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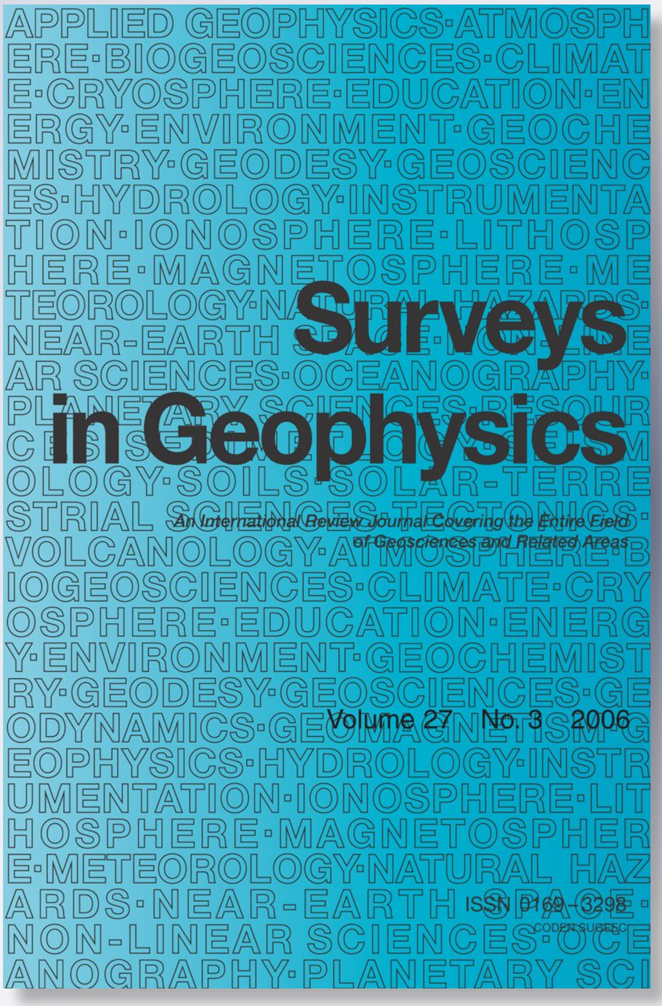

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Tropical and Extra-Tropical Influences on the Distribution of Free Tropospheric Humidity Over the Intertropical Belt

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Abstract Free tropospheric humidity (FTH) is a key parameter of the radiation budget of the Earth. In particular, its distribution over the intertropical belt has been identified as an important contributor to the water vapour feedback. Idealized radiative transfer computations are performed to underscore the need to consider the whole probability distribution function (PDF) rather than the arithmetical mean of the FTH. The analysis confirmed the overwhelming role of the dry end of the PDF in the radiative perturbation of the top of atmosphere longwave budget. The physical and dynamical processes responsible for the maintenance of this dry part of the FTH distribution are reviewed, and the lateral mixing between the tropics and the extra-tropics is revealed as a major element of the dry air dynamics. The evolution of this lateral mixing in the framework of the global warming is discussed, and perspectives of work are listed as a mean of a conclusion.

Keywords Free troposphere · Humidity · Satellite · OLR · Advection–condensation paradigm

Abbreviations

AC	Advection-condensation
AIRS	Atmospheric Infrared Sounder
AR4	Fourth Assessment Report
BLH	Boundary Layer relative Humidity
BT	Brightness temperature
DJF	December, January and February
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA-Interim	ECMWF ReAnalyses-interim
ERA-40	ECMWF ReAnalyses-40

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FIR	Far infrared
FTH	Free tropospheric humidity
IPSL	Institut Pierre-Simon Laplace
ITCZ	Inter Tropical Convergence Zone
JJA	June, July and August
NCEP	National Center for Environmental Prediction
OLR	Outgoing Long wave Radiation
PDF	probability distribution function
RH	Relative Humidity
TS	Temperature of the surface
TOA	Top of atmosphere

1 Introduction

Relative Humidity (RH) in the free troposphere (above the boundary layer and below the tropopause) plays an important role in the climate system (Sherwood et al. 2010a). In particular, over the intertropical regions, the free tropospheric humidity distribution is considered to contribute strongly to the water vapour feedback (e.g., Allan 2012). The climatological patterns of humidity distribution are recalled in Fig. 1 where satellite-derived multiyear estimates of seasonal mean relative humidity at 500 hPa are shown. The

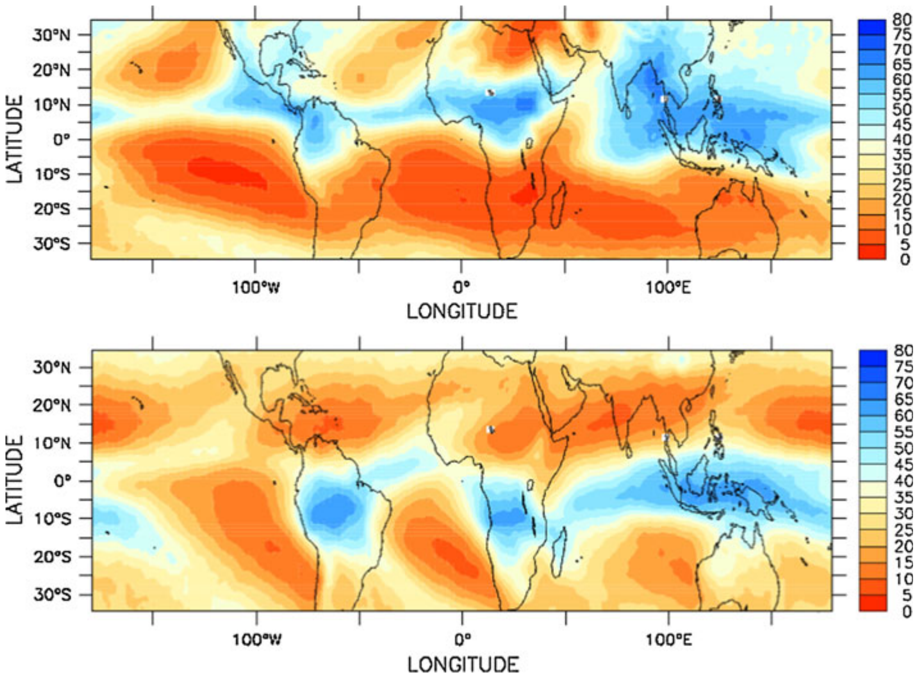
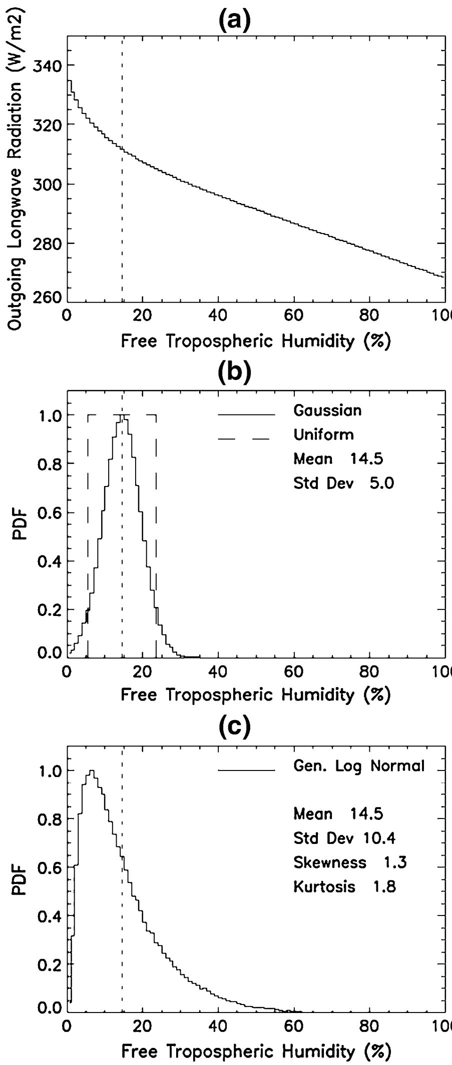


