Tropical Storm Sarika merging in Typhoon Songda Circulation by Strong Wind and Sufficient Moisture Transportation

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Abstract
The destruction of a small tropical storm pulled by a stronger typhoon was investigated using GOES-9 IR satellite images, weather maps and numerically calculated moisture fluxes and streamlines with strong wind bands by a meteorological model - the UM (British Unified Model) adopted by Korean Meteorological Administration (UM-KMA) from September 5 through 8, 2004. When Typhoon Songda-TY 0418 of 940hPa with a maximum surface wind speed of 80kts moved north-northwestward with its slow moving speed of 6kt at 00:00 LST, September 6, another severe Tropical Storm Sarika-STS 0419 of 980hPa with a maximum surface wind speed of 55kts was detected at 142.7°E and 19.3°N, showing its westward movement of 14kts.

Streamline and moisture flux at 850hPa level showed that Sarika maintaining an independent moving track before had an interaction with Sonda, especially its right quadrant of cyclonic circulation at 09:00LST September 6 and from 09:00LST September 7, persistent westward STS Sarika was strongly pulled north by northeastward TY Songda with a maximum surface wind of 80kts and its moving speed of 21kts and Sarika could be drawn into the wake of Songda's main streamline. Due to the prohibition of Songda, the cyclonic circulation of Sarika was destroyed from 21:00LST, September 7 and eventually there must have been a reduction in its strength, showing no longer tightly packed bands of cloud and spreading of clouds, that is, becoming extinct. The moisture transportation from tropical storm into stronger typhoon could cause a significant weakness of tropical storm and gradually disappeared.

Keywords: Typhoon Songda, Tropical Storm Sarika, Merging, GOES-9 satellite image, UM-KMA model, Moisture flux, Streamline.

Introduction
In general, typhoon is a mature tropical cyclone developing in the northwestern part of the Pacific Ocean between 120° and 140°E where its track is westward and later northward classes of typhoon by Hong Kong Observatory (HKO)[1] such as Super Typhoon, Severe Typhoon, Typhoon, Severe Tropical Storm, Tropical Storm and Tropical Depression on different maximum sustained wind speed for 10 minutes near the typhoon centre recommended by World Meteorological Organization (WMO)[2].

On the other hand, the classification of tropical cyclones suggested by Korean Meteorological Administration[3] defined four simplified classifications such as Typhoon, Severe Tropical Storm, Tropical Storm and Tropical Depression depending on surface atmospheric pressure and wind speed near the typhoon centre. Slightly differently, Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) also classifies as Typhoon, Tropical Storm, Tropical Depression and Tropical Disturbance, depending on maximum wind speed like typhoon with maximum speed over than 118km per hour, Tropical Storm with its speed between 64~118km per hour, Tropical Depression with its speed up to 63km per hour and Tropical Disturbance with its speed less than 62km, respectively.

Tropical cyclones frequently produce severe disasters of severe flooding by torrential precipitation, destruction of houses and buildings by persistent strong wind and heavy rainfall. For a short time period, coastal erosion and ships sunken can be caused by storm surges of up and down of sea levels and high waves, but for a long time period, the changes of marine eco-environment such as fishing farms and marine plants are also generated by cold sea outbreak responding to tropical cyclone, resulting in severe economical loss[4~8].

When two nearby cyclonic vortices orbit each other and close the distance between the circulations of their corresponding low-pressure areas, binary interaction of their circulations can cause the development of a larger cyclone or cause two cyclones to merge into one. This is called as Fujiwhara effect[9] or Fujiwara or binary interaction. Liu[10] explained the relative motion of typhoon pairs over the South China Sea and DeMaria and Chan[11] carried out a numerical study on the interactions between two cyclones. Kuo et al[12] further explained the interaction of tropic cyclones. Xu et al[13] presented the impact of a tropical storm on the intensity of a typhoon by moisture transportation.

The objective of this work was to investigate binary interaction of two tropical storms such as a tropical storm under the influence of a much stronger typhoon, using

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satellite images and numerically calculated moisture fluxes, winds, streamlines by a numerical model.

Numerical Model

For the calculation of moisture fluxes and streamlines with strong wind bands, the British Unified Model (UM) was adopted by Korean Meteorological Administration (KMA) in recent years and this model has been adjusted for local and regional scale forecasting by KMA (later called UM-KMA model). The UM-KMA model is a Numerical Weather Prediction and climate modeling software suite originally was developed by the United Kingdom Meteorological Office and now both used and further developed by many weather-forecasting agencies around the world. This model is grid-point based rather than wave based and can be run on a variety of supercomputers around the world.

Initial input data of the UM for numerical weather prediction is provided by observations from satellites, the ground weather stations, buoys at sea, radar, radiosonde weather balloons, wind profilers, commercial aircraft and a background meteorological field from which previous model runs. The UM software suite was written in Fortran-90. KMA adopted and modified this UM model (UM-KMA) for weather forecasting using nesting techniques for different domains of horizontal grid of 1.5km and 4km for local scale domain like a city, 12km for regional scale domain and 40km for global scale domain respectively for different forecasting purposes. Using the UM-KMA model, winds, relative humidity, moisture fluxes and streamlines were calculated to investigate how two typhoons could be associated with each other for the annexation of them.

