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An observational study of Super Typhoon *Rai*, a very late-season typhoon necessitating the issuance of a tropical cyclone warning signal for Hong Kong in December 2021

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Abstract

The key meteorological observations of a very late-season super typhoon over the northern South China Sea, namely, *Rai* in December 2021, are documented in this article for later reference. In particular, the very valuable dropsonde data in this season are presented. Meteorological data revealed the interaction between the northeast monsoon from the north and the outer circulation of *Rai* from the south, resulting in rapid weakening of *Rai* and probably a subtropical transition. *Rai* broke a number of tropical cyclone (TC) records over the South China Sea, necessitating the issuance of a TC warning signal in Hong Kong. The considerations in the issuance of the warning signal are also briefly described in this article.

Introduction

In late December 2021, the very late-season Super Typhoon *Rai* necessitated the issuance of a tropical cyclone (TC) warning signal in Hong Kong. The system of TC warning signals in Hong Kong, which is used to warn the public of the threat of winds associated with a TC, can be found in the Hong Kong Observatory (HKO) pamphlet (HKO, 2012) and Lui *et al*. (2018) (Table 1). As a result of the proximity of *Rai*, the Standby Signal, No. 1 was issued between 1120h, 20 December 2021 and 1220h, 21 December 2021 (in Hong Kong time, which is 8h ahead of UTC). The closest approach of *Rai* to Hong Kong occurred at 1100h on 21 December 2021, when *Rai* was located at about 140km south-southeast of Hong Kong.

TCs are taken to pose a threat to Hong Kong when they are located within 500km of the territory (Lee *et al*., 2012). The typhoon season in Hong Kong occurs mostly from May to October. TCs affecting Hong Kong in December are very rare. According to the best track dataset of HKO, from 1961 to 2020, there were only four TCs entering a 500km radius of Hong Kong, including TC *Irma* in 1974 (70km north of Hong Kong), TC *Lee* in 1981 (230km south-southeast of Hong Kong), TC *Axel* in 1994 (380km south-southeast of Hong Kong) and TC *Nanmadol* in 2004 (490km east-southeast of Hong Kong). Their tracks can be found in Figure 1. Among them, only *Irma* in 1974 necessitated the issuance of TC warning signals on 1 and 2 December of that year, including Standby Signal, No. 1 and the Strong Wind Signal, No. 3. Prior to *Rai* in 2021, this was the only time when the issuance of TC warning signals was necessary in December since 1946.

Rai has broken several records for TCs over the South China Sea:

a. It was the only super typhoon (TC with maximum 10-min mean wind ≥100kn [HKO, 2009]) affecting the South China Sea in December since records began in 1961.

b. It required the latest issuance of a TC warning signal in Hong Kong (*Irma* occurred in early December, whereas *Rai* occurred in late December).

c. It necessitated the issuance of a TC warning signal in Hong Kong in December for only the second time (the first time being *Irma* in 1974).

This short article is a documentation on the observation, forecasting and warning aspects of *Rai* in 2021. The authors hope it will be a useful reference for the study of TCs over the South China Sea.

Life history of *Rai*

The track and intensity changes of *Rai* can be found in Figure 1. *Rai* formed as a tropical depression over the western North Pacific about 2640km east-southeast of Manila on 12 December 2021. Moving west-northwestwards, it intensified during the following 2 days. *Rai* started to rapidly intensify on 15 December 2021 and developed into a super typhoon the next day. After moving across the Philippines, Super Typhoon *Rai* weakened into a severe typhoon and continued to move westwards entering the southern South China Sea on 17 December 2021. It re-intensified into a super typhoon on 18 December 2021 and reached its peak intensity with an estimated sustained wind of 105kn near its centre,

making it the first super typhoon to occur in the South China Sea in December since 1961 when the complete best track record began. On 19 December 2021, *Rai* gradually turned to move north towards the northern South China Sea along the periphery of the subtropical ridge and progressively weakened. *Rai* weakened into a severe tropical storm and tracked northeastwards towards the coast of Guangdong on 20 December 2021. Once it moved within 500km of Hong Kong, *Rai* weakened into a tropical storm with an estimated sustained wind of 45kn near its centre. It continued to weaken when it moved closer to Hong Kong and finally degenerated into an area of low pressure over the northern South China Sea shortly after noon on 21 December 2021.

Selected radar and satellite pictures of Rai are shown in Figure 2. Figure 2(a) shows *Rai* as a super typhoon over the central South China Sea. Figure 2(b) shows the weakening of *Rai* when it was over the sea east of Hainan Island. Figure 2(c) shows further weakening of *Rai* when it was close to Hong Kong, with significantly sheared convection and a lack of convection in its southeast quadrant. The radar image from the Hong Kong radar at the time of Figure 2(c) is shown in Figure 2(d). There was limited convection in association with *Rai* and there was no signature of a circulation from the radar reflectivity.

Surface weather charts from when *Rai* was close to Hong Kong are shown in Figure 3. They will be used for comparison with numerical weather prediction model results. It can be seen that the northeast monsoon was affecting southern China with a tight pressure gradient and surface northerly winds over the region at 0000 UTC on 21 December 2021. At that time, *Rai* was already a very weak system and later degenerated into an area of low pressure.

