The Monitoring and Analysis of Typhoons with Satellite Observations

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Abstract

Several algorithms converting satellite-measured radiance into various typhoon parameters such as rainfall rates, wind speeds, intensity, as well as the location of their center and path, are presented in our analysis of typhoons over the western Pacific Ocean. The main attention is focused on the important improvements and applications of the NOAA MSU and SSM/I microwave data. In addition, the role of some new data and methods are also reviewed.

1. Introduction

With the improvements in the techniques of satellite remote sensing, it can be of great help to us in the monitoring of a typhoon's behavior, especially over the oceans. During the early days, the satellite data were mainly confined to images of clouds that were viewed in the visible and IR regions of polar-orbiting satellites. Currently, geostationary observations can provide hourly scans or even half-hour scans for a quick analysis. In addition, many microwave sensors have been added to significantly enhance the capabilities of typhoon warnings.

Considering the measured radiance and the sensitivity of earlier sensors, the visible and IR cloud images are the most applicable satellite data. Due to the fact that they are incapable of penetrating through cloud layers, the data observed over these regions can only provide cloud and rain-belt patterns and the brightness temperature of cloud-tops. However, the growth and decay of the convective processes of typhoons can be obtained indirectly from such information. In order to retrieve more information under the cloud layers, it is necessary to conduct observations in the microwave regions. Microwave observations have become much more practical over the past decades due to the current improvements in the sensitivity of microwave sensors'.

In this paper, the developments in the history of the monitoring of typhoons are briefly reviewed, especially of its applications where we analyze cases that occur over the western Pacific Ocean.

2. Methods and Data

In the 1960, several algorithms were already proposed in converting satellite data into rainfall rates such as the cloud life-history method (Barrett and Martin, 1981). In most of these methods, the infrared data was the primary data set used, while the visible data was adopted as an auxiliary data set. By using them, severe rainfall events caused by cyclones can be investigated. The satellites utilized were mainly geostationary satellites where it can provide observations in an hourly or half hourly basis. Of course, the most useful application of the visible and infrared GMS data is to keep a close eye on a typhoon's location and pattern. The GMS-5 satellite provides one visible, one water vapor (6.5~7.0 μ m) and two thermal IR (10.5~11.5 and 11.5~12.5 μ m) channels.

However, these data are not enough for a detailed analysis, especially information related to a typhoons' intensity, the determination of the location of eyeless typhoons' and the decay and intensification of relevant environmental parameters, such as the sea surface temperature. Therefore, more satellite sensors, with channels in the microwave region have been designed. In this review, the applications of NOAA MSU and DMSP SSM/I microwave data are mainly discussed. The MSU sensor provides four channels in the 50.3, 53.7, 54.9 and 57.9 GHz with a 110-km spatial resolution in-nadir. The weighting functions of these four channels are related to the heights of the surface, 700, 300 and 90hPa, respectively. In other words, the data can be processed to retrieve the atmospheric temperature/humidity profiles. The SSM/I sensor also provides four passive channels, but in the 19.3, 22.2, 37.0 and 85.0 GHz with two polarizations. Its spatial resolution is 25km, except for the last channel, which is 12.5km.

3. Retrievals

Technically, IR data can be used to delineate the possible areas of rainfall and its intensity. In addition, the high spatial and temporal resolutions of the GMS satellite make it a very useful tool in the monitoring of typhoons. However, information concerning the inside of the cyclone cannot be completely gathered. Aircraft observations conducted by the U.S. Joint Typhoon Warming Center (JTWC) at Guam served as a very important tool in providing additional data. Unfortunately, it is no longer in operation now. To make up for the loss, the radiance pattern of typhoons observed by satellites is even more important.

