

Temperature Inversions over the Inland Indochina Revealed by GAME-T Enhanced Rawinsonde Observations

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Abstract

Detailed structures and variability of lower tropospheric temperature inversions are investigated, using two sets of high-resolution (50 m in height and 3 hours in time) rawinsonde data obtained by the GAME-T enhanced rawinsonde observations conducted over the inland Indochina Peninsula in March 1997 and January 2000. In both observation periods, the strong inversions were observed at 3–4 km height. The causes of variations in their occurrence time and height are discussed by comparing them with meteorological conditions. Five processes are found to be responsible for the inversion variations: 1) cold-air advection accompanied by a cold-surge event, 2) cloud-top radiative cooling, 3) adiabatic heating due to subsidence, 4) shallow convection at or near the observation site, and 5) diurnal heating process due to boundary-layer growth.

1. Introduction

Temperature inversion plays an important role in determining atmospheric circulation and structure by affecting vertical motion of air mass, the consequent convective activity and rainfall (e.g., Johnson et al. 1996; Mapes and Zuidema 1996; Esteban and Chen 2008). It can also affect heat and mass transports, and the radiative balance.

The Indochina Peninsula is known as a region where the earliest monsoon rainfall occurs in Southeast Asia (e.g., He et al. 1987; Matsumoto 1997). It is also shown that the inversion layer frequently occurs around the same region before the monsoon onset (Liu 1990). These facts suggest close relationship between inversion appearance and early rainfall over the Indochina Peninsula.

Nodzu et al. (2006) investigated climatological seasonal variation of temperature inversions over and around the Indochina Peninsula. They showed that in the inland Indochina the inversions appeared at about 2.5 km height during November and the following January, while the appearance height gradually increased up to about 5 km during the rest of the dry season until April. Although they depicted well the seasonal variation of inversion appearance in terms of its climatological feature, behavior of an individual inversion, its relation with meteorological conditions and its generation mechanism are not known.

We have conducted enhanced rawinsonde observations in the inland Indochina Peninsula in dry season. Using such high-resolution rawinsonde data, we carry out case studies to describe the detailed structure and variability of these temperature inversions.

2. Observation and data

Six enhanced rawinsonde observation campaigns were conducted by the GEWEX Asian Monsoon Experiment-Tropics (GAME-T) project, where GEWEX stands for the Global Energy and Water cycle EXperiment, from 1996 to 2000 in Thailand and its neighboring countries. Two of the campaigns were conducted in the dry season: February 28–March 15, 1997 at Sukhothai (17°N, 100°E) and January 12–21, 2000 at Nongkhai (18°N, 103°E). The launch interval during each of these two campaigns was 3 hours except for the 6-hourly launch during the beginning and ending phases of the 1997 campaign (February 28–March 4 and March 13–15). The two sets of 3-hourly data in March 1997 and in January 2000 are used in this study. The original sampling interval by each sounding was 10 s, which corresponds to a height interval of about 50 m. The original data were averaged at every 100 m bin to obtain equally-spaced vertical data series, which satisfactorily preserves the original vertical resolution. Further descriptions for the enhanced observation in January 2000 can be found in Ogino et al. (2006).

Additionally, daily-mean National Centers for Environmental Prediction (NCEP) Reanalysis 2 data¹ and daily-mean Geostationary Meteorological Satellite (GMS) black-body temperature data are used for describing meteorological fields in relation to the variation in temperature inversions.

In this paper, the vertical gradient of potential temperature ($\partial\theta/\partial z$) is used to measure the inversion intensity. A layer with relatively large value of $\partial\theta/\partial z$ is called “inversion,” regardless of the sign of its vertical temperature gradient ($\partial T/\partial z$) even though the original definition for temperature inversion is $\partial T/\partial z > 0$. In this paper, mainly layers with $\partial\theta/\partial z > 6 \text{ K km}^{-1}$ are discussed.

3. Time-height variation of temperature inversions

3.1 January 2000

Let us begin with the January data. Figure 1 shows a time-height section of $\partial\theta/\partial z$ observed during the ten-day observation period in January 2000. An inversion was clearly identified at 3–4 km height during January 15–20. This height is consistent with the climatological feature shown by Nodzu et al. (2006), although it seems somewhat higher than the most frequent height of about 2.5 km. The inversion intensity is weaker (stronger) in the first (second) half of the observation period. The inversion height increases from about 3 km to 4 km during January 18–22. In addition, a weak inversion is seen at about 1.5 km in the second half of the period. The relationship between these inversions and meteorological conditions will be discussed in Section 4.1.

