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Impact of Asymmetric Bogusing on Typhoon Track Forecasting - a Case Study of Typhoon Leo (9902)

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Abstract

Leo was an unusually early tropical cyclone to affect Hong Kong in 1999. It developed over the South China Sea in late April. In the early stage, it tracked northeastward and intensified into a typhoon. As it approached the south China coast, it weakened and changed its course first to the northwest and then north. This paper discusses the factors contributing to the changes of direction in Leo's track and the successful forecast by the Operational Regional Spectral Model. It is shown that the use of an asymmetric vortex to bogus the tropical cyclone in the model and the accurate forecast of the intensity change of the vortex contributed to this success.

1. Introduction

Based on a 53-year (1946-1998) database at the Hong Kong Observatory (HKO), on average five to six tropical cyclones (TCs) formed over the South China Sea (0-30 N, 105-120 E) each year, out of which one to two make landfall over the south China coast (108-120 E). TCs generally do not form over the South China Sea until May, while the maximum number occurs in August (Figure 1). It was rather unusual to have typhoons forming over the South China Sea as early as April and Leo set the record of being the earliest TC to affect Hong Kong, causing the hoisting of local warning signals.

The HKO analyzes the best-track positions of TCs each time after the event with the benefit of all available data and the wisdom of hindsight. Figure 2 shows the HKO analyzed best-track of Leo. Leo formed on 28 April 1999 and it took on a northeast track in its early stage as it intensified into a typhoon. On 1 May 1999, it weakened and took a rather sharp turn to the northwest, posing a potential threat to Hong Kong. It was closest to Hong Kong on 2 May and the local Signal Number 8 was hoisted to alert the public of the likelihood of gales. This was the earliest date for the Signal Number 8 to be hoisted since 1946. Shortly before realizing a direct hit, Leo once again veered to the north and missed Hong Kong narrowly by a distance of around 70 km.

Section 2 discusses the synoptic situation during the life span of Leo. Section 3 describes the use of the Operational Regional Spectral Model (ORSM) to simulate Leo's track as it approached the south China coast. The model configuration and the simulation results using the operational set-up and different experimental set-ups to investigate into the main contributors to the successfulness of the model forecast are discussed. Section 4 gives the conclusions.

2. Overview of the synoptic situation

2.1 During the transition from spring to summer, outbreaks of cool northeast monsoon over southern China are not uncommon. With the prevailing northeast monsoon, low level winds over southern China and the northern part of the South China Sea are generally easterlies or northeasterlies while winds at the mid and upper levels are mainly westerlies. TCs may be modified fairly rapidly when they encounter the northeast monsoon in the subtropical region as in the case of Leo. The associated impact on the TC track will be much related to the changes in the TC intensity, the vortex characteristics and how these relate to the background flow field. Figure 3 shows the Infrared satellite imageries during the period 27 April - 2 May 1999 at 24-hour intervals. A description of the synoptic pattern and the circulation features visualized from satellite imageries follows.

2.2 27 and 28 April 1999

A ridge of high pressure dominated over China and the northern part of the South China Sea on 27-28 April. At 00 UTC 28 April, the centre of the high pressure was located at around 30 N, 108 E. At the same time, southwesterlies originated from the Indian Ocean prevailed over the southern part of the South China Sea. A monsoon gyre with a diameter of around 1200 km formed over the South China Sea. Clusters of active convections occurred and multiple low level circulation centres were observed. The low level circulation centre off the coast of southern Vietnam near 16 N became the preferred location for TC genesis. The sea surface temperature (SST) in the region was around 28-29 degrees according to ship reports. Leo eventually formed near 16 N, 111 E in the morning of 28 April. With the support of divergent outflow at the upper levels, Leo continued to develop. As Leo was located poleward of the northeast-southwest oriented mid-tropospheric ridge extended from the western North Pacific to southern Philippines near 8 N in the early stage of formation, it was subjected to the predominantly northeastward steering flow (Figure 3(b)). Figures 4(a) and (b) are "space-mean" charts showing the smoothed geopotential height field at 500 hPa and 700 hPa respectively, after the removal of the TC circulation and other small-scale eddies for 12 UTC 28 April. The geostrophic steering vector at the TC centre on the space-mean charts provide some guidance to forecasters as to the movement of the TC (Dong and Liu, 1965), although allowance has to be given for deviations arising from the beta-effect, asymmetry, etc. (Bell and Lam, 1980). Leo tracked northeastward at around 5 knots during the period, consistent with the general synoptic scale steering flow indicated in the space-mean charts.

