Atmos. Chem. Phys. Discuss., 9, 13155–13176, 2009
www.atmos-chem-phys-discuss.net/9/13155/2009/


Atmospheric Chemistry and Physics Discussions

This discussion paper is/has been under review for the journal *Atmospheric Chemistry and Physics (ACP)*. Please refer to the corresponding final paper in *ACP* if available.

# A new transport mechanism of biomass burning from Indochina as identified by modeling studies

**C.-Y. Lin[1], H. M. Hsu[2], Y. H. Lee[2], C. H. Kuo[3], Y.-F. Sheng[1], and D. A. Chu[4]**

[1]Research Center for Environmental Changes, Academia Sinica, Taipei, Taiwan, 128 Sec. 2, Academia Rd, Nankang, Taipei 115, Taiwan
[2]National Center for Atmospheric Research, Boulder, Colorado, USA
[3]Department of Geology, Chinese Culture University, Taiwan
[4]Goddard Earth Sciences and Technology Center, NASA, USA

Received: 17 April 2009 – Accepted: 27 May 2009 – Published: 15 June 2009

Correspondence to: C.-Y. Lin (yao435@rcec.sinica.edu.tw)

Published by Copernicus Publications on behalf of the European Geosciences Union.

## Abstract

Biomass burning in the Indochina Peninsula (Indochina) is one of the important ozone sources in the low troposphere over East Asia in springtime. MODIS data showed that nearly 20 000 fires or more occurred annually in spring only from 2000 to 2007. In our tracer modeling study, we identified a new mechanism transporting the tracer over Indochina that is significantly different from the vertical transport mechanism over the areas around the equator such as Indonesia and Malaysia. Simulation results demonstrate that the leeside trough over Indochina played a dominant role in the uplift of the tracer below 3 km, and that the strong westerlies prevailed above 3 km to transport the tracer. They provided the fundamental mechanisms a major impact on the air quality downwind from Indochina over East Asia. And the climatological importance of such leeside trough is also discussed.

## 1 Introduction

The impact of biomass burning during spring over Southeast Asia on the atmospheric environment of East Asia has been getting more and more attention. It is believed that the ozone precursors and aerosols produced by the biomass burning can significantly affect the air quality over downstream areas. For example, the biomass burning over Indochina has been identified as a source of significant impact on the ozone concentration in Hong Kong during spring (Chan et al., 2003) and aerosols from such burning are one of the important sources of "Asian brown cloud" (Ramanathan and Crutzen, 2003; Ramanathan et al., 2005; Lau et al., 2008). Based on atmospheric conditions, the scale of these impacts can be regional and even global and thus can affect the regional and global climate.

It has been well documented that biomass burning frequently occurs during spring over areas of the Indochina Peninsula (Indochina) such as Thailand, Laos, Cambodia, and Vietnam (Dwyer et al., 1988; Christopher and Kimberly et al., 1996). Re-



ACPD

9, 13155–13176, 2009



Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂◂ | ▸▸
◂ | ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

cent progress of satellite monitoring, such as ATSR (Kasischke et al., 2003), AVHRR (Ichoku et al., 2003), and MODIS (Boschetti et al., 2008), provides useful information on identifying various aspects of fire events and duration of burning.

Lin et al. (2009) illustrated an average horizontal wind speed pattern above 700 hPa and identified a strong wind speed belt south of the Tibetan Plateau and north of 20° N over Indochina. They also suggested that a significant average peak of ozone concentration existed at around 4 km in spring that was attributed to the contribution of biomass burning across Indochina. Since the fires are abundantly and frequently occurrence in the Indochina, the key question is how the biomass-burning products can be uplifted to above 3 km and then transported by the strong westerly wind to downwind Taiwan and even the entire East Asia. Liu et al. (2003) indicated that transport of air pollutants from the boundary layer (BL) to the free troposphere (FT) was mainly facilitated by three mechanisms; fronts, convection, and orographic forcing over mainland China. Frontal lifting is an effective mechanism to transport surface pollutants to the FT over continents (Bethan et al., 1998), and fronts frequently occurred over China during winter and spring. Furthermore, orographic lifting over central and eastern China combined with cold fronts could enhance the transport significantly (Donnell et al., 2001; Liu et al., 2003).

“Deep convection” occurrence over South East Asia is the most popular and frequently mentioned mechanism for the transport of biomass burning products. Some researchers noted that the convective activity over SE Asia together with strong thermal buoyancy and turbulence created by the active fires is able to carry biomass air pollutants to higher altitude over SE Asia (Folkins et al., 1997; Jocob et al., 1999; Chan et al., 2003). However, so far, discussions of the biomass burning in conjunction with strong convection mechanism in previous studies is limited to the low latitude areas around the equator such as Indonesia, New Guinea, and Malaysia (Folkins, 1997; Hsu et al., 1996). In other words, the “deep convection” mechanism seems to apply only to the area around the equator due to the strong lifting from frequent and strong tropical convection. The inter-tropical convergence zone (ITCZ) can be the primary organizing contributor. For example, the studies by Folkins (1997) and Hsu et al. (1996) concerned such areas as New Guinea, Australia, Indonesia, and Malaysia. On the other hand, there is a lack of such tropical convective uplifting over Indochina during spring. Thus, it is important to identify a different mechanism responsible for the uplifting of biomass-burning products over Indochina below 3 km. The mechanism we propose is the leeside trough at the eastern frank of the Tibetan Plateau and the mountains of Indochina. The Tibetan Plateau represents a huge obstacle that can block basic atmospheric flows, and the leeside trough can form under favorable conditions. The leeside trough plays an important role as it can induce a significant upward motion. Once the trough is generated and associates with profound biomass burning, it would be favorable for the biomass-burning products to be transported aloft. As we understand, this is the first time this mechanism is being proposed as biomass-burning transport mechanism over Indochina.

