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OBSERVATIONAL STUDY OF MESO-β WAVE IN LOW LATITUDES OF SOUTH CHINA SEA OVER THE SUMMER MONSOON

YU Yu-xiao (余欲晓), LIU Zheng-qi (刘正奇)

(*Maritime & hydro-meteorological center of South China Sea Navy Fleet, Zhanjiang, Guangdong* 524001 *China*)

ABSTRACT: The intensive observation data of the Nansha Islands are used to study and discuss the meso-and fine-scale systems existing with large-scale monsoon circulation during the onset of the southwesterly monsoon in the low-latitude areas of the South China Sea. Effects of low-latitude tropical meso-scale gravity waves on weather have been disclosed. The generation and transportation of the local meso-scale gravity wave have been preliminarily studied from the viewpoint of dynamics.

Key words: meso-β scale; geostrophic adjustment; gravity wave

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1 INTRODUCTION

In contrast to previous research on the active and break phases of the South China Sea monsoon, which is addressed mostly from the background of large-scale circulation, discussions of mesoscale weather contained in the regional large-scale monsoon circulation have been little, due to the lack of observed data. The set-up of observation stations on the islands and reefs of the Nansha Islands has made it possible for us to probe into this aspect. The current paper specially gives preliminary discussions on the situation during the monsoon season.

In carrying out the duty of observation, we found that there were wind-speed fluctuations at the cycle of a few hours throughout the southwesterly monsoon and the wind direction obviously turns clockwise if wind speed suddenly increases. The strong wind was accompanied by intense phenomena such as thunderstorms and showers. On the satellite imagery, we can see that there are always convective clusters in the area of extensive clouds, aligning one by one in the size from dozens to hundreds of km. It is then obvious that there are certainly numerous meso-and fine-scale systems in the large-scale, powerful southwesterly monsoon circulation in the low latitudes of the South China Sea. With the observations of the summer of 1990 at Nansha Islands, the current work presents a brief discussion of the mesoscale systems in the monsoon and their synoptic characteristics.

2 COLLECTION OF DATA AND PROCESSING

The data were collected in sites as shown in Fig.1. The collection lasted 121 days from May 23 to September 20, 1990. The figure shows that the four reefs where the sites were located are about 220 km apart from north to south and about 140 km apart from east to west. It is nearly of the mesoscale range. The observation was made once per hour at the Yongshu Reef but on a 3-hourly basis at the other three (Zhubi, Chigua and Huayang). As the 3-hourly records have too

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Biography: YU Yu-xiao (1970 –), male, native from Yiyang County of Hunan Province, engineer, Bachelor of Science, mainly undertaking the safeguarding work of military hydro-meteorology.

long intervals to reflect synoptic processes on scales shorter than them, it is the emphasis of this paper to study the fluctuation of time sequence concerning the data taken at the Yongshu Reef (Measured every hour, winds and precipitation were throughout the day while air temperature, pressure and humidity only for the period from 0500 to 1700).

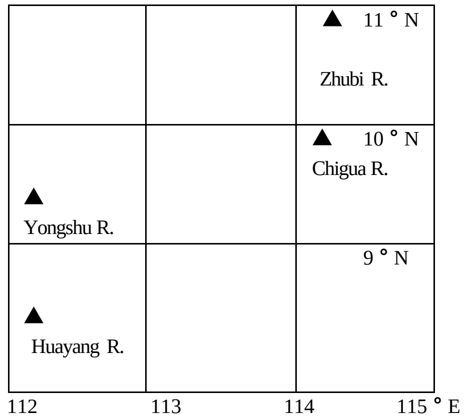


Fig.1 Distribution of data-collecting sites.