Wind profiler and radiosonde observations

Upper air measurements of *Rai* in Hong Kong were available from the radar wind profiler data in Hong Kong (measured at the site in downtown Hong Kong) and radiosonde data were available twice a day, launched at the King's Park radiosonde station in Hong Kong.

As observed by the wind profiler, though the east to southeasterly winds within the boundary layer were mostly of moderate to fresh strength (below 22kn, coloured purple in Figure 4), much stronger winds were recorded aloft, e.g. between 1400h and 1800h (local time) on 20 December 2021, an altitude of 5000–7000m above mean sea level, when storm force winds (coloured red in Figure 4) were prevailing. This southwesterly jet

is related to the mid-level subtropical ridge, which is centred over the seas east of the Philippines. In fact, *Rai* was turning northeastwards along the periphery of this subtropical ridge at that time. The veering of the winds (from easterly to southwesterly) from the boundary layer to 5000–7000m also signified considerable wind shear, resulting in the weakening of *Rai*. Of particular interest to the warning of *Rai* was the descending jet of gale force winds (coloured green in Figure 4, with a wind strength between 34 and 48kn). It can be seen that the bottom part of the gale force jet descended from about 4000m on 20 December 2021 to around 1000m the following day. This descending jet had significant implications to the TC warning service in Hong Kong, as will be discussed later in this article.

Selected 2-s radiosonde profiles in Hong Kong are shown in Figure 5. At 1200 UTC, 19 December 2021 (Figure 5a), the atmospheric boundary layer was still rather dry. The lower troposphere moistened up gradually with the approach of the cloud and rain bands associated with *Rai*. At 0000 UTC, 21 December 2021 (Figure 5b), the boundary layer became saturated. There was a significant temperature inversion of 5–6 degC between 900 and 950hPa. The cooler air associated with the northeast monsoon prevailed in the first 500–1000m or so. Above that, the south to southeasterly jet associated with the outer circulation of *Rai* affected the southern China region. This was a complicated interaction between the northeast monsoon and the circulation of *Rai*.

Dropsonde observations

Dropsondes are launched by the aircraft of the Government Flying Service in Hong Kong when there are TCs over the northern South China Sea (Hon and Chan, 2022). Before *Rai*, there had been no TCs over this region in December, so the dropsonde data collected for *Rai* are very valuable. This is the first time that dropsonde data have been collected in December over the South China Sea.

A total of eight sondes were launched during *Rai* in the morning of 21 December 2021. An overview of the horizontal wind distributions can be found in Figure 6. At the surface (10m above sea level), northwesterly to westerly winds prevailed to the southwest of *Rai* as shown in Figure 6(a). In the mid levels (600hPa), generally westerly flow prevailed over the region, as shown in Figure 6(b). The satellite-derived winds (AEMET, 2020) are overlaid on the same figure, and it can be seen that the dropsonde observations are generally consistent with the derived satellite winds, in both direction and speed.

An analysis of the dropsonde observations is performed following the method of He *et al*. (2022). The results are shown in Figure 7. The vertical profile of equivalent potential temperature is shown in Figure 7(a). It can be seen that, for sonde numbers 1, 4 and 6, there was a temperature inversion below around 2000m above sea level. These sondes might be measuring the cooler atmospheric boundary layer in association with the northeast monsoon. Such an inversion is not apparent in the other sondes, which might be related to the maritime airmass in the boundary layer.

The radial velocities measured by the sondes is shown in Figure 7(b). It can be seen that in general, there is no inflow/some outflow in the atmospheric boundary layer, with inflow aloft. Following the analysis of He *et al*. (2022), this is an indication that the TC was weakening, which is consistent with the strength of the TC as observed from mete-orological satellites.

Performance of numerical weather prediction model

The numerical weather prediction model did a very good job in forecasting the proximity of *Rai* to Hong Kong. A probabilistic forecast from the ECMWF (European Centre for Medium-Range Weather Forecasts) model initialised at 1200 UTC on 15 December 2021 is shown in Figure 8. The track and intensity errors of the ECMWF deterministic forecast and its ensemble prediction system (EPS) are shown in Table 2. Both the ECMWF deterministic and EPS forecasts generally have a good performance on the forecast track of *Rai*, and the deterministic runs performed better than EPS with an average position error of only around 220km for the T + 120h forecast. It is also noted that the position error is mainly due to the slow bias of the forecast and the cross track error is very small, with −1 and 47km for the deterministic and EPS forecasts of T + 120h, respectively. This is in line with Figure 8 that, at a 6 day lead-time, the model was able to forecast that *Rai* could come close to Hong Kong on 20/21 December.

