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In situ observations of dehydrated air parcels advected horizontally in the Tropical Tropopause Layer of the western Pacific

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Abstract. Water vapor observations by chilled-mirror hygrometers were conducted at Bandung, Indonesia (6.90°S, 107.60°E) and Tarawa, Kiribati (1.35°N, 172.91°E) in December 2003 to examine the efficiency of dehydration during horizontal advection in the tropical tropopause layer (TTL). Trajectory analyses based on bundles of isentropic trajectories suggest that the modification of air parcels' identity due to irreversible mixing by the branching-out and merging-in of nearby trajectories is found to be an important factor, in addition to the routes air parcels follow, for interpreting the water vapor concentrations observed by chilled-mirror frostpoint hygrometers in the TTL. Clear correspondence between the observed water vapor concentration and the estimated temperature history of air parcels is found showing that drier air parcels were exposed to lower temperatures than were more humid ones during advection. Although the number of observations is quite limited, the water content in the observed air parcels on many occasions was more than that expected from the minimum saturation mixing ratio during horizontal advection prior to sonde observations.

1 Introduction

Water plays a crucial role on the earth's radiation budget through cloud formation and greenhouse effect. Although its direct anthropogenic production is negligible, globally averaged evaporation from the surface is projected to increase in response to global warming (Houghton et al., 2001), leading to an increase in the tropospheric water vapor concentration. In the lower stratosphere, there is a cooling trend (Randel and Cobb, 1994; Ramaswamy et al., 2001) as a consequence of the decrease in the ozone concentrations (Ra-

maswamy et al., 1996; Hare et al., 2004) and possibly the increase in stratospheric water vapor (Forster and Shine, 1999, 2002). The water vapor increase estimated from NOAA Frostpoint Hygrometer (FPH) data amounts to about 1 % per year from the early 1980's to around 2000 (Oltmans and Hofmann, 1995), which, together with that derived from satellite data in the 1990's (Evans et al., 1998), is much greater than that estimated from the observed rise of methane concentration through its oxidation (Kley et al., 2000). The stratospheric temperature decrease could cause a delay in the expected ozone recovery due to the ban of chlorofluorocarbons (Shindell et al., 1998). Since water takes part in the ozone chemistry through the formation of hydroxyl radical and polar stratospheric clouds, the anthropogenic ozone loss will be enhanced if stratospheric concentration increases (Dvortsov and Solomon, 2001; Stenke and Grewe, 2005). Modification of stratospheric temperatures could lead to a modulation of transport properties which could further influence the stratospheric ozone and water vapor distributions on a global scale. Little is known about the complex feedback processes in the radiation-dynamics-chemistry of the troposphere-stratosphere system.

A basic understanding of water vapor in the stratosphere starts with the idea that it must reflect the temperature history the air experienced before entering the stratosphere. This, together with the global distribution of atmospheric ozone, lead to the description of the general circulation in the stratosphere in which air must enter the stratosphere through the cold tropical tropopause and descend in high latitudes of both hemispheres (Brewer, 1949). Newell and Gould-Stewart (1981) proposed the "stratospheric fountain" hypothesis in which the entry of tropospheric air must be restricted to the tropical western Pacific during boreal winter and the Bay of Bengal in summer. This hypothesis was generally accepted until Sherwood (2000) indicated that the vertical motion near the tropopause over the western Pacific is downward. This

finding was supported in numerical simulations (Gettelman et al., 2000; Hatsushika and Yamazaki, 2001).

Big conceptual changes took place in the 1990's. The upward motion in the tropical lower stratosphere was found to be driven by extratropical wave drag (Haynes et al., 1991; Holton et al., 1995; Plumb and Eluszkiewicz, 1999). Evidence of dehydration associated with passage through the tropical tropopause has been shown to be imprinted as an "atmospheric tape recorder" in the vertical profile of water vapor mixing ratio (Mote et al., 1996). Highwood and Hoskins (1998) shed light on the idea of the tropical transition layer (or tropical tropopause layer; TTL) introduced by Atticks and Robinson (1983). The tropical tropopause is now no longer a clearly defined boundary between the troposphere and the stratosphere but instead should be treated as a transition layer extending from around 200 hPa to 80 hPa levels. This layer is located above the reach of tropospheric deep convection but below the tight control of the extratropical suction pump, thus dividing the two major dynamical processes that could affect the tropical tropopause.

The introduction of the TTL prompted a novel idea on the dehydration processes in the tropical tropopause region. Holton and Gettelman (2001) proposed a new mechanism of dehydration by using a simple mechanistic model, in which the air parcels are dehydrated during the horizontal advection through the "cold trap" region in the western tropical Pacific. This hypothesis exhibits a strong contrast to earlier views in which the cooling due to vertical motion plays an essential role in dehydration. This hypothesis was further examined by using a trajectory model (Gettelman et al., 2002), GCM simulations (Hatsushika and Yamazaki, 2003), and satellite water vapor data (Randel et al., 2001). It is now becoming widely accepted as a key dehydration process for tropospheric air entering the stratosphere.

