Atmospheric Research 183 (2017) 362–370

Contents lists available at ScienceDirect

Atmospheric Research

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

Estimation of the marine boundary layer height over the central North Pacific using GPS radio occultation

Thomas E. Winning Jr. [a,b,*], Yi-Leng Chen [a], Feiqin Xie [b]

[a] Department of Atmospheric Science, School of Ocean and Earth Science and Technology, University of Hawai'i - Mānoa, 2525 Correa Rd, HIG 342, Honolulu, HI 96822, USA
[b] Department of Physical and Environmental Sciences, College of Science and Engineering, Texas A&M University Corpus Christi, 6300 Ocean Dr., Unit 5850, Corpus Christi, TX 78412, USA

ARTICLE INFO

Article history:
Received 12 June 2015
Received in revised form 31 July 2016
Accepted 8 August 2016
Available online 9 August 2016

Keywords:
Boundary layer
Boundary layer height
Trade wind
COSMIC
GPS radio occultation
Hawaii
Refractivity

ABSTRACT

Global positioning system radio occultation (GPS RO) refractivity data obtained from the first Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) for the years 2007 to 2012 were used to estimate an overall climatology for the height of the marine boundary layer (MBL) over the central North Pacific Ocean including the Hawaiian Island region (10°N–45°N; 125°W–175°W). The trade wind days are identified based on the six-year National Centers for Environmental Prediction (NCEP) global analysis for the same period. About 87% of the RO soundings in summer (June–July–August, JJA) and 47% in winter (December–January–February, DJF) are under trade wind conditions. The MBL height climatology under trade wind conditions is derived and compared to the overall climatology. In general, MBL heights are lowest adjacent to the southern coast of California and gradually increase to the south and west. During the summer (JJA) when the northeasterly trade winds are the dominant surface flow, the median MBL height decreases from 2.0 km over Kauai to 1.9 km over the Big Island with an approximate 2 km maximum that progresses from southwest to northeast throughout the year. If the surface flow is restricted to trade winds only, the maximum MBL heights are located over the same areas, but they increase to a median height of 1.8 km during DJF and 2.1 km during JJA. For the first time, the GPS RO technique allows the depiction of the spatial variations of the MBL height climatology over the central North Pacific.

1. Introduction

The northeasterly surface flow over the central North Pacific Ocean is a manifestation of the North Pacific sub-Tropical High (NPSTH). The resulting low level flow, referred to as the trade winds (TW), represent the world's most consistent surface wind field (Malkus, 1956). Along its trajectory, subsiding air from upper levels comes into contact with convectively driven maritime air ascending from the surface. The transition layer between the two represents the interface between the marine boundary layer (MBL) and the subsiding warm and dry air aloft (Riehl, 1979). The air within MBL is characterized as moist, conditionally unstable, and frequently populated with trade wind cumuli. The subsidence warming in the inversion layer is balanced by radiative cooling and evaporation from the tops of trade cumuli (Riehl, 1979; Albrecht et al., 1979; Betts and Ridgway, 1989). The transition layer is marked by a dramatic decrease in water vapor with respect to height and sometimes accompanied by an increase in temperature, which is referred to as the trade wind inversion (TWI). The inversion base varies from about 500 m at the eastern extreme of the subtropical high to about 2000 m at the western and equatorial extremities (Neiburger et al., 1961; Malkus and Riehl, 1964). The thickness of the transition layer, on average, is about 400–600 m; however, it can vary widely from a few tens of meters to almost 1 km (Bingaman, 2005). The influence of the MBL is expansive and is an instrumental component of stability and the vertical extent of the convective process, vertical heat and moisture fluxes, large-scale circulations, and energy transports (Trenberth and Stepaniak, 2003).