$$T_B(\bar{\nu}) = \Im_{\bar{\nu}}(\frac{\tau_1}{\mu}\left[\varepsilon_{\bar{\nu}_s} T_S + (1-\varepsilon_{\bar{\nu}_s})\int_0^{\tau_1} T(\tau')\frac{\partial \Im_{\bar{\nu}}^d(\tau_1 - \tau')}{\partial \tau'} d\tau'\right]$$

$$-\int_0^{\tau_1} T(\tau')\frac{\partial \Im_{\bar{\nu}}(\tau'/\mu)}{\partial \tau'} d\tau' \qquad (1)$$

where $\mu = \cos\theta$, and is the viewing angle of the satellite observation, $\Im_{\bar{\nu}}$ is the upwelling transmittance, $\Im_{\bar{\nu}}^d$ is the downwelling transmittance, τ is the optical depth, T_s is the surface temperature, and $\varepsilon_{\bar{\nu}_s}$ is the surface emissivity. As we see from the equation, $\mu=1$, when the satellite is in nadir. If the horizontal axis is designated to be in pressure coordinates, the microwave radiative transfer equation can be rewritten into the following,

$$T_B(\bar{\nu}) = \varepsilon_{\bar{\nu}_S} T_S \Im_{\bar{\nu}_S} + \int_0^P k(\bar{\nu}, P)T(P)\frac{dP}{P} \qquad (2)$$

where $k(\bar{\nu}, P)$ is the temperature weighting function. With the two equations mentioned above, the temperature (fields) of the oceans and the atmosphere can be retrieved. If the static equilibrium assumption is given, the typhoon wind speed, V, can be estimated by the gradient wind equation in terms of the microwave brightness temperature,

$$\frac{V^2}{r} + fV = -ART\frac{\partial T_B}{\partial r} \qquad (3)$$

where r is defined as the distance to the typhoon's center, A is a ratio factor, f is the Coriolis parameter, R is the ideal gas coefficient. Generally, the weighting function at the 850mb level of the MSU data is used to retrieve the wind speed.

However, a better model can be derived by considering the asymmetrical pattern of actual typhoons. The maximum wind speed can also be estimated by the MSU data,

$$V_s(r) = \frac{-fr + \sqrt{f^2r^2 - 4RT_s r\frac{\Delta \ln P_s}{\Delta r}}}{2} \qquad (4)$$

where the suffix s indicates the surface.

Although the MSU's sounding capability can be used to retrieve the temperature profiles at different levels, its poor resolution, either horizontally or vertically, makes it incapable for applications that require high spatial resolutions. Consequently, SSM/I microwave data serves as an alternative for typhoon monitoring. Contrary to the MSU, the SSM/I data can provide information regarding the ocean and the atmosphere at or near the surface of the sea. At the sea surface, various algorithms have been developed in estimating the wind speed, W_S, such as the one by Hollinger (1989),

$$W_s = 147.90 + 1.0969T_{b19V} - 0.4555\,T_{b22V} - 7600T_{b37V} + 0.7860T_{b37H} \qquad (5)$$

where the suffix V and H indicate their polarization directions. Due to the influence of rainfall and different regional environments, a refined retrieval algorithm was given by comparing them with ground station observations,

$$\begin{array}{ll} W_s' = W_s - 2.143 & d37 \geqq 55 \\ W_s' = W_s - 0.268(T_{b85V} - T_{b85H}) & 55 > d37 \geqq 45 \\ W_s' = W_s - 0.817 & 45 > d37 \geqq 35 \\ W_s' = W_s - 0.48(266 - T_{b85H}) & 35 > d37 \end{array} \qquad (6)$$

where W_S is the wind speed estimated by (5), W_S' is the corrected wind speed, d37 is defined as the brightness temperature difference of two polarizations at the 37 GHz channel.

In addition, the sensible heat flux, SHF, and latent heat flux, LHF, over the near-sea surface can both be estimated by derivations proposed by Liu et al. (2001a) from SSM/I data,

$$\begin{array}{l} SHF = -\rho c_p c_h (T_s - T_a) u \\ LHF = -l\rho c_e (q_s - q_a) u \end{array} \qquad (7)$$

units in W/m^2, c_h and c_e is the bulk parameters, c_p is the specific heat ratio, l is the latent heat of evaporation, q is the humidity, u is the wind speed that is 10 m above sea level. The suffix s and a indicates at the surface and 10 meters above the sea surface,respecitively. With the heat flux derived from satellite data, the analysis of the typhoon's energy transformation can be further analyzed.

