Journal of Atmospheric and Solar-Terrestrial Physics 164 (2017) 192–202

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

# Investigation of Kelvin wave periods during Hai-Tang typhoon using Empirical Mode Decomposition

P. Kishore[a,*], J. Jayalakshmi[b], Pay-Liam Lin[b], Isabella Velicogna[a,c], Tyler C. Sutterley[a], Enrico Ciracì[a], Yara Mohajerani[a], S. Balaji Kumar[b,d]

[a] Department of Earth System Science, University of California, Irvine, CA, 92697, USA
[b] Department of Atmospheric Science, College of Earth Sciences, National Central University, Zhongli City, 32001, Taiwan
[c] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
[d] Taiwan International Graduate Program (TIGP), Earth System Science (ESS) Program, Research Center for Environmental Changes, Academia Sinica, Taipei, Taiwan

A R T I C L E I N F O

*Keywords:*
Typhoon-rainfall
Empirical mode decomposition (EMD)
Kelvin and planetary waves
Winds
Precipitation

A B S T R A C T

Equatorial Kelvin waves (KWs) are fundamental components of the tropical climate system. In this study, we investigate Kelvin waves (KWs) during the Hai-Tang typhoon of 2005 using Empirical Mode Decomposition (EMD) of regional precipitation, zonal and meridional winds. For the analysis, we use daily precipitation datasets from the Global Precipitation Climatology Project (GPCP) and wind datasets from the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-analysis (ERA-Interim). As an additional measurement, we use in-situ precipitation datasets from rain-gauges over the Taiwan region. The maximum accumulated precipitation was approximately 2400 mm during the period July 17–21, 2005 over the southwestern region of Taiwan. The spectral analysis using the wind speed at 950 hPa found in the 2nd, 3rd, and 4th intrinsic mode functions (IMFs) reveals prevailing Kelvin wave periods of ~3 days, ~4–6 days, and ~6–10 days, respectively. From our analysis of precipitation datasets, we found the Kelvin waves oscillated with periods between ~8 and 20 days.

## 1. Introduction

Tropical Cyclones (TC) are the most catastrophic weather phenomenon in Taiwan. While several typhoons occur near and around Taiwan every year, only three or four make landfall in Taiwan. Hai-Tang was a category-5 typhoon with large intensity and coverage, long duration, and intense rainfall. The strong winds and heavy rainfall of these storms often cause catastrophic flooding, mudslides, debris flow, agriculture damage, tremendous loss of property and human lives (Wu and Kuo, 1990; Lee et al., 2006).

The creation of TC involves a tropical perturbation that quickly forms into a warm-centre, cyclonic framework with sustainable winds. The timing of TC formation depends crucially on the evolution of the planetary waves/disturbances (i.e. the observed qualities of tropical summertime synoptic-scale disturbances or ingrained mesoscale convective frameworks in terms of structure and propagation) preceding the formation of individual storm events (Fu et al., 2007). Numerous synoptic-scale patterns have been identified as favorable to tropical cyclogenesis, include but are not limited to: Tropical Upper Tropospheric Troughs (Sadler, 1978), mixed Rossby-gravity waves (Dickinson and Molinari, 2002), and easterly waves (Fu et al., 2007). The generation of a Rossby wave of a TC and the formation of a new clone demonstrated by Li et al. (2003). Planetary waves are global scale atmospheric oscillations with periods of 2–40 days, and originate in the lower troposphere due to large-scale disturbances that are closely coupled with weather systems (Lindzen, 1967). Matsuno (1966) predicted the basic structures of Kelvin waves (KWs), such as, mixed Rossby-gravity waves, east and westward propagating inertia-gravity waves. Kelvin waves are equatorially trapped oscillations, which play a fundamental role in the tropical convective process. Several studies provided observations of Kelvin waves over the Eastern Pacific (Straub and Kiladis, 2002), the Atlantic (Wang and Fu, 2007), Africa (Mounier et al., 2007), the Indian Ocean (Roundy, 2008), and South America (Liebmann et al., 2009). Dunkerton and Baldwin (1995) and Wheeler et al. (2000) both emphasized the existence of these waves with different spectral analysis techniques and filtering methods using satellite and ground-based instruments.

A wavelike disturbance was observed using meridional wind fields and low-level vorticity, and this wave propagates north-westward with a

* Corresponding author.
*E-mail address:* kishore@uci.edu (P. Kishore).

http://dx.doi.org/10.1016/j.jastp.2017.07.025
Received 15 April 2017; Received in revised form 13 July 2017; Accepted 27 July 2017
Available online 1 September 2017

