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First Observational Perspectives of "Millipede Clouds" Over the Eastern Pacific Ocean

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Key Points:

- The fundamental features of "Millipede Clouds" over the Eastern Pacific Ocean in 2017 were documented by using Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery
- The environmental backgrounds of these "Millipede Clouds" were analyzed by using ERA5 reanalysis data and MODIS data
- The cloud top pressures of these "Millipede Clouds" are between 850 and 800 hPa, and their top heights are about 1–2 km

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Abstract

The fundamental features of one kind of rarely known stratocumulus, which was termed as "Millipede Cloud," occurred over the Eastern Pacific Ocean in 2017 were first documented by using Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery. These clouds had long and meandering "central axes" extending from several hundreds to thousands kilometers, and a number of "radical cloud arms" extending several tens of kilometers in its two sides. Total 59 "Millipede Clouds," 4 and 55 of them, were formed over the Northern and the Southern Hemispheres, respectively. Their environmental backgrounds were analyzed by using ERA5 reanalysis data and MODIS sensor Level-2 data. The cloud top pressures of these "Millipede Clouds" were between 850 and 800 hPa, and their top heights were about 1–2 km. There existed "inversion layer" of air temperature near the cloud tops at 800 hPa, which strongly suggested that these clouds were lower stratocumulus in essence.

Plain Language Summary

"Millipede Cloud," one kind of rarely known stratocumulus which looks like "Millipede" shape, is termed for the first time in this paper. It has an obvious "central axis" and a number of well-organized "radial cloud arms" in two sides of the "central axis" extending in several tens of kilometers length. This paper introduces the fundamental features of "Millipede Clouds" occurred over the Eastern Pacific Ocean in 2017 from the perspective of satellite image. Totally, 59 "Millipede Clouds" were found to occur over the Eastern Pacific Ocean. Their geographic distribution, cloud top features and vertical structure of one typical case on 16 July 2017 were documented.

1. Introduction

Clouds in the Earth's atmosphere, the most complicated shapes and diverse-collections of tiny water droplets or ice crystals, are significant actors in weather, hydrology, climate, air chemistry, and several practical applications such as atmospheric aviation hazards and solar energy use (Spänkuch et al., 2022). Clouds differ significantly in sizes, shapes, colors, even definitions (Spänkuch et al., 2022), and may appear in various shapes such as thin and wispy, or bulky and lumpy forms. Observations and analyses of clouds are vital importance for understanding the atmospheric motions and predicting future weathers.

Previously, humans could only observe clouds at the Earth's ground from land or sea. In 1803, Luke Howard, an amateur English meteorologist, devised the cloud classification scheme (Howard, 1803). He defined three main cloud types, terming as "Cirrus," "Cumulus," "Stratus," and other four secondary types, terming as "Cirro-cumulus," "Cirro-stratus," "Cumulo-stratus," and "Cirro-cumulo-stratus" or "Nimbus," respectively (Howard, 1803, p. 345). According to the heights, clouds may be classified into high-clouds, middle-clouds, and low-clouds.

The first man-made satellite in the world, Sputnik 1, was launched on 4 October 1957 by the former Soviet Union. After the launching of the first weather satellite TIROS I on 1 April 1960 (Fritz & Wexler, 1960), it became possible to observe clouds from the outer space with "top-down" view. There were a lot of satellite imagery transmitted from TIROS satellites. Since January 1963, a series of "Picture of the Month" had been published in the Monthly Weather Review, which represented particularly puzzling phenomena (Singer, 1963). These papers featured satellite pictures including the first "actinoform patterns" from TIROS V photo, which was along 7°S, between 87°W and 97°W at 15:00 UTC 7 October 1962 (MWR, 1963; picture at page 2). In 2022, Schultz and Potter mentioned this picture again (Schultz & Potter, 2022; Figure 14 at page 36) when they reviewed the past 150-year history, impact and legacy of Monthly Weather Review. This picture was also kept as the first one of online special collection of all 158 items in Pictures of the Month (https://journals.ametsoc.org/collection/picture-MWR).

