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OBSERVATIONAL STUDIES OF TROPICAL CYCLONES WITH COLD-CORE OR SHEAR CHARACTERISTICS

by

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FIGURES

1. Introduction

Tropical cyclones with shear or cold-core characteristics are notoriously difficult to track, even at the post-analysis (or best track analysis) stage. One can therefore appreciate the uncertainties in the tracking of such tropical cyclones in an operational environment when data are often incomplete, time is always limited and the benefit of hindsight is a luxury not affordable to the forecasters.

This paper aims to summarize and document the observations made in some cases of "shear" or "cold-core" tropical cyclones during the routine best track analysis carried out at the Royal Observatory and attempts to translate these observations into operational guidelines that can be considered and applied by forecasters as appropriate.

The general characteristics of cold-core tropical cyclones and some suggested approaches in the tracking of these systems are given in Section 2. A case illustration based on Polly (9216) in August 1992 is described in Section 3.

The general characteristics of shear tropical cyclones and some suggested approaches in the tracking of these systems are given in Section 4. A case illustration based on Lois (9214) in August 1992 is described in Section 5.

Summary remarks and recommendations for future studies are discussed in Section 6.

2. Tracking of Tropical Cyclones with Cold-core Characteristics

Tropical cyclone is by definition a warm-core system. In mathematical terms, the warm-core structure of tropical cyclones can be derived by simply invoking the hydrostatic and gradient wind relationships (Holton 1979).

Over the western North Pacific, tropical cyclones with cold-core origin sometimes form in latitudes poleward of 20°N in mid-summer. The warm waters south of Japan and east of the Ryukyu Islands are the preferred genesis areas. The development of these tropical cyclones can often be linked to the upper cold lows (UCLs) which in some cases are cut-off vortices left behind by TUTTs (Tropical Upper Tropospheric Troughs).

For a more comprehensive discussion on UCLs, readers are referred to Carlson (1967). Typically, the circulation of the UCLs is rather shallow and is most prominent at the 300-hPa level. But under certain conditions (though it remains rather uncertain what these conditions are), the upper vortex extends downwards to the lower part of the troposphere and generates a weaker circulation at the lower levels, or even at the surface. On the surface pressure chart, this is often represented by a broad low complex. The surface circulation, if present, tends to be weak near the centre. The strongest winds are often found on the periphery about several hundred kilometres away from the centre.

The development of a tropical cyclone within the low complex requires a spin-up process which involves an inward contraction of the radius of maximum winds. The transition from a cold-core system to a warm-core system can be regarded as complete when a prominent low-level circulation becomes established.

However, in reality, the transition is by no means a straightforward and irreversible process. There may be occasions when strong tropical cyclone signatures do appear but fail to last, leaving the forecasters with very little alternatives but to persist with the tracking of a system which has not quite shaken off its cold-core heritage. In practice, owing to the chronic lack of data and information, the forecasters also find it difficult to determine at what point should the transition be considered as complete. (It must be said, however, that even at the post-analysis stage, the observational data are rarely fine enough near the vortex core to address the problem.) Operational considerations may sometimes dictate that the system be upgraded to a tropical cyclone, albeit prematurely. Therefore, even though it may sound contradictory in terms, tropical cyclones with cold-core characteristics refer to those marginal cases in which the transitional process has not quite run its course.

To make life easier, the forecasters should therefore exercise more care when upgrading vortices that are known to be of cold-core origin to tropical cyclones. There are two common red herrings that can mislead the forecasters: (a) strong surface wind along the periphery of the vortex which is actually more of a tell-tale sign for cold-core structure; and (b) organized convection along the periphery of the UCL which can be misinterpreted as spiral bandings of a developing tropical cyclone.

As an operational guideline, sustained convection near the vortex centre as observed from the satellite imageries is one of the criteria to be considered when a cloud cluster is to be upgraded to a tropical cyclone. Though not clearly specified, it is useful to interpret "sustained convection" as convection persisting for a 24-hour period in order to remove the diurnal effect. In the case of tropical cyclone genesis associated with an UCL, the requirement of sustained central convection should be assigned even more weight. It is hypothesized that organized convection within the broad low complex, through the CISK mechanism, may well play a crucial role in determining the evolution and extent of the cold to warm-core transition (Kelley & Mock (1982)). A more recent observational study by Mapes (1995) using TOGA-COARE data also provides some indirect evidences on the likely important role played by convective heating in the downward development of an elevated depression.

Because the low-level circulation is very often weak and ill-defined, multiple circulation centres on a smaller scale can sometimes be observed on the satellite imageries within the broad low complex. However, monitoring cyclone movement using these transient small vortices can be very frustrating and misleading. The forecasters may decide to home in on one prominent centre only to find out later that the target is fizzling out and another centre is taking over. A crude but probably more effective approach is to just draw a big circle around the peripheral convection and locate the centre. Even though the resultant track may not accurately reflect the truth, it will nonetheless be smoother with better continuity and hence facilitates short-term track extrapolation. For movement trend in the long run, the forecasters can monitor the behaviour of the associated UCL and consult the upper-air prognoses given by various NWP models.

3. Case Study - Polly (9216)

The life history of Polly was closely linked to the evolution of an UCL. From the perturbed easterly flow, signs of an upper circulation first appeared at the 200-hPa level on 24 August 1992 and by 00 UTC on 25 August, a prominent UCL was analyzed near 25°N and 140°E (Figure 1(a)). At the time, the vortex was still a rather shallow feature as no corresponding circulation could be found lower down, say at 850-hPa level (Figure 1(b)). As seen from the satellite imageries, some organized convection was present near a disturbance more than 700 kilometres south of the UCL.

Over the next several days, the UCL drifted generally to the west towards Taiwan. In the process, it became more closely aligned with the convective cloud mass further south. At times, its circulation was less well-defined. But more significantly, a warming process took place which transformed the UCL. At the 300-hPa level on 25 August, the UCL had temperatures as low as -33°C near its centre, two to three degrees lower than the surrounding temperatures. Five days later over Taiwan, temperatures near the vortex centre had risen to about -20°C, two to three degrees higher than the surrounding temperatures.

However, the cold to warm core transition was not without its complications. Both the upper-air and surface analyses revealed the presence of multiple centres as Polly struggled for cohesion and structure. The tortuous scenario was captured by the satellite imageries during the period. On 26 August, the main area of convective activity (say Polly-α) was located near 135°E (Figure 2(a)). During the night, another centre of activity (say Polly-β) appeared further west near 130°E (Figure 2(b)). The emergence of the secondary centre could also be observed from the 300-hPa winds. Temperatures reported near Polly-β to the west were found to be generally warmer than those of its parent vortex (i.e. Polly-α) to the east.

Over the next 24 hours, the dual centres of Polly competed for survival. Early on 27 August, peripheral convection seemed to be rotating around the convection-free centre of Polly-β near 20 - 21°N and 127 - 128°E (Figures 2(b) - 2(c)). During the day, convection associated with Polly-α showed no improvement in organization and was mainly confined to the south of the vortex centre. Meanwhile, Polly-β appeared to have made a northward jump or, more probably, another circulation centre to the north (say Polly-γ) had taken over (Figures 2(d) - 2(e)).

At 18 UTC on 27 August (Figure 2(f)), Polly-γ near 23°N and 125°E gained in prominence with enhanced peripheral convection all round. In the following 24 hours (Figures 2(g) - 2(j)), Polly-γ drifted slowly southwestwards while Polly-α gradually lost its identity. The axis of convection joining the two circulation centres was observed to turn cyclonically from a WNW - ESE orientation to a WSW - ENE orientation, reflecting a mutual rotation between the two weak vortices. However, the exact movement of Polly-γ was difficult to track as convection continued to fluctuate in intensity near and around its centre.

(a)

(b)

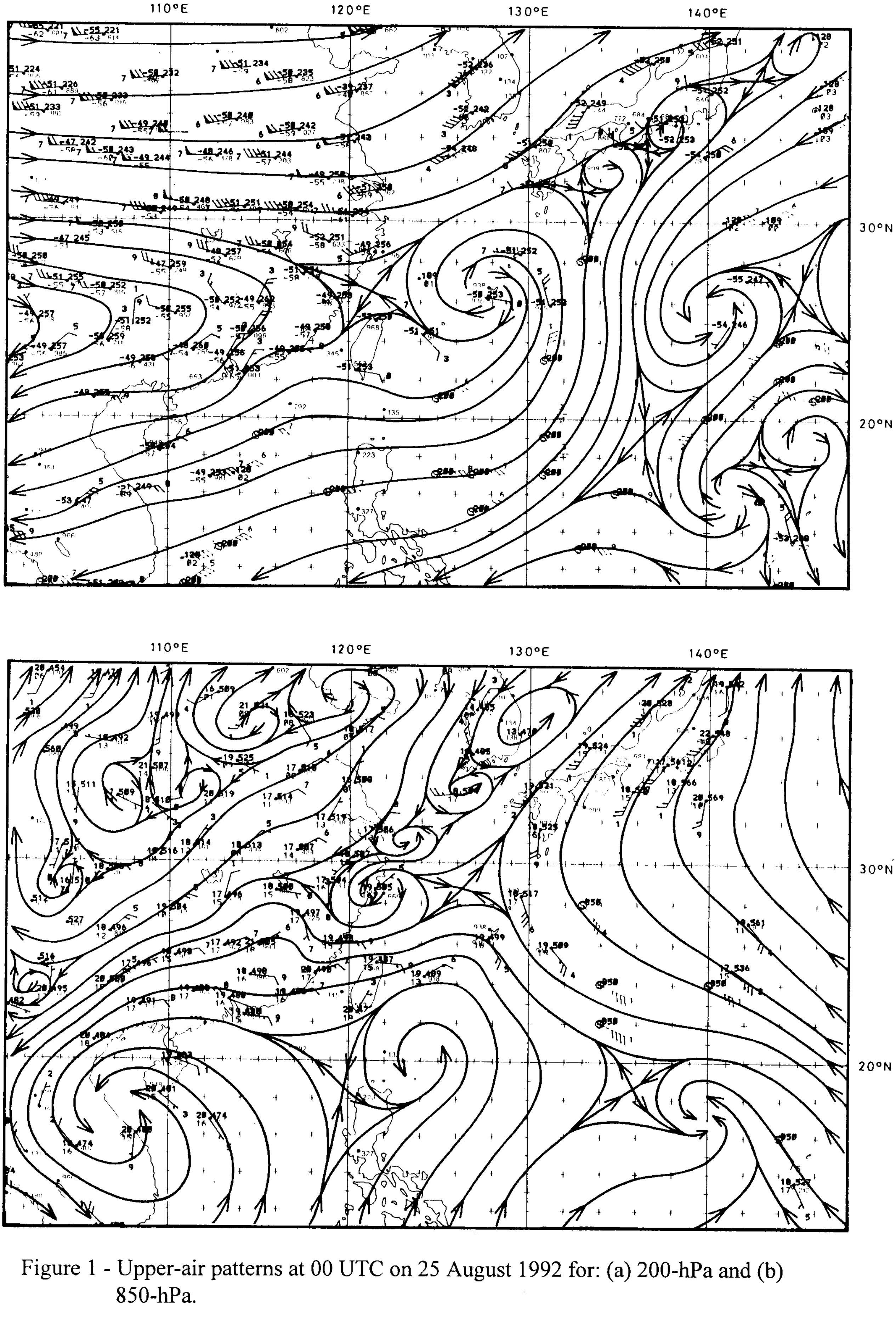
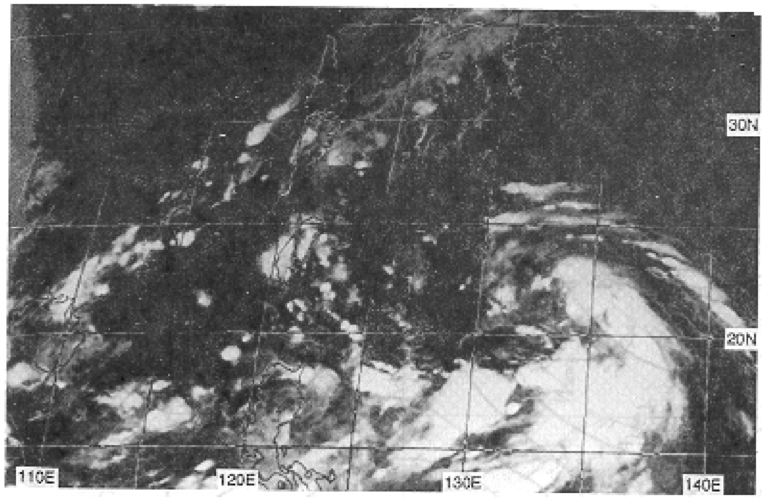
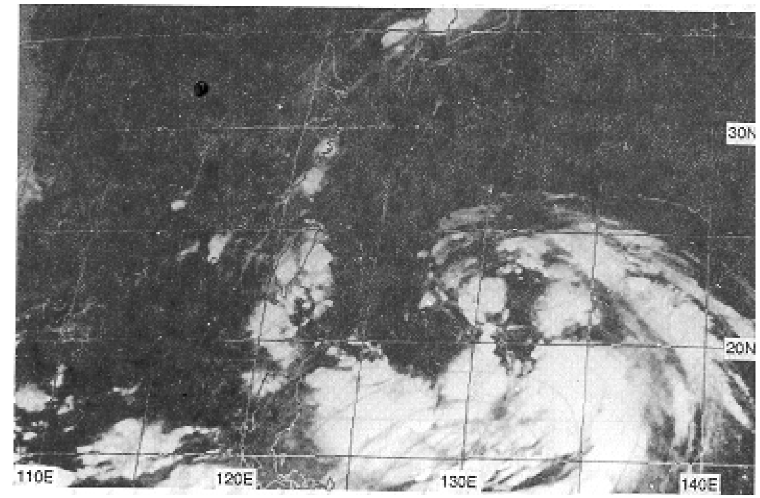