Whilst the models underestimated the intensity of *Rai* over the seas east of the Philippines and the southern South China Sea with some of the maximum wind errors as large as −60kn in T + 48h, as the model run progresses, it becomes more stable in forecasting the weakening of *Rai* in passing through the latitude of Hong Kong. Forecasts from a model run can be found in Figure 9. The weakening trend of *Rai*, together with the number of closed circulation isobars, were generally consistent with the actual observations in Figure 3. The intensity error for the T + 72h forecast is only 10kn. While the model

underestimated the intensity of *Rai* during its development stage, the generally satisfactory performance of the model for rapid weakening of *Rai* made it possible to prepare for the proximity of *Rai* rather early in December 2021.

Weather warning consideration

As *Rai* remained at least tropical storm strength as it entered about 500km from Hong Kong, it posed a threat to the territory, e.g. strengthening of local winds and the occurrence of significant rain in association with *Rai*. As such, the Standby Signal, No. 1 was necessary. The duration of this warning depended on the weakening trend of *Rai* over the northern South China Sea, which was forecast in various numerical weather prediction models, e.g. ECMWF, as in Figure 9.

The need for a higher TC warning signal for Hong Kong depended on whether the winds strengthened. One consideration was the descent of the gale wind force jet above the atmospheric boundary layer (e.g. Figure 4, the wind profiler measurement). Eventually, gale force winds appeared for a brief period of only 1min at the top of Tai Mo Shan, the highest mountain in Hong Kong with a height of about 1km above mean sea level, and Bluff Head, located in southeastern Hong Kong with a height of about 100m. The maximum 10-min mean wind data over Hong Kong, when the TC signal for *Rai* was in force, is shown in Figure 10 (the red number shows the gale force winds at Tai Mo Shan and Bluff Head). Strong winds were recorded over offshore waters in southern Hong Kong and on high ground (blue numbers in Figure 10). Strong winds did not prevail near sea level over the territory, and as such, it was not necessary to issue a higher TC warning signal.

Conclusion

Super Typhoon *Rai* broke a number of records for late-season TCs over the northern South China Sea. It weakened considerably when it traversed over the seas to the south of Hong Kong, as predicted by numerical models, yet it was so close to the territory that it necessitated the issuance of a TC warning signal for the first time in Hong Kong in late December. The consideration of the warning signal is summarised in this paper as a documentation of the event for future reference.

Along the south China coast and the coastal waters, there was an interaction between the northeast monsoon and the outer circulation associated with *Rai*. Satellite and radar images showed rapid weakening of *Rai* with convection significantly sheared and the cool boundary layer air associated with the monsoon also inhibited the development of convection. Such a complicated interaction showed up in the wind profiler measurements and radiosonde data over Hong Kong, as well as the dropsonde data, which were collected for the first time in a winter season over the northern South China Sea. The radiosonde and dropsonde data depicted the temperature inversion, which was related to the cooler atmospheric boundary layer in association with the northeast monsoon. Above 5000–7000m, the atmosphere was dominated by a subtropical ridge centred east of the Philippines. The interaction resulted in rapid weakening of *Rai* and probably sub-tropical transition. Although the numerical weather prediction model underestimated the intensity of *Rai* during its development stage, the interaction and the resulting rapid weakening of *Rai* were generally well captured by the model, so that the proximity of *Rai* to Hong Kong and its impact on the territory were well captured up to 5/6 days ahead. Nonetheless, the meteorological data collected will be a useful documentation of the interaction between the northeast monsoon and the south to southeasterly jet. They will be useful reference for future study of winter TCs in the region.

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Table 1 Definition of the tropical cyclone (TC) warning signals in Hong Kong.

Signal	**Meaning of signal**
1 Standby	A TC is centred within about 800km of Hong Kong and may affect the territory. Strong winds may occur over offshore waters.
3 Strong Wind	Strong winds are blowing or expected to blow generally in Hong Kong near sea level, with a sustained speed of 41–62kmh^{-1} and gusts that may exceed 110kmh^{-1}, and the wind conditions are expected to persist.
8 NW Gale or Storm 8 SW Gale or Storm 8 NE Gale or Storm 8 SE Gale or Storm	Gale or storm force winds are blowing or expected to blow generally in Hong Kong near sea level, with a sustained wind speed of 63–117kmh^{-1} from the quarter indicated and gusts that may exceed 180kmh^{-1}, and the wind conditions are expected to persist.
9 Increasing Gale or Storm	Gale or storm force winds are increasing or expected to increase significantly in strength.
10 Hurricane	Hurricane force winds are blowing or expected to blow with sustained speed reaching 118kmh^{-1} and gusts that may exceed 220kmh^{-1}.

Table 2 Verification of TC track forecasts (direct position error, along track error and cross track error) and intensity forecast from the European Centre for Medium-Range Weather Forecasts deterministic forecast and ensemble prediction system (EPS). For along track error, negative (positive) indicates a slow (fast) bias. For cross track error, negative (positive) indicates a left (right) bias. For intensity error, negative (positive) indicates model underestimates (overestimates) the intensity of *Rai*.

