Water vapor variability and comparisons in the subtropical Pacific from The Observing System Research and Predictability Experiment-Pacific Asian Regional Campaign (T-PARC) Driftsonde, Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC), and reanalyses

Junhong Wang,1 Liangying Zhang,1 Po-Hsiung Lin,2 Mark Bradford,1 Harold Cole,1 Jack Fox,1 Terry Hock,1 Dean Lauritsen,1 Scot Loehr,1 Charlie Martin,1 Joseph VanAndel,1 Chun-Hsiung Weng,2 and Kathryn Young1

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During the THORPEX (The Observing System Research and Predictability Experiment) Pacific Asian Regional Campaign (T-PARC), from 1 August to 30 September 2008, ∼1900 high-quality, high vertical resolution soundings were collected over the Pacific Ocean. These include dropsondes deployed from four aircrafts and zero-pressure balloons in the stratosphere (NCAR’s Driftsonde system). The water vapor probability distribution and spatial variability in the northern subtropical Pacific (14°–20°N, 140°E–155°W) are studied using Driftsonde and COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate) data and four global reanalysis products. Driftsonde data analysis shows distinct differences of relative humidity (RH) distributions in the free troposphere between the Eastern and Western Pacific (EP and WP, defined as east and west of 180°, respectively), very dry with a single peak of ∼1% RH in the EP and bi-modal distributions in the WP with one peak near ice saturation and one varying with altitude. The frequent occurrences of extreme dry air are found in the driftsonde data with 59% and 19% of RHs less than or equal to 5% and at 1% at 500 hPa in the EP, respectively. RH with respect to ice in the free troposphere exhibits considerable longitudinal variations, very low (<20%) in the EP, but varying from 20% to 100% in the WP. Inter-comparisons of Driftsonde, COSMIC and reanalysis data show generally good agreement among the Driftsonde, COSMIC, ECMWF Reanalysis–Interim (ERA–Interim) and Japanese Reanalysis (JRA) below 200 hPa. The ERA–Interim and JRA are approved to be successful on describing RH frequency distributions and spatial variations in the region. The comparisons also reveal problems in Driftsonde, two National Center for Environmental Prediction (NCEP) reanalyses and COSMIC data. The moist layer at 200–100 hPa in the WP shown in the ERA–Interim, JRA and COSMIC is missing in Driftsonde data. Major problems are found in the RH means and variability over the study region for both NCEP reanalyses. Although the higher-moisture layer at 200–100 hPa in the WP in the COSMIC data agrees well with the ERA–Interim and JRA, it is primarily attributed to the first guess of the 1-Dimensional (1D) variational analysis used in the COSMIC retrieval rather than the refractivity measurements. The limited soundings (total 268) of Driftsonde data are capable of portraying RH probability distributions and longitudinal variability. This implies that Driftsonde system has the potential to become a valuable operational system for upper air observations over the ocean.


1. Introduction

It is undisputable that water vapor in the atmosphere serves as an effective greenhouse gas and plays an important role in determining the sensitivity of Earth’s climate to anthropogenic forcing [Held and Soden, 2000;
Pierrehumbert et al., 2006]. The effect of water vapor on Earth’s radiation budget (mainly outgoing longwave radiation (OLR)) is approximately logarithmic in specific humidity and depends on vertical and horizontal distributions and magnitudes of water vapor [Held and Soden, 2000]. The OLR is more sensitive to water vapor changes in the free troposphere than in the boundary layer and is also more sensitive to very low humidity than high humidity [e.g., Shine and Sinha, 1991; Spencer and Braswell, 1997].