It should be worth mentioning, however, that the TTL is not a calm region but it is full of disturbances generated by atmospheric waves (Tsuda et al., 1994; Fujiwara et al., 1998). These waves are shown to work as a "dehydration pump" that introduces dry stratospheric air into the uppermost troposphere on the one hand and blocks the entry of humid tropospheric air into the stratosphere on the other due to adiabatic temperature change associated with the vertical displacement (Hasebe et al., 2000; Fujiwara et al., 2001). In case of wave breaking, irreversible mixing in the upper troposphere leaves it under the influence of ozone rich/dry stratospheric air. The variabilities with the intraseasonal oscillation (ISO) could also affect the dehydration efficiency of the TTL. Eguchi and Shiotani (2004) have shown that the "cold trap" dehydration does not occur continuously but rather takes place intermittently in an organized system that takes the form of the combined Kelvin- and Rossby-wave response to the thermal forcing. It is thus strongly controlled by the life cycle and the passage of the ISO. TTL is also subject to hydration due to the northern summer subtropical monsoon. There is evidence that the transport across the subtropical tropopause is strongly influenced by the upper-level anticyclones associated with the monsoons (Chen, 1995; Postel and Hitchman, 1999; Dethof et al., 1999, 2000). As the monsoon anticyclones extend up into the stratosphere, they could also contribute to tropical-extratropical exchange in the lower stratosphere (Horinouchi et al., 2000; Gettelman et al., 2004b).

We are now aware that a large variety of processes that are mutually dependent upon each other through complicated feedbacks are responsible for determining the climatology and the variability of stratospheric water vapor. The tropical tropopause temperature that could regulate the entry of tropospheric water vapor into the stratosphere is reported to have a cooling trend (Zhou et al., 2001; Seidel et al., 2001), indicating the opposite sign for what might be expected for a water vapor increase in the stratosphere. It has been reported, however, that the water vapor trend is not so evident as anticipated previously if viewed from satellite and that there was a sudden drop in the stratospheric water concentration in the year 2001 (Randel et al., 2004, 2006). They also emphasized that the water vapor variations are consistent with the TTL temperature changes on a year-to-year basis. Fueglistaler and Haynes (2005) estimated the interannual variations of stratospheric water vapor by employing numbers of trajectory calculations and suggested that the stratospheric water vapor increase estimated from FPHs could be an overestimate. In view of the great importance of water vapor in our climate system, however, much effort is required in trying to obtain a detailed description of stratospheric water vapor and in understanding the mechanisms of how it is controlled by examining the physical, chemical and radiative processes in the atmosphere.

The Lagrangian temperature history along trajectories has been a convenient measure for studying the dehydration of air parcels entering the stratosphere (e.g. Jackson et al., 2001; Jensen and Pfister, 2004; Fueglistaler et al., 2004, 2005; Fueglistaler and Haynes, 2005). However, there is little in situ water vapor data in the TTL over the western tropical Pacific to check the effectiveness of such calculations. In this paper, first results of the water vapor sonde observations by chilled-mirror hygrometers in the western tropical Pacific, conducted as part of the Soundings of Ozone and Water in the Equatorial Region (SOWER) project in December 2003, are presented along with isentropic trajectory calculations (Sect. 3). Problems in characterizing air parcels with the use of trajectories are investigated prior to it by examining typical examples (Sect. 2) intending to provide the framework for interpreting the water vapor sonde data. The efficiency of dehydration is discussed by comparing the observed water vapor mixing ratio with the saturation mixing ratio of the corresponding air mass estimated from trajectory calculations (Sect. 4).

2 Lagrangian Characterization of Air Parcels

In order to interpret the observed water vapor concentration by radiosondes in terms of dehydration along their excursion in the TTL, trajectory calculations provide useful information on the origin and the water vapor content of air parcels. In addition to the routes air parcels follow, it is also important to consider whether the air parcel retains its identity or is modified due to irreversible mixing along the trajectories. A method that could help investigate such processes is the one that deals with a bundle of trajectories being started simultaneously from multiple points surrounding the point of interest. Figure 1 shows two examples in which the air parcel is advected along the trajectories with its identity retained (top) and modified (bottom). In these calculations, four data points, each of which is distributed either 0.5° of longitude or 0.5° of latitude displaced from Tarawa, Kiribati (1.35°N, 172.91°E) are considered. The region shown by connecting these 4 points with purple lines has a horizontal extent of about 100 km and is hereafter referred to as the core of an air parcel. Additional 4 points connected by yellow-black dotted lines surrounding the core, distributed 1.0° longitude/latitude apart from Tarawa, define the vicinity of the air parcel with a horizontal extent of about 200 km. This will include the maximum range of the radiosonde drift along a single flight. The outermost boundary is defined by 8 points either 2.0° of longitude/latitude separated from Tarawa or both 1.4° longitude and latitude distant from Tarawa, and represents a region of about 400 km of horizontal scale. This will correspond to the horizontal resolution of limb-viewing satellite instruments. The bundle of 16 forward trajectories thus defined are calculated on the 370 K isentropic surface based on the European Centre for Medium-Range Weather Forecasts (ECMWF) operational analysis of 2.5° latitude-longitude grid spacing and 15 standard pressure levels with 12-hour time interval. The trajectories are color-coded by the saturation mixing ratio (SMR) of water vapor estimated from the air temperature along the trajectories; cold (warm) colors correspond to low (high) temperature and low (high) SMR. The location and the shape of the air parcel are expressed by connecting the data points with a time interval of 24 h. The data points that define an air parcel initialized on 00 UT on December 29, 1998 over Tarawa (Fig. 1 top) are advected more or less in parallel to the west for about 4 days. After the fifth day, however, when they encounter the subtropical jet, the core is elongated due to strong horizontal shear so that its identification is terminated for the sake of visibility. During its movement to the west along the equator the SMR takes the value near 2 ppmv so that effective dehydration is expected to occur.

