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## Diagnosis of tropical cyclone activity through gravity wave energy density in the southwest Indian Ocean

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[1] Tropical cyclone (TC) activity is diagnosed through convective gravity waves (GWs) observed in the upper troposphere (UT)/lower stratosphere (LS) above Tromelin island (15.53°S, 54.31°E) in the tropical southwest Indian Ocean. Monthly and weekly GW total energy densities derived from daily GPS windsonde data are compared with Outgoing Longwave Radiation (OLR) and TC hours in the vicinity of Tromelin. A relationship between GW energy density and TC activity is observed in the LS, for the TC season 2001/2002. Moreover TCs (local convection) produce GWs with total energy density mostly higher (lower) than  $12 \text{ J kg}^{-1}$ . A 10-season climatology (1997/1998–2006/2007) confirms that large values of GW total energy density in the LS are associated with weak values of OLR during the TC passage. Monthly total, kinetic and potential GW energy densities within 2000 km radius of Tromelin can be estimated using linear relationships with TC hours for a threshold of above 6 TC days per month. A linear relationship also exists between weekly GW total energy density in the LS and the activity of intense TCs above a threshold of 2 TC days per week within 1000 km radius of Tromelin. GW energy density in the LS could be used as a possible index to investigate TC activity in the UT/LS. **Citation:** Ibrahim, C., F. Chane-Ming, C. Barthe, and Y. Kuleshov (2010), Diagnosis of tropical cyclone activity through gravity wave energy density in the southwest Indian Ocean, *Geophys. Res. Lett.*, 37, L09807, doi:10.1029/2010GL042938.

### 1. Introduction

[2] Tropical cyclones (TCs) are the most severe meteorological phenomena in the tropical southwest Indian Ocean (SWIO; 30–90°E and 0–40°S). The TC activity in this basin represents 10–12% of the total annual TC activity [Neumann, 1993] with an annual average of 5 TCs [Caroff *et al.*, 2008].

[3] TCs, as convective systems, are identified to be the sources of low frequency convective gravity waves (GWs) in the tropical basins [Chane-Ming *et al.*, 2010]. The GW activity influences the dynamics of the middle atmosphere as well as the general circulation [Fritts and Alexander, 2003].

[4] Previously, Hung and Smith [1978] suggested ray tracing of acoustic GWs from the upper atmosphere as a possible warning for hurricanes. More recent studies based

on observations or numerical simulations have shown the characteristics of GWs, their relationship with TCs, and their possible impact on the environment over some TC basins. For example, Dhaka *et al.* [2003] used a MU radar to observe high frequency GWs in the lower stratosphere due to the passage of the typhoon Orchid near Japan islands. Chun *et al.* [2007] investigated the primary sources of high frequency GWs as convective clouds in rainbands associated with typhoon Rusa near the Korean peninsula.

[5] Using the MM5 model, Kuester *et al.* [2008] gave insight into source mechanisms of GWs from hot tower regions of hurricane Humberto (2001) in the north-west Atlantic. Zonal mean flux of TC induced GWs in the northern hemisphere (NH) was estimated and shown to be a significant contribution in stratospheric forcing during hurricanes seasons. The analysis of convective GWs generated by typhoons Rusa and Ewiniar modeled by the MM5 and WRF models, respectively, also supported the importance of eastward propagating convective GWs in the middle latitudes for positive momentum forcing in the mesosphere in NH summer [Kim *et al.*, 2009].

[6] During TC Hudah landfall in the SWIO, Chane-Ming *et al.* [2002] detected large amounts of inertia GW energy density from vertical GPS windsonde data at Tromelin island. Recently, Chane-Ming *et al.* [2010] revealed a clear correlation between the daily maximum surface wind speed and the total energy density of low frequency GWs produced by intense TCs Dina and Faxai in the upper troposphere (UT)/lower stratosphere (LS). Among others, a positive contribution in total energy density of about 30% in the LS was quantified above Tromelin during intense TC Dina as compared with climatology in austral summer [Chane-Ming *et al.*, 2007].

