SCALE ANALYSIS OF INFRARED WATER VAPOR BRIGHTNESS TEMPERATURES FOR TROPICAL CYCLONE ALL-SKY RADIANCE ASSIMILATION

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Abstract

We analyzed the scale features of satellite infrared (IR) water vapor (WV) brightness temperature observations of tropical cyclones (TCs). This is to characterize the storm information at dominate scales in all-sky radiance assimilation for TC numerical weather prediction. This paper presents the results from the study of Hurricane Patricia (2015). Our study shows that IR WV brightness temperatures have the ability to observe multiscale structures of TCs, ranging from a size of above 1,000 km that covers the entire storm and its surrounding areas to a scale resolving individual convective clouds embedded in the TC. The atmospheric moisture for TC development is mainly represented by large scales covering the storm and surrounding areas while the storm structures are characterized basically by all scales. The large-scale moisture and small-scale convection demonstrate strong correlation and are closely related to the TC development, suggesting the need for all-sky radiance assimilation at multiple scales.

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Key Points

- Satellite brightness temperatures of tropical cyclones were analyzed to characterize the scales that dominate the storm development.
- The moisture for tropical cyclone development is represented by large scales while the storm structures are characterized by all scales.
- The large-scale moisture and small-scale convection look correlated and closely related to the tropical cyclone development.

Abstract

We analyzed the scale features of satellite infrared (IR) water vapor (WV) brightness temperature observations of tropical cyclones (TCs). This is to characterize the storm information at dominate scales in all-sky radiance assimilation for TC numerical weather prediction. This paper presents the results from the study of Hurricane Patricia (2015). Our study shows that IR WV brightness temperatures have the ability to observe multiscale structures of TCs, ranging from a size of above 1,000 km that covers the entire storm and its surrounding areas to a scale resolving individual convective clouds embedded in the TC. The atmospheric moisture for TC development is mainly represented by large scales covering the storm and surrounding areas while the storm structures are characterized basically by all scales. The large-scale moisture and small-scale convection demonstrate strong correlation and are closely related to the TC development, suggesting the need for all-sky radiance assimilation at multiple scales.

Plain Language Summary

Scale analyses of infrared water vapor brightness temperature observations of tropical cyclones from geostationary satellites show that the moisture (and hence

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the moist energy) available for tropical cyclone development is mainly represented by the large scales that cover both the region near the tropical cyclone and the surrounding areas. The tropical cyclone structures, however, are characterized basically by all scales from the entire tropical cyclone to individual convection embedded in the tropical cyclone inner core and outer rainbands. The large-scale moisture and small-scale convection are also strongly correlated, and are closely related to the tropical cyclone development during the storm lifetime. These findings indicate the need to assimilate the brightness temperature at multiple scales covering the complete spectrum of the tropical cyclone features; ranging from larger scales covering the entire storm and surrounding areas, to scales that resolves structure of the tropical cyclone eye, eyewall, and embedded convection.

Keywords:

1. Remote sensing.
2. Tropical cyclone.
3. Satellite infrared water vapor brightness temperatures.
4. Scale analysis.
5. Multiscale data assimilation.

1. Introduction

In recent years, assimilation of cloud-affected radiances from satellite observations into numerical weather prediction (NWP) models has becoming a research and development priority at most operational NWP centers and within the research communities (Geer et al., 2018). Combined with clear-sky radiance assimilation techniques developed decades ago (Derber and Wu, 1998), the assimilation of radiances affected by clouds and precipitation gives a global all-sky approach for assimilating satellite observations and for a variety of weather conditions. Although the data assimilation techniques and the satellite radiance data used in many reported studies vary (McNally, 2009; Bauer et al., 2010; Geer et al., 2010; Okamoto, 2017; Zhang et al., 2018; Minamide and Zhang, 2018; Honda et al., 2018a, 2018b; Otkin, 2012; Otkin and Potthast, 2019; Zhang et al., 2016, 2019), the primary objective of the research is the same; to improve cloud and storm forecasts by assimilating satellite-observed atmospheric conditions in both cloud-covered and clear-sky regions into a global or regional NWP model. Due to the sparsity of surface-based observations, the assimilation of cloud- and precipitation-affected radiances becomes particularly important for improving the weather forecast over oceans. This is especially true for tropical cyclone (TC) forecasts.