2.3 29 and 30 April 1999

Figures 3(c) and (d) show a gradual contraction in size of the cloud mass surrounding the TC centre. The signature of the monsoon gyre gradually transitioned to that of a TC. At 00 UTC 30 April, Leo intensified into a typhoon and the eye became prominent. Along with this intensification, the steering level would be expected to reside higher up in the troposphere. When a TC reached typhoon strength, the steering level would normally be taken from around 400 hPa or 500 hPa (Dong and Neumann, 1983). Around the same time, the mid-tropospheric ridge became more east-west oriented with its axis moving northwards to around 17 N (Figure 3(d)). Leo also acquired a more significant northerly component in its movement as it approached the latitude of 20 N.

2.4 1 and 2 May 1999

The prevailing northeast monsoon brought cool and dry air to southern China and the northern part of the South China Sea. The coastal waters were also relatively cool and SST was around 25-26 degrees. The satellite imagery in Figure 3(e) gives a good indication of dry air from the north being drawn into the western half of the TC circulation. Convection was depressed and the active convective area became more compact. At the same time, Leo experienced increasing vertical shear as it moved into a region with strong westerlies in the mid and upper levels and easterlies in the low levels. Figure 3(f) shows that the high cloud cover was sheared off by the upper westerly flow to the east of the TC centre. The low level circulation centre was left exposed. In step with this change, Leo weakened rapidly as it moved towards the coast of southern China.

As the area of high pressure centred over Japan continued to move eastwards, the ridge of high pressure over the coast of eastern China retreated to the Pacific. The low-level flow over the region became southerlies to the west of the ridge as shown in the space-mean chart for 00 UTC 2 May (Figure 5). For a weakening tropical storm, the steering level would shift to a lower level. At 00 UTC 2 May, the steering flow at 700 hPa (Figure 5) had backed relative to that at earlier times (Figure 4b). This is consistent with the left-hand turn of Leo's track late on 1 May.

3. Model simulation of Leo's track changes

3.1 The Operational Regional Spectral Model (ORSM)

From the perspective of operational forecasting, it is of interest to see whether numerical modelling helps provide useful guidance to the front-line forecasters in predicting the changes of direction in Leo's track in the latter part of its life time, within a distance of 300 km of Hong Kong. It is of particular concern to HKO because of the proximity of Leo to Hong Kong during this period.

The ORSM was run at 60-km horizontal resolution with 20 vertical levels to provide 48-hour forecast in 1999. The lateral boundary conditions were taken from the Japan Meteorological Agency (JMA) Global Spectral Model (GSM). The model was adapted from JMA and was tuned for application in Hong Kong. Details of the model formulation are given in NPD/JMA (1997). TC bogusing was adopted in HKO to better initialize the position and strength of TC. Information on the position of TC, its estimated minimum central pressure and 30-knot wind radius were used in constructing the bogus profiles.

The surface pressure profile was calculated using the gradient wind balance in the Fujita's formula (1952) while the geopotential profile at the upper levels was determined by an empirical formula based on Frank's study (1977). Wind fields on the upper levels were derived from the geopotential profiles by gradient wind balance. Asymmetirc TC bogusing was used in the operational set-up. The asymmetric component was extracted from the first guess field which was the previous 12-hour forecast from the analysis-forecast cycle.

Observational data used in the data assimilation system include SYNOP, SHIP, BUOY, PILOT, TEMP, AIREP, AMDAR, SATEM and SATOB acquired through the Global Telecommunication System (GTS), and also cloud motion derived winds and 6-hourly digital cloud amount data from the Geostationary Meteorological Satellite (GMS) of JMA via the Integrated Services Digital Network (ISDN).