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¹provided by the National Oceanic & Atmospheric Administration/Earth System Research Laboratory/Physical Sciences Division, Boulder, Colorado, USA, from their Web site at <http://www.esrl.noaa.gov/psd/>

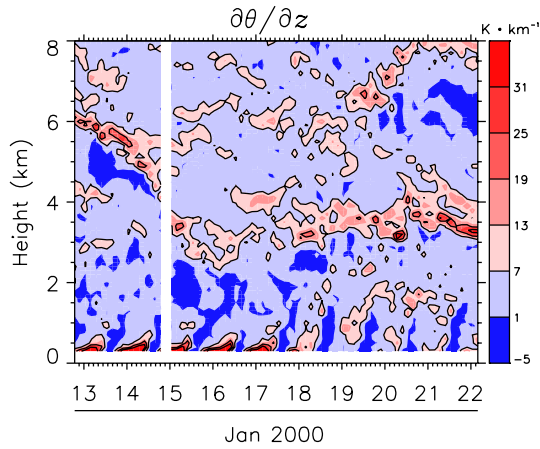


Fig. 1. Time-height section of vertical gradient of potential temperature $\partial\theta/\partial z$ observed by the GAME-T enhanced rawinsonde observation during January 12–22, 2000. Black contours denote the $\partial\theta/\partial z$ at 7, 19 and 31 K km^{-1} . Major tick marks in horizontal axis denote 0000 LT (local time; GMT+7 hours).

Inversions also appeared at higher or lower levels. During January 12–15, an inversion was seen to decrease its height from 6 km to 3 km. After that, the inversion seemed to split into two separate layers during January 15–19. The upper inversion stayed at around 6 km, and the lower one seemed to combine with the inversion at 3–4 km height described in the previous paragraph. During January 19–21, the upper inversion moved upward from 6 km to 8 km. These heights are much higher than the typical inversion of 2.5 km. Analyzing the NCEP reanalysis 2 data, the inversions seen in the higher levels were found to coincide with the large meridional gradient of potential temperature accompanied by the sub-tropical jet at about 12 km around 30°N , which indicates that the inversions were part of the sub-tropical frontal system. Surface inversions were also clear in the first half of the period. These inversions seen in the higher and lower levels are not discussed further in this study.

3.2 March 1997

During the seven-day observation in March 1997, inversions were found at around 4 km as shown in Fig. 2, which agrees well with typical inversions in March reported by Nodzu et al. (2006). The inversions behaved differently between the first half and the second half of the observation period. In the first half of the period, the inversion intensity was stronger, and a single inversion

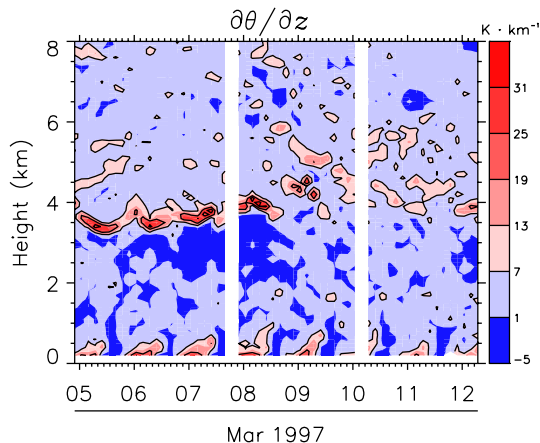


Fig. 2. Same as Fig. 1 except for March 4–12, 1997.

layer with a thickness of about 300 m appeared clearly at 3–4 km height. The height of the inversion roughly increased from about 3 km on March 5 up to about 4 km on March 9. Fluctuations with a time scale of about one day in both inversion height and intensity were also clear during the first half of the period.

In the second half of the period, the single-layered structure disappeared. Alternatively, multi-layered structures were found in relatively wide height range (4–6 km) and discontinuously in time.