In previous studies, trajectory analyses have generally identified ozone peaks as possible air masses coming in from the low troposphere (e.g. Harris et al., 1998; Oltmans et al., 2004). However, such traditional analyses can only describe atmospheric air mass motion in part as they do not consider important physical processes (e.g. dry and wet depositions) and dynamical process (e.g. small-scale convection and turbulent mixing). In this study, *a newly developed tracer module is integrated into the WRF/Chem model, and is utilized in our study*. We hence propose to apply this modeling system to demonstrate this newly identified transport mechanism for uplifting biomass-burning products from Indochina on the leeside of the Tibetan Plateau and the Indochina mountains.

In this report, evidences of biomass burning over Indochina are presented first, and followed by a case study using data from an ozone sonde and satellites, traditional weather data, and modeling results. Then the uplifting mechanism over Indochina is identified as the leeside trough at the eastern frank of the Tibetan Plateau. Finally the mean leeside trough over a period of 60 years during the springtime is described as a prominent feature of climatological importance.

## 2 Observations

Figure 1a shows the annual variation of fire spots in spring (March to May) over Indochina derived from the MODIS satellite images from 2000 to 2007. Clearly, there were many fire points over Indochina in the past few years; there have been more than 20 000 fire points annually during spring after 2004. Also, biomass-burning fire counts indicated a very remarkable seasonal variability over Indochina; fires occurred mainly during the later winter and spring (Fig. 1b).

According to an ozone sounding on 11 April 2005 in northern Taiwan (Panchiao station, 121.43° E, 24.98° N) the ozone concentration in the troposphere lower than 2 km was less than 50 ppb (Fig. 2a). However, there was a distinct peak of 120 ppb around 4 km with high relative humidity (greater than 80%). On the average, ozone concentrations in the lower troposphere between 3 and 6 km over northern Taiwan ranged from 70 to 80 ppb in spring (Lin et al., 2009). In other words, the ozone concentration for this episode was about 40 ppb greater than the average at 4 km. The peak ozone concentration around 4 km with high relative humidity implied that the air masses mainly came from the lower troposphere and low latitudes (Liu et al., 1999; Chan et al., 2003).

Figure 2b depicts the fire hot spots derived from MODIS satellite observations from 8 (blue cross) to 9 (red dot) April during the period of burning episodes when the air masses passed over South Asia (Fig. 2c, detail described in Sect. 4). Indeed, a large measure of biomass burning occurred over the Indochina region upstream of Taiwan.

The near surface (925 hPa) weather map in Fig. 3a illustrates a chain of low pressure systems located from central to south China and Indochina. At 850 hPa, a very deep trough extended southward from northern China to Indochina around 105° E, 20° N (Fig. 3b). Even at 700 hPa, there still was a deep trough over southern China and Indochina (not shown). This favorable weather condition should provide a lift of the local air masses over southern China and the Indochina region. The wind profile associated with the ozone sonde (Fig. 2a) shows that the wind direction changed to southwesterly when the elevation was greater than 1.0 km, and the wind speed steadily increased to more than 15 m/s as the altitude increased from 1 km to more than 3 km. Therefore, these favorable conditions, including weather patterns and abundant biomass emissions over Indochina, provided significant opportunity for ozone to form reactively to a 4-km altitude.

## 3 Trajectory and tracer/dynamic models

In order to identify sources of the high ozone episode that occurred on 11 April, 2005 and to examine how transport paths could affect the ozone concentrations profile in northern Taiwan, the HYSPLIT (Hybrid Single-Particle Lagrangian-Integrated Trajectory) model (Draxler and Hess, 1988) was used to trace the origins of the air masses. Furthermore, we employed the WRF/chem (Grell et al., 2005) modeling system to identify the long-range transport associated with biomass burning over Indochina in our case study. A newly developed tracer module was integrated into the WRF/Chem model, and applied to identify the transport. The tracers were assigned to the fire locations derived from MODIS satellite data over Indochina ranging from 5 to 25° N and 90 to 110° E. They were placed at near surface level (model level 1) and the concentration was 10,000 units per day (416.67 units/h) at each fire location. The meteorological initial and boundary conditions for WRF/Chem were obtained from NCEP-FNL data sets at 6-h intervals. The Yonsei University (YSU) (Hong and Dudhia, 2003) planet boundary layer scheme was selected in this study. The horizontal resolution for the simulation was 27 km. To assure the meteorological fields were well simulated, the four-dimensional data assimilation (FDDA) scheme was activated based on the NCEP-FNL analysis data.



ACPD
9, 13155–13176, 2009

## 4 Simulation results

Three-day back trajectory analyses using HYSPLIT at the altitudes of 3 km, 4 km, and 5 km from northern Taiwan for the event of 11 April, 2005 (Fig. 2c) suggested that the air masses in northern Taiwan originated from major biomass burning on 8 and 9 April in Southern China, Indochina, and possibly India where burning occurred at a lower elevation than the trace layer. The air mass paths revealed that the air masses of the ozone peak layer primarily came from biomass-burning regions for this episode. The trajectory at 3 km was back-tracked to the eastern Bay of Bengal, and it lowered to about 1.7 km over the Indochina burning region. The connection between the uplift from the burning surface to the steering flow at about 3–4 km requires further investigation.