Another example shown at the bottom of Fig. 1 is the case in which the treatment of a single air parcel will be unacceptable. This illustrates a bundle of trajectories that are initialized at 00 UT on 15 December 1998 over Tarawa. The air parcel suffers from east-west elongation while it is advected to the south for 2 days, and then the distortion reaches such
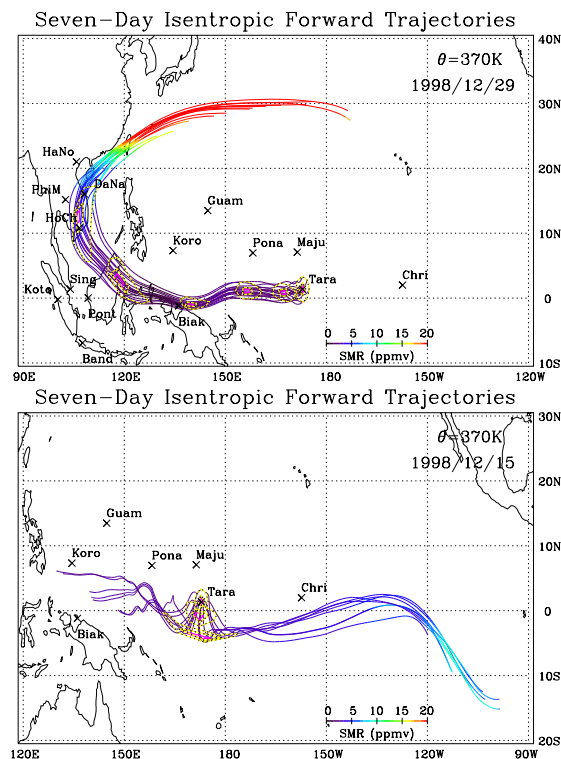

Fig. 1. Isentropic forward trajectories (370 K) initialized at 16 points surrounding Tarawa at 00 UT on December 29 (top) and 15 (bottom), 1998. The advective motion of the air parcel is visualized by identifying the location of its core (purple square) together with its vicinity (yellow-black dotted circles) for each interval of 24 hours. See text for more explanation.

an extent that its core is hardly regarded as a single region. That is, the purple-colored core region breaks up as the data points migrate away to reach thousands of kilometers of separation from each other. For visual clarity, the identification of the core is omitted after two days since initialization in this case. This kind of circulation field must involve a horizontal divergence in the region where the air parcel is advected. In such cases, the location of divergence is often different among altitudes, which results in a huge scatter in the trajectories depending on the layers being considered. Thus the vertical wind structure also plays an essential role in determining the fate of air parcels.

The characteristic features of a bundle of trajectories will thus help to estimate possible dehydration and irreversible mixing that have taken place for advecting air parcels. In the following section, in situ water vapor data given by chilled-mirror hygrometers are examined with the use of backward (rather than forward) trajectories corresponding to each sounding to see the level of coldness the observed air parcels have been exposed. All trajectory calculations are made on isentropes since the use of vertical wind has caused relatively

Table 1. Summary of water vapor soundings during the December 2003 SOWER campaign. Data from the hygrometers/flight numbers shown in italicare not used due to instrumental problems.

Bandung Date	LT–7 Universal Time	Flight Num.	Hygrometer
Dec. 5	0:27	BD210	SW
8	2:02	BD211/212	CFH, SW
10	1:19	BD213/214	CFH, SW
11	1:03	BD215/*216*	CFH, *SW*
12	1:49	*BD217*	*CFH*, *SW*
Tarawa	LT–12		
Dec. 8	6:29	TR001	SW
9	6:12	TR002	SW
10	3:17	TR003	SW

large scatter among trajectories and has shown strong dependency on the choice of analysis field.

3 Analysis of the Water Vapor Sonde Data

In order to capture the air parcels being dehydrated during horizontal advection in the TTL, a series of radio soundings using chilled-mirror hygrometers were conducted at Bandung, Indonesia (6.90°S, 107.60°E) and Tarawa, Kiribati in December 2003 as a part of the SOWER project. SOWER has been using the NOAA/CMDL frostpoint hygrometer (FPH) between 1998 and 2002 (Vömel et al., 2002) and the University of Colorado Cryogenic Frostpoint Hygrometer (CFH) since 2003 (Vömel et al., 2007). It has also been flying the Snow White (SW) hygrometers (Fujiwara et al., 2003) since the year 2000, and has flown nearly 100 sondes. It is not a cryogenic frostpoint hygrometer such as NOAA's, but it utilizes a peltier-based thermoelectric circuit to make a frost on the mirror. Its advantage is that it works without the use of a liquid cryogen so that the preparation and operation for soundings are much easier than FPHs. It also helps to reduce the observational cost remarkably. The applicability of SW to the TTL water vapor observations has been studied by Fujiwara et al. (2003) and Vömel et al. (2003). Although it has a clear limitation in that the cooling efficiency is not high enough for stratospheric measurements, it will operate accurately down to the frost points at –75 to –80°C, that is, up to the middle TTL. In the December 2003 SOWER campaign, some SWs were launched simultaneously with CFHs to reduce observational uncertainties by collecting mutually independent water vapor data (Table 1). The launches in Bandung were scheduled in the morning to avoid possible shower, while in Tarawa they were conducted in the evening in order not to interfere with the routine meteorological service. Although the diurnal variation could possibly bring about systematic difference in the tropospheric

features between the two stations, the TTL will be mostly free from tropospheric diurnal cycle as it is located above the altitude of main convective outflow. Possible effect of tides is also ignored.