It is also noted that $\partial\theta/\partial z$ below the inversion in the second half of the period was different from that in the first half of the period, in which $\partial\theta/\partial z$ had a small value in the 2–3 km height range. In the second half, $\partial\theta/\partial z$ did not have such a vertical variation but showed relatively homogeneous distribution in the 1–3 km height range.

4. Relation between inversions and meteorological conditions

The inversions observed by the two enhanced rawinsonde observations showed significant time-height variations during the several days of each observation period. How was the variation related to meteorological conditions?

4.1 January 2000

Figure 3 shows the potential-temperature anomaly from the period mean at each height. It is found that the inversion intensification at 3–4 km after January 18 was accompanied by the cooling just below the inversion. Strong cooling was also seen near the surface below about 1.5 km during January 19–21.

The NCEP reanalysis 2 data are used to describe the meteorological fields that caused the cooling. Figures 4 and 5 show horizontal maps of the NCEP reanalysis 2, including geopotential height, potential temperature and horizontal wind at 925 hPa on January 16 and 20, 2000, respectively, representing the first and second halves of the observation period. It is found that a high-pressure tongue with cold air protruded from the Eurasian Continent to the East China Sea on January 16. The high-pressure tongue extended southward and reached the Indochina Peninsula by January 20, which is considered to have provided the cold air near the surface just above the observation site to intensify the inversion at about 1.5 km. This type of cold advection is well known as a cold surge (e.g., Chang 2004; Wang 2006).

The cold surge signal was not clearly seen in the height range above about 1.5 km. Therefore, it is difficult to ascribe the cold surge to the inversion intensification at 3–4 km in the second half of the period. Alternatively, it is seen in the rawinsonde relative humidity data that water vapor was almost saturated in the height

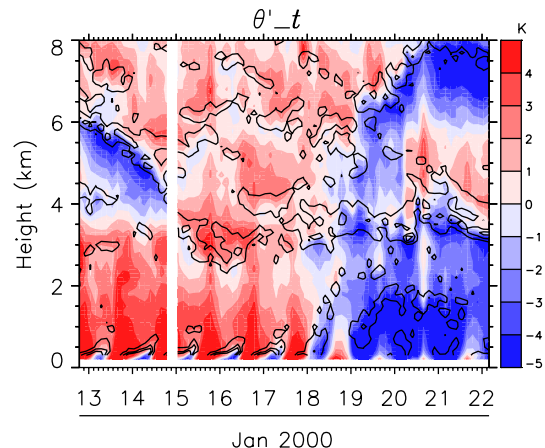


Fig. 3. Same as Fig. 1 except for potential-temperature anomaly from the period mean at each height.

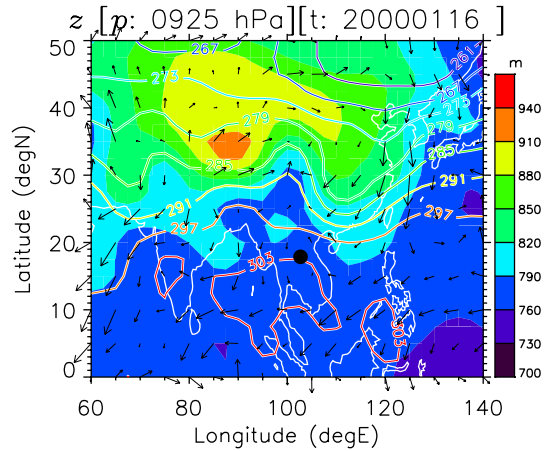


Fig. 4. Horizontal distribution of NCEP-reanalysis geopotential height (shade), potential temperature (contour) and horizontal wind (arrow) at 925 hPa on January 16, 2000. Black closed circle denotes the location of Nongkhai.

