SOLA, *2005*, *Vol. 1*, *069−072*, *doi*: *10.2151/sola. 2005−019*

Numerical Experiments on the Layered Structures in the Mid-Troposphere over the Equatorial Pacific

Shigenori Otsuka and Shigeo Yoden
Department of Geophysics, *Kyoto University*, *Kyoto*, *Japan*

Abstract

We performed numerical experiments on layered structures in the tropical mid-troposphere, which are often observed by radiosonde and airborne observations as anticorrelation between humidity and ozone, to investigate their three-dimensional structures and transport processes. We reproduced a thin layered structure of high humidity, which has a horizontal scale of about 1000 km and a vertical extent of about 1 km. Particle transport experiments around the layered structure show that the wet part of the layered structure is advected from the intertropical convergence zone by northwesterly winds, while dry parts above and below it come from the southeast direction. Streamline analysis shows that the thin layered structure is produced by vertical shear of a horizontal wind component. This shear is associated with longitudinal displacement of a stagnation point, which is located between two synoptic-scale vortices, with height.

1. Introduction

In 1999, ozonesonde observations were carried out in the equatorial eastern Pacific on board the research vessel "Shoyo-Maru" as a part of Soundings of Ozone and Water in the Equatorial Region (SOWER)/Pacific mission (Shiotani et al. 2002). The ship sailed eastward along 2°N from 140°W on September 21st to 110°W on September 28th, and sailed northeastward to 95°W and 10°N on October 7th (a green line in Fig. 1). Shiotani and his collaborators conducted ozonesonde observations during the period, and often observed layered structures in relative humidity and ozone around 2 km, 5 km, and 9 km in height with a vertical scale of 1−2 km. They also found that relative humidity often anticorrelated with ozone and meridional wind component; wet layers contained less ozone in the northerly winds. They supposed that the northerly wind may bring in wet and less ozone air southward from the intertropical convergence zone (ITCZ), which consists of convective regions, since air lifted from sea surface to the mid-troposphere by convections contains more water vapor and less ozone than ambient air.

Layered structures have been investigated by airborne observations since 1980s in terms of atmospheric tracer constituents to find the origin of those air masses (e.g., Danielsen et al. 1987; Newell et al. 1996; Stoller et al. 1999). Cloud layers in the middle troposphere associated with stable layers in the tropical convective clouds were investigated by Johnson et al. (1999), in which it was shown that the 0°C stable layers may limit cloud growth at around 5 km in height, enhancing wet outflow from convective clouds in the mid-troposphere.

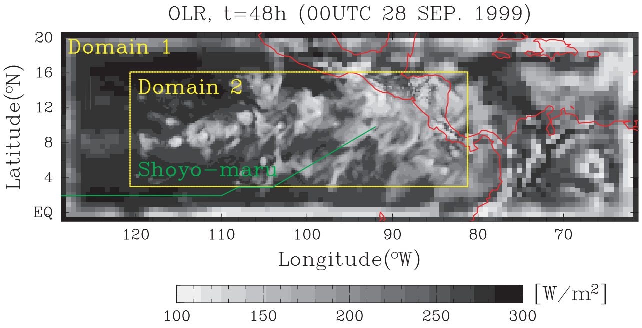

Fig. 1. Outgoing longwave radiation at 48 h from the initial time of the integration. An inner yellow box shows the area of Domain 2. A green line shows the cruise track of Shoyo-Maru.

Data from radiosonde or airborne observations are limited in space and time. Most global analysis data also have neither sufficient resolution in space nor in time; the typical vertical resolution is about 500−1000 m in the mid-troposphere, and the typical time step is 6 h. If we have four-dimensional data with sufficient resolution by numerical experiments, we can obtain more information about the layered structures: temporal variation of their three-dimensional structures, related physics, transport processes, and so on. In this study, we perform numerical experiments with a mesoscale model for a 3.5-day period in the Shoyo-Maru cruise. We use a large number of tracer particles in transport experiments to understand kinematic fields that produce the layered structures.