	Model	**T + 24h**	**T + 48h**	**T + 72h**	**T + 96h**	**T + 120h**
Mean track error (in km) (Direct position error / along track error / cross track error)	Deterministic	81/−41/−5	96/−30/11	116/−76/−21	171/−137/−16	220/−156/−1
	EPS	84/−50/−11	108/−87/−3	158/−148/−16	240/−237/0	320/−313/47
Mean intensity error (in kn)	Deterministic	−22	−18	−20	−19	−13
	EPS	−24	−26	−28	−28	−21

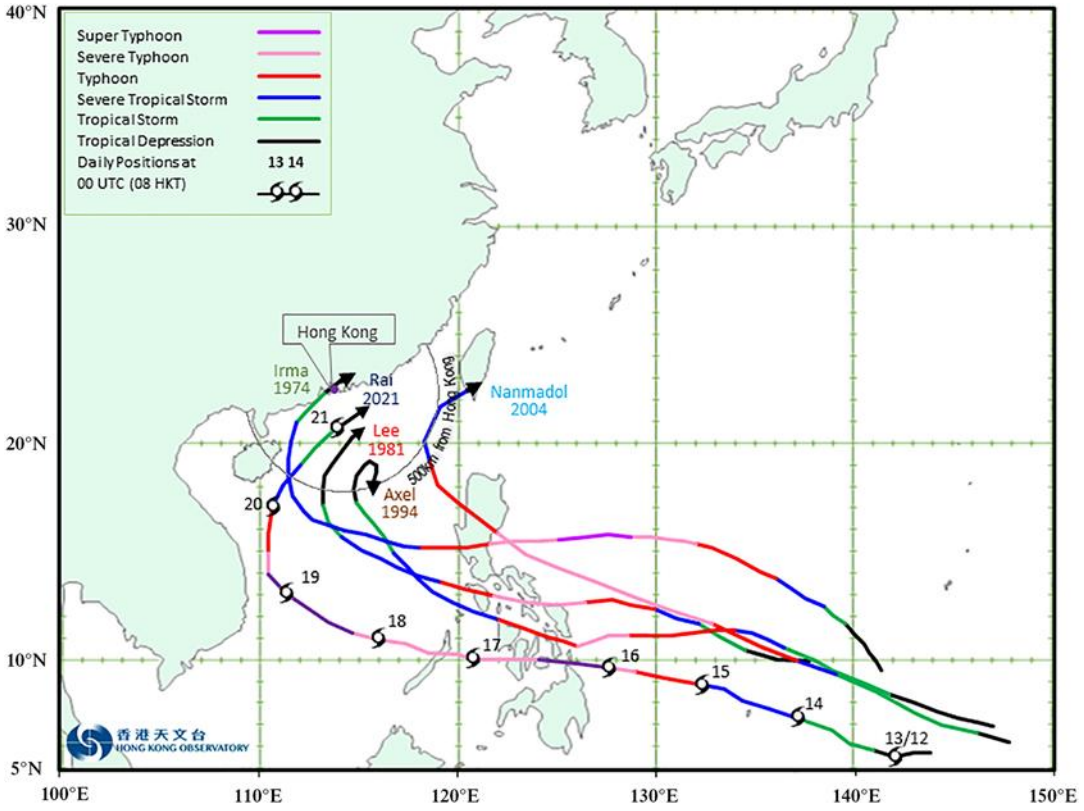


Figure 1 Tracks of the four tropical cyclones entering a 500km radius of Hong Kong from 1961 to 2020 and the track of *Rai* in December 2021.

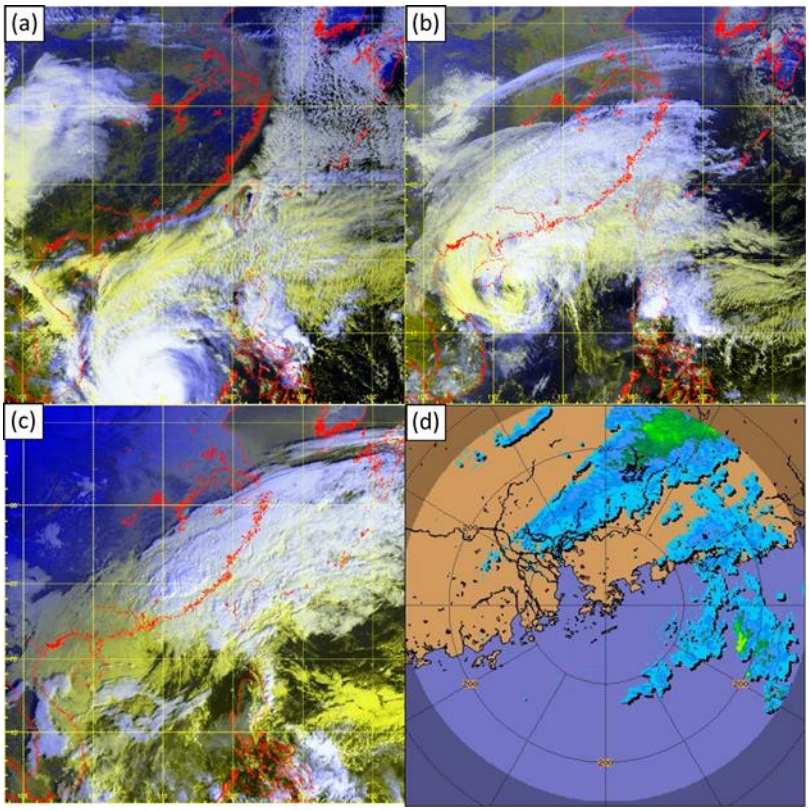


Figure 2 False-colour satellite images of *Rai* at (a) 0600 UTC 18 December 2021, (b) 0600 UTC 20 December 2021 and (c) 0000 UTC 21 December 2021. Radar image in Hong Kong (3km CAPPI) at 0800h (0000 UTC), 21 December 2021.

