RESEARCH ARTICLE

Anomalous wind circulation over Taipei, Taiwan during the northern winter seasons of 2004 and 2005- A case study

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Abstract: This research reports, for the first time, an anomalous wind circulation over Taipei (Latitude 25.030N, Longitude 121.510E), Taiwan during the northern hemisphere winter season (December, January, and February) of years 2004 and 2005. The anomalous wind circulation of meridional winds, which showed southward directions during the winter seasons of 2004 and 2005 instead of northward winds, is noticed from one kilometer altitude range (lower troposphere) and that trend continued till around 20 km altitude range (lower stratosphere). To ascertain whether such a disturbed nature of wind pattern existed over nearby locations to Taipei, we have analyzed radiosonde-measured meridional and zonal winds over four nearby stations station to Taipei including, Roig, Xiamen, Minami and Fuzhou. Surprisingly, no anomalous wind behavior is seen except over Taipei during the northern winter seasons of 2004 and 2005. On the other hand, the European Centre for Medium-Range Weather Forecasts (ECMWF) model-predicted winds do not show any anomalous wind patterns over Taipei and other nearby stations, possibly due to the large averaging of internal variabilities of reanalysis databases. The plausible physical mechanisms of these disturbed meridional wind patterns are not understood at this juncture, but it is believed that local winds and atmospheric pollutants might have created an amicable environment as to provide such a disturbed meridional wind pattern over Taipei, Taiwan in the winter season of 2004 and 2005.

Keywords: Radiosonde-measured winds; ECMWF- re-analysis winds; Evaporation minus Precipitation; Atmospheric pollutants.

1. Introduction

The Earth's atmosphere is characterized by thermally driven zonal Walker circulation along with two meridional circulation cells including the Hadley Cell (HC) and the Ferrel Cell (FC)[1]. Out of these important atmospheric circulations, a few aspects of HC have received paramount attention including, "the expansion and strengthening of HC". This is primarily due to its important role in the climate system since it is closely associated with water vapor, energy and angular momentum transport[2]. The HC is a north and south atmospheric circulating cell with respect to the equator. In the northern hemisphere, it starts rising up to the tropopause and moves towards northern side in the northern hemisphere at around 30^0, beyond that, it usually starts to sink. The earlier studies reported that within the latitude limits of 0^0 N-15^0 N, HC is in the ascending direction (upward) and at 15^0 N-30^0 N, it is in the descending (downward) direction. Then, it moves to the north side in the upper heights and sinks at 30^0 N to reach to south side at lower heights

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towards the equator.

Interestingly, the causes of HC expansion are not yet well understood[3], possibly because of the perplexing and highly dynamical nature of HC. There are a plenty of reports that reject the role of greenhouse gases, stratospheric ozone depletion, troposphere ozone and aerosols, and sea surface temperatures (SSTs) as causes for the expansion of HC[2,4–9]. Further, while discussing the incapable nature of well-known climate models and reanalysis databases, Garfinkel *et al*.[3] put forward the models that are incapable of capturing the magnitude of the observed expansion, perhaps due to missing crucial physical processes or forcings that cause the expansion[10,11].

Databases generated by a few remote sensing instruments (radiosonde, weather balloons and space LIDAR) as well as reanalysis (observations assimilated into, and analyzed by, an atmospheric model) have shown the existence of a more complicated, seasonally varying distribution of HC dominated by a cross-equatorial cell[12–15]. A few previous studies categorically confirmed that HC shows a strengthening characteristic during the northern winter season (December, January, and February)[7,16], although no such features have been observed during only the southern winter season (June, July, and August)[17].

On the other hand, a unique study from the Indian region reports a disturbed nature of HC[18]. By effectively utilizing the Indian Mesosphere-Stratosphere-Troposphere (MST) radar (located at Gadanki, India) derived vertical and horizontal winds, Jagannada Rao *et al*.[18]found an anomalous wind pattern and a disturbed HC pattern over Gadanki during the 1997/98 El Nino period. Using the same radar data along with reanalysis data sets, Roja Raman *et al* (2008)[19]reported the normal and disturbed HC features during active and break phases of the Indian Summer Monsoon (ISM). On similar lines, this present research also reports a disturbed HC pattern over Taipei region by using radiosonde- measured horizontal winds, although other nearby stations (four in number) did not show any such dominant features. For this paper, we have extensively verified various databases including, radiosonde measured winds, the ERA-Interim, and precipitation minus evaporation to ascertain whether the disturbed HC is represented in those parameters or not. This study, therefore, may be considered as an extension of the research work done by[18], but away from a near equatorial Indian station i.e. Gadanki.

The organization of this article is as follows: Section 2 provides the details of databases used and method of analysis in this research. Section 3 will have observational results including, radiosonde-based and reanalysis-based wind observations, both climatologically and season averaged winds. Section 3 includes the possible physical mechanisms responsible for the observed features of HC. The conclusions of this research are summarized in section 4, followed by acknowledgments.

