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Boundary layer dynamics associated with a severe air-pollution episode in Hong Kong

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Abstract

In this study, field data and modeling results from a three-dimensional atmospheric model are analyzed and compared to investigate the local boundary-layer dynamics on 28–31 December 1999. The atmospheric model simulates the local wind fields over the complex terrain of Hong Kong, showing a good agreement with the observations from 40 weather stations. Under the weak synoptic conditions, local effects dominate the boundary-layer flows. The calm winds and the delicate interaction between the synoptic forcings and the local circulations and between the different sea-breeze circulations are the dominant factors responsible for the severe air-pollution episode on 29 and 30 December 1999. During the night, the interaction among local forcings such as upstream blocking, streamline dividing, downslope winds, channel flow, and land breezes are the dominant causes of the temporal and spatial variations of the wind fields. During the day, several sea-breeze circulations develop from different directions, creating convergence zones that can trap air pollutants in some locations. A low dome-shaped internal boundary layer is also present during the day, which acts as a lid to limit pollutant dispersion. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Numerical simulations; Local forcings; Wind field; Sea–land breezes; Internal boundary layer; Complex terrain in Hong Kong

1. Introduction

Hong Kong is situated on the south coastal region of China with a rough area of 1000 km^2. Fig. 1a shows the complex topography map of this area, which is characterized by numerous hills, islands and complex coastlines. It is surrounded by water on three sides. The differential solar heating and radiative cooling between land and sea cause influential sea–land breezes over 90 days/yr according to the analysis of 10-yr meteorological data (Zhang and Zhang, 1997). More complex air flow patterns may be present due to the complicated interaction of thermally induced circulations such as sea–land breezes, mountain–valley winds and drainage flows, and mechanically induced circulations such as blocking and dividing, wake vortices, gravity waves, and flow meandering over the complex terrain (Sang et al., 1999). Large-scale synoptic forcing may have a dominant influence on the development and the evolution of the local circulations. These complex interactions are not yet well understood. This is the motivation for many studies in air-pollutant transport over coastal areas, especially the area with complex topography. These studies should be carried out using a combined approach of three-dimensional boundary-layer simulations and observations (Zhong and Takle, 1993; Melas et al., 1998a, b).

Experimental and numerical studies have been performed in the coastal Greater Athens area to investigate boundary-layer dynamics and the mechanisms of air-pollutant transport, and to assess the capability of models to predict photochemical pollutant

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concentrations in order to develop air-pollutant abatement strategies in the region (e.g. Kambezidis et al., 1995; Melas et al., 1995, 1998a, b; Ziomas, 1998). It is believed that the interactions among local-circulation systems, coastal topography and synoptic forcing plays an important role in air-pollutant transport (Melas et al., 1998a, b). Moreover, the delicate balance between local circulation systems and large-scale synoptic forcing or between various sea-breeze circulations can enhance pollutant recirculation and is responsible for severe air-pollution episodes in this region (Kallos et al., 1993).

Results from studies of air-pollutant transport in the Los Angeles Basin also suggest that the local climate, including sea–land breezes and mountain-induced flows, is the principal factor in governing air-pollutant transport and horizontal and vertical distribution of pollutants (e.g. Lu and Turco, 1995).

In Hong Kong, the urban areas account for about 15% of the total land areas, most of which are located along the irregular coastline, in the north bank of Hong Kong Island and Kowloon Peninsula with the combination of residential, commercial and industrial activities. Some new towns such as Tung Chung, Yuen Long, Sha Tin and Tai Po are situated in valley-like areas (see Fig. 1). Vehicles, power plants, fuel combustion, and marine vessels are the main pollutant sources in Hong Kong. On 29 and 30 December 1999, a severe air-pollution episode occurred in Hong Kong. The NO, NO_2, SO_2, RSP and CO concentrations in the urban areas such as in Hong Kong Island, Kowloon Peninsula, Kwai Chung and Tsun Wan as well as in the new towns such as in Tung Chung (Lantau Island), Yuen Long and Sha Tin were much higher than their monthly averaged values with temporal and spatial variations. According to environmental authorities, there were no special emissions in Hong Kong (local) and Guangdong province (non-local) before, during and after this episode. Therefore, we propose that this episode is closely related to local boundary-layer flow. This study aims to investigate the boundary-layer dynamics associated with this episode on 29 and 30 December using field data and modeling results. Meanwhile, we have also simulated the wind fields for the non-episode days on 28 and 31 December (before and after the episode) with the observed synoptic conditions (see Section 3 for detail) for comparison.

2. Description of the modeling system

The simulation is performed by utilizing a three-dimensional, hydrostatic atmospheric model that is thoroughly documented in the previous studies (e.g. Sang et al., 1999, 2000; Liu et al., 2001). The model consists of the governing equations for the mean longitudinal and latitudinal wind components, virtual potential temperature, turbulence kinetic energy, and mass continuity. The hydrostatic equation is also included. The turbulence exchange coefficients are determined in terms of the turbulence energy equation (Yamada, 1983). The ground-surface temperatures are computed from the surface energy balance equation. The model has been verified against numerous field and laboratory experiments (e.g. Sang and Reiter, 1982; Sang and Weng, 1988; Sang et al., 1999, 2000). Previous comparisons between the results from a non-hydrostatic model and the present model have shown that the present model can well reproduce boundary-layer dynamics and the most essential features over such moderate complex terrains as Hong Kong (e.g. Sang et al., 1999). In the present study, simulated surface wind fields are evaluated against measurements taken at 40 meteorological stations in Hong Kong.

The model equations are solved using a finite-difference scheme in a terrain-following coordinate system. To avoid the reflection of vertically propagating gravity waves, a sponge upper boundary condition is used. Zero-gradient inflow and outflow lateral boundary conditions are utilized. Some previous studies suggest that a fine grid resolution as small as 200 m be used in a hydrostatic model (Sang and Weng, 1988; Walker et al., 1996). In this study, the entire domain is divided into 135×96 grids with a horizontal grid size of 500 m (Liu et al., 2001). At the lateral boundaries, 20 additional grids are added to each lateral side to move the lateral boundaries away from the domain of interest to reduce their influence on the flow. By defining internal boundary layer (IBL) height as the height at which the temperature-gradient values return to the background over-sea values, three-dimensional IBL structures can then be reproduced simultaneously. Liu et al. (2001) have found that the modeled IBL heights are in good agreement with lidar observations. In order to reproduce better three-dimensional IBL structures, the vertical grid is taken as ~ 100 m, consisting of 22 levels: 0, 10, 50, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, 1400, 1500, 2000, 3000, 5000, and 6500 m.

Since the sounding data for model initialization are available at 0800 and 2000 LT[1] every day, the simulation starts at 2000 LT on 27 December and ends at 0800 LT on 28 December. After an initialization at 0800 LT on 28 December, the simulation starts again and ends at 2000 LT on 28 December. This process is repeated until 0800 LT on 1 January 2000. The aim of the repeated initialization in the model is to include the influence of variations of the synoptic forcings during the different periods of the 4 days. The modeled wind fields are output every hour. Representative results at 0200, 0800,

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[1] Hong Kong local time (LT) = UTC + 8 h.

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