Fig. 1 Multiyear 2003–2007 average of seasonal mean relative humidity at 500 hPa from AIRS measurements for JJA (*top*) and DJF (*bottom*). Units are in percentage

Fig. 2 **a** Outgoing longwave radiation as a function of the free tropospheric humidity simulated using a radiative transfer model and idealized profiles (see text for details). **b** two distributions (uniform and Gaussian) of FTH and **c** a log-normal distribution of FTH



intertropical region (roughly between 30°S and 30°N) is characterized by a strong meridional contrast: a very dry troposphere in the subsiding branches of the Hadley/Walker circulations (RH $< 10\%$) and a very moist region (RH $> 70\%$) associated with the ITCZ and the upward branch of the tropical circulation. The seasonal cycle is clearly depicted as well. The boreal summer migration of the ITCZ over the tropical land masses corresponding to the setting of the monsoon circulations over East Asia and West Africa is associated with an overall moistening of these areas. The subtropical winter cell appears more spread and dryer than the summer one, especially during the boreal summer. The extension and dryness of these regions have been highlighted as key elements of radiative-convective-dynamic equilibrium at play in the tropical climate (Pierrehumbert 1995).

The main reason for water vapour to be of importance to the energetics of the climate lies in the nonlinearity of the radiative transfer to the humidity. The outgoing longwave radiation (OLR) is indeed much more sensitive to a given perturbation in a dry rather than

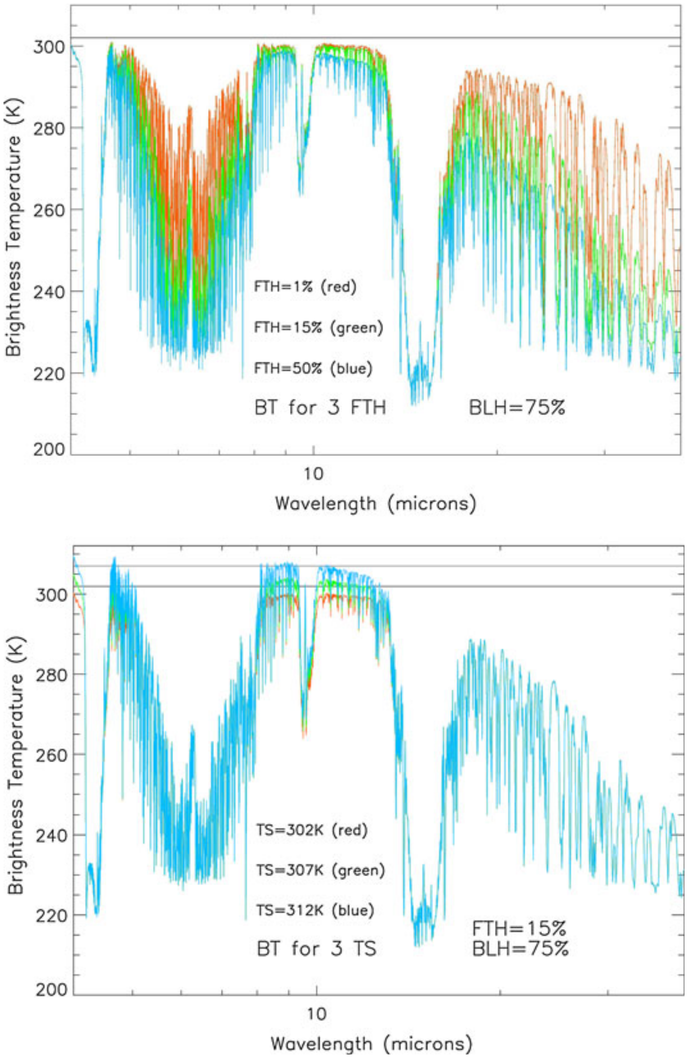


Fig. 3 *Top*: Brightness temperature (K) as a function of wavelength (micron) computed for a suite of idealized atmospheric profiles (see text for details). The colours correspond to the variation of the free tropospheric humidity parameters as indicated on the plot. *Bottom*: Same but for variation in the surface temperature

moist environment (Spencer and Braswell 1997; Held and Soden 2000; Sohn and Schmetz 2004), conferring a central role of the moisture distribution in these regions to the radiation budget of the planet and to the overall climate sensitivity. This nonlinearity is further illustrated in Fig. 2a that shows sensitivity of the OLR to idealized distribution of humidity in the free troposphere obtained from computations similar to that of Spencer and Braswell (1997). Radiative computations have been performed as discussed in Roca et al. (2005) but with the use of the MODTRAN code (Bernstein et al. 1996; Berk et al. 2000) instead of a broad-band model. The vertical profile of temperature is a multiyear summer average of Bay of Bengal conditions from ERA-40. Ozone and CO_2 are fixed at climatological values.

Relative humidity is constant in the boundary layer (at 75%), and a vertically constant RH profile is used over the troposphere and is varied from 1 to 99%. In the stratosphere, the RH profile is relaxed to climatological values (Roca et al. 2004). These computations confirm previous such calculations of the OLR sensitivity to FTH fluctuations and illustrate the nonlinearity of OLR to FTH at the dry end of the distribution (RH < 15%). This non-linearity results from both the vibration–rotation bands of water vapour near 6.3 μm and the far infrared region ($\lambda > 18$ μm), the two regions that contribute the most to the whole OLR (e.g., Harries et al. 2008) and to its sensitivity to FTH (Fig. 3a). Overall, changing FTH from 1 to 15% decreases OLR by $\sim$23 $\mathrm{Wm^{-2}}$, while from 35 to 50%, it only decreases it by $\sim$8 $\mathrm{Wm^{-2}}$. Out of the 23 $\mathrm{Wm^{-2}}$ decrease, $\sim$8 are accounted for by the 4- to 8-μm band, while $\sim$10 $\mathrm{Wm^{-2}}$ are due to the 18- to 30-μm region. In the second case, both spectral regions contribute with $\sim$1.5 $\mathrm{Wm^{-2}}$. In the dry (moist) case, these two bands account for 80% (40%) of the radiative cooling. The spectral dependency of the OLR sensitivity to FTH is further illustrated in Fig. 3a. Changing FTH from 1 to 15% indeed reveals a cooling over both the vibration–rotation and FIR regions and hardly modifies the OLR over the window region. While moistening up to 50% does not strongly affect the OLR, the window region exhibits a few Kelvin cooling of similar magnitude to a 5-K change in the surface temperature (Fig. 3b). This suggests an enhanced role of the continuum absorption (Shine et al. 2012) in the moist case that would explain the more linear sensitivity in the moist case although it is difficult to decipher the continuum effect over the FIR region (Harries et al. 2008). Guzman et al. (2012) extended such analysis to various surface types (beyond oceanic conditions) and confirmed that, over the inter-tropical belt, the main determinants of the clear-sky OLR and its sensitivity can be resumed to FTH and the surface temperature. They underscore that as far as the variability of OLR is concerned, though, the FTH variability dominates the signal and the surface temperature variability can be ignored. Hence, because of its radiative importance, the understanding of the distribution of relative humidity in the free troposphere and, in particular at the dry end of the spectrum, requires a great deal of attention.