According to the trajectory analysis at 3–5 km (Fig. 2c) the air masses passed over Indochina during 8 and 9 April before reaching Taiwan. To examine the impact of biomass burning on East Asia, we conducted tracer simulations with WRF/Chem with tracers placed on April 8 and 9 over the fire locations reported by the MODIS satellite. Figure 4 depicts the horizontal distribution of tracer concentration and wind field at the level of 650 hPa (around 4 km). The relatively strong wind belt (wind speed >10 m/s) at 650 hPa located just south of the Tibetan Plateau (Fig. 4a) merged into a higher-latitude strong-wind belt over East Asia's marginal seas at around 01:00 UTC 9 April (Fig. 4b). Simulation successfully produced the necessary flow pattern for long-range transport. At 12:00 UTC 9 April, the high concentration tracers were transported to the coastal areas of China following the strong wind belts that extend to east Taiwan (not shown). As a consequence, the strong wind belt extended in an East-West direction after 01:00 UTC 10 April and the light tracer concentration had already reached northern Taiwan (Fig. 4c). The elevated tracer concentration lay in northeast-southwest belts and covered northern Taiwan at around 02:00 UTC 11 April (Fig. 4d).

To further illustrate what mechanism dominates the vertical tracer transport over Indochina, tracer and other variables are presented on a cross-section along line AB in Fig. 5a. Figure 5a shows the geographic locations and the terrain in Asia. Along



ACPD
9, 13155–13176, 2009

line AB, the enhanced absolute vorticity (colored) developed to as high as 700 hPa, showed an upward motion (>8 cm/s, contour lines) just over the lee side of the mountain at 12:00 UTC 9 April (Fig. 5b). Actually, the enhanced absolute vorticity over the leeside lasted during the study period until 11 April (not shown). Concurrently, the wind speed greater than 10 (15) m/s (contour line) was from 300 hPa down to 900 (800) hPa and existed for more than 2 days (Fig. 5c–f). The enhanced vorticity over the southern part of the leeside trough was rather shallow (up to 700 hPa), and the significant upward motion was on the eastern side of the trough (12:00 UTC 9 April, Fig. 5b and d). The upward warm advection on the eastern side of the leeside trough and the downward cold advection on the western side supported the growth of the lee-side trough, as indicated by the enhanced vorticity, during the period between 8 and 11 April. Additional plots, not shown here, indicate the synoptic-scale dynamics is supported by the quasi-geostrophic dynamics (Holton, 2004; chap. 6). Further interesting synoptic- and meso-scale evolutions and their dynamics will be discussed elsewhere later.

The upward motion carried the tracers to reach as high as 700 hPa (Fig. 5c–e). After the tracers be uplifted to a high elevation and then followed the strong winds to the downwind areas (Fig. 5e–f). Obviously, the existence of the leeside trough played a dominant role for uplifting the tracer to the high altitude. After that, the tracers were carried away from the source area to downwind Taiwan and even East Asia by the strong westerly wind. The leeside trough and strong prevailing wind provide favorable weather conditions for the transport of tracers to the downstream areas.

Figure 5g shows the vertical distribution of the tracer concentration at Panchiao station over northern Taiwan at different times from the WRF/Chem simulation. In general, the peak of tracer concentration was located around 650 hPa (~4000 m) from 12:00 UTC 10 April to 02:00 UTC 11 April. As shown in Figs. 4 and 5c–f, the highest peak of the hourly tracer concentration was around 650 hPa over northern Taiwan, which agrees with the ozone sounding measurement at 02:00 UTC 11 April (Fig. 2a). The modeled results identify the long-range transport of the trace species following the strong westerly wind from the biomass burning source areas, i.e. from South Asia and

Indochina.

## 5 Sensitivity study

To further examine the role of the leeside trough formation in tracer transport, a case on 14 April, 2005 with no significant trough presence was studied to conduct a sensitivity experiment. According to weather maps a high pressure system dominated over southern China and Indochina at 850 hPa with no significant trough at levels 850 and 700 hPa (not shown). In this study, we assumed fire points to be the same as the control study case (Fig. 2b) and put the tracers at the lowest level of the model for the air masses that passed through Indochina on 11 and 12 April, 2005. Simulation results indicated that no significant peak existed for the tracer vertical distribution over northern Taiwan (Fig. 6g, line with cross). The sensitivity study suggested what we proposed; no tracer concentration peaks when there is no leeside trough.

## 6 Mean leeside trough

The mechanism we propose in this study is the uplifting by the leeside trough at the eastern flank of the Tibetan Plateau and the mountains over Indochina. The Tibetan Plateau represents a huge obstacle which can block basic atmospheric flows and split the prevailing westerlies into the northern and southern branches (Yeh, 1950; Staff Member, 1957). The interaction between the westerly flow and the Tibetan Plateau causes the production of shallow vortices in the lee of the Plateau (Staff Member, 1958; Wu et al., 1985; Wang and Orlanski, 1987; Wang et al., 1993; Chang et al., 2000; Yasunari and Miwa, 2006). These vortices are obviously related to the leeside trough, and their relationship with the trough will be discussed later in a separate report.

The leeside trough is the dominating feature over southern China and Indochina. The associated upward motion and the low-level southerly flow provide the uplift and northward movements for the biomass-burning products at the surface. In the average between 1948 and 2008 for the spring (March, April, and May), this feature appears to be persistent at the eastern flank of the Tibetan Plateau at 850 hPa (Fig. 6a), and only extends from surface to 700 hPa. The vertical motion field at 925 hPa (Fig. 6b) supports the leeside trough with a broad region of the upward motion extending southward over Indochina. Moreover, the vertical cross-sectio ns of the vertical motion and the meridional flow along 105° E (Fig. 6c and d, respectively) indicate that the trough is really shallow (below 700 hPa), that the north-south range of the upward motion extends more than 20 degrees (from 15° N to 35° N), and that the southerly flow also prevails more than 20 degrees (between 10° N to 30° N) with a peak speed of 5 m/s at 850 hPa.

