Ten Years of Measurements of Tropical Upper-Tropospheric Water Vapor by MOZAIC. Part II: Assessing the ECMWF Humidity Analysis

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ABSTRACT

In a recent publication (Part I), the authors introduced a data source—Measurement of Ozone and Water Vapor by Airbus In-Service Aircraft (MOZAIC)—for monitoring and studying upper-tropospheric water vapor (UTWV) and analyzed 10 yr (1994–2004) of MOZAIC measurements of tropical UTWV in its climatology, variability, transport, and relation to deep convection. In this study (Part II), MOZAIC is used to assess the ECMWF humidity analysis over the tropics, taking advantage of the unique nature of the MOZAIC data, namely, the long data record, near-global coverage, and high accuracy.

In parallel to Part I, the ECMWF UTWV analysis is assessed against MOZAIC in the following five aspects: 1) annual cycle, 2) vertical structure, 3) probability density functions (PDFs), 4) moisture flux divergence, and 5) interannual variability. The annual cycle of the ECMWF UTWV shows a similar pattern as MOZAIC but has an overall dry bias of about 10%–30% relative humidity with respect to ice (RHi). The dry biases are larger in the deep tropics than the subtropics and larger over the Asian monsoon region than the tropical Atlantic region. The increase in RH with height (from about 300 to 200 hPa) as observed by MOZAIC is largely missing in the ECMWF analysis, which has a roughly constant RH profile. The bimodal distribution of tropical UTWV is well established in MOZAIC, but for ECMWF, the moist mode is abruptly cut off at 100% RHi due to the lack of ice supersaturation (ISS) in the forecast model. Lack of ISS capability is, however, not the only cause for the dry bias in the ECMWF; it also has more occurrences of lower humidity compared to MOZAIC. There is also evidence that ECMWF underestimates the range of upper-tropospheric humidity (UTH) variation. A comparison of moisture flux divergence is conducted to assess the ability of ECMWF to capture the divergent transport of water vapor. It is shown that the ECMWF can represent the distribution of this quantity fairly well, although the dry bias leads to some underestimate of the magnitude. Finally, the authors show a comparison of the ECMWF and MOZAIC depictions of the interannual variation of UTWV during the 1997/98 ENSO event as an illustration that UTWV variations are more difficult to capture than those of the UT temperature.

1. Introduction

Upper-tropospheric water vapor (UTWV) is one of the least well measured and thus most poorly understood atmospheric variables. Although occurring in very small amounts, its radiative effects are significant in determining the energy budget of the earth's climate system and the overall climate sensitivity to the buildup of anthropogenic greenhouse gases (Houghton et al. 2001). Regular observations by the meteorological services are usually confined to the pressure levels below 300 hPa as radiosonde humidity sensors fail at low temperature (Elliot and Gaffen 1991; Wang et al. 2003). Operational satellites, on the other hand, provide coarse vertical resolution (Soden and Bretherton 1993; Stephens et al. 1996) and are not usable in the presence of high cloudiness (Wu et al. 1993; Bates et al. 1996). In a recent publication by Luo et al. (2007, hereafter Part I), we introduced an alternative data source for moni-

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toring and studying UTWV: the Measurement of Ozone and Water Vapor by Airbus In-Service Aircraft (MOZAIC).

MOZAIC was a project of the Commission of the European Union. From August 1994 to April 2004, regular observations of ozone and water vapor were made on board five A340 aircraft, yielding data around the globe (with the exception of the Pacific and Australia). A more detailed description of MOZAIC, its follow-on activities to the present, and its prospect for the future is given in the appendix. The MOZAIC data on upper-tropospheric humidity (UTH)[1] have a quality-assured mean accuracy of 5% (Helten et al. 1998, 1999), superior to that of most other humidity data sources. UTH data with high vertical resolution, more accurate than those from MOZAIC, are only obtainable from campaign-style research instrumentation on dedicated balloons and research aircraft (Kley et al. 2000). In Part I, we have analyzed 10 yr (1994–2004) of measurements of tropical UTWV[2] by MOZAIC and described in detail its climatology, variability, transport, and relation to deep convection. The unique nature of the MOZAIC UTWV data—long record, near-global coverage, and high accuracy—also makes them a valuable basis or "ground truth" against which other UTWV products can be evaluated. In this study, we use MOZAIC to assess the European Centre for Medium-Range Weather Forecasts (ECMWF) humidity analysis. Several key variables from the ECMWF analysis—specific humidity, RH, temperature, and winds—are included in the MOZAIC database being interpolated spatially and temporally to match up with each MOZAIC measurement.

Unlike a free-running general circulation model (GCM), ECMWF analysis incorporates observations from radiosondes and satellites through an elaborate data assimilation system (Courtier et al. 1998; Rabier et al. 2000) and is therefore, in principle, capable of providing a fairly accurate account of the humidity field. In fact, the analysis is often used as the verification of forecasts from the same system: forecasts that come closer to the analysis are considered to have better forecasting skills (e.g., Andersson et al. 1998; Klinker et al. 2000). However, humidity analysis, especially tropical UTH analysis, is still uncertain because both radiosondes and satellites have difficulties in measuring humidity with high accuracy, making the UTH analysis, to a large extent, a forecast model product. Several previous studies have attempted to evaluate the ECMWF UTH analysis using reliable, in situ measurements. Ovarlez and van Velthoven (1997) and Ovarlez et al. (2000) used data collected from two field campaigns called Pollution from Aircraft Emission in the North Atlantic Flight Corridor (POLINAT). They found in this particular region (i.e., North Atlantic) that the ECMWF upper troposphere (UT) shows a moist bias under dry conditions and a dry bias under wet conditions. A similar conclusion was also drawn from the study of ECMWF and MOZAIC for the whole Atlantic region by Smit et al. (2005). In a recent publication, Oikonomou and O'Neill (2006) briefly compared UTWV from the 40-yr ECMWF Re-Analysis (ERA-40) with MOZAIC (although the bulk of their paper concerns the ERA-40 stratospheric ozone and water vapor in comparison with satellite data). They only considered zonal means[3] and found that the ERA-40 UTWV is considerably overestimated, compared to MOZAIC, by 20% in the tropical latitudes and even more in midlatitudes.

A question to ask of these previous studies is as follows: are they consistent with each other in the assessments of the ECMWF UTWV product? There are several difficulties in directly comparing the conclusions from Ovarlez and van Velthoven (1997) and Ovarlez et al. (2000) with those from Oikonomou and O'Neill (2006), aside from the fact that UTWV of the operational ECMWF analysis may differ somewhat from that of the reanalysis (although they use similar forecast systems with different resolutions). First, they examined different statistics of UTWV: Ovarlez and van Velthoven (1997) and Ovarlez et al. (2000) focused on the modes (i.e., dry and moist conditions) whereas Oikonomou and O'Neill (2006) looked at the means. Since UTWV often shows bimodal distribution (Zhang et al. 2003; Part I), especially over the tropics, the bulk mean usually lies between the two modes. Similar means can be obtained through very different combinations of the modes. A more desirable approach would therefore be to study entire probability density functions (PDFs). Very few previous studies adopted this PDF-oriented approach [with the notable exception of Nawrath (2002) and Smit et al. (2005), who analyzed the UTH

[1] Following the terminology used in Part I, UTH refers particularly to upper-tropospheric RH, UTWV to upper-tropospheric moisture in general, and RHi to RH with respect to ice.

[2] Only the tropics are considered because the flight levels of MOZAIC aircraft (300–200 hPa) are almost always below the tropical tropopause layer (TTL) there, but may extend into the lower stratosphere in higher latitudes.

[3] In Oikonomou and O'Neill (2006), zonal means were actually calculated over the regions where MOZAIC data are available. In the tropics, these regions are the tropical Atlantic, tropical Africa, and Asian monsoon region (see Fig. 1 for MOZAIC coverage).

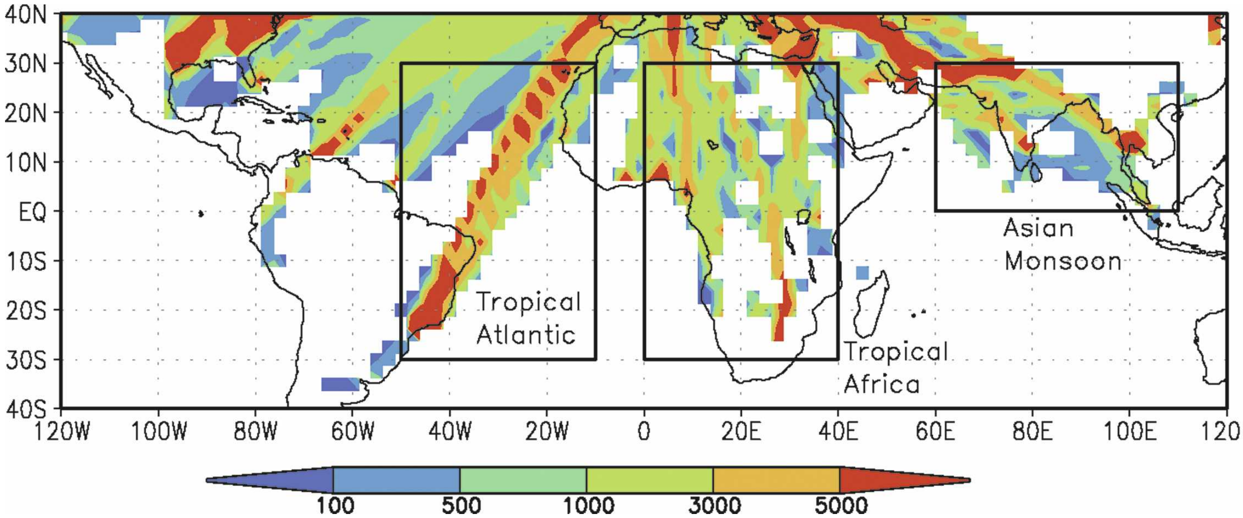

FIG. 1. Geographical map of the three tropical regions and the number of measurements per 2.5° box (August 1994–2004).

