Tropospheric dryness and clouds over tropical Indian Ocean

Gian Luigi Liberti a, Frederique Chéruy b.*,  

a ISAC-CNR, Via Fosso del Cavaliere 100, I-00133 Roma, Italy  
b LMD/IPSL-CNRS, UPMC, Case courrier 99, 4 pl. Jussieu, 75252 Paris-cedex05, France  

Accepted 4 October 2005

Abstract

Dry layers in the free troposphere over Tropical Oceans have been studied for their role in convective activity and for their effects in the radiation budget. Previous studies concentrated, mostly, on the Western Pacific region because of the abundance of observations during the TOGA-COARE. This study aims to document the occurrence of dry layers over the Indian Ocean and to investigate the cloudiness observed, but poorly documented, during such events. One month (March 1999, during INDOEX) of combined Visible/Infrared and Microwave data from the TRMM radiometers had been processed to classify observations in terms of total precipitable water vapour (TPWV), cloud occurrence and type. Soundings (1978–2004) from the Seychelles station have been analysed to validate the capability, through the analysis of TPWV, to detect dry layers.

The study area (40°E–80°E, 30°S–30°N) had been portioned into 2.5°×2.5° boxes to investigate the spatial distribution of occurrence of dry events with associated cloudiness. South of the ITCZ cloudiness associated with low TPWV is due to low-level clouds: probably generated by shallow convection trapped by the trade inversion. North of the ITCZ cirrus are mostly observed during relatively dry events. Further analyses, concentrating on possible links between occurrence of cirrus and TPWV, suggest, in addition to the obvious mechanism (i.e. the higher the moisture, the higher the convective activity and as a consequence the higher the occurrence of cirrus), a second one that would be responsible of relatively high occurrence of cirrus for low TPWV.

A case (14th–15th March 1999) is studied in detail with TRMM observations, sounding data and METEOSAT imagery. The observed cirrus, generated by convection, migrate over relatively dry air of extra-tropical origin. Cirrus extend as filaments for more than 1000 km in length and about 50 to 100 km in width, and they last for 2–3 days. A retrieval method is designed and applied to the data giving as cirrus top pressure approximately 250 hPa while the retrieved effective radius value is consistent with what expected, from literature, for dissipating cirrus at that pressure.

The vertical structure of the atmosphere, observed during such event suggests the hypothesis that a combination of presented radiative and dynamical mechanisms could be responsible, through the supply of moisture from lower levels, of increasing the cirrus lifetime and, as a consequence, increasing the occurrence of cirrus over relatively dry air columns.

A larger data set is investigated to confirm the results based on the March 1999 data set analysis. The average vertical structure of the atmosphere, during such events, as obtained from the Seychelles sounding data set (>7000 soundings) analysis confirms the occurrence of the features observed in the study case. Similarly, the analysis of 105 days of TRMM orbits over the box containing the Seychelles station, confirms the statistical features that indicate a possible relationship between the occurrence of dry air and associated cirrus. However, possible interaction between dry layer and cirrus occurrence should be

* Corresponding author.  
E-mail addresses: g.liberti@isac.cnr.it (G.L. Liberti), cheruy@lmd.jussieu.fr (F. Chéruy).
investigated in a detailed modelling framework (beyond the scope of this study) such as the one offered by the cloud resolving models.

© 2006 Published by Elsevier B.V.

Keywords: Troposphere; Dry layers; Indian Ocean; TRMM; Cirrus

1. Introduction

Dry layers are frequently observed in atmospheric soundings from the climatologically humid warm pool region (Mapes and Zuidema, 1996). When the humidity drops are drastic, they are also identified by Special Sensor Microwave Imager (SSMI; Sheu and Liu, 1995). Previous studies established that, in some cases dry air results from transient adiabatic vertical displacements in the vicinity of mesoscale convective systems (Zipser, 1977), in these cases the drying is limited. In other cases dry air may originate from aloft at higher latitudes and subsides into the tropics as filaments, several hundred kilometres in width (Yoneyama and Parson, 1999; Waugh and Polvani, 2000). Due to their potential impact on the convective activity, anomalies in the water vapour vertical distribution over the tropical oceans have received a great deal of interest since the Tropical Ocean Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA-COARE, Webster and Lukas, 1992).

Combining Special Sensor Microwave Imager (SSM/I) and GMS/IR data over the TOGA-COARE area, Liberti et al. (1994) observed that quite often low total precipitable water vapour content (TPWV), as retrieved from SSM/I measurements, occurred in cloudy sky according to the IR GMS. Mapes and Zuidema (1996) stressed the role of the particular longwave (LW) cooling profile created by the dry layer in establishing a stable stratification at the base of the dry tongue. They hypothesize that when convection manages to penetrate a stratification anomaly such as at the base of the dry tongue, it may detrain an anomalous amount of mass in the stable layer. This may create layers of clouds. By looking at the frequency distribution of the nearly saturated layers (as a proxy for the clouds), the authors found considerable similarity to that of the humidity drops. The capping effect of the dry layer and its direct consequences on the cloudiness produced by the convection is also discussed by Parsons et al. (2000) and Redelsperger et al. (2002). They found that the effect of dry air was generally to limit the vertical extent of convection producing shallow middle-level clouds.

Also during TOGA-COARE, on the basis of radiosoundings and Geostationary Meteorological Satellite (GMS) Infrared (IR) maps over the site of Kapinga, Johnson et al. (1996) found that the driest and warmest cases were cloudy. Brown and Zhang (1997), estimated cloud occurrence and cloud top pressure from hourly window IR brightness temperature averaged over 4 pixels centre at each Integrated Sounding System (ISS) site. By analysing the variability of the mid-troposphere moisture and its effect on the cloud type distribution during TOGA-COARE, they noted that during dry events, substantial amount of mid-level clouds was present.