Based on the conservation of the potential-vorticity, a trough is frequently and easily formed at the leeside of major mountains under favorable conditions (Gill, 1982; Holton, 2004). The leeside trough plays an important role as it can induce a significant upward motion. It is important to note that the effect of the leeside trough provides an important process for the tracer to be uplifted. Once the trough is generated and associates with profound biomass burning, it would be favorable for the biomass-burning products to be transported aloft. The existence of this trough can support this most important mechanism for the average ozone peak to be observed at around 4 km in northern Taiwan.

## 7 Conclusions

In this study we analyzed the seasonal variability of biomass fire events from the MODIS data over Indochina and examined the tracer transport mechanism by a newly developed tracer module in the WRF/Chem model. Satellite data show nearly 20 000 fires per year from 2000 to 2007 over Indochina. Seasonal variation statistics indicate that biomass fires occurred most frequently during the late winter and spring over Indochina and hence they had a significant impact on the ozone concentration of downwind Taiwan and even East Asia. Based on the WRF/Chem tracer transport simulation results, we found that the existence of the mountain leeside trough can be the most important mechanism for tracers to be transported from the surface to above 3 km. The sensitivity study suggested what we proposed; there is no tracer concentration peak when there is no leeside trough. Previously, studies commonly indicated the thermal buoyancy and turbulence created by active fires as the primary mechanism for pollutants to be transported. Over Indochina, such strong convection of tropical type did not prevail during spring; it would be too weak for the pollutants to be transported above 3 km. The existence of the leeside trough over Indochina reasonably provides a linkage between biomass burning in Indochina and the peak ozone concentration at about 4 km over downwind northern Taiwan.

*Acknowledgements.* This work was supported by NSC-2111-M-001-004-MY3. The authors gratefully acknowledge the NOAA Air Resources Laboratory (ARL) for the provision of the HYSPLIT transport and dispersion model and/or READY website (http://www.arl.noaa.gov/ready.html) used in this publication.

## References

Bethan, S., Vaughan, G., Gerbig, C., Volz-Thomas, A., Richer, H., and Tiddeman, D. A.: Chemical air mass differences near fronts, J. Geophys. Res., 103, 13413–13434, 1998.

Boschetti, L., Roy, D. and Justice, C.: Using NASA's world wind virtual globe for interactive visualization of the global MODIS burned area product, Int. J. Remote Sens., 29(11), 3067–3072, 2008.

Chan, C. Y., Chan, L. Y., Chang, W. L., Zheng, Y. G., Cui, H., Zheng, X. D., Qin, Y., and Li, Y. S.: Characteristic of a tropospheric ozone profile and implications on the origin of ozone over subtropical China in spring 2001, J. Geophys. Res., 108(D20), 8800, doi:10.1029/2003JD003427, 2003.

Chang C. P., Yi, L., and Chen, G. T. J.: A numerical simulation of vortex development during the 1992 East Asian summer monsoon onset using the Navy's regional model, Mon. Weather Rev., 128, 1604–1631, 2000.

Christopher, D. E. and Kimberly, E. B.: Survey of fires in Southeast Asia and India during 1987,

in: Global Biomass burning, vol. 2., edited by: Levine, J., MIT Press, Cambridge, Mass, 663–670, 1996.
Donnell, E. A., Fish, D. J., Dicks, E. M., and Thorpe, A. J.: Mechanisms for pollutant transport between the boundary layer and the free troposphere, J. Geophys. Res., 106, 7847–7856, 2001.
Draxler, R. R. and Hess, G. D.: An overview of the Hysplit-4 modeling system for trajectories, dispersion, deposition, Aust. Meteorol. Mag., 47, 295–308, 1998.
Dwyer, E., Gregoire, J. M., and Malingreau, J. P.: A global analysis of vegetation fires using satellite images: Spatial and temporal dynamics, AMBIO, 27, 175–181, 1998.
Folkins, A. R., Chatfield, D., Baumgardner, D., and Proffitt, D.: Biomass burning and deep convection in southeastern Asia: results from ASHOE/MAESA, J. Geophys. Res., 102, 13291–13299, 1997.
Gill, A. E.: Atmosphere-Ocean Dynamics, Academia Press, New York, 662 pp., 1982.
Grell G. A., Steven, E. P., Rainer, S.: Fully coupled “online” chemistry within the WRF model, Atmos. Environ., 39, 6957–6975, 2005.
Harris N., Oltmans, R. S. J., Dlugokencky, E. J., Novelli, P.C., Johnson, B. J., and Mefford, T.: An investigation into the source of the springtime troposphere ozone maximum at Mauna Loa Observatory, Geophys. Res. Lett., 25, 1895–1898, 1998.
Holton, J. R.: An Introduction to Dynamic Meteorology, 4th edn., Elsevier Academic Press, MA, USA, 2004.
Hong, S.-Y. and Dudhia, J.: Testing of a new non-local boundary layer vertical diffusion scheme in numerical weather prediction applications, 16th Conference on Numerical Weather Prediction, Seattle, WA, 2003.
Hsu N. C., Herman, J. R., Bhartia, P. K., and Seftor, C. J.: Detection of biomass burning smoke from TOMS measurements, Geophys. Res. Lett., 23, 745–748, 1996.
Ichoku, C., Kaufman, Y. J., Giglio, L., Li, Z., Fraser, R. H., Jin, J. Z., and Park, W. M.: Compariative analysis of daytime fire detection algorithms using AVHRR data for the 1995 fire season in Canada: perspective for MODIS, Int. J. Remote Sens., 24, 1699–1690, 2003.
Jocob, D. M.: Transport and chemical evolution over the Pacifice (TRACE-P): a NASA/GTE aircraft mission white paper prepared for the Global Tropospheric Experiment (GTE) of the National Aeronautics and Space Administration (NASA), available at http://www-as.harvard.edu/chemistry/trop/tracep/whitepaper/text.html, 1999.
Kasischke E. S., Hewson, J. H., Stocks, B., van der Werf, G., and Randerson, J.: The use of