PDFs for the Atlantic region]. Second, unlike many well-mixed trace gases, tropical UTWV is highly variable; substantial regional differences are found even for a single latitudinal band (Part I). Zonal averages largely smear out regional contrasts, which contain valuable information about the influences on UTWV distribution of different dynamic regimes and convective activities. Third, water vapor is measured by at least two quantities—specific humidity (or mixing ratio) and relative humidity (RH). They are linked together through temperature. Oikonomou and O'Neill (2006) only compared water vapor mixing ratios and concluded that the ECMWF has a wetter UT than the MOZAIC. But this could be made possible through several different combinations of biases in RH and temperature. An important point made in this paper is that although specific humidity is a more direct measure of the water vapor amount in the atmosphere, it is often RH, with its intimate connection to cloud microphysics, that is more informative and revealing in exposing the model deficiencies (e.g., cloud and convection parameterizations). Therefore, more emphasis is placed on RH in this study although all three fields (specific humidity, RH, and temperature) are also cross-examined.

In light of these considerations, we conduct a detailed evaluation study of tropical UTWV analysis by the ECMWF using MOZAIC, in parallel to Part I. The overarching goals are to 1) characterize the biases in the ECMWF in a comprehensive and unambiguous way, and 2) explore possible relationships between these biases and underlying model deficiencies. The ECMWF UTWV analysis is assessed against MOZAIC in the following five aspects: annual cycle, vertical structure, PDFs, moisture flux divergence, and interannual variability. This article is organized as follows: section 2 briefly describes the MOZAIC program and data and the ECMWF humidity analysis; section 3 presents the comparison results placed in the context of our understanding of climate dynamics of the tropical upper troposphere and of the ECMWF assimilation system; finally, section 4 summarizes the study.

2. Overview of the MOZAIC data and the ECMWF analysis

Part I has provided a detailed description of the MOZAIC program and data. Here, we only cover a few essential facts for completeness (see the appendix for more detail of the MOZAIC program and observations). MOZAIC was sponsored by the European Commission and major European airlines for automated measurements of ozone and water vapor on board five Airbus A340 long-range passenger aircraft on scheduled flights. It was launched in January 1993 and has been operational from August 1994 to April 2004. The measurements were continued after 2004, although on fewer aircraft, and are still ongoing. The time resolution of the MOZAIC RH measurements is 1 min; consequently, the equivalent spatial resolution, given the cruise speed, is about 15 km. Aircraft data such as position, pressure, temperature, wind speed, and Mach number are also recorded. In the tropical regions, MOZAIC aircraft at cruise altitude fly at five discrete pressure levels: 288, 262, 238, 217, and 197 hPa. Roughly 32% of the flights cover the three tropical regions selected for Part I and this study (Fig. 1).

Included in the MOZAIC database are also the ECMWF humidity analysis (both specific humidity and RH), temperature, and winds. The ECMWF analysis is produced operationally through an elaborate data assimilation system that evolves with time, namely, optimal interpolation (OI) algorithm before January 1996, three-dimensional variational data assimilation (3DVAR) assimilation from January 1996 to November 1997 (Courtier et al. 1998; Rabier et al. 1998; Andersson et al. 1998), and four-dimensional variational data assimilation (4DVAR) afterward (Rabier et al. 2000; Mahfouf and Rabier 2000; Klinker et al. 2000). Both conventional, in situ observations (e.g., radiosonde measurements) and nonconventional remote sensing observations (e.g., satellite-measured radiances) are assimilated in the ECMWF analysis. However, MOZAIC data were not included, thus guaranteeing an independent assessment of the ECMWF analysis. The horizontal resolution of the ECMWF analysis saved in the MOZAIC database is T213 (~0.5°). The vertical resolution was 31 levels until 8 March 1999, 50 levels from 9 March 1999 to 10 October 1999, and 60 levels afterward. The time resolution is 6 h at 0000, 0600, 1200, and 1800 UTC. To match each MOZAIC measurement, the ECMWF analysis data are interpolated through a cubic interpolation in space and a linear interpolation in time. The differences in spatial and temporal resolutions between MOZAIC and ECMWF data are a potential source for uncertainty and will be discussed in interpreting the following comparison results.

3. Comparison between MOZAIC and ECMWF analysis

In parallel to Part I, the ECMWF analysis is evaluated against MOZAIC data for the following five aspects related to UTWV climatology and variability: annual cycle, vertical structure, PDFs, moisture flux divergence, and interannual variability for each of the three tropical regions—the tropical Atlantic (30°S–30°N, 50°–10°W), tropical Africa (30°S–30°N, 0°–40°E), and the Asian monsoon region (0°–30°N, 60°–110°E).[4]

a. Annual cycle

We constructed, in Part I, a composite annual cycle of UTH as a function of latitude, based on nearly 10 yr of MOZAIC data. The same analysis procedure is performed on the ECMWF data and the comparison is shown in Fig. 2. Only RH is considered in Fig. 2 because it has a relatively weak dependence on height (see section 3b) so all five flight levels can be used to calculate the composite annual cycle giving a larger sample size. Specific humidity, on the other hand, decreases dramatically with height. But specific humidity is examined alongside RH in some other subsections.

Overall, the MOZAIC and the ECMWF UTH annual cycles show similar patterns: their seasonal migration keeps close pace with that of the corresponding ITCZ in each region, indicating the convective influence on UTH distribution. Nevertheless, it is also noticed that UT of the ECMWF analysis is much drier than that observed by MOZAIC aircraft by about 10%–30% RHi, with the difference being larger in the deep tropics than the subtropics. This dry bias has been seen by Nawrath (2002) and Smit et al. (2005) over the tropical Atlantic and is now extended to include more regions. There are also some regional differences as larger dry biases are seen over the Asian monsoon region and tropical Africa than the tropical Atlantic, particularly in the corresponding deep tropics. Tropical Atlantic has less coverage of conventional observations (e.g., radiosondes) than the tropical Africa and Asian monsoon regions. The fact that the Atlantic UTH analysis contains less bias than the other two regions suggests that satellite observations have a larger (positive) impact on the analysis over this oceanic area. Note that because of less high cloudiness over the tropical Atlantic (Part I), it has more usable satellite radiance measurements. This interpretation is also consistent with Klinker et al. (2000), in which they found that satellite data have a larger influence on the forecasts than conventional data over the tropics and Southern Hemisphere (the reverse is true for the Northern Hemispheric continents). Another reason for the regional differences is that the Asian summer monsoon region and tropical Africa have much more frequent occurrences of ice supersaturation associated with more extensive cirrus, which the ECMWF has a more difficult time capturing (see Part I and also section 3c for comparison of PDFs of UTH).

b. Vertical structure

UTH vertical structure has not been well studied, owing to the sparseness of observations. RH usually increases with height in the tropical UT as observed by a number of field campaigns (e.g., Kelly et al. 1993; Jensen et al. 1999; Wang et al. 2003) and is further corroborated and generalized to include almost the whole tropics with 10 yr of MOZAIC measurements (Part I). Folkins et al. (2002) explain this phenomenon through a simple model in which convective detrainment moistening and subsidence drying work together to determine the unique vertical structure of tropical UTH. In going from 9 to 12 km (the altitude range of the MOZAIC flight cruise levels), one would in general

[4] The choice of the three regions is attributed to their climatological importance and the geographical coverage of the MOZAIC flights.