Before presenting the sounding data, it is useful to take a look at the background meteorological condition during the campaign. Figure 2 shows the longitude-time sections of temperature (top) and zonal wind (second from top) on 100 hPa over the equator (area-weighted mean within ± 6.25° latitudes) obtained from the ECMWF operational analysis for the month of December 2003. The crosses on the diagram mark the longitude and time corresponding to the sonde observations. The lower two panels are the same as the top except that the monthly mean values are subtracted for each longitude. We could see that the eastward propagating disturbances with simultaneous temperature minimum/zero zonal wind (dashed lines on the lower panels) are superposed on the stationary wavenumber 1 structure with easterly wind maximum around 120°E (upper panels). The sonde observations in Bandung (the crosses on the left hand side) took place during the passage of this disturbance; the first sounding on 5 December may correspond to the westerly maximum (little temperature deviation) while the last one on December 12 may have taken place in the easterly maximum (little temperature deviation) after experiencing the temperature minimum in-between. Those in Tarawa (three marks on the right) took place appreciably earlier than the passage of this disturbance.

The time-height sections of several meteorological quantities as obtained from the ECMWF analysis are shown in Fig. 3, by interpolating the gridpoint values to the location at Bandung. The solid lines in the vertical direction indicate the time of sonde launches. The downward phase propagation such as that shown in purple dashed lines, mutual phase relationship between temperature (left hand diagram in the lower row) and zonal wind (lower middle), and the lack of perturbations in the meridional wind component suggest that this disturbance is brought about by Kelvin wave. The TTL during the period from 8 to 11 December is experiencing the coldest phase of this event. On the other hand, no appreciable disturbances are observed over Tarawa (not shown).

According to the hypothesis of the dehydration pump by Kelvin waves (Fujiwara et al., 2001), the water vapor in the TTL during the campaign period will be saturated so that the intrusion of tropospheric moist air is inhibited by the closed "valve" shut off by Kelvin waves. Figure 4 shows the vertical distributions of the water vapor mixing ratio (thick lines) given by CFH (solid) and SW (dashed), the SMR (thin lines), the ozone mixing ratios (dotted lines), and the potential temperature (dash-dot lines) observed at Bandung (top) and Tarawa (bottom). The water mixing ratio and the SMR are estimated from saturation water pressure e_{sat} corresponding to the frostpoint and atmospheric temperatures,
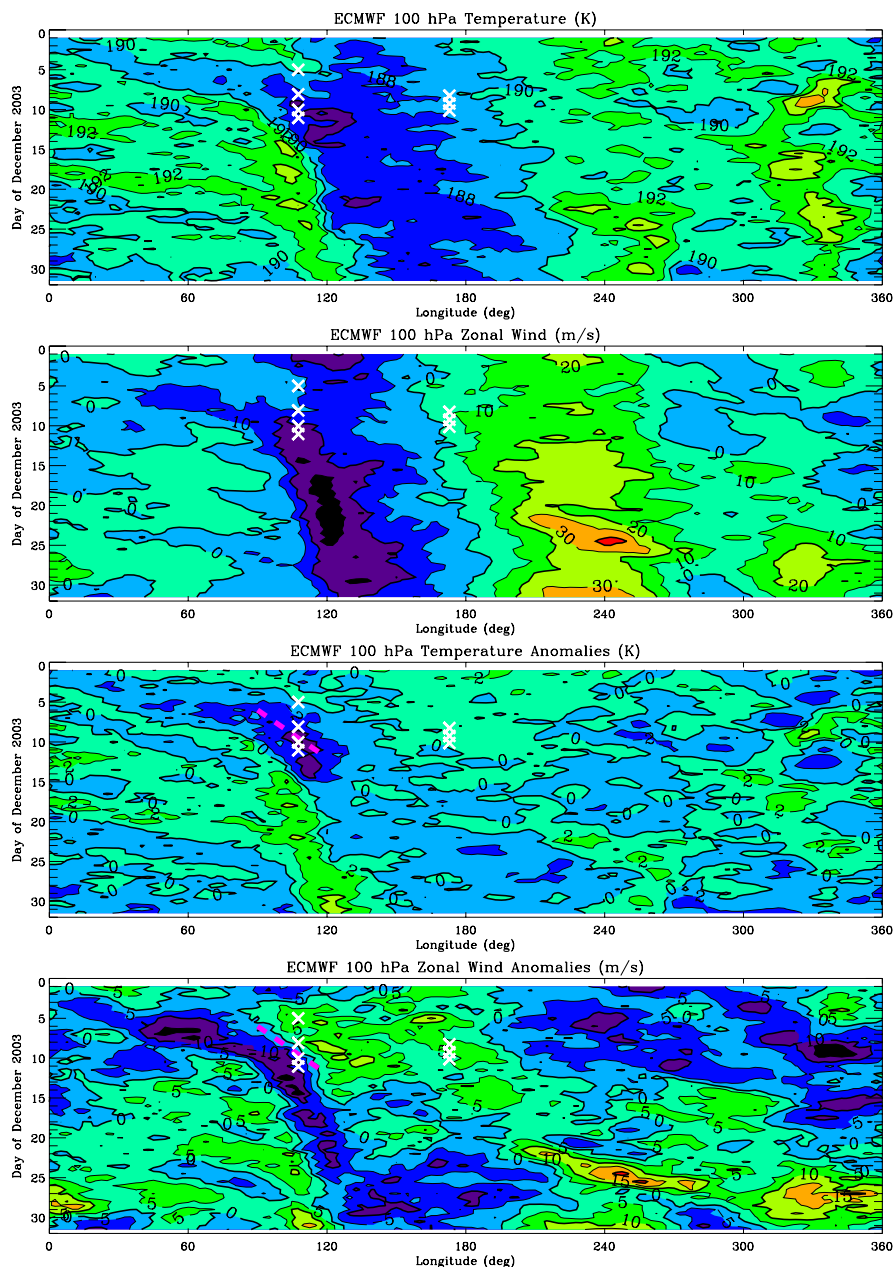
Fig. 2. Longitude-time sections of temperature and zonal wind (upper two panels) on 100 hPa over the equator (area-weighted mean within $\pm 6.25°$ latitudes) being obtained from the ECMWF operational analysis for the month of December 2003. The lower two panels are the same as the top two except that the monthly mean values are removed for each longitude. The crosses in white mark the longitude and time of the radiosonde observations. The dashed purple lines on the lower panels show approximate phase propagation of temperature minimum and zero zonal wind associated with the Kelvin wave.