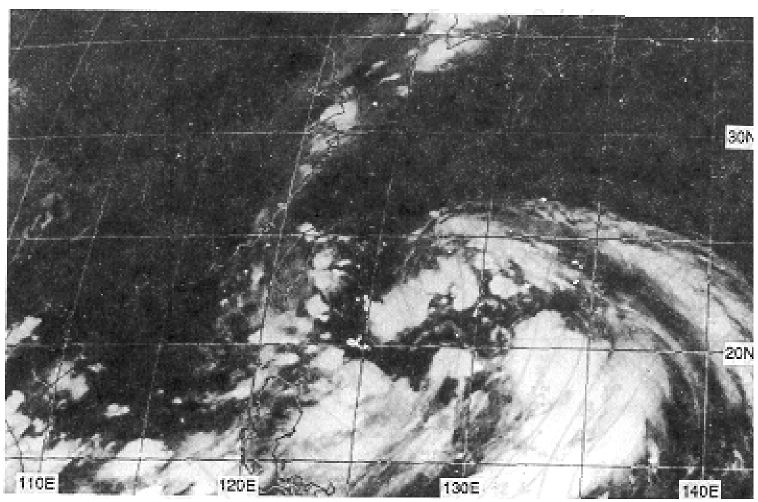
Figure 1 - Upper-air patterns at 00 UTC on 25 August 1992 for: (a) 200-hPa and (b) 850-hPa.



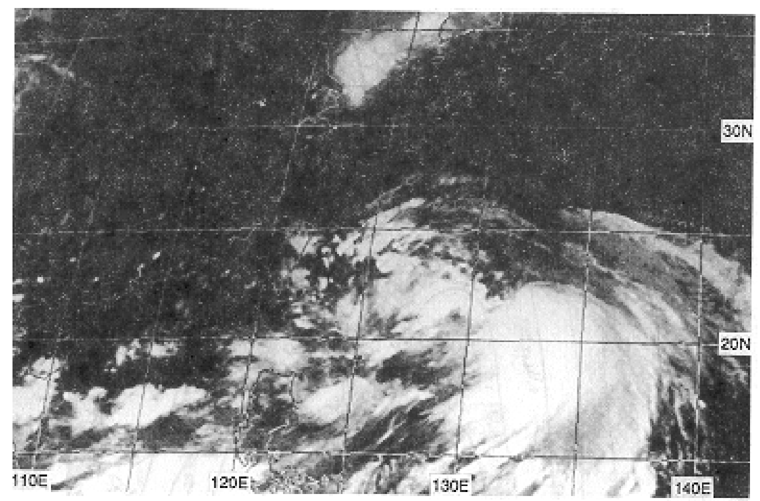
(a) 12 UTC 26 August 1992 (α at 19.8N 134.1E, β at 20.5N 128.2E)



(b) 18 UTC 26 August 1992 (α at 20.3N 133.8E, β at 20.8N 127.6E)

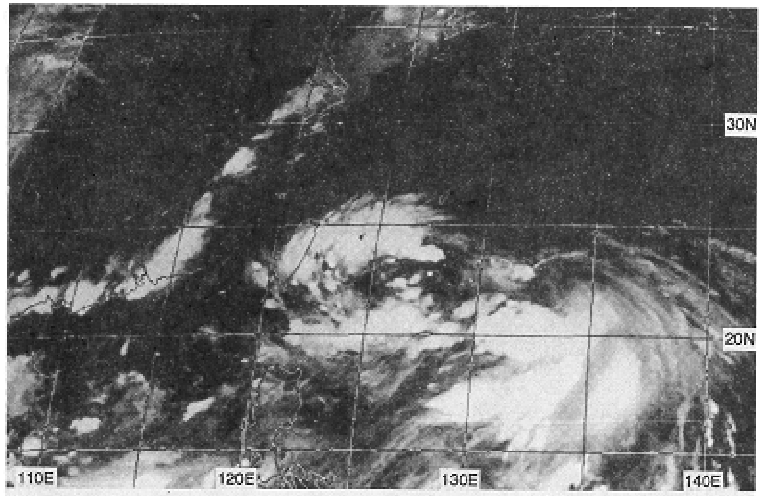


(c) 00 UTC 27 August 1992 (α at 20.8N 133.5E, β at 21.0N 127.2E)

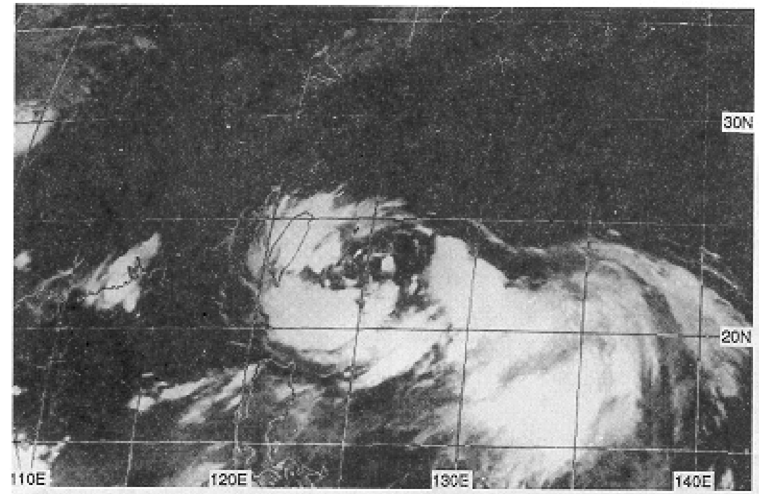


(d) 06 UTC 27 August 1992 (α at 21.4N 133.2E, γ at 23.2N 125.8E)

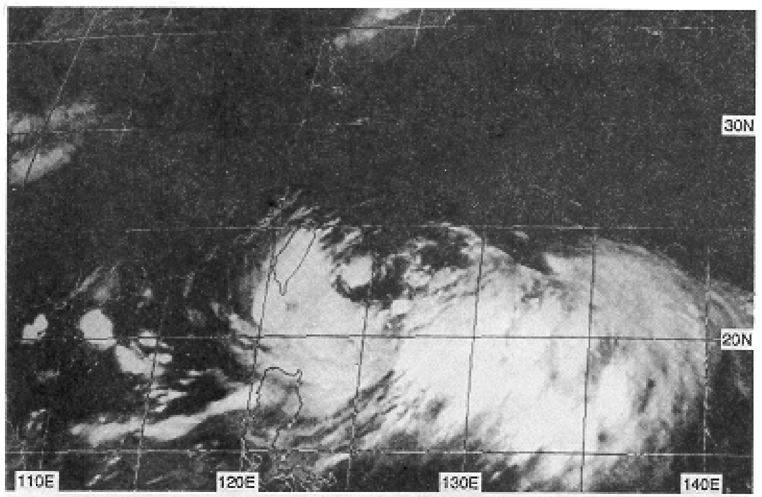
Figure 2 - Six-hourly infra-red satellite imageries of Polly (9216) and its multiple centres (see text for details).



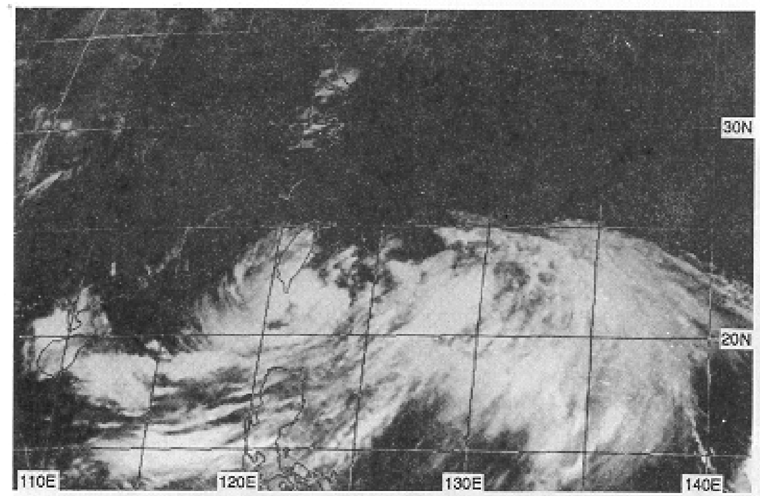
(c) 12 UTC 27 August 1992 (α at 22.1N 133.0E, γ at 23.0N 125.2E)



(f) 18 UTC 27 August 1992 (γ at 22.7N 124.8E)

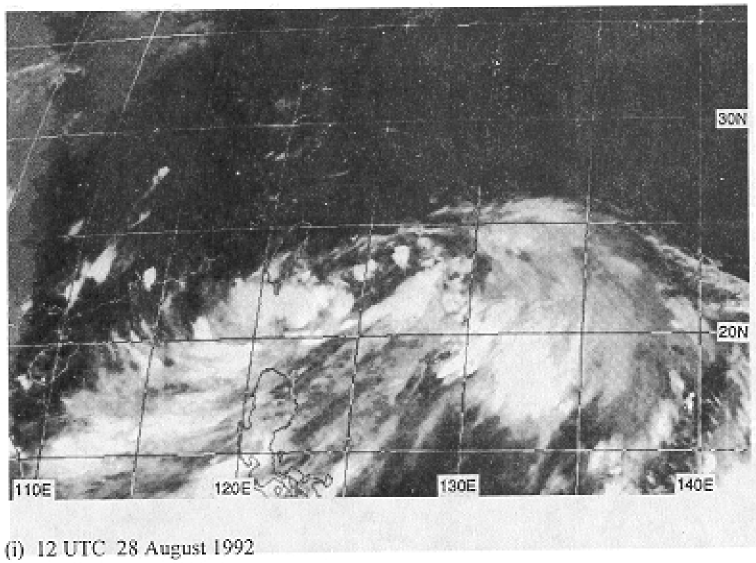


(g) 00 UTC 28 August 1992 (γ at 22.5N 124.5E)