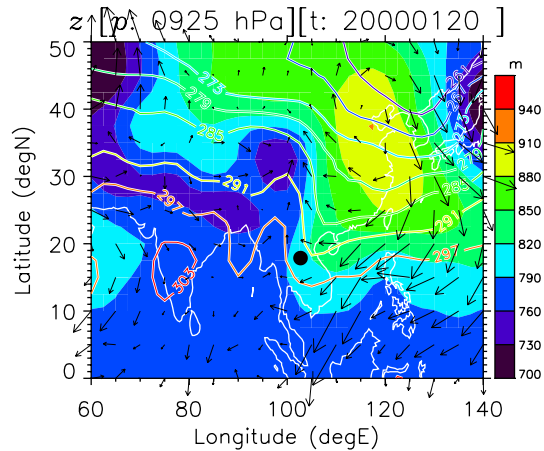


Fig. 5. Same as Fig. 4 except for January 20, 2000.

range between 2 km and 3 km after January 18. It is likely that the low-level cloud formed at this height range associated with the cold surge intrusion near the surface. If this was true, the cloud-top radiative cooling could cause the inversion intensification at 3–4 km in the second half of the period.

4.2 March 1997

The inversions in the March 1997 observation showed stronger intensity and a thin layered structure in the first half of the observation period. In contrast, it had weaker intensity and a broad vertical distribution in the second half.

Similar contrast in time was also observed in other meteorological variables. Figure 6 shows the potential-temperature anomaly from the period mean at each height, in which it is found that warming gradually progressed in the whole region below the inversion from the beginning to the end of the observation period, involving the diurnal warming and cooling. This suggests that the boundary-layer process reached up to the inversion height during this period.

Further, the relative-humidity data showed that the water vapor was almost saturated frequently in the second half of the period, which suggests an increase of convective activity. Indeed, after March 9, shallow clouds were observed near the observation site (Fig. 7). Therefore, there was a possibility that the con-

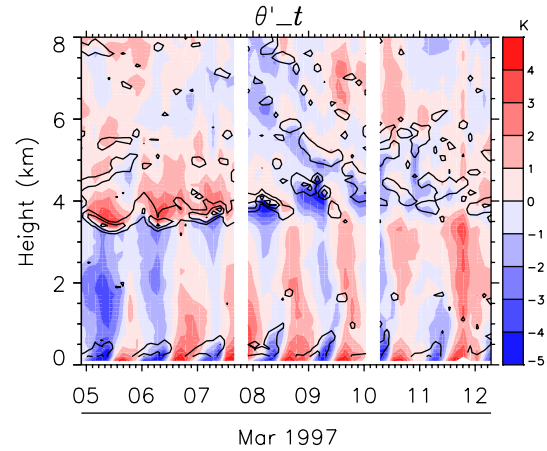


Fig. 6. Same as Fig. 2 except for potential-temperature anomaly from the period mean at each height.

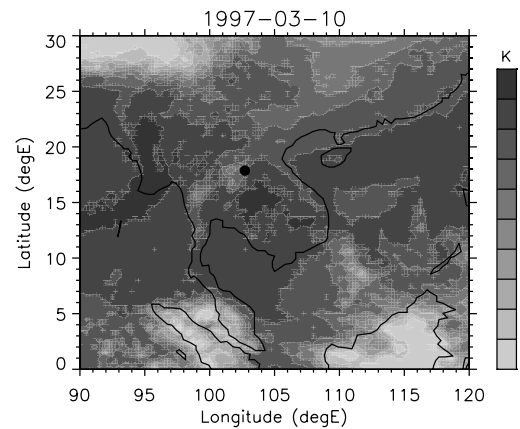


Fig. 7. Daily mean GMS black-body temperature on March 10, 1997. Black closed circle denotes the location of Sukhothai.

vections at or near the observation site disturbed and destroyed a single inversion layer into a broad and multi-layered structure. This hypothesis is supported by the fact that the stability below the inversions became homogenized in the second half as pointed out in the previous section.

It must be noted that the NCEP data indicated a large descending motion around and above the inversion height as a mean feature for the first half of the period (not shown). This descending motion must have provided adiabatic heating and is consistent with the positive potential-temperature anomaly just above the inversion, which could produce and maintain a thin-layered structure during the first half of the period.

It is also seen that layers with negative potential-temperature anomaly capped by a weak inversion were descending from 7 km on March 7 to 5 km on March 9 and from 8 km on March 8 to 6 km on March 9. They seemed to form part of the multi-layered structure of inversion in the second half of the period and possibly affected the convective activity.

5. Diurnal variation of inversions

In the first half of the observation period in March 1997, a single-layered and strong inversion appeared at about 3.5-km height. It showed significant fluctuations in its intensity and height with a time scale of about one day. Detailed description of this variation is given next.