2. Data and method of analysis

Radiosonde measured winds and temperatures, ERA- Interim (European Centre for Medium Weather Forecasts (ECMWF) Re-analysis Interim (a detailed explanation of Re-analysis Interim can be found in[20]) wind data products (zonal, U- component, and meridional winds, v- component) and evaporation minus precipitation data retrieved from the NCAR's Climate and Global Dynamics (https://www2.cgd.ucar.edu/) were analyzed extensively in order to verify the HC features. The radiosonde measured winds over five east-Asian stations were retrieved from the Wyoming University website (http://weather.uwyo.edu/upperair/sounding.html) and the list of stations along with their numbers and geographic coordinates are provided in Table 1. Upper-air measurements from radiosondes (commonly called weather balloons) have long been the primary source of information, with measurements going back more than 60 years and the radiosonde measurements are unique with regard to the length of the available time series as well as with their high vertical resolution[21]. The unique features of radiosondes might have instigated several researchers around the world to make validation studies of various atmospheric parameters (temperatures, winds, and humidity and others) between radiosonde-measured and other remote sensing instruments including, advanced microwave sounding units (AMSU) and the microwave humidity sounders[22], radio occultation (RO) technique performed on COSMIC micro-satellites[23–24], and ground-based wind profiling radars[25].

Station Name	Station Identifier	Station number	Latitude (^{0}N)	Longitude (^{0}E)	MSL (meters)
Roig	ROIG	47918	24.33	124.16	7.0
Xiamen	ZSAM	59134	24.48	118.08	139.0
Taipei	TAIBEI	58968	25.03	121.51	9.0
Minami	ROMD	47945	25.83	131.23	20.0
Fuzhou	ZSFZ	58847	26.08	119.28	85.0

Table 1. List of stations and their coordinates along with other details

It may be worth mentioning here that, in general, radiosonde based winds are measured at irregular height resolutions, ranging from ten to hundred meters. Nevertheless, for the sake of convenience, the wind data were processed to have an even height resolution (200 m) by appropriate interpolation methods. We chose the altitude of 20 km as the upper height limit of our analysis to make sure that most balloons can reach this upper altitude limit. We present both zonal and meridional winds (radiosonde-measured and reanalysis- predicted winds). The schematic diagram of HC is presented in **Figure 1**, wherein red (blue) color lines depict warm (cool) and dry air existence at various places of the meridional circulating cell. It is to be noted that though this schematic shows the geographical locations of HC are exactly located at 30^0 N and 30^0 S latitudes but the observed cell is entirely different and such differences/dynamics are the main research aspects of this present research. The geographical locations of various stations used in this study are provided in **Figure 2** along with their elevations in meters. It is clear from this figure that the central mountain range (CMR) or the Zhongyan Range (or Chungyang Range) of Taiwan is clearly visible with two peaks and the elevations of those peaks are found to be at around 3900 meters.

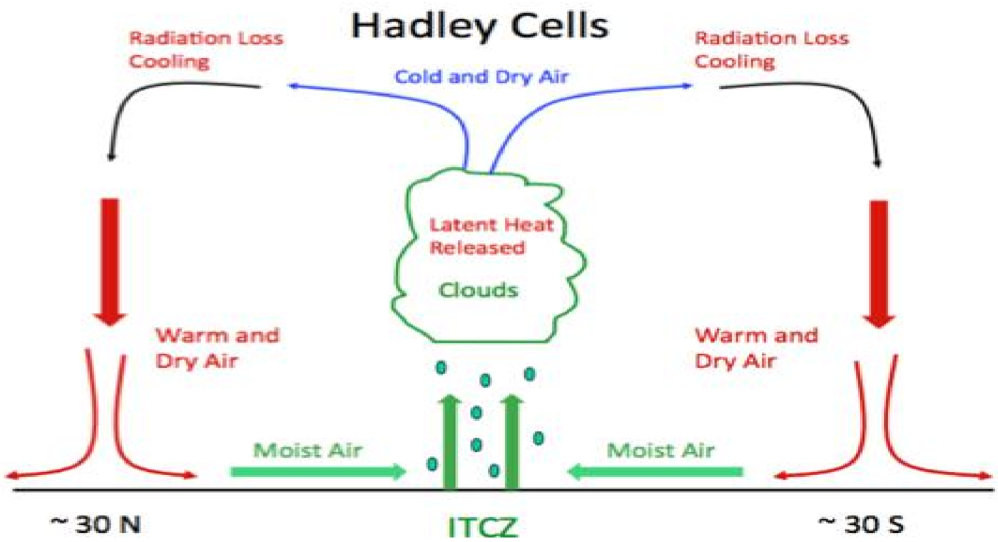

Figure 1. Schamtic shows the dynamics of Hadley cell along with ITCZ.