Geostationary satellites provide global data coverage over tropical and subtropical oceans, where TCs develop, with frequent data availability and high spatial resolution. Some of the aforementioned studies have reported successful use of infrared (IR) water vapor (WV) radiances from geostationary satellites in all-sky radiance assimilation for TC forecasts. A good example is the ensemble Kalman filter (EnKF) all-sky radiance assimilation system developed by Penn State University (PSU). Their studies focused on assimilating high-resolution IR WV radiances into the model's TC inner core region to improve TC eyewall structures in the model initial state. Significant improvements in TC initialization and the subsequent forecasts have been achieved through the high-resolution all-sky radiance assimilation (Zhang et al., 2018; Minamide and Zhang, 2018; Zhang et al., 2019). However, an interesting question remains unaddressed; will assimilating all-sky IR WV radiances within the entire model TC and surrounding environment, as opposed to just the TC inner core region, provide greater improvement for the TC development in the model forecasts? As the entire TC occupies a much larger area than just the inner core region, different data resolutions may be needed for the inner core region, the outer rainbands, and the surrounding areas. So the research question then shifts to one concerning multiscale data assimilation for TCs. Multiscale data assimilation is becoming more important today since global models at major NWP centers are moving toward higher resolutions sufficient to resolve individual convective storms, such as those embedded in the TC eyewalls, while still capturing the large-scale environment very well. We anticipate these models will eventually replace the current regional TC models with nested grids. These new global models provide favorable platforms for multiscale data assimilation, particularly all-sky radiance assimilation, for TCs.

Needless to say, a TC contains dynamical structures at various scales (Rogers et al., 2012). These dynamical scales and their interactions play an important role in TC development, especially during the TC rapid intensification processes (Rogers et al., 2015). It is not the intention of this study to investigate TC dynamical structures since an all-sky IR WV brightness temperature (T_b) cannot reveal wind fields by itself and hence these observations may not be the right for that purpose. Instead, from a data assimilation perspective, we are more interested in investigating this questions: at what scales we should assimilate the T_b data into the model to achieve the maximum impacts? This will help us optimize assimilation procedures and parameters-such as spectral frequencies (channels), data coverage, data thinning, assimilation time window and frequency-for T_b data. This is also useful in determining the length scales for the initial static or climatological background error covariance for variational or hybrid assimilation methods, and for the localization for ensemble data assimilation algorithms.

At the Naval Research Laboratory (NRL), techniques are under development to assimilate all-sky IR WV radiances from geostationary satellites into Navy NWP models to improve TC forecasts. As a part of this study, we are studying the multiscale features of TC storms observed by IR WV radiances and investigating the possibility to assimilate all-sky radiances at a multiscale approach instead of just convective-scale data assimilation. For this purpose, we collected satellite IR WV radiances for several past major TCs and applied scale analyses to the data. These studies will help us to better understand the scale-dependent features of the satellite radiances, and their relationships with storm structures and development. This in turn will help us improve the assimilation of the data into the model to achieve the optimum data impacts.

In this paper, we present the results from our studies for Hurricane Patricia (2015). We chose Patricia because it was one of the strongest TC storms on records. More importantly, this was the TC case that we had the most complete satellite data covering the entire life cycle of the TC development. In section 2, we analyzes the satellite data we collected and show the spatial scales that carry the dominant atmospheric moist energy for TC development. In section 3, we will discuss the observed scales that reflect the TC storm activities at different stages of TC development. Section 4 gives the interactions between the large and convective scales and their relationship with TC development. Finally, a brief summary of the study is given in section 5.

2. Scale analysis of observed atmospheric moisture

Hurricane Patricia was an East Pacific storm (Kimberlain et al., 2016). It started from a tropical depression at 0600 UTC 20 October, and then became a Category-1 hurricane at around 0100 UTC 22 October. This was followed by rapid intensification at a rate rarely observed in a tropical cyclone, with Patricia becoming a Category-5 hurricane around 24-hrs later at 0000 UTC 23 October. Patricia reached peak intensity at about 1200 UTC 23 October, with a maximum surface wind of greater than 185 kt and a minimum sea level pressure (SLP) of around 872 hPa. Patricia subsequently made landfall around 2300 UTC 23 October, and weakened rapidly, and dissipated at about 1800 UTC 24 October.