respectively, by using Goff-Gratch equation:

$$\log_{10} e_{sat} = -7.90298(T_s/T - 1) + 5.02808 \log_{10}(T_s/T)$$
$$-1.3816 \times 10^{-7}(10^{11.344(1-T/T_s)} - 1)$$
$$+8.1328 \times 10^{-3}(10^{-3.49149(T_s/T-1)} - 1)$$
$$+ \log_{10} e_{ws} \quad \text{for liquid surface,} \quad (1)$$

$$\log_{10} e_{sat} = -9.09718(T_0/T - 1) - 3.56654 \log_{10}(T_0/T)$$
$$+0.876793(1 - T/T_0) + \log_{10} e_{io}$$
$$\text{for ice surface,} \quad (2)$$

where T is absolute temperature, T_s=373.16 K, T_0=273.16 K, e_{ws}=1013.246 hPa, and e_{io}=6.10714 hPa (Goff and Gratch, 1946; Murray, 1967). See also Murphy and Koop
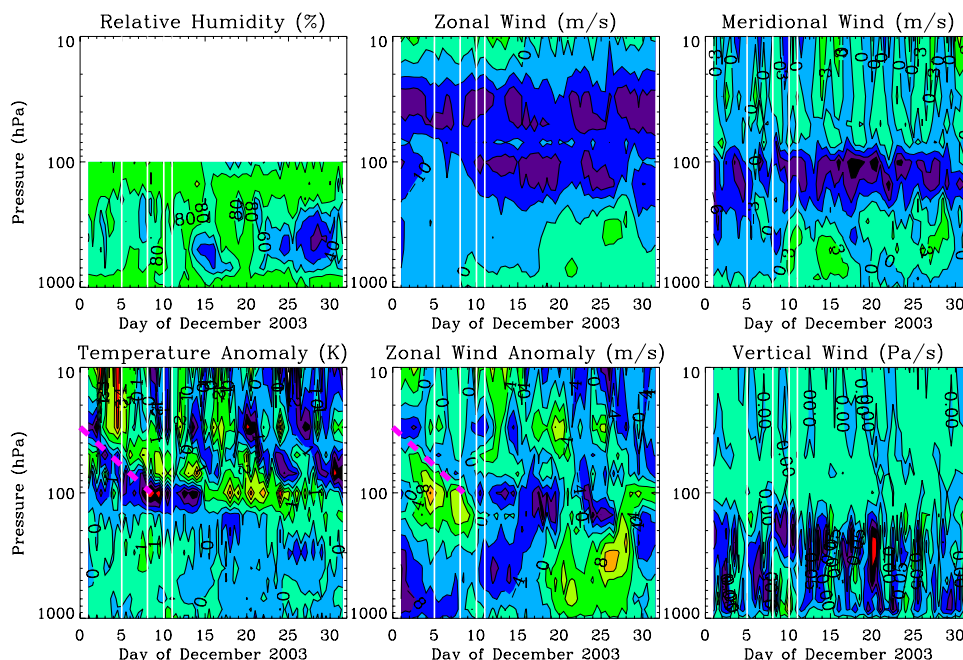
Fig. 3. Time-height sections of relative humidity (%), zonal and meridional wind (m s^{-1}) (upper row from left to right), temperature (K) and zonal wind (m s^{-1}) anomalies, and vertical wind (Pa s^{-1}) (lower row from left to right) for December 2003 interpolated to Bandung from gridpoint values of ECMWF analysis. Relative humidity above 100 hPa is omitted. The dashed purple lines on the lower panels show approximate location of the cold phase of Kelvin wave. Vertical lines in white mark the time of the radiosonde observations.

(2005) for a review. The water mixing ratios are estimated from smoothed frostpoint temperature profile to reduce instrumental noise and are shown only below 80 hPa pressure level as the data above it are not reliable. The SW data above the pressure level that reached the frostpoint temperature below –80°C are also omitted. For the data at Bandung, those on December 5 (BD210) and 12 (BD217) are excluded because the CFH data are not available for the former and some instrumental problem is recognized for the latter. The CFH data above 110 hPa on December 8 (BD211) and the SW data on December 11 (BD216) are also omitted due to an instrumental problem. Although the water vapor data are rather noisy and some discrepancy between the CFH and the SW values is noticeable, we can see that the thick solid and dashed lines (observed water mixing ratio; OMR) almost overlap with thin solid lines (SMR) indicating that the upper troposphere above 150 hPa in Bandung is almost saturated. This is consistent with the expectation from the Kelvin wave effect mentioned above, though other factors may also contribute. In Tarawa, on the other hand, the OMR was often less than SMR in the TTL. The stepwise increase of ozone mixing ratio and potential temperature above 130 hPa in days 9 and 10 reminds us a possible role of small scale waves on the vertical transport of stratospheric ozone rich/dry air into the TTL (Hasebe et al., 2000). The lack of reliable water vapor data up into the lower stratosphere, however, makes it hard

to further explore the drying mechanism.