To study the mesoscale systems over the enhancement of the southwesterly monsoon, days that had average daily mean winds ≥12 m/s and significant amount of precipitation were made the days of interest. Then, we had 23 days meeting the criterion in the summer half of the year. All elements were graphically expressed on single-station profile by time for wave analysis. Treatment of diurnal variations was added in the case of pressure, humidity and relative humidity[1]. All samples observed from 0500 to 1700 were averaged in terms of individual running hourly differences to determine the diurnal variation of hourly differences. Then, the diurnal variation is subtracted from the observed element values. It is effective to remove the effect of diurnal variation. Such sequences with diurnal variation eliminated are then put through the treatment of running hourly difference to seek a new sequence having the variable of first-order running difference. They are then point-plotted on figures of temporal profile. As a matter of fact, this step of procedure involved the treatment of temperature, pressure and humidity that brought forward their phase by $\pi/2$ as compared to the original sequences. If the diurnal variation of the original sequence is a sinusoidal wave, the first-order hourly difference will be

$$m = A\sin(x - ct)$$

$$\frac{\partial m}{\partial t} = -sA\cos(x - ct)$$

There is difference in phase but that does not affect the result of our study.

3 BASIC FEATURES AND NATURE OF MESO-β WAVE

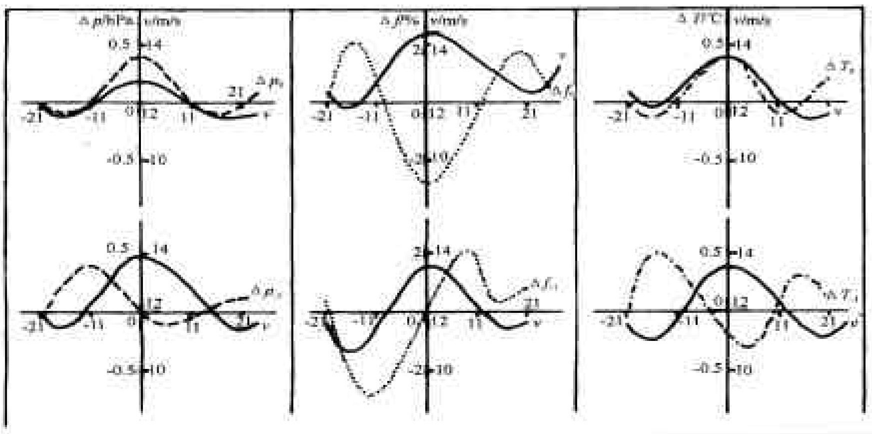
3.1 *Statistical results*

With the time profile chart of wind speed/direction for the 23 days, we find that every 3 ~ 4 hours, 6 hours at most and 1 hour at least, there is a relative peak value. Such perturbation of wind speed amount to 160 over the 23-day period, averaging at 3.5 hours. It agrees well with the periodic characteristics of the meso-β wave. In addition, when the wind increases to the maximum, the direction usually turns clockwise, changing from SW to WSW, W, WNW, NW. Statistically, there is 70.3% of frequency for clockwise turning of wind direction when wind speed ≥ 16 m/s. When the direction is at west, the wind cuts across the isobaric lines by much increased, sometimes perpendicular, angles. When the speed decreases, the direction turns gradually to the southwest. The whole process is just a perturbation cycle in which the nature changes from ageostrophic to geostrophic. For the wave motion of individual elements between 0500 and 1700, pressure is in phase with wind speed by a rate of 48%, 1-h ahead of it by 43%

and 2-h ahead of it by 9%; temperature is in phase with pressure by 38%, 1-h ahead of it by 39% and 2-h ahead of it by 23%; low humidity is in phase with peak wind speed by 33%, 1-h ahead of it by 49% and 2-h ahead of it by 18%.

3.2 *Composite results*

In view of the fact that the phase of the elements of temperature, pressure and humidity are all brought forward by 2 h with a relatively small rate, only the cases of in-phase and 1-h advancement will be discussed here. The objects are the records taken just before and after the time when the wind speed has the peak, which is marked as "0". The composite results are divided to two groups, the in-phase and the 1-h advancement, for these elements. The wind speed associated with individual elements in either group and the elements themselves are averaged. The results, six in all, are plotted in a sheet of coordinates, with the abscissa depicting the time and the ordinate the mean winds and variation of each element, as shown in Fig.2. It is seen that the elements all have a complete sinusoidal wave, which corresponds well with the 3.5-h period of wind speed, though with some difference of phase.



WS perturbation & pressure change WS perturbation & RH change WS perturbation & temp. change

Fig.2 The variation of wave motion of wind speed corresponding to individual elements. The thick, solid line is the wind, the dashed line the air pressure, thin, the dotted line the humidity and the dashed, dotted line the temperature.