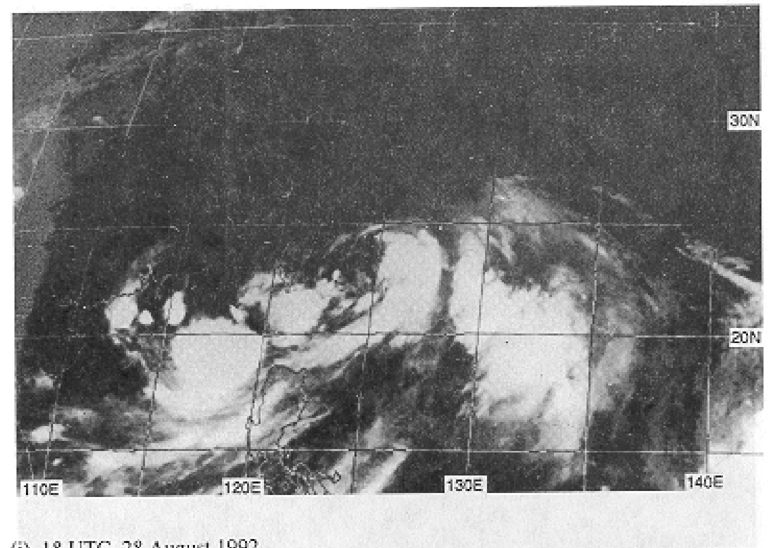


(h) 06 UTC 28 August 1992

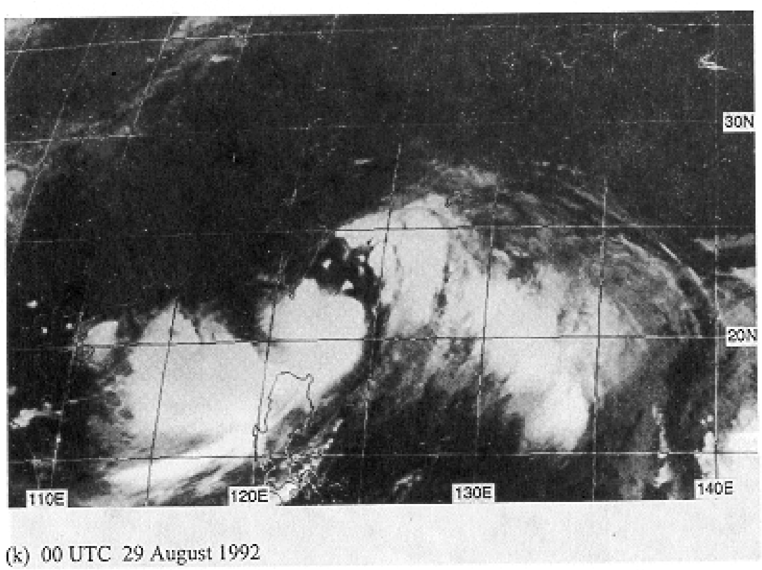
Figure 2 (continued)



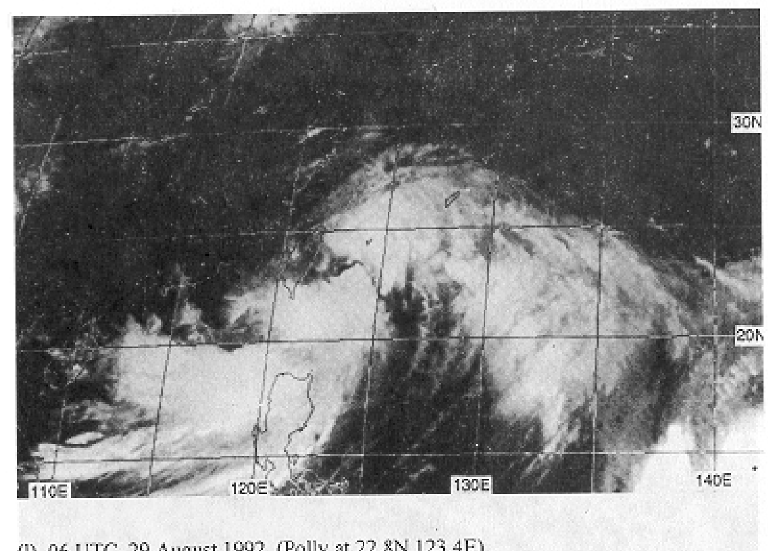
(i) 12 UTC 28 August 1992



(j) 18 UTC 28 August 1992

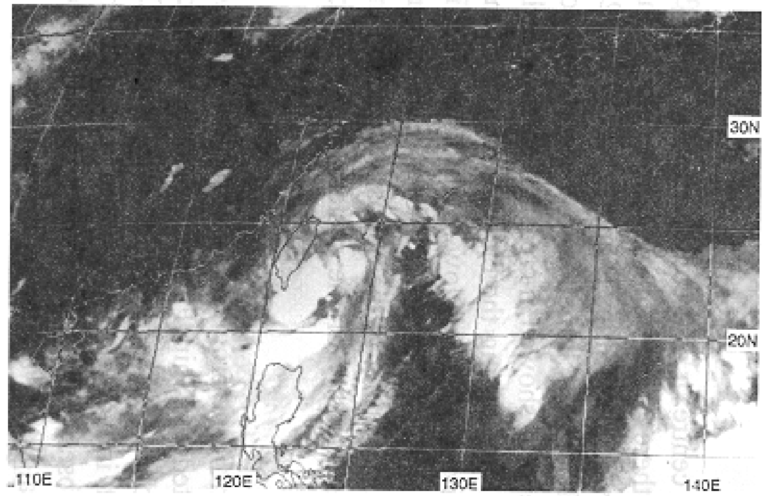


(k) 00 UTC 29 August 1992

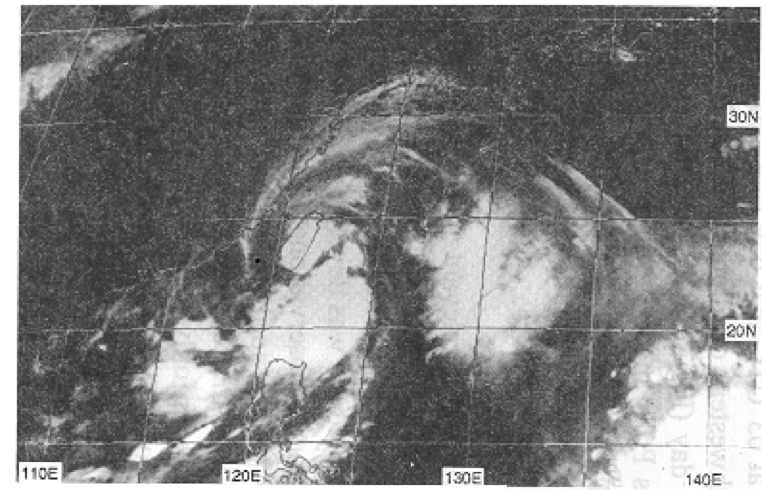


(l) 06 UTC 29 August 1992 (Polly at 22.8N 123.4E)

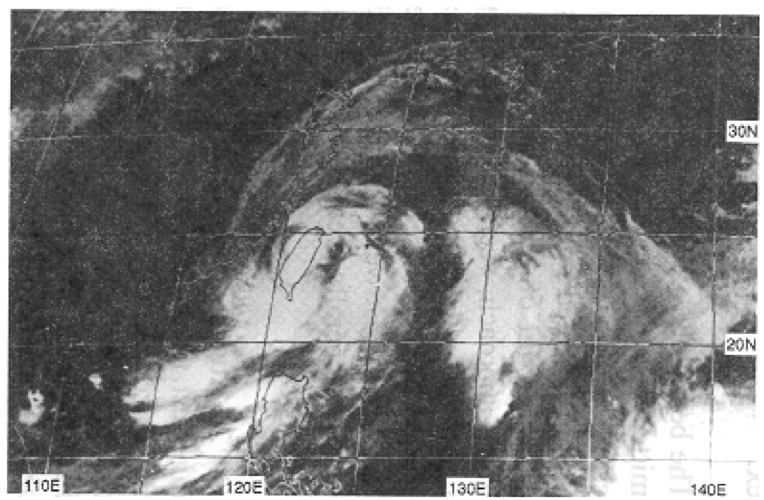
Figure 2 (continued)



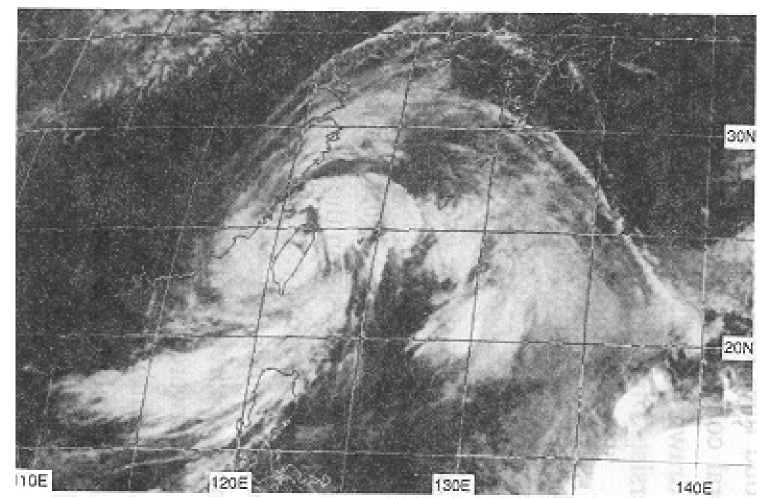
(m) 12 UTC 29 August 1992 (Polly at 23.0N 123.0E)



(n) 18 UTC 29 August 1992 (Polly at 23.3N 122.5E)



(o) 00 UTC 30 August 1992 (Polly at 23.6N 122.1E)



(p) 06 UTC 30 August 1992 (Polly at

Figure 2 (continued)

By daybreak on 29 August, it was obvious that Polly-γ had become the dominant centre. Its position could be pinpointed at 22.6°N and 123.6°E by following some faint low-level cloud lines observed from the visible imagery at 03 UTC that day (not shown here). Peripheral convection over the northeastern and southwestern quadrants (Figure 2(k)) were clearly drawn inwards towards the centre during the day (Figure 2(l)). Central convection then persisted into the night (Figures 2(m) - 2(n)) as Polly made its mark as a warm-core system. Typical tropical cyclone signatures with prominent spiral bandings and central convection appeared in the satellite imageries on 30 August as Polly swept across Taiwan (Figures 2(o) - 2(p)).