2. Model

We use the Fifth-Generation NCAR/Penn State Mesoscale Model (MM5), which is a non-hydrostatic regional numerical model. The calculation region is the tropical eastern Pacific shown in Fig. 1 (longitude: 62°W-128°W, latitude: 1°S-20°N), and the calculation period is from 00 UTC September 26th 1999 to 12 UTC September 29th. The model has two domains which are 2-way nested. The coarse domain (Domain 1) has 40×120 grids with the grid distance of 63 km, while the fine-meshed domain (Domain 2) has 73×211 grids with the grid distance of 21 km. The model has 62 levels from the ground to the lower stratosphere (∼25 hPa) with non-uniform vertical resolutions. The grid distance is about 300 m in the mid-troposphere. We use cumulus parameterizations for both Domains. Rain, cloud water, ice, and snow are contained in parameterizations of microphysics. Both longwave and shortwave radiation are calculated, including longwave radiation from clouds. We use the NCEP Global Tropospheric Analyses (FNL) as an initial and boundary conditions, which has 1×1 degrees resolution and 6 h time interval. The vertical resolution

---

Corresponding author: Shigenori Otsuka, Department of Geophysics, Kyoto University, Kyoto 606-8502, Japan. E-mail: otsuka@kugi.kyoto-u.ac.jp.

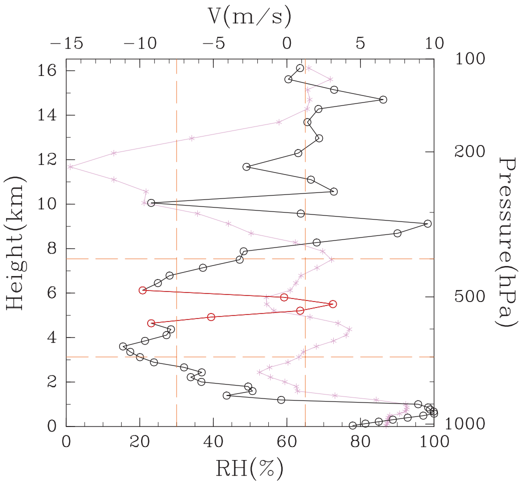

Fig. 2. Vertical profiles of relative humidity (RH, a black or red line with open circles) and meridional wind component (V, a purple line with asterisks, positive values mean southerly) at 109.7°W and 4.9°N, t=48 h. Orange and vertical dashed lines show thresholds to extract the layered structure. Orange and horizontal dashed lines show the range of the analysis. Red part of the profile is an example of the layered structure.

of the FNL is 50 hPa in the middle troposphere.

To demonstrate the model performance, Fig. 1 shows outgoing longwave radiation (OLR) at 48 h from the initial time of the integration. The horizontal distribution of OLR shows similar pattern to that of satellite infrared images, which are available online (e.g., Kochi University "Weather home"). The cloud band of the ITCZ is well reproduced along 10°N, from 120°W to 80°W.

Vertical variation of relative humidity also has similar features to the observations in the Shoyo-Maru survey. Figure 2 shows an example of the obtained layered structures of high relative humidity in the middle troposphere. Meridional wind component (a purple line with asterisks in Fig. 2) shows anticorrelation with relative humidity between 2–6 km; northerly winds blow in the wet layer, while southerly winds in the dry layers. In the Shoyo-Maru observations, relative humidity was high around 5 km in height, and the vertical extent of the wet layer was 1–2 km. Our result shows similar longitudinal dependence in relative humidity to the Shoyo-Maru observations shown in Fig. 7 of Shiotani et al. (2002) and Fig. 3a of Fujiwara et al. (2003).

Our numerical results simulated well the various aspects of the layered structures, and are robust in terms of the choice of cumulus and microphysical parameterization schemes included in MM5. Thus, we further investigate the properties of the layered structures reproduced in the numerical model.