[5] Above the boundary layer, much of the atmosphere is unsaturated and often contains very dry air of less than 10% relative humidity (RH) in the subtropics and extratropics [e.g., Spencer and Braswell, 1997; Zhang et al., 2003]. The sensitivity of the OLR is greater to perturbations in water vapor in the tropical free troposphere than that in the tropics [Held and Soden, 2000]. There have been extensive studies on probability density functions (PDFs) of RH in the tropical and subtropical troposphere [e.g., Spencer and Braswell, 1997; Zhang et al., 2003; Sherwood et al., 2006; Ryoo et al., 2009]. Given the importance of the subtropical dry air to the radiation budget, a number of studies have been focused on understanding large-scale control of subtropical humidity using Lagrangian techniques [e.g., Salathé and Hartmann, 1997; Soden, 1998; Pierrehumbert, 1998; Pierrehumbert and Roca, 1998; Galewsky et al., 2005]. The humidity simulated by the Lagrangian schemes or other empirical models needs to be evaluated against in situ or satellite observations.

[4] Upper air moisture observations over the ocean are primarily obtained from satellites, especially microwave satellites for all weather conditions. Satellite data can only provide total column water vapor (TCWV) or layer mean humidity. As elaborated above, Earth’s radiation budget is very susceptible to the free troposphere humidity, which contributes less to TCWV. The layer mean humidity would smear out the large humidity variability and skew the RH humidity distribution. In situ soundings (both ship and island radiosonde and dropsonde from aircrafts) from special field experiments have been used to study water vapor distribution in the tropics [Brown and Zhang, 1997; Pierrehumbert, 1998; Zhang et al., 2003]. However, those soundings are subject to spatial and temporal sampling biases.

[5] Global reanalysis is a comprehensive global, multi-decadal data set generated by a constant state-of-the-art numerical data assimilation technique using various past observations. Satellite upper-air observations have been the primary input data for global reanalyses. The NCEP reanalysis products only assimilate satellite temperature soundings over the ocean. Without the observational constraint to the moisture field, NCEP reanalyses perform poorly over the ocean [Trenberth and Guillemot, 1998; Trenberth et al., 2005]. There is an urgent need to validate all reanalysis products over the ocean using independent data that are not assimilated into the reanalyses. The data over the ocean collected from various field campaigns can partially meet this need.

[6] In recent years, the Global Positioning System (GPS) radio occultation (RO) technique has shown promise in measuring the atmosphere with high vertical resolution and global coverage and under all weather conditions. The Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC), composing of six satellites in separate orbits, was successfully launched in April 2006, and provides about 2,500 RO profiles every day around the globe [Anthes et al., 2008]. Atmospheric temperature and water vapor profiles are derived from the COSMIC RO profiles. In order to improve the retrieval algorithms and use the COSMIC data to study various scientific problems, we need to first evaluate the COSMIC-retrieved water vapor profiles to gain confidence on the data, especially over the ocean, where upper-air observations with high vertical resolution are missing.

[7] In this article, we analyzed upper-air observations from dropsondes deployed from zero-pressure balloons in the stratosphere (NCAR’s Driftsonde system) over the Pacific Ocean during T-PARC between 1 August and 30 September 2008. Driftsondes were launched from Kona, Hawaii, drifted with winds to cross the Pacific Ocean, deployed dropsondes along the way, and provided good spatial coverage of subtropical Pacific Ocean. The aims of this paper are (1) to use this unique, high-quality and high vertical resolution data set to study water vapor distribution and variability in the region; (2) to use the reanalysis data with better spatial and temporal coverage and sampling to test whether the findings from (1) are representative of general conditions in the region; and (3) in turn, to assess the performance of humidity profiles from the reanalysis, COSMIC and Driftsonde by intercomparing them. The instruments and data are briefly described in section 2. RH frequency distributions and longitudinal variability are presented in section 3. In section 4, we discuss the problems in Driftsonde, reanalysis and COSMIC data.