Hourly T_b observations from GOES-13 Imager WV channel (CH-3, 6.48 µm) were collected for Hurricane Patricia from 0600 UTC 20 to 1200 UTC 24 October 2015 covering the entire storm development from TC generation, through the rapid intensification period to a strong Category-5 hurricane, and finally to a dissipated storm after landfall. Figures 1 shows the images of T_b observations of Patricia at (a) 0600 UTC 20, (b) 1800 UTC 21, (c) 1200 UTC 23, and (d) 1200 UTC 24, corresponding to the times when the TC was a tropical depression, a tropical storm, a strong Cateogory-5 hurricane, and a dissipated TC after landfall, respectively. To focus on Hurricane Patricia and the surrounding environment, the data was centered on the storm at all times with data cut-off radius of approximately 900 km.

To take advantage of the symmetric features of the TC for this particular case, and to simplify the data analysis procedures, we selected the T_b data along the latitude line that goes through the storm center (referred to the storm center line hereafter). This data processing was done for all the hourly T_b data. Figure 2 shows the T_b values along the storm center lines corresponding to the storm images in Fig. 1. The T_b structures of Hurricane Patricia at different scales are well displayed (Fig. 2) for all storm stages. The fine structures of the TC at maximum strength are fully resolved and readily apparent in Fig. 2c, with colder T_b in the hurricane eyewall (near 900 km) and warmer T_b inside the eyewall.

A Fourier analysis was conducted for the T_b data along each of the storm center lines in Fig. 2 to compute the amplitudes of the harmonics (A_n) for selected wavelengths, $_n$. Since the IR WV T_b is related to atmospheric water vapor, it is reasonable to assume that the amplitudes of the harmonics (A_n, where n=1, 2… is the harmonic number) can, to some extent, represent the moist energy of the atmosphere inside and surrounding the storm. The moist energy is part of atmospheric moist static energy that is defined as (Yano and Ambaum, 2017)

$$E_{\mathrm{sw}} = C_p T + \Phi \ + L_w q_v \ (1)$$

where C_p is air heat capacity, T is the atmospheric temperature, Φ is geopotential height, L_w is the latent heat of condensation of water vapor to liquid water, and q_v is water vapor mixing ratio. The third term on the right hand side of (1) is the moist energy, one of the main energy sources for storm development in tropics. The distributions of A_n at selected $_n$ are given in Fig. 3 for the same four TC stages in Fig. 1. The largest harmonic amplitudes from the Fourier analysis are A_1 with $_1$ =1799 km and A_2 with $_2$=900 km, indicating that atmospheric moisture for TC development is mainly contained at large scales (Fig. 3). These two scales approximately represent the TC plus surrounding areas ($_1$) and about half of the size ($_2$) of the TC with its surrounding environment. The remaining scales contribute to less than 30 percent of the total moist energy. The maximum harmonic amplitude A_1 corresponds to the time when the TC reaches maximum strength (Fig 3c), which is consistent with the storm becoming more symmetric as it intensifies. Based on these results, we can conclude that to appropriately assimilate moisture information into the model, we should assimilate T_b data for a spatial area that covers both the entire storm and its surrounding areas. In this way, we can assimilate the majority of the atmospheric moist energy, as represented by the T_b data, into the model initial fields to capture the full storm development and dissipation cycle.

3. Scale analysis of observed storm structures

As seen in Fig. 1, sharp horizontal T_b gradients along the storm edges clearly define the large areas of storms. Also in Fig. 1c where the TC was at its strongest state, the mesoscale and small-scale structures of hurricane eye, eyewall, the inner core, the large outer rain bands, and individual convection embedded inside the storms are clearly seen by the sharp T_b gradients. This is an indication that horizontal gradients in T_b can be used to represent the structures of the TC storm at various scales. From data assimilation point of view, this means that integrating these T_b gradients into the model can be helpful to define the TC structures in the model initial state.