In 1973, Bugaev (1973) reviewed the achievements of various meteorological satellites and spaceships, and indicated that the global satellite imagery might be used to analyze the features of main climatic zones of the earth. He mentioned that "To the west, over the ocean, low clouds assume the structure of convective cells and an original mesometeorological disturbance in the form of a scolopendra appears (A-A)" (the last 3 lines, page 404). He also showed a "scolopendra" shaped cloud which was located around from (20°S, 76°W) to (27°S, 74°W) in the Meteor-11 satellite television picture on 30 July 1972 (see Figure 13 at page 405). As far as we know, this was the earliest paper mentioning the "Scolopendra Cloud" in academic journal.

Based on systematic investigation of satellite imagery from 2012 to 2021, our recent study indicated that these "Scolopendra/Millipede"shaped clouds occurred frequently over the Eastern Pacific, Atlantic and Indian Oceans. Their main features are as follows: (a) They have long and meandering "central axis" extending from several hundreds to thousands kilometers. (b) There are a great number of well-organized "radial cloud arms" in two sides of the "central axis" extending several tens of kilometers, those look like "Millipede Legs." (c) As the shapes of these clouds look like "Scolopendra/Millipede," they are termed as "Millipede Clouds." We used manual approach to identify "Millipede Clouds" based on their main features.

This paper aims to present the fundamental features of this kind of rarely known "Millipede Clouds." The rest of this paper is organized as follows. Section 2 introduces the data and methodology. Section 3 describes the results. Finally, Section 4 provides the summary and discussion.

2. Data and Methodology

2.1. Data

In the present study, we employed the following data: (a) Moderate Resolution Imaging Spectroradiometer (MODIS) visible cloud imagery taken by NASA's Aqua and Terra satellites. (b) Visible cloud imagery from the Visible Infrared Imaging Radiometer Suite (VIIRS) carried by NASA/National Oceanic and Atmospheric Administration (NOAA)'s Suomi NPP (Suomi National Polar-orbiting Partnership) satellite. (c) MODIS sensor Level-2 data from NASA. (d) ERA5 reanalysis data (Hersbach et al., 2020) from European Centre for Medium-Range Weather Forecasts (ECMWF) with $0.25° \times 0.25°$ spatial resolution and 1-hourly time interval are used for synoptic analyses.

2.2. Methodology

Since NASA's polar-orbiting Aqua and Terra satellites rarely provided imagery on the "whole hour" moment, it is necessary to use the Lagrangian time interpolation method to interpolate the ERA5 data to those data at the moment when satellite imagery were available.

$$c_t(x) = \frac{(x - x_1)(x - x_2)\cdots(x - x_{t-1})(x - x_{t+1})\cdots(x - x_n)}{(x_t - x_1)(x_t - x_2)\cdots(x_t - x_{t-1})(x_t - x_{t+1})\cdots(x_t - x_n)} \tag{1}$$

$$y(x) = \sum\nolimits_{t=1}^{n} c_t(x) \cdot y_t \tag{2}$$

Equation 1 is the Lagrangian interpolation coefficient. Here, x_t means the t-th moment, and x means the occurrence moment of "Millipede Cloud" with available satellite imagery. In the present study, we accepted $n = 6$. Equation 2 is the Lagrangian time interpolation polynomial, in which y_t is the ERA5 data at the t-hour.

3. Results

Table 1 shows the monthly occurrence number of "Millipede Clouds"over the Eastern Pacific Ocean in 2017. There were total 59 "Millipede Clouds" occurred over the region (35°S–35°N, 170°W–70°W). It was interesting that most of them occurred from June to August, that is, 15 for June, 10 for July, 20 for August, and a total of 14 for January, April, May, September, October, November, respectively. However, it was a little surprising that there were no "Millipede Clouds" in February, March and December.