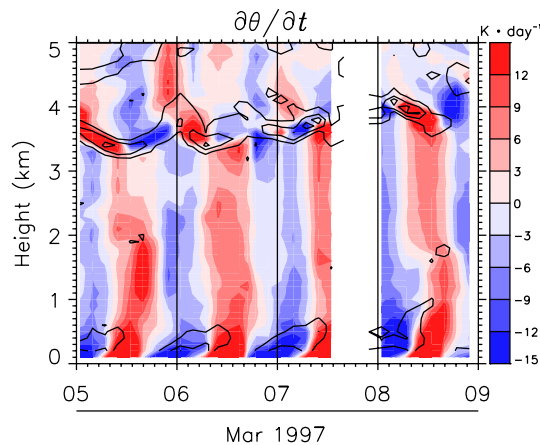


Fig. 8. Time-height section of time differential of potential temperature (shade) $\partial\theta/\partial t$ and vertical gradient of potential temperature $\partial\theta/\partial z$. Time and height ranges are different from those of the time-height sections shown earlier. Contours are the same as in Fig. 2. Vertical lines show 0000 LT.

Figure 8 shows the change rate of potential temperature $\partial\theta/\partial t$ together with $\partial\theta/\partial z$. The figure is a close-up on the lower troposphere in the first half of the period. It is clear that the diurnal warming and cooling occurred in the whole height range just above the surface up to the inversion height. This must be related to the boundary-layer process.

First, let us focus on the variation of inversion intensity. It is found that the daytime warming (nighttime cooling) just below the inversion weakened (intensified) the inversion intensity, which resulted in a clear diurnal cycle of the inversion intensity. Therefore, it is concluded that the variation in inversion intensity in this period was caused by the heating and cooling processes associated with the daily boundary-layer growth.

In Fig. 8, the diurnal variation of the inversion height is also clear, suggesting its relation to the boundary-layer process. It is found that the inversion moved upward (downward) in the afternoon (morning) to arrive at the maximum (minimum) height around 0000 LT (local time) (1200 LT), except that the diurnal variation was not clear during evening time on March 6 and midnight on March 7 partly due to the data missing.

Hashiguchi et al. (1995) showed a clear diurnal cycle of the top height of boundary layer detected by radar echo intensity, which they called “necklace echo,” near Jakarta, Indonesia. They showed an upward propagation of an echo layer in the daytime arriving at the maximum height at around 1800 LT, and a downward propagation in the nighttime arriving at the minimum height at around 0600 LT. The “necklace” shape shown by Hashiguchi et al. (1995) is similar to the height variation of the inversion discussed here. However, the local time of the maximum and minimum heights is different from each other, which should be examined by future study.

6. Summary

The detailed structures and variability of lower tropospheric temperature inversion are investigated, using two sets of high-resolution (50 m in height and 3 hours in time) rawinsonde data obtained by the GAME-T enhanced rawinsonde observations conducted over the inland Indochina Peninsula in March 1997 and January 2000. In both periods, strong inversions were found at around 3 km height.

Significant variations in inversion height and intensity were observed in both enhanced observation periods with a time scale of several days. During the second half of the observation period in January 2000, the inversion variation at about 1.5 km height was caused by cold-air advection accompanied by a cold surge

event, while the one at 3–4 km seemed to be caused by cloud-top radiative cooling. In the first half of the March 1997 observation, adiabatic heating due to subsidence seemed to generate and maintain a thin-layered inversion at about 3.5 km height. This inversion also showed a clear diurnal variation. The boundary-layer process was shown to be a major cause of this variation. In the second half of the March 1997 observation, the inversion variation may be closely related to the convective activity at or near the observation site.

In this study, five processes are found to affect the inversion variation over the inland Indochina. However, other processes might be involved in other periods. Different types of seasonal variation have been shown by Nodzu et al. (2006) in the adjacent region, such as the coastal Indochina and the Malay Peninsula. Accumulation of case studies in other periods and other regions is necessary for better understanding of inversion properties. High-resolution rawinsonde observations provide valuable information for inversion variability that cannot be resolved by operational rawinsonde observations or reanalysis data. Therefore, the accumulation of case studies using high-resolution data is important for better understanding of temperature inversions.

Acknowledgments

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