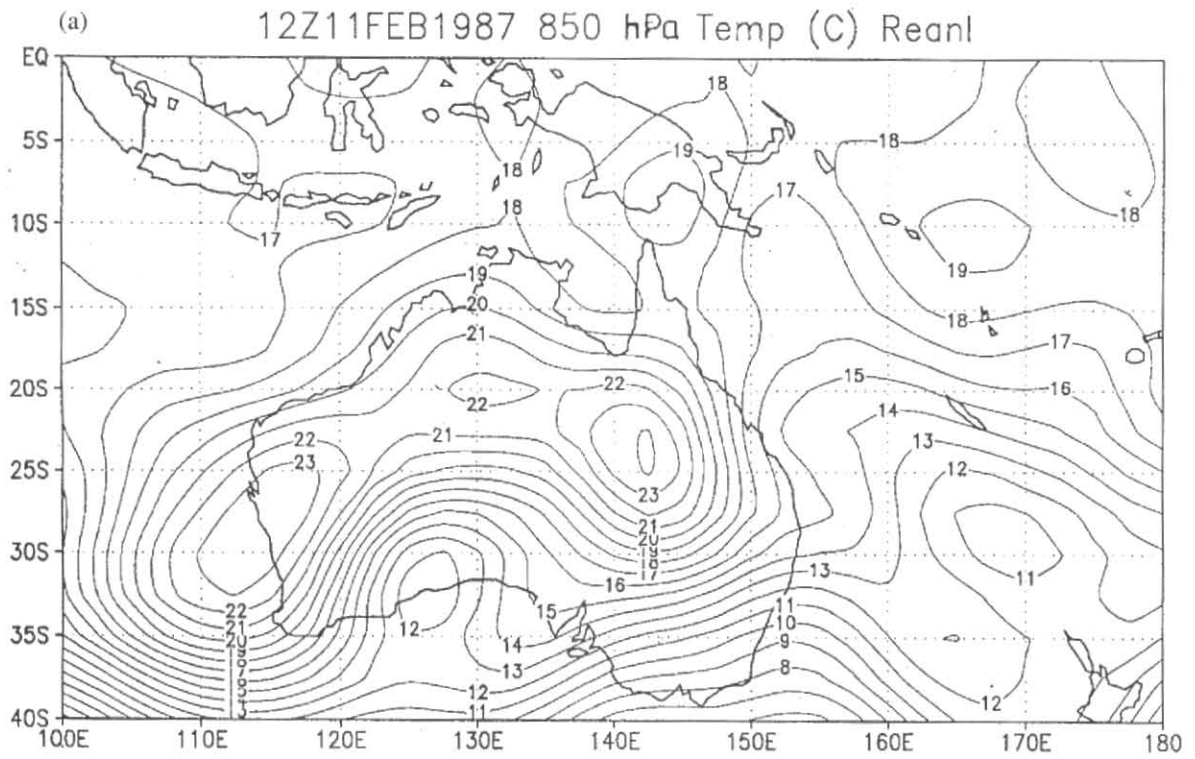
(a) *Depression/storm of 6-15 February 1987*

This disturbance first formed as a closed low with a central pressure of 1007 hPa over the extreme western part of Cape York peninsula on 6 February and moved with only a slow change of intensity west-southwestward across the Gulf of Carpentaria to arrive at its western shore on or around 11 February. It then developed into a depression with a central pressure of 1004 hPa at MSL. The fields of temperature and airflow at 850 hPa at this stage are presented in Figs.8(a&b) respectively. The corresponding upper-air fields at 200 hPa relating to the situation are presented in Figs.9(a&b) respectively. It is clear from the maps presented that the depression centered near the southwestern coast of the Gulf of Carpentaria at this stage was under the influence of a wave in the subtropical westerlies with which it interacted with the extended wave