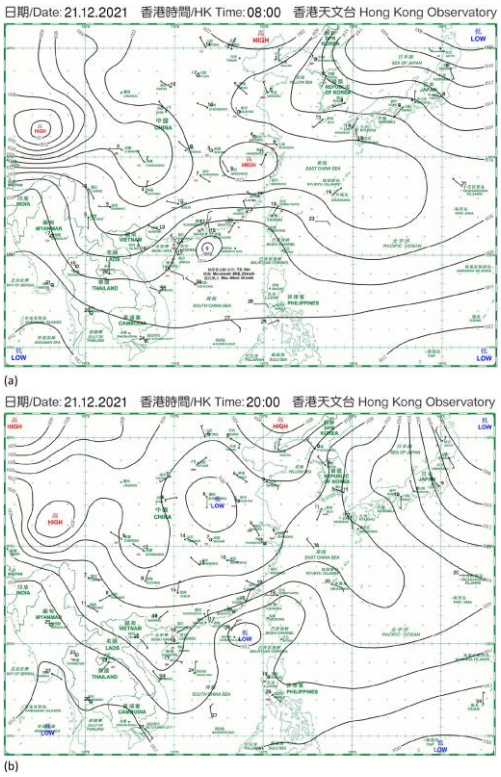


Figure 3 Surface isobaric chart at (a) 0800h (0000 UTC) and (b) 2000h (1200 UTC), 21 December 2021.

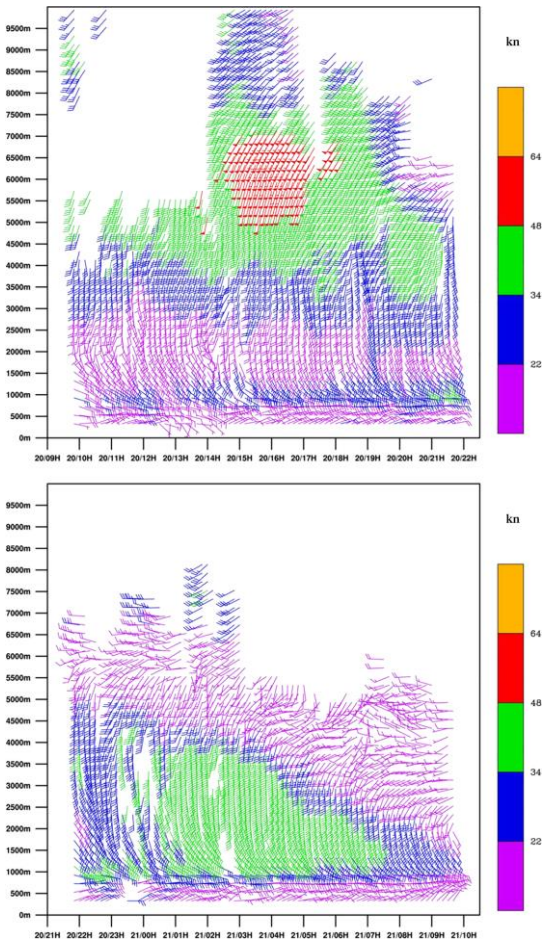


Figure 4 Wind profiler measurements at Sham Shui Po, Hong Kong, on 20/21 December 2021. The x-axis is the local time in the format of DD/HH, and the y-axis is the height.

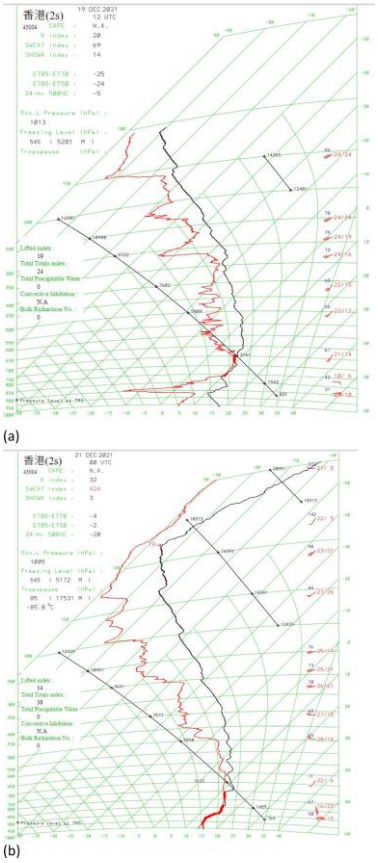


Figure 5 Tephigram from radiosondes launched in Hong Kong at (a) 1200 UTC 19 December and (b) 0000 UTC 21 December 2021.