To study the distribution of the T_b gradients as a function of scale, we define T_b horizontal gradient as

$$T_b' = \frac{dT_b}{\mathrm{dx}}, \ (2)$$

where x is distance from left to right along the storm center line. Fourier analysis is then applied to $T_b^{'}$ with $A_n^{'}$ representing the magnitude of harmonics (where n again is the wave number). The $A_n^{'}$ values for the same selected harmonic numbers displayed for $\mathrm{A_n}$ (Fig. 3) and same TC stages are given in Fig. 4. The spectrum for $A_n^{'}$ at all TC stages appears to be much broader than those for $\mathrm{A_n}$, implying that substantial horizontal $\mathrm{T_b}$ gradients can be found basically at all spatial scales. It is also interesting to notice that when the TC was weak (i.e., at the tropical depression and dissipated storm stages), $A_n^{'}$ distributions look relatively flat along the scales (see Fig. 4a). At the time just prior to TC intensification, there are notable increases in $A_n^{'}$ values between =900 km and =69 km (Fig. 4b). When the TC reached the strongest status, $A_n^{'}$ has the largest value at $_{\mathrm{max}}$=~50km (Fig. 4c). It is interesting to note that the TC inner core size (radius) during the TC peak time was estimated at 20~25 km (Stern et al., 2020), which is about 0.5 $_{\mathrm{max}}$. It looks that the large value of $A_n^{'}$ at $_{\mathrm{max}}$ was related to the strong convective TC inner core at this time. The broad spectrums of $A_n^{'}$ in Fig. 4 may suggest the need for assimilation of TC storm structures at multiple scales.

4. Synergy between the large-scale moisture and small-scale convection and their relationship with TC development

To get a clearer picture of the evolution of the observed large-scale moisture and small-scale storm structures during the entire storm development, we calculated hourly $\mathrm{A_n}$ and $A_n^{'}$ over the whole period from 0000 UTC 21 to 1200 UTC 24 October 2015. The $\mathrm{A_n}$ values for scales $_{\mathrm{n}}>$ 500 km are then averaged for each hour to obtain the average hourly large-scale moisture amplitude, denoted by A. Similarly, the average hourly amplitudes of small-scale storm structures values were computed for scales $_{\mathrm{n}} <$ 50 km, and are denoted by $A^{'}$.

The hourly A and $A^{'}$ are given in Figs. 5a and 5b. To match these numbers with the TC development, the National Hurricane Center (NHC) Best Track minimum sea level pressure (SLP) data for Hurricane Patricia over the same time period are also given in 5c. As seen in Fig. 5, the large-scale moisture in the area increased rapidly when the TC began intensifying. The moisture continued to increase until the TC became a category-2 hurricane, and then remained level (until TC landfall) to provide sufficient moist energy in the area for the TC to develop to a strong catogery-5 hurricane. After landfall, the large-scale moisture in the area began to decrease as the TC weakened and then dissipated. The changes in the small-scale storm structures also appear to be related to the TC development, which is consistent with the analysis from Munsell et al. (2021) for hurricanes Harvey, Irma and Maria. It is interesting to note that there are numerous spikes in $A^{'}$ in Fig. 5b. Most of these spikes have a duration of less than 3 hours. Considering that the TC eye and eyewall structures last for much longer than 3 hours, it is likely that these small-scale spikes are primarily due to the convection embedded in the TC system. The convection began to pick up energy at about the same time when the TC started to intensify and the large-scale moisture in the area began to increase. Convection became more active after the TC became a catogery-2 hurricane. Most of the strong convection occurred as the TC became a strong category-5 hurricane. Shortly after that, the convection decreased rapidly, and the TC began to weaken.

The strong correlations among the large-scale moisture, the small-scale storm structures, and the TC development seem to again advocate for the need for multi-scale assimilation of the T_b data into the model. It is especially important to assimilate the changes at dominant scales representing correlations between the large-scale moisture and small-scale storm structures, over the entire TC development to appropriately represent the storm features in the model initial state necessary for TC development in the forecasts. Temporally, the frequency of T_b data needs to be sufficient to resolve convective activities, and the data assimilation window should be long enough to filter out the short-lived spikes (Fig. 5b) while still preserving the overall development and dissipation tendencies in small-scale convection. The EnKF data assimilation system originally developed by PSU and later implemented at NRL uses 1-hour analysis-forecast cycles over a 6-hour data assimilation window. In this respect, this is a suitable system for all-sky WV T_b data assimilation for TC forecasts.