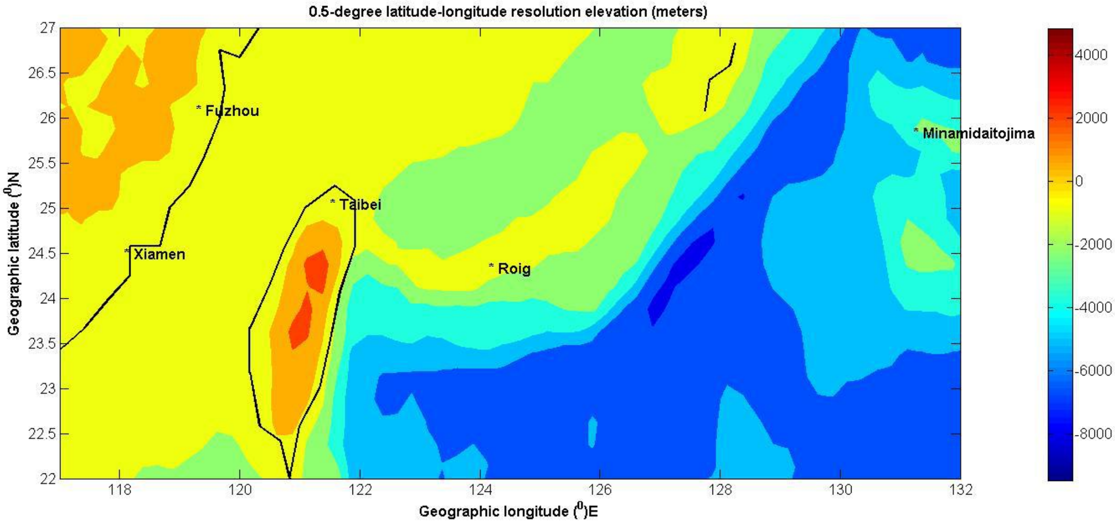

Figure 2. Geographic locations of various stations along with their elevations (in meters) used in this study, over which radiosonde measured winds were collected.

3. Results and discussion

3.1 Radiosonde-based observations at Taipei

Figure 3a shows latitude vs. pressure cross sections of the northern winter (December, January, and February) average (thick red line) as well as monthly average of zonal winds (u-components), with a vertical resolution of 200 m, from winter 2002 to winter 2007, while **Figure 3**b depicts the meridional winds (v-components) over Taipei, Taiwan. It is clear from **Figure 3**a that though the mean zonal wind blows from east to west direction (westward wind) till around 1.2 km altitude from the surface of the ground, it is all the way eastward wind up to 20 km during the winter seasons during 2002-2007. On the other hand, interesting wind dynamics are observed in meridional wind: the meridional wind shows binary peaks (shown with black colored arrows) one at near 3 km and another at around 13 km during most of the years and southward wind is observed during the winter seasons of 2002, 2003, 2006 and 2007 from the surface of the ground to around 1 km. Beyond that, it shows northward wind till 20 km altitude. Further, contrary to the above observations, an interesting wind pattern is seen exclusively during the winter seasons of 2004 and 2005 i.e. a northward wind is present up to around 1 km from the surface of the ground and beyond that it is a southward wind up to 20 km altitude range. This shows the regular wind pattern is highly disturbed over this station, particularly during the northern winter seasons of years including, 2004 and 2005.

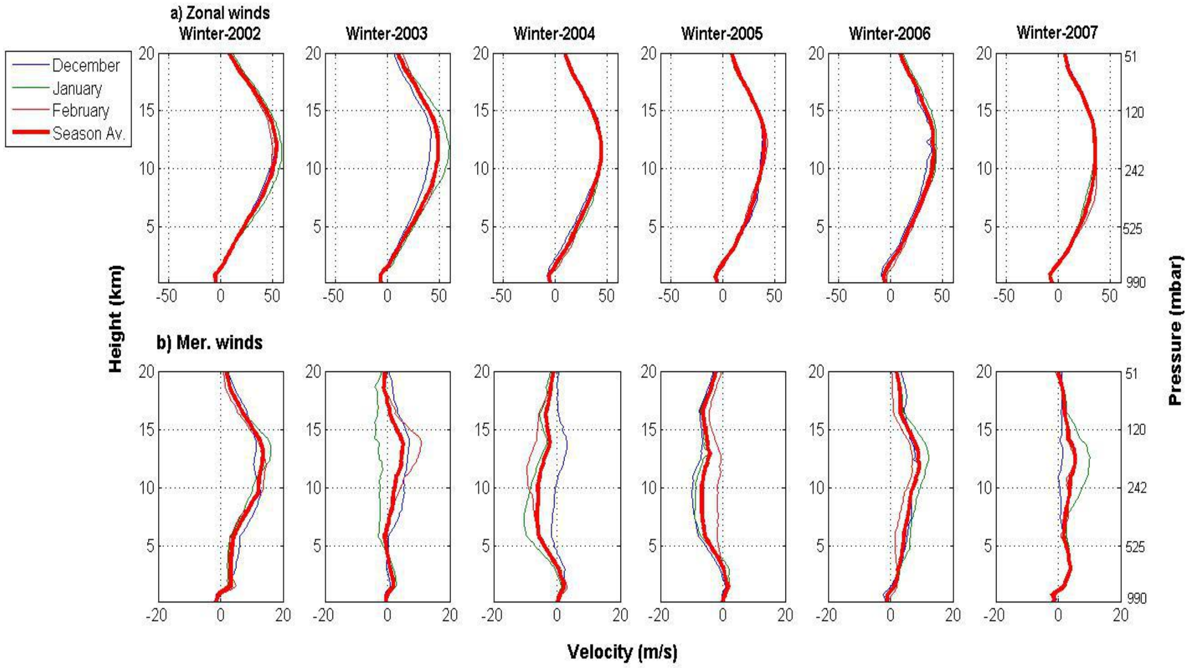

Figure 3. Radiosonde measured winter winds (monthly and season mean) over Taipei including, zonal (upper panels) and meridional (lower panels) components starting from 2002 to 2007.