3.3 *Large-scale circulation background for the formation of wave*

As indicated in the research results of [2], one of the concrete features of strengthened summer monsoon in East Asia is the formation of the southwesterly gale in the waters of the South China Sea. The monsoon is driven by three mechanisms. The first mechanism is the increased cold high in the Southern Hemisphere, which enhances the cross-equatorial airflow near 105°E. The second is the tropical cyclone active on the ITCZ in the Northern Hemisphere. The third is the strengthened easterly jet in the upper level of the troposphere. From the low-level (850 hPa) horizontal flow field, we know that there is an obvious closed circulation over the Australian continent during the onset of the cold austral high so that the northern southeasterly jet extends to 105°E ~ 110°E and beyond to cross the equator, changing into a southwesterly flow. It explains the first case. For the second case, there are two cyclone centers in the western Pacific and northern South China Sea to the northeast of the Philippines and the jet stream is to the south of the cyclones. In the vertical circulation, the first mechanism works first on the meridional circle at 110°E ~ 120°E when the meridional circulation increases till the stage of gale persistence. Then zonal circulation enhances at the zonal circle of 10°N ~ 20°N, i.e. cold air starts the meridional circulation enhancement in which the meridional energy transforms to zonal one to cause the southwesterly gale in the South China Sea. In the second mechanism of onset, the tropical cyclone acts as an intense branch of updraft, which distributes extensively from 110°E to 140°E, and helps strengthen a complete zonal circulation. In turn, the increased equatorial westerly is favorable for the increase of the tropical cyclone, which then enhances the meridional circulation to bring about the onset of the southwesterly gale. For the third case, the South Asia high moves northward and eastward so that the easterly jet to the south keeps increasing in thickness and the strong divergence of the easterly jet sets off the southwesterly gale at the lower levels over the Nansha Islands waters. In the flow field, two other branches of airflow are not negligible, too. One is the monsoon flow over the Indian region that moves eastward. In the former two cases, it often meets the westerly jet extending from the Bay of Bengal over the southern South China Sea. The other branch is the southwesterly flow in the west of the anticyclone over the equator that increases in intensity while the anticyclone strengthens around the Kalimantan to cause the southwesterly to increase in the western part. Over the 23-day period of interest, the three onset mechanisms are found in 20 days, leaving the remaining three without the cross-equatorial flow. In the flow field, however, the Indian monsoon transports eastward in company in each of the 23 days.

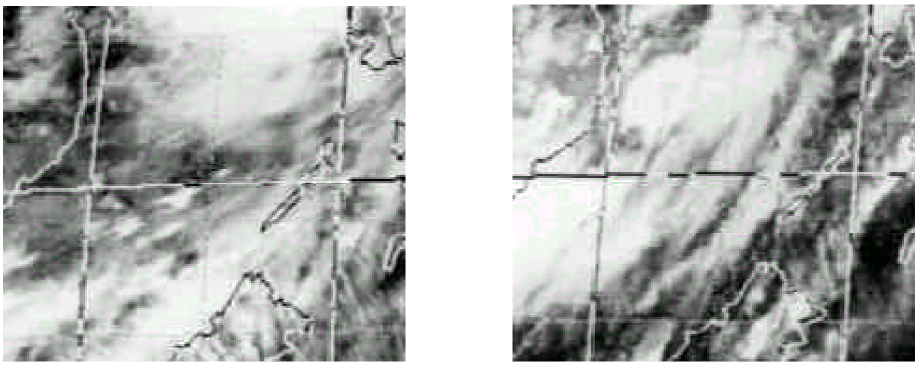
3.4 *The nature of wave*

On the cloud imagery for the 23 days of interest, extensive cloud regions are recognized that stretch southwest-northeast from around the equator to the South China Sea, sometimes with cloud regimes of the tropical cyclone in the northern edge.