5. Summary

In this study, we examined the IR WV T_b observations of Hurricane Patricia (2015) from geostationary satellites for all-sky radiance assimilation for the storm forecasts. Scale analyses of T_b data shows that the moisture (and hence the moist energy) available for the Patricia development is mainly represented by the large scales that cover the both the region near the TC and the surrounding areas. The storm structures, however, are characterized basically by all scales from the entire TC to individual convection embedded in TC inner core and outer rainbands. The large-scale moisture and small-scale convection look correlated, and are closely related to the TC development during the TC lifetime. These findings may indicate the need to assimilate the T_b data at multiple scales covering the complete spectrum of the TC features; ranging from larger scales covering the entire TC and surrounding areas, to scales that resolves structure of the TC eye, eyewall, and embedded convection. High-resolution T_b assimilation into the TC inner core has shown from previous studies (Minamida & Zhang, 2018; Zhang et al., 2019) to be beneficial in improving TC initialization and subsequent forecasts. But the results from this study suggest that the TC initialization and forecasts could be further improved by including T_b assimilation over a larger domain to the high-resolution inner core T_b resolution.

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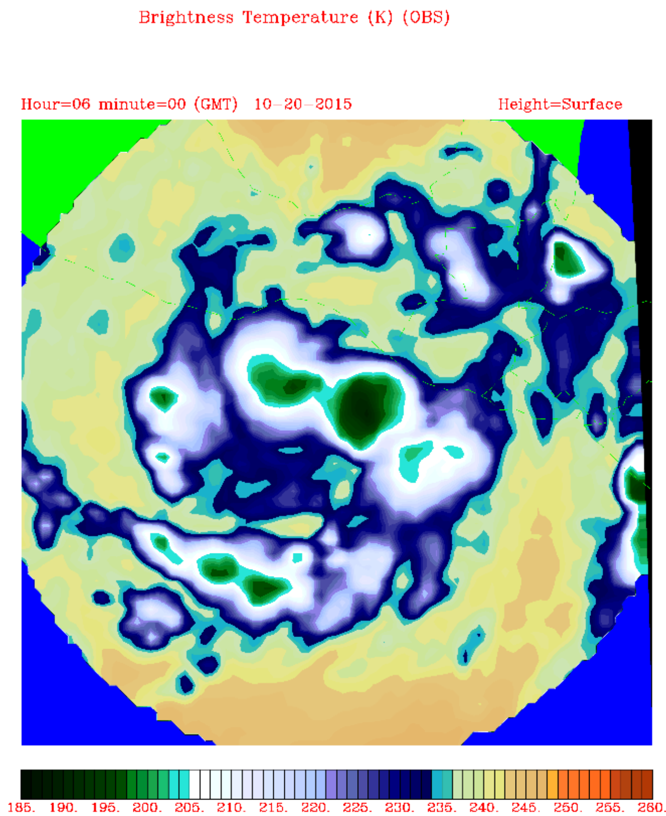
Data Availability Statement

All satellite data used in this paper can be downloaded from the Satellite Data Services (SDS) group GOES Online Geostationary Archive at the University of Wisconsin-Madison Space Science and Engineering Center (SSEC) Website **https://inventory.ssec.wisc.edu/inventory/?date=2013/06/10&time=&satellite=GOES-13&search=1.**

The Hurricane Patricia observational data used in this paper can be found in National Hurricane Center Tropical Cyclone Report, Hurricane Patricia (EP202015), available at **https://www.nhc.noaa.gov/data/tcr/EP202015_Patricia.pdf.**



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Supporting Information for “SCALE ANALYSIS OF INFRARED WATER VAPOR BRIGHTNESS TEMPERATURES FOR TROPICAL CYCLONE ALL-SKY RADIANCE ASSIMILATION”

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Content of this file

1. Figure S1

Introduction This supporting information contains an additional figure that supplements the discussion in the text.