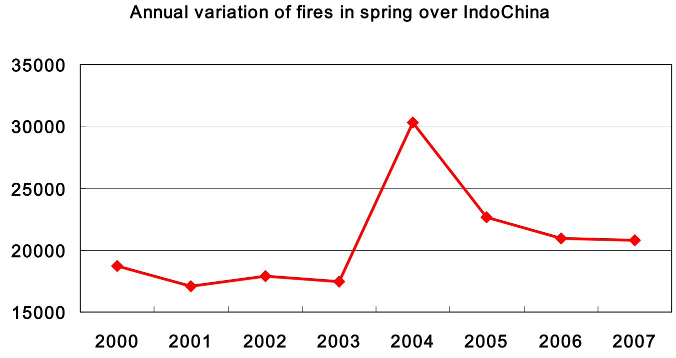


ACPD
9, 13155–13176, 2009

ATSR active fire counts for estimating relative patterns of biomass burning: a study from the boreal forest region, Geophys. Res. Lett., 30(18), 1969, doi:10.1029/2003GL017859, 2003.
Lau, K.-M., Ramanathan, V., Wu, G.-X., Li, Z., Tsay, S. C., et al.: The joint aerosol-monsoon experiment: a new challenge for monsoon climate research, B. Am. Meteorol. Soc., 89, 369–383, 2008.
Lin C. Y., Chang C. C., Chan, C. Y., Kuo, C. H., Chen, W. C., Allen Chu, D., and Liu, S. C.: Characteristics of springtime profiles and sources of ozone in the low troposphere over northern Taiwan, Atmos. Environ., in review, 2009.
Liu, H., Chang, W. L., Oltmans, S. J., Chan, L. Y., and Harris, J. M.: On springtime high ozone events in the lower troposphere from southeast Asian biomass burning, Atmos. Environ., 33, 2493–2410, 1999.
Liu, H., Jacob, D. J., Bey, I., Yantosca, R. M., Ducan, B. N., and Sachse, G. W.: Transport pathways for Asian combustion outflow over the Pacific: interannual and seasonal variations, J. Geophys. Res. , 108(D20), 8786, doi:10.1029/2002JD003102, 2003.
Oltmans, S. J., Johnson, B. J., Harris, J. M., and Thompson, A. M.: Tropospheric ozone over the Northern Pacific from ozonesonde observations, J. Geophys. Res., 109, doi:10.1029/2003JD003466, 2004.
Ramanathan, V. and Crutzen, P. J.: New directions: atmospheric brown clouds. Atmos. Environ., 37, 4033–4035, 2003.
Ramanathan V., Chung, C., Kim, D., Bettge, T., Buja, L., Kiehl, J. T., Washington, W. M., Fu, Q., Sikka, D. R., and Wild, M.: Atmospheric brown clouds: impact on South Asian climate and hydrologic cycle, P. Natl. Acad. Sci. USA, 102, 5326–5333, 2005.
Staff Members, Academia Sinica: On the general circulation over Eastern Asia (I), Tellus, 9, 432–446, 1957.
Staff Members, Academia Sinica: On the general circulation over Eastern Asia (II), Tellus, 10, 58–75, 1958.
Wang W., Kuo, Y. H., and Warner, T. T.: A diabatically driven mesoscale vortex in the lee of the Tibetan Plateau, Mon. Weather Rev., 121, 2542–2561, 1993.
Wang, B. and Orlanski, I.: Study of a heavy rain vortex formed over the eastern flank of Tibetan Plateau, Mon. Weather Rev., 115, 1370–1393, 1987.
Wu, G. X. and Chen, S. J.: The effect of mechanical forcing on the formation of a mesoscale vortex, Q. J. Roy. Meteor. Soc., 111, 1049–1070, 1985.
Yasunari, T. and Miwa, T.: Convective cloud systems over the Tibetan Plateau and their im-

pact on meso-scale disturbances in the Meiyu/Baiu frontal zone – a case study in 1998, J. Meteorol. Soc. Jpn., 84, 783–803, 2006.
Yeh, T.-C.: The circulation of high troposphere over China in winter of 1945–1946, Tellus, 2, 173–183, 1950.

(a)




(b)

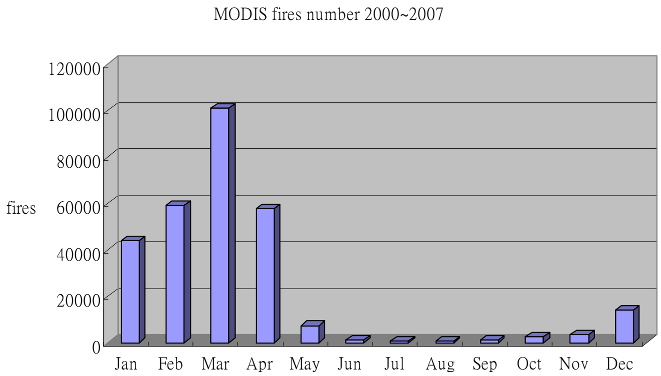



**Fig. 1. (a)** The annual variation of fires from MODIS satellite in spring (March, April, and May) over Indochina (10° N to 25° N, 90° E to 110° E) from 2000 to 2007. **(b)** The seasonal variation of fires in Indochina (10° N to 25° N, 90° E to 110° E) from 2000 to 2007.