In order to verify the disturbed features of HC very clearly during the winter seasons of 2004 and 2005, the climatology of zonal and meridional wind starting from 2002 to 2008 is shown in **Figure 4.** A close look at the bottom panels of this Figure 4 reveals a beautiful picture of Hadley cell. At the same time a disturbed HC pattern (shown with an open square box) is clearly seen in meridional winds during the winter seasons of 2004 and 2005. Particularly, during the winter season of the year 2004 a fully disturbed HC can be seen, as the meridional wind shows a southward direction with magnitudes of as low as around 10 m/s. It is, therefore, Hadley cell circulation existed over Taipei station with alternative southerlies and northerlies during winter and other seasons during 2002-2007, with a highly-disturbed HC exclusively during the winter seasons of 2004 and 2005. However, since HC is a global scale phenomenon, single station wind data cannot provide any conclusive clues about the HC upward and downward limbs, which means it is still unclear whether the Taipei station is located in the upward or downward limbs of HC (for instance, see Figure 1 to have a better clarity on the downward and upward limbs of the HC despite an HC pattern existing over Taipei with a disturbed nature during the winter seasons of 2004 and 2005.

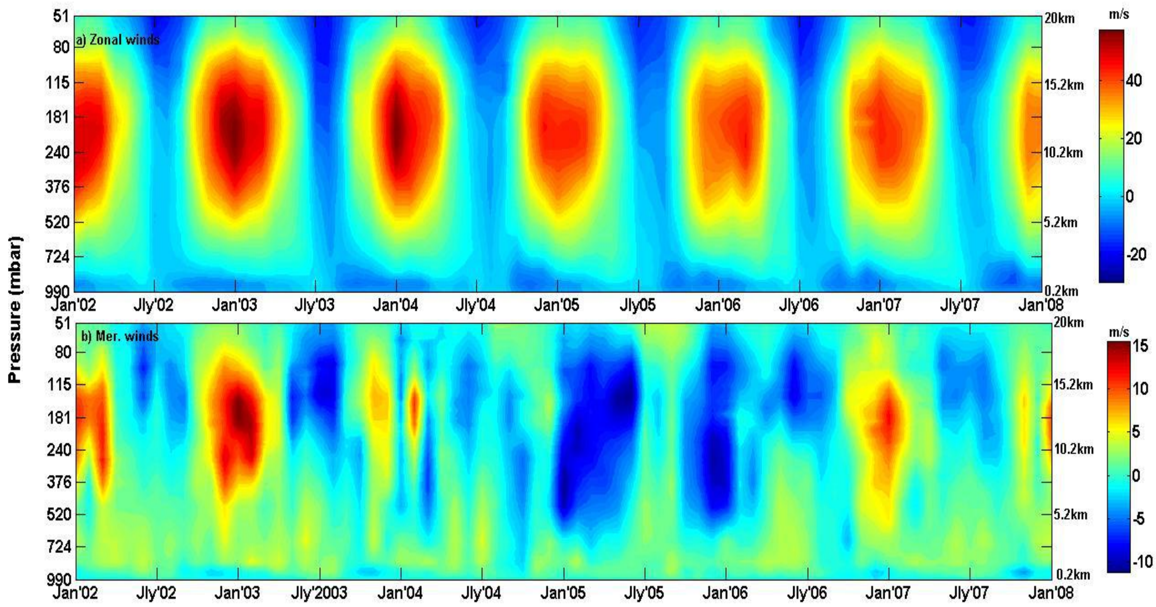

Figure 4. Radiosonde measured mean winds (climatology) over Taipei including, zonal (upper panels) and meridional (lower panels) components during January 2000 and January 2008, in which the meridional winds during the winter season of years 2004 and 2005 are heavily disturbed.

In order to understand the 'latitudinal extent' and multi-dimensional view of HC, we have analyzed various databases and present them here. Since Hadley cell is a 'circulation system', several metrics to reckon its latitudinal extent have been proposed in the literature[26]. Birner *et al.*[26] discussed a more sophisticated circulation-based metric i.e. the mass transport along meridians. This circulation-based metric is defined as follows: Because the Hadley and Ferrel cells circulate air in opposite directions, the edge of each Hadley cell can be defined conveniently as the latitude where the circulation changes from clockwise to counterclockwise. The other proposed methods including outflows away from the equator that would occur near to the tropopause to create an appreciable change in the height of the tropopause at tropical and extra tropical latitudes; other indirect method based on the tropical climate in which the thermal infrared (IR) radiation that reaches to space from the Earth to create a maximum value in the subtropics, the amount of ozone in the atmosphere can also be used to mark edges since less of it resides in the tropics than outside of it, and, finally, one can rely on the precipitation- evaporation (P-E) difference. The difference of P-E or E-P, which represents the boundaries of the water-deficit region[27], can effectively be used to define the HC edges at the northern and the southern hemispheres respectively. Here we have relied on evaporation minus precipitation (E-P) trend to identify the latitudinal edges of HC as can be seen from the **Figure 5**, in which we have plotted average E-P data from 2000 to 2010 (left side panel) and their zonal mean (right side panel). The tropical belt can easily be identified from the right-side panel of **Figure 5**, where the evaporation and precipitation balance each other (shown with closed circles in blue). These respective locations are situated at 36^0 and 40^0 in the northern and southern hemispheres, respectively.