On the gale day (when the monsoon is in onset), vast layers of cloud can usually be found over the Yongshu Reef region. There are a few strips of intense convective clouds inside, which usually align in the direction of SW-NE. When the wind speed significantly increases, the cloud zones change to E-W arrays, which is in good consistency with the observed facts stated above. With the cloud imagery examined, we can always find 2 ~ 6 cloud clusters being active in regions at 7°N ~ 12°N, 110°E ~ 115°E on the scales between a few dozens to over two hundreds of km. They can be tropical cloud clusters in the usual sense, or cloud strips imbedded with squall lines and parent bodies containing a series of convection cells. Cloud clusters or strips in a group of two to four take up more than 80% of the total occurrence (Fig.3).

It is apparent that a large-scale southwesterly monsoon system can be home to mesoscale systems in the size of a few dozens to over two hundreds of km.

Following the definition of Atkinson[3], a meso-β scale system is one that covers a horizontal scale of 20 ~ 200 km and temporal scale of 3 ~ 6 h. The statistic results given above generally sum up the basic characteristics of such mesoscale systems, which are also convective. The viewpoint is supported by the fact that sudden increase of wind speed is accompanied by obvious clockwise turning of the wind direction, with the latter intersecting with the isobarometric line by an increasing angle and a geostrophic equilibrium is regained after a few hours' geostrophic adjustment. In addition, in the southwesterly flow that is consistently convergent towards the convergence zone becomes divergent at the lower levels due to decreasing convergence caused by the veering of wind direction but changes to convergence from divergence at the upper levels. In the meantime, the ascending motion reduces and changes to descending one, becoming equilibrium (of thermal winds) again with the lapse of a few hours. In this way, the inertial oscillation excited by geostrophic deviation is transporting around in the form of waves, which are the so-called gravity inertial waves, a kind of motion widely existent in the low latitudes of the South China Sea.



a. 08: 00-08-18-1990 b. 14: 00-09-03-1990

Fig.3 Cloud imagery of wind speed increasing over Nansha Islands.

4 DYNAMIC ANALYSIS OF THE GENERATION AND TRANSPORTATION OF MESO-β GRAVITY INERTIAL WAVES IN THE TROPICS

4.1 *Generation of gravity inertial waves*

It is appropriate to define the state of atmosphere of the Nansha Islands, which is situated in vast, low-latitude waters of the South China Sea, as barotropic in the discussion of the triggering mechanism of waves in a large-scale circulation setting. The barotropic primitive equation set is a basis from which derivation can be made that gravity inertial external wave is excited from geostrophic deviation at the initial moment[4]. The wave so excited will attenuate and disappear over time as a result of dispersion of ageostrophic perturbation energy to the whole space. The motion will tend to return to stationary, i.e. geostrophic equilibrium will set up. As the attenuation is caused by dispersion rather than frictional consumption, the dispersion of energy by the gravity inertial wave is the most fundamental physical mechanism in geostrophic adjustment. When ageostrophic deviation occurs, convergence and divergence vary alternatively throughout the entire column with the Corialis force so that the field of pressure and vorticity adapt to each other until the set-up of a new geostrophic equilibrium. The adaptation needs 3 ~ 4 h, as cited by Hopfov, coincides with the periods of wind speed fluctuation observed by us. The gravity inertial external wave normally transports quite fast at 300 m/s, which is near the speed of sound.

For the tropical atmosphere, the motion will tend to be barotropic only when the zonal scale is larger than l_s ($l_s \approx 1.4\sqrt{U/b}$ with U the characteristic zonal velocity and β the change of geostrophic parameter with latitude)[5]. The motion is 3-dimensional and baroclinic rather than barotropic in vortexes and mesoscale systems. As we are dealing with tropical mesoscale systems, thermodynamic energy equations must be used. The Baosineisk's equation can be useful in the study. Neglecting the term of pressure disturbance, the equation is rewritten as

$$\frac{\partial u}{\partial t} - fv = -\frac{\partial p}{\partial x}$$
$$\frac{\partial v}{\partial t} + fu = -\frac{\partial p}{\partial y}$$
$$l\frac{\partial w}{\partial t} - gq = -\frac{\partial p}{\partial z}$$
$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$
$$\frac{\partial q}{\partial t} + wS = 0$$

With the elimination of unknowns and following the definition that the wavelength L ~ 100 km and disturbance thickness H ~ 10 km in the mesoscale gravity inertial internal wave, we know that the velocity of the internal wave is C ~ $10^0 - 10^1$ m/s, i.e. in a range from a few meters to a few dozen meters, which is far smaller than the external wave.