3. Analysis Results

The first and most important task in analyzing the parameters of a typhoon is to determine the location of their center. Basically, the location can be easily detected for eye-existing typhoons, whenever infrared or microwave data are used. Of course, the former data set, especially the hourly GMS images, is a better choice due to their sharper spatial resolutions. However, in some situations, it is better to employ microwave data, especially for eyeless typhoons. Comparisons of our data with the observations of JTWC, we see that the application of MSU and SSM/I data can be of help in tracking typhoon locations (Fig. 2).

However, for eyeless typhoons their center is generally hard to determine, which explain why we need to have a better understanding of it. In such cases, MSU data has proven to be a piece of useful data in overcoming this problem over the past two decades. Liu et al. (2001b, Fig.1) have demonstrated the application of MSU in the estimation of typhoon intensity and the prediction of its track. They proposed several relationships between a typhoon's parameters and the MSU's brightness temperature. For example, the intensity (maximum wind speed, Vmax) can be estimated by one of these equations,

$$Vmax=1.682 * (\Delta T_{250} * T_{c850})^{0.5} + 0.401 * (\Delta T_{700} * T_{c850})^{0.5} - 1.63 \quad (8)$$

where ΔT_{250} and ΔT_{700} are the 250-mb and 700-mb temperature anomalies, respectively, and T_{c850} is the 850-mb cold-core temperature. In fact, the one variable and two variable modes along with various combinations have been tested in their study. Generally, the root mean square for three typhoons is roughly between 15 to 20 kts, and varies with the changes of the typhoons' intensity.

In addition, the track of a typhoon can be predicted with similar methodology by using the same data set. The following set is an example,

$$y=0.701x+23.182 \quad \text{(cold-core mode)}$$
$$y=0.83x+28.48 \quad \text{(original mode)}$$

where y is the angle relating the orientation of the current typhoon center versus the location 6 hours earlier. x is defined in relating the positions of the cold-core versus the typhoon center in a similar fashion where the typhoon center serves as the intersection point with the vertical lines. Their result showed a correlation of 0.93 and the standard error in the direction angle was at 17.9 degrees. The correlation error and standard error in the directional angle for the original mode were 0.92 and 14.3 degrees, respectively. Overall, the two models both provided a satisfying typhoon track prediction.

Generally speaking, our study results showed that the typhoon track can be accurately determined with the combination of visible, IR and microwave data, even if the typhoon is eyeless when we have a better knowledge of the structure of the warm-core and cold-core (Liu et al., 2001b).

Moreover, satellite observations not only provides applications in location and intensity estimations (Fig.3), but it can also provide additional information regarding the heat flux, mass flux and environmental parameters for further analysis, mainly in conducting forecasting. This is considered the most crucial task for typhoon monitoring even though there are still many unsolved mysteries that need to be looked into. Liu et al. (2001) proposed an objective potential index (OPI), which is calculated from several important ocean-atmosphere parameters (Liu et al., 200c). In their results, the OPI can be used for severe weather monitoring, including heavy rainfalls and typhoons (Fig. 4). However, more studies should be conducted to obtain more accurate forecasts of the typhoon track and intensity evolutions.

4. Conclusion Remarking

So far, the prediction mentioned above is only based upon a statistical relationship. However, the dynamic mechanism of a typhoon track should be taken into account to obtain a more accurate prediction.

For typhoons that lack the structure of an eye, microwave images are still not capable of providing sufficient information for a firm judgment, unless more analysis is conducted, especially on the scattering effects of rainfall and cloud water-form particles whether in the presence of cold-core and warm-core structures. Of course, we understand that a typhoon center cannot be exactly pinpointed, but the more information we have, the better our estimations will be. Hence, extra data, such as the QuickSCAT, SeaWinds, and NOAA AMSU data, is strongly encouraged to be added in the monitoring of typhoons.

As discussed previously, the prediction of a typhoons' track and intensity evolutions is of great importance. With the advent of wide-coverage satellites along with their various capabilities, this goal seems closer and closer despite the fact that there are still many barriers for us to overcome. The next crucial task for us to do is obtaining the knowledge and modeling of the ocean-atmosphere interaction processes.