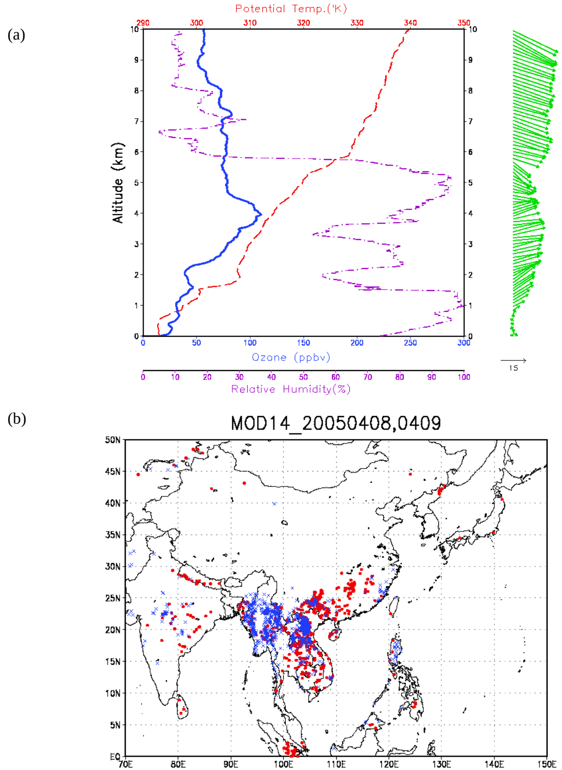



**Fig. 2.** **(a)** The vertical profile of ozone (solid), relative humidity (dash dot), potential temperature (dash), and wind field launched at 01:46 UTC (09:46 LST) 11 April, 2005. **(b)** Geographical distributions of fires from 8 (denoted by cross) to 9 (red dots) April, 2005.

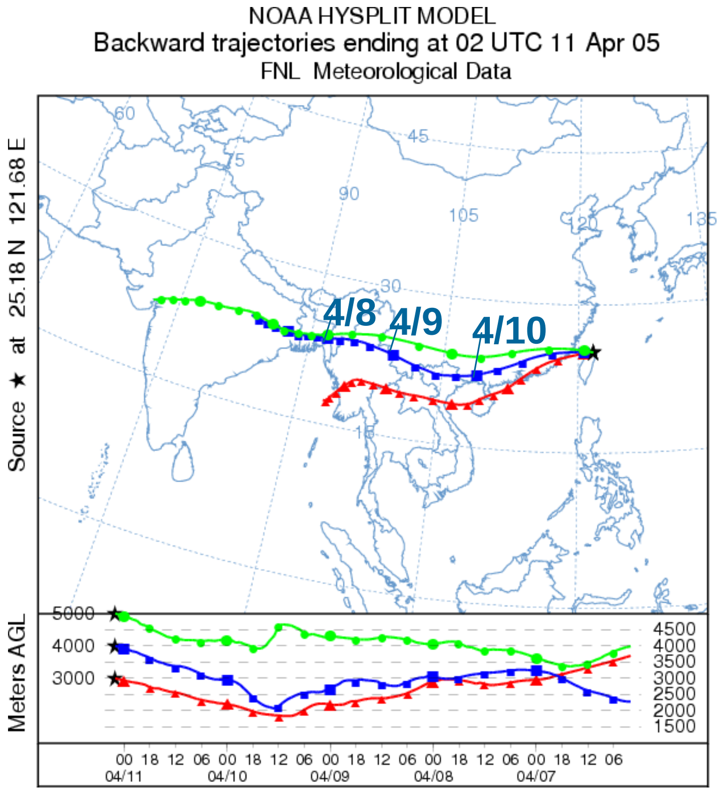



**Fig. 2. (c)** Result of the HYSPLIT model 3-day backward trajectory analysis started at 02:00 UTC (10:00 LST), 11 April, 2005 at altitudes of 3000, 4000, and 5000 m at Panchiao station in northern Taiwan.

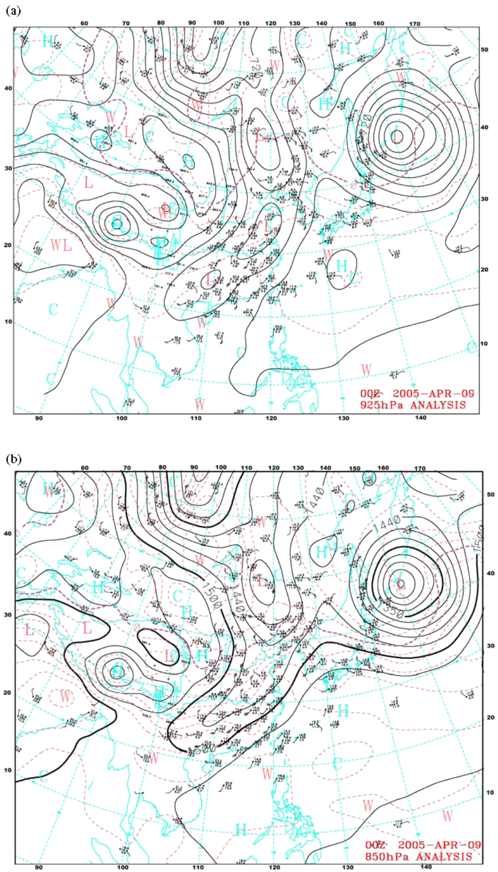



**Fig. 3.** The near surface weather charts at 00:00 UTC on 9 April, 2005. Symbols of H and L show the location of major high and low pressure systems. **(a)** 925 hPa, **(b)** 850 hPa.