Table 1
Monthly Occurrence Number of Total 59 "Millipede Clouds" in 2017 Over the Southern and Northern Hemispheres

Month	Southern Hemisphere	Northern Hemisphere	Total
January	0	2	2
February	0	0	0
March	0	0	0
April	0	1	1
May	1	0	1
June	15	0	15
July	10	0	10
August	20	0	20
September	7	0	7
October	1	0	1
November	2	0	2
December	0	0	0

3.1. Cloud Features

After examining all MODIS satellite imagery in 2017, cloud features of four selected cases are displayed. They occurred on 20 January (case 1, No.2), 16 July (case 2, No.25), 05 August (case 3, No.31), 03 September 2017 (case 4, No.52), respectively (Figure 1), and had typical feature of "Millipede" with one main body and multiple feet in its two sides.

Figure 1a showed the Aqua satellite visible image over the Northeastern Pacific Ocean at 22:20 UTC 20 January 2017. In the northwest of 18°N and the southeast of 16°N, there were many closed cellular cloud patterns (Houze, 2014; Figure 5.19 at page 120). This cloud system occurred within a region of dense marine stratocumulus. From 16°N to 18°N, there was a cloud which looked like a "Millipede" with one main body and multiple feet in its two sides. This "Millipede Cloud" had a long axis extending about 730 km with a slight southwest-northeast orientation, and its cloud area was about 131,792 km^2.

Figure 1b showed the Aqua satellite visible image over the Southeastern Pacific Ocean at 19:35 UTC 16 July 2017. There were a clear "central axis" and a number of well-defined "radical cloud arms" in its two sides. This case was a typical "Millipede Cloud" occurred over this region. Its long axis was about 2,569 km, and its cloud area was about 787,198 km^2. The vertical structure of this cloud system, along the line AB, will be examined later.

Figure 1c showed the Terra satellite visible image over the Southeastern Pacific Ocean at 20:50 UTC 05 August 2017. There were many closed cellular clouds in the southwest of 11°S and the northeast of 9°S. In the middle part, there was a clear "Millipede Could" with northwest-southeast orientation. Its long axis was about 666 km and the cloud area was about 187,400 km^2.

Figure 1d showed the Terra satellite visible image over the Southeastern Pacific Ocean at 17:30 UTC 03 September 2017. In the north of 12°S and the south of 16°S, there were many closed cellular clouds. There were clear "central axis" and a number of well-defined "radical cloud arms" in its two sides. Its horizontal length, with near west-east orientation, was about 1,405 km, and the cloud area was about 338,874 km^2.

3.2. Geographic Distribution

Figure 2 displays the geographical distribution of total 59 "Millipede Clouds" over the Eastern Pacific Ocean in 2017. It was found that there were only two regions for their frequent occurrence: 4 clouds occurred over the Northern Pacific Ocean (Figure 2a), and 55 occurred over the South Pacific Ocean (Figure 2b), concentrating in the region (5°S–25°S, 130°W–75°W). Some useful information such as point-point distance and cloud area may be determined by using tools in the website https://worldview.earthdata.nasa.gov/. Table 2 summarizes the basic information of these 59 clouds, including their long axis lengths, short axis lengths, and cloud areas. The mean, maximum, minimum horizontal lengths of "central axis" are about 1055.0, 5,070.0, 183.0 km, respectively. The mean area of these cloud systems is 257,012 km^2, and the maximum area is 1,331,327 km^2, and the minimum area is 28,462 km^2.