2. Instrument and Data

T-PARC was an international field project, conducted in the western Pacific from 1 August to 30 September 2008, to enhance our understanding in the mechanisms relevant to improving prediction of weather events with high impacts and to provide data to examine typhoon genesis. During T-PARC, ~1900 dropsondes were dropped from four aircrafts (NRL-P3, AF-C130, DLR-Falcon and DOTSTAR) and the NCAR Driftsonde system (see Figure 1 for sounding locations). RH probability distributions for all soundings from the NRL-P3, AF-C130 and DOTSTAR in Figure 2 show that the peak probability occurs at higher RHs (>70%) throughout the troposphere. This is mainly because the dropsondes from these three aircrafts were targeted for tropical cyclones and dropped in the vicinity of cyclones. The soundings from the DLR-Falcon reveal bimodal distributions of RH in the free troposphere (above 700 hPa) with one peak at RH less than 10% and the other one around ice saturation RH. This is not surprising because the sondes from DLR-Falcon were dropped in the edges of cyclones, the areas that the formation of cyclones was sensitive to, or the extratropical cyclonic environment. Therefore, the aircraft soundings are not representative of all conditions and unsuitable for comparing with RH probability distributions presented by previous studies. In contrast, Driftsonde soundings cover the subtropical Pacific from 140°E to 155°W and sample all weather conditions (Figure 1). Therefore, this study mainly uses the soundings from Driftsonde, including total 268 soundings dropped from
16 balloons with an average drop altitude of 22.5 km above mean sea level.

The NCAR GPS dropsonde includes a pressure, temperature, humidity sensor module, a code-correlating GPS receiver module for wind measurements and a 400 MHz telemetry transmitter to transmit data from the sonde to the onboard receiving system [see Hock and Franklin, 1999, Figure 1]. The dropsonde is deployed from research aircrafts or other platforms over remote areas such as the ocean, polar regions and sparsely inhabited landmasses. It descends through the atmosphere on a parachute measuring pressure, temperature, humidity and wind profiles at a 0.5 s vertical resolution (equivalent to ∼5–10 m). T-PARC was the second deployment of Driftsonde system. Driftsonde was developed in an effort to produce a low-cost measurement system capable of capturing vertical profiles of in situ

Figure 1. (top) Map with all dropsonde sounding locations from four aircrafts and Driftsonde system. (bottom) Driftsonde tracks (colored lines), dropsonde locations from Driftsonde (circles), COSMIC sounding locations (triangles) and mean RH (percent) at 500 hPa from ERA-Interim (background color contour with color bars on right side).
measurements in forecast sensitive regions, and filling critical gaps in data coverage over remote locations. Driftsonde system consists of a zero-pressure or super-pressure polyethylene balloon attached to a gondola that houses up to 50 Miniature In situ Sounding Technology (MIST) dropsondes. The MIST dropsonde has the same sensors as the standard dropsonde, but it is smaller and lighter. The balloon floats along with the wind currents in the lower stratosphere or upper troposphere between 16 and 30 km, and can remain airborne for a minimum of six weeks (depending on the battery life) for super-pressure balloons. The MIST sondes are released upon command via the ground operations center. The zero-pressure balloon has shorter life time than the super-pressure one, and was used for T-PARC. Sixteen balloons launched during T-PARC stayed in the air for 3–6 days. During the recent test of the driftsonde system with super-pressure balloons, two fights had the lifetime of 105 and 53 days. Sometimes the flight has to be terminated because of political issues, flight permission, instrument failure and other reasons.

[10] All dropsonde data have been carefully quality-controlled using several postprocessing methods including applying automatic sounding quality-control software called Atmospheric Sounding Processing Environment (AScEN; see http://www.ess.ucar.edu/isl/facilities/software/asp/en/asp.html), visually examining each sounding and plotting the histogram and time series of each parameter. Special problems in data quality are identified and corrected if possible.

[11] COSMIC includes six micro satellites launched into a circular, 72° inclination orbit at an altitude of 512 km in April 2006 [Anthes et al., 2008]. The COSMIC employs the GPS RO limb-sounding technique to measure the atmosphere. The GPS-RO receiver on each of COSMIC satellites receives the radio waves from GPS satellites. The measured phase delay of radio waves is used to derive accurate and precise vertical profiles of the bending angles of radio wave trajectories. The refractivity profiles are then obtained from the bending angles. The refractivity depends on temperature (T), pressure (P), water vapor pressure (Pw) and electron density. The Pw profile is retrieved by using the 1-dimensional variational (1D-Var) data assimilation technique. The temperature and moisture gridded analysis from ECMWF forecasting model is used as the first guess of the 1D-Var technique; the refractivity profile is utilized to improve the first guess field to obtain final retrieved Pw profile. The COSMIC post processed data are used in this
study and include the COSMIC atmospheric profiles (referred as “wetPrf”) and ECMWF gridded analysis (referred as “ecmPrf”). The data are retrieved from the COSMIC Data Analysis and Archive Center Version 3.0 (http://cosmic-io.cosmic.ucar.edu/cdaac/index.html). The “wetPrf” data are available from surface to 40 km above mean sea level in a 100 m resolution. The “ecmPrf” data are available from surface to about 1 hPa at 25 levels.