3.2 Operational run results

The forecast positions of Leo represented by centres of the minimum mean-sea-level pressure obtained from the model run initialized at 00 UTC 1 May 1999 are plotted and marked at 6-hourly intervals in Figure 6(a). For easy comparison, the best-track positions are also plotted. The model successfully captured the left-hand turn followed by the right-hand turn of Leo's track as it approached the south China coast. As the model forecast Leo to weaken rapidly starting from 1 May 1999, the steering level of the vortex would be expected to change to a lower level than previously.

Figure 6(b) shows the forecast positions of the maximum vorticity centres at different pressure levels of 850 hPa and 500 hPa together with those of the minimum mean-sea-level pressure centres. It is seen that the positions of the vorticity centres at higher levels are displaced to the east of the lower level ones. This is indicative of a vortex being embedded in a strongly sheared environment and a sign of weakening. Furthermore, the movement of the circulation at sea-level would be more closely related to steering at lower levels. The first left-hand turn of Leo could thus be understood as the increasing influence of the prevailing easterlies at 850 hPa or below along the south China coast (Figure 7). The final right-hand turn however was more subtle and has yet to be understood.

3.3. Model experiments

In order to understand the model performance better, three sets of model simulation experiment were carried out. The model results from the operational set in 1999, in which an asymmetric weak (AW) vortex was prescribed, served as the control set.

Three sets of experiment with modifications in TC bogus information were carried out to investigate the impact of vortex asymmetry and strength on Leo's track :

(a) symmetric strong (SS) vortex

(b) symmetric weak (SW) vortex

(c) asymmetric strong (AS) vortex

The strong vortex was specified with a central minimum pressure of 920 hPa and a strong wind radius of 350 nautical miles in Sets (a) and (c). The weak vortex was specified with 980 hPa and 210 nautical miles in Set (b) as in the control run. 36-hour forecasts were made with initial time at 00 UTC 1 May 1999.

Forecast tracks from the four runs together with the best track are shown in Figure 8. Their forecast position errors are given in Table 1. The position errors are great circle distances between the forecast positions and the best-track positions. The turns in the TC track were best represented in the control model run. Besides, the forecast errors were the smallest among several sets beyond T+12 hours. When compared with the result with the"SW" vortex, the introduction of asymmetric components alleviated the systematic northward drift of the TC. This is consistent with the findings of Ueno (1995).

Result from Set (a), the"SS" run, shows the largest deviation from the best track beyond T+12 hours. In particular, the run forecast Leo to move northwards instead of northwestwards as in the control run. As a strong bogus vortex was used at the model initial time, the vortex strength was also greater than that in the control run in subsequent forecast hours. Figure 9 shows the forecast positions of the maximum vorticity centres on 850 hPa and 500 hPa levels for Set (a) "SS". It is seen that the circulation centres at different vertical levels aligned closer when compared with those for the weak vortex in the control run (Figure 6(b)). In association with the strong bogus vortex, Leo was predicted to move much faster than that in the control run. It demonstrates that accurate forecasting of the TC intensity change is important to track forecasting.

Forecast tracks from Sets (b) "SW" and (c) "AS" as shown in Figure 8 show that the northwest movement of the vortex was not as well predicted as in the control run, though the forecast performance was better than that of Set (a). The results from Sets (b) "SW" and (c) "AS" were similar except that the latter set forecast the vortex to move at a faster speed apparently in association with the strong bogus vortex.

Results from the model experiments suggested that both asymmetry in the initial vortex and the weakening of the vortex contributed significantly to the northwest turning of the track of Leo on 1 May 1999. This was most likely a consequence of a lowering of the steering level as the TC weakened, bringing it increasingly under the influence of the easterly background flow at 850 hPa and below along the south China coast.

4. Conclusions

Leo was an unusually early tropical cyclone to affect Hong Kong in late April. It weakened rapidly on encountering the cool northeast monsoon with prevailing easterlies at the low level and westerlies at the upper levels over southern China and the northern part of the South China Sea. Leo changed its track from northeast to northwest and then north as it approached the south China coast. The turning of Leo's track was associated with its weakening and the change in the steering level from mid to low levels. This change was well captured by the Operational Regional Spectral Model at the Hong Kong Observatory. Results from the model experiments suggested that bogusing of an appropriate weak asymmetric vortex and the accurate forecast of the intensity change of the vortex were important in determining the movement of an early season tropical cyclone.

