Typhoon Vamei: An Equatorial Tropical Cyclone Formation

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Abstract. Due to the diminishing Coriolis effect, the belt 300 km either side of the equator has been considered tropical cyclone-free. Typhoon Vamei, which developed near Singapore on 27 December 2001, was the first recorded tropical cyclone formation within 1.5 degrees of the equator. The development was the result of two interacting systems, a weak Borneo vortex that drifted into the southern tip of the South China Sea and remained there for four days, and a strong and persistent cold surge that created the large background cyclonic vorticity at the equator. The probability of a similar equatorial development is estimated to be once every 100-400 years.

1. Introduction

Historically, the equatorial zone has been considered by sailors to be free from tropical storms. This is because tropical cyclones have rarely been observed to form equatorward of 5° latitude (e.g., *Gray,* 1968, *Anthes,* 1982, *McBride,* 1995), where the diminishing Coriolis effect prevents effective generation of relative vorticity by horizontal convergence. Since tropical cyclone observations started in 1886 in the North Atlantics and 1945 in the western North Pacific, the previous recorded lowest latitude for a typhoon was 3.3°N for Typhoon Sarah in 1956 (*Fortner*, 1958). Typhoon Vamei formed near Singapore on 0600 UTC 27 December 2001. With its circulation center at 1.5°N and a radius of convective cloud area of near 200 km (Fig. 1a), the storm circulation was on both sides of the equator. Naval ships reported maximum sustained surface wind of 39 m s^{-1} and gust wind of up to 54 m s^{-1} (*Joint Typhoon Warning Center*, 2002), which caused damages to the carrier USS Carl Vinson and an accompanying ship. This was the first-ever recorded tropical cyclone formation at such equatorial latitude.

In this work we will analyze the low-level wind fields to determine the roles played by monsoonal cold surges, pre-existing disturbances, and upper level divergence in the formation of Vamei. We will try to answer the question that while all these factors are frequently present during the boreal winter monsoon, why Typhoon Vamei was such a rare event.

2. Data

Three sets of wind data are used in this study. 1) the Naval Operational Global Atmospheric Prediction System (NOGAPS) (*Hogan and Brody*, 1993) 1° X 1° analyzed winds at 850 hPa; 2) the QuikSCAT 25 km X 25 km surface winds (*Liu et al*., 2000), and 3) the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) 2.5° x 2.5° reanalysis winds (*Kalnay*, *et al*., 1996) at the surface and 925 hPa. Both the NOGAPS and QuikSCAT data are available for the three boreal winters (December-February, or DJF) of 1999/2000 – 2001/2002. The NCEP/NCAR data are available for 51 boreal winters of 1951/1952-2001/2002.

3. The formation of Typhoon Vamei

During the northern hemisphere winter monsoon, northeasterly cold surges sporadically spread equatorward from the East Asia continent on the southeast edge of surface highs (*Chang et al*., 1983; *Chang and Chen*, 1992). The strongest cold surges occur over the South China Sea, where the air is no longer cold but the freshening of the northeast winds progresses southward rapidly as the sea narrows towards the equator. The cold surge air can reach the equator in about two days (*Chang et al*., 1983). Conservation of potential vorticity causes the air to turn eastward after it crosses the equator. These Southern Hemisphere equatorial westerlies may enhance the Australian monsoon trough farther south between 10°S-20°S where tropical cyclogenesis occurs frequently (*Holland*, 1984; *McBride*, 1995).

Southeast of the main surge wind belt in the South China Sea is the island of Borneo, where a quasi-stationary low-level cyclonic circulation centered near its northwest coast is a persistent feature of the boreal winter climatology (*Johnson and Houze*, 1987, see Fig. 10.2). This circulation will be called the Borneo vortex even though its circulation may not be completely closed on the east side over the island. It is maintained by the shear vorticity and convergence that result from the interaction between the northeast monsoon winds and the mountainous Borneo terrain (*Cheang*, 1977; *Chen et al*., 1986; *Johnson and Houze*, 1987). The mean location of the vortex along the northwest coast of Borneo may be seen in Fig. 1b, which shows the 1999/2000 to 2001/2002 December-February mean 850 hPa vorticity from the 1° x 1° NOGAPS analysis, overlaid with the surface vorticity derived from the QuikSCAT satellite scatterometer winds. The Borneo vortex is often associated with deep convection and intense latent heat release, and upper-level divergence is often present. However, because most of the time a significant part of the vortex circulation is over land, even when a vortex drifts to northern Borneo between 5°N-7°N, which are latitudes considered more favorable for tropical cyclone development, it is very difficult for the vortex to develop into a tropical cyclone.