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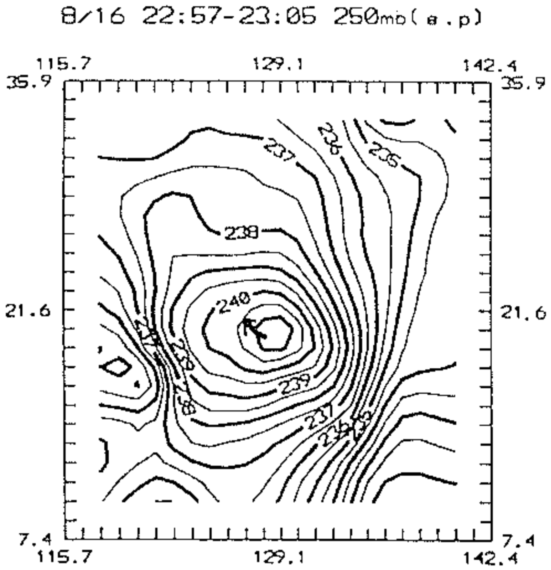

Fig.1 An example of a typhoon pattern delineated by MSU brightness temperature contour at the level of 250mb.

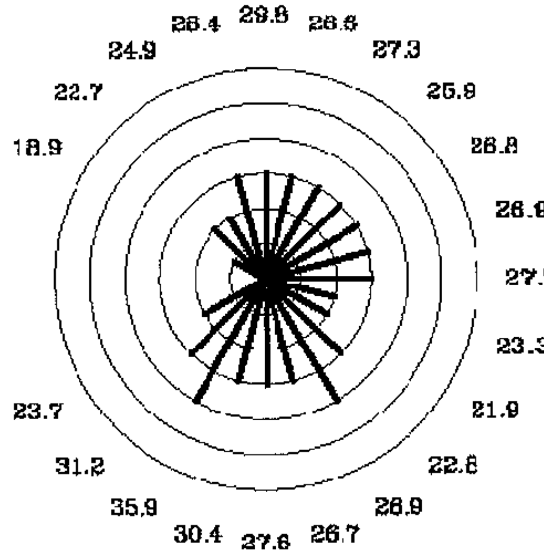

Fig. 3 The wind speed at different radial directions derived from SSM/I data (unit in kts).

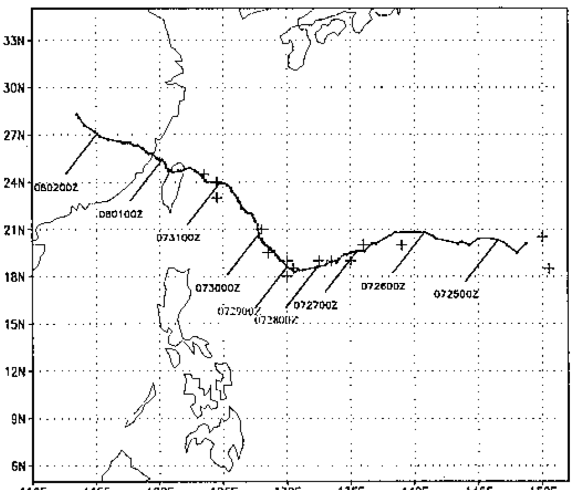

Fig.2 Comparison of the tracks of typhoon Herb derived by MSU observation (+ sign) and JTWC (solid line).

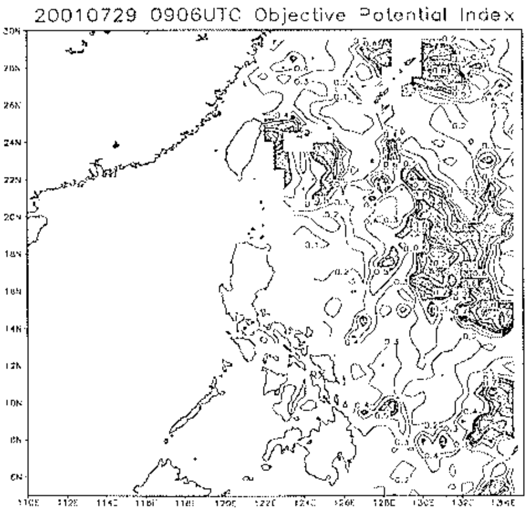

Fig. 4 A map of the objective potential index (OPI) of typhoon Toraji.