However, in all of the above studies, cloud information was inferred from the analysis of IR window brightness temperature from radiometers on board the GMS. It is widely known that with single IR channel measurements relatively optically thin clouds can be incorrectly interpreted. Brown and Zhang (1997) pointed out that in the case of thin high cirrus overlaying thick middle cloud, cloud top height for the latter could be overestimated, similarly relatively thin cirrus clouds could also be misinterpreted as middle level clouds. For a 5° by 5° array (1°N–4°N, 153E–158°E), including the TOGA-COARE Intensive Flux Array, Fig. 1 shows the bi-dimensional histogram of occurrence of GMS derived IR brightness temperature versus the SSM/I derived TPWV for class width of 1 K and 1 kg/m², respectively. A maximum of 30-min time lag is allowed between the SSM/I and the GMS data. The TPWV is calculated with the algorithm proposed by Alishouse et al. (1990). The average brightness temperature for each TPWV class is also reported (black line). The main feature of the bi-dimensional histogram is the expected increase of cold (i.e. cloudy) pixels for increasing TPWV with the consequent decrease of average brightness temperature with increasing TPWV. However, a relative maximum of occurrence of cloudy pixels is observed also for relatively dry pixels (i.e. TPWV ≈ 40 kg/m²). For such value of TPWV, the corresponding average value of the brightness temperature is of the order of 260 K. This value is classically interpreted as referring to mid-level clouds, however relatively thin cirrus can produce the same value.

The Tropical Rainfall Measuring Mission (TRMM), posterior to TOGA-COARE, provides almost coincident, multi-spectral and relatively high spatial resolution
observations from the TRMM Microwave Imager (TMI), an SSM/I-like passive microwave imager, and the Visible Infrared Scanner (VIRS), an Advanced Very High Resolution Radiometer-like (AVHRR) narrow band radiometer. This gives a unique opportunity for a more detailed analysis of the interaction between clouds and dry layers. TMI observations allow the retrieval of total precipitable water vapour (TPWV) content also for non-precipitating cloudy conditions while the set of wavelengths of the VIRS radiometer allow the detection of cloud as well as the inference of some microphysical characteristics of the clouds such as the phase, the cloud optical thickness and the cloud top level (e.g. Ackerman et al., 1995; Wu, 1987).

The focus of the present study is to document the occurrence of dry layers and the associated cloudiness over the tropical Indian Ocean where it has been poorly documented up to now. The correlation between dry layers and total water vapour over tropical Indian Ocean is explored in order to support the use of TMI derived TPWV as a proxy of the humidity in the free troposphere.

This work is mainly based on the analysis of satellite observations (TRMM) and radio-soundings recorded over the Indian Ocean (40°E–80°E, 30°S–30°N) during the INDOEX experiment (Ramanathan et al., 1996). The study area and period have been selected to take advantage of any possible ancillary observations, especially in situ ones, that over tropical oceans are available almost uniquely during international experiments.

In Section 2, a data set of all the radio-soundings recorded over the Seychelles site from 1978 until 2004 is analysed. The variability of the total precipitable water vapour (TPWV) is shown to be mainly due to the humidity in the free troposphere. Based on this, we assume that anomalously dry TPWV is likely to be generated by intrusion of dry air in the free troposphere. With this assumption, the analysis of satellite-derived TPWV is expected to give similar results to those obtainable from the analysis of soundings. Satellite data processing, including the algorithms used for the detection of the dry events and clouds’ detection and classification are described. The results of 1 month of data (March 1999) are reported. In order to test the generality of the results, the analysis of all the radio-soundings recorded over the Seychelles from 1998 until 2004 is performed, the satellite analysis is carried out to identify the cloudiness for all radio-soundings when a dry event is identified.

In Section 3, the results are discussed. The case of an event of dry-extratropical air partly covered by cirrus is described in order to draw also the synoptic conditions. The environmental conditions in terms of temperature and wind profiles are discussed. Physical mechanisms that could explain the observed link between dry layer and cirrus and consistent with the environmental conditions are tentatively proposed. In Section 4, the results are summarized.

2. Data analysis

2.1. Tropospheric dryness over tropical oceans

Although there have been, in the last decades, considerable improvements in innovative techniques to measure vertical distribution of atmospheric water vapour (for example: satellite sounding and Raman...
lidar), outside experimental sites, the most accurate way to study the detailed vertical structure of tropospheric humidity still remain the analysis of radio-soundings. However, their spatial distribution over tropical ocean is very scarce, except during international experiment when their number and quality is increased. From the perspective of investigating the variability of water vapour distribution over the whole tropical oceans, or even over a portion of tropical oceans where soundings are not available, the use of satellite observations should be considered. Time series of satellite-derived soundings (i.e. TIROS Operational Vertical Sounder (TOVS) products) are available and they cover the whole globe (e.g. Scott et al., 1999). However, the capability of such products to correctly detect and represent intrusions in the middle troposphere of anomalously dry air is questionable. In addition, in the presence of clouds, such capability is even reduced. Relatively robust and almost all-weather information on the TPWV over the ocean can be obtained from passive microwave radiometry.

In order to use the TPWV as a proxy to study dry layers in the free troposphere over tropical oceans, it is necessary to investigate, through radio-sounding analysis, the relationship between dry layers and TPWV.

Over tropical oceans, the boundary layer humidity is mostly controlled by the sea surface temperature that has a relatively low variability, while free troposphere may receive extra-tropical air masses with very different characteristics in terms of humidity. As a consequence, while the largest contribution to the TPVW, in terms of absolute amount, is expected to be in the boundary layer, the TPVW temporal variability should be mostly due to the variability of humidity in the free troposphere. This is evident, at least in terms of relative humidity, in Fig. 2 of Brown and Zhang (1997) which represents the time series of relative humidity profiles from the TOGA-COARE soundings and shows that the highest variability arises between 850 and 200 hPa.