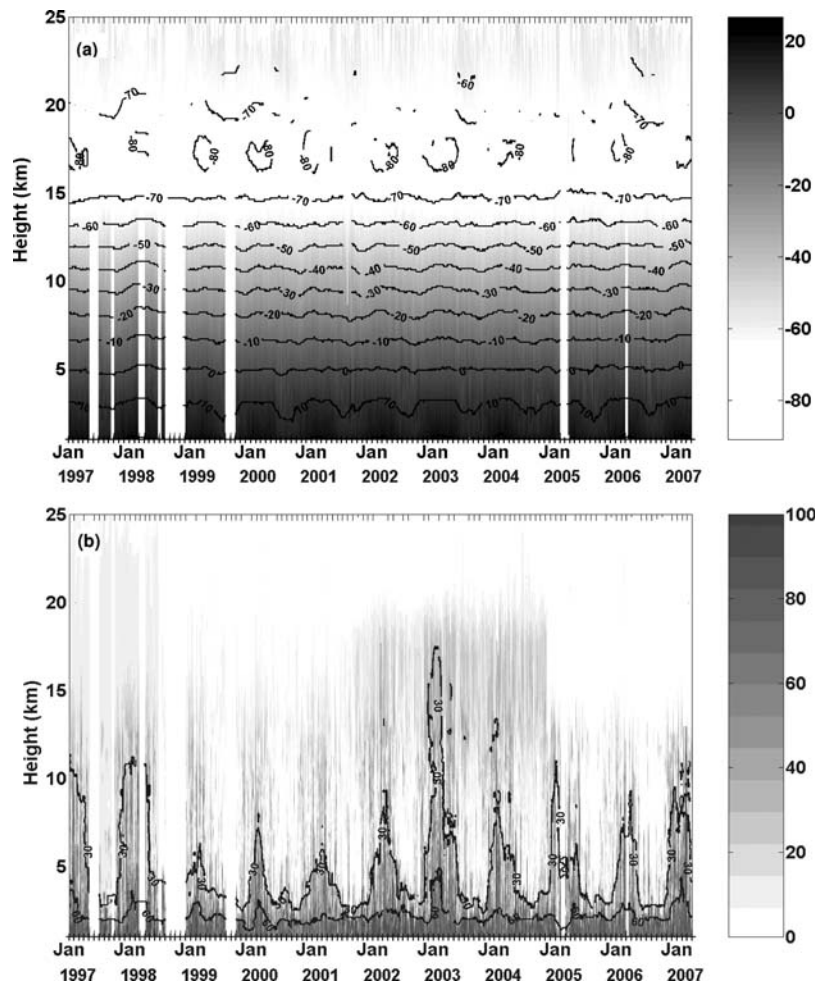
[7] This study aims at diagnosing TC activity through the total energy density of low frequency convective GWs.

### 2. Data and Analysis

[8] A 10-year daily GPS windsonde dataset (1997–2007) is used to determine the GW energy density above Tromelin (15.53°S, 54.31°E). Daily vertical profiles of temperature, horizontal winds and relative humidity with 100-m vertical resolution are available from the surface up to ~25 km heights [Chane-Ming *et al.*, 2002]. Temperature and horizontal wind data accuracies are  $\pm 0.1 \text{ K}$  and  $< 1 \text{ m s}^{-1}$  respectively. More than 75% of daily profiles reached the altitude of 23 km. In this study, a first quality control procedure was applied to raw temperature and wind profiles at heights of 10–15 km (UT) and 19–23 km (LS) for GW analysis to remove erroneous profiles. Temperature profiles were selected using criteria of annual mean temperature and standard deviation  $\pm 3\sigma$  while monthly mean values were

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**Figure 1.** (a) Temperature ( $^{\circ}\text{C}$ ) and (b) relative humidity (%) profiles from January 1997 to March 2007 at Tromelin (quality-controlled data).

used for selecting horizontal winds because of the seasonal and interannual variability. The quality-controlled dataset finally consisted of 1235 and 927 profiles in the UT and the LS, respectively, over 10 TC seasons. Figure 1 shows the temperature and humidity profiles at Tromelin from January 1997 to March 2007. The convective seasonal activity at Tromelin is highlighted with maxima in temperatures near the surface and minima at the tropopause height between February to March. Although possible important biases of radiosonde humidity values exists in the UT, large relative humidity occurs during TC seasons from December to early June with maxima in the LS during El Niño years (1997/1998, 2002/2003 and 2006/2007) and minima during La Niña years (1998/2001) as shown by *Kuleshov et al.* [2009].