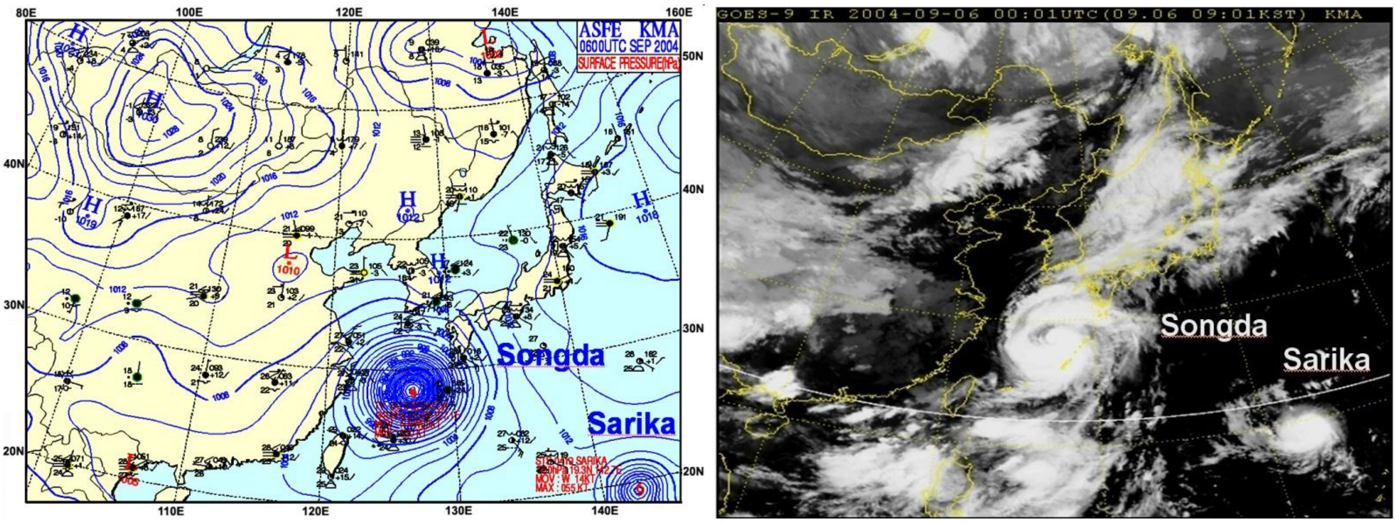
Results and Discussion

Joint Typhoon Warning Centre, USA (JTWC) at 12:00 UTC, August 27 gave the first warning on Tropical Depression-22W with its center at 270 nautical miles east of Eniwetak Atoll in the Pacific Ocean. At 00:00 UTC, August 28, the tropical depression with its surface wind speed of 35kts was assigned the name as Songda as a tropical storm. At 18:00 UTC, August 30, it became a typhoon with a maximum surface wind speed of 95kts and situated about 17 nautical miles north-northeast of Agrigan Island in the Northern Mariana Islands. Then the typhoon moved northwestward continuously until September 4.

When Typhoon Songda-TY 0418 of 940hPa and a maximum surface wind speed of 80kts moved north-northwestward with its slow moving speed of 6kts at 09:00 LST, September 6, another severe Tropical Storm (STS) Sarika-STS 0419 of 980hPa and its maximum surface wind speed of 55kts was detected at 142.7°E and 19.3°N showing its westward movement of 14kts (Figs. 1a and 1b). GOES-9 IR images showed the proximity of the two storms to one another. Two typhoons orbited independently each other at this time with no any interaction between them (Figs. 2a and 2b). Table 1 indicates the movement tracks of two typhoons which were classified by Typhoon Songda and Tropical Storm Sarika from 21:00LST (Korean Local Standard Time = 9 hours + UTC), September 6 through 09:00LST, September 8, when Tropical Storm Sarika almost disappeared.