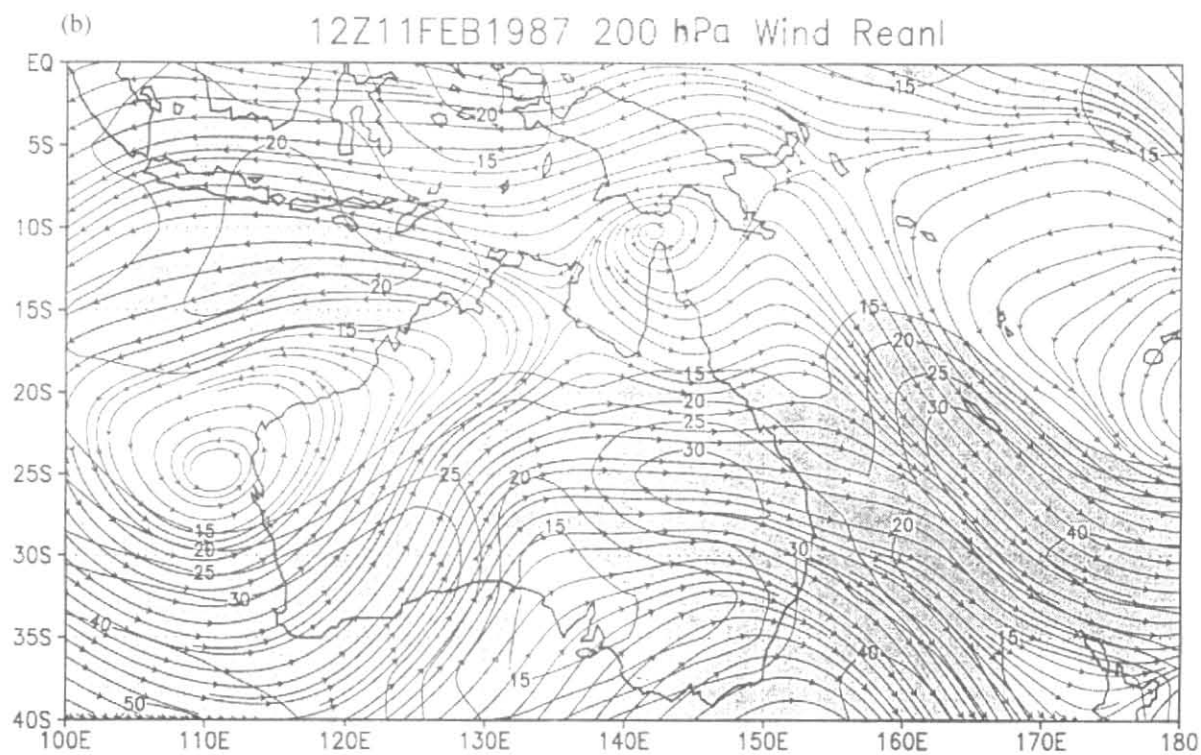
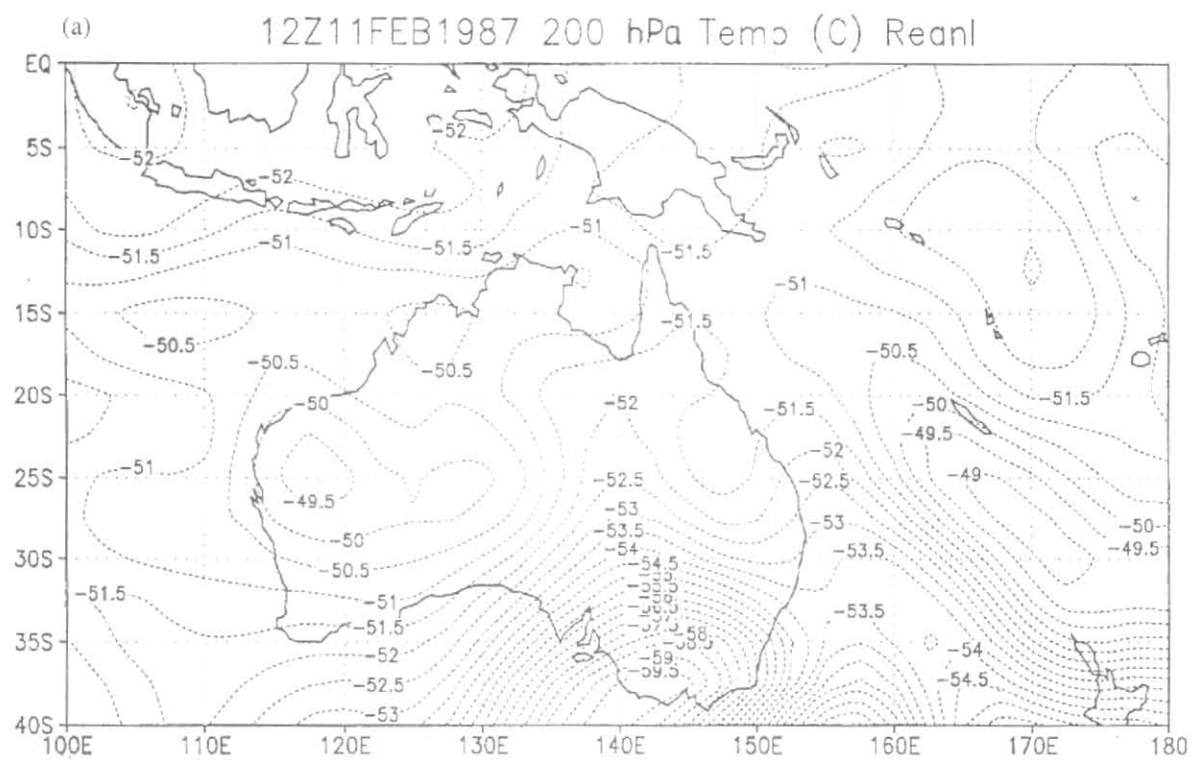
trough passing through the Tasman sea at both the pressure surfaces. Figs.8(a&b) show that on the day of development, there was a cold air surge from the N/NW into the Gulf of Carpentaria region and a warm air surge from the South to its west in the lower troposphere. In the upper troposphere, there was strong divergence of warm air to the south/southeast of the depression center and convergence of cold air to the west. Thus the necessary conditions for development of the depression, as required by Eqn. (1) were present and the isallobaric gradient, as evident from the computed pressure tendency field presented in Fig.10, forced the depression to move to an almost south-southeasterly direction during the following 24 hours.