[9] The total GW energy density ( $E_t$ ) is calculated as the sum of kinetic ( $E_k$ ) and potential ( $E_p$ ) energy densities from temperature and wind profiles at heights of 10–15 km and 19–23 km [Vincent and Alexander, 2000]. Perturbations are obtained using 2nd and 3rd order polynomial fits for temperature and winds respectively. A second quality control on intensity and time variation of monthly and weekly energy densities is finally performed to produce high-reliable values for climatological purposes. The present study investigates GWs with period 6 h–2.5 days [Chane-Ming et

*al.*, 2002, 2010]. TC parameters such as location and intensity are retrieved from the best track data for the SWIO provided by Météo-France. Developing TC climatologies, it is common to use TC days as a measure of storms' life time [Wu et al., 2008]. In this study, we use TC hours to develop climatology at a finer time scale. They are computed within 2000 km (1000 km) of Tromelin for monthly (weekly) energy densities for tropical disturbances with 10-min sustained surface winds  $>64$  kt. In the SWIO, TC, intense tropical cyclones (ITC) and very intense tropical cyclones (VITC) are defined as attaining 10-min sustained surface winds of [64–89 kt], [90–115 kt], and  $>115$  kt, respectively [World Meteorological Organization, 2006].

[10] Daily and monthly  $2.5^{\circ} \times 2.5^{\circ}$  gridded NOAA/ESRL/PSD OLR datasets [Liebmann and Smith, 1996] were used to identify the convective activity around Tromelin for the area between  $6^{\circ}$ – $24^{\circ}\text{S}$  and  $46^{\circ}$ – $64^{\circ}\text{E}$ .

### 3. Tropical Cyclone Season 2001/2002

[11] The 2001/2002 TC season was reported as the second most active season over the past 30 years in the SWIO with 11 convective tropical disturbances including 4 TCs, 4 ITCs and 1 VITC [Caroff et al., 2008]. A list of TCs which passed near Tromelin (within 1000-km radius) together with their

**Table 1.** Respective Periods of Occurrences of TCs Dina, Guillaume, Hary and Kesiny in the Vicinity of Tromelin and Their Durations<sup>a</sup>

	Period	TC (hours)
Dina (ITC)	01/20/2002–01/24/2002	108
Guillaume (ITC)	02/17/2002–02/21/2002	102
Hary (VITC)	03/07/2002–03/12/2002	114
Kesiny (TC)	05/09/02	6

<sup>a</sup>Within a 1000 km radius of Tromelin. Durations expressed as TC hours.

lifetimes measured by TC hours is presented in Table 1. Successive landfalls of TCs Guillaume, Hary and Kesiny were observed over Madagascar whereas TC Dina passed close to the Mascareignes Archipelago [Roux *et al.*, 2004]. TCs Dina, Guillaume and Hary had a complete and classical evolution in the studied area with stages of intensification and decay, but TC Kesiny had a weak period of activity. A large number of high quality daily windsonde data were also available during the 2001/2002 TC period. Thus the 2001/2002 TC season was selected to illustrate the relationship between the GW energy density and the TC activity.