Diabatic heating is generally small in the TTL (Gettelman et al., 2004a), although the heating rate strongly depends on the cirrus formation and the existence of underlying convective clouds (Hartmann et al., 2001). Therefore the day-to-day fluctuations of water vapor and ozone mixing ratios are better examined by changing the vertical scale to the potential temperature. In this framework, any variability due to adiabatic vertical motion such as that brought about by Kelvin and small scale waves will disappear during the one-week campaign period in which the diabatic heating could be mostly neglected. Figure 5 shows the vertical distributions of temperature (left), ozone (center) and water vapor mixing ratios (right) given by CFH (solid lines) and SW (dashed). Top panels show the profiles taken at Bandung while those on the bottom are from Tarawa. Some trimming (as in Fig. 4) of water vapor data are applied due to instrumental limitations. The vertical distribution of temperature shows a specific structure exhibiting curvature changes at around the 345 K and 355 K isentropes. The atmospheric region between these isentropes corresponds to the lower TTL. The water vapor mixing ratio shows a rapid decrease with respect to height in this region. The profiles between 350 and 360 K isentropes in Bandung are in two groups; the one having higher water vapor values in the earlier days of the campaign (December 5 (black) and 8 (red)) and the other with lower values during the later
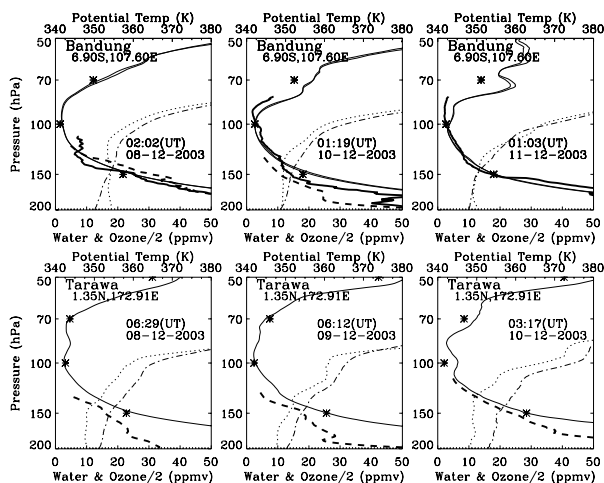
Fig. 4. Vertical distributions of water vapor mixing ratio (heavy lines) observed by CFH (solid) and SW (dashed) hygrometers, saturation mixing ratio (SMR) estimated from temperature (thin lines), ozone mixing ratio scaled by a factor of 2 (dotted lines), and potential temperature (dash-dot lines) at Bandung (top) and Tarawa (bottom) in December 2003. Note that two SMR profiles appear on the diagram for Bandung due to the dual launch of radiosondes. The asterisks are the SMRs given from ECMWF temperature field interpolated to the corresponding station.

Fig. 5. Vertical distributions of temperature (left), ozone mixing ratio (center), and water vapor mixing ratio (right) obtained by chilled-mirror hygrometers SW (dashed lines) and CFH (solid) in December 2003. Top panels show those from Bandung and the bottom are from Tarawa.

days (December 10 (green) and 11 (blue)). This grouping does not apply, however, for the ozone mixing ratio; the profile for December 5 shows a decrease with respect to altitude while the others are almost constant in this height range with the values for December 8 a little higher. In Tarawa, the water vapor mixing ratio on December 10 is generally higher than the others below 360 K. These two profiles lie between the two groups in Bandung. The ozone profiles over Tarawa remain almost the same for three days. The dry layer between the 350 and 355 K isentropes observed during the later period of the Bandung observations could be brought about by the dehydration that took place during horizontal advection before arriving at Bandung. To examine if such differences could be interpreted by the level of coldness the air parcels have experienced during horizontal advection, the backward trajectories corresponding to the sonde observations provide useful information. A brief examination on the accuracy of meteorological field is made as shown in Fig. 4, in which the SMRs given from the ECMWF temperatures interpolated to the corresponding station (asterisks) are compared against those observed by chilled-mirror hygrometers. The agreement is good on 150 and 100 hPa except when the wavy structure due probably to small scale waves modifies the profile. Some examples of isentropic backward trajectories corresponding to sonde observations are shown on 355 K surface in Fig. 6 for Bandung (left) and Tarawa (right). The trajectories for Bandung can be regarded as the case in which
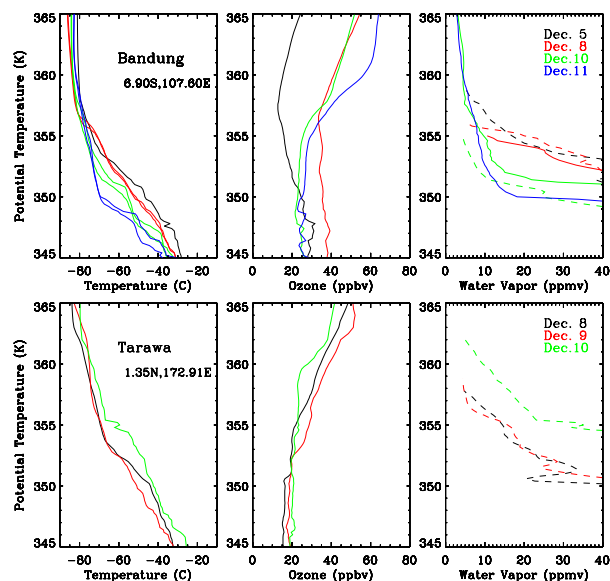
the air parcel retains its identity during advection. Trajectories corresponding to the relatively humid days of December 5 (top) show that the air parcels originated in midlatitudes have not been exposed to extremely low temperature (SMR of about 10 ppmv), while those of the dry days of December 11 (bottom) have spent a relatively long time advecting along the 5°S latitude circle and are processed by low temperatures (SMR of around 5 ppmv) just before the arrival at Bandung. Thus the temperature history that the air parcels have experienced could well be reflected in the observed water vapor mixing ratio. The trajectories for Tarawa, on the other hand, show a large scatter between the members in each bundle of trajectories, so that the identification of the core is abandoned for those earlier than four days before the sounding. Thus it suggests that the air parcels' identity was established just a few days earlier (Sect. 2). It is also seen that the temperature they have been exposed to is appreciably higher than that for the soundings at Bandung. The range of SMR during 24 h before arrival at Tarawa is about 16–23 ppmv for those parcels observed on the days 8 and 9 and about 20–33 ppmv for that of the day 10, again corresponding qualitatively to the observed difference in the water vapor mixing ratio around 350–355 K level (Fig. 5).