Of particular relevance to the study of the tropospheric humidity in the subsiding, dry regions is the advection–condensation (AC) paradigm (Pierrehumbert and Yang 1993; Sherwood 1996; Pierrehumbert et al. 2007). Such a perspective states that it is possible to account for the observed humidity distribution by only considering the large-scale transport and the saturation process. The only water vapour source is concentrated in the boundary layer, and the water sink is simply the saturation; the excess moisture is assumed to rain out without re-evaporating in the atmosphere. Similarly, any cloud materials' re-evaporation is neglected and is not accounted for in the water vapour source. While such strong assumptions might not be accurate in the vicinity of deep convection (Su et al. 2006; Sohn et al. 2008), it has been shown useful for the dry subsiding regimes (e.g., Schneider et al. 2010) where the humidity distribution is hence only driven by the large-scale dynamics and the atmospheric temperature field. Such a paradigm has been implemented in various ways over the last decade: from an idealized model of the PDF of relative humidity (Sherwood et al. 2006; Pierrehumbert et al. 2007; Ryoo et al. 2009; O'Gorman et al. 2011) to Lagrangian-based computations (Salathé and Hartmann 1997; Pierrehumbert 1998; Pierrehumbert and Roca 1998; Dessler and Sherwood 2000; Cau et al. 2007; Dessler and Minschwaner 2007; Brogniez et al. 2009) as well as the Eulerian version of this simplified view (Sherwood 1996; Galewsky et al. 2005; Couhert et al. 2010; Hurley and Galewsky 2010a; Wright et al. 2010). Despite its oversimplification of the problem, the advection–condensation paradigm has been successfully confronted to a large amount of observations over a variety of regions (Sherwood et al. 2010a) and has hence become a useful tool to investigate the dynamics of relative humidity in the troposphere.[1] The Lagrangian studies revealed the importance of the statistics of the last saturation of the air mass to discuss the origin and fate of humidity. Such statistics have been computed here for relative humidity at 500 hPa over a 20-year period using the large-scale winds and temperature fields from the NCEP reanalysis and back trajectories (Pierrehumbert 1998; Pierrehumbert and Roca 1998). The transport model is configured as in previous work (Roca et al. 2005). The reverse domain–filling integrations are performed using a 0.5°×0.5° grid over the 35°S–35°N area for all longitudes, every 6 h, over the whole period. The longitude, latitude and pressure of last saturations have been computed along with the relative humidity. These computations will here be used to investigate the tropical versus extra-tropical influences on the PDF of tropospheric humidity.

The paper is organized as follows. First, the importance considering the dry end of the PDF of relative humidity for radiative transfer considerations is explored. Tropical and extra-tropical influences on the distribution of relative humidity are further investigated in both current and warmer climates. A conclusion ends this survey.

2 The PDF of Relative Humidity in the Troposphere

2.1 PDF of RH and OLR

Energy constraints on planet Earth (i.e. applying the first law of thermodynamics) require that, at equilibrium, the Earth emits in the long wave as much radiation as its gets from the Sun. This budget approach is hence focused on the mean values of the OLR over the whole planet and over long time scales corresponding to the global radiative-convective equilibrium theory. While the mean OLR is the constrained parameter, owing to the nonlinearity of the clear-sky radiative transfer to water vapour (Figs. 2a, 3), the whole distribution of moisture has to be considered rather than its mean in order to link the distribution of humidity to that of radiation. To illustrate this, the OLR sensitivity to FTH curve (Fig. 2a) and four distributions of FTH for a dry case are considered (Fig. 2bc): a constant distribution with mean of 14.5%, an uniform distribution with mean of 14.5% bounded within plus or minus 5%, a Gaussian distribution with mean of 14.5% (and a 5% standard deviation) and a generalized log-normal distribution with a mean of 14.5% shown in Fig. 2c. The mean OLR corresponding to the constant distribution is 311 Wm^{-2}. The uniform and normal distribution yield to a mean OLR larger by 0.7 Wm^{-2} in both cases. The log-normal PDF, on the other hand, gives a 3-Wm^{-2} overestimation of the OLR with respect to the constant case. At the scale of the doubling of CO_2 problem, such a systematic bias could be significant depending on its geographical spread, which is explored next.

2.2 Time and Geographical Variations of the PDF of RH

At the intraseasonal scale, the PDF of RH reveals a variety of behaviours and strong departure from normal distribution. On the other hand, at the interannual scale, the moments of the intraseasonal PDF are normally distributed. The skewness of the intraseasonal PDF indeed is well characterized over our multiyear period by a mean and a standard deviation. Hence, in the following, we will make use of multiyear averages when mapping our variables. It is also important to note that, while we here focus on the relative

[1] And more recently for the stratospheric water vapour as well (Liu et al. 2010).