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	Control	Set (a)	Set (b)	Set (c)
Bogus vortex	Asymmetric weak	Symmetric strong	Symmetric weak	Asymmetric strong
0 hour initial	10 km	11 km	15 km	0 km
12-hour forecast	63 km	35 km	57 km	69 km
24-hour forecast	70 km	182 km	113 km	156 km
36-hour forecast	68 km	323 km	211 km	147 km

Table 1 : Forecast position errors for Typhoon Leo in model simulation experiment.

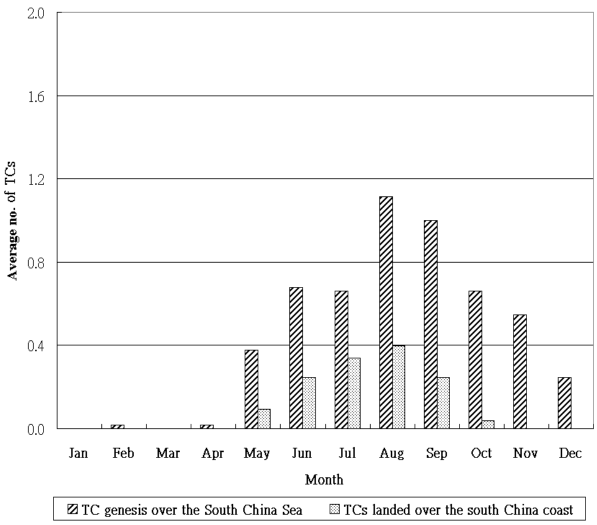


Figure 1. Monthly distributions of tropical cyclones developed over the South China Sea (0-30 N, 105-120 E) and landed over the south China coast (108-120 E). Data set based on 1946-1998 HKO records.

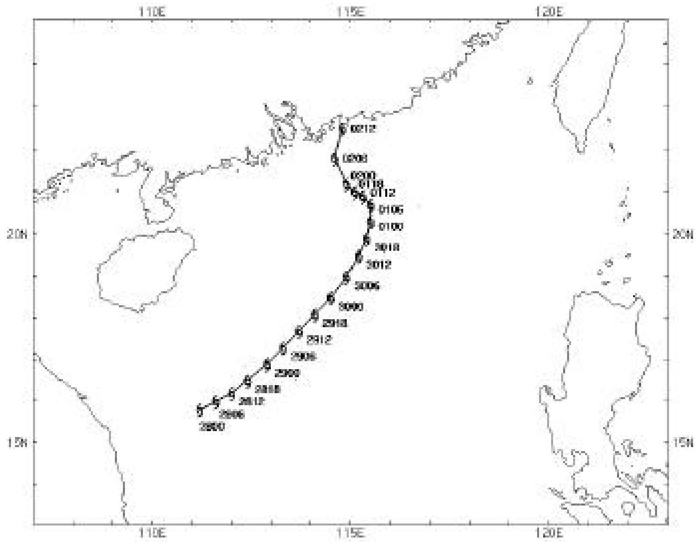


Figure 2. Best-track positions of Typhoon Leo (9902) analyzed by the Hong Kong Observatory at 6-hourly intervals.