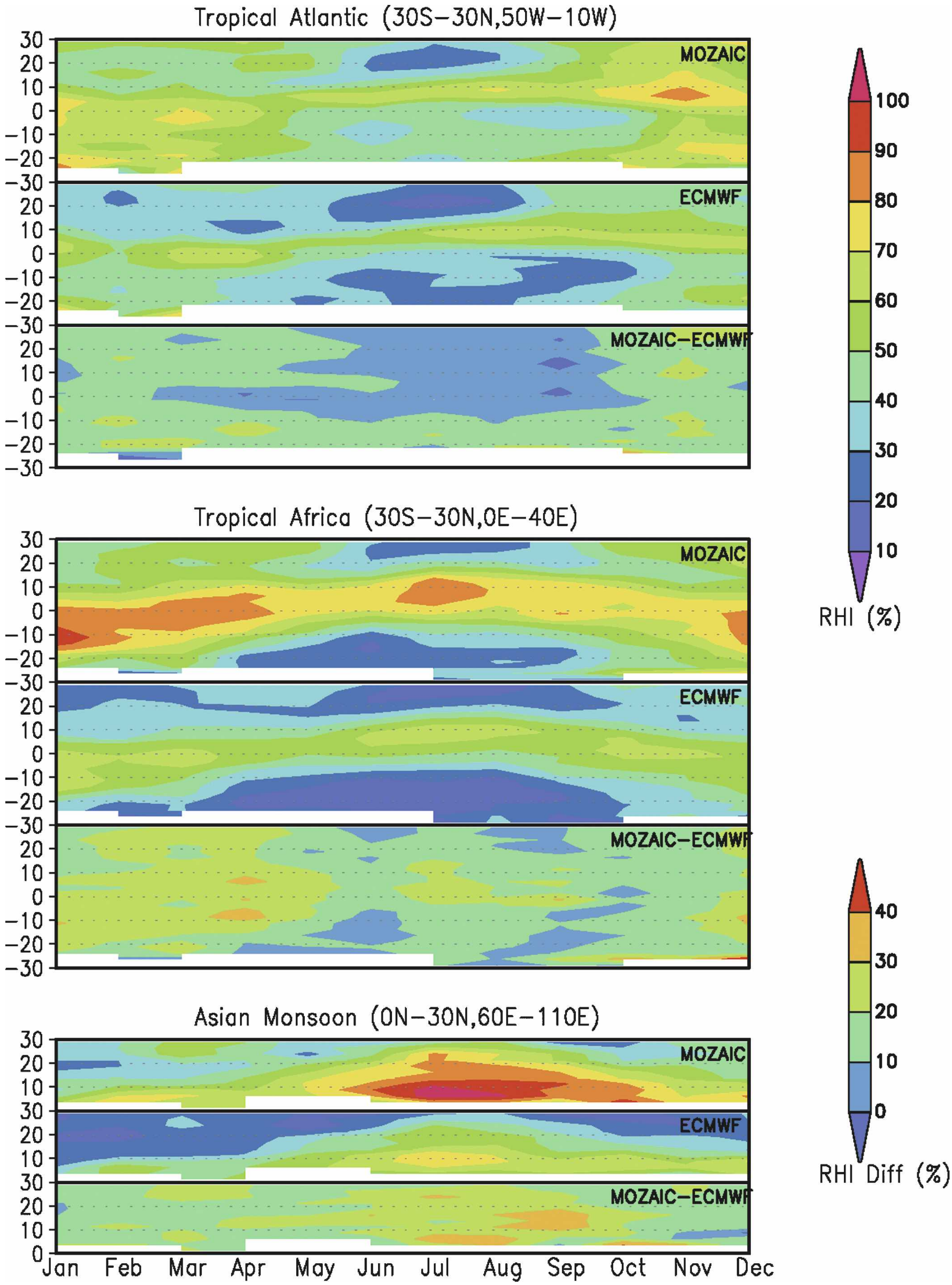

FIG. 2. Composite annual cycle of UTH or RHi as a function of latitude for MOZAIC, ECMWF, and their differences (MOZAIC − ECMWF).

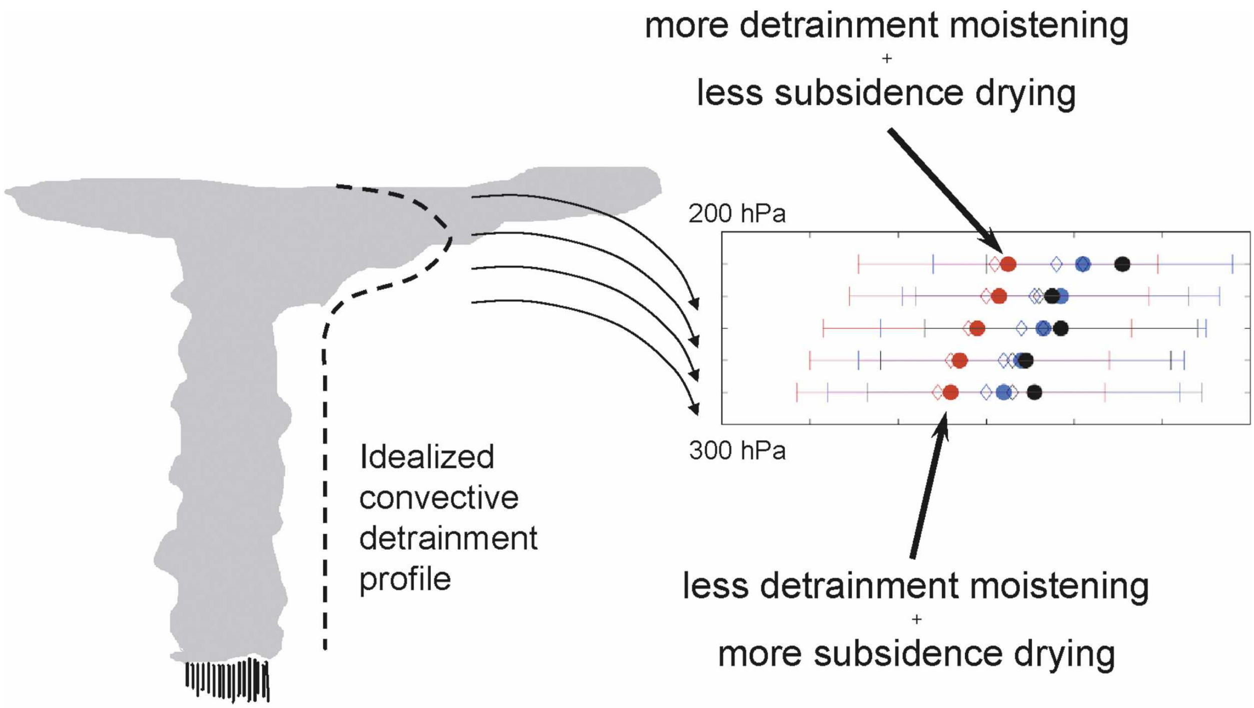

FIG. 3. Schematic summarizing the mechanisms that control the vertical structure of UTH, following Folkins et al. (2002). The inset is adopted from Fig. 4a, which is intended to show that UTH increases with height. See Fig. 4a for the meanings of the dots, bars, and colors (the detail of these symbols is not important here).

expect the RH to increase with altitude because the average amount of subsidence decreases with height.[5] Furthermore, moistening through convective detrainment increases with height (from 9 to 12 km) because the averaged maximum outflow level at the tropical latitudes is located at about 12–13 km (Folkins et al. 2002), although it can vary from 13 km in the western Pacific to 11 km in the eastern Atlantic where there are lower sea surface temperatures (Thompson et al. 1979). Therefore, over much of the tropics, both subsidence drying and detrainment moistening contribute positively to the increasing RH with height as observed by MOZAIC (see the schematic in Fig. 3). This also explains why subtropical UTH shows a less rate of increase with height than does the deep tropics as observed by MOZAIC (Part I; also see the top panels of Figs. 4a,b) because convection and the associated detrainment moistening are infrequent in the subtropical regions, leaving subsidence, to a large extent, to operate alone.

Figures 4a,b compare the height dependence of UTH (in RHi). Deep tropics (10°S–10°N) and subtropics (30°–20°S and 20°–30°N) are plotted separately to take into account their different characteristics. It is seen that in addition to an overall dry bias for the ECMWF (10%–30% RHi), the increase in UTH with height as shown in MOZAIC is largely missing in the ECMWF; instead, it shows a rather constant UTH nearly independent of height (except perhaps in the Asian monsoon region). At face value, the apparent reason for the lack of UTH vertical structure in the ECMWF is due to larger dry bias at higher levels (such as 197 hPa) than at lower levels (such as 288 hPa), as shown in the bottom panels of Figs. 4a,b (which plot the differences). There are, however, deeper and more fundamental reasons. Based on the simple model in Folkins et al. (2002), one would expect there might be deficiencies in the ECMWF's representations of the subsidence and/or convective detrainment. One possibility would be that the maximum outflow level in the ECMWF model is too low compared to the real world (which is about 13 km), thus, negatively biasing RH (i.e., decreasing it) at higher altitudes (~12 km) and positively biasing it (i.e., increasing it) at lower altitudes (~9 km), the net effect being a diminished increase rate of RH with height. Some hints may be seen from the middle panel of Fig. 4a: instead of having RH monotonically increasing

[5] Subsidence will eventually approach zero higher up at the level of zero radiative heating (~15 km); above this level, slight net radiative heating will lead to ascent.

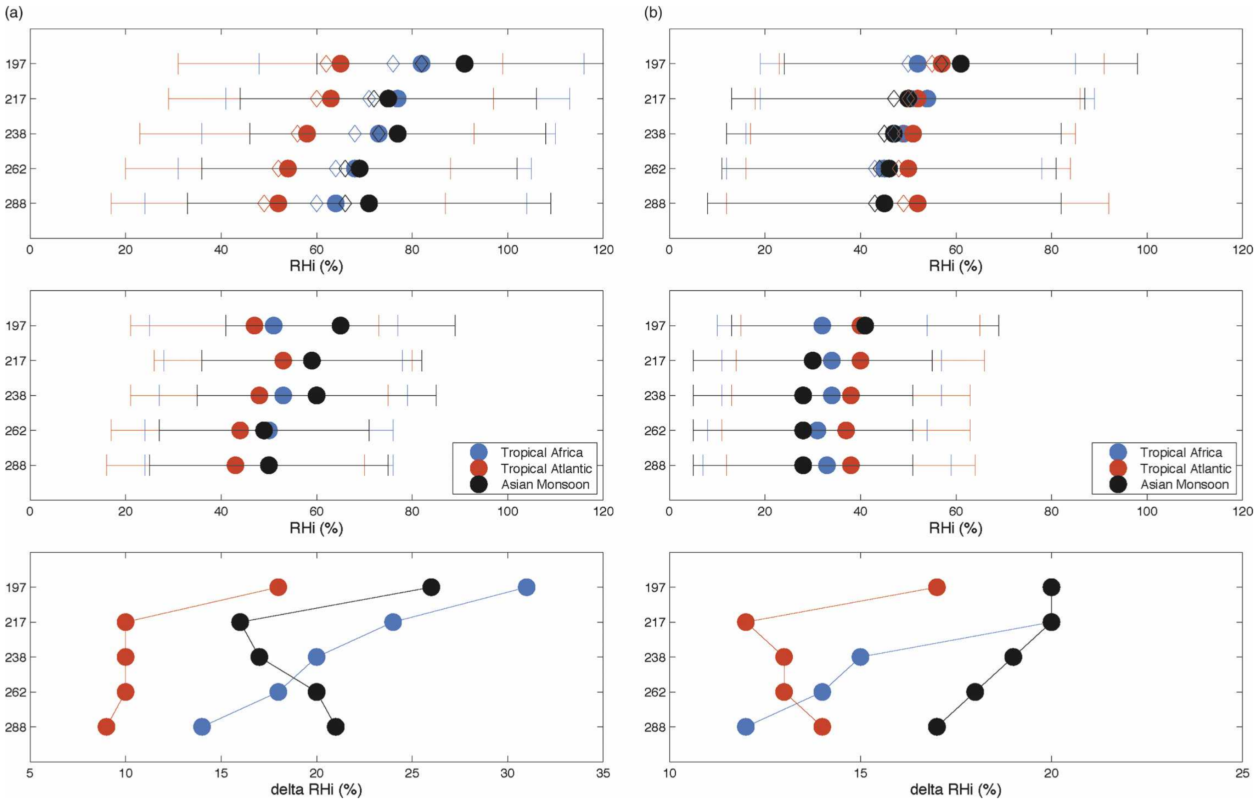

Fig. 4. (a) Mean and std dev of RHi (%) as a function of height for (top) MOZAIC, (middle) ECMWF, and (bottom) the differences (MOZAIC − ECMWF). Only observations equatorward of 10° are shown. (b) The same as in (a), but for the subtropical regions (30°–10°S and 10°–30°N).