Over the Indian Ocean, a relatively long time series (1978–2004) of soundings is available for the Seychelles (4.66°S, 55.5°E) sounding site. Fig. 2 shows the average water vapour mixing ratio profile (Fig. 2A) and its standard deviation (Fig. 2B) computed using 7733 soundings available during the period and binning the single vertical measurements in a 25-hPa grid. The absolute maximum of the standard deviation occurs around 825 hPa. Fig. 2C represents the portion of total precipitable water content below a particular pressure level for the profile of Fig. 2A. Boundary layer (p>900 hPa) accounts for about 50% of the total water vapour content. The remaining 50% is however in the portion of the atmosphere with larger relative variability. These observations support the idea that, over the Indian Ocean, the largest contribution to the variability of the vertical distribution of water vapour could be due to humidity in the free troposphere. As a consequence, the presence of a dry layer in the free

![Fig. 2. Statistics computed using 7733 radio-soundings from the Seychelles (4.66°S, 55.5°E) site. A) Average water vapour mixing ratio profile. B) Standard deviation of the average mixing ratio. C) Portion of total precipitable water content, for the average profile (A), below a particular pressure level.](image-url)
troposphere should be detectable as a negative anomaly in the TPWV retrievable from satellite passive radiometry. The capability of detection of dry layers is then investigated with the Seychelles soundings data set firstly defining a ‘dry layer’ and then computing the portion of relatively dry, in terms of TPWV, soundings that do not contain dry layer according with the above definition. Detailed procedures to define dry layers, or alternatively humidity drop, are described in Mapes and Zuidema (1996) as well as in Johnson et al. (1996). Each author adopted its own definition which differ in the variable used to represent the vertical humidity (specific humidity or relative humidity) as well as in the vertical extension and expected position of the dry layer. However, the main limit in adopting one of the definitions available in literature is due to the vertical resolution of the sounding. Actually, both referred studies analyse soundings from the TOGA-COARE database that have high vertical resolution (<10 hPa) while soundings currently available are not on a regular vertical grid and the sampling in the free troposphere is rarely better than 20 hPa. Finally, because of the technique proposed to detect dry layers (i.e. through the TPWV) as well as because their radiative impact will be discussed, the mixing ratio is preferred here to study the humidity vertical structure.

A dry layer is then defined. For each sounding, the average of the mixing ratio within a regular 25-hPa grid from 400 to 1025 hPa, is computed. Inversions are identified according to the following procedure: starting from 400 hPa, the method searches for inversions in the expected tendency of the mixing ratio: i.e. growing mixing ratio for increasing pressure. Once an inversion is found, the case is retained only if the inversion is at least 100 hPa width: i.e. the mean mixing ratios values for four 25-hPa layers are lower than the value at the top of the inversion for all four layers. Only one missing level is allowed out of the four analysed. The search is repeated by increasing the inversion top of 25 hPa up to 825 hPa in order to exclude inversion clearly within the boundary layer. This definition of dry layer is also used to create the data set analysed in Section 3.2. The possibility of using TPWV dry anomaly as a proxy for dry layers located in the free troposphere is then investigated based on this data set. For each month of the period, cumulative histograms are computed. A sounding is classified as dry when its TPWV is lower than the value associated with a given percentile of the cumulative histogram. Soundings are also classified according to the occurrence of at least one humidity inversion as defined above. This allows to compute contingency tables as well as skill scores such as the False Alarm Ratio (FAR). Here, the FAR corresponds to the number of cases without inversion out of the total number of cases with TPWV less than the given percentile value. Fig. 3 shows the FAR as a function of the threshold corresponding to the percentile of the population. A minimum value of the FAR of about 30% is reached for a percentile value of the order of 10%. This means that in 70% of the cases, a water vapour profile whose TPWV is less than the 10% percentile will exhibit an inversion. While only high vertical resolution soundings allow to define unambiguously dry layers, the above study indicates that optimal conditions can be found for using TPWV as an indicator of dry inversion in the free troposphere in order to benefit from the better spatial and temporal coverage of satellite observations.

![Figure 3](image-url)
2.2. TRMM narrow band radiometers data processing

A data set of match-upped TMI microwave and VIRS visible/infrared observations from TRMM (Kummerow et al., 1998) orbits over the study area (40°E–80°E, 30°S–30°N) during the month of March 1999 (about 500 orbits) was created. In this data set, various classes are defined according to the degree of dryness of the observations, the presence of cloud or not and when cloudy the type of cloud (cirrus or not).

In order to build a database of combined TMI-VIRS observations, data from each single instrument were processed and merged according to the following steps: The surface type was determined for each TMI low resolution measurement (i.e. 10.7, 19, 21.3 and 37 GHz). Land contaminated measurements were carefully excluded according to a land/sea mask accounting for coastal and neighbouring pixels. The highest resolution (approximately 2.11 km at nadir) VIRS data of the same orbit were selected within a distance of 16 km from the geo-located TMI ocean observations. Such a distance represents the footprint in the down-track direction of the 37-GHz channel. Note that because of the different scanning geometry of VIRS and TMI, observations are made a few seconds apart and the sampled air column can be not the exactly the same. For the synoptic nature of the investigated phenomenon, we assume that such sampling differences should not introduce significant errors. The VIRS channel 3 (3.75 μm), 4 (10.8 μm) and 5 (12 μm) radiances were converted into brightness temperatures $T_3$, $T_4$, $T_5$. The VIRS observations falling within each TMI low-resolution footprint have been represented by statistics such as: average, standard deviation, minimum and maximum value. The following analyses use the average value as representative. An estimation of the TPWV and precipitation (Wentz, 1997) is associated with each low resolution TMI footprint.

The detection of dry events and the cloud classification are performed according to a simple threshold technique. As the region of interest extends over a zone with different climatologic characteristics, the threshold definition and the successive analyses were performed on a grid basis. $2.5^\circ \times 2.5^\circ$ boxes have been defined. The size of the boxes is a compromise between the following factors:

- getting close to General Circulation Model (GCM) grid box resolution
- having a large amount of data to build significant statistics
- having a resolution able to reproduce the gradient of total precipitable water vapour from the ITCZ to the driest subtropical regions

- having an area comparable with the Intensive Flux Array (IFA) of TOGA-COARE, where previous studies were carried out.

A total of 315 boxes, with about 40,000 to 80,000 individual observations per box, results from the present data set once boxes including lands or with less than 10,000 data points were eliminated. In the following, unless specified, we use pixel to refer to a single TMI footprint. In order to study the cloudiness associated with dry events 3 classes are defined according to the following criteria: dry or moist, cloudy or clear, cirrus or no cirrus. Note that a pixel can be classified as cirrus only if it has been previously classified as cloudy, therefore the cirrus represent a subset of the cloudy observations.