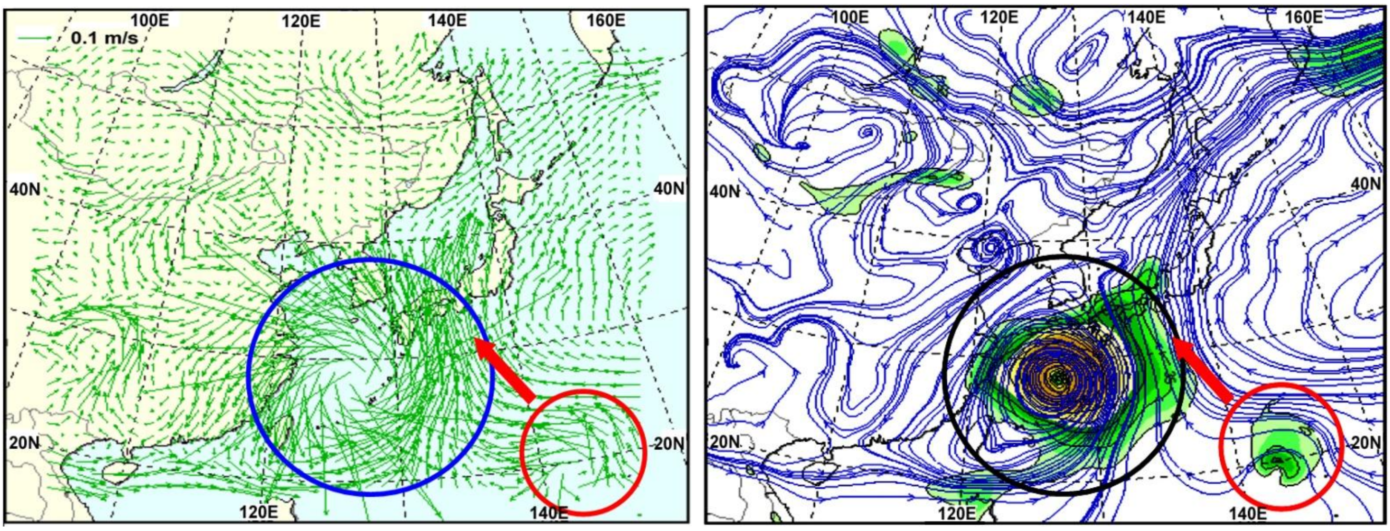
Table 1
Comparison of TY-0418 Songda (TY) and STS-0419 Sarika (TS) from September 6 through 8, 2004

Date	Surface Press (hPa)	Position	Max. surface wind (kt)	Moving speed (kt)
(TY) 09:00LST, Sept. 6	940	28.4N°; 127.1°E	80	NNW06
(TS)	980	19.3°N; 142.7°E	55	W14
(TY) 21:00LST, Sept. 6	940	29.9N°; 127.3°E	80	NNE06
(TS)	980	19.8N°; 139.5°E	55	W15
(TY) 09:00LST, Sept. 7	945	32.7°N; 129.6°E	80	NE21
(TS)	985	21.8°N; 138.7°E	50	N10
(TY) 21:00LST, Sept. 7	960	38.7°N; 135.9°E	70	NE44
(TS)	996	23.7°N; 138.1°E	35	N07
(TY) 09:00LST, Sept. 8	970	43.6°N; 140.4°E	55	NNE20
(TS)	1000	26.0°N; 138.0°E	10	N15



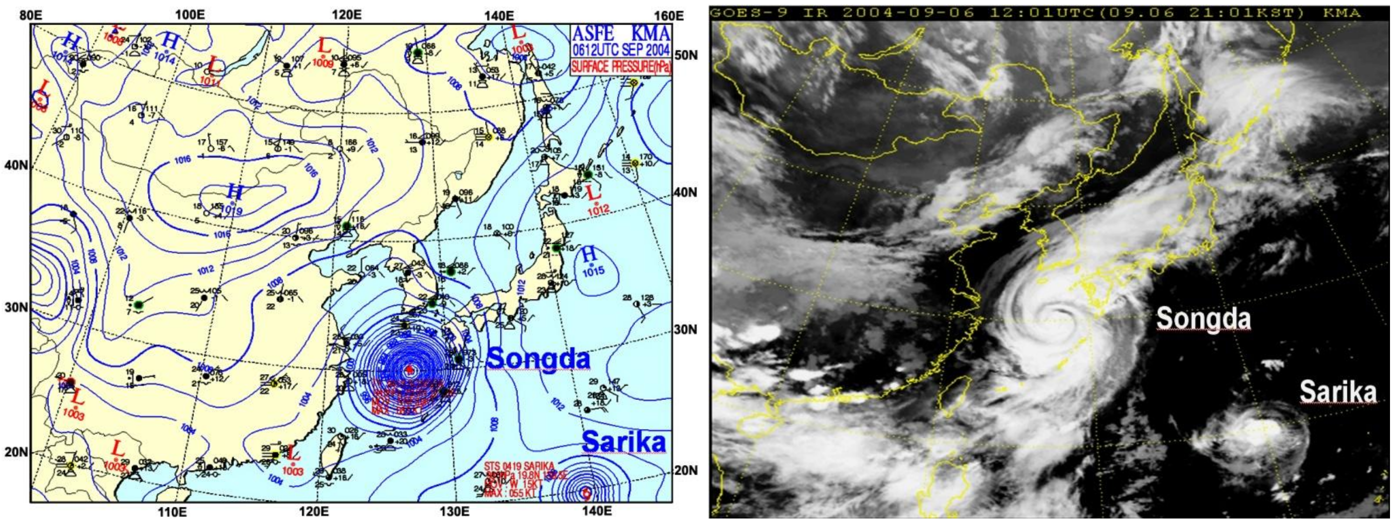
(a) (b)

Fig. 1: (a) Surface weather map and (b) GOES-9 IR satellite image of Typhoon Songda and Tropical Storm Sarika at 09:00LST, September 6, 2004 respectively.