3.3. Features of Cloud Tops

Level-2 data from the MODIS sensor carried by Aqua and Terra satellites may characterize the heights (Figures 3a, 3d, 3g, and 3j), air pressures (Figures 3b, 3e, 3h, and 3k) and air temperatures (Figures 3c, 3f, 3i, and 3l) of the cloud tops. Figure 3 shows that the cloud tops of "Millipede Clouds" are not flat, which are particularly obvious in the cloud top pressure field of those four cases. All those four cases have "central axis" with higher cloud top pressure and lower cloud top height, while the "radial cloud arms" away from the "central axis" have lower cloud top pressure and higher cloud top height. Regardless of the differences of occurrence area and the "central axis" orientation of the "Millipede Clouds," the features exhibited by their cloud top information are common: "Millipede Clouds" are low clouds, with the cloud top pressures between 850 hPa and 800 hPa.

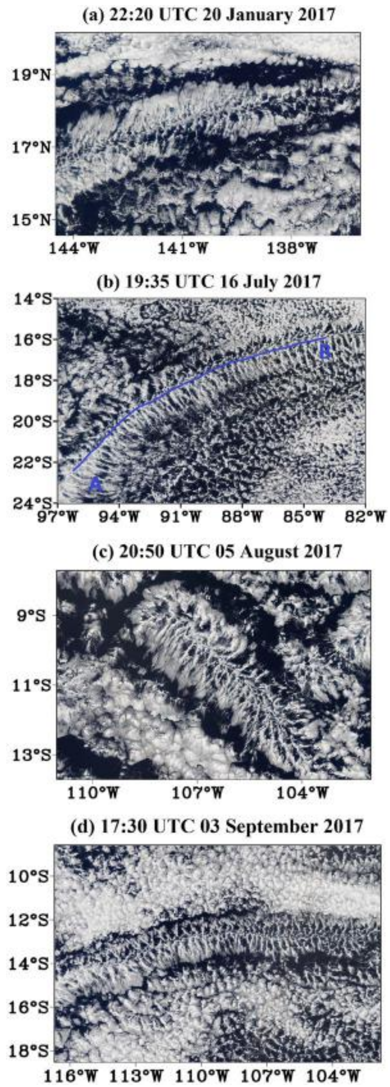

Figure 1. Four satellite imagery of "Millipede Clouds" over the Easter Pacific Ocean. (a): Aqua satellite visible image at 22:20 UTC 20 January 2017. (b): Aqua satellite visible image at 19:35 UTC 16 July 2017, wherein the blue line AB labeling the location of vertical cross-section analyses later. (c): Terra satellite visible image at 20:50 UTC 05 August 2017. (d): Terra satellite visible image at 17:30 UTC 03 September 2017.

Correspondingly, the cloud top heights are from 1 to 2 km. But for "radial cloud arms," their cloud top heights may reach above 2 km.

The cloud top information are only the basic information from the perspective of satellite. In order to understand the vertical structures of "Millipede Clouds," it is necessary to use ERA5 data for vertical analyses.

3.4. Vertical Features

The ERA 5 data around 19:35 UTC was estimated by interpolating the ERA5 data at 17:00, 18:00, 19:00, 20:00, 21:00, and 22:00 UTC 16 July 2017 based upon Equation 2. The vertical cross-section features of "Millipede Cloud" occurred at 19:35 UTC 16 July 2017, along the line AB, were shown in Figure 4. The vertical profile of air temperature (Figure 4a) showed that there was an "inversion layer" in the cloud top, which was near 800 hPa in A point, and near 850 hPa in B point. Air temperature increased from 5°C to 8°C at A point within this layer, from 8°C to 11°C at mid-point and from 8°C to 16°C at B point. Correspondingly, water vapors were almost trapped down below this cloud top, as the vertical profile of specific humidity (Figure 4b) showed that its zero