A pixel is defined as dry when the TPWV value is in the lowest 10% (within a 1 kg/m² class width) of the TPWV cumulated distribution computed, for each box and over the whole period, using all non-precipitating pixels. As a consequence of the above definition, a set of dry measurements will always be detected. The threshold of 10% corresponds the percentile value that minimizes the FAR as described in Section 2.1. A pixel is defined as cloudy when the 10.8-μm brightness temperature ($T_4$) satisfies the following criteria:

$$T_4 < T_{\text{moda}} - (T_{\text{MAX}} - T_{\text{moda}}).$$  \(\text{(1)}\)

In (1), $T_{\text{moda}}$ (the moda of the distribution) and $T_{\text{MAX}}$ are determined for each individual box. $T_{\text{moda}}$ is the temperature of the most frequent 1 K width class in the $T_4$ distribution for the box and $T_{\text{MAX}}$ is the maximum observed $T_4$ brightness temperature for the same box. This approach is based on the assumptions that the moda of the distribution represents a clear-sky situation and that the variability of $T_4$ for clear-sky conditions, mostly due to sea surface temperature and clear-sky TPWV, is symmetric with respect to the moda. Therefore, the lower limit for the clear-sky pixels (i.e. the cloudy threshold) is obtained by subtracting the quantity $T_{\text{MAX}} - T_{\text{moda}}$ to the moda value that represents the warmer half width of the clear-sky variability. This approach allows pixels to be classified as cloudy even if their window brightness temperature is close to 290 K.

Finally, a cloudy pixel is classified as cirrus when:

$$T_4 - T_5 > 3 \text{ K}.$$  \(\text{(2)}\)

This criteria is chosen according to the relatively rich and consolidated literature on cirrus detection through the split window technique (e.g. Inoue, 1987). The cirrus definition is independent of the box.
The method is illustrated in Fig. 4 when applied to the TRMM observations within in the grid box containing the Seychelles (4.66°S, 55.5°E) sounding site. The left upper panel shows the scatter plot of TPWV versus $T_4$ brightness temperature. The thresholds to identify the dry (respectively cloudy) pixels are reported on the y (respectively x) axis. The upper right panel shows how the dry threshold is determined while the lower left panel corresponds to the determination of the cloudy pixels. On the lower right panel, the scatter plot of $T_4 - T_5$ for all points (grey) and for the dry and cloudy (black) pixels is plotted. For this case, it appears that $T_4 - T_5$ for the dry and cloudy pixels is greater than 3 K, which corresponds to cirrus clouds.

2.3. Results

Results of the TRMM based classification are summarized in Fig. 5. Fig. 5A shows, for each 2.5° × 2.5° grid box, the value of the TPWV threshold used to define dry pixels. As expected, there is a strong latitudinal gradient of the TPWV threshold as a consequence of the effective TPWV distribution. Even though the definition adopted for the dryness ensures that dry pixels are always defined, the values of the thresholds found over the ITCZ (30 kg/m²) correspond effectively to relatively dry values since the mean values are in order of 50 kg/m² (not shown). The grid box for a given longitude where the maximum of the TPWV threshold is found will be used in the following to identify the ITCZ. In Fig. 5A–D, this is represented by the dotted line that passes through the above described grid boxes. The adopted definition of the ITCZ may not be in accordance with other possible definitions: for example if we were to use the distribution of occurrence of precipitation (not shown) as a parameter to define the ITCZ position, this would be located about 2.5° to 5° more south, however the position, relative to the ITCZ, of cloud type occurring during dry events (see below) would be the same for both definitions.

The map of occurrence of cirrus clouds (Fig. 5B) shows that the maximum value corresponds roughly to the moister boxes. This is consistent with the idea that most of the cirrus are generated by the convection which

![Fig. 4. TRMM March 1999 data analysis for the grid box containing the Seychelles sounding station [4.66°S 55.53°E]. (A) TMI derived TPWV versus $T_4$ brightness temperature. The lines correspond to the threshold used to define cloudy and dry. Black points are the dry and cloudy ones. (B) Histogram of the distribution of the TPWV. The continuous line represents the 10% cumulative frequency TPWV value used to define dry pixels. (C) Histogram of the distribution of the $T_4$ brightness temperature. The line represents the cloud/clear threshold. (D) $T_4 - T_5$ versus $T_4$ brightness temperature.](image-url)
occurs in the moister part of the tropical oceans. Fig. 5C shows the percentage of dry pixel classified as cloudy too (dry and cloudy) for each 2.5° by 2.5° grid box as blue portion of the box. The percentage of dry pixels classified as cirrus too (dry and cirrus) is the red portion of the box. 100% coverage (i.e. all dry pixels are also cloudy or cirrus) corresponds to the whole box area filled with colour. From this panel, it appears that the majority of the boxes reporting significant percentages of dry and cloudy pixels (blue area) are located North and South of the ITCZ. South of the ITCZ, dry and cloudy are seldom classified as cirrus. From the analyses of VIRS data, dry and cloudy pixels, in this zone, seem to be associated with water clouds (as derived from the split window cloud classification) with cloud top brightness temperatures of about 280 K. Fig. 6 shows $T_4 - T_5$ versus $T_4$ brightness temperatures scatter-plot for one of the grid box (30°–27.5°S, 65°–67.5°E) where a large amount of dry and cloudy pixels not classified as cirrus as well is detected. Compared with
Fig. 4D, the dry and cloudy pixels (black points) lie mostly below the 3 K ($T_4-T_5$) cirrus threshold and have the typical signature of thick clouds: i.e. $T_4-T_5$ approaching to 0 K. Given the temperature at which ($T_4-T_5$) reaches the 0 K value (about 280 K), we can also conclude that the corresponding pixels refer to liquid clouds. Unfortunately, it is difficult to control the vertical distribution of the water vapour since no soundings are available for the southern part of the region (south of 25°S). However few cases of dry and cloudy pixels not classified as cirrus have been also detected in the box containing the Vacoas [20.30°S, 57.50°E] sounding site (the closest sounding site to the box showed in Fig. 6). The soundings from this site show, often during March 1999, a temperature inversion at about 280 K with a relatively dry layer above it. In this case, the observed clouds could be due to shallow convection limited by the temperature inversion.

North of the ITCZ, almost the whole set of dry and cloudy pixels are instead associated to cirrus clouds.