Starting from 19 December 2001, a cold surge developed rapidly over the South China Sea while the Borneo vortex center was located near 3°N on the northwest coast (not shown). The 850 hPa NOGAPS wind analysis and vorticity (Fig. 2) depict the southwestward movement of the vortex from along the Borneo coast toward the equator. By 21 December, the center of the vortex had moved off the coast to be over water, where the open sea region in the southern end of the South China Sea narrows to about 500 km with Borneo to the east and the Malay Peninsula and Sumatra to the west. This over-water location continued for several days. While the vortex center remained in the narrow equatorial sea region, the strong northeasterly surge persisted, and was slightly deflected to the northwest of the vortex. Consequently, the cross-equatorial flow wrapped around the vortex and the net result was a spinning up of a rapid counter-clockwise circulation that is similar to the spinning of a top played by a child, and this led to the development of Typhoon Vamei.

Fig. 3 shows the location of counterclockwise circulation centers in the domain of study during the 51 boreal winters of 1951/52 – 2001/02, based on a streamline analysis of the NCEP/NCAR reanalysis 925 hPa wind. The distribution of the frequencies of vortex centers in four sub-regions near the northwestern coast of Borneo is superimposed on the diagram. There were only six occurrences of a Borneo vortex center that stayed continuously for 96 h in this narrow equatorial sea region (the southwestern box) in the 51 boreal winters.

While cold surges are frequent events in the South China Sea during boreal winter, the surge preceding the development of Typhoon Vamei was especially intense and long lasting. The twice-daily time series of a cold surge index shown in Fig. 4 is calculated over the rectangular area 110°E-115°E, 7.5°N-12.5°N (dashed box in Fig. 3), which is upstream from the region of the Borneo vortex. This surge index is the average of all northeasterly wind components from QuikSCAT reports within this box during the three boreal winters of 1999/2000-2001/2002. A strong surge index (≥ 10 m s^{-1}) is indicated by a shaded bar. The period of 00 UTC 19 - 00 UTC 25 December 2001 was the most sustained and intense surge period in terms of a continuous average wind speed exceeding 10 m/s. None of the other surge periods coincided with the occurrence of a Borneo vortex that migrated into, and stayed in, the narrow open sea region.

Besides processes in the lower troposphere, upper-level processes have also been suggested as mechanisms for tropical cyclone development (*e.g., Anthes, 1982; McBride, 1995*). Fig. 5 shows the 200 hPa large-scale divergence over the equatorial area of 5°S-5°N, 102.5°E-112.5°E, computed from NCEP/NCAR reanalysis, for the boreal winters of 1999/2000-2001/2002. An increase in the 200 hPa divergence over the region was observed from 19 to 22 December 2001, but the tendency and maximum magnitude are no greater than many other events during the boreal winter.

4. Concluding Remarks

In conclusion, the development of Typhoon Vamei was a result of several factors. Prior to its formation, a strong cold surge persisted for nearly one week over the narrowing South China Sea provided a source for background cyclonic vorticity as the surge wind crossed the equator. The anomalous strength and persistence of this surge was related to the anomalously strong meridional gradient of sea-level pressure in the equatorial South China Sea during December 2001 (*Bureau of Meteorology Northern Territory Region*, 2002, Fig. 6). The narrowing of the South China Sea at the equator appears to be an important factor for the rare occurrence of the typhoon formation. On the one hand, the channeling and strengthening of the cross-equatorial surge winds helps to produce the background cyclonic vorticity at the equator. On the other hand, the open water region of approximately 5° longitude is just sufficient to accommodate the diameter of a small tropical cyclone. However, it is too small for most synoptic-sized disturbances to remain over the water for more than a day or so. In the unusual case of Typhoon Vamei, the Borneo vortex migrated to this small region and stayed for 96 hours – long enough to become the early stages of the typhoon.