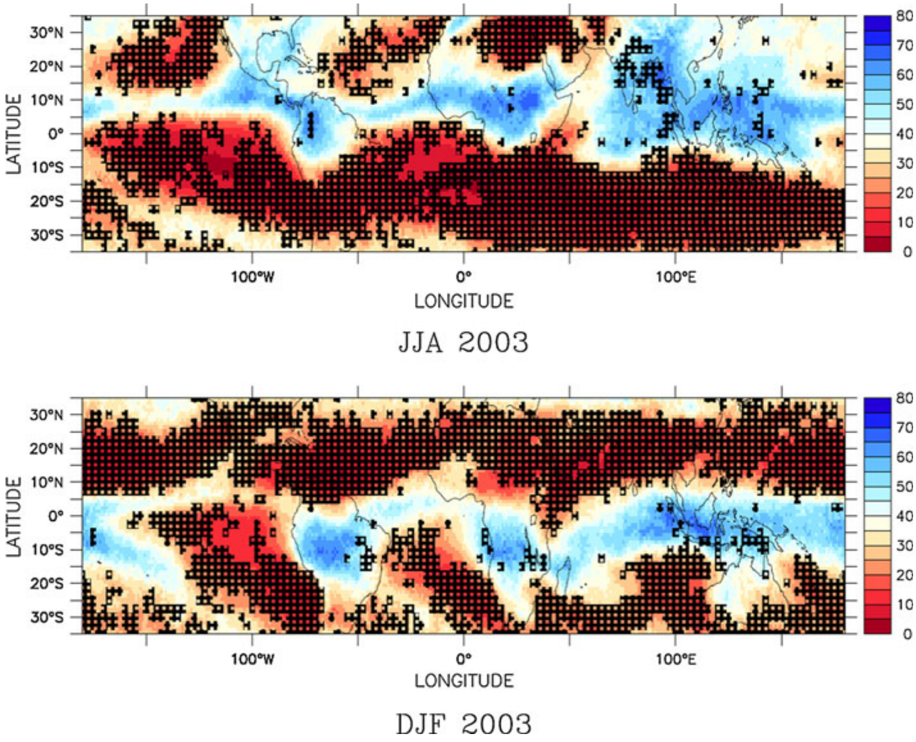


Fig. 4 Seasonal mean of relative humidity at 500 hPa for 2003 for JJA (*top*) and DJF (*bottom*) derived from AIRS measurements. Units are in percentage. The *black squares* represent the region where the intraseasonal PDF departs from a normal distribution according to a Kolmogorov–Smirnoff test at the 99% level

humidity distribution, the emphasis is set on the absolute humidity distribution underneath. The temperature distribution and its variability are neglected on the grounds that, within the tropical free troposphere, such temperature fluctuations are small and do not change significantly the relative humidity (Peixoto and Oort 1996). This is confirmed by recent investigation into the covariability of temperature and relative humidity in the free troposphere (Lemond 2009), but it should be kept in mind that this is a strong characteristic of the intertropical belt that is not valid elsewhere.

Departure from the normal distribution of the relative humidity is investigated through a Kolmogorov–Smirnoff (KS) test applied on the intraseasonal 500 hPa relative humidity distribution obtained from the daily average measurements of the AIRS instrument onboard the Aqua mission (Aumann et al. 2003; Fetzer et al. 2003). The regions corresponding to the dry areas (in the mean) depart significantly from normality, while the convective moist regions show a distribution of relative humidity within the season close to a Gaussian distribution (Fig. 4). For instance, over the moist Indonesian region (110–160°E and 0–15°N in summer; see Fig. 1) characterized by an multiyear average value of 58%, the KS test does not reject the normal assumption; indeed, the skewness and kurtosis are not departing much from zero (−0.53 and −0.33, respectively). Over the Mediterranean region, on the other hand (15:40°E and 25–35°N), the multiyear mean is low (11%) and the skewness and kurtosis strong (2.4 and 6, respectively) as also depicted in Fig. 7.

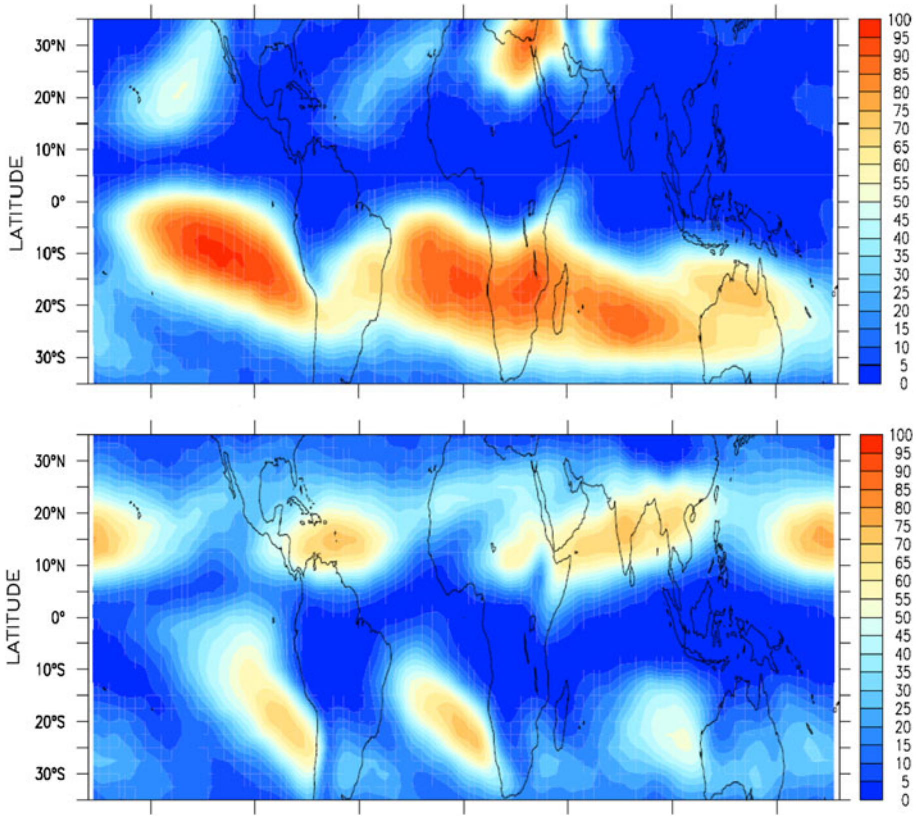


Fig. 5 Multi year 2003–2007 average of the frequency of occurrence of 500 hPa relative humidity below 10% within the season from AIRS measurements for JJA (*top*) and DJF (*bottom*). Units are percentage

The spatial variation of the PDF of the relative humidity in the free troposphere between the moist and dry regions is well explained by a simple theoretical implementation of the AC paradigm. Ryoo et al. (2009) indeed provided a generalized version of the model of Sherwood et al. (2006) for the humidity distribution that captures the difference in PDF between the dry and moist areas. It is assumed that relative humidity results from a uniform subsidence and random moistening events. Two parameters are used to quantify these processes: the ratio of drying time by subsidence to the interval time in between moistening events and a measure of the randomness of these events. In the convective moist region, the fitting of the model parameters to satellite estimates of relative humidity yields to large ratio and small randomness factor, indicating a rapid random moistening there, compatible with a local moistening by deep convection, and an almost Gaussian PDF. On the other hand, the nonconvective regions, which depart significantly from the normal distribution, are characterized by a small ratio and large randomness factor, suggesting a slow, less random moistening, likely linked to quasi-horizontal transport (Ryoo et al. 2009). Such analysis also indicates that a significant fraction of the intertropical belt area departs from the normal distribution, and hence, this departure, if not accounted for, could have a