### 3.1. Energy Densities in the UT/LS

[12] Monthly and weekly total energy density series in the UT/LS during the 2001/2002 TC season are compared with a 10-year climatology (1997/1998–2006/2007) of monthly total energy density during the TC seasons (Figure 2). This updated climatology is consistent with that previously presented in *Chane-Ming et al.* [2007] from 1998 to 2003 above Tromelin with minima (maxima) in the UT (LS) during the convective season in austral summer. Monthly energy densities during the 2001/2002 TC season are larger than climatological values from January to April in the LS when TCs and other convective events occurred (Figure 2a). During this TC season, an increase of GW activity in the LS is associated with a decrease in the UT. Four peaks of weekly total energy density in the LS are associated with passage of TCs Dina, Guillaume, Hary and Kesiny in the studied area (Figure 2a). The opposite is observed in the UT: GW energy densities mostly increase before or after the passage of TCs (not shown). Signature of the VITC Hary is observed in GW energy density both in the UT and the LS (Figure 2), similar to that as reported on VITC Faxai [Chane-Ming *et al.*, 2010]. The daily OLR values indicate that the three other peaks of GW energy are linked to the local convective activity without TCs (hereafter called “local convection”).

[13] In conclusion, variations of weekly and monthly total energy densities show evidence of strong GW activity during active periods of convection and especially during TCs in the LS for the 2001/2002 TC season, and the relative contribution of TC-induced GWs during convective austral summer above Tromelin.