The simultaneous occurrence of cirrus and anomalously dry air column could be casual: in a relatively convectively active region, such as the tropics, cirrus clouds can be considered somewhat as a persistent characteristic resulting from aging convective active systems. In such a scenario, the presence of a dry layer would simply inhibit the development of middle/high troposphere clouds (i.e. relatively thick clouds), increasing the ‘visibility’ of the cirrus with the adopted technique. If the occurrence of a dry event is independent from the occurrence of cirrus, the probability of concurrent occurrence of dry and cirrus should be approximately equal to the product of the probability of the occurrence of the two events separately. Assuming that the number of data point is sufficiently large to approximate the probability of occurrence with the frequency of occurrence, we define for the whole month of March 1999:

\[ P_d \] Number of dry pixels/total number of pixels
\[ P_c \] Number of cirrus pixels/total number of pixels
\[ P_{d\&c} \] Number of dry and cirrus pixels/total number of pixels.

In Fig. 5D, the grid box area covered by colour is proportional to the absolute value of the ratio:

\[ (P_d * P_c - P_{d\&c}) / P_d * P_c. \]

For uncorrelated events, this ratio should be 0, while large values of the ratio would indicate that the events are not independent. The information on the sign of the difference ($P_d * P_c - P_{d\&c}$) is given by the colour of the fraction of the grid box coloured area. Boxes are blue if the expected occurrence, in the hypothesis of independent cases, is larger than the observed one ($P_d * P_c > P_{d\&c}$). A similar result is expected in the obvious scenario where cirrus depends on moisture availability and as a consequence a dry event would decrease the probability of occurrence of cirrus. Boxes are red in the opposite case ($P_d * P_c < P_{d\&c}$). In this case, the occurrence of a dry layer is a favourable condition for occurrence of the cirrus.

Note that the fact that the ratio may assume both signs means that the case where $P_d * P_c = P_{d\&c}$, as for example just below the ITCZ, could be either the case of uncorrelated events or the case of a box where the effects of mechanisms that generate the different type of correlation compensate.

We have already mentioned the possibility that the occurrence of a dry layer in the free troposphere inhibits the formation of convection and makes the cirrus detectable with the adopted split window technique. This would appear, in the representation adopted in Fig. 5D, as a larger probability of detection of cirrus in case of dry atmosphere (red boxes). However, if this was the case either the majority of the boxes would indicate positive correlation (red), if the ‘visibility’ mechanism was the dominant one, or alternatively the distribution would be rather noisy. We observe that the distribution of red and blue follow a sort of zonal pattern. North of the ITCZ we also find several boxes with the difference ($P_d * P_c - P_{d\&c}$) close to 0 even if the probability of cirrus (Fig. 5B) is relatively high.

Fig. 6. Same as Fig. 4D but for the grid box [30°–27.5°S, 65°–67.5°E].
The increased occurrence of cirrus for relatively dry air columns, as revealed from the above analysis, could be still a questionable consequence of the arbitrary selection of the 10% percentile for the definition of dry as well as a result of the detection technique as discussed above. Additional analysis are performed, over the March 1999 TRMM data set, to investigate whether the observed cirrus–dryness relationship is a result of the adopted analysis techniques or more physical causes should be searched as responsible. For each 2.5°×2.5° box the number of observations within 1 kg/m² TPWV width classes is computed. Similarly, the number of observations classified as cirrus for each class is computed too. Fig. 7 shows, for each box, the ratio of the number of pixels classified as cirrus in each 1 kg/m² class out of the total population of the class. Each bar represents the value of the ratio for a 1 kg/m² class from 20 to 70 kg/m² class. Bars are red (blue) if the corresponding TPWV class is below (above) the 50% percentile of the TPWV distribution within the box. Note that, due to the shape of the distribution of TPWV (see for example Fig. 4B), results are very similar if the average TPWV is used to define the colour of the bars.

Firstly, we observe that for the majority of the boxes an increase of the ratio is observed with growing TPWV class. This would not be true if the detection mechanism was the dominant one, it is instead the expected consequence of the link between available moisture and convection that would generate the cirrus. Secondly, we observe that while for several boxes cirrus do not occur if the TPWV is below the 50% percentile (i.e. boxes with only blue bars), for the boxes where cirrus occurs for TPWV below the 50% percentile, a bi-modal distribution is most frequently observed. Note that the 50% percentile would separate quite well, in most of the bi-modal boxes, the two distributions. As a consequence, the 10% percentile arbitrary definition of dry, supported on the other hand by the sounding analysis (Fig. 3) it is expected not to influence drastically the relative distribution of regions where dryness and cirrus occurrence seems to be positively linked.

3. Discussion of the results

The above analysis demonstrated the frequent coincident occurrence of cirrus clouds and dry events north of the ITCZ over the Indian Ocean during the month of March 1999. In addition to the classical scenario where increased humidity in the tropics leads to increased convective activity hence increased cirrus, a more subtle process seems to appear linking low water vapour content and cirrus clouds. Now, by studying a particular case when sounding data are available, we aim at characterizing better the clouds and the environmental characteristics when such events occur. Tentative mechanisms are also proposed and supported by further data analysis over an enlarged data set.

3.1. Case study

From the analysis of daily mean TMI derived TPWV maps (not shown), it is possible to identify anomalies in the TPWV distribution. During the month of March 1999, a dry anomaly is observed, roughly along the equator (North of the ITCZ) and from 50° to 70° East, lasting from the 13th until the 17th of March. The same area is also mostly classified as cloudy. The analysis of the measurements taken at the Seychelles sounding station, located in the area interested by the previously detected dry event, confirms the occurrence of a dry anomaly: Fig. 8 (upper panel) shows the time series for the month of March of the profile of water vapour mixing ratio, while in the lower panel the time series of
TPWV as derived from the radio-sounding at the Seychelles station is presented. The presence of a dry air mass is observed between 600 and 800 hPa from the 13th to the 15th of March. In the TPWV time series the dry event is also evident. It is interesting that the dry event occurs after a very moist period around the 10th of March when relatively high water vapour mixing ratio values are reported between 400 and 600 hPa. Similar events are also observed between the 5th and the 8th of March as well as around the 23rd of March.

From the point of view of wind characteristics (direction and intensity), the dry layer and the troposphere above are quite different, supporting the hypothesis of advective origin of at least one of the two layers.