Four global reanalysis products are used in this study to characterize the water vapor distributions during August and September 2008, in the T-PARC Driftsonde region (14°–25°N, 140°E–155°W) and compare with Driftsonde and COSMIC data. They, along with Driftsonde and COSMIC data, are summarized in detail in Table 1. One may notice that the number of profiles during T-PARC in the study region ranges from 268 (Driftsonde) to 129,320 (JRA).

Table 1. Characteristics of Six Data Sets Used in This Study

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<th>JRA</th>
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<td>(1000–1 hPa)</td>
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<td>Temporal resolution</td>
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<td>Number of profiles in T-PARC</td>
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Figure 3. RH probabilities (percent) of Driftsonde data for the (right) eastern and (left) western Pacific. The RH interval is 4%. Solid and dashed black lines are RH means and standard deviations (percent), respectively. The dotted lines are ice saturation RHs. The red lines are mean temperature profiles (in degrees Celsius, top x axis). Mean and standard deviation of RH profiles in the WP (green line) are replotted for the eastern Pacific.
Different humidity parameters are included in six data sets, RH for driftsonde, ERA-Interim and two NCEP reanalyses, specific humidity for JRA and water vapor pressure for COSMIC. For this study, they all are converted to RH with respect to water or ice using Goff Gratch equations for saturation vapor calculation over water or ice [Smithsonian Institution, 1984].

3. RH Variability
3.1. Probability Distributions

The RH probability distribution of Driftsonde data shows two distinct features below and above 700 hPa (Figure 2). The probability below 700 hPa maximizes at 70–90% RHs and has a narrow distribution. Around 700 hPa, there is a jump in locations of peak probability from ~70% to less than 10% RH. Such discontinuous profile of RH probability distribution was shown in the work of Sun and Lindzen [1993, Figure 2]. There is a bimodal distribution in ~700–600 hPa with one peak at ~70% and one at RH less than 10%. This is consistent with the findings of Zhang et al. [2003] and Ryoo et al. [2009]. Above 600 hPa, the distribution shows a primary peak at RH less than 10% and a secondary peak near ice saturation.

It is important to understand what causes the RH bimodal distribution shown in Driftsonde data in Figure 2. Both the sampling and actual RH variability on the spatial and temporal scales can contribute to the bimodal distribution. Mean ERA-Interim RH at 500 hPa averaged for the 2 month period in the background of Figure 1 (bottom) shows the transition from RH below 20% in the eastern Pacific (EP, east of 180°) to gradually increase of RH with longitude in the western Pacific (WP, west of 180°). Therefore, the data are first divided into the eastern and western Pacific regions (Figure 3). The EP and WP have similar distributions below 700 hPa, but dramatic discrepancies above (Figure 3). The free troposphere is very dry in the EP with a single peak of ~1% RH and is drier in the EP than the WP by more than 20% on average, but has a broad distribution in the WP with one peak near ice saturation and one varying with altitude. It suggests that the bimodal distribution above 700 hPa seen in Figure 2 is primarily the result of mixing the EP and WP soundings together. Another thing worth notice is that the top of the moist layer with a single peak at RH > 70% is ~700 hPa in the EP, but 600 hPa in the WP. Therefore, the following analyses are separated into the EP and WP. Such RH contrast between the EP and WP in the subtropics seems more profound in summer and fall than in winter [see Peixoto and Oort, 1996, Figure 3]. Ryoo et al. [2009] show insignificant differences in subtropical Pacific upper troposphere humidity between the EP and WP in winter using Atmospheric Infrared Sounder (AIRS) data. The primary reason for the EP and WP RH distinction in the free troposphere is the Walker circulation over the region, the subsidence of dry air in the EP and the lifting of moist air from the boundary layer to the free troposphere in the WP, as shown by the pressure vertical velocity from the ERA-Interim data (Figure 4). The spatial and temporal sampling of Driftsonde data is not comprehensive (Figure 1). Thus, it is crucial to examine whether the RH distributions in Figure 3 are representative of general conditions (i.e., climatology) of the region. The global reanalysis data are used to test