from 288 to 197 hPa, the tropical Atlantic (red) and tropical African (blue) regions show an RH "bulge" at around 217 hPa, indicating that the maximum outflow level in the ECMWF analysis might be located around that level for those two regions. Confirmation of this speculation, however, needs additional runs of the ECMWF model, saving output of such fields as convective mass fluxes, which are "buried" in the model's convective parameterization. Such an analysis is beyond the scope of this study; nevertheless, this issue should be explored further. It is worth noting that a recent study of a superparameterization GCM or multiscale modeling framework (see Khairoutdinov et al. 2005 for a description of the model) shows that the modeled tropical deep convection appears to have shallower penetration compared to CloudSat data (Luo et al. 2006). Nevertheless, it should be pointed out that subsidence, as well as processes neglected in the Folkins et al. (2002) model, such as evaporation of cloud ice, may also contribute to the ECMWF's lack of RH vertical structure. Convection parameterization is a likely candidate for this model deficiency, a conclusion supported by previous studies suggesting that it is the key component that controls the model moisture budget (Luo and Stephens 2006).

Another possibility for the ECMWF to have larger dry bias at higher levels could be attributed to the model's inability to represent ice supersaturation (ISS). Because of the coarse horizontal spacing (~50 km), ISS is simply not implemented in the current operational ECMWF model, although experiments are being conducted to include this important physics (Tompkins et al. 2007). This would affect the UTH vertical structure even if the simulated convective detrainment mass flux was perfect because ISS is more frequent at higher levels of the tropical UT (Folkins et al. 2002). When ISS is totally turned off (as in the ECMWF model), one would expect that higher levels are most affected. Also, the deep tropics are expected to be more affected than subtropics because there are fewer occurrences of ISS in the latter region. We remove all ISS in the MOZAIC data and replace them with ice saturation as a crude way to estimate the impact of not having ISS (see the diamonds in Figs. 4a,b). It is seen that even so, the MOZAIC (now without ISS) is still moister and has a more distinct increase in UTH with height than the

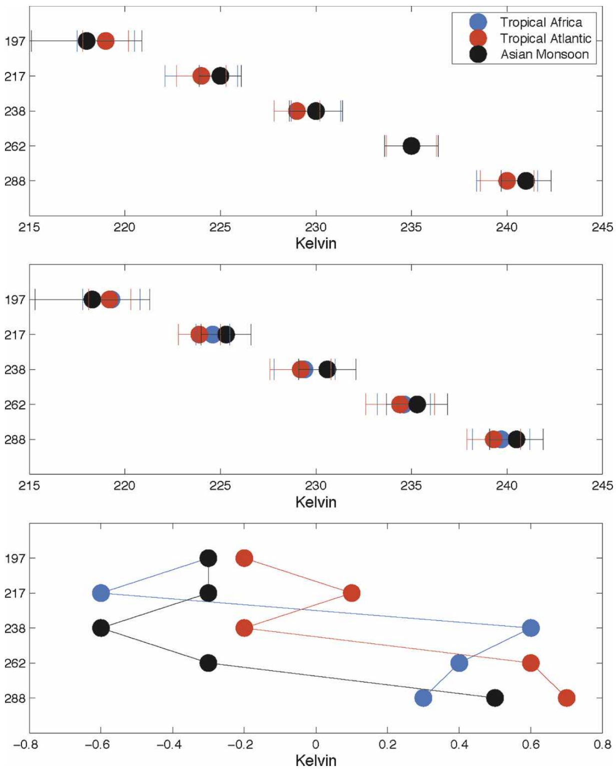

FIG. 5. Same as Fig. 4a, but for temperature (K).

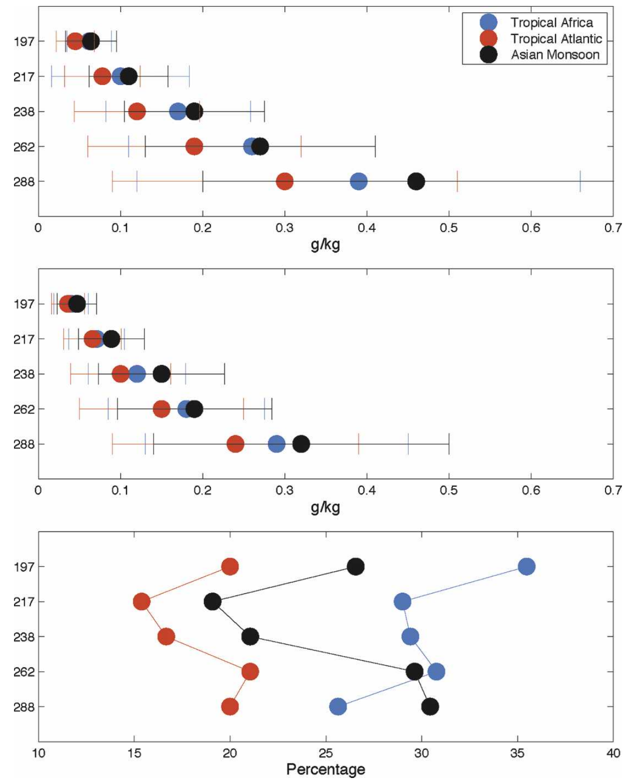

FIG. 6. Same as Fig. 4a, but for specific humidity (g kg^{-1}).

ECMWF. A recent study by Tompkins et al. (2007) also found that with a new ISS parameterization implemented in the ECMWF model, the 200–300-hPa pressure level becomes no more than only 4% (in RHi) moister than the control run (but it is significantly moister at the tropical lower stratosphere by as large as 20% RHi; see their Fig. 3). These results therefore suggest that lack of ISS alone does not explain all the dry biases and the missing vertical structure in the ECMWF, lending further support to our speculation that other model deficiencies such as those in convective parameterization may be responsible for the discrepancy. The recent launch of the CloudSat (Stephens et al. 2002) with the first global observation of cloud profiles provides a good opportunity for the ECMWF to test its convective scheme, in particular to evaluate the modeled maximum outflow level.

In addition to RH, we also compare temperature (Fig. 5) and the specific humidity (Fig. 6). The ECMWF is drier than the MOZAIC by 15%–35% as measured by specific humidity, comparable to the dry bias measured by RH. Temperature differences are generally small. Only the results from the deep tropics are shown but a similar conclusion is drawn from the subtropics. Note that the dry biases in ECMWF shown in Fig. 6 contradict the results of Oikonomou and O'Neill (2006), in which ECMWF reanalysis (ERA-40) was found to have a moist bias of 20% (in terms of specific humidity) over the tropical latitudes compared to MOZAIC. A detailed cross comparison of ECMWF analysis and reanalysis is needed to resolve the discrepancy.

c. *UTH probability distribution function*

As discussed in depth by Zhang et al. (2003), tropical UTH often has a bimodal distribution because processes that homogenize the UTH (i.e., mixing) are slower than those that maintain the two distinct modes (i.e., subsidence for the dry mode and convection for the moist mode). Figures 7a,b show the PDFs of tropical UTH for MOZAIC and the ECMWF. Figures 7a,b (left columns) show that the UTH bimodality is well established in the MOZAIC over the deep tropics and, to a far lesser extent, the subtropics. The values of the two modes (~20%–30% and ~100%) stay rather constant but the proportions of them change from one region to another, giving different mean RH values. The ECMWF, however, has difficulty in capturing the moist mode due to the lack of ISS. There are occasions where the ECMWF shows a tendency to develop the moist mode (such as over the deep tropics of the Atlantic and

Asian monsoon regions), but it is abruptly cut off at ice saturation. Lack of ISS capability in the ECMWF is, however, not the only cause for the overall dry bias; it also has more occurrences of lower humidity than MOZAIC. For example, the dry mode (~10%–20% RHi) over the subtropics extends distinctively "taller" for the ECMWF than MOZAIC. Similar examples can also be found for the deep tropics. This explains why a dry bias still exists for the ECMWF even if all the ISS cases are removed from MOZAIC (see the diamonds in Figs. 4a,b).

Another way of characterizing the bias in the ECMWF UTH field, alongside the PDFs, is to stratify the ECMWF biases with respect to the MOZAIC observations (right panels of Figs. 7a,b). It is shown that the ECMWF has moist bias when MOZAIC sees dry conditions (except in the Asian monsoon region from 10° to 30°N) and dry bias when the MOZAIC observes moist conditions. This is consistent with the findings by Ovarlez and van Velthoven (1997) and Ovarlez et al. (2000), who used moisture measurements from two field campaigns (POLINAT) to assess the ECMWF humidity analysis. One of the campaigns happened to be conducted in dry weather and the other in moist weather. While the two POLINAT campaigns were carried out over limited areas in the North Atlantic, the MOZAIC – ECMWF comparison extends their conclusion to include almost the whole tropics. The persistent pattern that the ECMWF has moist bias at low UTH and dry bias at high UTH suggests that the ECMWF analysis underestimates the range of UTH variation.