In order to illustrate on a synoptic scale the main cloud features associated with the dry event, the TPWV deduced from TMI is mapped in Fig. 9A for both ascending and descending orbits of the 15th of March. The corresponding IR ($T_4$) VIRS images are reported in Fig. 9B. The black frame, just below the Equator, outlines the largest cloud, within the image, classified as "dry and cirrus". Time series of hourly METEOSAT5 IR images for the same event have been inspected. From the IR images, the cirrus clouds appear to be generated by the convective systems lying southeast of the back rectangle, these cirrus extend as filaments for more than 1000 km in length and about 50 to 100 km in width and cover part of the dry zone which extends along the equator (blue-green on the figure). These dimensions prohibit neglecting the investigation of possible interaction between cirrus and dry events over the tropical oceans.

A retrieval method, described in Appendix A, provides a rough estimation of parameters which are characteristic of the observed cirrus. In our case, we obtain the cirrus height at around 10–11 km (200–250 hPa), well above (see Fig. 8) the level of the mixing ratio negative anomaly. Assuming a log normal size distribution with fixed standard deviation of 2 μm, the retrieval gives a modal radius of 14 μm as most a result. The retrieved average cirrus optical thickness is about 0.8 at 10 μm. While it is difficult to quantitatively evaluate the accuracy of the retrieved parameters, they appear to be consistent with the fact that the potential temperature lapse rate of the Seychelles radio-sounding is relatively low around the pressure level where the retrieval locates the cirrus. Moreover, the retrieved modal radius is quite close, when converted to effective radius, to the value reported, as a summary of several in situ observations, by McFarquhar and Heymsfield (1996), for dissipating cirrus at the temperature of the retrieved cirrus pressure height. This is consistent with the hypothesis that the cirrus was generated by convective activity before the occurrence of the dry event.

Fig. 8. March 1999 Seychelles radio-sounding time series: upper panel—water vapour mixing ratio [g/kg] profile, lower panel—total precipitable water vapour (continuous line). As a reference the mean monthly value (dashed line) is reported.
3.2. Possible mechanisms

The analysis of the 15th March 1999 case supports the hypothesis on the independent origins of cirrus and dry layer. Cirrus are generated by close and/or previous convective activity while the dry air is the results of large-scale circulation. However when cirrus and dry layer occurs within the same air column it seems that the two events are not fully independent. In this section, we propose the hypothesis that the presence of the dry layer may be responsible for increasing the lifetime of previously formed optically thin cirrus making their occurrence relatively larger than in case of moister air columns. The proposed hypothesis is based on the combination of two mechanisms: a radiative and a dynamical one.

We observe that during the 15th March 1999 case:

a) cirrus are quite above the top of the dry layer;
b) at the boundary between the top of the dry layer and the troposphere above there is still considerable amount of moisture;
c) the dry layer and the troposphere above it have quite different wind characteristics (direction and intensity) supporting the hypothesis of advective origin of both cirrus and dry layer.

Let us consider a clear sky atmosphere originally moist, especially in the upper levels, as a consequence of previous and/or close convective activity. Due to large-scale circulation mid-latitude relatively dry air is advected and generates a dry layer in the mid-troposphere.

From a radiative point of view, because of the presence of a relatively dry layer in the middle troposphere, the LW flux emerging from the warm levels below the dry layer will not be absorbed by the dry layer but mostly at the boundary between the latter and the upper layer. Such absorption would be quite localized because of the relative abundance of water vapour in the lowest levels of the upper boundary. As a consequence, the atmospheric levels just above the dry layer would have a cooling rate close to 0. This is confirmed by computations of the cooling/heating rates for the profile of the 15th March with the Chou et al. (2002) radiative transfer model that is similar to what shown in Fig. 11 from Mapes and Zuidema (1996).

From the dynamical point of view, dry intrusions in the mid-troposphere are clearly due to advection of air mass of different origin and therefore characterized by different wind intensity and direction compared to the tropospheric levels below and above. At the upper boundary of the dry layer, we expect the wind shear to generate turbulence.

The combined effect of such turbulence and the relatively low cooling rate would make the air parcel just above the dry layer potentially unstable and therefore a possible source of moisture for the cirrus above. In this case, the presence of a dry layer would delay the extinction of the cirrus by supplying humidity by the layers below it.
3.3. Further analyses

We presented a possible physical mechanism that would explain the link between dryness and cirrus occurrence based mostly on what observed with satellite and sounding during a single event. In this section, we perform further analyses to support the proposed mechanism.

In particular, two issues are addressed:

1) given the presence of a dry layer, as detected in a sounding, what is the average vertical structure of the atmosphere? The proposed mechanism requires a relatively large moisture at the interface between the dry layer and the troposphere above it (where the cirrus is suppose to be) as well as a wind profile that would generate wind shear at the same interface. Do these features occur for a generic profile with a dry layer?
2) Are the satellite analysis results dominated by a single and particularly intense events during a single month? Analysing a larger data set do we still obtain the same results?

In order to address the first issue, using the definition of inversions described in Section 2.1 we select all soundings, in the periods 1978–2004, with at least an inversion detected and, in order to have a consistent definition with the satellite analysis with TPWV in the lowest 10% of the distributions.

The vertical distribution of such dry inversions, soundings is plotted in Fig. 10. The left panel shows for each 25 hPa defined level the total number of dry inversions detected. Several relative maxima of occurrence appear in Fig. 10a: at 450, 500, 575 and 700 hPa. However, the analysis of the time series of occurrence and position of the dry inversion suggests two separate regimes during the year that can be identified. The right panel in Fig. 10 shows the seasonal occurrence of dry inversion, normalised for the number of month, with month grouped according with the usual definition of wet (JJAS: black bars) and dry (JFMAM-OND: grey bars) monsoon months. During the wet months dry inversions occur mostly above 550 hPa or below 750 hPa, while during the dry months there is a relatively large amount of inversions occurring between 550 and 750 hPa. In order to study cases similar to the one described in Section 3.1 we concentrate our attention on the dry months. During such period the maximum of occurrence is at 575 hPa that corresponds as expected (Johnson et al., 1996) to the 0 °C mean level. The inversion occurring 15th March 1999 was located around the 575-hPa level.

Fig. 11 shows the average profile (continuous line) of relative humidity (a), potential temperature (b) and wind components (c, d) computed selecting the soundings, during the month of March, where the dry inversion is detected at 575 hPa. As a reference, the mean computed using all sounding during the month of March is reported too (dashed line).