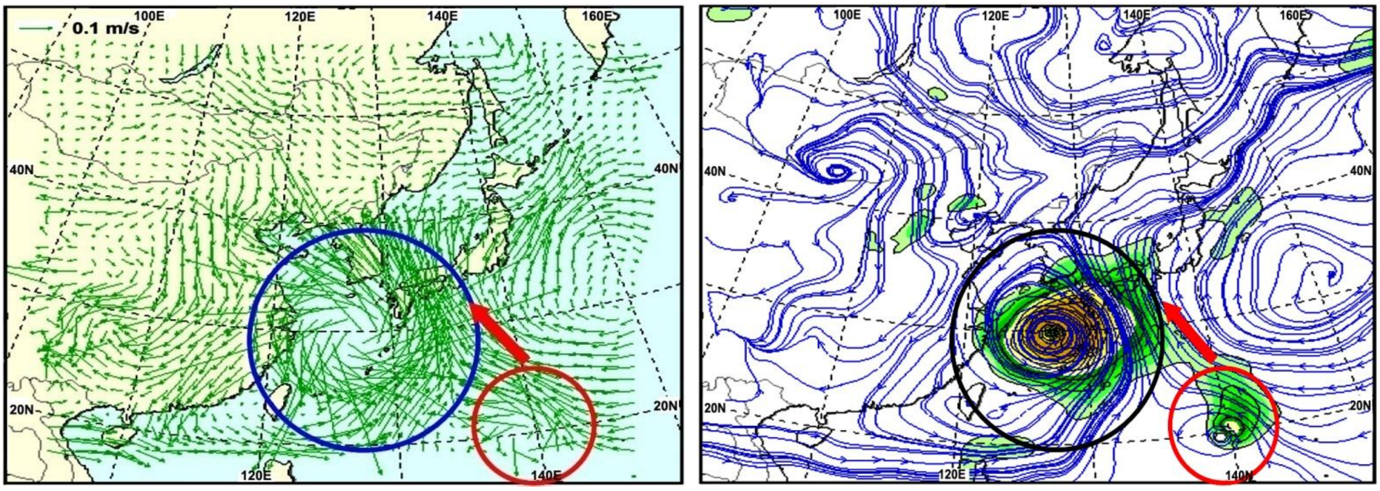
(a) (b)

Fig. 2: (a) Moisture flux (m/s) and (b) streamline with isotech (green color area over 25kts) at 09:00LST, September 6, 2004 respectively. TY Songda moved northward, while TS Sarika still westward.



(a) (b)

Fig. 3: (a) Surface weather map and (b) GOES-9 IR satellite image at 21:00 LST, September 6, 2004 respectively.



(a) (b)

Fig. 4: (a) Moisture flux (m/s) and (b) streamline with isotech over 25kts at 21:00LST, September 6, 2004 respectively. As TS Sarika was drawn by strong wind in the right quadrant of Songda circulation toward TY Songda and by getting sufficient latent heat fluxes from northward moisture advection for its development, it became stronger with wider storm area and moved resultantly westward.

Moisture flux (Fig. 2a) and streamline at 850hPa level (Fig. 2b) calculated by UM-KMA model showed that Sarika having an independent moving track before began to have an interaction with Songda, connecting with its right quadrant of stronger wind band at 09:00LST September 6, but their interaction was weak.

At 21:00LST, September 6, the persistent westward STS Sarika was strongly pulled northwest by north-northeastward TY Songda of a maximum surface wind of 80kts with its moving speed of 6kts and their storm areas of wind speed greater than 25kts were directly connected each other (Figs. 4a and 4b). Simultaneously, as Songda was connected with Sarika, it got sufficient latent heat fluxes from northward moisture advection between two cyclones which could be converted into kinetic energy for its further intensification. Thus, Songda could pull more strongly STS Sarika into the main streamline in its right quadrant of its cyclonic circulation and Sarika became slightly stronger with wider storm area, still moving westward (Figs. 3a and 3b).

At 09:00LST, September 7, as TS Sarika moved westward, but oppositely, TY Songda moved north-northeastward, the distance of two cyclones became shortened (Figs. 5a and 5b). As main stream of southerly wind of TY Songda's cyclonic circulation moved eastward due to the further movement of north-northeastward TY track, northerly cyclonic wind in the right quadrant of Songda was firmly connected with northerly cyclonic wind of Sarika and Songda's strong northerly wind could pull Sarika northward more close, resulting in annexation of their storm bands.

This binary interaction through momentum transport by connected wind bands each other could also increase the rotation speeds of their cyclonic circulations as shown in Figs. 6a and 6b.

However, the prohibition of southwesterly wind in the left-bottom quadrant of TY Songda's circulation to northerly wind in the left quadrant of TS Sarika's circulation is smaller rather than the association of southerly winds of two cyclones in their right quadrants. Thus it resulted in a connected strong wind band over 25kts (Figs. 4a, 4b, 6a and 6b) in both cyclones.

We found that a great amount of moisture transport took place between two tropical cyclones, especially showing major suction of moisture by Typhoon Songda from Tropical Storm Sarika in their right quadrants of two circulations into the East Sea, from 21:00LST, September 6 to 09:00LST, September 7. This moisture suction could cause their simultaneous development of two tropical cyclones where the accumulation of latent heat energy released from the formation of huge size clouds induced the increase of kinetic energy to draw powerful cyclonic circulations.