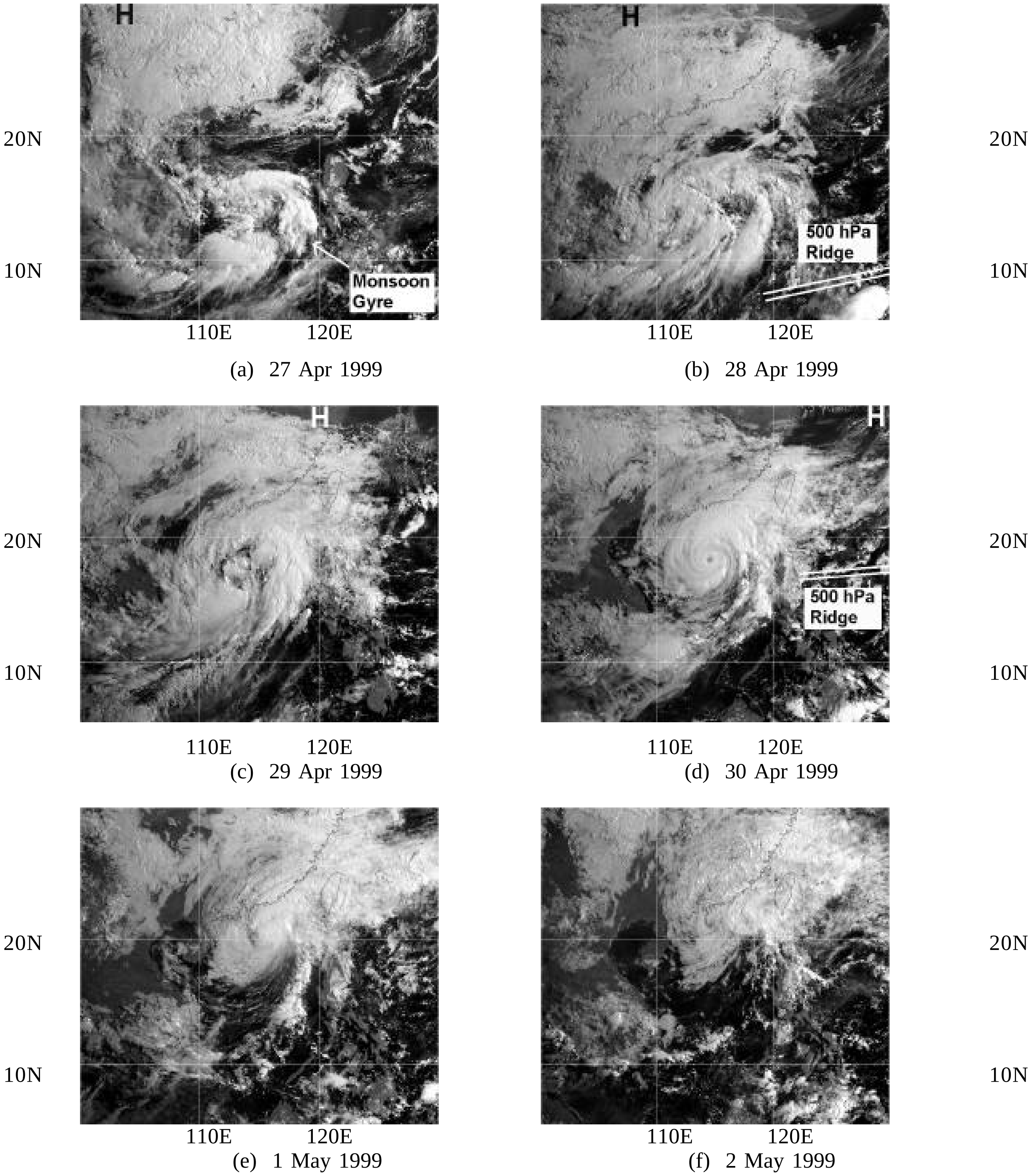


Figure 3. Infrared satellite imageries originally captured by GMS of JMA from 00 UTC 27 April to 2 May 1999 at 24-hour intervals.