A summary of the evolution of Polly, along with some relevant surface observations used in the best track analysis, is given in Figure 3. There were no ship reports in the vicinity of Polly-α on 26 and 27 August and the north-northwestward movement was mainly obtained from satellite re-analysis on the premise that a secondary centre was developing further to the west. But at the early stage of Polly-α's development, observations of strong east to southeasterly winds were made by two ships (Ships A and B) to the north and northwest of the embryonic circulation on 25 August. Ship A, sailing to the south-southeast, passed to the east of a westward-moving Polly-α later that day. However, only fresh southerly winds (i.e. less than 40 km/h) were reported when the ship was about 60 kilometres southeast of Polly-α. The wind distribution of stronger winds on the outside seemed to confirm that Polly-α was still rather immature as a warm-core system.

Polly-β, moving to the west-northwest, was monitored by Ships B and C on 26 August. Ship C sailed southwards, passing in the wake of Polly-β to the east. The reported winds veered from strong east-northeasterlies to strong southwesterlies. In between, winds dropped below 30 km/h during the closest approach. Meanwhile Ship B, after passing to the north of Polly-α and maintaining a westward course, ran right across the path of Polly-β. Its observations also showed that the circulation was weak with stronger winds further out from the vortex.

The behaviour of Polly-γ (either as a separate centre or as a continuation of Polly-β) was admittedly more speculative. Nevertheless, there were some tangible supporting evidences in the form of wind observations made by two ships (Ships D and E) on 27 and 28 August. Ship D sailed northeastwards and passed about 50 kilometres to the northwest of Polly-γ on the night of 27 August. Its 3-hourly reports showed increasing northwesterly winds on the approach, veering and reaching strong force during the closest encounter, and remaining strong as the ship moved into a belt of active easterly airflow south of the Pacific ridge. The detailed cross-sectional profile seemed to indicate the making of a more mature warm-core system. However, winds reported by Ship E sailing in the opposite direction the next day were generally weaker, suggesting that the intensity of the system could not be sustained.

On 29 August, Polly finally made some significant progress as a tropical cyclone. Increasing west to southwesterly winds were reported by Ship F heading northeastwards across the Luzon Strait. Gales of 70 km/h were observed as the ship came within 100 kilometres of Polly. With a marked improvement in vortex organization and with the availability of radar fixes as well as land-based observations, the monitoring of Polly's subsequent passage across Taiwan was a relatively straightforward matter by comparison.

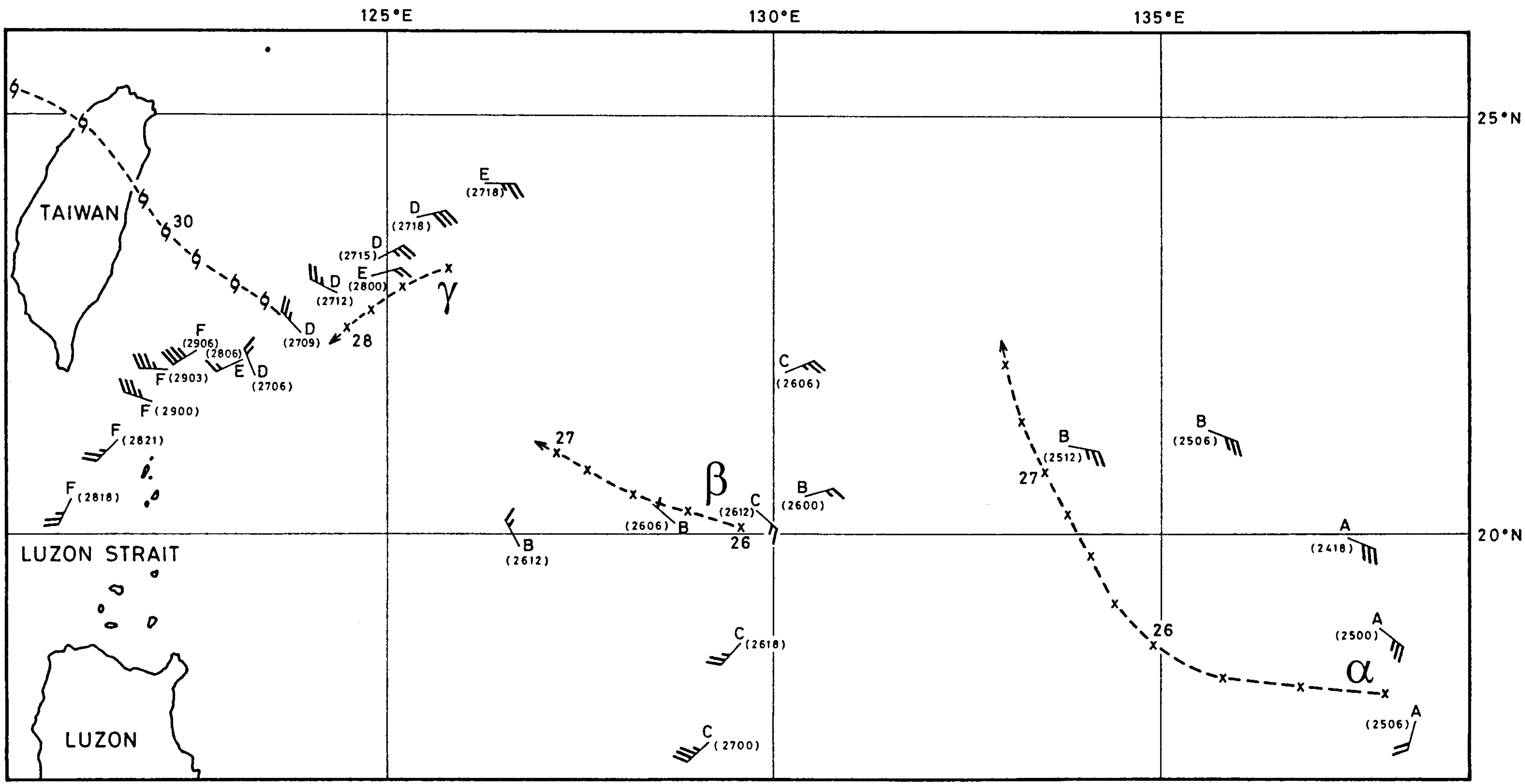


Figure 3 - Six-hourly positions of the best track of Polly (ϭ--ϭ--ϭ) in August 1992. Probable tracks of its multiple centres (labelled α, β, γ) are also shown (x--x--x). Daily positions at 00 UTC are marked with dates alongside. Wind reports from six ships (labelled A to F) are plotted. Times of reports (in brackets) are given in DDZZ where: DD = day of the month; ZZ = hour in UTC.

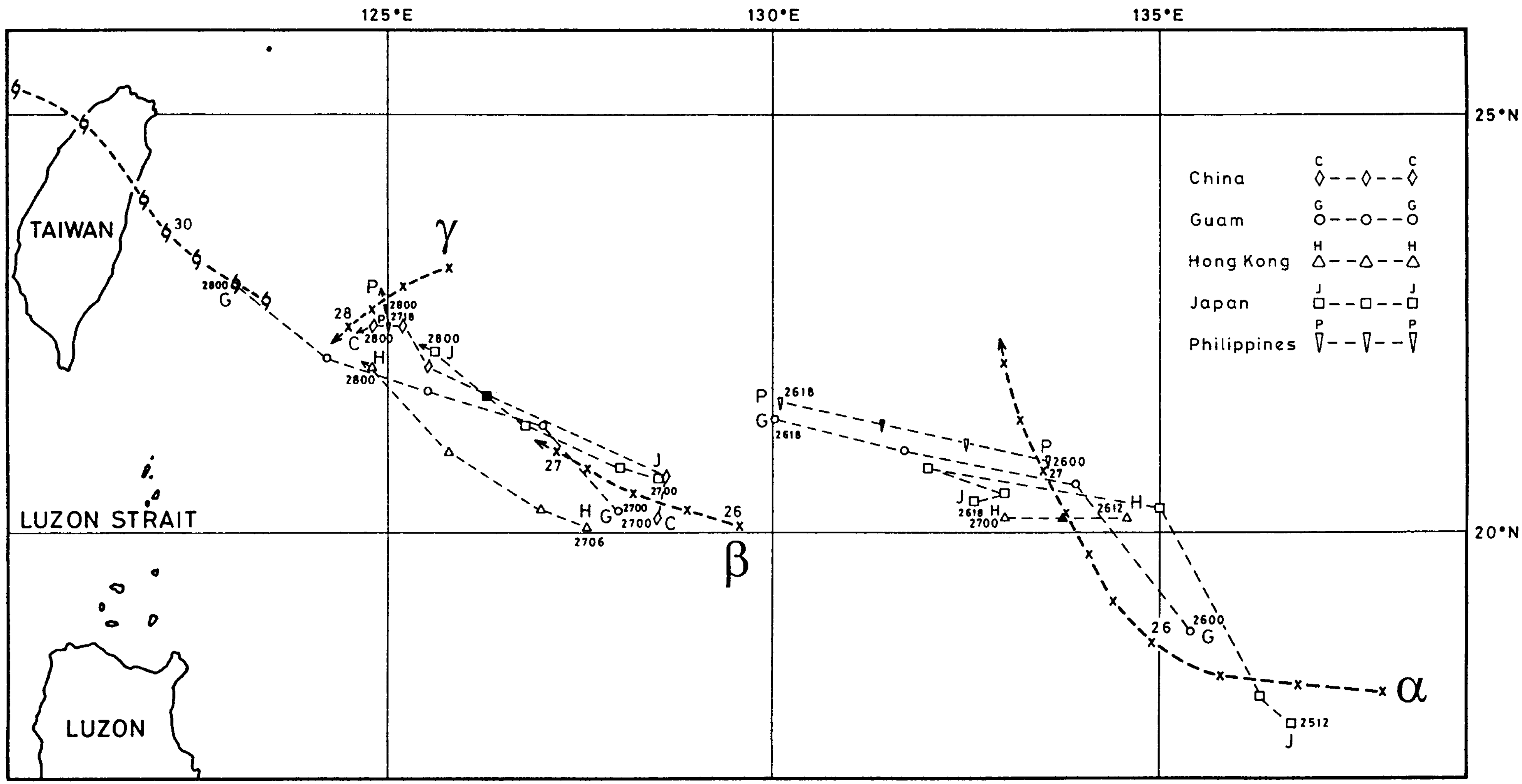


Figure 4 - Tracks of Polly and its multiple centres as in Figure 3. Six-hourly operational warning positions up to 00 UTC 28 August 1992 issued by various meteorological centres are also shown, with solid symbols indicating interpolated positions owing to non-availability of warning positions.

The operational warning positions and intensities issued by various meteorological centres in the region are shown in Figure 4. The difficulties and uncertainties experienced by the forecasters could be readily appreciated in view of the much diversified scenarios presented. Once Polly-α was upgraded to a tropical cyclone, an operational re-location could not be avoided as the centre of activity subsequently shifted to the west. In hindsight, life would have been much easier for the forecasters if the upgrading was delayed until the emergence of Polly-β or Polly-γ. Even though both Polly-β and Polly-γ were difficult to track, continuity in warning could at least be preserved by holding on to a slow west-northwestward track.

4. Tracking of Tropical Cyclones with Shear Characteristics

Tropical cyclones experiencing strong vertical shear pose another difficult problem in operational tracking. Carried along by the upper-level winds, high clouds at the convective outflow layer move in the direction of the vertical shear. In the absence of visible satellite imageries at night, the forecasters using the cold dense overcast as reference tend to either over-predict or under-predict the displacement of the surface centre, depending on whether the cyclone motion is along or opposite to the direction of the shear respectively. When daylight emerges, a low-level circulation centre (LLCC) can often be observed a certain distance (can be as much as 100 - 200 kilometres) away from the convective cloud mass.