3. Results

3.1 Distribution of the layered structures

We define a layered structure using vertical profiles of relative humidity. We analyze the model output of Domain 2 from 700 hPa to 400 hPa (orange horizontal lines in Fig. 2) to focus on the mid-troposphere. We extract the layered structure that has a wet region of more than 65% in relative humidity, and has dry regions of less than 30% both above and below the wet region (orange vertical lines in Fig. 2). In order to extract thin layers in this vertical range, maximum vertical extent of the layered structure is limited to 150 hPa (about 2 km). Figure 2 shows a typical example of the layered structure in a red line. The vertical extent is about 1.5 km.

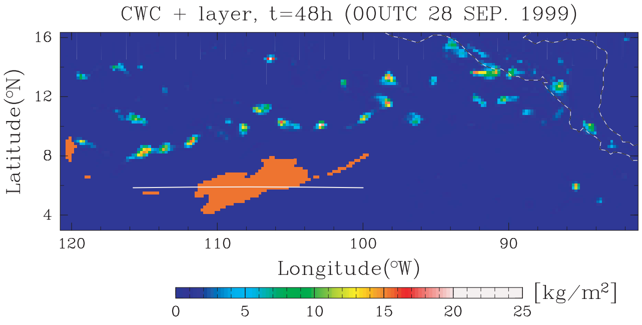

Fig. 3. Horizontal distribution of the areas where the layered structures are obtained at t=48 h in orange color. Column amount of cloud water content (CWC) is also shown with color tones. A white line indicates the initial positions of the particles of the forward transport experiment shown in Fig. 4 at t=24 h. An animation is available in the Supplement 1.

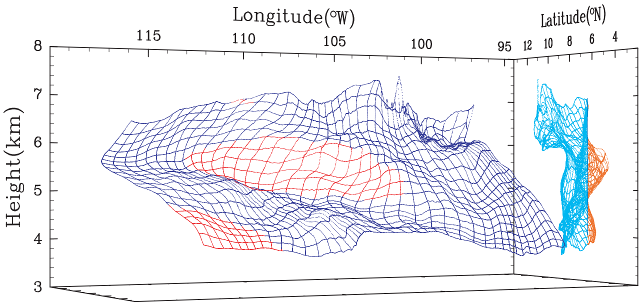

Fig. 4. Three-dimensional transport process visualized by deformation of a lattice, which consists of a large amount of tracer particles. The particles that moved southward are shown in red, and those moved northward are shown in blue. A blue line on the meridional plane shows the initial position of the lattice. Orange lines and light blue lines on the meridional plane are the projection of the particles that moved southward and northward, respectively. An animation is available in the Supplement 2.

Figure 3 shows horizontal distribution of the areas where the layered structures are obtained at t=48 h in orange color together with the column amount of cloud water content. An animation is available in the Supplement 1. Between 8–12°N, there are convective cloud clusters of the ITCZ. The layered structure appears to the south of the ITCZ in calm region without convective activity, while it rarely appears to the north of the ITCZ. Zonal extent of the layered structure is about 1000 km, while meridional extent is about 400 km. The largest patch of the layered structure begins to appear at around t=20 h. Its size becomes maximum at t=48 h, and after that the patch becomes smaller, being stretched in east-west direction. The lifetime of the patch of the layered structure is about 1–2 days. The bottom height of the layered structure, where relative humidity becomes 30%, is almost uniform in the horizontal direction, and is about 4.5 km, within the patch. However, the