The relative humidity profile (Fig. 11A) shows a positive anomaly of relative humidity, the same is observed in terms of mixing ratio even if this could be somehow a consequence of the definition of humidity inversion. The positive and quite localized anomaly in moisture content is what, according with the radiative mechanism, would be responsible for the absorption of LW radiation from the layer below the inversion with the consequent low cooling rate within such level.

![Fig. 10](image-url) Vertical distribution of mixing ratio dry-inversions (1978–2004 ≈ 7000 soundings) at the Seychelles sounding site. Number of cases (left). Number of cases for wet monsoon months (JJAS: black bars) and dry ones (JFMAM-OND: grey bars). The number of cases is normalized to the number of months in the season: wet=4, dry=8.
In the potential temperature profile (Fig. 11B), it is possible to identify three distinct regions according with the sign of the anomaly. The layers between 900 and 700 hPa and between 550 and 450 hPa, i.e. the layer just below and above the top of the mixing ratio inversions, are characterized by a positive anomaly, while in correspondence of the top inversion (i.e. around 575 hPa) a negative anomaly is found. The maximum of the anomaly within each of the sub-layers mentioned is larger than 1 K and is above the value of the standard deviation computed over the whole month of March data set. Note also the change of lapse rate in the potential temperature profile. Note that according to the proposed radiative mechanism, a positive anomaly above the dry layer could be the consequence of the relatively efficient transfer of LW from the layer below the dry one to the one above it.

Fig. 11C–D shows the average wind component profile for the whole data set as well as for the subset of profiles including a dry layer. It is evident that the intensity of the wind component is larger as well as the difference between wind within and above the dry layer, indicating a relatively larger wind shear compared with the overall average profile. This would support the proposed dynamical mechanism.

In order to address the second issue, i.e. how representative are the TRMM results of March 1999 of more generalized conditions, we should perform the same analysis for an extended satellite data set. Because of the relatively high requirements, in terms of available computing resources, needed to perform over the same area the analysis for extended time period, we concentrate on the box containing the Seychelles sounding site. For this box, a larger data set of TRMM processed observations was created adding to the March 1999 orbits: the orbits from November 1999, as another dry monsoon month (see Fig. 10), and the orbits that occurred during dry events, according to the sounding-based definition given in this section that lasted at least 48 h. The second conditions was added to be sure of the large-scale nature, and consequent possibility to detect interesting cases from satellite data, of the dry inversion. A total of 105 days, for which both ascending and descending orbits where analysed constitute this extended data set. Fig. 12 shows the days included in this data set except for the month of October, at least one for each month is included in the extended TRMM data set.

Fig. 13A shows the cumulative histogram for the TPWV (continuous line) and the cirrus (dashed line). Fig. 13B shows the portion [%] of the pixels with TPWV lower than the threshold indicated on the x-axis that are also classified as cirrus. Fig. 13C shows the histogram of distributions of non-precipitating
observations for 1 kg/m² width TPWV classes (thin line) as well as the histogram of distributions of non-precipitating observations classified as cirrus for 1 kg/m² width TPWV classes (thick line). Fig. 13D shows the ratio of the number of pixel classified as cirrus in each 1 kg/m² class out of the total population of the class.

Fig. 13B shows the maximum frequency is of the order of 20% and it is reached for TPWV values that include all observations. The above definition of frequency, i.e. ratio of cirrus pixels vs. total, corresponds to a cloud cover and an average of 20% cirrus cover is consistent with the currently available climatologies.
over the same area both based on surface (e.g. Hahn and Warren, 1999, www.atmos.washington.edu/~ignatius/CloudMap) as well as on satellite (e.g. Rossow and Schiffer, 1999, iscep.giss.nasa.gov/products/browsed2.html, Wylie and Menzel, 1999, www.ssec.wisc.edu/~donw/PAGE/CLIMATE.HTM) observations. Similar consistency is found in terms of cirrus occurrence: i.e. number of orbit for which cirrus where detected (≈ 70%).

However, all the above statistical representations of the TRMM observations confirm the two regimes of dependence, between dryness and cirrus occurrence.

From example, from Fig. 13B and D, it is obvious that the occurrence of cirrus clouds increases as the TPWV increases, presumably as the result of anvils produced by the convective activity. More subtle, a secondary maximum occurs around 35 kg/m² this is consistent with that observed over the larger area for March 1999 (Fig. 7).

4. Conclusions

The aim of this study is enhance information on the presence of clouds during the occurrence of dry anomalies over the Tropical Oceans. It has been poorly documented in previous studies that often cover the same area (TOGA-COARE) and the study period (November 1992–February 1993). The growing interest in the physical mechanisms relevant in the interaction between mid-tropospheric humidity and convective activity calls for a better documentation of cloud occurrence during the dry events and for the description of their characteristics.

While only high vertical resolution soundings allow to define unambiguously dry layers, we found on a 26-year-long radio-sounding record carefully screened that in 70% of the cases, a water vapour profile whose TPWV is less than the 10% driest profiles of the month will exhibit a humidity inversion in the free troposphere. This legitimates the use of TPWV as an indicator of dry layer in the free troposphere in order to benefit from the better spatial and temporal coverage of satellite observations. According to these results, a technique that partially uses the potential of the TMI and VIRS radiometers on board of the TRMM to detect dry air columns, cloudy pixels and cirrus is presented (TRMM was unavailable during the TOGA-COARE). The use of this technique is an improvement compared to the simple analyses of IR brightness temperatures from single broadband radiometers as far as it is able to distinguish between low clouds and relatively thin cirrus. However, the available information content, in terms of cloud characteristics, is only partially used: we do not show any application of the 0.6-, 1.6- and 3.7-μm VIRS channels that, during daytime, can give additional information especially regarding cloud top phase and microphysical properties of liquid clouds. No application of such VIRS channels is reported in this study because we mainly focused on cirrus clouds that may be studied with the split window channels. In addition, the use of ‘solar’ channels would have reduced the data set analysed and introduced possible biases due to the varying geometry of observations of TRMM during a month.

The investigated area is the tropical Indian Ocean because we wish to document the occurrence of cloudy and dry events over tropical oceans other than the Western Pacific. Because of the general lack of data, especially in situ, over tropical oceans, the majority of the satellite analyses have been performed for 1 month (March 1999) of the INDOEX experiment. This was done in order to take full advantage of the additional information, both in terms of data availability as well as literature that characterize similar experiments that involve the international scientific community.