![Figure 4. Longitudinal variations of pressure vertical velocity (hPa/s) from ERA-Interim.](image-url)
because of their better spatial and temporal coverage and sampling (see Table 1). However, we need to first test the validity of the reanalysis moisture fields in the region. Figure 5 shows RH PDFs at three levels (900 hPa, 500 hPa and 300 hPa) in the EP and WP from all six data sets using all available data. It is apparent that the two NCEP reanalyses are outliers compared to the others. ERA-Interim and JRA show similar distributions. Hence ERA-Interim is used here. The RH PDFs at 900 hPa, 500 hPa and 300 hPa are displayed in Figure 6 using all ERA-Interim data in the region and during the T-PARC period and the data matched to Driftsonde locations and times along with the driftsonde data for comparisons. There are no significant differences between all and matched soundings from the ERA-Interim in the shapes of PDFs. The PDF variations with height and differences between the EP and WP are larger than the differences between all and matched ERA-Interim data. Qualitatively the sampling bias (differences between all and matched ERA-Interim) is smaller than the discrepancies between matched ERA-Interim and driftsonde. This indicates that the limited sampling of Driftsonde (total 268) is enough to depict the RH PDF in the region. Figure 6 also shows that the matched-data sample less dry events (RH < ~40%) and more moist events at 300 hPa and 500 hPa in the WP.

3.2. Zonal Variations

The RH longitudinal variability from six data sets is shown more clearly in Figure 7. RH with respect to water is converted to RH with respect to ice at temperatures below 0°C (RHi), and RHi is presented in Figure 7 in order to depict ice supersaturation (ISS) more clearly. All data except the two NCEP reanalyses show that the free troposphere is very dry and has less variability in the EP, whereas RHi can vary from ~20% to ~100% in the WP. The limited sampling in the matched ERA-Interim data is capable of showing the increase of RH in the free troposphere from the EP to the WP and the longitudinal variability of RH in the WP with a peak around 150°E (Figure 7). However, the matched data show drier free troposphere in the EP than all data and less smooth changes in the WP. Figure 7 suggests that the trajectory of Driftsonde with easterly winds enables it to sample the RH longitudinal variability very well in spite of this because of their better spatial and temporal coverage and sampling (see Table 1). However, we need to first test the validity of the reanalysis moisture fields in the region.
only 268 soundings, which is less than 0.3% of all 96624 ERA-Interim soundings.

Driftsonde data completely miss the high RH (close to ice saturation) layer at 200–100 hPa in the WP shown by ERA-Interim, JRA and COSMIC, which is discussed in more detail in section 4. The RH zonal variations obtained from 1625 COSMIC soundings are in accord with ERA-Interim, especially the high RH layer at 200–100 hPa in the WP. However, caution has to be taken to interpret this as GPS-RO’s capability to accurately measure water vapor in the upper troposphere. This will be explained in section 4. The ERA-Interim and JRA show very similar features although the JRA is drier than the ERA-Interim at west of ∼160°E in the free troposphere. The NCEP/DOE reanalysis shows very small RH longitudinal variation and fails to identify the EP/WP contrast. The NCEP/NCAR is only available below 300 hPa and shows the EP/WP contrast, but significantly underestimates RH below 700 hPa. The shortfall in NCEP reanalyses is also manifested in RH PDFs in Figure 5. We will come back to the poor performance of NCEP reanalyses in section 4.