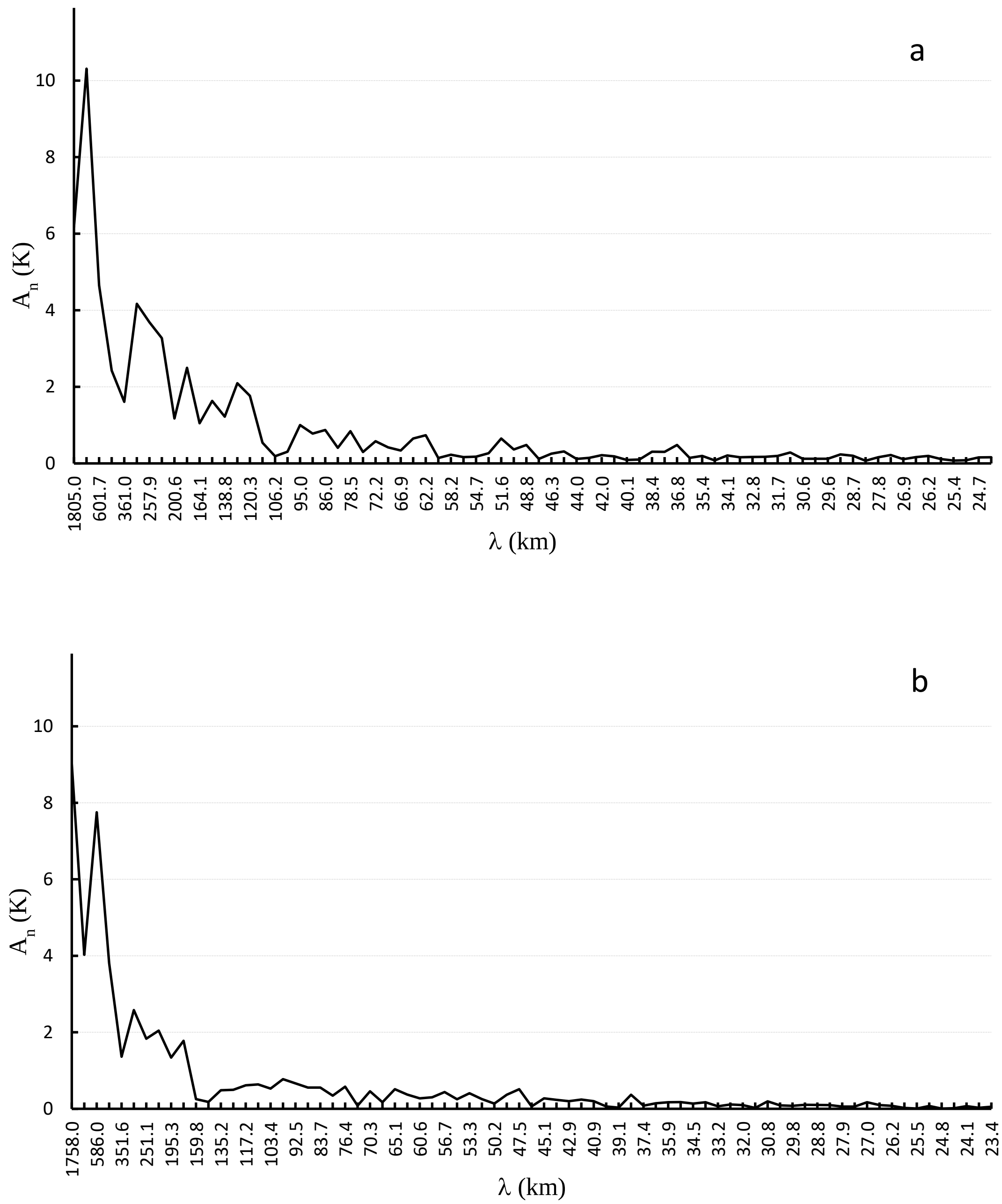

Figure S1. Amplitudes of the harmonics, A_n (K), corresponding to the T_b data along (a) the latitude and (b) the longitude lines through the storm center at 1800 UTC 21 October 2015 when Hurricane Patricia was a tropical storm.