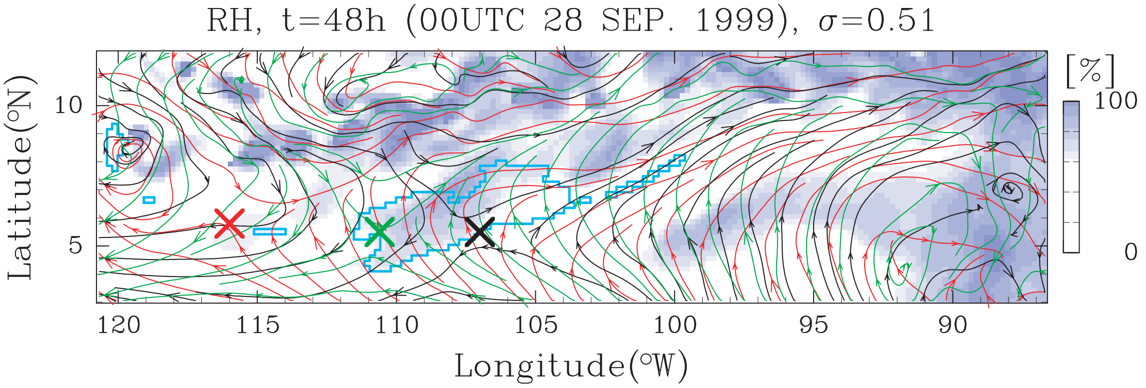

Fig. 5. Streamlines at 0.45 (green, ~460 hPa), 0.51 (black, ~520 hPa), and σ=0.57 (red, ~580 hPa), at t=48 h. Cross marks indicate saddle points of flow at each level. Light blue lines indicate regions of the layered structures. Background color map shows relative humidity at σ=0.51.

vertical extent of the layered structure is larger in the western part of the patch (~1.5 km) than that in the eastern part of it (<1 km).

3.2 Particle transport experiments

We perform several types of transport experiments to understand kinematic fields that produce the layered structures, using tracer particles. Firstly, a backward trajectory experiment is done from t=48 h to t=12 h, by locating a large number of particles in small regions at the wet part of the layered structure (550 hPa), above it (500 hPa), and below it (600 hPa) at the “initial” time of t=48 h. The particles located in the wet part of the layered structure come from northwest (not shown). A large part of the trajectories are from the marine boundary layer, lifted by convections. On the other hand, the particles in the dry parts above and below the layered structure come from southeast almost horizontally. These results are consistent with the observational fact that wet parts of the layered structures corresponded to northerly winds, and give a support to the suggestion by Shiotani et al. (2002) that wet air came from the ITCZ by horizontal advection.

Secondly, another backward transport experiment is done from t=48 h to t=12 h by locating particles horizontally in the wet region of the layered structure shown in Fig. 3. As time goes on, the marked region is stretched in southwest-northeast direction, and compressed in northwest-southeast direction. This is because the horizontal flow field has a stagnation point, or a saddle point around there, as described in detail in the next subsection.

Figure 4 is the result of a 24-hour forward transport experiment from t=24 h to t=48 h to investigate the vertical and longitudinal dependence of the layered structure. An animation of the plots is available in the Supplement 2. We set the initial positions of particles in a lattice form, which is parallel to a zonal plane, located at 5.9°N, 115.8−99.9°W in longitude (a white line in Fig. 3), and 4−7 km in height. The red and blue lines are the particles after the 24-hour tracing that moved southward and northward, respectively. The whole lattice was stretched in east-west direction, but the meridional displacement is rather complicated. Most part of the particles move northward, and the large movement is seen in the upper eastern part of the lattice. On the other hand, particles in the central part of the lattice around 5.5 km move southward. Altitude of the southward movement is higher in the western part. This longitudinal dependence gives a gentle slope of the layered structure with higher altitude in the western side. This gentle slope is related to the result that the layered structure is thicker in the western side.

3.3 Streamline analyses

As shown in Fig. 2, at the south side of the ITCZ, winds blow northward toward the ITCZ near the surface, while southward from the ITCZ in the upper troposphere. Basically this structure can be considered as a part of the Hadley circulation. In the middle troposphere, however, the situation is rather complicated. To understand Eulerian motion of the air associated with the layered structure, we perform streamline analyses.