As shown in Figure 3, the free troposphere in the EP has a single peak of ∼1% RH. Owing to the logarithmic dependence of OLR on humidity noted in the introduction, it makes a big difference whether RH is 1% or 2%. Spencer and Braswell [1997, Figure 2] show that the sensitivity of OLR to additive change of 3% RH could be doubled when averaged RH in the free troposphere is reduced from ∼6% to ∼3%. Therefore, measurements of lower RHs (<20%) are preferred to be accurate within 1% or better, have high horizontal and vertical resolution, and be made by in situ sensors rather than remote sensing. The latter two requirements would minimize spatial and temporal averaging, which averages out extreme values. The historical radiosonde data at lower RHs are often missing, are artificially set to a constant value, or contain significant biases. For example, before October 1993, the humidity data in the U.S. radiosonde network that used VIZ radiosonde were not reported at temperatures below −40°C, and the dew point depression was reported as a constant value of 30°C [Elliott and Gaffen, 1991]. Afterward, RHs were reported at all temperatures and as measured values, but contain significant moist bias [Spencer and Braswell, 1997; Wang et al., 2001]. All satellite data include some kind of averaging spatially, and thus overestimate RHs at lower RH. In contrast, the driftsonde data used in this study can meet the requirements for better RH measurements in dry regions as a result of the high accuracy (2% in RH) and quick response of Vaisala H-HUMICAP thin film capacitor used in the MIST sonde, its in situ measurement technique and its high vertical resolution. The percentage of RHs equal to and less than 5% at 500 hPa in the EP is 59%, 48% and 28% for the driftsonde data, and matched and all ERA-Interim data, respectively. For the
driftsonde data, nineteen percent of cases have RHs at 1%. Such extreme dryness (RH < 5%) of the free troposphere in the tropics has been reported by Spencer and Braswell [1997] and Sherwood et al. [2006] on the basis of microwave and GPS-RO satellite data, respectively. The latter concluded that one-quarter of the tropical air at 8 km is below 4% RH. However, the AIRS data only report ~0.5% of samplings in the tropics with RHs less than 5% [Ryoo et al., 2009, Figure 5a]. The higher population of extreme dry cases in the driftsonde data is likely because the driftsonde measurement is instantaneous at a point, while all others include averaging either spatially or temporally.

4. Problems in Driftsonde, Reanalysis, and COSMIC Humidity Data

RH distributions and variability presented in section 4 from Driftsonde, reanalysis and COSMIC data reveal
problems in them. In summary, the following serious problems are identified:

1. Driftsonde completely misses the moist layer with RH > 70% in the WP above ~200 hPa.
2. Both NCEP reanalyses are incapable of correctly simulating RH magnitudes and variability in the subtropical Pacific.
3. The good performance of COSMIC above 200 hPa is questionable.

These three problems are investigated carefully below.

As shown in Figure 7, Driftsonde hygrometers fail to capture the large RH (>70%) layer above 200 hPa displayed in the ERA-Interim, JRA and COSMIC data. The matched Driftsonde and ERA-Interim data show that in the WP above 200 hPa Driftsonde RH has a constant value of 1%, which is the lowest limit the MIST hygrometer can measure, while the ERA-Interim contains a layer of high RH (>70%) (not shown). Twelve percent of ERA-Interim data points above 200 hPa in the WP have RH above ice saturation. This is inconsistent with Luo et al. [2008], who found 100% RH cutoff in the ECMWF analysis. This can be explained by the change of the ISS scheme around 2006 [Tompkins et al., 2007]. RH in the old scheme was not allowed to exceed 100%, whereas the new scheme allows ISS [Tompkins et al., 2007]. Figure 8 (top) provides two cases where the ERA-Interim shows moist layers at or above 200 hPa. Driftsonde RH values started to increase below 150 hPa and reached a local maximum at lower al-