4 Discussion

During the SOWER campaign December 2003, two kinds of hygrometers, CFH and SW, were flown in the tropical
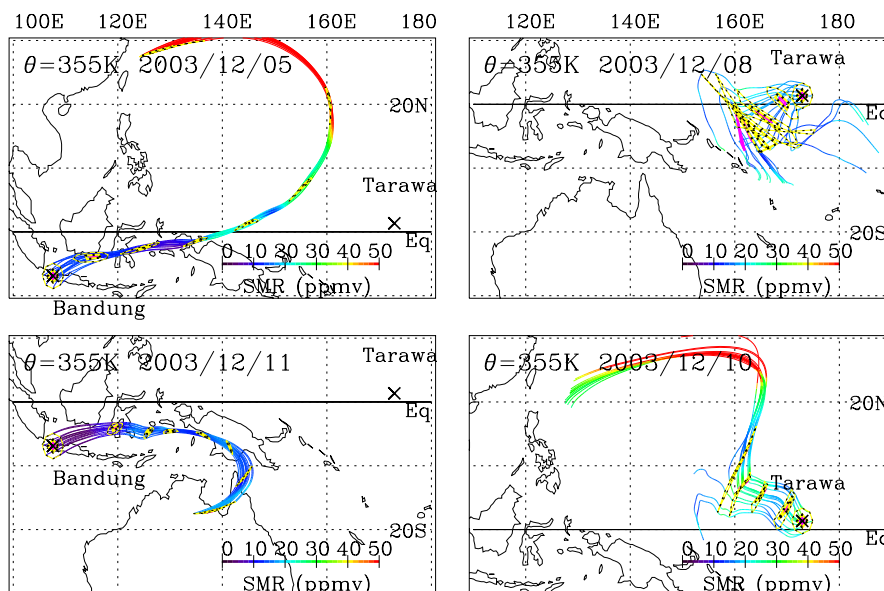
Fig. 6. A bundle of isentropic backward trajectories (355 K) corresponding to the soundings on December 5 and 11 over Bandung (left), and December 8 and 10 over Tarawa (right) color-coded by saturation mixing ratio of water vapor. See text for the details.
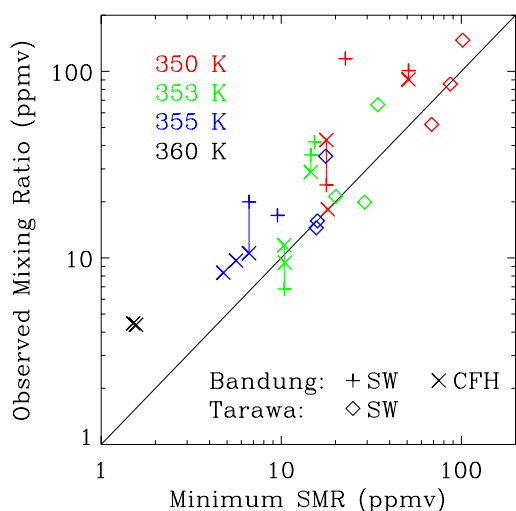

Fig. 7. A scatter plot between the minimum saturation mixing ratio of the core region along isentropic backward trajectories (abscissa) and the observed mixing ratio (ordinate) on the surfaces of 350 (red), 353 (green), 355 (blue) and 360 K (black). Observational stations and instruments are identified by specific marks. Simultaneous observations by CFH and SW are connected by solid lines.

western Pacific to observe dehydrated air parcels horizontally advecting in the TTL. Reasonable agreement was attained between the two up to around 355 K isentropic surface. The OMRs on 355 K isentrope at Bandung are grouped into wet (about 20 ppmv) and dry (about 10 ppmv) cases observed on

5–8 and 10–11 December , respectively. The trajectory calculations suggest that such differences reflect the coldness the air parcels have experienced during advection. However, several other causes could be pointed out: Sub-grid scale motion that is missing in the analysis field might have affected trajectories and water content, the analysis field could have a bias against sonde observations, small errors in pressure and temperature could have resulted in large difference in the OMR on a specified isentrope due to strong vertical gradient of water profile, organized convection along the trajectories might have moistened the air parcel during advection, or the efficiency of dehydration is affected by supersaturation which is not well understood. All these possibilities need to be considered before concluding any definite statement.