There are two commonly observed scenarios in the western North Pacific basin: (a) strong easterly shear in the case of embedded tropical cyclones within the ITCZ or tropical cyclones moving along the southern periphery of a prominent subtropical ridge; (b) strong westerly shear in the case of embedded tropical cyclones within the monsoon trough or tropical cyclones undergoing recurvature ahead of a mid-latitude trough.

Whenever high winds are reported at the upper levels in the vicinity of the tropical cyclone, the forecaster should be mindful of the possibility of a shear-off scenario. Rapid movement of the dense overcast, say in excess of 40 kilometres per hour, should be interpreted with care. The forecasters should put more weight on surface observations if available and keep a watchful eye for any exposed low-level circulation centre.

If a tropical cyclone is known to be sheared off and if no exposed LLCC can be found on the visible satellite imageries, it is reasonable to assume that the LLCC is probably hidden by the dense overcast. In the absence of other evidences and as a rule of thumb, the LLCC is often positioned a certain distance away from the centre of the cold cloud mass but within the coverage of the overcast, say just near the edge of the overcast on the upwind side of the shear (e.g. on the eastern periphery of the overcast in the case of easterly shear and on the western periphery in the case of westerly shear).

Obviously, it is always useful to have the magnitude of the vertical shear in mind when making positional adjustments in cyclone location. A velocity differential indicating the shear magnitude can be derived either from observed winds at the upper and lower levels in the vicinity of the cyclone or from the travelling distances covered by the dense overcast and the LLCC between two previously known (or reliable) positions.

It is important that the reliable positions should be clearly highlighted as benchmarks, both for speed calculation and for track extrapolation (particularly during night time when the LLCC, even if exposed, cannot be readily seen). While the LLCC can be found by tracing the low-level cloud lines in the visible satellite imageries, fresh convection is the thing to search for in the infra-red imageries. This is because the dense overcast, as it becomes detached from the LLCC as a result of the strong shear, will eventually fizzle out and rejuvenated convection often develops near where the LLCC is. In effect, this gives away the position and movement of the LLCC and can, on occasions, serve as very good benchmarks.

5. Case Study - Lois (9214)

The best track of Lois from 14 to 19 August 1992 is shown in Figure 5. Ship reports were mostly confined to the early part of the track and were not particularly helpful. But because a low-level centre was exposed by the sheared-off structure of Lois, there were some very reliable satellite fixes obtained from the visible imageries (and marked in triangles in Figure 5) to serve as benchmarks. Some interesting observation could be made when these fixes were compared with the convection patterns as seen on the infra-red satellite imageries (Figure 6).

During the day on 15 August, no exposed low-level circulation could be seen on the visible imageries. Convective outflow at the upper levels was mainly to the west and southwest (Figures 6(a) - 6(b)). This agreed with the observed winds at 200-hPa level (Figure 7(a)). At this time, the surface centre of Lois was placed under the convective overcast towards its eastern sector.

At 12 UTC on 15 August (Figure 6(c)), a small area of fresh convection appeared outside the main overcast to the southeast. It was hidden momentarily as the main overcast grew more extensive during the night (Figure 6(d)). By the next morning, it re-appeared as an overlapping convective cell southeast of the main overcast (Figure 6(e)). Visible imageries confirmed the presence of a low-level circulation centre on the eastern periphery of this new cell.

Over the next few days, a similar sequence of events recurred. While the main overcast lagged behind the low-level centre and fluctuated in intensity, fresh convection often occurred outside the overcast at locations near where the low-level centre was. From the infra-red satellite imageries, such occurrences were most noticeable at 18 UTC on 16 August (Figure 6(h)), 12 UTC on 17 August (Figure 6(k)), 00 UTC on 18 August (Figure 6(m)), 12 UTC on 18 August (Figure 6(o)), and 00 UTC on 19 August (Figure 6(q)). Confirmation was provided either directly by the visible satellite fixes or indirectly by the interpolated positions obtained from the visible satellite fixes.

The resultant best track gave the consistent scenario of a weak tropical depression tracking generally to the northeast with speeds ranging from 10 to 15 km/h at the beginning and accelerating to more than 20 km/h near the end. It was also interesting to note that convection associated with Lois, sheared to the west for the most part, had shifted to the south and southeast by 19 August (Figures 6(q) - 6(t)). The observed change agreed well with the evolving upper-air patterns as the poleward movement of Lois placed it under increasing northwesterly flow aloft (Figure 7(b)).

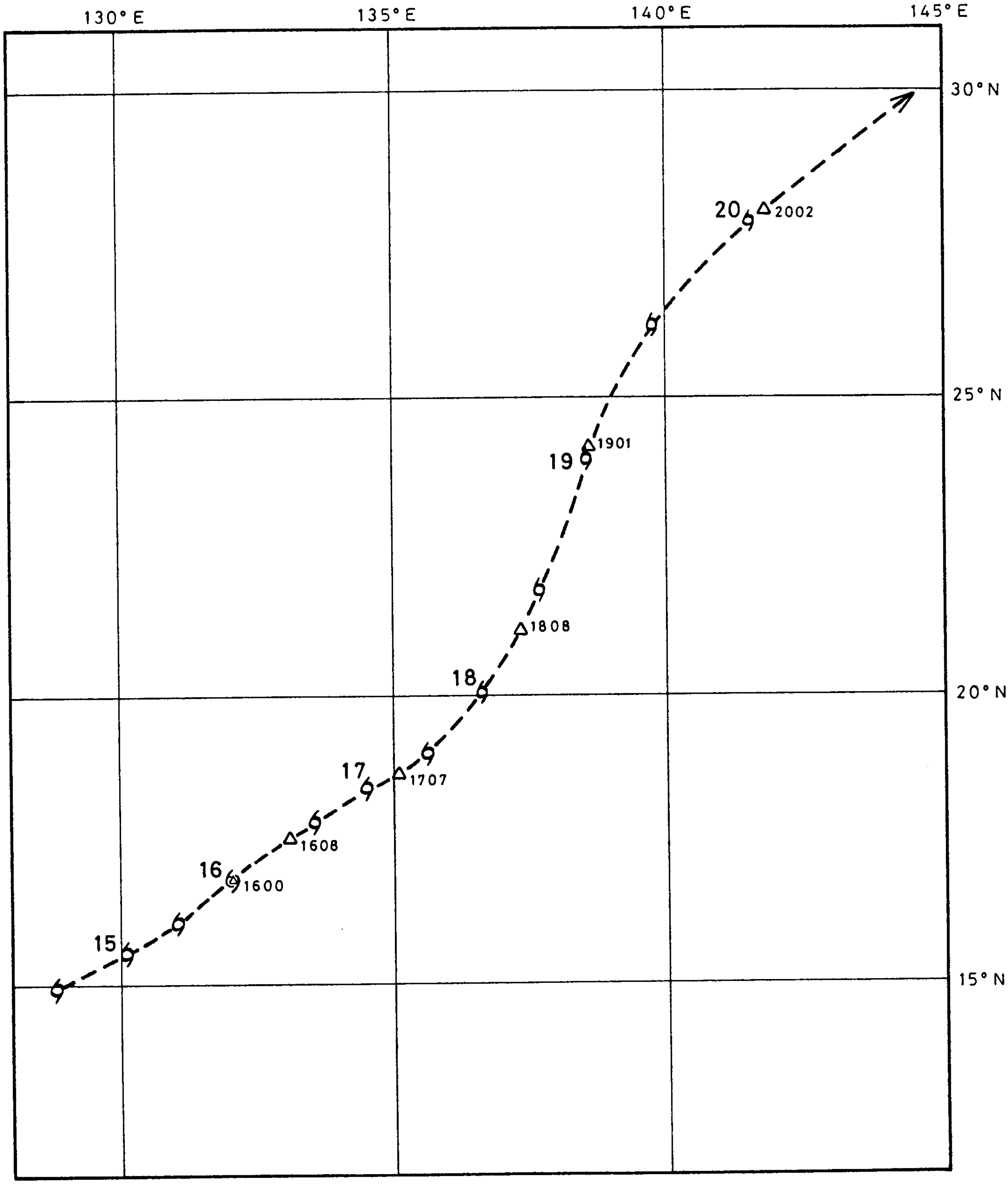
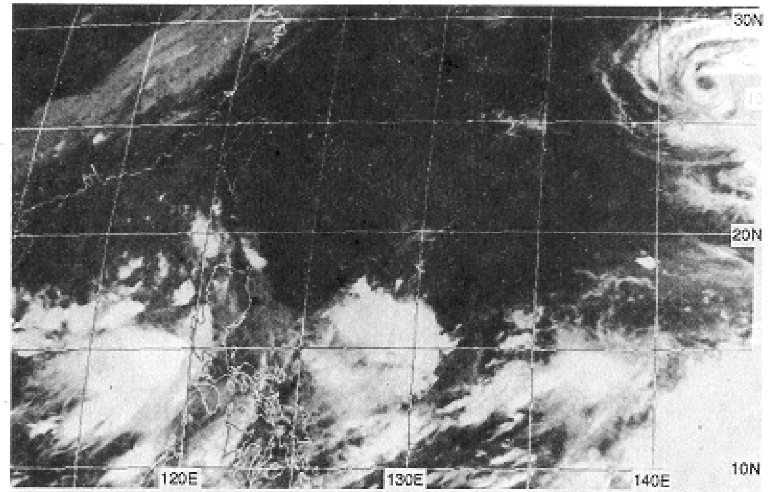
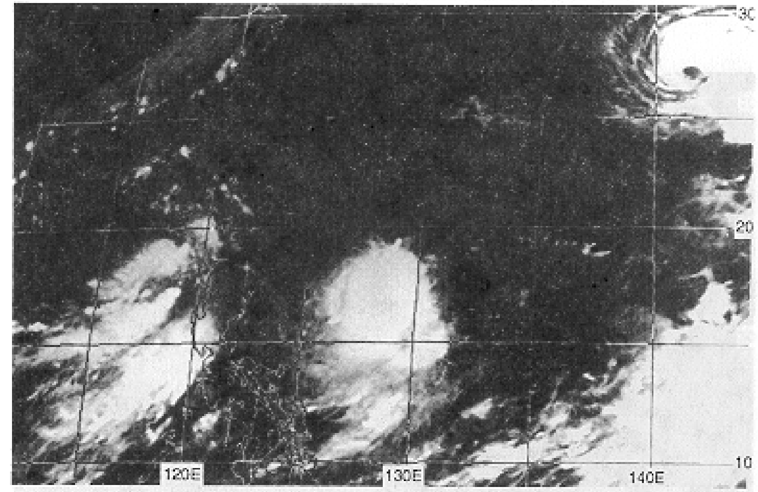


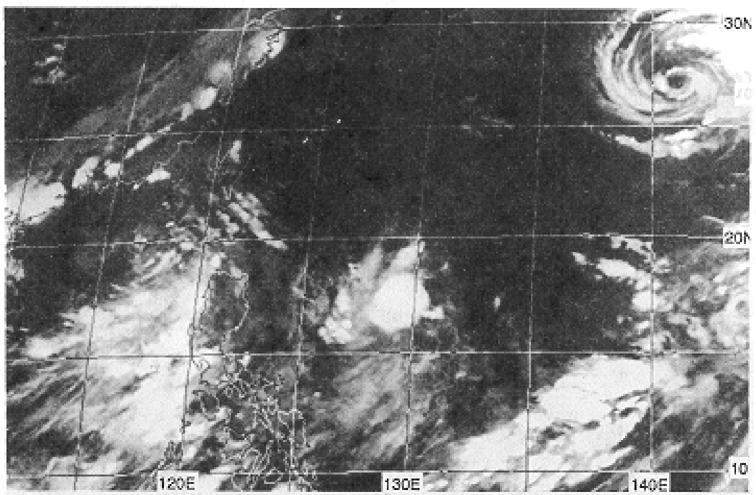
Figure 5 - 12-hourly positions of the best track of Lois (ϭ--ϭ--ϭ) in August 1992. Daily positions at 00 UTC are marked with dates alongside. Positions of well-defined low-level centres from visible satellite imageries are indicated in triangles with times given in DDZZ where: DD = day of the month; ZZ = hour in UTC.