The QuikSCAT surge index (Fig. 4) is available only since 1999. Table 1 shows the frequency of surges sustained for different durations, based on a surge index computed from the surface winds in the NCEP/NCAR reanalysis during the boreal winters of 1951/52-2001/02. A total of 61 strong surge events lasting one week or more in the southern South China Sea occurred. The total number of days under these persistent surges is 582. Assuming that the vortex needs at least a three-day overlap with the surge to develop, the sustained "spinning top effect" is estimated to be present at the equator about 10% of the boreal winter days. If the minimum persistent surge duration required is reduced from seven days to five days, the available time of the spinning top effect is increased to 14%. During the 51 boreal winters, the frequency of a pre-existing Borneo vortex staying over the equatorial water continuously for four days or more is six, or a probability of 12% in a given year. Whether a pre-existing disturbance develops into a tropical cyclone depends on background vertical shears of wind and vorticity, upper level divergence, and a variety of environmental factors (*Anthes* 1982, *McBride* 1995). In the more favored tropical cyclone basins of the western Pacific and North Atlantic, the percentage of pre-existing synoptic disturbances developing into tropical cyclones during their respective tropical cyclone seasons ranges between 10-30%. Thus, of all the conditions that led to the formation of Vamei, we estimate the probability for a typhoon to develop in the equatorial South China Sea to be about 0.12-0.49% a year, or an expectation of about once every 300-400 years. This probability may be increased by a factor of 3.5, to about once every 100 years, if we lower the required persistence period of a Borneo vortex center in the equatorial sea region to 72 h, which occurred 21 times during the past 51 boreal winters. Since cold surges are strongest and penetrate deepest into the tropics in the South China Sea, it is unlikely that such a tropical cyclone formation scenario can take place elsewhere along the equator.

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Table 1. The frequency of surge durations. The first column is the number of consecutive days (duration) that the northeast surge index ≥ 10 m s^{-1} at least once during each day of the duration. The second column is the total number of events associated with the duration. The third column is the cumulative number of events that lasted for at least the duration, and the fourth column is the maximum value of surge index among surges of the duration.

Surge duration	Number of events	Cumul-ative no. events	Max surge index	Surge duration × number of events for duration ≥ 7 days	Surge duration × number of events for duration ≥ 5 days
1	151	449	13.0		
2	87	298	13.6		
3	62	211	14.3		
4	40	149	15.3		
5	27	109	15.0		135
6	21	82	15.8		126
7	11	61	14.2	77	77
8	13	50	16.5	104	104
9	15	37	15.1	135	135
10	6	22	15.4	60	60
11	6	16	15.1	66	66
12	4	10	16.0	48	48
13	2	6	15.2	26	26
14	1	4	14.3	14	14
15	0	3	0	0	0
16	1	3	14.6	16	16
17	1	2	14.6	17	17
18	0	1	0	0	0
19	1	1	14.9	19	19
Total boreal winter days with spinning effect				582	843
Sum of last two days of each long surge				122	218
Total without the last two days of each surge				460	625
Probability of TC development				0.10	0.14