Over the Hawaiian Islands, the trade wind flow and TWI have significant impacts on island-scale airflow as well as local weather and climate. For islands with tops above the inversion, the TWI base serves as a lid forcing the incoming low-level trade wind flow to be deflected on the windward side (Leopold, 1949). Using model sensitivity tests Chen and Feng (2001) proved that airflow around the island is affected by the TWI and not by the upstream Froude number ($Fr = U / Nh$, where U is the cross mountain wind speed, N is stability, and h is the mountain height) alone (Smolarkiewicz et al., 1988; Rasmussen et al., 1989). For mountains with tops or ridges above the base of the TWI, areas of maximum rainfall correspond to regions of persistent orographic lifting of moisture-laden northeast trade winds up the windward slopes. Conversely, areas of low rainfall are found in the leeward areas and atop the highest mountains (Giambelluca et al., 2013) and result in a semi-

* Corresponding author at: Department of Physical and Environmental Sciences, College of Science and Engineering, Texas A&M University Corpus Christi, 6300 Ocean Dr., Unit 5850, Corpus Christi, TX 78412, USA.
E-mail addresses: twinning@islander.tamucc.edu (T.E. Winning), yileng@hawaii.edu (Y.-L. Chen), Feiqin.Xie@tamucc.edu (F. Xie).

http://dx.doi.org/10.1016/j.atmosres.2016.08.005

arid local climate (Giambelluca and Nullet, 1991; Chen and Nash, 1994; Chen and Wang, 1994). For islands with mountaintops or ridges below the TWI base, a rainfall maximum occurs at the summits (Giambelluca et al., 2013; Nguyen et al., 2010).

The height and strength of the TWI vary on a daily basis (Neiburger et al., 1961; Chen and Feng, 1995). The presence of the TWI limits the vertical extent of convective processes like cloud development. The short term variations of the TWI affect the day to day local weather over the Hawaiian Islands. Chen and Feng (1995) examined rainfall patterns over the Island of Hawaii (Big Island) under high and low trade wind inversions during the Hawaiian Rainband Project (HaRP). Their results suggest that for the low- (high-) inversion days, the median daily rainfall on the windward side of the Big Island is about one-half (more than twice) of the HaRP median daily rainfall. On high inversion days, the afternoon orographically induced clouds and showers extend closer to the summits than during low inversion days because the afternoon upslope flow can bring the low-level moist air to higher elevations. Chen and Feng (2001) simulated island airflow and weather for the Big Island under summer trade wind conditions. They showed that the TWI height represents the depth of the moist layer that affects cloud development and convective feedback to the island airflow. For islands with tops below the trade wind inversion, the daily rainfall amounts on the windward side and the mountaintops are higher when the inversion is higher (Hartley and Chen, 2010).

Despite its significant impacts on local weather and climate, except two sounding sites (Hilo and Lihue) (Fig. 1), information on the trade wind inversion over the central North Pacific is very limited. Soundings from these two stations are strongly affected by the terrain and local winds and may not be representative of the open ocean conditions. Throughout the year, radiosonde analysis reveals the MBL height on the windward side of the southeastern island of Hawaii (Fig. 1) is >200 m higher than at Lihue, which is located on the windward side of the northwestern island of Kauai (Tran, 1995; Bingaman, 2005; Cao et al., 2007). However, because the Island of Hawaii has massive volcanic cones with heights exceeding 4000 m, the differences in MBL height between Hilo and Lihue may not represent the actual spatial variations over the region (Garrett, 1980). Over the open ocean, the satellite derived temperature and moisture profiles do not have adequate resolution to depict the TWI layer. The launch of the first Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) in 2006, allows for atmospheric profiling with 100 m vertical resolution to be extended over the open ocean using the GPS radio occultation (GPS RO) technique.

Previous research demonstrated the effectiveness of using the refractivity gradient method to detect the boundary layer height in the presence of a moisture gradient and temperature inversion (e.g., Basha and Rantam, 2009; Guo et al., 2011; Ao et al., 2012; Xie et al., 2012; Ho et al., 2015). Additionally, Zhou and Chen (2014) assimilated the high vertical resolution GPS RO data from COSMIC satellites into the initial conditions of the Weather Research and Forecasting (WRF) model. They showed that the TWI is better predicted for a summer trade wind case when GPS RO data is assimilated into the regional WRF models. Additionally, for a winter cold front case, the propagation of the cold front, prefrontal moisture tongue, and postfrontal inversion are better predicted in the high resolution regional domain over the Hawaiian Islands.