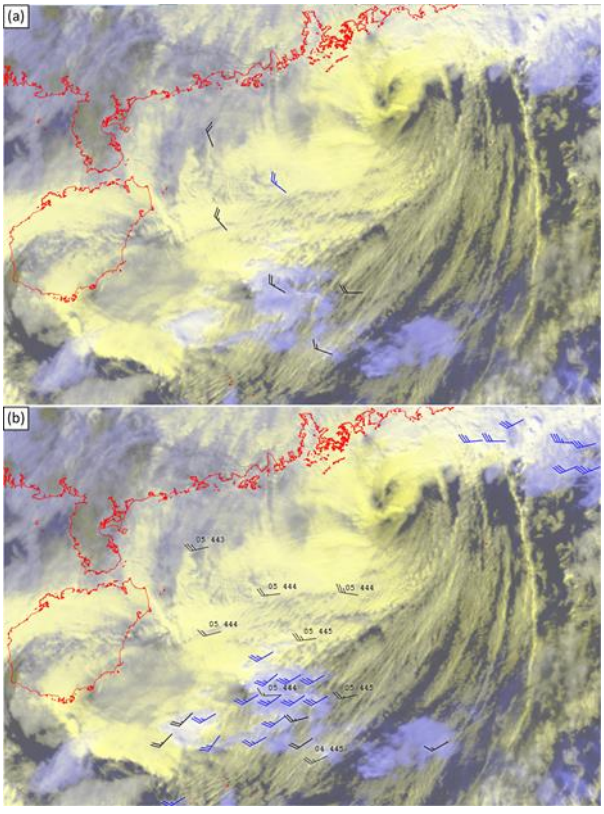


Figure 6 Dropsonde data overlaid on false-colour satellite imagery: (a) 10m winds and (b) 600hPa winds together with the satellite-derived winds around that height.

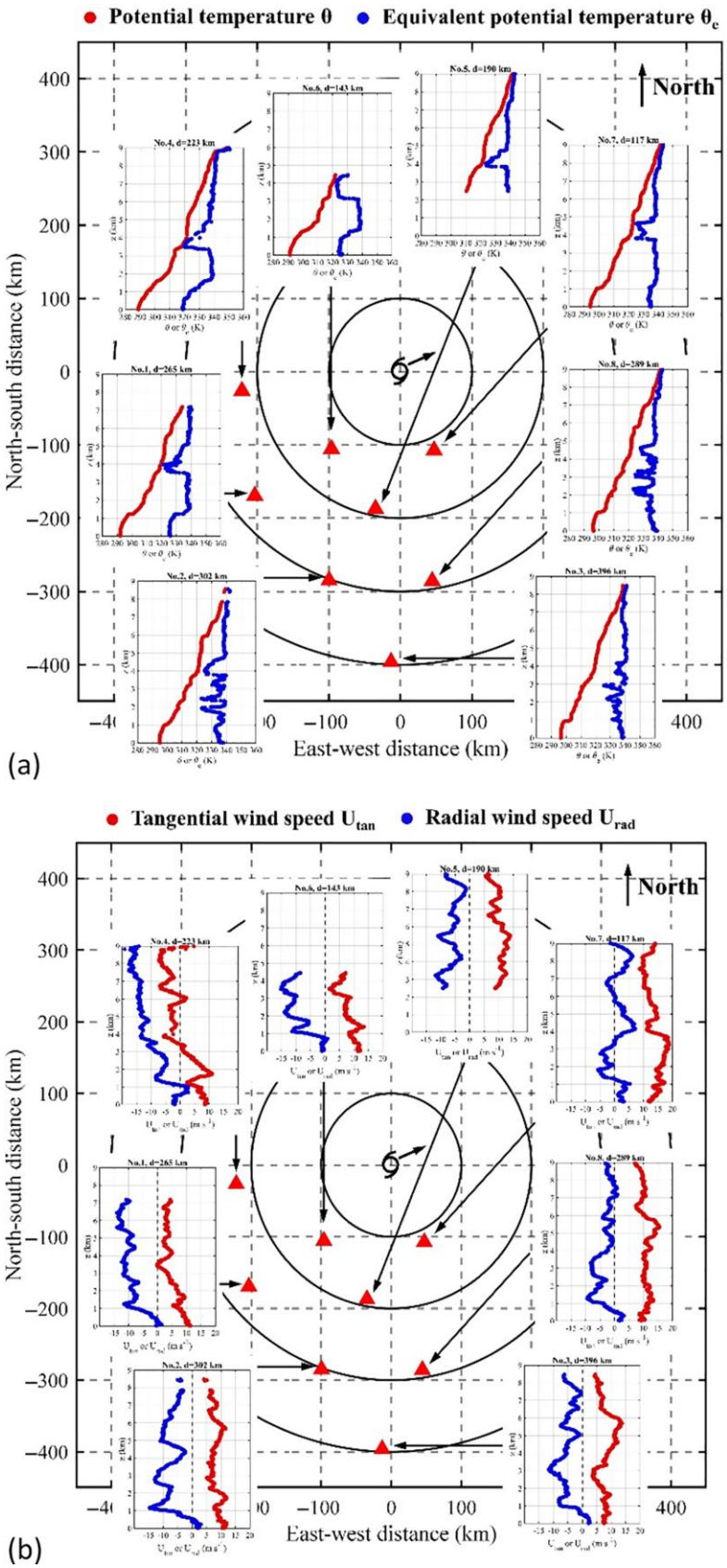


Figure 7 Dropsonde-derived data: (a) potential temperature and equivalent potential temperature and (b) tangential and radial velocities with respect to the centre of *Rai*.