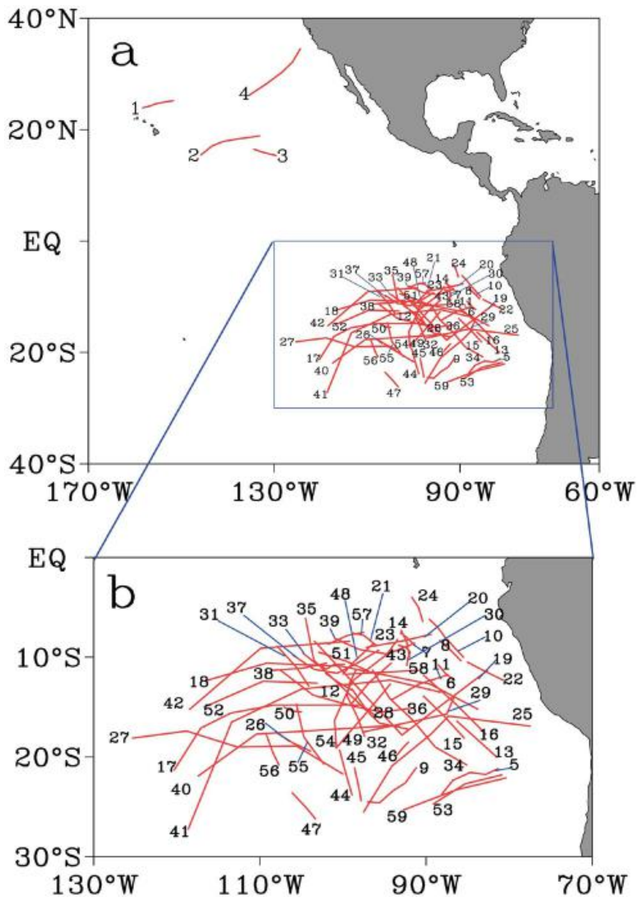

Figure 2. Geographic distribution of total 59 “Millipede Clouds” over the Eastern Pacific Ocean in 2017. The solid red lines indicate the locations of “long axis” of “Millipede Clouds.” The serial numbers present the order of their occurrence time from January to December 2017.

contour was located below 750 hPa. Meanwhile, it can be seen from the vertical profile of horizontal divergence of velocity (Figure 4c) that, roughly distinguished by 900 hPa, the horizontal divergence of velocity is negative below 900 hPa, suggesting that there are weak convergence in the lower layer. Above 900 hPa, in the layer from 900 hPa to the cloud top, the horizontal divergence of velocity is positive with the magnitude of 6×10^{-5}/s, suggesting the divergence in this layer. The vertical profile of vertical velocities (Figure 4d) show that their value are positive, suggesting that there are upward motions in this layer (under 800 hPa at A point, under 850 hPa at B point). Vertical velocities reach the maximum value of 0.04 m/s. Above 800 hPa, there are downward motions with the magnitude of −0.02 m/s.

Further analyses indicated that there was a vertical wind shear around 2.5 ~ 5.5 m/s between 775 and 800 hPa, and a horizontal gradient of air temperature at 2 m-height ranging from 0.005 ~ 0.05 K/km.

Finally, it can be summarized as follows. There exited an “inversion layer” of air temperature around 850 ~ 800 hPa within this layer (Figure 4a). Due to the limitation of this inversion layer, water vapors were almost confined below the cloud top (Figure 4b). The lower-level (below 900 hPa) convergence (Figure 4c) might produce upward motions within this layer (Figure 4d). Also due to the limitation of the inversion layer, the upward motions were trapped down near the cloud top (Figure 4d).

Table 2
Statistics of Basic Information of 59 “Millipede Clouds” in 2017

	Long axis length (km)	Short axis length (km)	Cloud area (km^2)
Mean Value	1,055	184	257,012
Maximum Value	5,070	321	1,331,327
Minimum Value	183	76	28,462