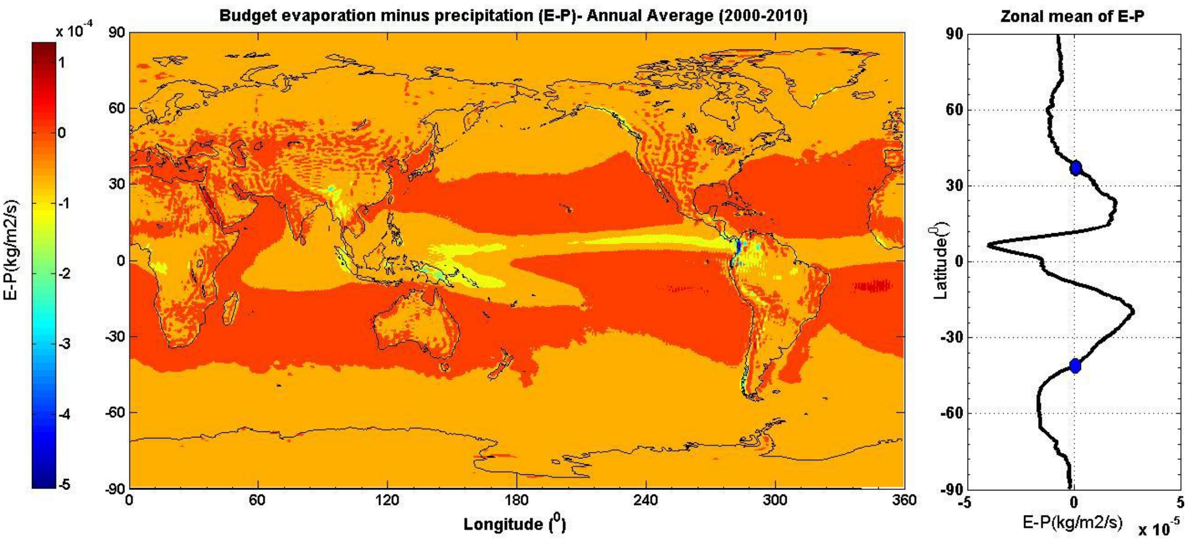

Figure 5. Average evaporation minus precipitation (E-P) trend during 2000-2010 (left side figure). Edges of the tropical belt can be found from the right side panel of the Figure, where evaporation and precipitation balance each other as shown with blue color closed circles.

3.2 Radiosonde winds- Nearby stations to Taipei

As mentioned before, we have gathered radiosonde-measured winds at near-by locations to Taipei in order to verify the existence of disturbed HC features over those locations. The zonal and meridional winds during the winter seasons and the monthly averages of winds between 2002 and 2007 over Roig, Xiamen, Minami, and Fuzhou are shown in Figures 6, 7, 8 and 9 respectively. It is to be noted that the selection of nearby stations to Taipei is done randomly and merely based on the availability of radiosonde measurements as provided by the Wyoming University website. A close look at these figures reveals that meridional winds over Roig and Minami stations exhibit lower level northerlies and upper-level southerlies which resemble a complete Hadley circulation while remaining stations show southerlies from lower to upper troposphere.

It is clear from Figures 3, 4, 6, 7, 8, and 9 that the Taipei station winds show different zonal and meridional winds compared to other locations. Meridional winds observed over Taipei show binary peaks one near 3 km and another around 13 km altitude range clearly in 2007, 2008, 2009 and 2010, and, further, wind strength at 13 km is nearly 5 m/s, whereas at other stations it is around 8-12 m/s. As discussed earlier, during the winter seasons of 2004 and 2005 meridional wind has totally reversed at this station. In general, the lower peak is seen in zonal winds, but it is seen in the meridional wind as witnessed from the present study. Further, it has been demonstrated that a strong Hadley Cell contributes to a strong zonal mean wind[28]. We believe that these trends are definitely interesting ones though the exact physical possible driving mechanisms of these are not known to us at this juncture.