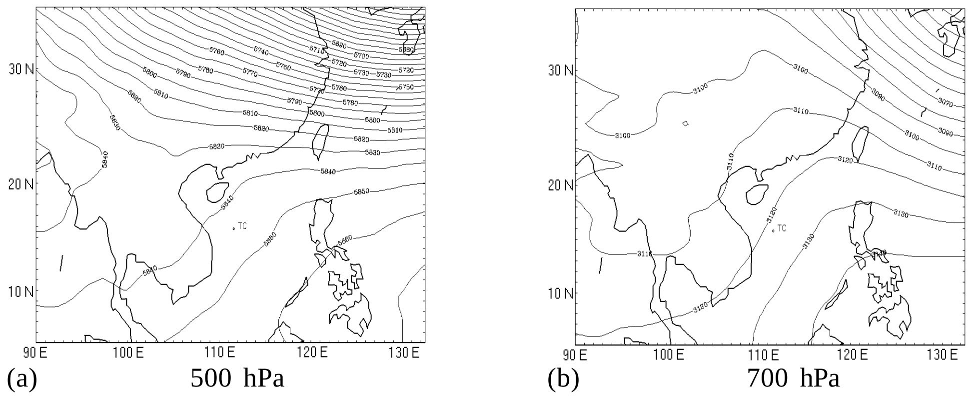


Figure 4. Space-mean charts for (a) 500 hPa and (b) 700 hPa at 12 UTC 28 April 1999. "TC" marked the position of Leo.

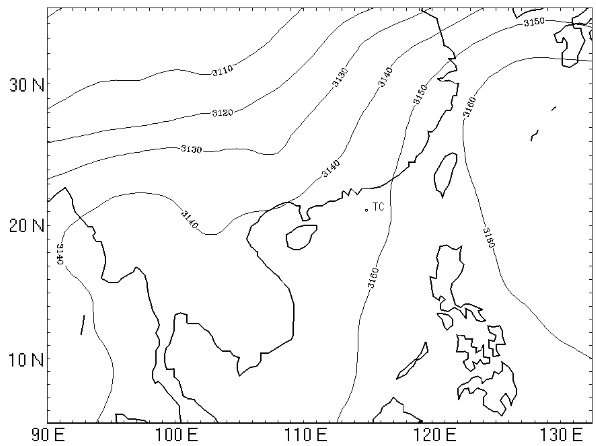
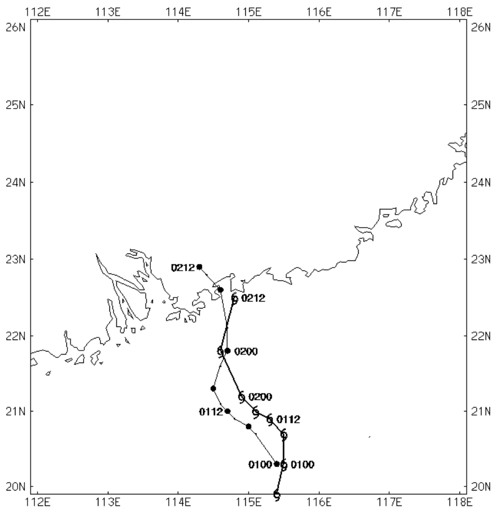
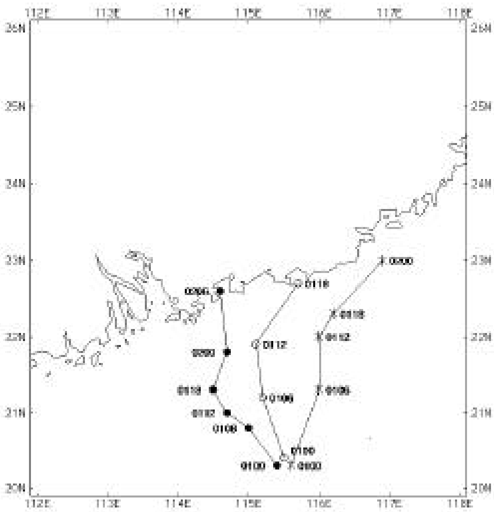


Figure 5. Space-mean chart for 700 hPa at 00 UTC 2 May 1999. "TC" marked the position of Leo.



(a)



(b)

Figure 6. (a) Forecast track positions (filled circles "•") and best-track positions (TC symbols " ") of Typhoon Leo. Forecasts initialized at 00 UTC 1 May 1999. (b) Forecast positions of the maximum vorticity centres on 850 hPa (open circles "o") and 500 hPa (star symbols "✳"). Filled circles have the same meaning as in (a). Positions drawn at 6-hourly intervals.