(b) *Tropical storm/cyclone affecting northwestern Australia, 18-28 Feb, 1995*

This system was located as a closed low with a central pressure of about 1005 hPa over the extreme northwestern shore of the Gulf of Carpentaria on 18 February 1995. A gradual fall in its central pressure occurred as it moved over the coastal belt of northwestern Australia and its track gradually recurved towards the southwest during the following three days. However, as it emerged over the warm ocean on 21 February, it developed into a depression with a central pressure of 1004 hPa. It became a deep depression or a tropical storm with a central pressure of 1000 hPa on 22 February and a



Figs. 8(a&b). Fields of (a) temperature and (b) wind at 850 hPa at 12 UTC, 11 February, 1987



Figs. 9(a&amp;b). Same as Fig 8. but at 200 hPa

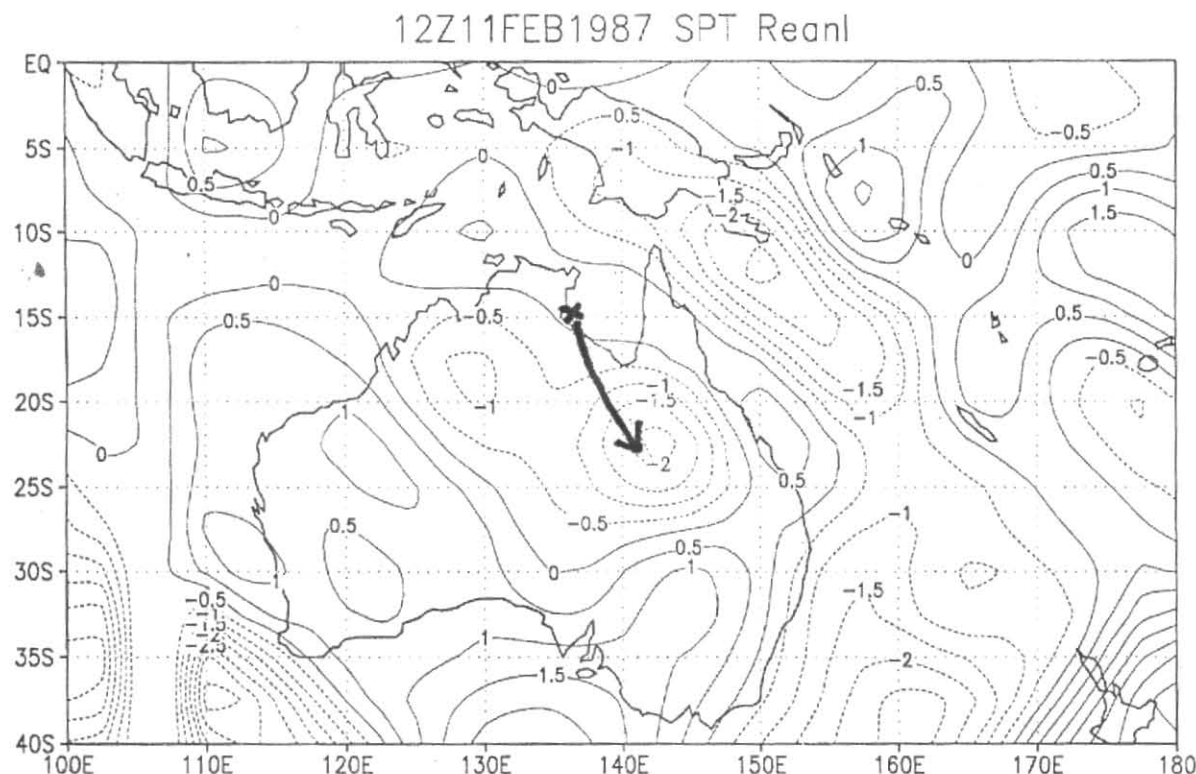
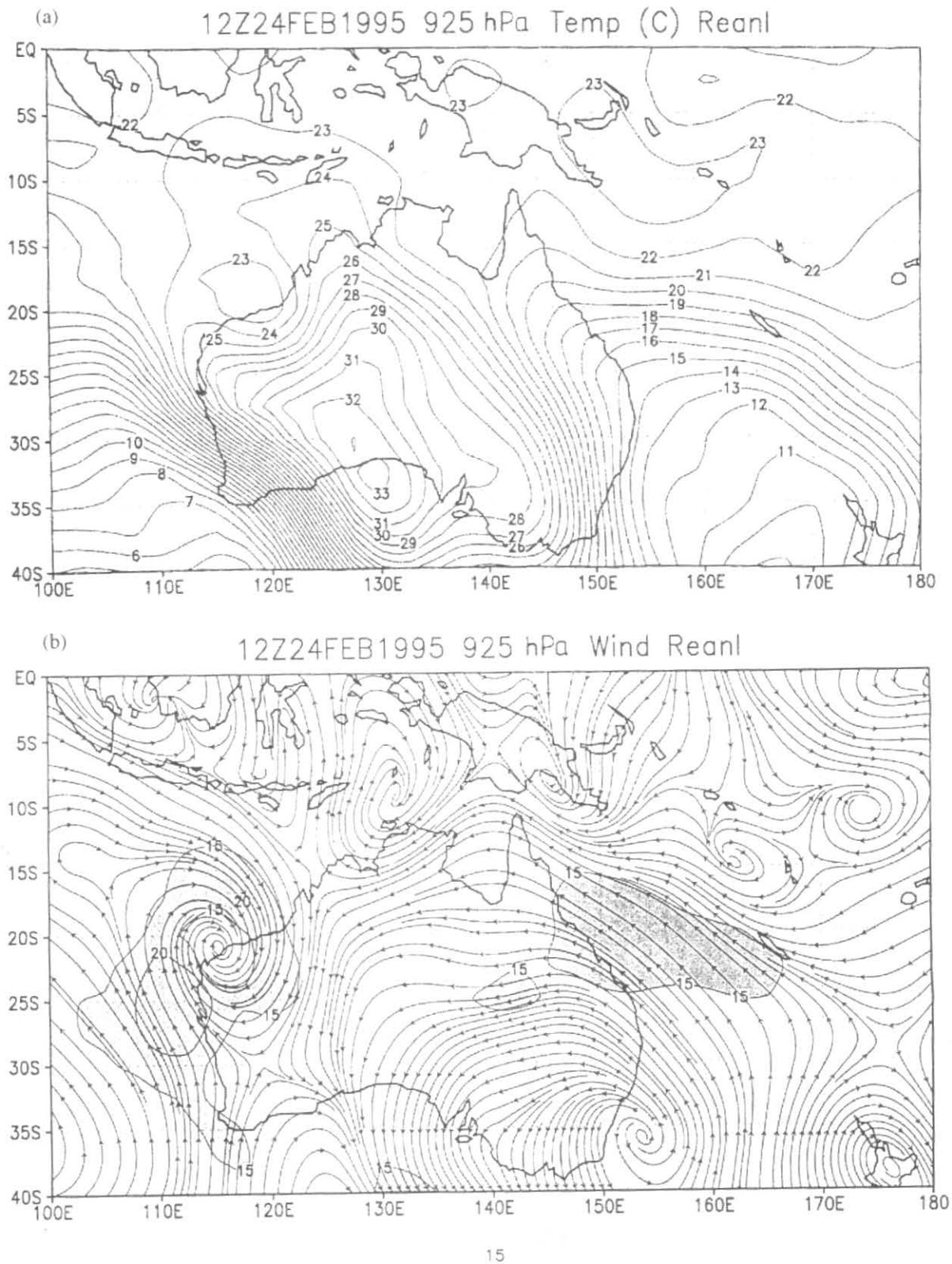