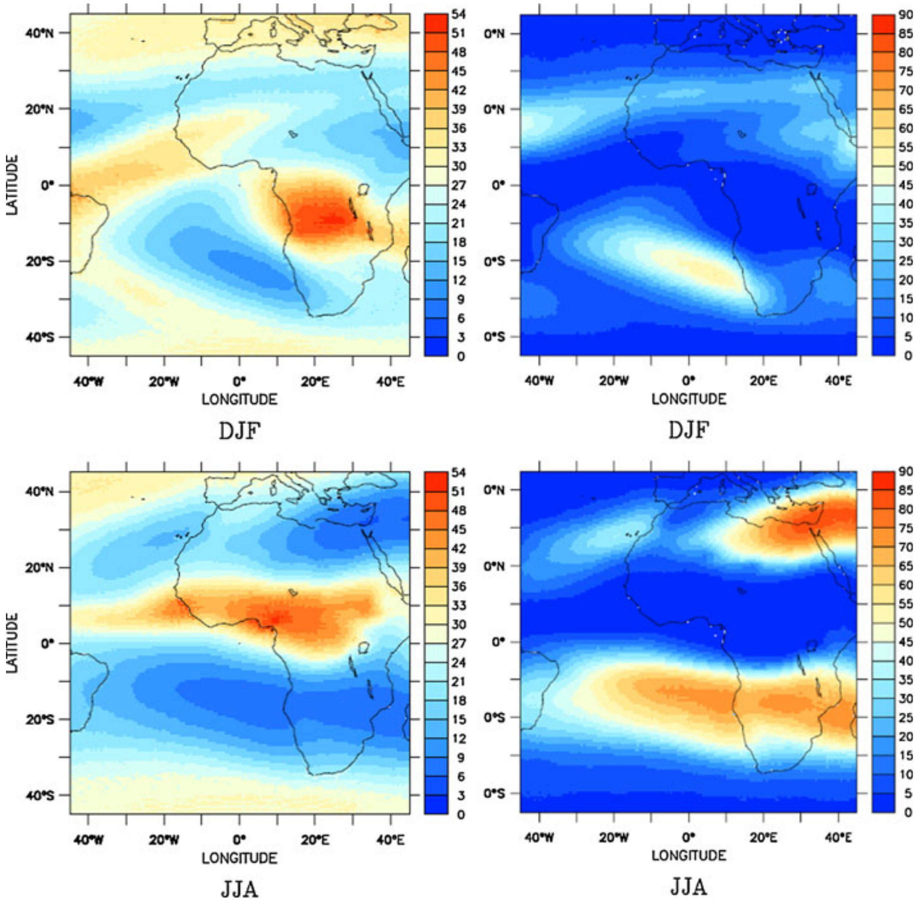


Fig. 6 Multiyear 1983–2004 average of the seasonal mean of FTH (*left panels*) and of the frequency of occurrence of FTH below 10% within the season (*right panels*). For DJF (*top*) and JJA (*bottom*), data are from METEOSAT measurements. Units are in percentage

significant impact on our understanding of OLR. In the next section, we explore a simple way to account for the PDF of the relative humidity.

2.3 A Simple Way to Account for the Non-normality of Relative Humidity Distribution

The need of handling the whole PDF of humidity instead of only the mean of the field implies the manipulation of the upper moments of the distribution (skewness and kurtosis). While the computations are straightforward, the comparison of two PDFs through the comparison of their 4 moments is not. Assuming a generalized log-normal distribution also requires 4 parameters to be fitted. It can be brought down to 2 parameters by imposing the lower and upper range limit of the distribution (0 and 100% for instance) at the cost of limiting the possible distributions. The simplified model (Ryoo et al. 2009) also comprises only two parameters, linked to the first two moments of the distribution. Still, the moments-to-moments comparison of PDFs remains difficult. Here, it is proposed to limit the analysis to a single parameter characterizing the PDF with

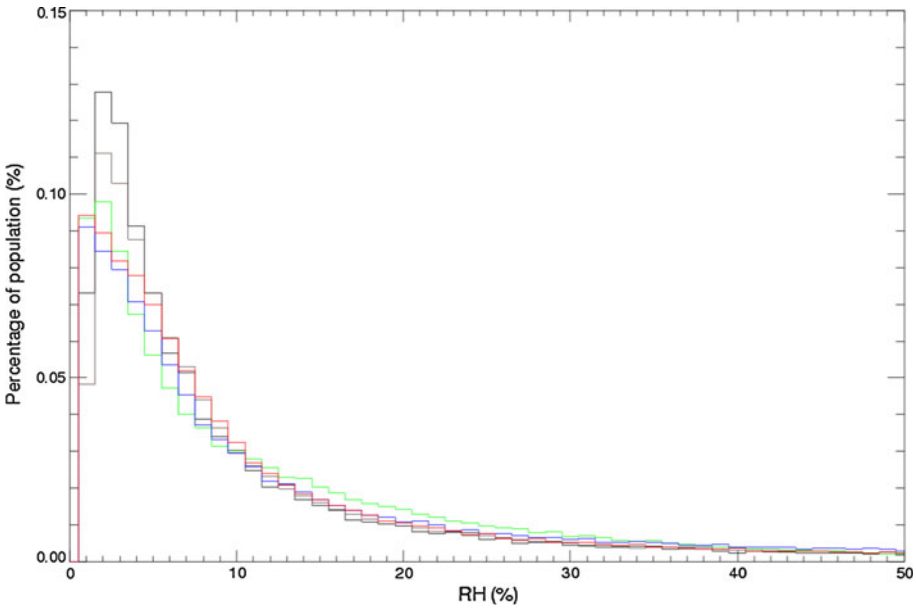


Fig. 7 Probability density functions (PDFs) of relative humidity at 500 hPa pressure level, for the JJA seasons over the 2003–2007 period, on the east Mediterranean area (15E:40E/25°N:35°N). PDFs are computed from AIRS (*black*), ERA-interim (*brown*), RH reconstructed (*green*), NCEP2 (*blue*), NCEP (*red*) estimations

emphasis on the dry foot of the distribution: the frequency of occurrence of RH below 10%, noted in the following as RHp10. Indeed, such a frequency parameter has been found to well discriminate the various PDF under considerations (Lemond 2009). Figure 5 shows the AIRS-based climatology of RHp10 for the 500 hPa level for boreal summer and winter periods. While the large-scale features seen in Fig. 1 are retained (contrast between boreal summer and winter, contrast between winter/summer hemisphere, moist and dry regions, etc), the patterns are here sharper. The gradients between the core regions of the winter cell subtropics and the poleward regions are stronger than when the mean is used. The delineation of the regions where dry air is prevalent and that are of importance to the radiation budget is also more effective. For instance, the boreal winter mean field (Fig. 1) suggests a dry extreme in the Eastern subtropical Pacific (90°W) between 10°S and 15°S, while the RHp10 computation reveals an homogeneous extreme region spreading from 17.5°S to 25°S. The frequency approach further helps to discriminate regions of identical mean. For instance, using the METEOSAT Free Tropospheric Humidity climatology (Roca et al. 2003; Brogniez et al. 2006; Brogniez et al. 2009; Roca 2011), the difference between the Eastern Mediterranean region and the southern Atlantic ocean, unseen in the classical climatology, is revealed in the frequency computations (Fig. 6). The frequency approach furthermore makes the comparisons between various humidity sources easier and is found to be a robust diagnostic not only for satellite-based relative humidity estimates but also for the models-based one (Fig. 7). In particular, the RHp10 map for the 500 hPa reconstructed relative humidity field using the Lagrangian modelling framework (See Introduction for details) reveals very realistic patterns (Fig. 8). Indeed, despite an overall low bias in the frequency of occurrence, the reconstructed field exhibits the patterns seen in the satellite measurements. The contrast between the winter and summer hemisphere is well captured as well as the regional details like the extended dry feature from the Sahel to the Bangladesh area during the boreal