After having divided the study area into 2.5°×2.5° grid boxes, the analysis of monthly statistics of the data shows two separate regions where clouds occur during dry events; where a dry event is defined when TMI derived TPWV is in the lowest 10% of the monthly cumulative distribution. During dry events, cirrus clouds are observed North of the ITCZ, while shallow cumulus is observed South of it. The cloud type classification is not only based on satellite data but also supported by the analyses of radio-soundings. South of the ITCZ, a strong ‘trade wind’ temperature inversion separates moist marine boundary layer—lower troposphere from relatively dry middle upper troposphere. For this case, the occurrence of low level clouds, during dry events, can be easily explained by the fact that convection is inhibited by the temperature inversion and can develop only shallow cumulus. While shallow convection occurs very often South of the ITCZ, the observed occurrence of cirrus North of the ITCZ is mostly due to a unique large and long-lasting case. Compared to the shallow cumulus South of the ITCZ, during the dry and cirrus event, the dry air is located in the middle troposphere between two relatively moist layers. Qualitative analysis of time series of METEOSAT 5 hourly IR images indicates that the cirrus are generated by the convective systems. Daily maps of SSM/I and TMI derived maps of TPWV support the hypothesis of extratropical origin of the dry intrusion. This would bring
us to the conclusion that the two events are independent. However, a simple test comparing the product of the occurrence frequency of the two separate events (cirrus and dry) against the one of the occurrence of both events at the same time shows a positive correlation for the region North of the ITCZ.

In order to extend the validity of the study, time series (1978–2004) of radio-soundings from the Seychelles site were analysed. Within the period 1999–2004, when TRMM data are available and radio-soundings were of a relatively good quality, a total of 97 events were found. Within this set, TRMM data were processed for all dry events lasting for more than 48 h (as seen in the radio-soundings). The analysis of this data sets for 1 kg/m² width classes as a function of the cirrus/no cirrus diagnostic shows a bimodal distribution. As expected for the highest values of the water vapour content, the probability of occurrence of cirrus clouds increases. However, a secondary maximum occurs around 35 kg/m², corresponding to an increased probability of occurrence of cirrus clouds for these low values of the TPWV. Consistent with an analysis of the environmental conditions occurring when cirrus clouds are present at low water vapour content, dynamical and radiative arguments are tentatively proposed to explain this increased probability of occurrence.

Luo and Rossow (2004) compare the satellite derived time-life for tropical cirrus with the expected one and they conclude that the observed one is longer than as expected if usual mechanisms for the cirrus dissipation are considered. In this study, we propose a combination of physical mechanisms that would increase the lifetime of cirrus generated by convection when they occur over a relatively dry layer, this could partially explain the Luo and Rossow (2004) observed increased cirrus lifetime.

Further elucidation of the observed behaviour would require detailed modelling framework (beyond the scope of the present work) such as the one offered by the cloud resolving models.

Acknowledgments

The TRMM data used in this study were acquired as part of the NASA’s Earth Science Enterprise and Archived and distributed by the Goddard Earth Sciences (GES) Data and Information Services Center (DISC) Distributed Active Archive Center (DAAC).

TMI derived Total Precipitable Water Vapour and Precipitation are produced by Remote Sensing Systems (www.remss.com) and sponsored by the NASA Earth Science REASoN DISCOVER Project.

Appendix A. Retrieval of cirrus characteristics

In order to investigate further the characterization of clouds, a simple retrieval procedure has been developed. The retrieved macrophysical and microphysical cirrus properties are:

- the altitude/pressure of the cirrus top ($Z_{\text{top}}$)
- its optical depth $\tau$ (or the emissivity) at a given wavelength: in this case $10 \mu$m.
- the size distribution (through the modal radius) needed to compute radiative properties over the whole spectrum.

The sensitivity of the split window difference ($T_4–T_3$) and of the $T_4$ value to the above variables (see for example Wu, 1987) makes it possible to retrieve parameters describing these variables from narrow band observations. The retrieval is done under the following assumption:

- cirrus particles are spherical;
- ice particle size distribution log-normal with a fixed $\sigma=2 \mu$m and therefore represented from a single parameter: for example the modal radius $r_{\text{modal}}$;
- plane parallel infinite and vertically homogeneous (i.e. same size distribution) single layer cirrus;
- the clear sky contribution to the radiative transfer can be calculated using temperature and water vapour profiles from the radio-sounding at the Seychelles site, assuming for the surface temperature value the air temperature at lowest sounding level.

Using a combination of MODTRAN (Berk et al., 1983) to compute spectrally detailed atmospheric gas extinction profiles and POLRAD (Evans and Stephens, 1991) to solve the multiple scattering, look-up tables of $T_4–T_5$ versus $T_4$ are constructed. Each of the table corresponds to a given cirrus top height, a given modal radius of the size distribution, and various optical depth. The retrieval of 3 cirrus parameters (i.e. $\tau$, $Z_{\text{top}}$ and $r_{\text{modal}}$) from only 2 observations ($T_4$ and $T_3$) per pixel, even assuming the clear sky properties known from the radio-sounding and the hypothesis on surface temperature and ocean emissivity as correct, requires some additional information. Consequently, within a given box, the detected cirrus is assumed to have its top at a constant height and particles with a constant size distribution, only the optical thickness is allowed to vary. The retrieval is performed by minimizing the distance between the observed brightness temperature
and the simulated brightness temperature archived in the look-up tables.

Given the above assumptions, observations of the 15th of March, over the box including the Seychelles location, have been compared against the radiative transfer model simulations by computing, for each $Z_{\text{top}}$ and $r_{\text{modal}}$ combination, Bias and Root Mean Square (RMS) between observed and simulated brightness temperatures. The set of $Z_{\text{top}}$ and $r_{\text{modal}}$ values that minimizes the distance between the observations and the radiative transfer simulations is the result of the retrieval. In addition the average $\tau$, for the whole cirrus is the third retrieved parameter. In our case, we obtain $r_{\text{modal}}=14$ $\mu$m and $Z_{\text{top}}$ around 10–11 km (200–250 hPa), well above (see Fig. 6) the level of the mixing ratio negative anomaly. The retrieved average cirrus optical thickness is about 0.8 at 10 $\mu$m.

References