In the meantime, one should, however, be aware that the differences in temporal and spatial resolutions (i.e., 50 km and 6 hourly for the ECMWF and 15 km and 1 min for the MOZAIC) can introduce uncertainties and may be responsible for some of these discrepancies because spatial or temporal averaging tends to smear out the individual humidity ups and downs. In this study, the coarser-resolution data (ECMWF) were interpolated to match each higher-resolution measurement (MOZAIC), but by no means can such an interpolation help capture the fine structures of MOZAIC that are not resolved in the model in the first place. On the other hand, it is also difficult to average the MOZAIC to exactly match the ECMWF resolutions because aircraft fly over an ECMWF grid box (~50 km for T213) within 3–4 min whereas ECMWF analysis is the 6-hourly average. Nevertheless, we average every three neighboring MOZAIC measurements ($3 \times 15 = 45$ km, close to ECMWF resolution) as a crude way to account for the spatial resolution difference. Figure 8 shows the UTH PDFs and biases (stratified with respect to the MOZAIC measurements) for both the original and the averaged MOZAIC data, following the procedure in Figs. 7a,b. Only tropical Africa is shown, but a similar conclusion is drawn for other regions. Almost negligible differences are seen for the two cases, which suggests that the spatial variability of tropical UTH over the scale of 50 km is not large enough to greatly affect the conclusion drawn from Figs. 7a,b. Of course, temporal variation of UTH during the ECMWF time window (6 h) is still a remaining source of uncertainty. Geostationary satellite with water vapor imagery may give some hint on this issue, although contamination from high cloudiness is a potential problem. But we feel that resolution differences probably would not explain all the biases seen in the PDFs and that some of them are still attributable to model deficiencies. We leave them to a future, more-dedicated diagnostic study.

d. Moisture flux divergence

In Part I, we have analyzed the UT moisture fluxes[6] as measured by MOZAIC, taking advantage of the fact that both specific humidity and flight-level winds are readily obtainable from the MOZAIC aircraft. We also calculated the moisture flux divergence ($\nabla \cdot q\mathbf{V}$).[7] Moisture flux divergence is an important quantity in that it measures the net source or sink of water vapor through transport. It has a close connection to deep convection and large-scale subsidence, two key processes governing the distribution of tropical UTWV. In the ECMWF model, the wind field is decomposed into divergent and rotational components (Courtier et al. 1998). The rotational component is highly constrained by the geostrophy (Rabier et al. 1998) although it becomes less so as one moves closer to the equator, due to the diminishing Coriolis force. The divergent component, on the other hand, is related to baroclinic and diabatic processes but mainly the latter in the tropics.

[6] Only horizontal fluxes are considered. Vertical fluxes cannot be directly measured from the MOZAIC aircraft but their contribution will be estimated from horizontal flux divergence.

[7] Although at any given time, the MOZAIC measurements are made along the flight corridors that usually cover some narrow "lines" (and as such there are no simultaneous measurements of moisture fluxes in the direction perpendicular to the flight track), one can still get a composite depiction of the moisture flux divergence based on multiple flights (and eventually 10 yr of data) that give larger spatial coverage. Nevertheless, some eddy contributions on short time scales (e.g., shorter than a week) are missed because of undersampling. The undersampling issue was acknowledged and discussed in Luo et al. (2007). However, this issue is not so serious here because both MOZAIC and ECMWF are sampled the same way, so any difference should be attributed to the model bias.

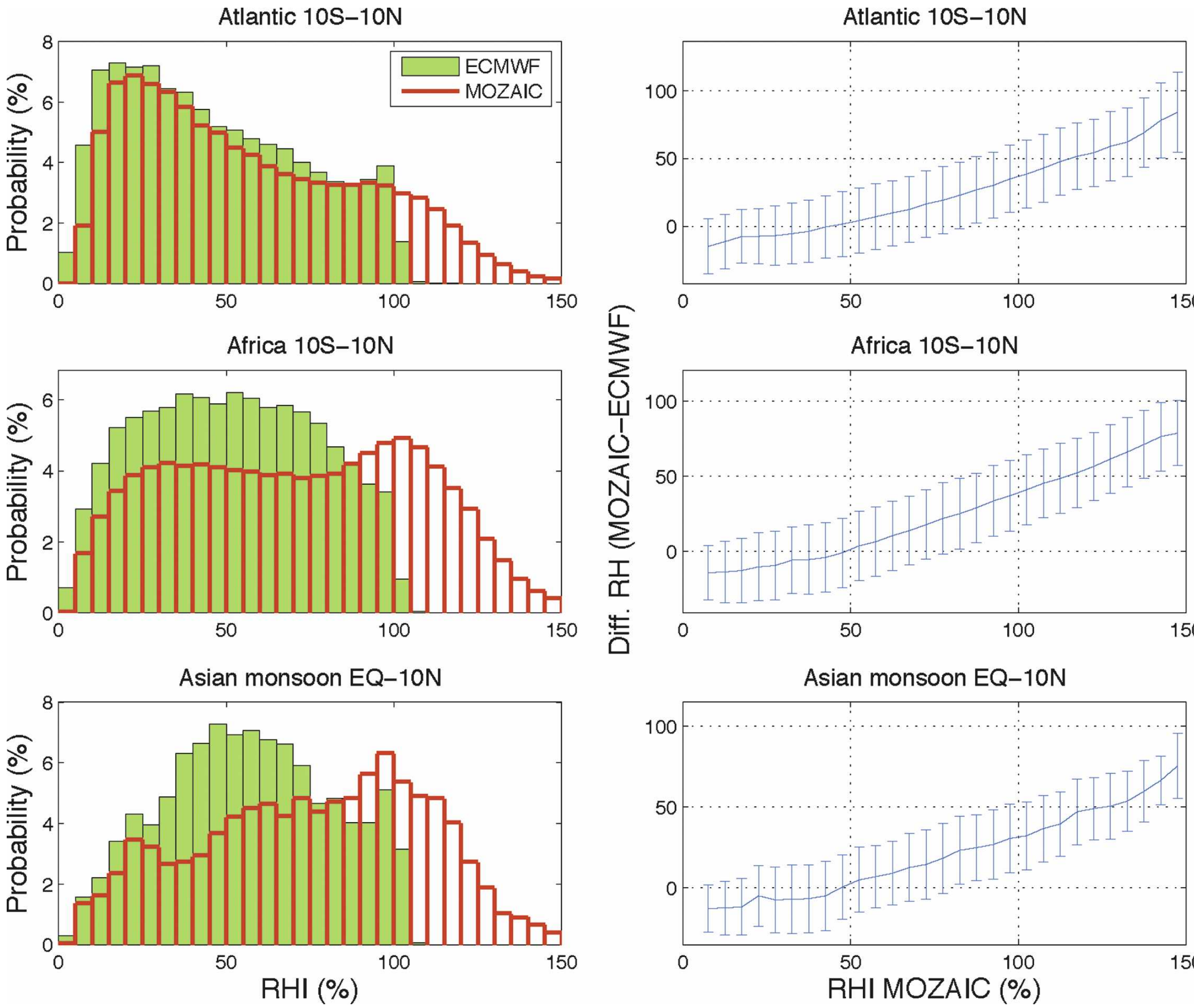

FIG. 7. (a) (left) PDFs of RHi for MOZAIC and ECMWF and (right) mean and std dev of the ECMWF biases (MOZAIC − ECMWF) stratified with respect to MOZAIC observations. Only observations equatorward of 10° are shown. (b) Same as in (a), but for the subtropical regions (30°–10°S and 10°–30°N).

The diabatic processes (e.g., convective heating) are not well constrained by observations but are largely model dependent (Klinker et al. 2000). The MOZAIC observations of the UTWV flux divergence thus pose a unique opportunity for evaluating the ECMWF analysis in this particular aspect.

Figure 9 shows the seasonal composite of horizontal moisture flux divergence for the three tropical regions, based on nearly 10 yr of data. The MOZAIC observations are in the left columns and the ECMWF on the right. We choose the most frequent 238-hPa flight level to maximize the total number of observations for all three regions. Following Part I, the spatial resolution for diagnosing the flux divergence is 2.5°. It was shown for MOZAIC that moist regions (such as the deep tropics) are usually associated with horizontal moisture divergence exporting water vapor to the neighboring regions, whereas dry regions (such as the subtropics) are associated with moisture convergence importing water vapor from other regions. In other words, horizontal transports are a net moisture sink for moist regions (usually the deep tropics) and a net moisture source for dry regions (usually the subtropics), which are balanced, in a climatological sense, by vertical transports associated with convection and subsidence, respectively. By and large, the ECMWF gives similar patterns of moisture flux divergence as MOZAIC, suggesting that the ECMWF analysis is capable of capturing the distribution of the divergent moisture transports in the tropical UT. Nevertheless, it is also noticed that the