At 21:00LST, September 7, as the center of TY Songda moved toward the central part of the East Sea, main stream of southerly wind of Songda also moved further eastward. Northward main streamline of Songda could strongly draw Sarika to follow directly in the wake of Songda and cause the decrease of rotation speed in the left quadrant of Sarika's cyclonic circulation. The compensation of reversal wind systems of two cyclones each other caused the cyclonic circulation of Sarika to be weaker and weaker (Figs. 7a, 7b, 8a and 8b).

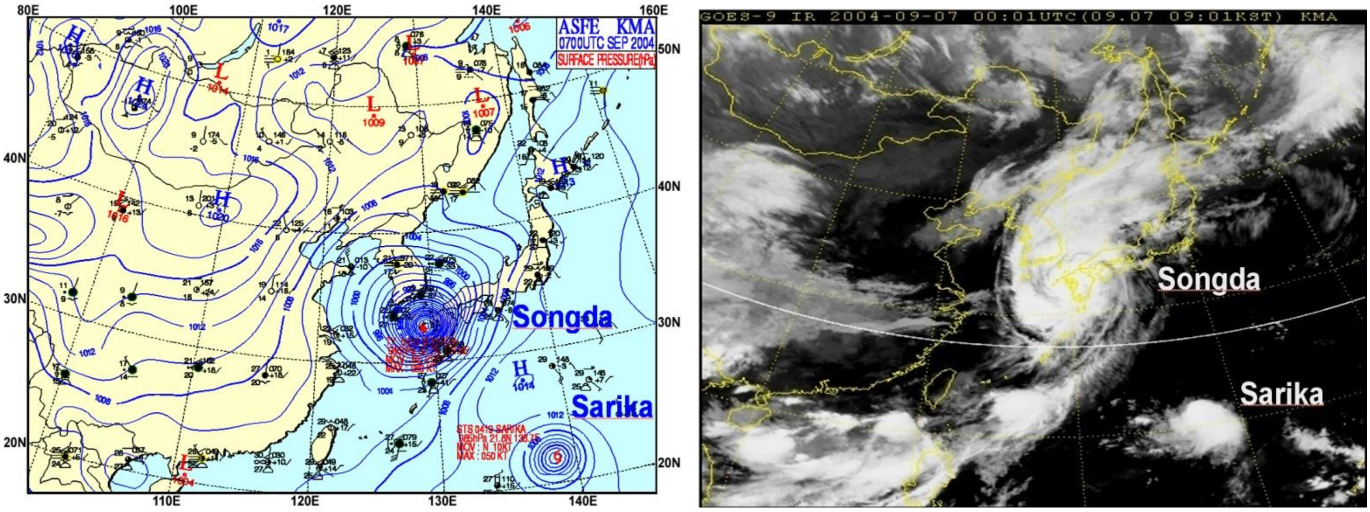
At 09:00LST, September 8, Tropical Storm Sarika became an extra-tropical cyclone, that is, a low pressure of 1000hPa (Figs. 9a, 9b, 10a and 10b). At 21:00LST, it did not maintain a spiral shape, but disappeared. As result, as TY

Songda and Tropical Storm Sarika were very close together, the stronger of the two storms (Songda) could help to cancel out the strength of the weaker second storm (Sarika).

A possible explanation on these effects is the directional change of moisture transport from Sarika at its intensifying stage to Songda, because a great amount of latent heat fluxes released from cloud bands formed in the main streamline of moisture could supply sufficient energy for further development of Songda and the intensified Songda could draw more strongly Sarika into the wake of main streamline in the right quadrant of Songda circulation resulting in its weakening through a binary interaction due to their proximity.

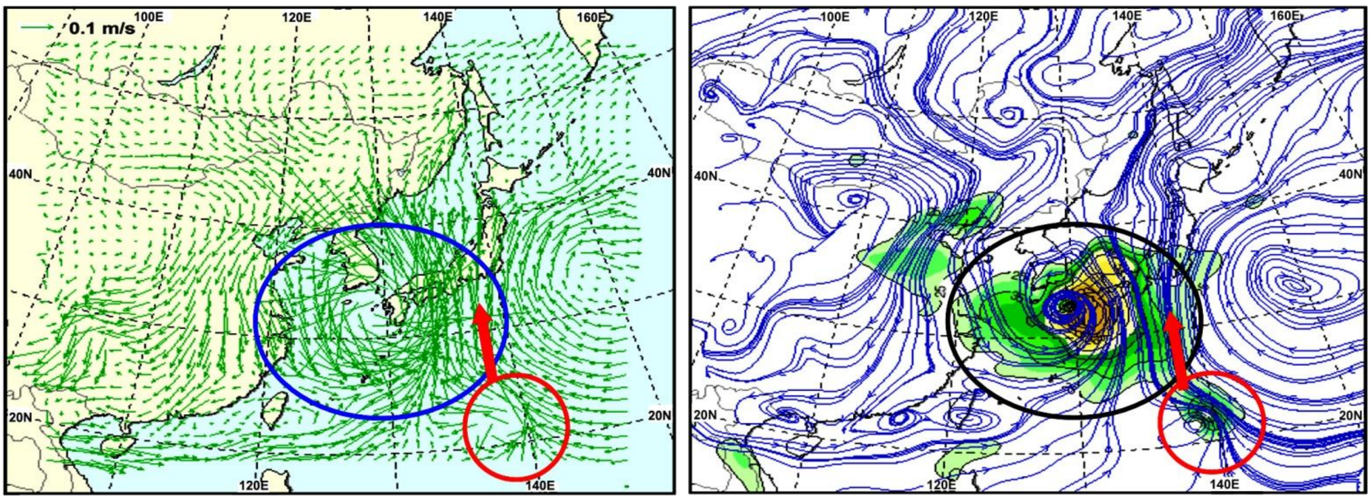
Fujiwhara[9] indicated when cyclones are in proximity of one other, their centers will begin orbiting cyclonically around a point (centroid) between the two systems due to their cyclonic wind circulations. As the two vortices (cyclones) will be attracted to each other, they eventually spiral into the center point and merge.