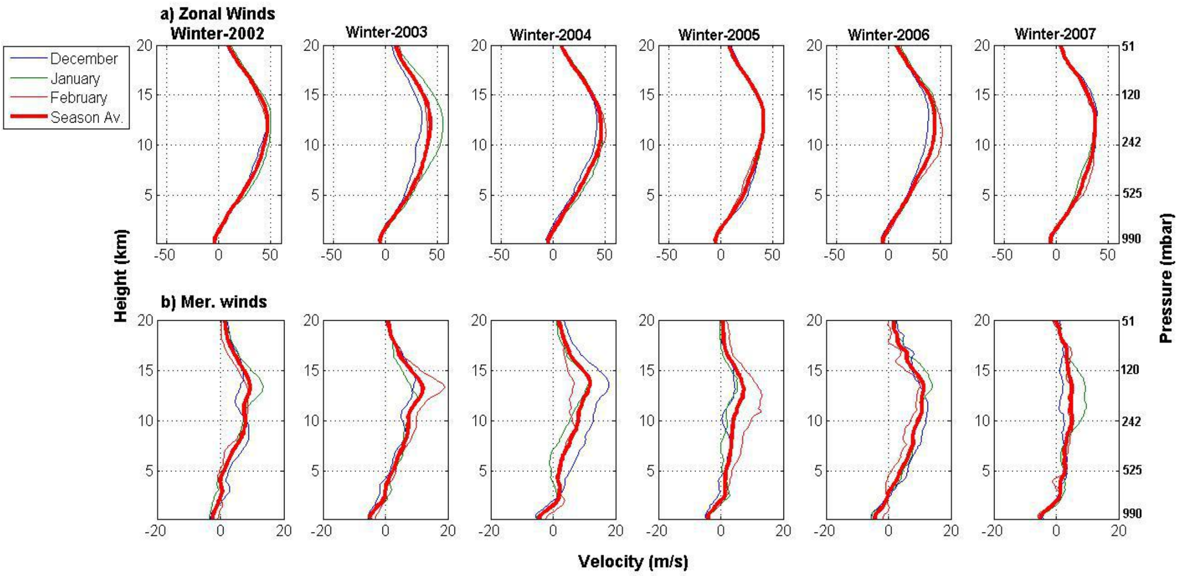

Figure 6. Same as Figure 3, but over Roig (24.33^0 N, 124.16^0 E).

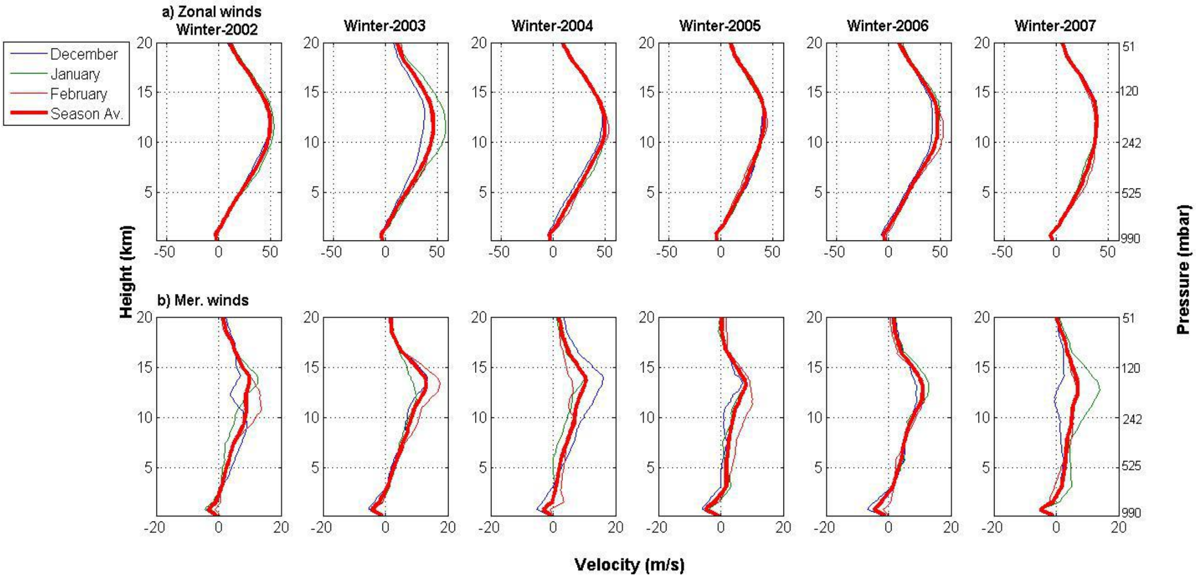

Figure 7. Same as Figure 3, but over Xiamen (24.48^0 N, 118.08^0 E)