The gravity inertial internal wave is also generated in the ageostrophic motion of air. Because of the converging/diverging flow resulted from it, the air mass in stable stratification oscillates under the effect of gravity and triggers the transportation of the gravity inertial internal wave. The gravity inertial internal wave is also a dispersive wave, which transports the ageostrophic disturbance energy into the whole space so that the fields of pressure, flow and temperature are adjusted among themselves to be at equilibrium constantly.

4.2 *Concrete processes of adaptation*

Whether geostrophic equilibrium can be gained depends on how the gravity inertial wave disperses the energy of disturbance. The dispersing rate of energy depends on the group velocity of the wave on the one hand, and on the initial distribution of disturbance energy, on the other. The larger the disturbance energy distributes over a range and higher its intensity, the longer the energy is dispersed and the geostrophic adaptation takes. Following Ye's results[4], whether geostrophic adaptation is a process in which the wind field changes significantly to adapt to the pressure or the otherwise depends on the horizontal scale of ageostrophic disturbance. When the scale $L \gg L_0$ (L_0 is the radius of deformation), the wind field adapts to the pressure field; when $L \ll L_0$, the pressure field adapts to the wind field.

As for mesoscale systems in the low-latitude areas of the South China Sea, the scale is far less than L_0, which leads to our judgement that the pressure field adapts to the wind field. Let's study the statistical results based on observation described in Section 3.1. As they have been processed with difference, the values are brought forward by $\pi/2$ as compared to the observation. It is therefore reasonable to determine that the case with wind-speed increase before pressure takes up by 48%, the case with in-phase change by 43% and the case with pressure increase before wind speed by 9%. It accounts well for the adapting relationship between the wind field and pressure field in the region — the pressure field adapts to the wind field in most of the situations, followed by largely in-phase adaptation and then by the least situation in which the wind field adapts to the pressure field. Additionally, the case with temperature lagging behind wind field takes up by 38%, the case with in-phase change by 39% and the case with the decrease of relative humidity lagging behind the wind field by 1 h takes up by 33% and the case with in-phase change by 49%. The two cases for temperature and humidity all account for most of the situations, serving as a sound footnote to the conclusions above: It is mainly all other meteorological elements that adapt to the change in wind field in the low latitude areas of the South China Sea. Following the definition that the meso-β spatial scale is within 200 km and the observed duration of adaptation is of in-phase or 1-h in advancement, we can infer that the adaptation speed is from a few dozen to a few hundred meters per second, which agrees well with the velocity of gravity inertial wave. For the meso-and fine-scale disturbances in the region, the wave disperses the disturbance energy spatially, constantly setting up geostrophic equilibrium which is constantly destroyed.

5 EFFECTS OF GRAVITY WAVE ON WEATHER

With the passage of migrating gravity wave, disturbance will be resulted in the surface pressure and wind fields by amplitude varying with the former. Some large-amplitude mesoscale gravity inertial waves are closely linked with the evolution of severe convective weather such as the squall line and severe local thunderstorm. According to the airflow model assumed for the gravity inertial wave in [6], we know that high pressure tends to move towards a converging zone while low pressure is likely to move near a diverging zone with the disturbance transporting in the direction of the flow. If the atmosphere is unstable, the most intense convection will take place in locations where the air parcel has the maximum displacement, i.e. being consistent with the ridge of wave, over the ascending region where there has been the passage of gravity inertial wave and trough. Appearing before the development of convective weather, the gravity inertial wave is playing some kind of triggering role. When it occurs in a region where there is already convective weather, the convection intensity will change periodically. Thunderstorm develops behind the trough of the wave with the strongest convection appearing on the ridge. With the approach of the next trough, however, convection will weaken; when the next ridge comes near, convection will intensify again. Fig.4 is a sketch map based on observations. It shows that strong winds or thunderstorm and cumulonimbus occur by a rate of 70% at the Chigua Reef 3 ~5 hours after the appearance of the same phenomenum at the Yongshu Reef. In other words, in association with the westerly disturbance and eastward transportation of gravity wave at the Yongshu Reef, another peak of the gravity wave is just over the Chigua Reef (Fig.4). From the measurements at the Yongshu Reef, the fluctuation of wind speed has a period of 3.5 h, which excites the gravity wave at the same period. The velocity is about 11 m/s judging from the distance of about 140 km between the Yongshu Reef and Chigua Reef. The result agrees well with the classical velocity of C ~ $10^0 \sim 10^1$ m/s.