However, in our case, two tropical cyclones which had different sizes did not orbit around their centroid. Due to unequal sizes of two vortices, the larger vortex (Songda) tended to dominate the interaction and the smaller vortex (Sarika) did not orbit around a centroid, but much stronger northeastward Songda firmly pulled the persistent westward Sarika to the north. Then, Sarika could be drawn into the wake of main streamline in the right quadrant of Songda circulation. Resultantly Songda's circulation prohibited Sarika's circular motion and Sarika should be weakened to be extinct.



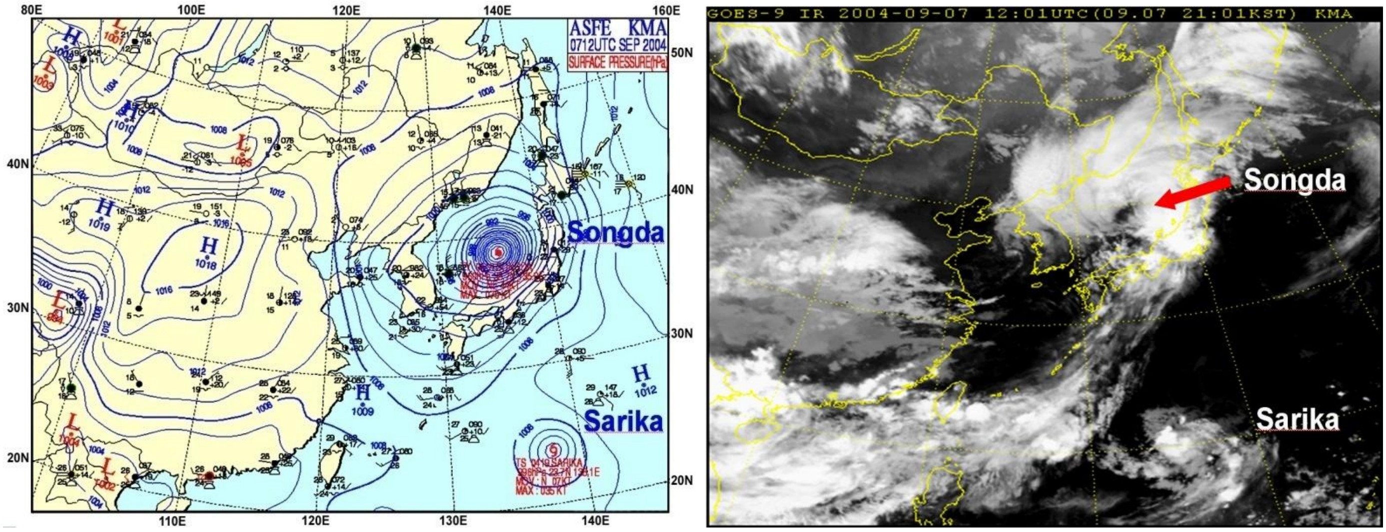
(a) (b)

Fig. 5: (a) Surface weather map and (b) GOES-9 IR satellite image at 09:00LST, September 7, 2004 respectively.