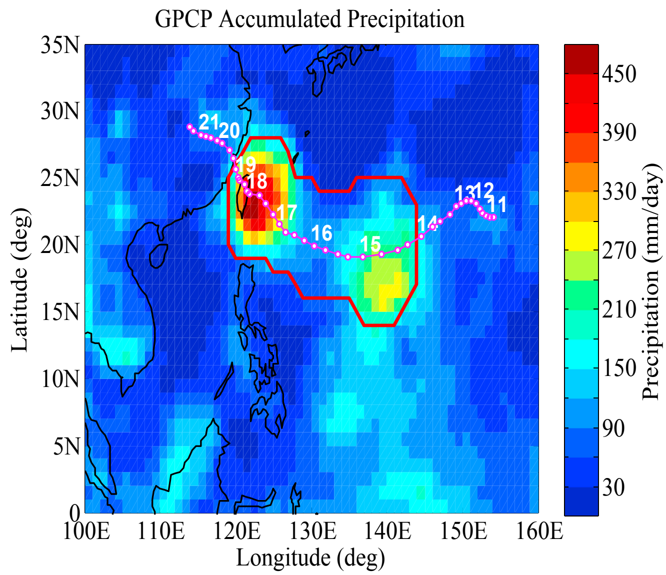


**Fig. 1.** Total accumulated rainfall (10–21 July 2005) of typhoon Hai-Tang along with its best track.

period of 6–10 days (Lau and Lau, 1990). Chang et al. (1996) found TC centers are collocated with the cyclonic vorticity region of the wave train, which suggests a possible role for the wave train with different periods in triggering TC formation. Fu et al. (2007) examined the 34 typhoon cases in Western North Pacific (WNP) occurring in 2000 and 2001, and extracted the planetary wave structures present during the typhoon period with low and high pass filter techniques. They concluded that, TC energy dispersion for six cases, 11 cases for synoptic wave trains, easterly waves for 7 cases, and remaining 10 cases are associated with other synoptic disturbances. Dickinson and Molinari (2002) discovered synoptic waves with periods of 5–10 days, which are initially located near the equator and later tilt northwestward and transition into an off-equatorial disturbance. In all of the above studies, the importance of background wind flow variations is emphasized for producing the growth of synoptic-scale events with a period of oscillations. None of the studies explain the number of embedded frequencies during the passage of typhoon. In this study, we demonstrate the characteristics of planetary waves during the typhoon period using different spectral analysis techniques. In Section 2, we describe the data and methods used in this study. In Section 3, an overview of Hai-Tang TC formation, wind characteristics and results are discussed. Spatial and temporal distribution of planetary waves modes and his characteristics are discussed in Section 4. Section 5 provides conclusions.

## 2. Data and method

### 2.1. GPCP precipitation data

The Global Precipitation Climatology Product (GPCP) is one of the most accurate high-resolution precipitation datasets spatially and temporally. The GPCP data combine satellite and in-situ rainfall data to create quality controlled daily 1° × 1° longitude-latitude gridded precipitation products (Huffman et al., 2001). The one-degree daily (1DD) product uses data from geostationary-satellite IR sensors to compute the threshold-matched precipitation index (TMPI) to estimate precipitation for each grid cell. The multi-satellite estimates are combined with rain gauge data over land by inverse variance weighting (Huffman et al., 1997). The gridded daily data have been validated against land-based rainfall gauges (Rajeevan et al., 2006) and ocean surface buoys (Bowman et al., 2005). In the present study, we use version 1.2 of GPCP precipitation data product for the periods covering June 30th to August 18th, 2005.

In addition to precipitation data, zonal and meridional wind fields from European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-analysis (ERA-Interim) are utilized (Dee et al., 2011). The datasets are available four times daily (0, 6, 12, and 18 h) at several spatial resolutions and at 37 vertical levels, which range from 1000 to 1 hPa. Some major advances of the ERA-Interim over the past ERA-40 reanalysis are the increase in spatial resolution, the utilization of four-dimension (4D-Var), a new moisture analysis, enhanced model physics, and an enhanced fast radiative exchange model (Simmons et al., 2005; Dee et al., 2011). For our analysis, we retrieved zonal and meridional winds with 1° × 1° resolution at four vertical levels 950, 800, 600 and 500 hPa.

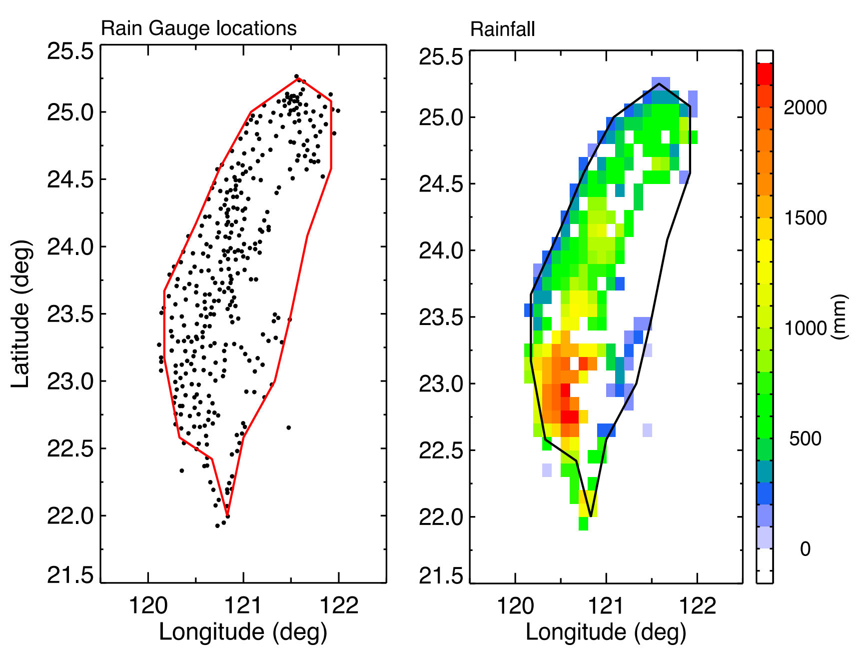


**Fig. 2.** Spatial distributions of typhoon accumulated rainfall for Typhoon Hai-Tang with (a) rain gauge stations and (b) rainfall during 17 July 2005 to 21 July 2005.