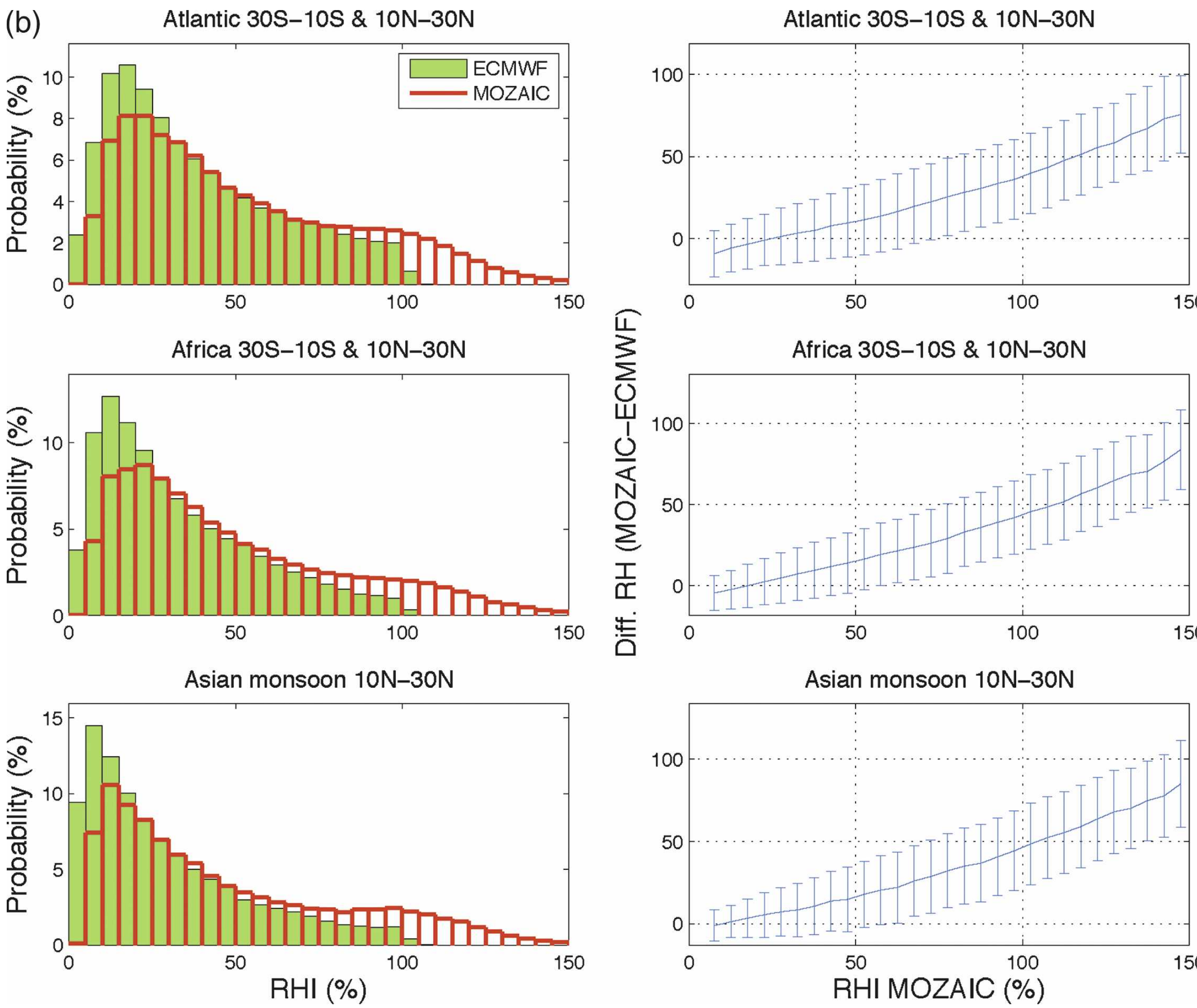

Fig. 7. (*Continued*)

divergence/convergence of the ECMWF tends to be weaker than that of MOZAIC. This is seen, for example, over the ITCZ of tropical Africa (10°S–10°N), the subtropics of the Atlantic [20°–10°S for June–August (JJA) and September–November (SON)], and the Asian monsoon region during the wet season. Since the ECMWF has an overall dry bias compared to the MOZAIC, an underestimate of the moisture flux divergence/convergence is possible even if the divergent winds themselves are well captured. We thus plot in Fig. 10 the horizontal divergence of the wind field for the same level (238 hPa), which shows a better agreement between observation and analysis, suggesting that the dry bias is the main reason for the underestimate of the moisture flux divergence. Moreover, Fig. 10 lends some support to the validity of the divergent component of the wind field in the ECMWF.

e. Interannual variability

The ECMWF operational analysis is not designed for monitoring climate variability but for forecasting short-range and medium-range weather, so the assimilation system is not "frozen" but keeps being upgraded over time (e.g., Courtier et al. 1998; Rabier et al. 2000). Consequently, there may be artifacts in its depiction of the interannual variability of the humidity field (this problem will not completely go away even for the reanalysis because, despite the use of the same assimilation system, available observations still change with time). Nevertheless, we present here a comparison of the ECMWF with MOZAIC not as a way to validate the humidity analysis but more to illustrate some large changes associated with a major ENSO (1997/98) that stand out above all background noise. Following

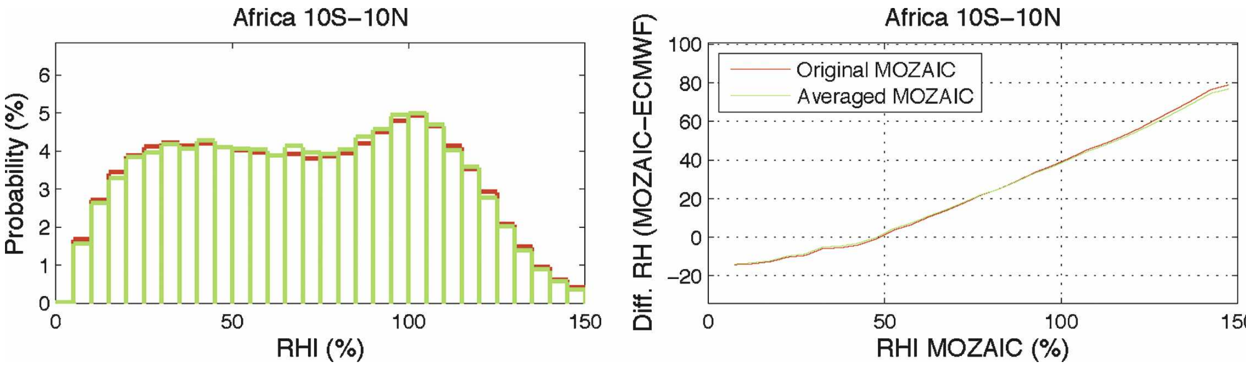

FIG. 8. (left) PDFs of RHi for the original (red) and averaged (green) MOZAIC data. (right) The ECMWF UTH biases (MOZAIC − ECMWF) stratified with respect to MOZAIC observations for both the original (red) and averaged (green) MOZAIC data.

Part I, Figs. 11 and 12 show the deseasoned variability of RH, specific humidity (normalized at each level),[8] and temperature for both MOZAIC and the ECMWF. Only tropical Africa and the tropical Atlantic are shown because of large data gaps for the Asian monsoon region. If we focus on the period enclosed by two thick solid lines, it is noticed that a warming of 1°–2°C occurs during the 1997/98 ENSO, which is well captured by the ECMWF although there is a little overestimate. Despite the success in its depiction of temperature variation, the ECMWF has difficulty in capturing the variability of the humidity field. As discussed in Part I (and shown in Fig. 11), MOZAIC shows an increase in specific humidity along with the ENSO-related warming, but the increase in temperature (which tends to decrease RH) outweighs the increase in specific humidity (which tends to increase RH) such that RH decreases by 5%–15% RHi. The ECMWF, however, generally fails to capture such subtle changes. This is a good example that UTH is not as well constrained by observations as the temperature field.

4. Summary and discussion

In a recent publication (Part I) we introduced an alternative data source—MOZAIC—for monitoring and studying UTWV and have analyzed 10 yr (1994–2004) of MOZAIC measurements of tropical UTWV in its climatology, variability, transport, and relation to deep convection. In this study (Part II), we used MOZAIC to assess the ECMWF humidity analysis over the tropics, taking advantage of the unique nature of the MOZAIC data, namely, long data record, near-global coverage, and high accuracy. Although several previous studies have attempted to evaluate the ECMWF humidity product using various in situ data, ambiguities still linger, as it is not a straightforward practice to compare the UTWV distribution because of its unique distribution (e.g., bimodal and highly variable). Moreover, less emphasis has been placed on relating the ECMWF biases to the underlying model deficiencies. The overarching goals of this study are therefore to characterize the biases in the ECMWF UTWV analysis in a comprehensive and unambiguous way and to infer from them the potential forecast model deficiencies.

The annual cycle of the ECMWF UTH shows a similar pattern as MOZAIC, keeping close pace with the corresponding ITCZ. Nevertheless, the ECMWF has a much drier UT than that observed by MOZAIC (by about 10%–30% RHi), with larger differences in the deep tropics than the subtropics. It is also noticed that the tropical Atlantic has smaller dry bias than tropical Africa and the Asian monsoon region, suggesting the possible positive impact of the satellite data on humidity analysis and also indicating problems in the ECMWF model treatment of cirrus and ice supersaturation (ISS). The increase of RH with height (from about 300 to 200 hPa as observed by MOZAIC is, however, largely missing in the ECMWF, which has a roughly constant RH profile. Drawing on a previous modeling study by Folkins et al. (2002), we discussed the potential attribution of this bias to the deficiency of the model representation of deep convective detrainment. Although lack of ISS in the ECMWF model may also contribute to the missing UTH vertical structure, it is found that replacing all ISS in the MOZAIC with ice saturation would not alter the height dependence of UTH by much.

[8] Since specific humidity decreases sharply with height (see Fig. 5), we normalize it by the level-mean value to include measurements from all five flight levels (to maximize data coverage). It is found in Part I that the normalized variation of specific humidity (in terms of fractional changes) stays roughly constant across all five flight levels.