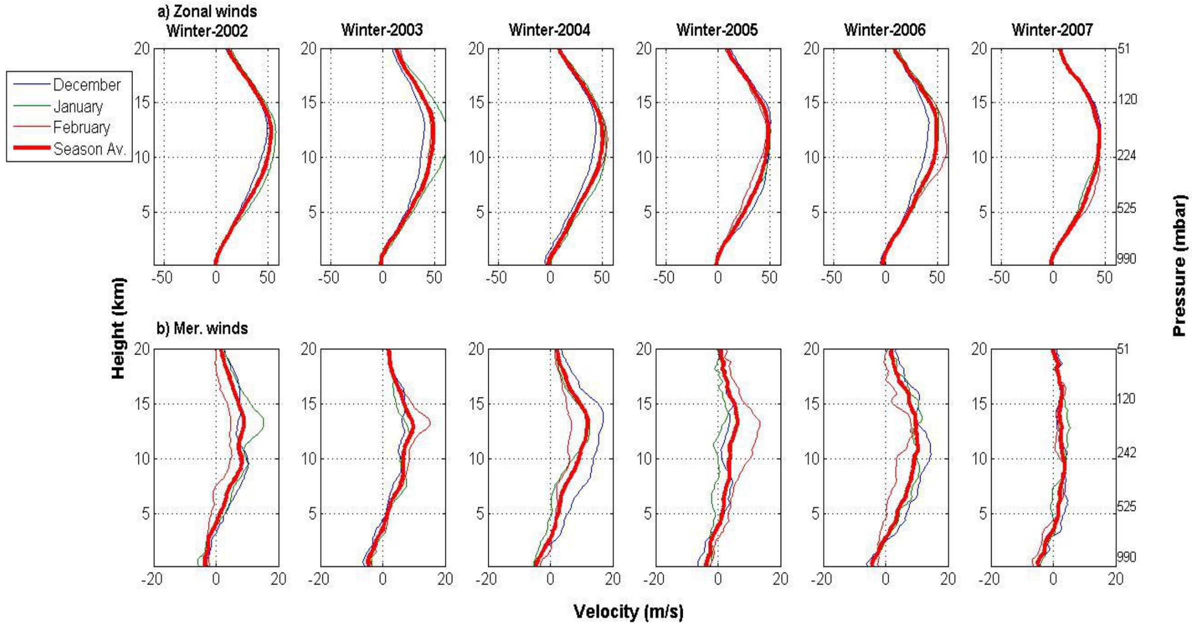

Figure 8. Same as Figure 3, but over Minami (25.83^0 N, 131.23^0 E)

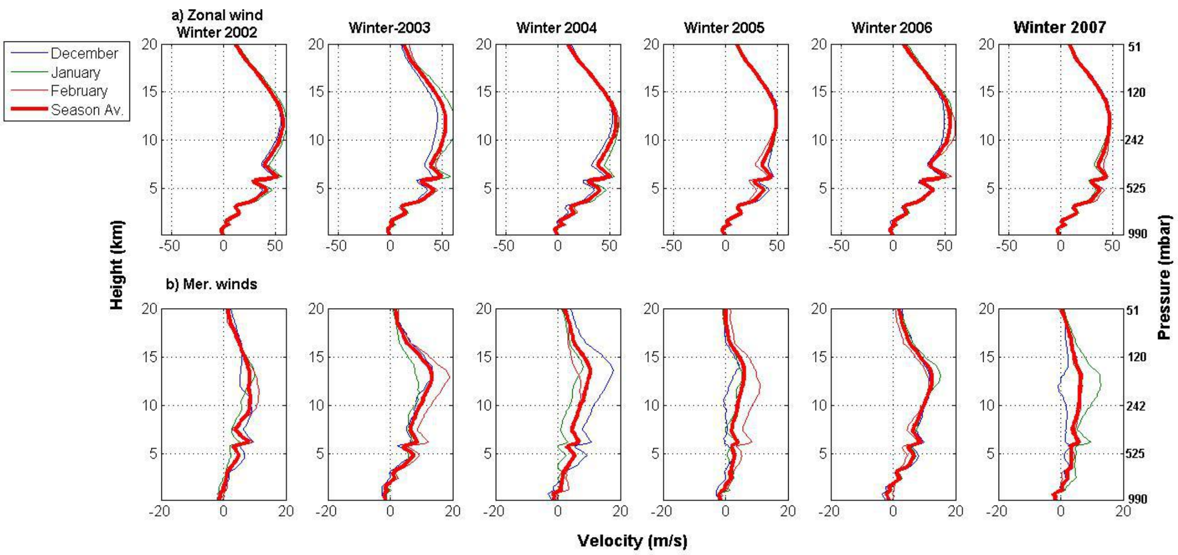

Figure 9. Same as Figure 3, but over Fuzou (26.08^0 N, 119.28^0 E)

3.3 Reanalysis winds

As mentioned earlier, in order to verify the disturbed features of HC over Taipei, this work also uses the ECMWF Re-Analysis (ERA-Interim) derived horizontal and vertical winds at Taipei and other near-by locations. Simmons *et al*.[29] and Simmons *et al*.[30] and Uppala *et al*.[31] have demonstrated the important ERA-Interim improvements over the 40-yr ECMWF Re-Analysis (ERA-40) in many areas, including the representation of the hydrological cycle and the strength of the Brewer–Dobson circulation, which have been identified as two special difficulties in ERA-40[32]. The ERA-Interim data are available since 1979 at 0.125^0 x 0.125^0latitude-longitude grids with more (37) pressure levels than the ERA-40 and 15-yr ECMWF Re-analysis data sets.

Figure 10 depicts the ECMWF derived winds over Taipei (Taiwan), wherein Figures 10(a), 10 (b) and 10 (c) show zonal, meridional and the vertical components between January 2000 and January 2008. Surprisingly no disturbed features are noticed in horizontal (zonal and meridional components) and vertical components. Vertical wind shows downward movement at low altitudes which indicate HC is on the downward limb. Furthermore, contrary to radiosonde-measured trends, the northern winter seasons of 2004 and 2005 did not show any disturbing features.

Similar is the case with the ECMWF-interim derived horizontal and vertical winds over other nearby locations to the Taipei including, Roig, Xiamen, Minami, and Fuzhou (not shown here). As concerns are raised by various researchers, the absence of disturbed HC features and other features is mostly due to the large averaging of internal variabilities of reanalysis databases[3].