### 3.2. Relationship Between GW Variability and TC Activity

[14] Two types of GWs can be distinguished: those associated with TCs and those induced by local convection. Figure 2c shows the weekly OLR as a function of the weekly total energy density in the LS for the 2001/2002 TC season. Total energy densities  $<12 \text{ J kg}^{-1}$  are mostly linked to GWs produced by local convection while large  $E_t$  values

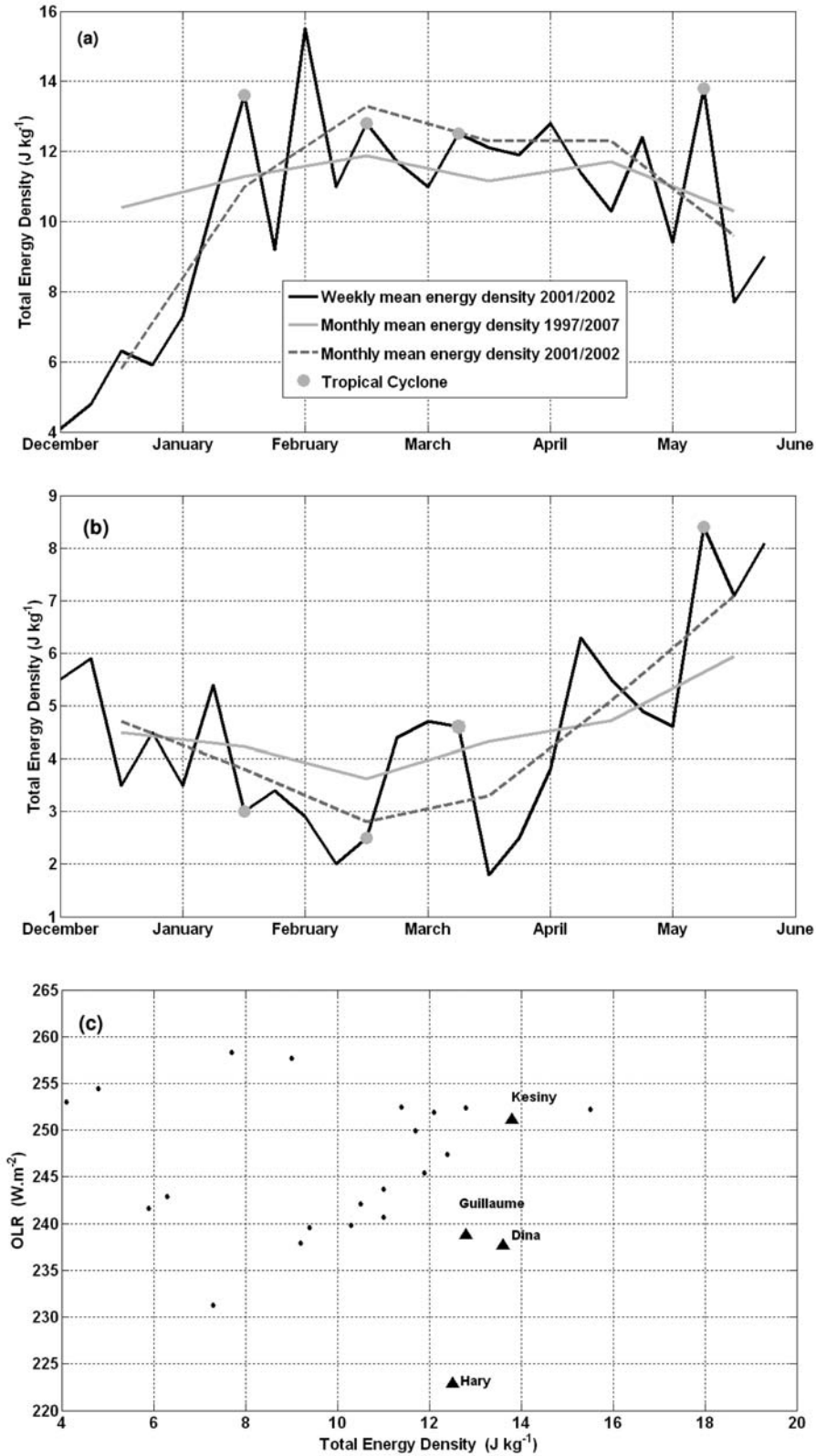
( $>12 \text{ J kg}^{-1}$ ) and very low OLR values ( $<240 \text{ W m}^{-2}$ ) are observed during ITCs and VITC. For similar magnitudes of OLR, GW energy densities associated with TCs are larger than those produced by local convection (Figure 2c). In addition, weekly total energy density is 5% to 25% larger than climatological values for TCs Dina, Hary and Guillaume. During the 2001/2002 TC season, GW total energy density peaks in the LS at the passage of TCs and weak values of OLR are associated with strong values of  $E_t$ . Conversely, weak values of OLR are associated with weak values of total energy density for TCs in the UT (not shown). This agrees with the increase of total energy density before or after the passage of TCs. Thus the results confirm a link between the GW variability and the TC activity for the 2001/2002 TC season especially in the LS. In the following section, only the total energy density in the LS is examined for the climatology.