Fig.10. Distribution of computed surface pressure tendency (unit:  $\text{Pas}^{-1}$ ) at 12 UTC on 11 February, 1987. The arrow indicates the approximate direction of the isallobaric gradient

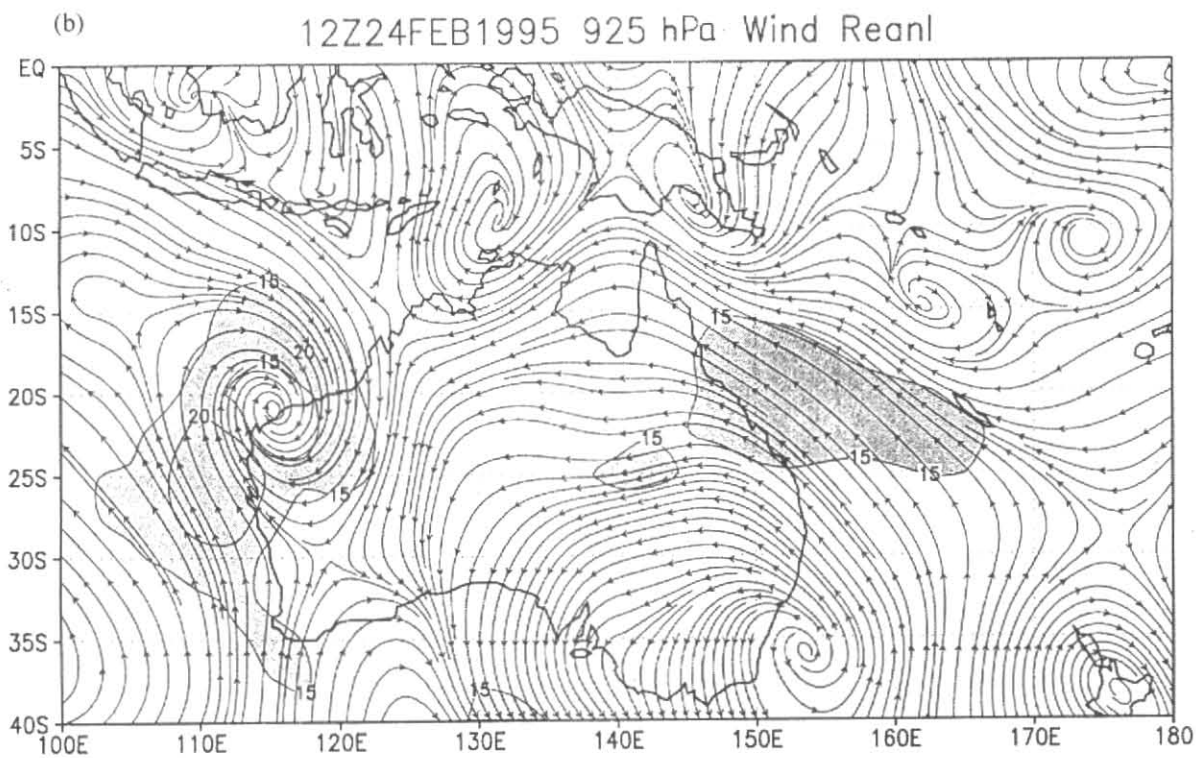
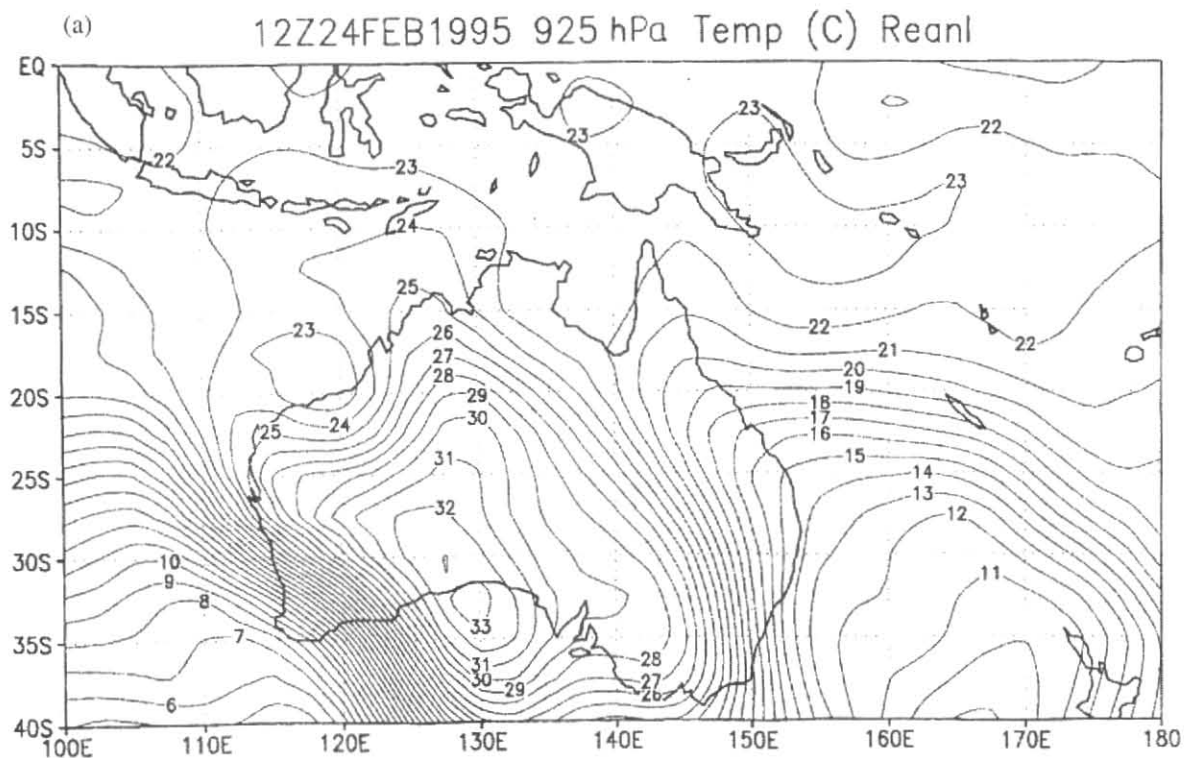
cyclone with a central pressure of 994 hPa on 24 February. At this stage, moving almost due southward, it re-entered land and by 25 February was located over the coastal belt of western Australia with a central pressure of 995 hPa. It appeared to be weakening after entering land as its central pressure rose to 999 hPa by 26 February and 1002 hPa by 27 February and its track rapidly curved towards the east. Maps of temperature and streamline-isotachs at 925 hPa relating to this storm on 24 February, a day before it re-entered land over western Australia, are presented in Figs. 11(a&b) respectively. The corresponding upper-air maps at 300 hPa are presented in Figs. 12(a&b) respectively. Distribution of computed surface pressure tendency at 12 UTC on 24 February is shown in Fig. 13. A NOAA-12 satellite view of the cyclone as on 26 February, reported by Japan Meteorological Agency, is presented in Fig. 14. A close examination of the maps shows that this monsoon depression/cyclone was under the influence of a large-amplitude subtropical/midlatitude westerly wave throughout its life cycle, *i.e.*, from the time of its inception