Using the data collected by COSMIC GPS RO, an analysis focusing on seasonal spatial variations of MBL height and strength over the Hawaiian region will be performed. Focus will then turn to a comparison between the mean seasonal climatology and those under trade wind conditions during summer and winter. The structure of the paper is as follows. In Section 2, the multi-year mean seasonal climatology of trade wind and non-trade wind conditions are presented. The data and methodology used for the study are described in Section 3. Section 4 presents the seasonal MBL height climatology as well as the climatology during trade wind only conditions; both derived from COSMIC RO refractivity measurements. Results during trade wind conditions are then compared with the seasonal MBL height climatology. Our analyses of the MBL heights over the open ocean will also be compared with those at the two Hawaii sounding sites. Finally, Section 5 contains the summary and conclusion.

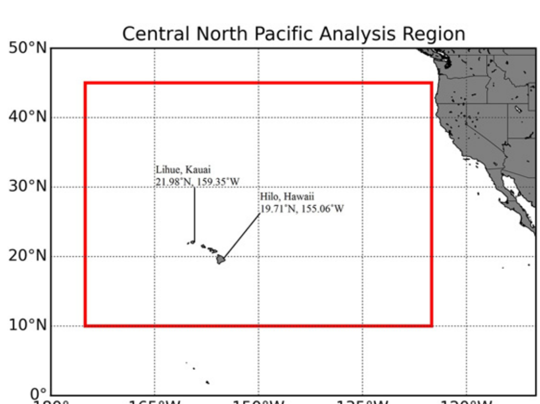

Fig. 1. Map of central North Pacific Ocean with the locations of Lihue and Hilo shown. The red box denotes the analysis region: 10°N–45°N; 125°W–175°W.

2. Seasonal climatology

Throughout the summer months of June, July, and August (JJA) the northeasterly surface flow is the most dominant flow regime and present approximately 90% of the time (Schroeder, 1993). Conversely, during the cool season (November–April) the wind pattern is not as uniform as its summer counterpart (Schroeder and Giambelluca, 1998). The pattern difference can be attributed to the annual migration of the NPSTH and polar jet stream, which leave the islands vulnerable to Kona low pressure systems, upper level troughs, and cold fronts (Kodama and Businger, 1998; Schroeder, 1993). As a result, the surface trade wind flow is present <50% of the time during the core winter months of December, January, and February (DJF) (Schroeder, 1993). The interaction between the islands and the prevailing weather patterns over the Pacific region add layers of complexity during DJF.

2.1. Sea level pressure and surface wind

The maximum surface pressure associated with the NPSTH during JJA is approximately 1024 hPa and located near 35°N, 150°W as seen in the six year mean (2007–2012) from the National Centers for Environmental Prediction (NCEP) Final (FNL) Operational Global Analysis (Fig. 2). During the DJF season, the center of the NPSTH (1022 hPa) is located in the vicinity of 30°N, 130°W, southeast of the JJA position (Fig. 2). The location and strength of the NPSTH governs the prevailing surface wind over the central North Pacific region; accordingly, the effects of island interactions vary by season. Climatologically, the surface winds are predominantly from the northeast during JJA with a maximum mean velocity of approximately 7.5 m s^{-1} in an area located south of the Island of Hawaii and bisected by the 15°N latitude line between 150°W and 165°W (Fig. 2). Note that while the mean minimum surface wind vectors are seen in the lee of the Hawaiian Islands, the wake circulations (Hafner and Xie, 2003; Smolarkiewicz et al., 1988; Yang and Chen, 2003) are not properly resolved by the NCEP-FNL analysis. As the NPSTH shifts southeastward during DJF, the surface winds upstream of Hawaii shift to a more easterly direction with slightly slower wind speed, which moves the area of maximum mean wind speed (7.5 m s^{-1}) to the south side of the Big Island and east to west across the entire analysis domain south of 20°N (Fig. 2).