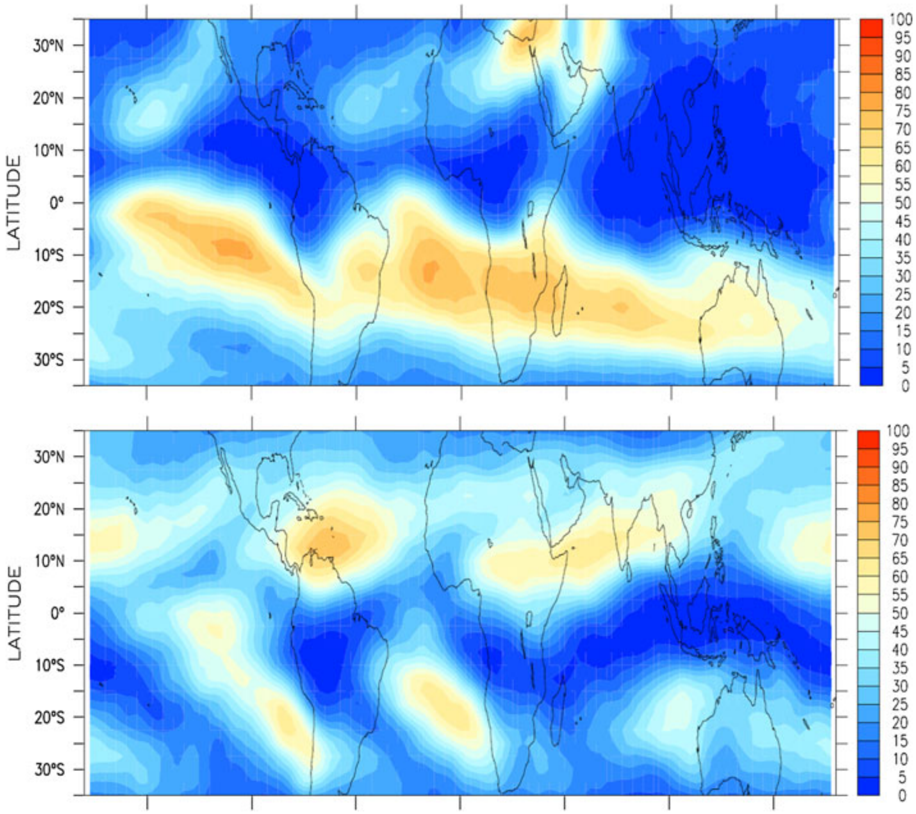


Fig. 8 Multi year 2003–2007 average of the frequency of occurrence of 500 hPa relative humidity below 10% within the season from the Lagrangian based reconstruction for JJA (*top*) and DJF (*bottom*). Units are percentage

winter. Similarly, the three dry patterns of the DJF summer hemisphere, east of the subtropical ocean basins, and their relative intensity are well reproduced. In boreal summer, the unique strong dry region over the Eastern Mediterranean region (Brogniez et al. 2009) is very well simulated so is the quasi-zonally extended subtropical dry region in the winter cell. These quick comparisons further confirm the usefulness of the advection–condensation paradigm and its present Lagrangian implementation for investigating the dry end of the relative humidity distribution through a frequency approach.

3 Extra-Tropical Influence on the Relative Humidity PDF

The tropical and extra-tropical influences of the *mean* humidity in the free troposphere have been investigated either from a water vapour budget (Schneider et al. 2006) or from a last saturation perspective (Galewsky et al. 2005) with the emphasis on the *zonal mean* view, offering contrasted conclusions (O'Gorman et al. 2011; see also discussion by Sherwood et al. 2010a). Here, the discussion is focused on the geographical patterns of the dry end of the relative humidity distribution.

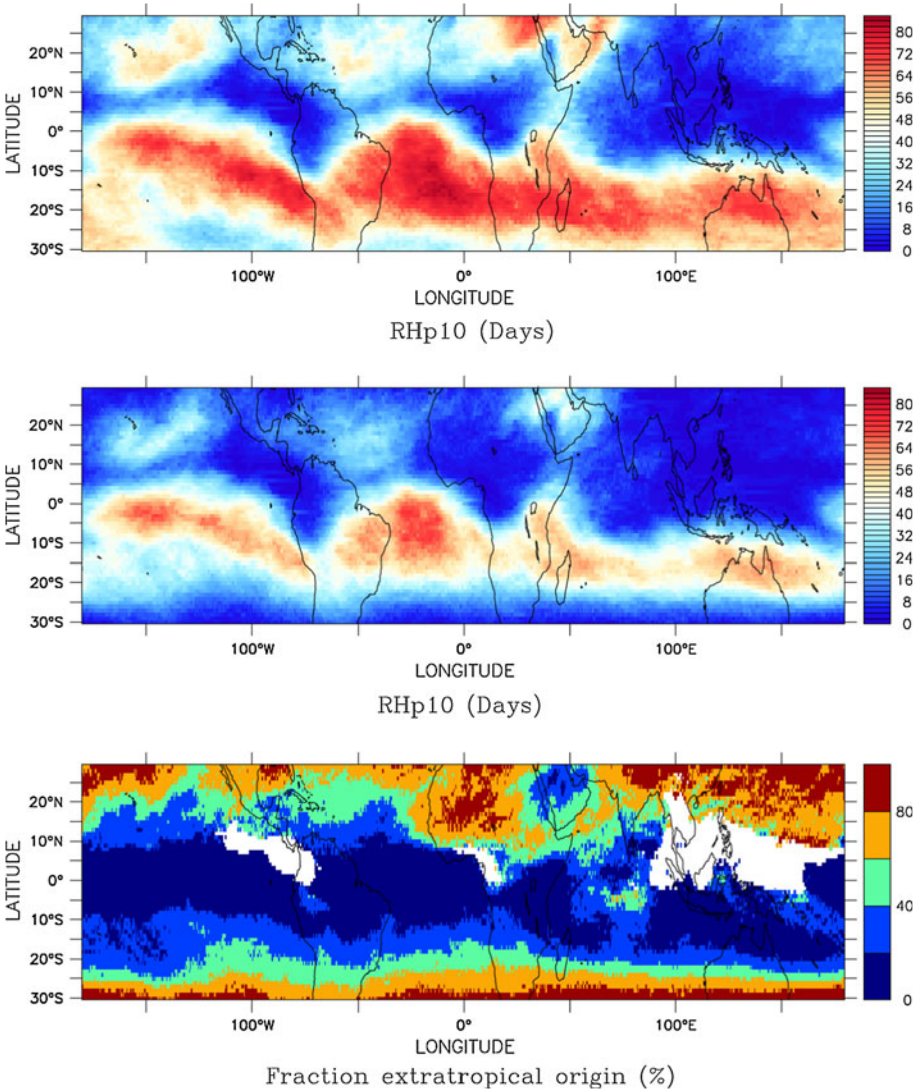


Fig. 9 Frequency of occurrence of 500 hPA relative humidity below 10% within the JJA 2003 season from the Lagrangian reconstruction. *Top*: full origin result. *Middle*: Tropical origin only results (latitude of last saturation equatorward of 35°). *Bottom*: the fraction of extra-tropical origins. Value with RHp10 lower than 10 have been blanked out. Units are in percentage. Lagrangian computations performed using NCEP temperature and winds information. See text for details