## 4. A Climatological Study of 10 TC Seasons (1997/1998–2006/2007)

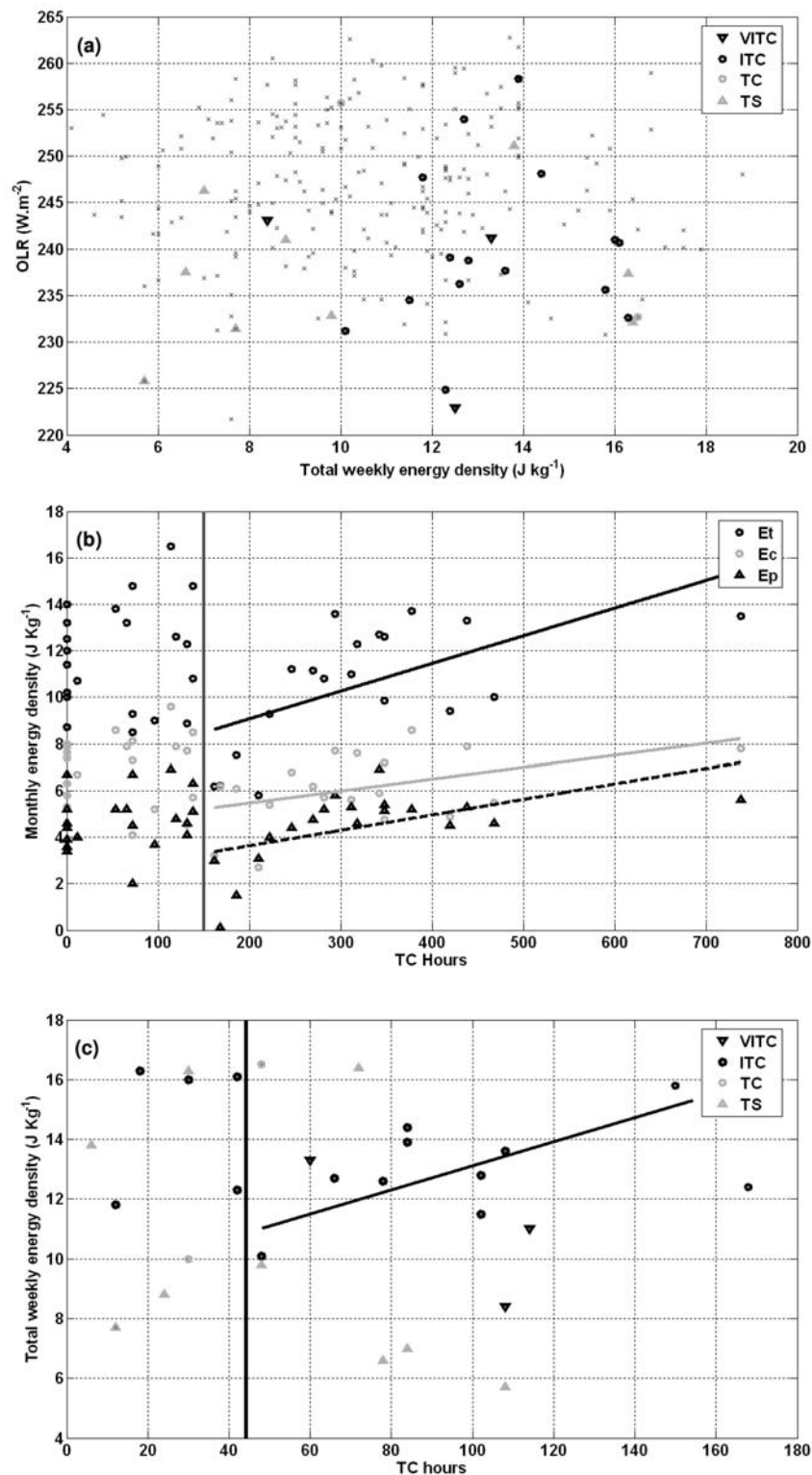
[15] The method used for the 2001/2002 TC season is extended to 10 TC seasons (1997/1998–2006/2007). The seasonal variability of convection is examined to determine a threshold for active convection. During warmer months (December to May), mean value of OLR is  $245 \text{ W m}^{-2}$  whereas during cooler months (July to October), OLR mean value is larger ( $253 \text{ W m}^{-2}$ ). Subsequently, the convection will be hereafter considered very active below a climatological threshold of  $251 \text{ W m}^{-2}$ . From Figure 3a, stronger values of  $E_t$  and weaker values of OLR ( $12 \text{ J kg}^{-1}$  and  $247 \text{ W m}^{-2}$ , respectively) are observed to be associated with TCs, in opposition to the local convection ( $10.5 \text{ J kg}^{-1}$  and  $257 \text{ W m}^{-2}$ , respectively). The mean  $E_t$  produced by TCs is larger than that produced by local convection, especially for ITCs. No trend is clearly observed for tropical storms (TS). Figure 3b displays the monthly GW total energy density as a function of TC hours, in the area of 2000 km around Tromelin, for the period 1997/1998–2006/2007. Above a threshold of 150 TC hours per month, the evolution of monthly total energy density as a function of TC hours can be estimated by a linear regression disregarding the TC intensity. This relationship also exists for both monthly kinetic and potential energy densities. At a smaller time-scale, weekly total energy density as a function of TC hours is examined in within 1000 km radius of Tromelin (Figure 3c). Above a threshold of 45 hours per week, a linear increase of  $E_t$  with TC hours for ITCs is also observed in the LS. At such time and spatial scales, the small number of TCs and VITCs poses limitations on the study on the relationship with GW density. Conversely, in the UT, the TS and TC distributions are displaced toward low values of  $E_t$  and OLR (not shown) which is in agreement with the observation of weak (strong) GW activity mostly observed during (before and after) TC events (see section 3).