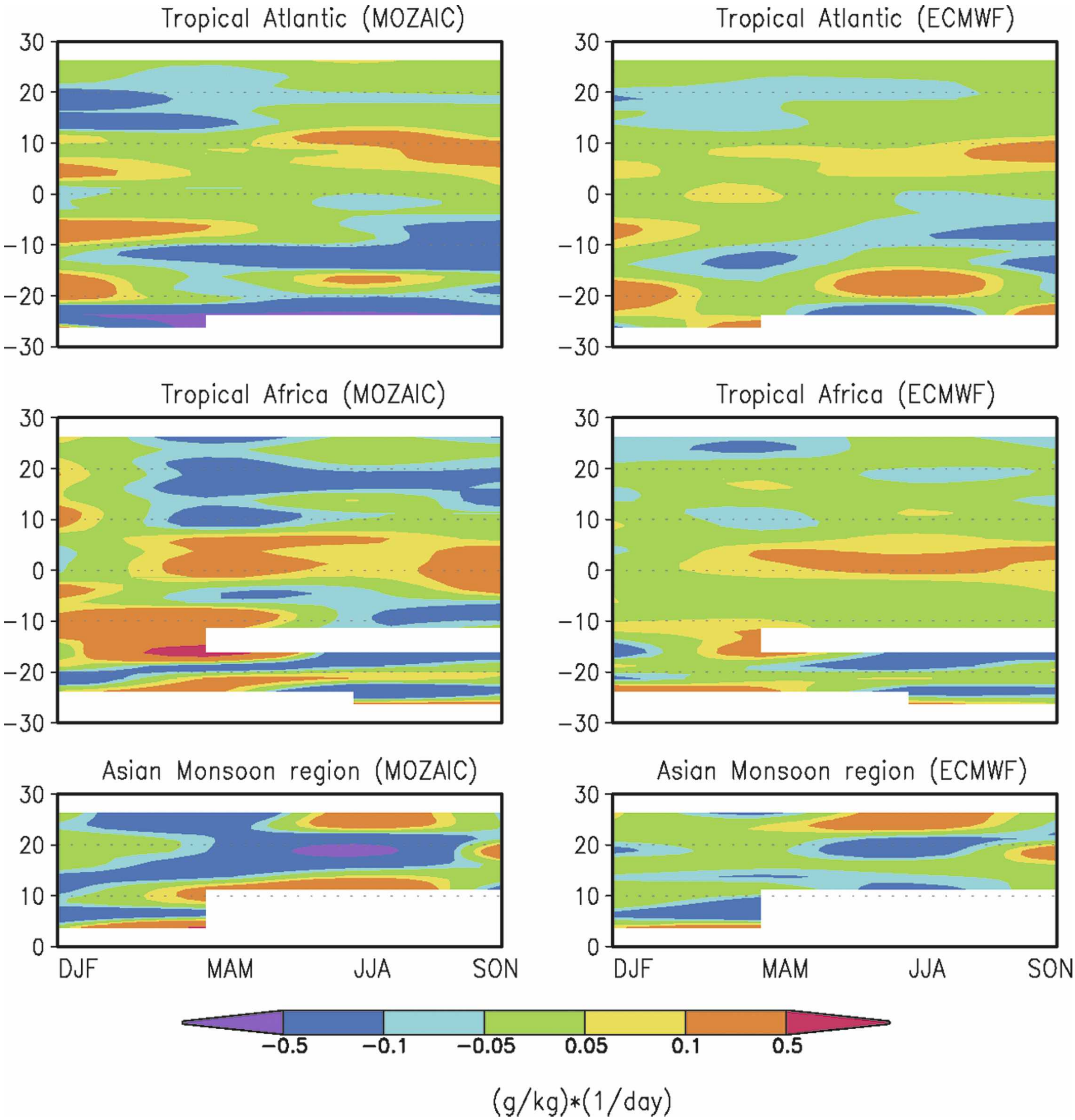

FIG. 9. Composite annual cycle of horizontal moist flux divergence (g kg^{-1} day^{-1}) at the 238-hPa level for (left) MOZAIC and (right) ECMWF.

The bimodal distribution of tropical UTH is well established in MOZAIC, but due to the lack of ISS, the moist mode (at around ice saturation) is abruptly cut off for the ECMWF. Lack of ISS capability is, however, not the only cause for the overall dry bias in the ECMWF; it also has more occurrences of lower humidity than MOZAIC. Stratifying the ECMWF biases with respect to the MOZAIC measurements further shows that the ECMWF underestimates UTH content at high humidity while overestimating it at low humidity, consistent with findings from previous comparisons with field campaigns conducted over limited regions. This may suggest that the ECMWF underestimates the range of UTH variations. However, one should be cautious since the coarser resolutions of the ECMWF may introduce such an artifact as this. A crude way of

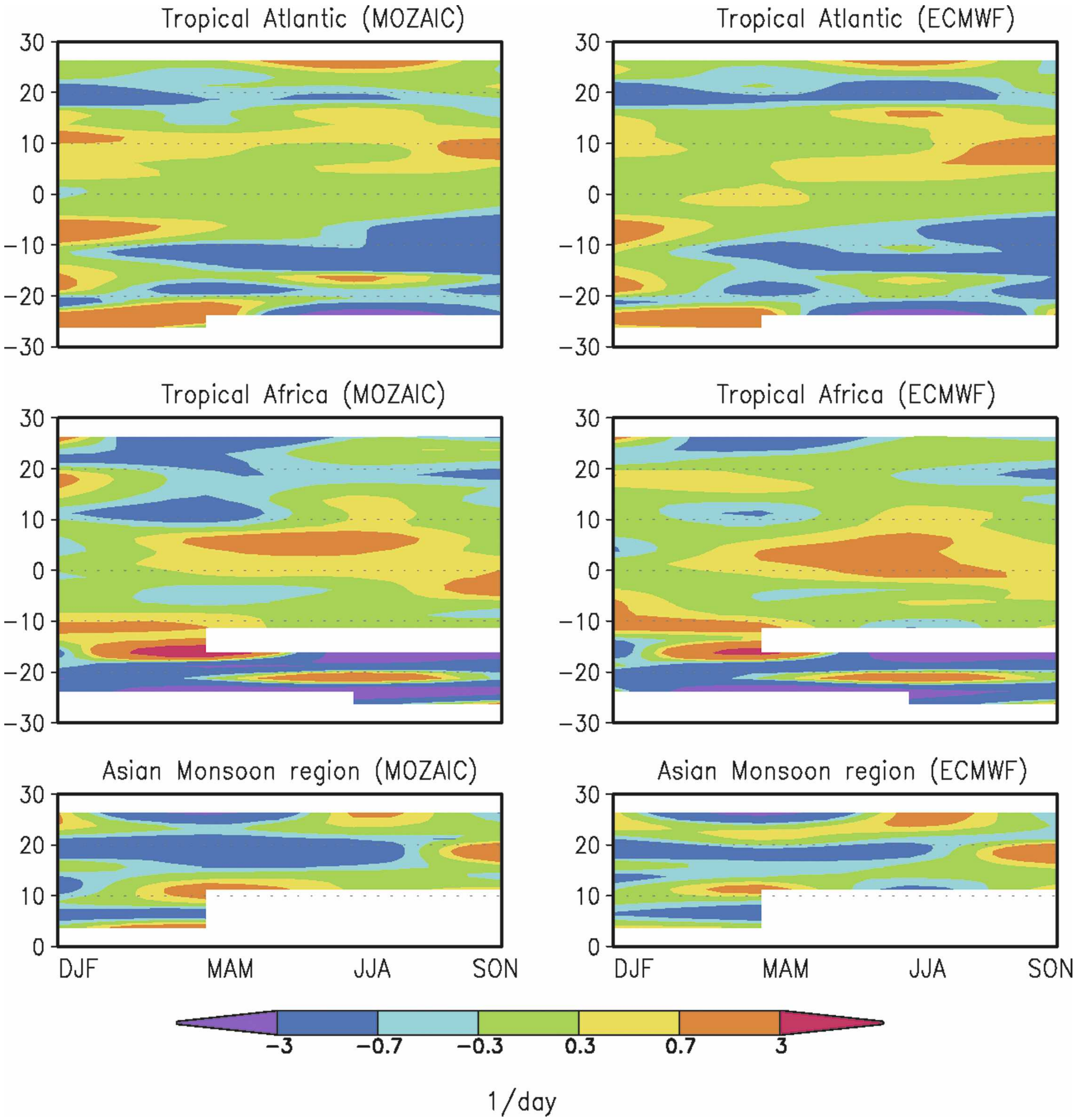

FIG. 10. Same as Fig. 9, but for horizontal wind divergence (day^{-1}).

accounting for this difference (i.e., averaging the MOZAIC data to match the ECMWF spatial resolution) suggests that the effect of the spatial resolution difference is small. A deep understanding of both the spatial and temporal variations of tropical UTH within the ECMWF assimilation window may help resolve how much of the discrepancy is attributable to the differences in resolutions and how much is to the ECMWF model deficiency (which we leave to a future study).