3.1 Current Climate

The RHp10 distribution of the reconstructed field for the boreal summer 2003 is compared to the RHp10 distribution obtained by keeping only the air masses that experienced last saturation within the intertropical belt (35°S–35°N) in Fig. 9. Excluding the extra-tropical last saturated air masses overall moistens the atmosphere. The domain averaged RHp10 decreases from 37 to 23% without the extra-tropical influence. While the patterns overall

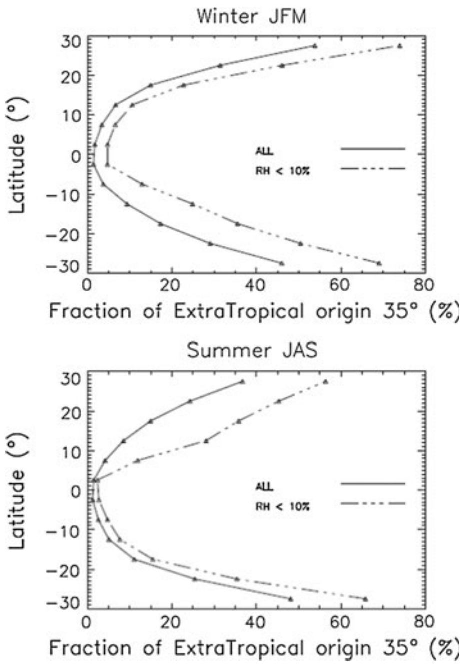


Fig. 10 Multiyear average 1983–2004 of the zonal mean of the fraction of extra-tropical air masses for all (*plain line*) and for the one with relative humidity below 10% (*dashed line*) for winter (*top*) and summer (*bottom*). Lagrangian computations performed using NCEP temperature and wind information. See text for details

remain similar within the two computations, the driest areas nevertheless appear more impacted and less spread in the tropics only case (Fig. 9 middle). The very dry features in the subtropical south Atlantic is mainly built from tropical originating air with the fraction of extra-tropical influence less than 10% (Fig. 9c). Globally, the winter hemisphere seems to be characterized by a less pronounced influence of the extra-tropics than the summer one with fraction above 60% hardly reaching the 25°S parallel, while, over Sahara and over the Arabian Sea for instance, the 60% iso-line penetrates southward down to 10°N. This seasonal contrast appears as a robust characteristic of the 500 hPa relative humidity field and is confirmed when the whole 1983–2004 period is considered. Very dry air (RH < 10%) is relatively more frequently originating for the extra-tropics than the environmental air, at all latitudes (Fig. 10). Extra-tropical influence on dry air occurrence is stronger in the summer hemisphere and is significantly so closer to the tropics into the summer hemisphere as shown in Fig. 10.

Dry air is brought to these regions through subsidence that brings air from aloft, lateral mixing that brings air from the tropics and the extra-tropics (Pierrehumbert 1998). While the primary source of dry air is the extra-tropical cold processing by isentropic mixing (Yang and Pierrehumbert 1994; Galewsky et al. 2005), breaking Rossby waves have also been identified as a mechanism to bring dry extra-tropical air in the subtropics (Waugh 2005; Allen et al. 2009). During boreal winter, Cau et al. (2007) highlighted a suite of dynamic mechanisms related to transport of dry air into the subtropics (descending air masses associated with extra-tropical baroclinic systems, the subtropical anticyclone variability and the upper level jets dynamics). Such extra-tropical source is usually completed by a tropical upper tropospheric source region as far as dry air is concerned (e.g., Dessler and Minschwaner 2007) or local convective source from below. Focusing on the summer dry region of the Eastern Mediterranean region, Brogniez et al. (2009) showed that the local source could be ruled out in favour of the extra-tropical source as a better predictor of

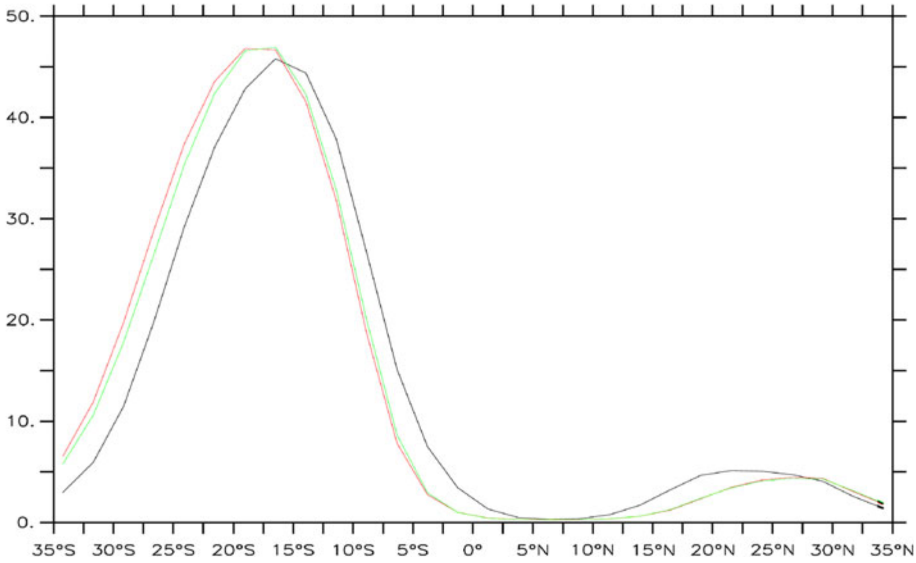


Fig. 11 Zonal mean of 500 hPa RHp10 in summer averaged over 20 years. In *black*, control run simulations (1970–2000), in *red* for A1B and *green* for A2B scenario (2070–2100)

the FTH interannual variability there. The difficulty still remains high in associating a given geographical source and process and their relative contributing role on the dry air production and calls for a dynamically based analysis of the climatology. Focusing on the dry foot of the PDF of humidity in the subtropics would help revealing the dominant mechanisms at play to explain the importance of the extra-tropical region as a source for it. The contribution of the extra-tropical source in the summer cell is indeed enhanced in boreal summer with respect to boreal winter (Fig. 10) and might suggest the importance of the more frequent breaking Rossby waves in the northern hemisphere during boreal summer.