Figure 8. RH profiles (percent) for four matched Driftsonde (solid lines) and ERA-Interim (dashed lines) soundings.
attitudes. It suggests that the Driftsonde hygrometer is able to respond to humidity changes in the upper troposphere, but has time lags and a dry bias. This is due to the slower response of the Humicap used as the MIST hygrometer at cold temperatures and the fact that the sonde descends from colder to warmer environments. The Humicap in Driftsonde is the same as that used for Vaisala RS92 radiosonde. Previous studies have shown the time lag error, dry bias and other errors in the Humicap [e.g., Wang et al., 2002; Voemel et al., 2007; Miloshevich et al., 2009]. Figure 8 (bottom) uses two examples to illustrate the advantages of high vertical resolution of Driftsonde data, including showing much more detailed vertical structures of RH and better describing the strong gradients of RHs around 700 hPa. On average, Driftsonde data agree with ERA-Interim and JRA within ±5% in RH below 500 hPa (Figure 9).

The two NCEP reanalyses are incapable of producing accurate RH values and its vertical and horizontal variations (Figures 5, 7, and 10) over the ocean. At 500 hPa, the correlations between matched Driftsonde and the two NCEP reanalyses (NCEP/NCAR and NCEP/DOE) are 0.53 and 0.26, respectively. In comparison, the correlations for ERA-Interim and JRA are both 0.92. The disagreements between NCEP reanalyses and other data are also manifested by the

Figure 9. Mean and root mean square (RMS) profiles of RH differences (between four reanalysis products and Driftsonde (percent)).

Figure 10. Spatial distributions of mean RH (percent) at (left) 300 hPa and (right) 500 hPa from four reanalyses.
large mean differences and root mean square of the differences in RH profiles (Figure 9). Trenberth et al. [2005] and Trenberth and Guillemot [1998] also demonstrated poor performance of both NCEP products over the ocean. They found that over the region studied here, NCEP reanalyses significantly underestimate total column water vapor (TCWV) values and its temporal variability compared to SSM/I and ERA-40 data. This is supported by smaller RH values below 500 hPa in the two NCEP data sets (Figure 9). The humidity above 500 hPa only contributes to less than 3% of TCWV [Wang et al., 2007]. The deficiency of NCEP reanalyses in water vapor over the ocean is most likely because NCEP reanalyses did not assimilate satellite water vapor soundings and had no in situ soundings over the ocean to constrain the data assimilation, except for a few island radiosonde observations [Kistler et al., 2001]. Figure 9 also shows that at ~450 hPa, NCEP/NCAR changes from a dry bias to a moist bias relative to Driftsonde data. This feature is expressed in RH PDFs in Figure 5. This is consistent with the finding of >30% higher NCEP/NCAR humidity than the COSMIC data by Chou et al. [2009]. Kanamitsu et al. [2002] concluded that the NCEP/DOE RH is lower than NCEP/NCAR by 10–15% at 300 hPa in the tropics and is suspected to be higher in the lower troposphere since TCWV from both NCEP are about the same. We reach the same conclusions from Figures 5 and 9. It is not clear what causes the unrealistically large ISS above 200 hPa in NCEP/DOE (Figure 7).

5. Conclusions

[26] High quality, high vertical resolution upper air observations over open oceans have historically been scarce because of the limited availability of in situ data and because available satellite data is typically low resolution, and of questionable quality. During T-PARC from 1 August to 30 September 2008, ~1900 soundings were collected over the Pacific Ocean. These include dropsondes deployed from four aircrafts and zero-pressure balloons in the stratosphere. The sounding data include profiles of pressure, temperature, humidity, wind speed and direction from the ocean surface to the troposphere for dropsondes, and from the surface to ~50 hPa for Driftsondes. The data are 0.5 s vertical resolution, corresponding to ~10 m near surface and ~30 m at 50 hPa. All soundings underwent a series of vigorous quality control at NCAR. Such an unprecedented sounding...
data set is valuable for achieving scientific objectives of T-PARC that address various aspects of typhoon activity including examining typhoon genesis and better understanding of the mechanisms that lead to improved predictive skill of typhoon. However, this study has a general goal of exploring the scientific applications of this unique data set beyond T-PARC’s specific objectives. Specifically, it focuses on making use of this unique data set to study detailed water vapor variability over the Pacific Ocean and evaluate global reanalysis products and the COSMIC data in the region.