to final decay. However, on or about 24 February when the storm had reached its peak intensity, there appeared to be a coupling between it and the westerly wave trough, the two having been located over almost the same longitudinal belt across the southwestern part of Australia. Fig.12(b) testifies that at this stage of the interaction, there was a strong warm outflow from the outer periphery of the cyclone towards the southsoutheast.

It is noted that the intensity and central pressure of the above-mentioned two cases, obtained from Reanalysis, differed considerably from those reported by a few others (McBride and Holland, 1989; JTWC, 1995). According to the latter, both the disturbances had reached the stage of tropical cyclones and the central pressure in Bobby on 24 February, 1995, was reported to be about 933 hPa (JTWC, 1995), as against 994 hPa reported by Reanalysis, the large disparity is, perhaps, due to the coarse horizontal resolution of the model used for Reanalysis.



Figs. 11(a&b). Fields of (a) temperature and (b) wind at 925 hPa at 1200 UTC, 24 February, 1995



Figs. 12(a&b). Same as Fig.11, but at 200 hPa

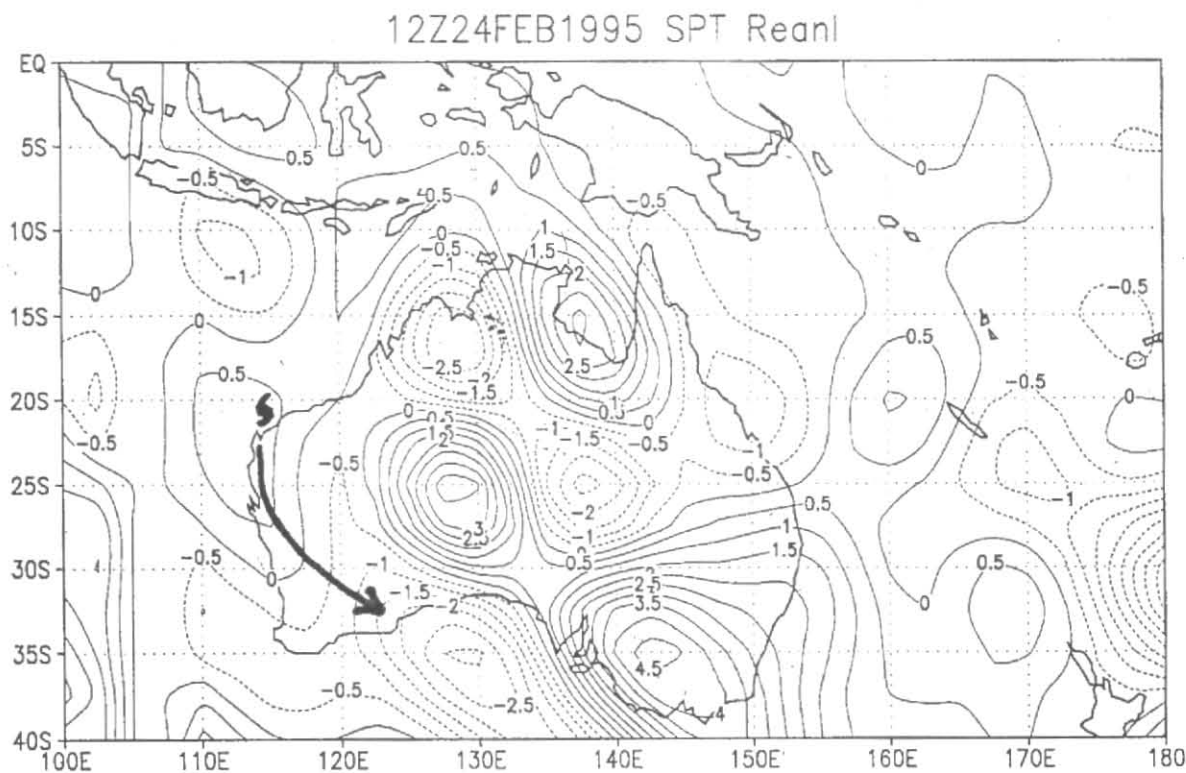


Fig. 13. Distribution of computed surface pressure tendency (unit:  $\text{Pa s}^{-1}$ ) at 12 UTC on 24 February 1995

## 6. Findings and conclusion

The findings of the present study (Part 2) may be summarized as follows:

- (i) In the Australian monsoon region, most of the depressions and cyclones appear to form and develop in the trough zone of a quasi-stationary wave which forms near the northern Australian coastline due to land-sea thermal contrast. The close association of monsoon depressions or cyclones with the monsoon trough or shear zone in the lower troposphere had been noted earlier.
- (ii) The monsoon trough in space appears to exist in two segments, one in the lower troposphere tilting eastward with height and the other in the upper troposphere tilting westward with height. It has a baroclinic structure with cold air below and warm air above.
- (iii) An increase in the baroclinicity of the monsoon trough zone leads to the formation of a low or depression. In a depression, a direct energy-producing secondary vertical circulation cell serves to lift the moisture-bearing cold air that converges into it to higher levels. However, the height to which moisture can be lifted is limited to midtropospheric levels by the stability of the upper troposphere.
- (iv) A depression appears to be transformed into a cyclone when strong condensation heating in the lower troposphere builds up enough saturation vapour pressure to overcome the stability barrier of the upper troposphere. Condensation heating and humidification of the air column leads to a rapid RH of pressure under the rising air currents but a steeper fall is observed near the center where the warm air subsides adiabatically to produce the eye of the cyclone.
- (v) Depressions and cyclones in the Australian region usually move westward. However, their track recurves towards the southwest, south or even southeast when they come under the influence of large-amplitude subtropical westerly waves with which they often interact.