In Fig. 5, green, black, and red lines are streamlines at σ=0.45 (~460 hPa), 0.51 (~520 hPa), and 0.57 (~580 hPa), respectively, at t=48 h, where σ represents pressure normalized by surface pressure. At each level, there is a vortex rotating clockwise centered at around (120° W, 8°N). There is another vortex rotating clockwise centered at around (90°W, 5°N). Between these two vortices, there is a stagnation point, or more specifically, a saddle point indicated by a cross mark at each level. At σ=0.51, the saddle point is located far east to those at other two levels, and it is close to the region of the layered structure which is surrounded by a light blue line in Fig. 5. In the region between the saddle point at σ=0.51 and saddle points at other levels, the meridional wind component has a tendency to produce the layered structure, that is, northerly winds blow at σ=0.51, while southerly winds blow at other two levels. The northerly brings wet air from the ITCZ, while the southerly brings relatively dry air. Consequently, the layered structure in relative humidity is produced by the vertical shear of the horizontal wind component.

The location of the saddle point is continuously displaced eastward, when we see it downward from the level of σ=0.45. The saddle point at σ=0.57 is discontinuously located far west in comparison to the location of the saddle point above the level. The continuous displacement of the saddle point with height above the layered structure produces the gentle slope of the layered structure as shown in Fig. 4. The upper boundary between blue and red parts almost corresponds to the positions of the saddle points.

4. Concluding remarks

We performed a series of numerical experiments using the MM5 to investigate layered structures in relative humidity in the equatorial eastern Pacific, which were observed during the Shoyo-Maru survey in 1999. We reproduced the layered structure of relative humidity around 5 km in height to the south of the ITCZ. The patch of the layered structure has a zonal scale of about 1000 km and a meridional scale of about 400 km. A typical vertical scale of it is about 1–2 km. These features are similar to the observations during the Shoyo-Maru survey. A time scale to form the patch of the layered structure is about 1–2 days. This time scale is mostly controlled by synoptic-scale air flow because eddy diffusion is so large in this model that layered structures disappear in a day without processes to maintain them. In the tropics, cumulus convections may mix air throughout the troposphere. However, the layered structure survived without being mixed by cumulus convections. This indicates that calm and stratified atmospheric condition may exist in the tropics with a synoptic spatial scale and a typical time scale of several days or more, until it is destroyed by convections.

The backward particle transport experiments showed that air in the wet layer comes from the north, where the ITCZ lies, being advected almost horizontally, while air in the dry layers comes from the south. The experiments also showed that a large part of the air in the wet layer comes from the marine boundary layer, lifted by convections. These results support the speculation by Shiotani et al. (2002) that northerly winds bring in wet air from the ITCZ.

The forward transport experiment showed that the layered structure has a gentle slope in longitudinal direction as shown in Fig. 4. The streamline analysis unveiled the role of the saddle point, which is located between two synoptic scale vortices with their centers around the locations (120°W, 8°N) and (90°W, 5°N), in the formation of the three-dimensional layered structure. The gentle slope of it is associated with the continuous westward displacement of the saddle point with height above the wet layer. At the present stage we do not know how the vortices and the saddle point were produced.

In general, layered structures can be categorized in terms of vertical extent of the air mass before it forms the layered structures: a thin air mass or a thick one. Thin layered structures can be created in a stably stratified condition when the original air masses are thin enough. On the other hand, they can also be created without any thin air masses, when circulation itself has large vertical shear. Air that is injected into the free atmosphere from the boundary layer by cumulus convections can be an example of thick origin, when vertical shear stretches the convectively lifted vertical column.

In Fig. 13(b) of Johnson et al. (1999), thin shelf clouds near the 0°C stable layers represent detrainment from cumulus convections. These clouds are examples of thin and wet origin of layered structures. Though 0°C stable layers exist in this model, the spatial resolution is not enough to represent the shelf clouds. On the other hand, our transport experiments showed that the vertical shear of the horizontal wind component stretched thick and wet air masses of the convective region and produced thin layers. The vertical shear is the main reason to produce thinness of the wet layer in this experiment.