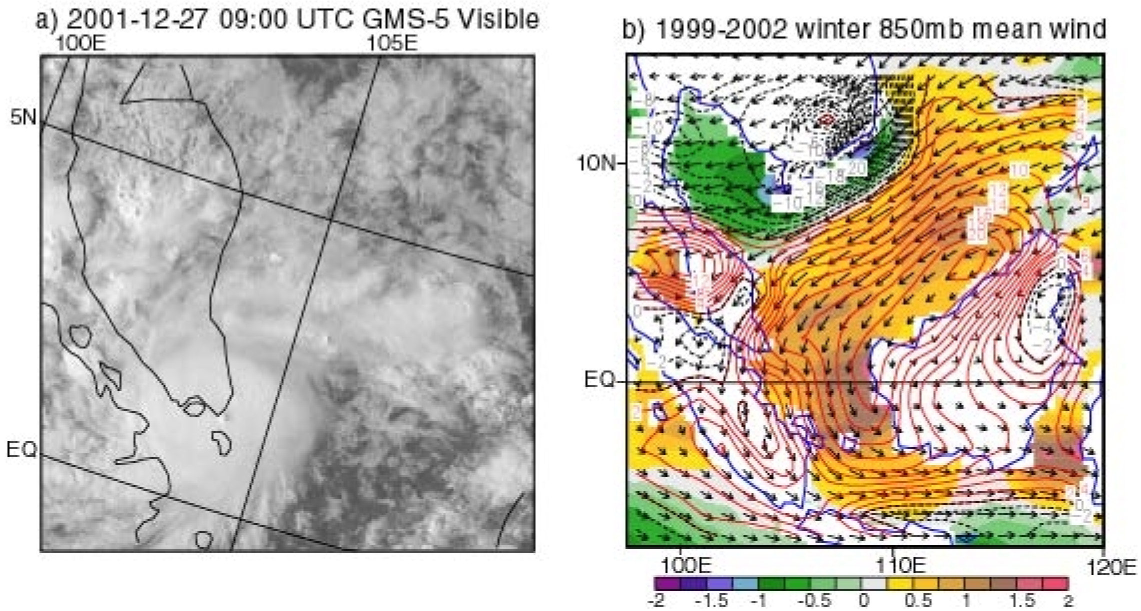

Figure 1. a) GMS visible satellite picture of Typhoon Vamei, 09 UTC 27 December 2001.
b) 1999/2000 -2001/2002 boreal winter (DJF) mean of 850 hPa NOGAPS 1° x 1° wind and vorticity (contours: solid positive, dashed negative, interval 2x10-5 s^{-1}), and surface vorticity based on 25 km resolution QuikSCAT winds (yellow positive, green negative).

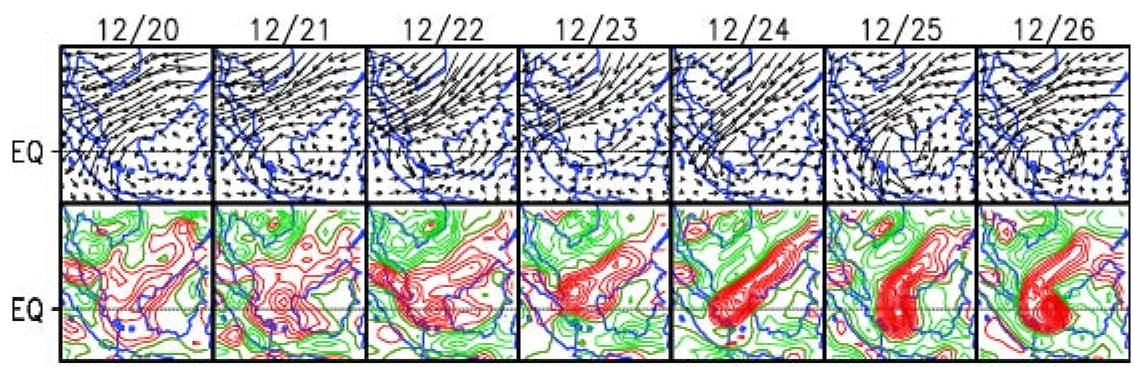

Figure 2. NOGAPS 1° x 1° 850 hPa wind and vorticity (red positive, green negative) at 00 UTC 20-26 December 2001.