In spite of these limitations, it is interesting to look into some more details on the relationship between the OMR and the degree of coldness the air parcels are exposed to during horizontal advection before soundings are made. Such a relationship is examined in Fig. 7, in which the ordinate is the OMR by SW (+ in Bandung and ◇ in Tarawa) and by CFH (×) and the abscissa is the minimum SMR (SMR_{min}) of corresponding air parcel that is defined by the average of the core region (Sect. 2). The period searching for the SMR_{min} is taken to be seven days for the trajectories from Bandung, but it is chosen to be four days for those from Tarawa considering the modification of air parcels' identity (Fig. 6). The values on 360 K are also shown relying on the CFH soundings on 10 and 11 December. There found no systematic difference between the simultaneous observations by SW and CFH (connected by solid lines in Fig. 7). The

well-defined correspondence between OMR and SMR_{min} depicted in Fig. 7 is due primarily to the strong vertical gradient of water mixing ratio in the lower TTL; the values on 350 K (red) are much greater than those on 360 K (black) with some intermediate values on 353 (green) and 355 K (blue). In addition to this general behavior, however, we could see that the air parcels with lower SMR_{min} tend to have lower OMR on each of the three isentropes (350, 353 and 355 K) at both stations though the sample size is small.

Another point of interest is that, while some plots sit quite close to the "saturation line" connecting the lower left and upper right corners, more data points are located above it rather than below it. It implies that appreciable number of air parcels go through the cold region without being dehydrated to the level of SMR. It is quite natural if some processes such as supersaturation and/or re-evaporation before sedimentation are important. Another possibility is that the air parcels were moistened by deep convection. Actually our investigation on the satellite (GOES 9) IR images, while those on 4 December are missing, detected some events in which the temperature of advecting air parcel was higher than that of the cloud top corresponding to its location. In such cases, appreciable amount of water could be injected to the air parcels and isentropic trajectory calculations may not be properly extended backward beyond that point. Those on 350 K surface, sometimes coming down to around 200 hPa, are frequently affected by convection, while those on 360 K travel mostly above convective clouds. On 355 K surface, the most prominent convective event was observed on December 5 for the trajectories corresponding to the sounding on December 10 at Bandung. However, the OMR for this sounding appears similar to that of others (Fig. 5). The air parcels will be more liable to be affected by convection in Tarawa than in Bandung as can be expected from the divergent/convergent nature of the trajectories (Fig. 6). We found that the air parcels on 355 K corresponding to the soundings of December 9 (dry) and 10 (wet) in Tarawa may be subject to convective moistening a few days before soundings. As a whole, however, there found no systematic correspondence between the OMR and the possible convective moistening in Fig. 7.

The effect of wave-driven temperature perturbations unresolved in the analysis field (Jensen and Pfister, 2004) does not help reduce the difference between OMR and SMR_{min}, although this does not rule out possible contribution of such an effect. Information on the formation of TTL cirrus clouds, such as that given by lidars, will help reduce such uncertainties (Shibata et al., 2007). Accumulation of observational evidences such as those shown in the present study is quite important to examine the efficiency of dehydration in the TTL and to better parameterize microphysical processes in dehydration models. It will also serve to confirm if the simplified treatment of dehydration such as that performed by Fueglistaler et al. (2005) could be justified for the purpose of estimating the annual mean and the seasonal and interannual variations of stratospheric water.

It is also worth mentioning that both OMR and SMR_{min} are mostly higher in Tarawa than in Bandung if compared on the same isentropes (Fig. 7). Although the observed air masses are not identical between the two stations, this will be related to the fact that Tarawa is generally located on the upstream side of Bandung for the air parcels migrating in the TTL. Thus the difference in the climatological OMR between the two stations is a measure of the efficiency of dehydration during horizontal advection in the western tropical Pacific. To make this argument more quantitative, repeated sonde observations of the same air mass following its motion is quite interesting. Such an idea, "match" technique, was put forward and brought into practice for the study of ozone depletion in the stratospheric winter polar vortex (Rex et al., 1998). The water vapor "match" in the TTL of the western Pacific, if successful, will give us interesting information for the study of TTL dehydration. Relatively good agreement seen in the SMRs estimated by ECMWF analysis and sonde observations (Fig. 4) is encouraging, although the analysis is not yet comprehensive and things might look different away from sounding sites.

5 Concluding Remarks

The accumulation of observational evidence on the distribution and variability of water vapor in the TTL is crucial for understanding the dehydration processes acting on air parcels entering the stratosphere. In situ balloon-borne chilled-mirror hygrometer observations are effective for this purpose due to their high vertical resolution and instrumental mobility. The Lagrangian characterization of air parcels suggests that the modification of air parcels' properties could result from the branching-out and merging-in of nearby trajectories.

Water vapor data taken by chilled-mirror hygrometers in the western tropical Pacific during the December 2003 SOWER campaign have been analyzed to study the efficiency of dehydration by taking the advantage of four dual launches of SW and CFH (in addition to several single launches of SW alone). The day-to-day variations of the water vapor mixing ratio in the region between the 350 and 355 K isentropes can be interpreted on the basis of the origin of the air parcels and by the degree of coldness the air parcels are exposed to during horizontal advection. Although the number of observations is still too small, the air parcels observed in the current study retained the water vapor more than that expected from the minimum saturation mixing ratio along trajectories on many occasions.

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