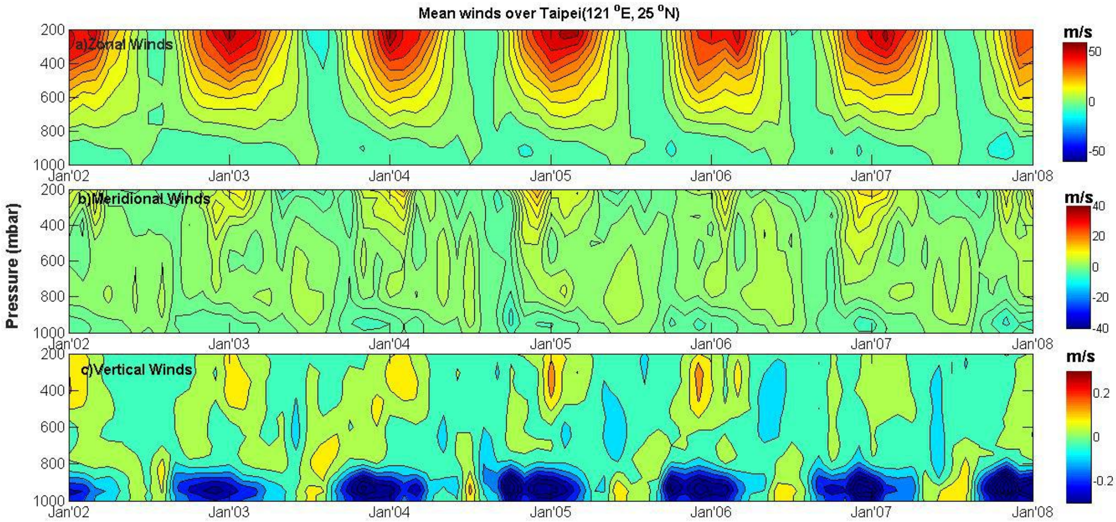

Figure 10. ECMWF derived mean winds over Taipei including, a) zonal b) meridional, and c) vertical winds between January 2000 and January 2008.

3.4 Role of various factors that influence the HC circulation

It is well known that the variations in heating (solar radiation) at various places of the Earth's surface leads to pressure gradients and these differential heating and pressure gradients, consequently, influence buoyancy. It is to be noted that pressure variations also drive horizontal air movement (as air moves from areas of high to low pressure). The combination of vertical (buoyant) and horizontal motions would allow the development of the circulation cells (or, Hadley Cells) between the tropics and the extra tropics. Since Hadley cell is almost independent of season over Taiwan unlike the Indian region where the Hadley circulation reverses during monsoon season[33], the role of other factors influencing the HC dynamics need to evaluated including, topography, sea surface temperatures (SSTs), mid-latitude zonal jets, and others. For instance, the Bjerknes[34] study revealed that anomalously high SSTs during the 1957-58 El Nino event contributed to a stronger HC, increased northward transport of angular momentum and stronger than normal westerlies in the mid latitudes. Hou[35] reported that a reduction of HC intensity is associated with increased meridional temperature and potential vorticity (PV) gradient (low zonal index). Most importantly, one cannot rule out the role of atmospheric aerosols and their implications on radiative forcing and, thereby, influence the Hadley circulation changes[7,17]. It may be worth mentioning here that aerosols arising from natural causes and human activities, as well as changes in cloud properties, have a strong influence on incoming solar radiation thus leading to solar dimming[36–38].

Though we do not understand the plausible physical mechanisms of these disturbed nature of meridional wind pattern particularly during the northern winter season of two consecutive years (2004 and 2005) over Taipei, it is likely that local wind dynamics, geography of the location, elevation of the location, and the atmospheric pollutants and others might have created an amicable environment as to provide such a disturbed meridional wind pattern particularly during specific seasons over a temperate mid-latitude location (Taipei) in Taiwan. Hence, the disturbed HC during 2005-05 could be attributed to a local phenomenon, pertinent only to Taipei region.

4. Conclusions

The salient observational findings of this research are summarized in the following lines:

It is reported, for the first time, a disturbed HC over Taipei (Latitude 25.03^{0}N, Longitude 121.51^{0}E), Taiwan during the northern hemisphere winter season (December, January, and February) in 2004 and 2005.

Analyzed various databases of several remote sensing instruments including, meridional and horizontal winds as measured by radiosondes over Taiwan along with nearby four stations (Roig, Xiamen, Minami, and Fuzhou), global evaporation minus precipitation (E-P), and the ECMWF re-analysis model predicted winds with a view to succinctly verify whether such a disturbed pattern existed over nearby stations or not.

To our surprise, no other station has recorded such a disturbed wind pattern as observed over Taiwan during any season of years starting from 2002 to 2008.

ECMWF model-predicted winds did not show any anomalous wind patterns over Taipei and over other nearby stations, possibly due to the large averaging of internal variabilities of reanalysis databases.

Evaporation minus precipitation (E-P) trend has provided excellent clues about the latitudinal edges of HC and these are found to be situated at around 36^0 and 40^0 in the northern and southern hemispheres, and

The plausible physical mechanisms of these disturbed meridional wind patterns are not understood by us at this juncture, but the local wind dynamics and atmospheric pollutants could have created an amicable environment as to provide such a disturbed meridional wind pattern over Taipei region in Taiwan.

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