ACPD
9, 13155–13176, 2009



Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

ACPD

9, 13155–13176, 2009



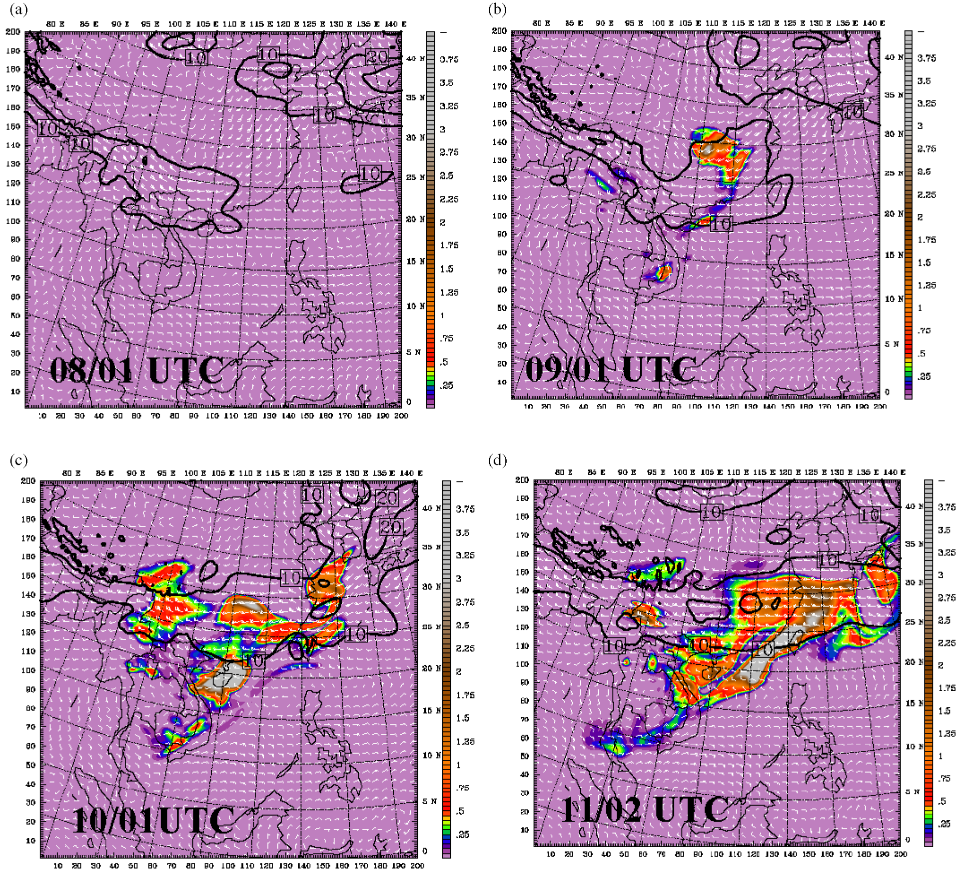



**Fig. 4.** Simulated distributions of tracer concentration (colored) and wind field at **(a)** 01:00 UTC 8 April, **(b)** 01:00 UTC 9 April, **(c)** 01:00 UTC 10 April, **(d)** 02:00 UTC 11 April. The contour represents the wind speed starting at 10 m/s and at 10 m/s interval.

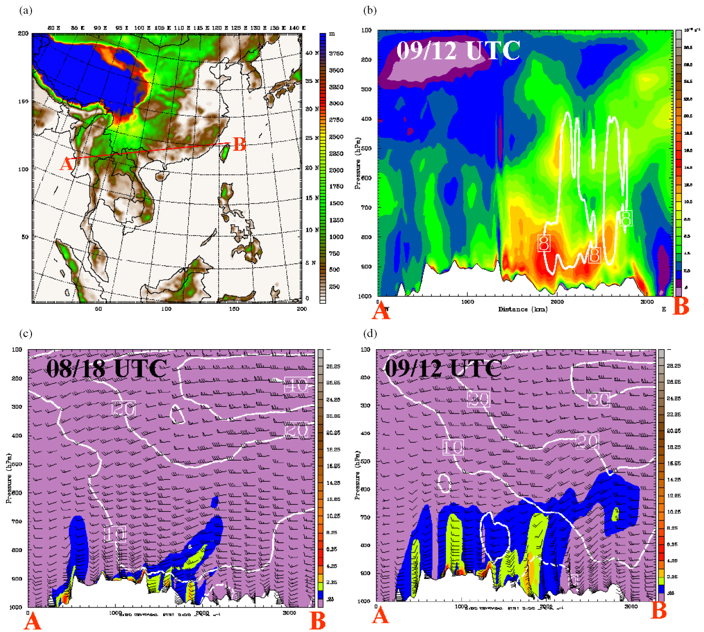



**Fig. 5.** **(a)** The geographic locations of East and the terrain in Asia. Line AB displays the location of East-West cross section in Fig. 5b–f. **(b)** The East-West cross section passes through line AB in Fig. 5a at 12:00 UTC 9 April. The colored area represents the amount of absolute vorticity. The vertical velocity equals 8 cm/s and is denoted by solid line. **(c)** The vertical distribution of tracer concentration (colored) and wind field along cross section line AB at 18:00 UTC 8 April. The solid contours are westerly wind speed equal 10 m/s and at 10 m/s interval. The dashed line represents 0 m/s. **(d)** same as 5 (c) but for 12:00 UTC 9 April.