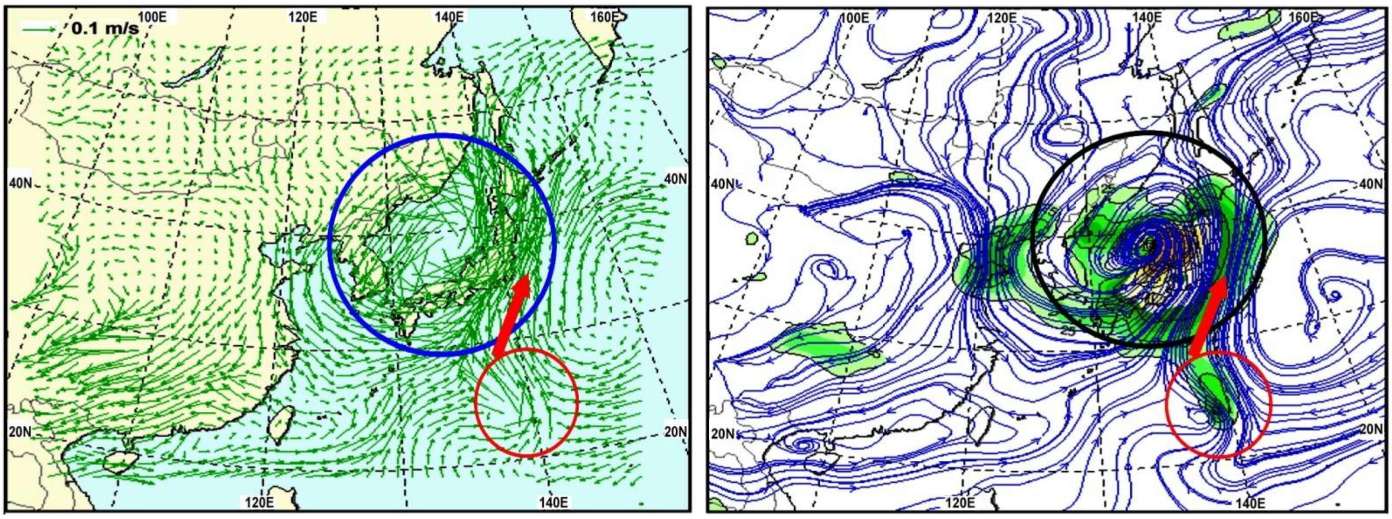
(a) (b)

Fig. 6: (a) Moisture flux (m/s) and (b) streamline with isotech (green color area over 25kts) at 09:00LST, September 7, 2004 respectively. As TY Songda moved north-eastward, the distance between two tropical cyclones became shortened by strong northward wind in the right quadrant of its circulation pulling Sarika which merged into the right hand side-strong streamline (wake) of Songda.



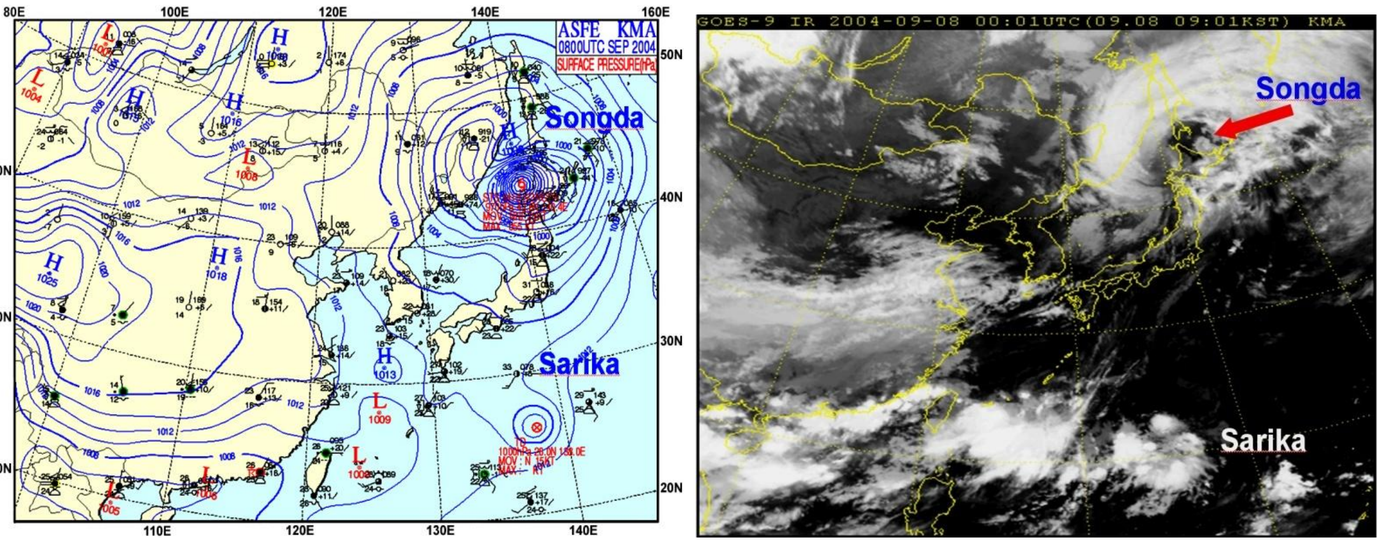
(a) (b)

Fig. 7: (a) Surface weather map and (b) GOES-9 IR satellite image at 21:00LST, September 7, 2004 respectively.