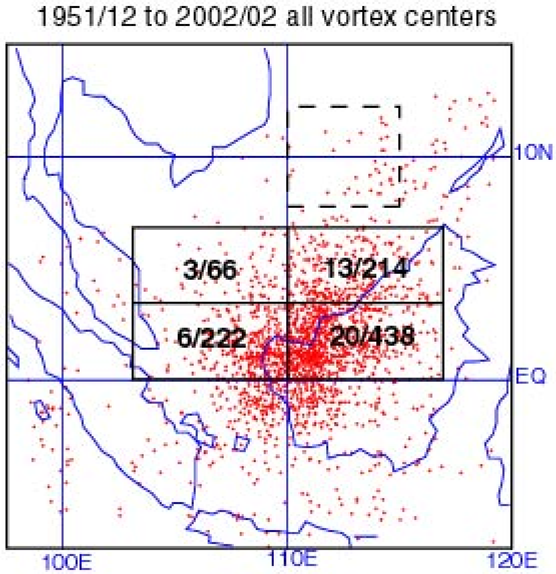

Figure 3. Location of NCEP/NCAR 925 hPa counterclockwise circulation centers during the 51 boreal winters. The four sub-regional boxes are enclosed by equator - 7°N, and 103°E - 117°E. The internal partitions are 3°N and 110°E. The first number in each box indicates the frequency of persistent 925 hPa cyclonic circulation center that lasted for 96 h or more, based on the 1951/52-2001/02 DJF NCEP/NCAR 2.5 x 2.5° reanalysis. The second number is total number of days a center is identified. The heavy dashed box indicates the area in which the northeasterly component of QuikSCAT winds is averaged to produce the surge index.

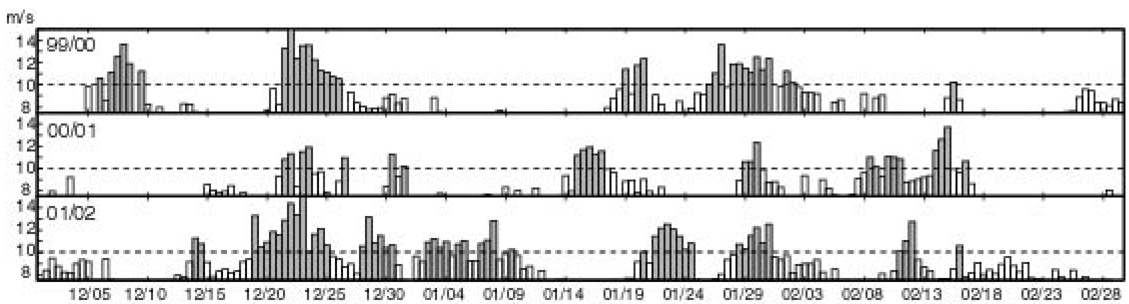

Figure 4. QuikSCAT surge index upstream from equatorial South China Sea at 00 and 12 UTC during boreal winter 1999/2000 - 2001/2002. Values ≥10 m s^{-1} (dashed line) are shaded.

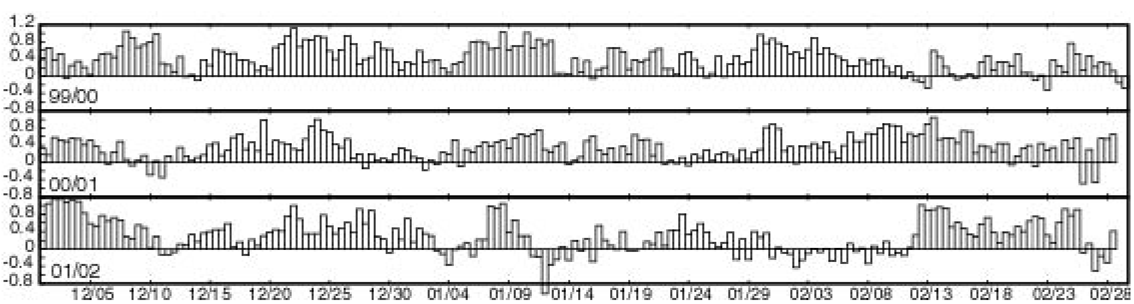

Figure 5. NCEP/NCAR 200 hPa divergence over 5°S-5°N, 102.5°E-112.5°E at 00 and 12 UTC during boreal winter 1999/2000 - 2001/2002. Units: 10^{-5} sec^{-1}.