Small vertical extent of the outflow and large vertical shear are possible in the tropics because the Coriolis parameter is small enough that the atmospheric flow is not strongly constrained by the thermal wind relationship; the flow is relatively independent in the vertical. This is a possible reason why the layered structure is formed mostly in the southern side of the ITCZ, i.e., in the region near the equator, in the present experiment.

Preliminary investigation using NCEP/NCAR Reanalysis data shows that these vortices and saddle points are often seen in the equatorial eastern Pacific in September and October, indicating that the layered structures associated with this type of vortex motion could be climatological features in this region. Further investigation is necessary on the frequency of the appearance of the layered structures and their possible role in transporting and mixing processes in the tropical troposphere.

Acknowledgments

We thank Dr. H. Kanzawa and two anonymous reviewers for helpful comments. Trajectory calculating routine of RIP was used for the particle transport experiments in Section 3.2. The figures were produced by GFD-DENNOU Library. This work was supported by Kyoto University Active Geosphere Investigations for the 21st Century Centers of Excellence Program (KAGI21), which was approved by the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) of Japan.

Comments and supplements

1. An animation of the distribution of the layered structure and cloud water as shown in Fig. 3 is given in the Supplement 1 (Δt=1 h).

2. An animation of the forward transport experiment shown in Fig. 4 is given in the Supplement 2 from t=24 h to t=48 h with an animation time step Δt=0.25 h.

References

Danielsen, E. F., S. E. Gaines, R. S. Hipskind, G. L. Gregory, G. W. Sachse, and G. F. Hill, 1987: Meteorological context for fall experiments including distributions of water vapor, ozone, and carbon monoxide. *J. Geophys. Res.*, **92**, 1986–1994.

Fujiwara, M., S.-P. Xie, M. Shiotani, H. Hashizume, F. Hasebe, H. Vömel, S. J. Oltmans, and T. Watanabe, 2003: Upper tropospheric inversion and easterly jet in the tropics. *J. Geophys. Res.*, **108**, 4796, doi:10.1029/2003JD003928.

Johnson, R. H., T. M. Rickenbach, S. A. Rutledge, P. E. Ciesielski, and W. H. Schubert, 1999: Trimodal characteristics of tropical convection. *J. Climate*, **12**, 2397–2418.

Kochi University: Weather home (in Japanese). [Available online at http://weather.is.kochi-u.ac.jp/.]

Newell, R. E., Z.-X. Wu, Y. Zhu, W. Hu, E. V. Browell, G. L. Gregory, G. W. Sachse, J. E. Collins Jr., K. K. Kelly, and S. C. Liu, 1996: Vertical fine-scale atmospheric structure measured from NASA DC-8 during PEM-West A. *J. Geophys. Res.*, **101**, 1943–1960.

Shiotani, M., M. Fujiwara, F. Hasebe, H. Hashizume, H. Vömel, S. J. Oltmans, and T. Watanabe, 2002: Ozonesonde observations in the equatorial eastern Pacific —the Shoyo-Maru survey—. *J. Meteor. Soc. Japan*, **80**, 897–909.

Stoller, P., J. Y. N. Cho, R. E. Newell, V. Thouret, Y. Zhu, M. A. Carroll, G. M. Albercook, B. E. Anderson, J. D. W. Barrick, E. V. Browell, G. L. Gregory, G. W. Sachse, S. Vay, J. D. Bradshaw, and S. Sandholm, 1999: Measurements of atmospheric layers from the NASA DC-8 and P-3B aircraft during PEM-Tropics A. *J. Geophys. Res.*, **104**, 5745–5764.

(*Manuscript received 14 March 2005, accepted 12 May 2005*)