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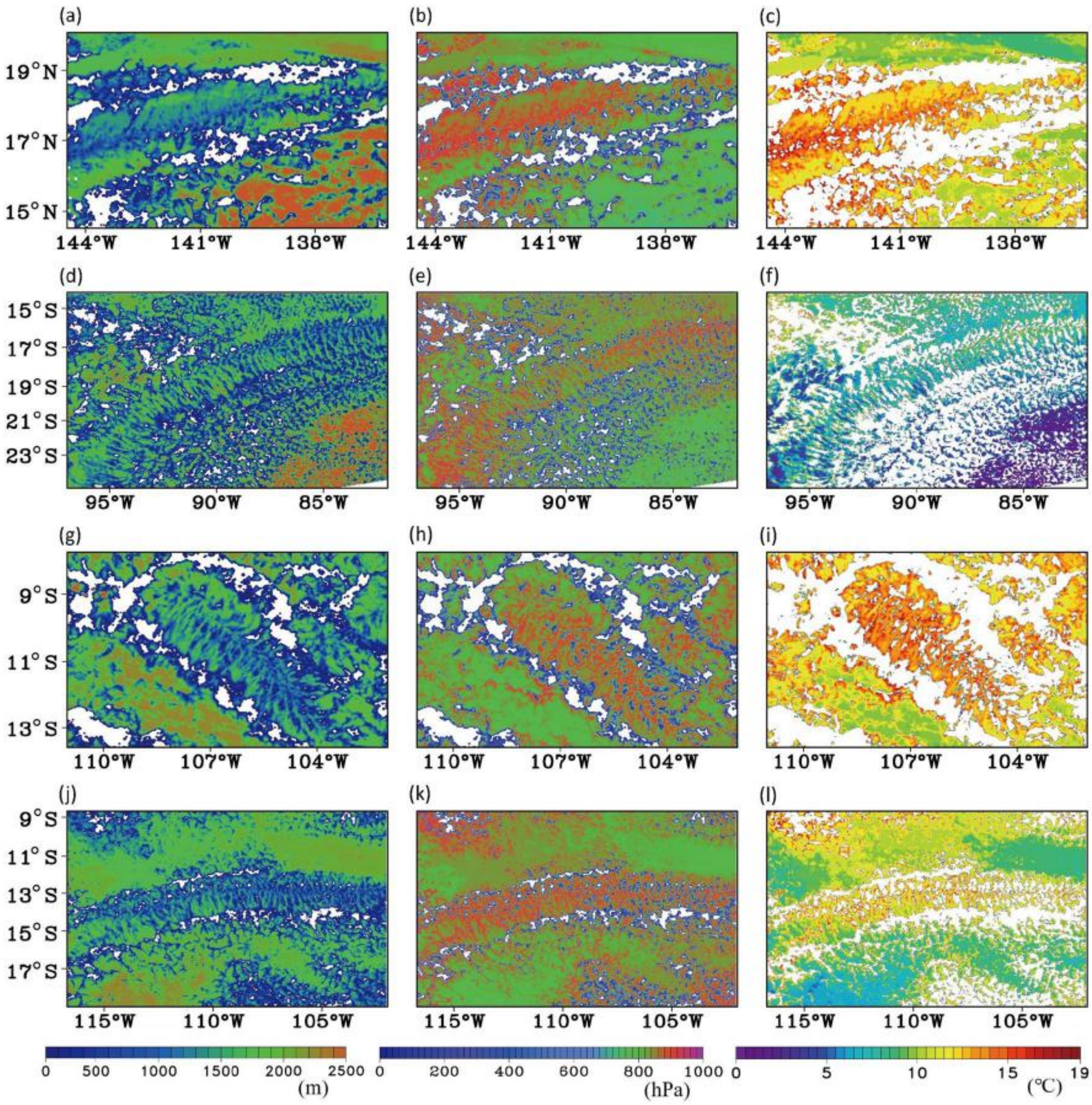

Figure 3. Cloud top heights (shaded, unit: m) for (a): 22:20 UTC 20 January 2017, (d): 19:35 UTC 16 July 2017, (g): 20:50 UTC 05 August 2017, (j): 17:30 UTC 03 September 2017. Cloud top pressures (shaded, unit: hPa) for (b): 22:20 UTC 20 January 2017, (e): 19:35 UTC 16 July 2017, (h):20:50 UTC 05 August 2017, (k): 17:30 UTC 03 September 2017. Cloud top temperatures (shaded, unit: °C) for (c): 22:20 UTC 20 January 2017, (f): 19:35 UTC 16 July 2017, (i): 20:50 UTC 05 August 2017, (l): 17:30 UTC 03 September 2017.