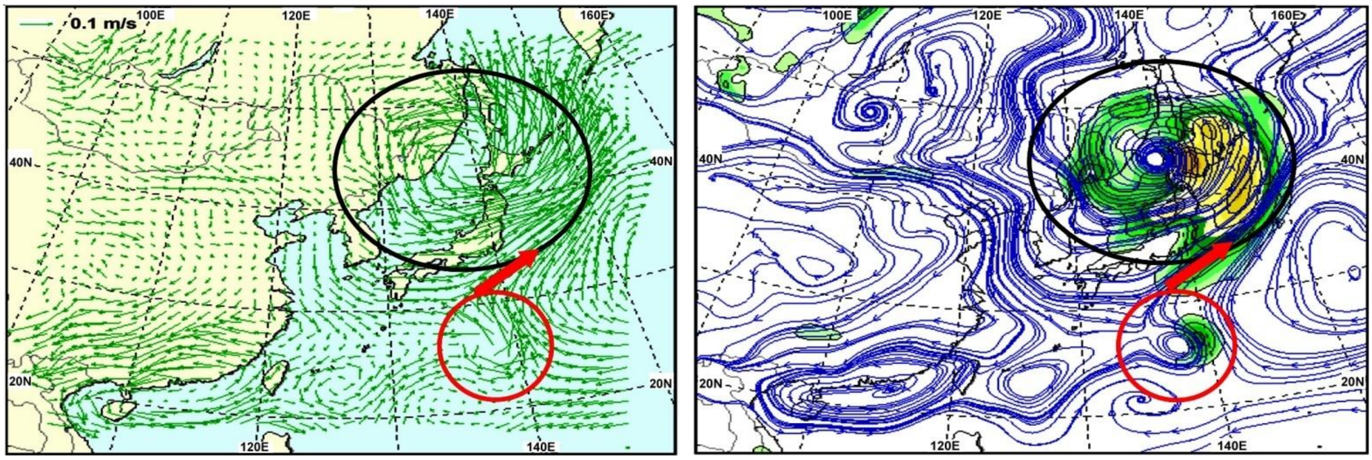
(a) (b)

Fig. 8: (a) Moisture flux (m/s) and (b) streamline with isotech over 25kts at 21:00LST, September 7, 2004 respectively. As Sarika merged into the right hand side-strong streamline (wake) of Songda, its circulation became weak due to the prohibition by strong northward wind of Songda circulation.



(a) (b)

Fig. 9(a): Surface weather map and (b) GOES-9 IR satellite image at 09:00LST, September 8, 2004 respectively.



(a) (b)

Fig. 10: (a) Moisture flux (m/s) and (b) streamline with isotech (green color area over 25kts) at 09:00LST, September 8, 2004 respectively. Sarika became weak and just a low pressure.

Conclusion

When two tropical cyclones were very close together, the stronger of the storms can cancel out the strength of the weaker storm. Thus, two tropical cyclones became absorbed by the stronger of the two storms. Typhoons Songda and severe Tropical Storm Sarika had an interaction that steered Sarika in the wake of Songda's main streamlines to the north, in the East China Sea. First time, much stronger northeastward Songda firmly pulled the persistent westward Sarika to the north and then, Sarika could be drawn into the wake of Songda's main streamline. The prohibition of Songda to Sarika's circulation caused Sarika weakened and extinct, showing no longer tightly packed bands of cloud.

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References

1. Hong Kong Meteorological Observatory (HKO), Classification of Tropical Cyclones, http://www.hko.gov.hk/informtc/class.htm **(2012)**

2. World Meteorological Organization (WMO), Guidelines for converting between various wind averaging periods in tropical cyclone conditions, 62 **(2009)**

3. Korea Meteorological Administration (KMA), Guide book, http://www.kma.go.kr/eng **(2013)**

4. Anthes R.A. and Chang S.W., Response of the hurricane boundary layer to changes in sea surface temperature in a numerical model, *Journal of Atmospheric Sciences*, **135**, 1240-1255 **(1978)**

5. Cheung T.C. and Chan P.W., Improving wind and rain simulations for tropical cyclones with the assimilation of Doppler radar data, Proceeding of the 10th Annual WRF Users' Workshop, Boulder, Colorado, 1-835 **(2009)**

6. Choi H., Extreme cold sea outbreak near Cheju Island, Korea by strong wind and atmospheric pressure change under typhoon Rusa, *Disaster Advances*, **3(1)**, 32-41 **(2010)**

7. Choi H., Extreme decrease of air temperature modified by a Typhoon Passage in the Korean Eastern Coast, *Disaster Advances*, **5(1)**, 45-51 **(2012)**

8. Choi H., Lee M.S. and Choi S.M., Cold sea surface temperature near Cheju Island responding to strong cyclone wind and positive geopotential tendency behind a typhoon center along its track, *Journal of Marine Science and Technology,* **20(6)**, 684-692 **(2012)**

9. Fujiwhara S., The natural tendency towards symmetry of motion and its application as a principle in meteorology, *Quarterly Journal of Royal Meteorological Society*, **47(20)**, 287–293 **(1921)**

10. Liu K. Y., On the relative motion of typhoon pairs over the South China Sea and Northwest Pacific Region (in Chinese with English abstract), NSC73-0202-M072-02.38, NSC, Taipei, Republic of China **(1983)**

11. DeMaria M. and Chan J.C.L., Comments on A Numerical Study of the Interactions between Two Cyclones, *Monthly Weather Review*, **112**, 1643-1645 **(1984)**

12. Kuo H. C., Chen G. T. J. and Lin C. H., Merger of tropical cyclones Zeb and Alex, *Monthly Weather Review,* **128**, 2967-2975 **(2000)**

13. Xu H., Zhang X. and Xu Xi, Impact of Tropical Storm Bopha on the Intensity Change of Super Typhoon Saomai in the 2006 Typhoon Season, *Advances in Meteorology*, Article ID 487010, 1-13 **(2013)**.

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