3.2 Warmer Climate

The evolution of relative humidity in the free troposphere under climate change is important to the understanding of the role of the water vapour feedback in the climate system (Schneider et al. 2010). It is usually considered that climate model simulations act as if relative humidity remains unchanged, which is to be understood as the magnitude of the water vapour radiative feedback being similar in these climate models to the one in earlier radiative-convective climate change computations and even earlier energy balance calculations (Inamdar and Ramanathan 1998). Within the radiative-convective equilibrium framework, such constant RH behaviour explains the strong magnitude of the water vapour feedback. If RH were allowed to increase instead, the water vapour feedback would be diminished. Under the radiative-convective dynamic equilibrium assumption, it is the relative humidity of the dry subtropical regions that is key to the radiation budget. Analysis of relative humidity of climate model simulations of climate change scenario reveals an overall complex pattern of change with a notable feature relevant to our region of interest: the subtropical troposphere is the locus of a marked decrease in mean relative humidity

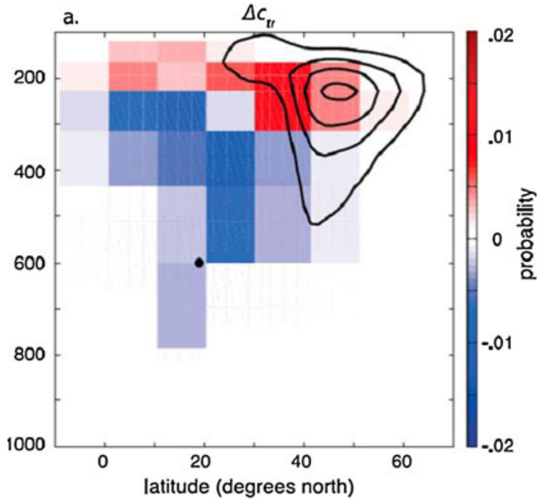


Fig. 12 DJF zonal means for global warming change in probabilities of last saturation for the RH minimum (19 N, 601 hPa), (contours are differences in the 2.5–6 day variance of the meridional wind, and contour interval is 5 m^2/s^2). The RH minimum is indicated by the *black circles*. From Hurley and Galewsky (2010a, b) copyright AGU

(Sherwood et al. 2010b). Two IPSL CM4 model (Marti et al. 2005) simulations of climate change within the AR4 effort have been analysed and compared to a control simulation. The statistics of RHp10 at 500 hPa further support the poleward shift of the relative humidity minima in both hemispheres together with a slight increase in the frequency of occurrence of dry air (Fig. 11). Various explanations have been presented to account for such poleward migration and extension of the Hadley cell (see Sherwood et al. 2010b for a summary).

As discussed all through this paper, such dry regions are under the control of the large-scale dynamics. The understanding of the relative humidity there requires the consideration of both the statistics of local temperature and the temperature of last saturation. Under an uniform warming of the atmosphere, it is straightforward to show that one does not expect any strong modifications of the RH distribution as far as the temperature change is small to moderate (Pierrehumbert et al. 2007). Trajectory computations under such uniform warming but with realistic circulations and last saturations statistics indeed confirmed the relative constant behaviour of the whole RH distribution. Nevertheless, one rather expects a nonuniform warming with increasing CO_2 concentration: stronger warming in the upper troposphere of the deep tropics (than in the mid troposphere) and small warming (if not a cooling) below the extra-tropical tropopause (Sherwood et al. 2010b). Such a differential lapse rate change is expected to perturb untrivially the last saturation statistics for the dry subtropical regions of the free troposphere. Experiments using climate change simulations and advection–condensation modelling indicate that, despite such complexity, the dynamics of air masses seem to change along with the differential lapse rate changes, in a way as to maintain near-constant distribution of relative humidity, be it at 500 hPa (Pierrehumbert et al. 2007) or all through the free troposphere (Brogniez and Pierrehumbert 2007). One reason for such a small response may lie in the relatively small-amplitude temperature changes that are occurring within these climate change simulations, and it would be interesting to extend such diagnostics to widely varying climates (O'Gorman and Schneider 2008). The investigation into the evolution of the last saturation statistics for the zonal mean relative humidity tropospheric minimum in the AR4 model (Huxley and Galewsky 2010b) reveals a poleward and upward shift (Fig. 12), which correspond to a contemporaneous shift in the mid-latitude baroclinic activity (Wright et al. 2010). These recent analyses indicate that the use of the AC paradigm along with the focus on some part of the whole PDF of the free tropospheric humidity is an encouraging step towards a better identification of the lead processes driving the water vapour feedback. This endeavour was once (even many times) considered as an unreachable perspective owing to the complexity of the sources (the so-called microphysics effect) and transport mechanisms (Renno et al. 1994; Couhert et al. 2010). It is nevertheless noted that the zonal averaging of the results is not well suited for investigating the dry end of the PDF due to the co-existence of moist and dry regimes at the same latitude (Figs. 1 and 4), which are fed by different physics and dynamics. The investigation of these subtropical features (like the summer time minimum of Brogniez et al. 2009) rather than the zonal mean in conjunction with the use of the adequate PDF characteristic instead of the first moment of these non-normal distributions is likely to help clarify the process at play in the maintenance of relative humidity under climate change.

4 Conclusions

This survey focused on our increased understanding of the drivers of the PDF of relative humidity in the free troposphere over the intertropical belt that the last decade has witnessed. The advection–condensation paradigm has shown its ability to clarify the dynamics of relative humidity in current climate, thanks to confrontation with a large number of mature (and maturing) observations. The dual origin of subtropical dry air, tropical deep convective regions and extra-tropical upper troposphere and the importance of this lateral mixing have also been recognized. The suite of available tools dedicated to the study of the relative humidity distribution is well furnished (idealized, Lagrangian, Eulerian frameworks). Incentive (through the use of a simple parameter) to go beyond the use of normal statistics for such non-normal moisture distribution in the subtropics has been provided. More generally, the need to avoid averaging (in time or zonally) the humidity fields to help sharpen the delineation of the physics underlying the distribution and its radiative impact onto OLR has been underscored. The interpretation of the water vapour feedback under the AC assumption is still linked to temperature through the Clausius–Clapeyron law although indirectly, through the statistics of last saturations. Differential temperature changes between the subtropical free troposphere and the main last saturation regions are identified as one of the major point to further clarify in the future. Already first attempts have shown encouraging results towards such an endeavour with the AR4 climate simulations and an appropriate diagnosis. Such efforts should help providing the important physical connection between the lapse rate and water vapour feedbacks.

The extra-tropical influence on the PDF of relative humidity is not confined to the subtropical regions nor is the importance of dry free tropospheric layers. In the deep tropics, dry air also has some connections to mid-latitudes (Yoneyama and Parsons 1999; Roca et al. 2005; Casey et al. 2009). There, dry air is important to the development of deep convection as surveyed in details in Del Genio (2011 this issue). The moisture distribution in the moist regions is also radiatively important through the modulation of the longwave cloud radiative forcing of high clouds (Sohn and Bennartz 2008) that can impact these deep convective systems' cloud feedback (Del Genio and Kovari 2002; Roca et al. 2005). The investigation into the importance of the lateral mixing and the extra-tropical source there is nevertheless made more difficult than that for the subtropical regions. One can nevertheless be optimistic with the current advent of a long-term record of space-based microwave measurements (e.g., John et al. 2011) that can probe the moisture vertical distribution in the near environment of convection and will definitely help these investigations, so will the upcoming Megha-Tropiques mission that will fly a dedicated payload to measure humidity profiles and TOA radiation in clear and cloudy regions over the intertropical belt (Roca 2011).

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