4. Summary and Discussion

A great number of MODIS satellite imagery showed that there usually occurred a lot of cloud systems over the Eastern Pacific Ocean, those had long and meandering "central axes" extending from several hundreds to thousands kilometers, and a number of "radical cloud arms" extending several tens of kilometers in two sides. As the shapes of these cloud systems looked like "Millipede/Scolopendra," they were termed as "Millipede Clouds." This paper first documented the fundamental features of "Millipede Clouds," one kind of rarely known stratocumulus, occurred in 2017 by using MODIS satellite imagery. Totally, 59 "Millipede Clouds" were found to occur over the Eastern Pacific Ocean. 4 and 55 "Millipede Clouds" were formed over the Northern and Southern Hemispheres, respectively. The environmental backgrounds of these "Millipede Clouds" were analyzed by using ERA5 reanalysis data and MODIS sensor Level-2 data from NASA. It was shown that the cloud top pressures associated with these clouds were between 850 and 800 hPa, and the cloud top heights were about 1–2 km. There exited an "inversion layer" of air temperature above the cloud tops, which strongly suggested that these clouds were lower

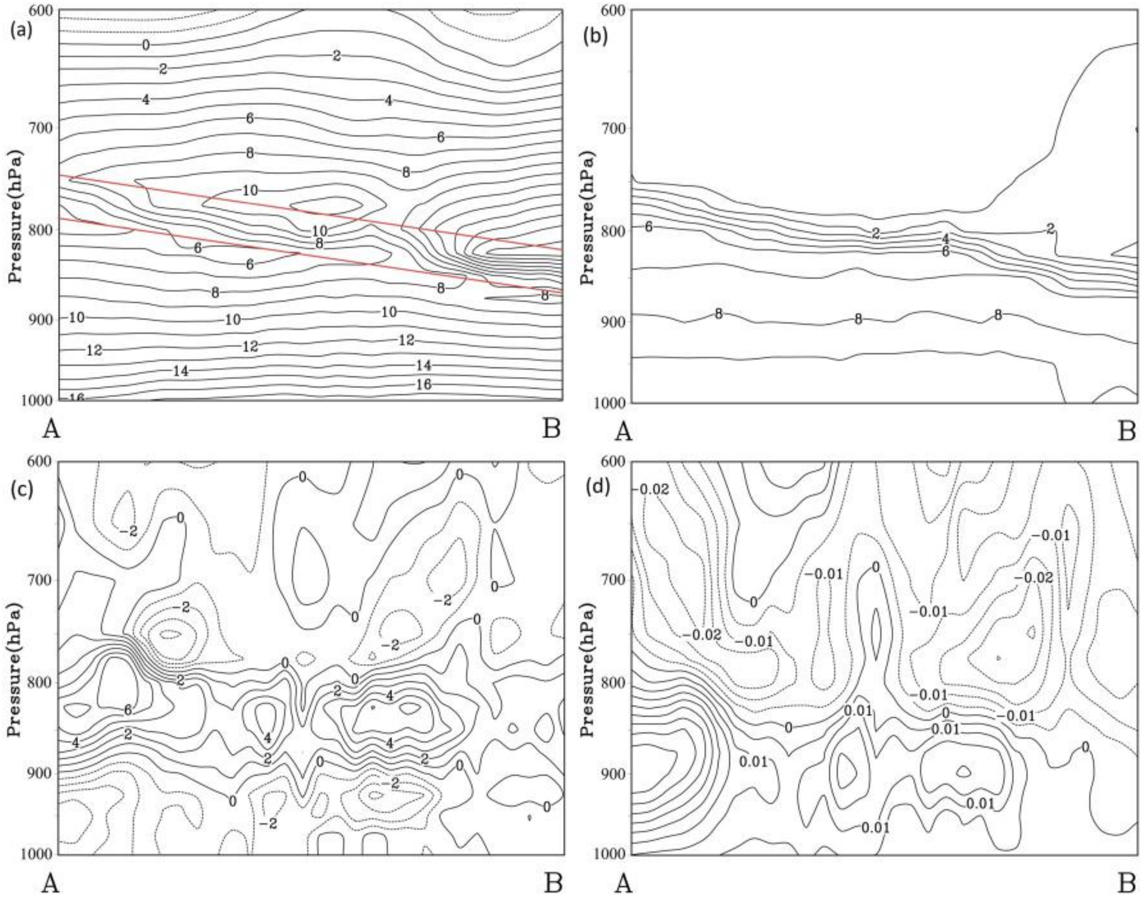

Figure 4. The vertical cross-section analyses of the "Millipede Cloud" occurred at 19:35 UTC 16 July 2017 along the line AB. (a): air temperature (unit: °C), two red lines mark the range of the inversion layer. (b): specific humidity (unit: g/kg). (c): horizontal divergence of wind velocity (unit: 10^{-5}/s). (d): vertical velocity (unit: m/s).

stratocumulus in essence. Further analyses indicated that there was a stronger vertical wind shear between 775 and 800 hPa, and a stronger horizontal gradient of air temperature at 2 m-height, which raised a meaningful topic about the formation mechanism of this kind of clouds that needs further investigation.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All three data used in this paper: (a) NASA's satellite imagery, (b) MODIS Level-2 data, (c) ERA5 reanalysis data from ECMWF (Hersbach et al., 2020) are publicly available.