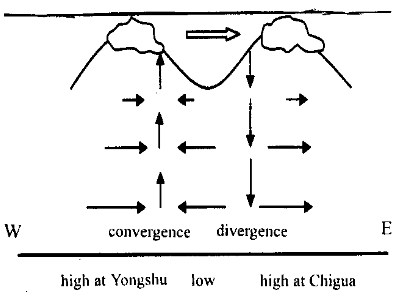


Fig.4 Sketch map of gravitational inertia wave (the rough arrow is the spreading direction).

Examining the 23 days of interest, we have located a number of processes of typical squall line passing over the points of observation, such as sudden increase of wind speed, abrupt change of wind direction, sharp rise of pressure, substantial drop of temperature and strong showers, etc. As there is mesoscale thunderstorm and high pressure after the squall line, pressure rises sharply at the observation station and surface winds are cutting across the isobaric lines to diverge outwards. In other words, the wind direction has an obvious veering, even going vertical to the isobaric line sometimes. The phenomenon occurs when air stays out of high gradient of pressure for extended time. The pressure rise is usually 2 hPa ~ 5 hPa due to high pressure associated with thunderstorm. According to the Bernoulli's equation of

$$\Delta P/\rho = \Delta \frac{V^2}{2}$$

the flow has a velocity between 18 m/s and 28 m/s from high to low pressure[1]. All of these phenomena have been proved by the observation at the Yongshu Reef. When the wind speed increases, the southwesterly changes to westerly or northwesterly with gusts above 18 m/s, 30 m/s at the most. Take the case of June 14 as example. There are seven peak values of strong winds throughout the day with mean period of 3.4 h and direction fluctuation period of about 4 h. Five of the transient strong winds are all westerly. Substantial changes have taken place in other meteorological elements with the change in wind direction/speed. The pressure rises by 3.4 hPa between 0600 and 1000 and temperature drops by 4°C between 0600 and 0800. Cb clouds begin to appear at 0600, heavy precipitation at 0700 ~ 0800 and strong winds at 0820 ~ 0915. The same sequence is repeated at the Chigua Reef, where the pressure maximum occurs at 1100, temperature decreases to 25.3°C, precipitation is continuous and high winds are observed at 1250 ~ 1320. The meteorological elements change by a difference between 3 and 5 hours at the two sites, which are separated by a distance of 140 km. It is a process in which the typical meso-β wave triggers the onset of severe convective weather.

6 CONCLUDING REMARKS

a. With intensive observation of time and space in the waters of the Nansha Islands, we have found that there are always mesoscale convective systems at periods of 3 ~ 4 h and scales of a few dozen to about 200 km against the large scale background when there is onset of southwesterly summer monsoon in the low latitudes of the South China Sea.

b. When these meso-β scale systems pass over an observing station, obvious periodic oscillations are measured in pressure, temperature and relative humidity, sometimes by large amplitude, with the periodic fluctuations in wind speed. It is a feature associated with the passage of tropical squall lines.

c. The development of convection results in abrupt increase of wind force and obvious veering of wind direction and strong ageostrophic periodic disturbance in the wind and pressure fields cause frequent geostrophic adjustment. During the process, the pressure field mainly adapts to the wind field and geostrophic adjustment triggers gravity wave, which in turn causes the development of convective weather.

d. Based on comprehensive analysis of the data and the speed at which the gravity inertial wave disperses the energy of disturbance in the low latitudes of the South China Sea, we determine that it is the internal gravity inertial wave that is playing a significant role. It is also an indication that local baroclinity is still strong at meso-and fine-scales under the large-scale barotropic condition in the tropical atmosphere.

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