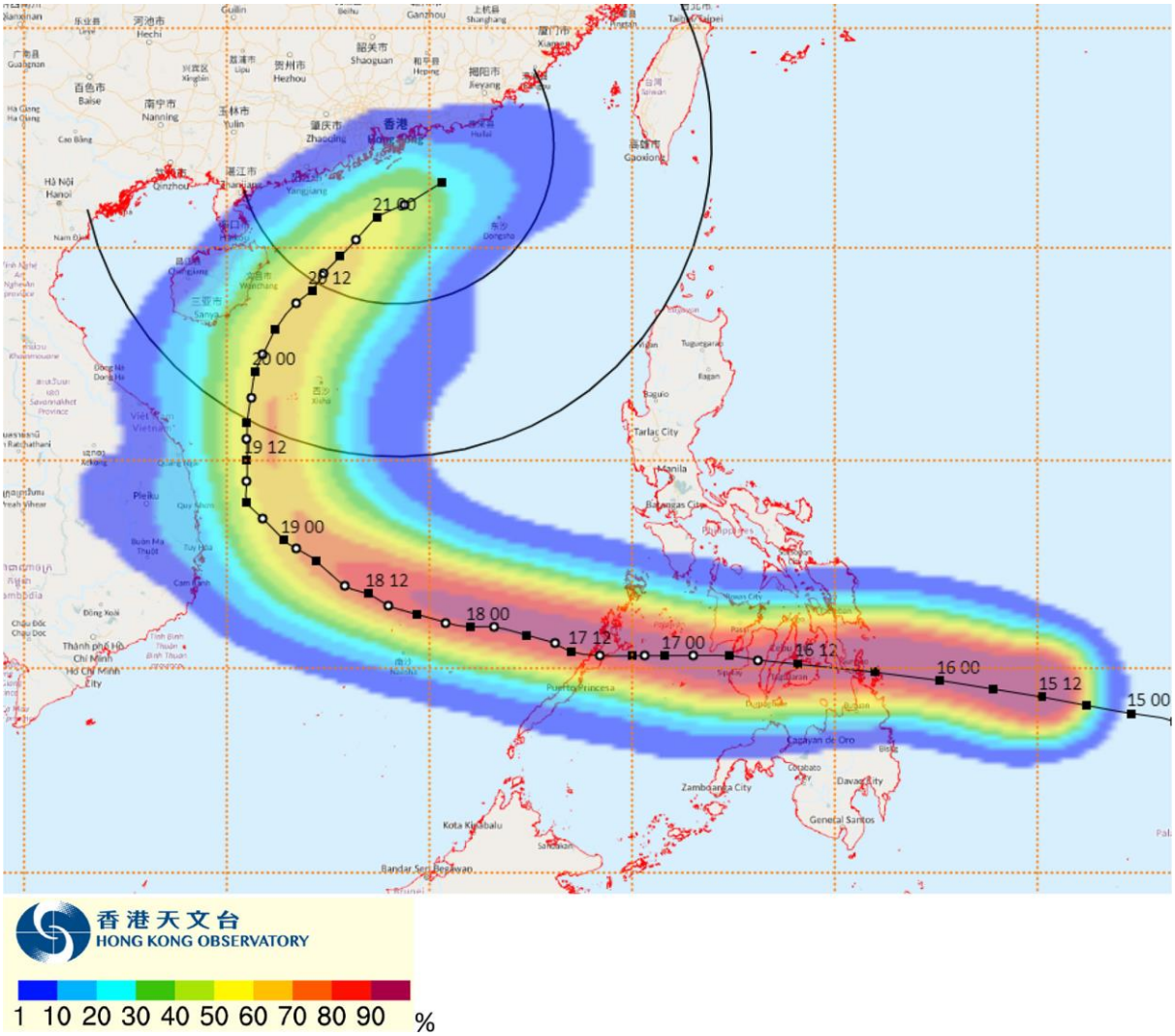


Figure 8 Probabilistic strike map based on ECMWF ensemble prediction system initialised on 15 December 2021 (colour shading) and the actual warning positions of *Rai* (black curve).