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References

Bugaev, V. A. (1973). Dynamic climatology in the light of satellite information. *Bulletin of the American Meteorological Society*, *54*(5), 394–418. https://doi.org/10.1175/1520-0477-54.5.394

Fritz, S., & Wexler, H. (1960). Cloud pictures from satellite TIROS I. *Monthly Weather Review*, *88*(3), 79–87. https://doi.org/10.1175/1520-0493(1960)088<0079:CPFSTI>2.0.CO;2

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis [Dataset]. Quarterly Journal of the Royal Meteorological Society, *146*, 1999–2049. https://doi.org/10.1002/qj.3803

Houze, R. A. (2014). Chapter 5—Clouds in shallow layers at low, middle, and high levels. *Cloud Dynamics, International Geophysics*, *104*, 101–140. https://doi.org/10.1016/B978-0-12-374266-7.00005-6

Howard, L. (1803). LXIV. On the modifications of clouds, and on the principles of their production, suspension, and destruction; being the substance of an essay read before the Askesian society in the session 1802-3. *Philosophical Magazine*, *16*(64), 344–357. https://doi.org/10.1080/14786440308676358

MWR. (1963). Picture of the month. *Monthly Weather Review*, *91*, 2. https://doi.org/10.1175/1520-0493(1963)091<0002:POTM>2.3.CO;2

Schultz, D. M., & Potter, S. (2022). Monthly weather review at 150 years: Its History, impact, and legacy. *Monthly Weather Review*, *150*(1), 3–57. https://doi.org/10.1175/MWR-D-21-0267.1

Singer, S. F. (1963). Introduction to picture of the month series. *Monthly Weather Review*, *91*, 1. https://doi.org/10.1175/1520-0493(1963)091<0001:ITPOTM>2.3.CO;2

Spänkuch, D., Hellmuth, O., & Görsdorf, U. (2022). What is a cloud? Toward a more precise definition. *Bulletin of the American Meteorological Society*, *103*(8), E1894–E1929. https://doi.org/10.1175/BAMS-D-21-0032.1