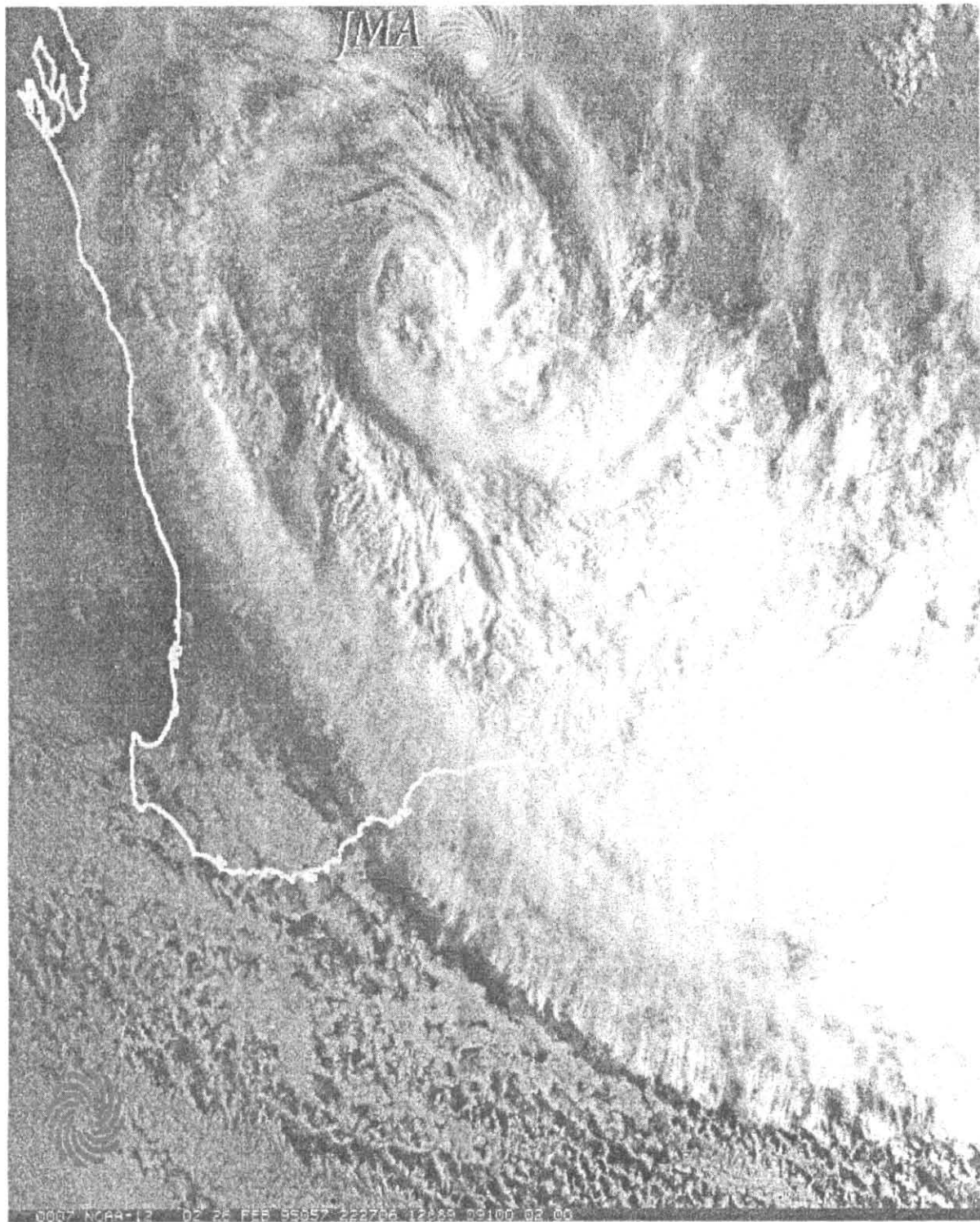


Fig.14. A NOAA-12 satellite view of the tropical cyclone Bobby over southwestern Australia on 26 February 1995

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