A comparison of moisture flux divergence is conducted to assess the ECMWF in its ability to capture the divergent transport of water vapor. It is shown that the ECMWF can represent the distribution pattern of this quantity fairly well, although some underestimate in the magnitude of the moisture divergence/convergence is seen. The underestimate of the divergent moisture transport is shown to be more related to the dry bias in the ECMWF than to bias in the divergent wind field. Finally, we show the comparison of the ECMWF

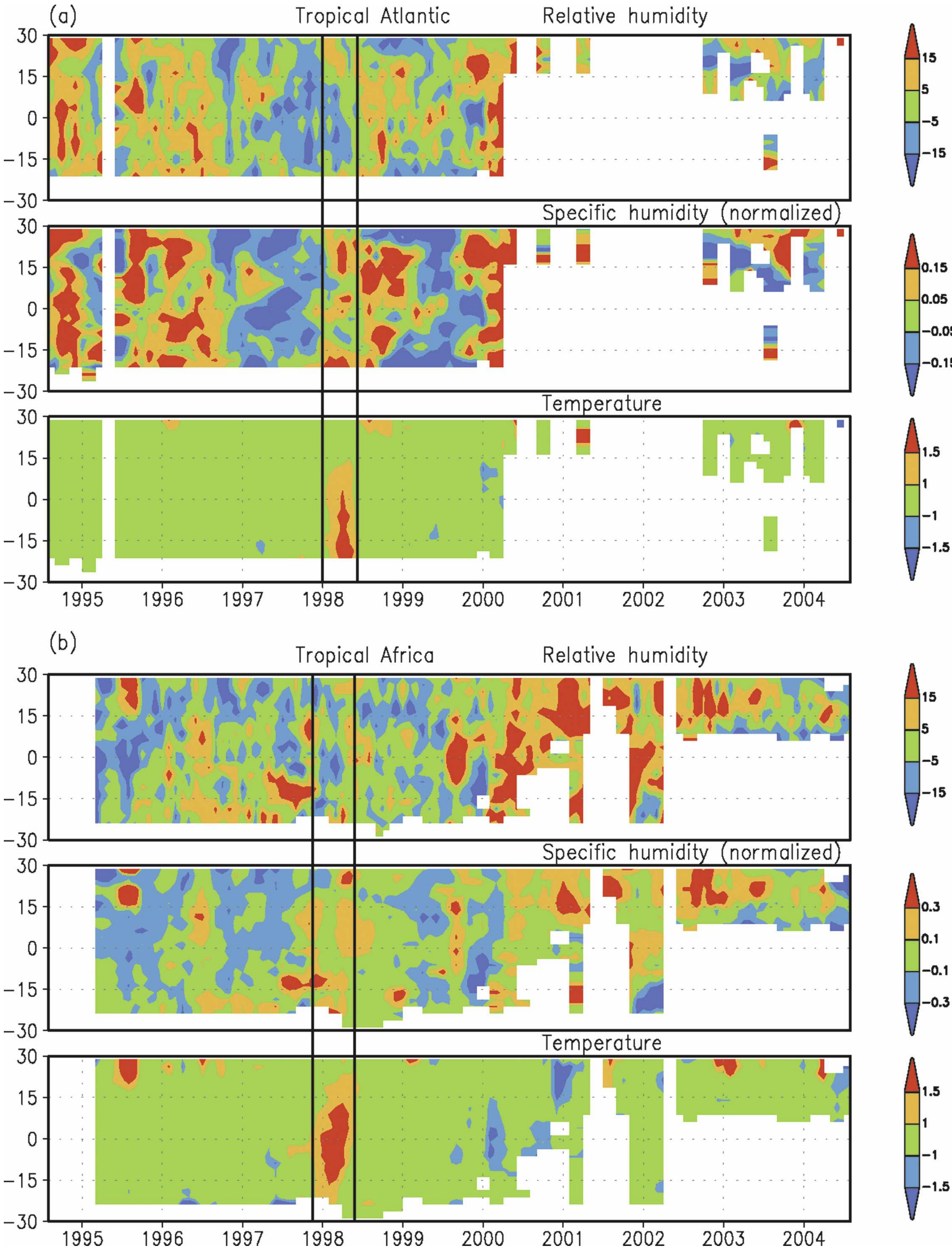

FIG. 11. MOZAIC-observed interannual variation of monthly mean RHi, specific humidity, and temperature (K) with annual cycles removed for (a) the tropical Atlantic and (b) tropical Africa. To accommodate all five flight levels, the specific humidity is normalized by the corresponding mean values at each level. The two thick solid lines mark the 1997/98 ENSO warm event.

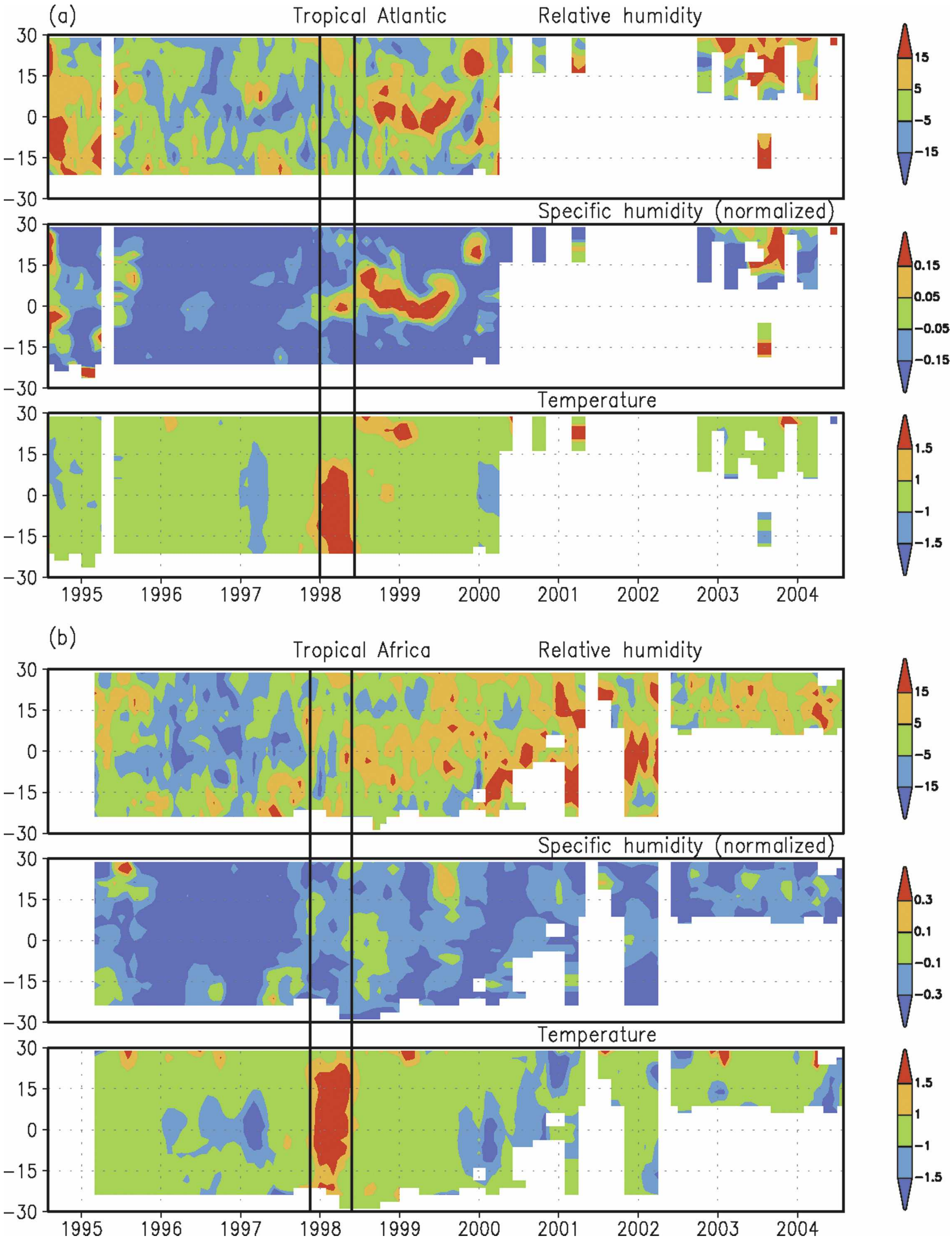

FIG. 12. The same as Fig. 11, but for the ECMWF.

and MOZAIC depictions of UTWV interannual variation during the 1997/98 ENSO event as an illustration that UTWV variations are more difficult to capture than those of the UT temperature.

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APPENDIX

MOZAIC Program and Observations

Measurement of Ozone and Water Vapor by Airbus In-Service Aircraft (MOZAIC; see http://mozaic.aero.obs-mip.fr/web/) is a project that was funded by the Commission of the European Union, for the measurement of the large-scale distribution of ozone and water vapor on board commercial Airbus A340 aircraft during scheduled flights (Marenco et al. 1998). Five A340 long-range passenger aircraft were equipped with semiautomated instrumentation to measure relative humidity, ozone, and temperature (and several other trace gases and aerosols after 2001) and to record aircraft data such as position, pressure, temperature, wind speed, wind direction Mach number, etc. MOZAIC was launched in January 1993 and was operational from August 1994 to April 2004. It was originally funded for three years, not long enough to generate meaningful climatology or to analyze long-term variability of UTH. Fortunately, the project's lifetime was extended to 2004. Since then, and up to the present, the MOZAIC activities continue with support from Centre National de la Reserche Scientifique (CNRS), Centre National de la Reserche Météorologique (CNRM), Forschungszentrum Jülich (FZJ), Air France (until October 2006), Austrian Airlines (until October 2006), and Lufthansa. Air Namibia operates one aircraft with MOZAIC instrumentation since December 2005. Presently, data are taken on three aircraft (Lufthansa, with two, and Air Namibia). At present, the MOZAIC project is in transition to becoming a larger program called Integration of Routine Aircraft Measurements into a Global Observing System (IAGOS; see http://www.fz-juelich.de/icg/icg-2/iagos). More than 2500 flights per year with a total of about 125 000 flight hours of measurements were made by MOZAIC as of December 2003 (data used in this study are extended to until August 2004). For this time period ronghly 50% of the flights occur between central Europe and locations in North America and about 32% of the flights cover the three tropical regions that are selected for detailed analysis in the study, namely, tropical Africa, the tropical Atlantic, and the Asian monsoon region. In the tropical regions, MOZAIC aircraft at cruise altitude fly at five discrete pressure levels of 288, 262, 238, 217, and 197 hPa, roughly corresponding to 9–12 km, which are almost always below the tropical tropopause layer (TTL). The time resolution of the MOZAIC humidity measurements in the upper troposphere is 1 min, which, at cruising speed, corresponds to a spatial resolution of 15 km. In addition to higher-resolution and near-global coverage, another major strength of the MOZAIC RH measurements is a quality-assured mean accuracy of 5% (Helten et al. 1998, 1999).

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