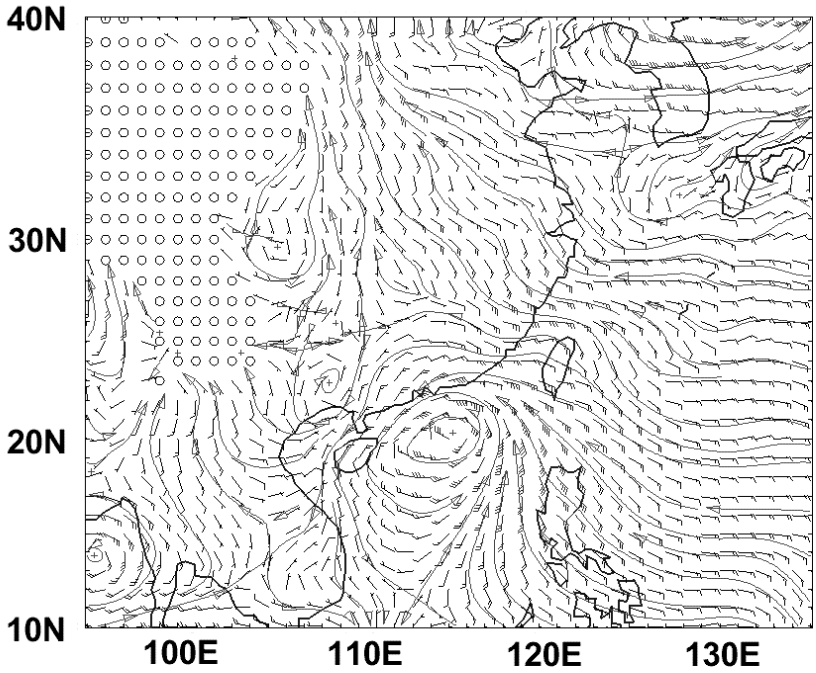


Figure 7. 850 hPa wind field at 00 UTC 1 May 1999.

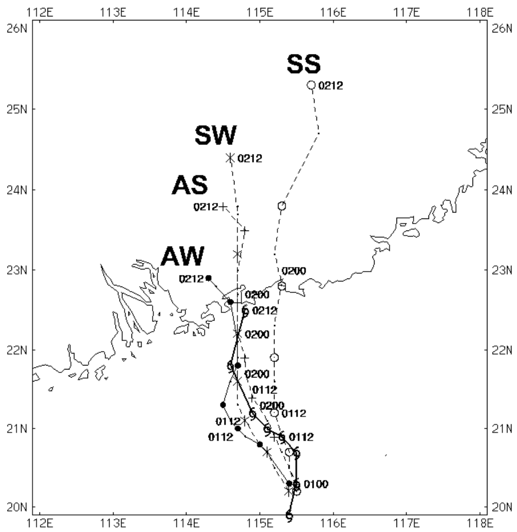


Figure 8. Forecast track positions of Typhoon Leo in Set (a) (open circles "o"), Set (b) (star symbols " ✳"), Set (c) (plus symbols "+"), the control (filled circles"•") model experiments and the best-track positions (TC symbols " § "). Positions marked at 6-hourly intervals.

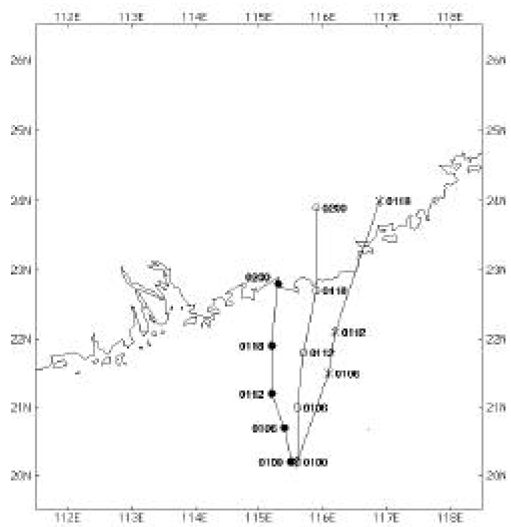


Figure 9. Forecast positions of the minimum mean-sea-level pressure centres (filled circles "•") and the maximum vorticity centres on 850 hPa (open circles "o") and 500 hPa (star symbols "✳") in Set (a) "SS" model experiment.