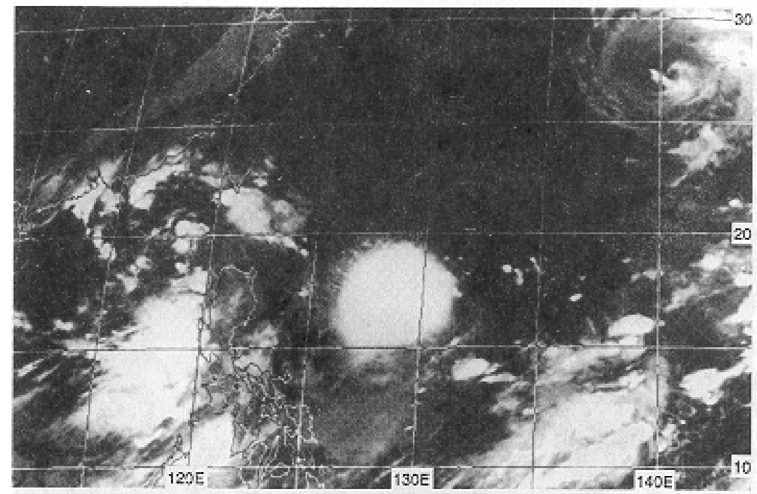
(a) 00 UTC 15 August 1992 (Lois at 15.5N 130.1E)



(b) 06 UTC 15 August 1992 (Lois at 15.8N 130.6E)

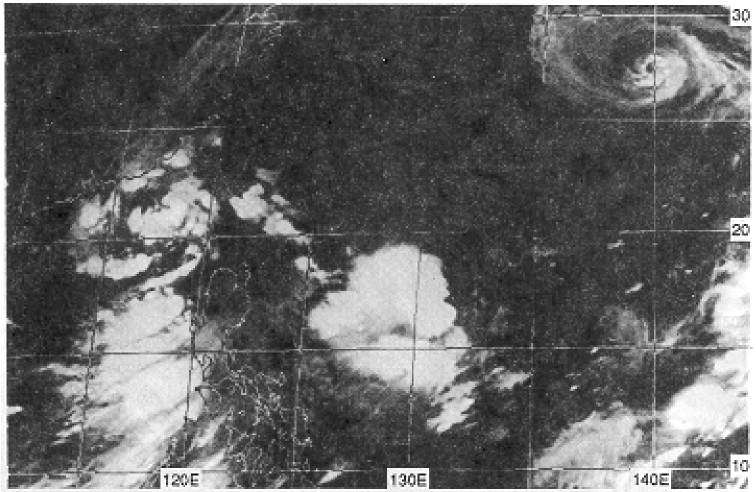


(c) 12 UTC 15 August 1992 (Lois at 16.1N 131.0E)

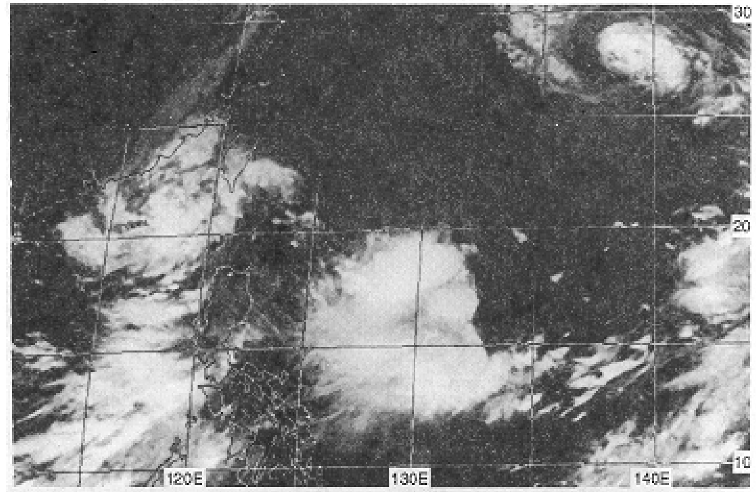


(d) 18 UTC 15 August 1992 (Lois at 16.5N 131.4E)

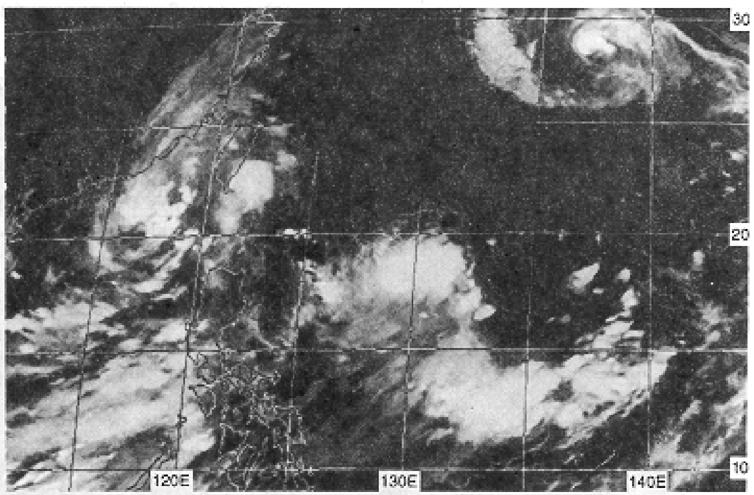
Figure 6 - Six-hourly infra-red satellite imageries for Lois (9214) (see text for details).



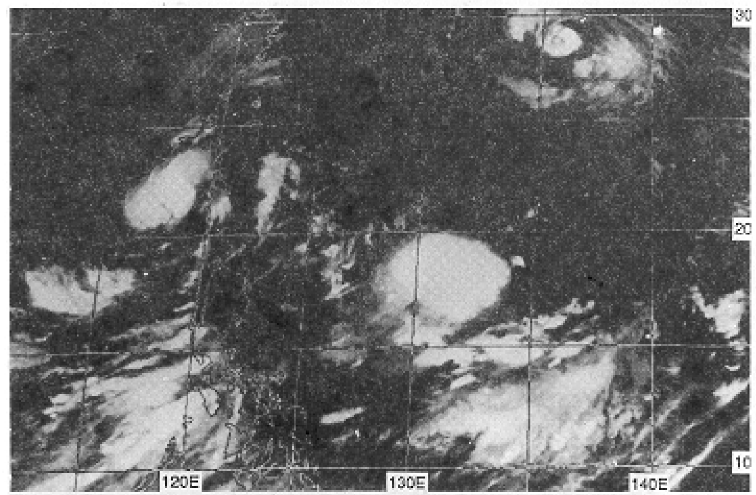
(e) 00 UTC 16 August 1992 (Lois at 16.9N 132.0E)



(f) 06 UTC 16 August 1992 (Lois at 17.4N 132.8E)

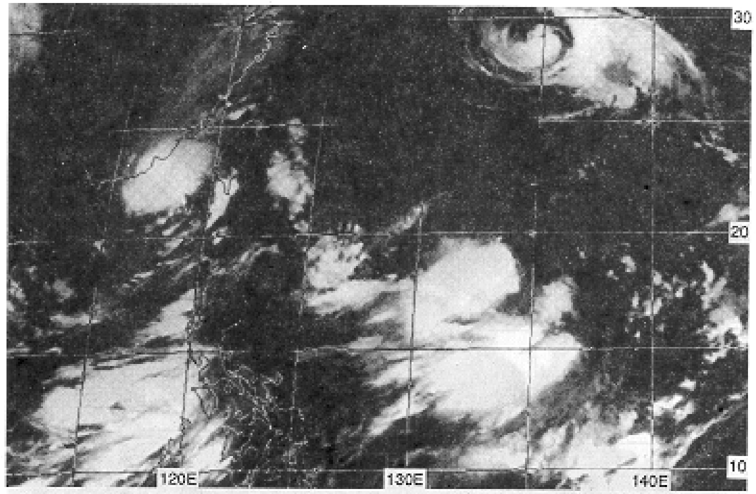


(g) 12 UTC 16 August 1992 (Lois at 17.8N 133.5E)

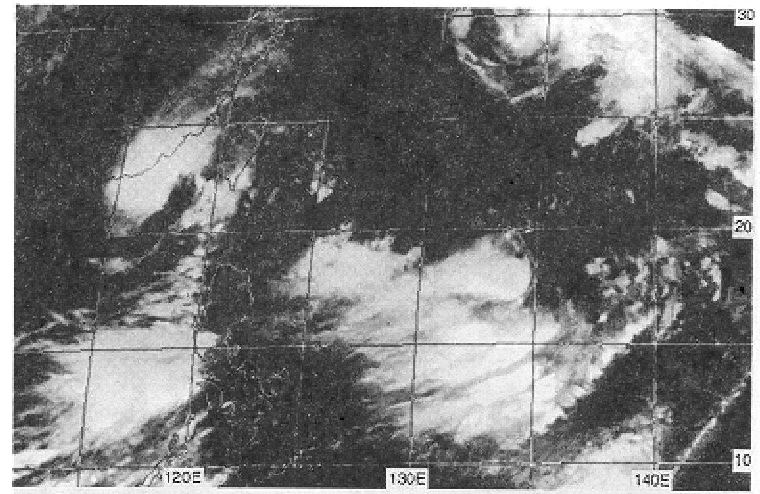


(h) 18 UTC 16 August 1992 (Lois at 18.1N 134.1E)

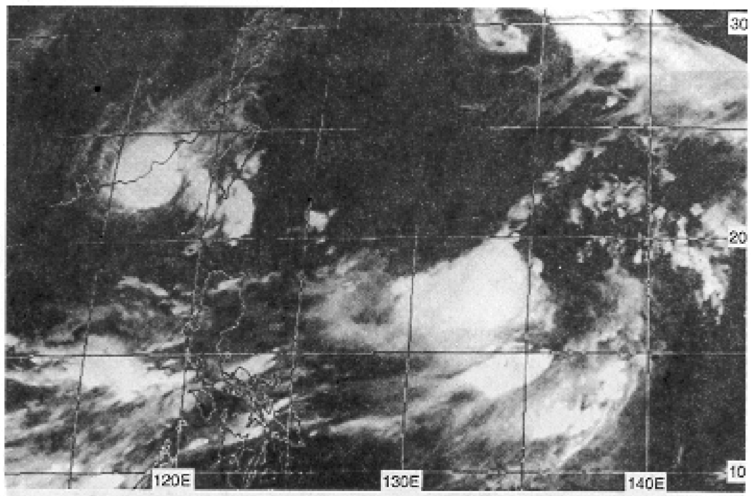
Figure 6 (continued)