## 5. Summary and Conclusion

[16] In this study, the first climatology of low-frequency convective GWs over SWIO has been developed and linked to TC activity. Monthly and weekly GW energy densities derived from GPS windsonde data in the UT/LS were examined using OLR and TC best track datasets to diagnose



**Figure 2.** Total energy density ( $\text{J kg}^{-1}$ ) (a) in the LS and (b) in the UT from 1 December 2001 to May 2002, and (c) weekly OLR ( $\text{W m}^{-2}$ ) within a 1000-km radius of Tromelin vs. weekly total energy density in the LS for the 001/2002 cyclone season. In Figures 2a and 2b, weekly (black curve) and monthly (grey dashed curve) values for the 2001/2002 cyclone season are plotted along with monthly values for the 1997/1998–2006/2007 cyclone seasons (grey curve). Tropical cyclone events are identified with grey dots, (c) dots and triangles correspond to local convection and TCs, respectively.



**Figure 3.** (a) Weekly OLR ( $W m^{-2}$ ) in within 1000-km radius of Tromelin vs. weekly total energy density ( $J kg^{-1}$ ) in the LS for the 1997/1998–2006/2007 cyclone seasons. (b) Monthly and (c) weekly energy density vs. TC hours in within 2000-km and 1000-km radius of Tromelin, respectively, in the LS for the 1997/1998–2006/2007 period. In Figure 3b, the black circles, grey circles and black triangles are associated with the total, kinetic and potential energy densities, respectively, while the black solid, grey solid and black dashed lines represent the regression line between the TC hours and the total, kinetic and potential energy densities, respectively. In Figures 3a and 3c, the black triangles, black circles, grey circles are associated with very intense tropical cyclones, intense tropical cyclones, tropical cyclones, respectively, and the grey triangles are associated with tropical storms. Black vertical lines indicate TC hour thresholds above which a regression line between TC hours and the total energy density is identified.

TC activity in the vicinity of Tromelin island. For the 2001/2002 TC season, a strong GW activity was observed in the LS during active periods of convection and especially during TC events. In addition, values of GW energy density produced by TCs are larger than those produced by local convection.

[17] Investigation on the relationship between TC activity and GW total energy density was extended to 10 TC seasons (1997/1998–2006/2007). Monthly and weekly GW energy density series as a function of TC hours (within 2000 and 1000 km radius of Tromelin, respectively) also confirm increasing GW energy density with the TC activity (intensity and duration). Above a threshold of 150 TC hours (6.7 TC days per month), the monthly total, potential and kinetic energy densities increase linearly with TC hours irrespective to the TC intensity. This study could then be extended to other datasets of high resolution vertical profiles including temperature or horizontal winds only. If TCs are categorized with respect to their intensity, the corresponding  $E_t$  of ITC events (majority of studied cases in the area within 1000 km radius of Tromelin) linearly increases with TC hours above a threshold of 45 hours (2 TC days per week) in the LS. An increase in the number and duration of intense TCs (Saffir-Simpson categories 4 and 5) globally including SWIO over the past 35 years was reported [Webster et al., 2005]. However, detailed examination of the TC best track data over the SWIO suggests that positive trends in the most intense TCs appear to be influenced to some extent by changes in data quality [Kuleshov et al., 2010]. Consequently, independent assessments of TC intensity using alternative indices such as developed in this study are important to reliably evaluate TC intensity and consequently to address a question of detecting possible changes in TC activity as a response to a warmer climate. In conclusion, this climatological study supports previous findings that TCs are important sources of low-frequency convective GWs in the UT/LS and GW energy density is linked to the duration of TCs and the intensity as previously mentioned by Chane-Ming et al. [2010] for two case studies. In addition, several indices were proposed to study TC activity in relation with prediction of TC genesis or for climate change [Camargo et al., 2007; Wu et al., 2008]. For extension, such sophisticated TC indexes in particular those that combine duration and intensity of TCs could be used to improve the study. The GW energy density index might then also be used to investigate TC activity in relation to the multiscale variability of the tropical UT/LS and the possible impact of climate change.

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