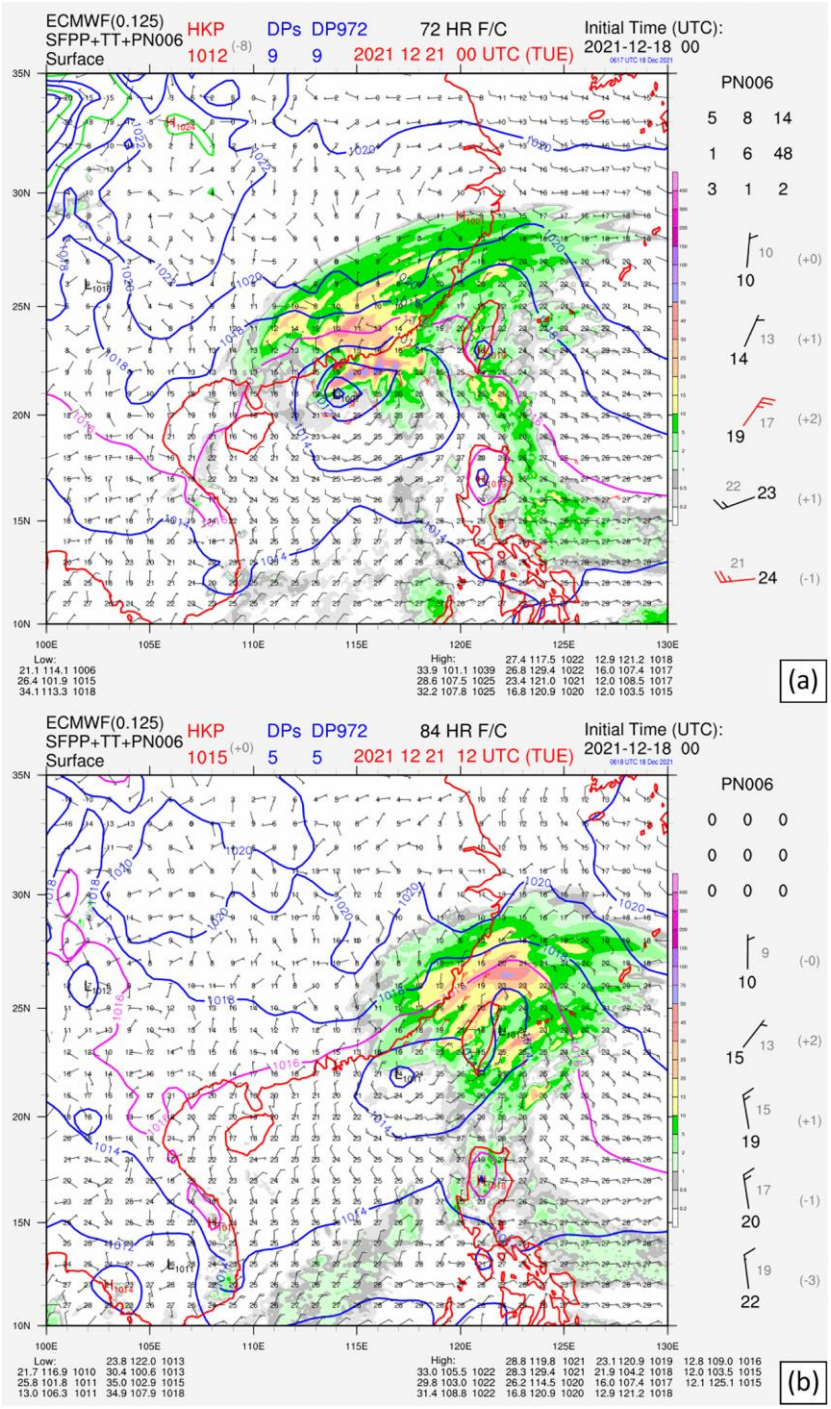


Figure 9 The 72-hour (a) and 84-hour (b) forecasts from the ECMWF global model at the surface, including surface wind (wind barbs over the grid points), temperature (numbers over the grid points), precipitation (colour shading) and pressure contours, from the run initialised at 0000 UTC, 18 December 2021.

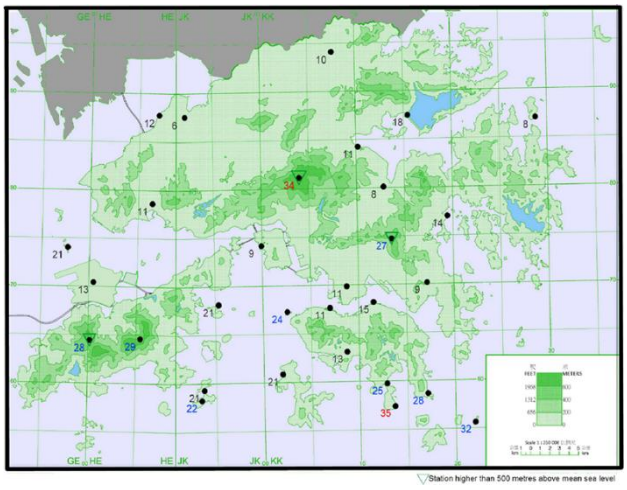


Figure 10　The maximum 10-min wind (in kn) recorded at various stations in Hong Kong when the tropical cyclone warning signal for *Rai* was in force. The green shading of the map represents height. Blue and red numbers represent wind speed reaching strong and gale force, respectively.