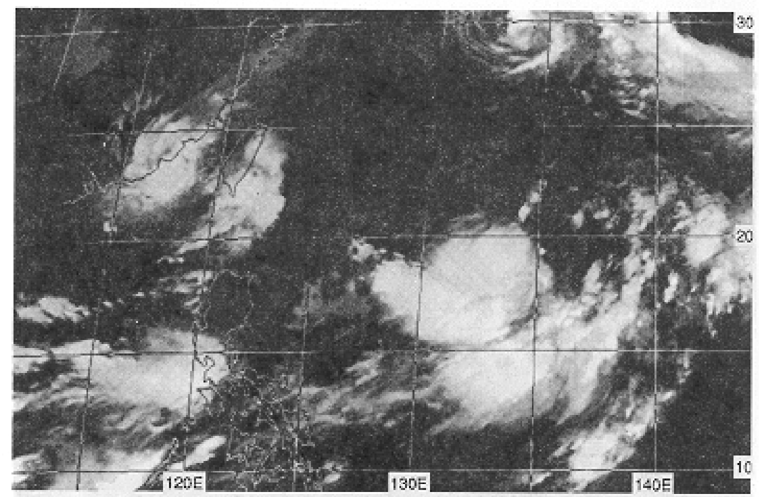
(i) 00 UTC 17 August 1992 (Lois at 18.4N 134.5E)



(j) 06 UTC 17 August 1992 (Lois at 18.7N 135.0E)

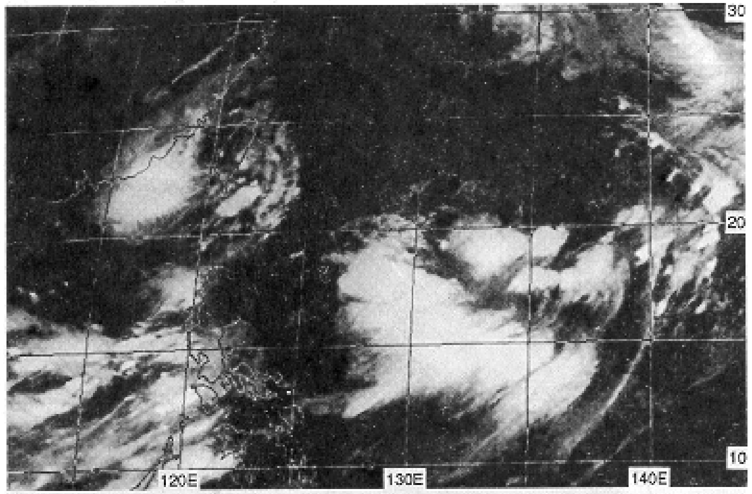


(k) 12 UTC 17 August 1992 (Lois at 19.0N 135.6E)

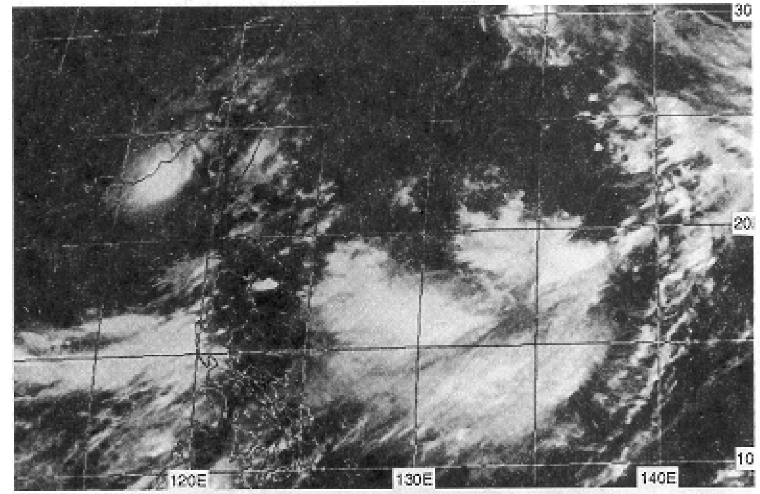


(l) 18 UTC 17 August 1992 (Lois at 19.5N 136.1E)

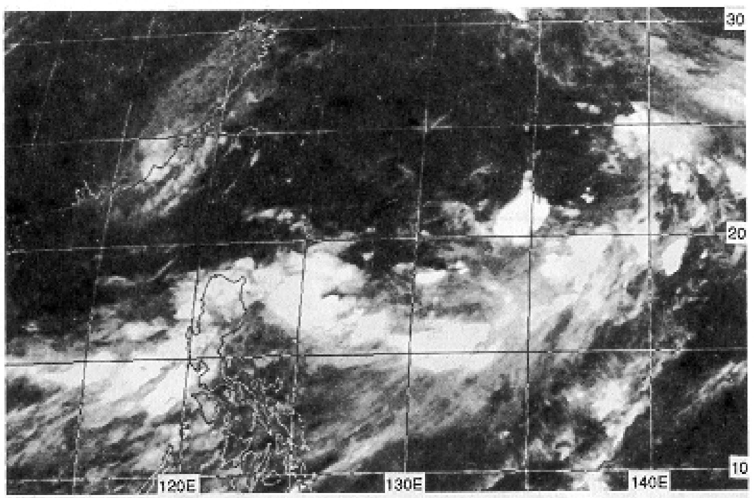
Figure 6 (continued)



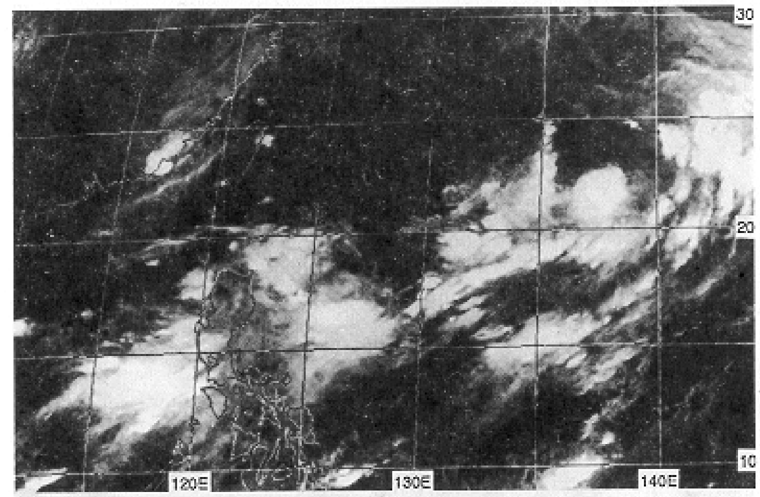
(m) 00 UTC 18 August 1992 (Lois at 20.1N 136.6E)



(n) 06 UTC 18 August 1992 (Lois at 20.9N 137.1E)

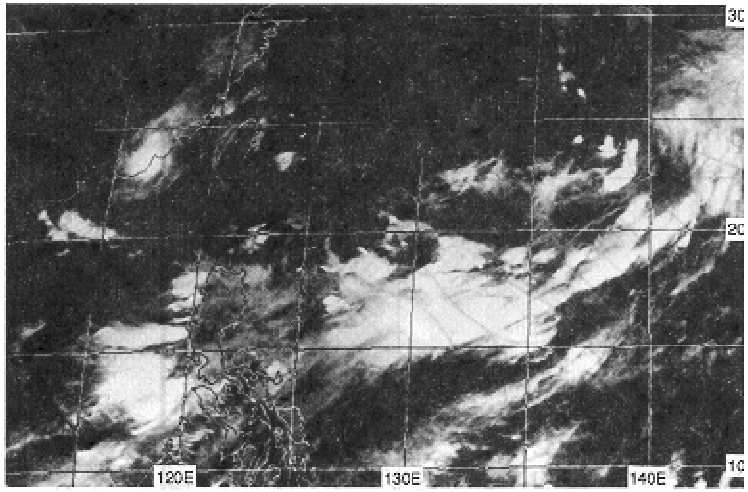


(o) 12 UTC 18 August 1992 (Lois at 21.8N 137.6E)

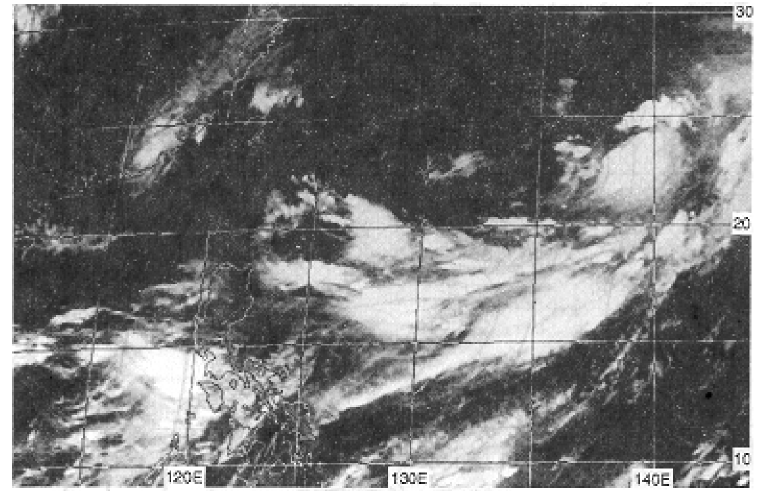


(p) 18 UTC 18 August 1992 (Lois at 22.8N 138.1E)

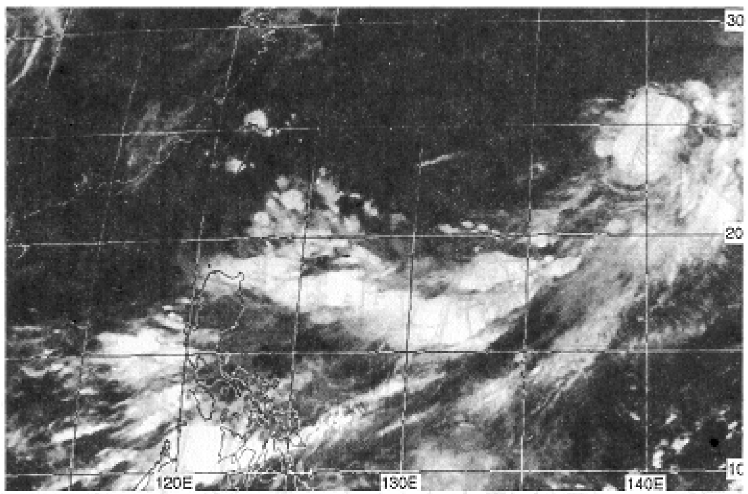
Figure 6 (continued)



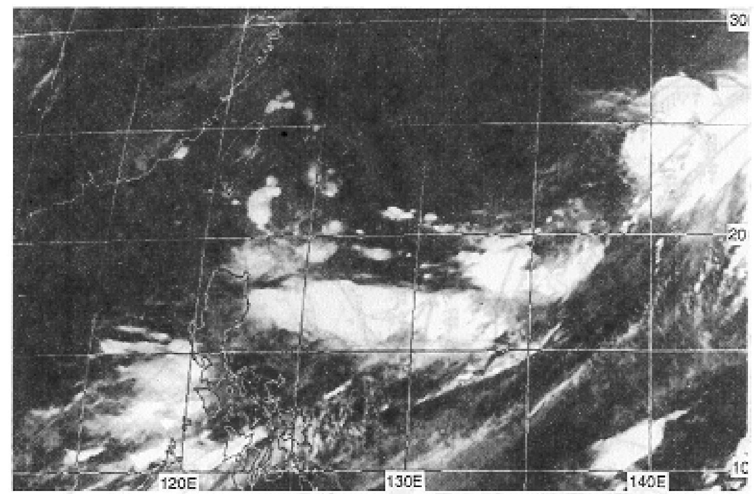
(q) 00 UTC 19 August 1992 (Lois at 24.0N 138.5E)



(r) 06 UTC 19 August 1992 (Lois at 25.2N 139.0E)