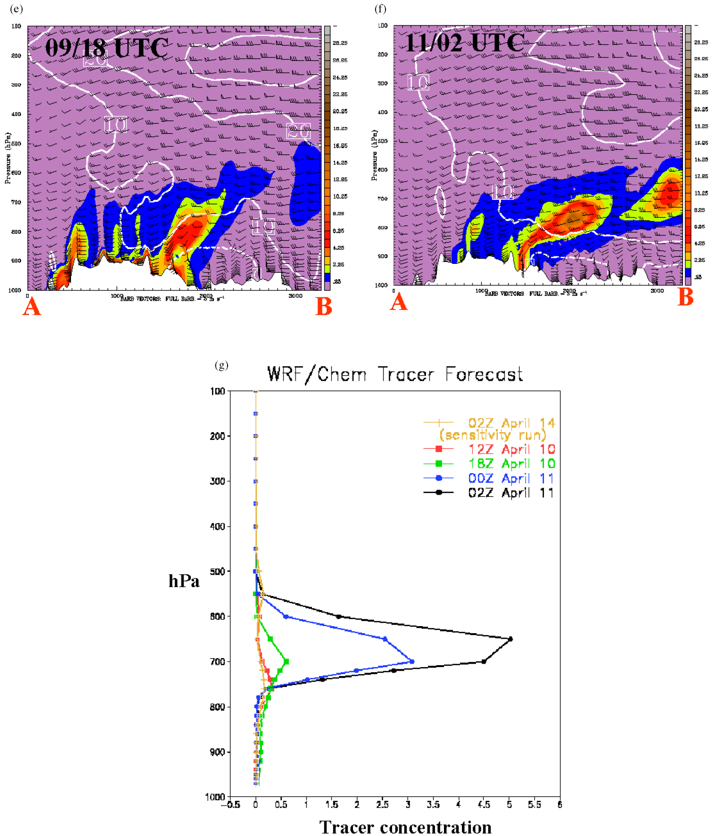



**Fig. 5.** **(e)** same as Fig. 5c but for 18:00 UTC 9 April. **(f)** same as Fig. 5c but for 02:00 UTC 11 April. **(g)** Simulation vertical distribution of tracer concentration for different dates (12:00 UTC 10 April, 18:00 UTC 10 April, 00:00 UTC 11 April, 02:00 UTC 11 April, and 02:00 UTC 14 April) over northern Taiwan.



ACPD

9, 13155–13176, 2009

Biomass burning transport from Indochina

C.-Y. Lin et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

ACPD

9, 13155–13176, 2009

Biomass burning transport from Indochina

C.-Y. Lin et al.



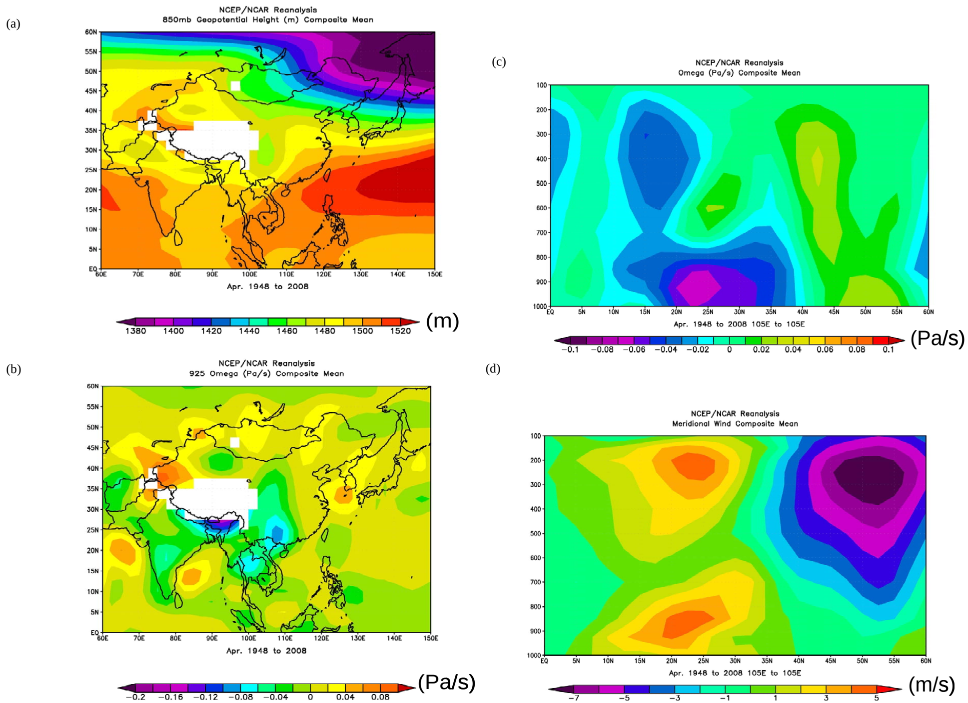



**Fig. 6. (a)** The average geopotential height during the spring months (March, April and May) between 1948 and 2008 deduced from NCEP/NCAR reanalysis at 850 hPa. **(b)** Same as Fig. 6a except for the vertical motion in the pressure coordinate at 925 hPa (unit: Pa/s). **(c)** The meridional cross section along 105° E for the pressure-coordinate vertical motion (unit: Pa/s). **(d)** Same as Fig. 6c except for the wind speed (unit: m/s).