The 268 Driftsonde soundings are analyzed in detail to document RH probability distributions and vertical and longitudinal variability over the subtropical Pacific region (14–25°N, 140°E–155°W). Unfortunately, the aircraft soundings were targeted for specific weather events, and thus are not representative of common climatology of the area. The analysis shows the distinct contrast between the Eastern and Western Pacific in RH PDFs in the free troposphere. The EP is very dry with a single peak of 1% RH and is drier in the EP than the WP by more than 20% RH on average. The frequency of RHs at 1% and less than or equal to 5% is 19% and 59% at 500 hPa in the EP, respectively. Such frequent occurrences of extreme dryness in the free troposphere have significant radiative impacts and call for better sampling of them in the future. In contrast, RH in the free troposphere in the WP has a broad distribution with one peak near ice saturation and one varying with altitudes. Such distinction between EP and WP is attributed to the Walker circulation over the region. The RH longitudinal variability is studied and compared using Drifsonde, COSMIC and four reanalysis data sets. The free troposphere is very dry and has less variability in the EP, whereas RH with respect to ice in the WP can vary from 20% to 100% with a consistently moist layer above 200 hPa. It is found that the limited sampling of Drifsonde (total 268) is sufficient to adequately describe RH PDFs and its longitudinal variability in the region because the trajectory of Drifsonde with easterly winds enables it spatially sample the area well.

The intercomparison of RH distributions and variations using six data sets from three sources shows that the ERA-Interim and JRA perform very well. But it also reveals problems in the data sets. Driftsonde hygrometer is incapable of measuring larger RHi (>70%) in the WP above 200 hPa because of its slower response at colder temperatures. Both NCEP reanalyses fail to produce the correct magnitudes and variability of RH in the subtropical Pacific as a result of not assimilating satellite water vapor soundings and lack of in situ observations. Overall, the COSMIC water vapor data show good performance although one has to be cautious on simply interpreting the COSMIC retrieved RHs as true measurements. We propose that the higher RHs at 200–100 hPa in the WP in the COSMIC data are ascribed to the ECMWF first-guess data rather than the refractivity measurements.

The NCAR Drifsonde system has been demonstrated here to be a valuable, cost-effective observing system to fill critical gaps over oceanic and remote polar and continental regions during periods of days and weeks. Its drifting nature with winds and its long duration provide good spatial sampling and coverage. The high-quality and high vertical resolution temperature, pressure, humidity and wind profiles measured by the dropsonde enable detailed thermodynamical and kinematical profiles of the atmosphere, especially over remote and less well observed areas. This paper shows one example, an in-depth study of RH probability distributions and its vertical and horizontal variability in subtropical Ocean. In addition, Drifsonde data are essential to validate models, reanalyses and satellite observations, especially over data-sparse areas. We have shown the shortcomings of the two NCEP reanalyses over the ocean, on the basis of comparisons with Drifsonde data, and illustrated the strong need for in situ upper-air observations over the ocean to constrain global reanalysis. The limitation of the driftsonde hygrometer in measuring high RHs in 200–100 hPa layer pointed out in section 3 calls for future development of better driftsonde hygrometer capable of measuring upper troposphere and even lower stratosphere humidity. In addition, efforts could be made in the future to maximize the usage of the unique driftsonde platform by deploying other sensors to measure ozone and other trace gases. In summary, Drifsonde system has the potential to become a valuable, cost-effective operational system over the ocean for upper air observations.

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M. Bradford, H. Cole, J. Fox, T. Hock, D. Lauritsen, P.-H. Lin, S. Loehrer, C. Martin, J. VanAndel, J. Wang, K. Young, and L. Zhang, Earth Observing Laboratory, National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307, USA. (junhong@ucar.edu)
C.-H. Weng, Department of Atmospheric Sciences, National Taiwan University, No. 1, Sec. 4, Roosevelt Rd., Taipei, 10617 Taiwan.