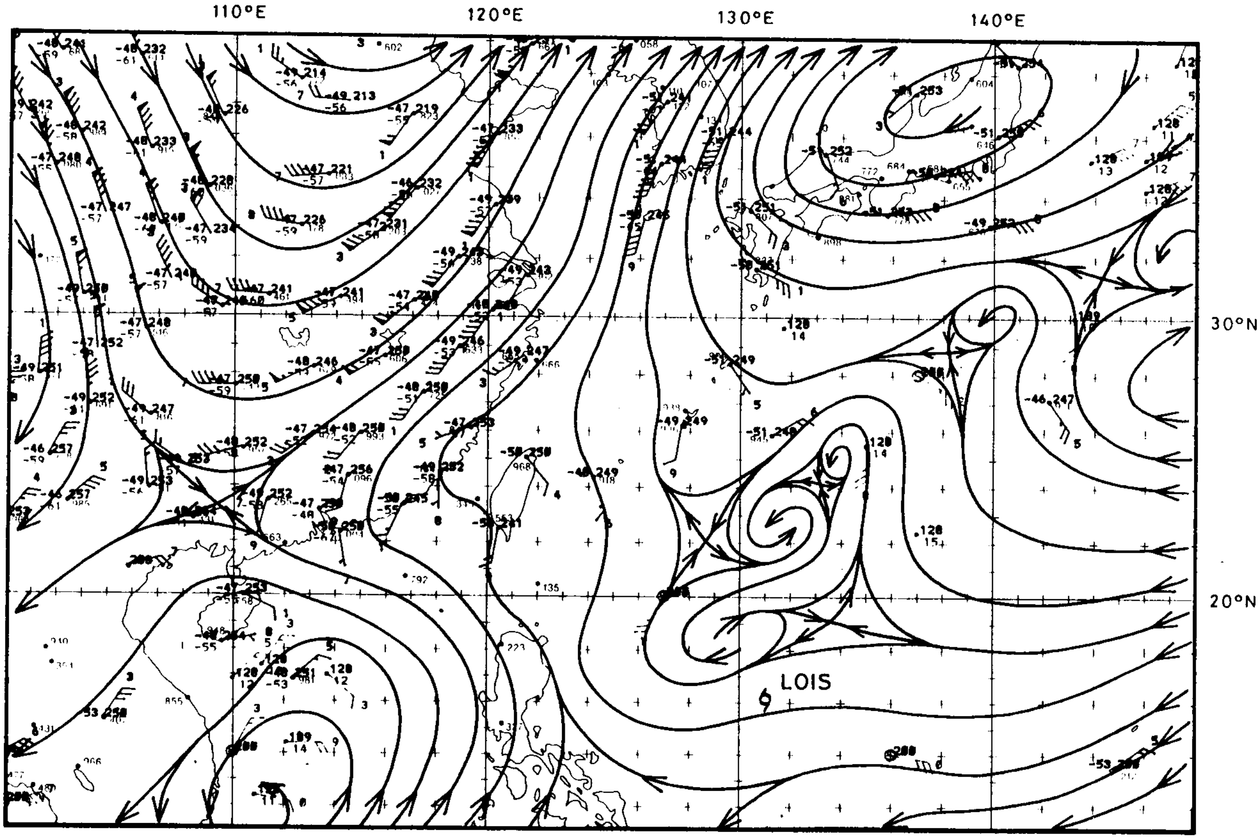
(s) 12 UTC 19 August 1992 (Lois at 26.2N 139.7E)



(t) 18 UTC 19 August 1992 (Lois at 27.1N 140.5E)

Figure 6 (continued)

(a)



(b)

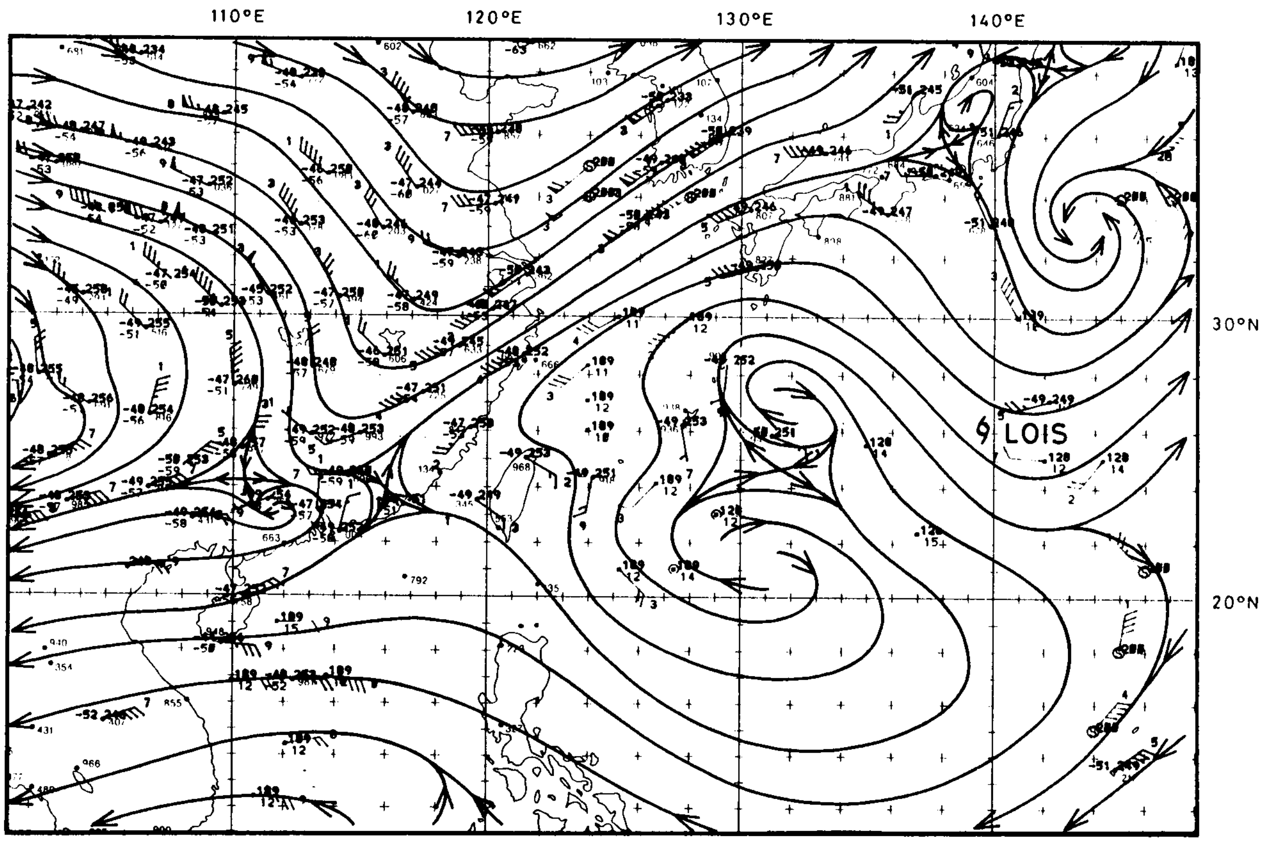


Figure 7 - 200-hPa streamline analysis at: (a) 12 UTC on 15 August 1992 and (b) 12 UTC on 19 August 1992. The surface positions of Lois according to the best track analysis are indicated as ϭ .

6. Summary and Discussion

The examples of Polly and Lois illustrate the problems involved in the tracking of tropical cyclones with cold-core or shear characteristics. Multiple centres and sheared-off convection can often mislead the forecasters. Sometimes, the magnitude of errors is such that a re-location of cyclone centres in operational warnings becomes unavoidable. With short-range (say 24-hour) track forecasts relying heavily on persistence and extrapolation, the resultant forecast error is also likely to be significant.

But detailed observational studies and post-analyses also show that if the relevant mechanisms determining the evolution of tropical cyclones are correctly diagnosed, then some allowances can indeed be made in an operational environment to limit the damage. In the case of Polly, operational tracking would have been much easier if the upgrading to tropical cyclone status was withheld until central convection could be sustained. In the case of Lois, knowing the prevailing direction of shear would alert the forecasters to the possibility of under-estimating the speed of movement and the extent of eastward motion.

Admittedly, operational requirements are always likely to over-ride meteorological considerations. In the example of Polly, the forecasters would be under a lot of pressure to upgrade the disturbance to a tropical cyclone as the system was already hovering over a busy ship route and was fast-approaching land. As such, it is imperative that forecasters should also learn to master the techniques for monitoring this special breed of tropical cyclones.

The observations made in this study and the guidelines suggested are mainly intended as points for reference in an operational environment. They are at best short-term remedies to some profound meteorological problems that as yet are not well studied and understood.

For instance, while Lois is obviously a good example for sheared-off systems (another similar case closer to home is Tropical Storm Deanna over the northern part of the South China Sea in June 1995), there are undoubtedly cases in which the tropical cyclone appears to be relatively unaffected by the strong vertical shear or, towards the other extreme, the tropical cyclone will simply dissipate rapidly in the face of such adversity. The combination of circumstances that allows Lois to survive, albeit as a weak circulation, is itself rather unusual. Recent studies by DeMaria (1995) and Hanley et. al. (1955) suggest that the effect of vertical shear on tropical cyclones could well be related to the latitudinal position and size of the vortex as well as the direction of the shear itself. More numerical and analytical studies on similar cases should help to unravel the mechanisms that help to sustain such strongly sheared systems.

The problems associated with "cold-core tropical cyclones" are just as intriguing. It is commonly observed that upper cold lows may or may not induce a significant low-level circulation. It is also recognized that organized convection, in connection with one or more than one of the transient multiple centres within a broad low complex, appears to play a crucial role in the cold to warm-core transitional process. But is the chance of success purely random? If not, what are the contributing factors? (For example: in the case of Polly, did the terrain of Taiwan actually help to get things organized by introducing more lateral shear at the lower levels?) And what are the favourable conditions required? Answers to such questions need more observations and data, particularly near the core of the vortex.

Unfortunately, even an enhanced observational data set such as SPECTRUM (i.e. SPecial Experiment Concerning Typhoon Recurvature and Unusual Movement conducted by the ESCAP/WMO Typhoon Committee in the summer of 1990) cannot resolve adequately the core structure of the observed cyclones. With most operational NWP models still at the stage of trying to get the large-scale features right, the mesoscale details of tropical cyclones are likely to remain a matter of low priority in the foreseeable future. To fully explain the observations made in this study would require a better knowledge of the interactive mechanisms between synoptic and sub-synoptic scales as well as between tropical and extratropical systems. The immediate objective, therefore, is first to acquire some basic understandings of the problem. Purposely designed numerical experiments, even using simple models, should prove useful in establishing hypotheses and eliminating possibilities.

References

Carlson, T.N., 1967: Structure of a steady-state cold low. *Mon. Wea. Rev.,* **95,** 763-777.

DeMaria, M., 1995: Another look at the effect of vertical shear on tropical cyclone intensity change. *Preprints, 21st Conference on Hurricanes and Tropical Meteorology*, Miami, 323-325.

Hanley, D.E., J. Molinari and D. Keyser, 1995: A study of the role of vertical shear in tropical cyclone development. *Preprints, 21st Conference on Hurricanes and Tropical Meteorology*, Miami, 71-73.

Holton, J.R., 1979: *An Introduction to Dynamic Meteorology (2nd Edition).* Academic Press, London.

Kelly, W.E., and D.R. Mock, 1982: A diagnostic study of upper tropospheric cold lows over the western North Pacific. *Mon. Wea. Rev.,* **110,** 471-481.

Mapes, B.E., 1995: Self-adjusting convective heating profiles and the downward development of cool core depressions. *Preprints, 21st Conference on Hurricanes and Tropical Meteorology*, Miami, 66-67.