Available online at www.sciencedirect.com
SCIENCE DIRECT
ELSEVIER
Atmospheric Environment 39 (2005) 2021–2034
ATMOSPHERIC ENVIRONMENT
www.elsevier.com/locate/atmosenv

High-resolution model simulations of anthropogenic sulphate and sulphur dioxide in Southeast Asia

U. Siniarovina[a], M. Engardt[b,*]

[a]Malaysian Meteorological Service, Jalan Sultan, 46667 Petaling Jaya, Selangor, Malaysia
[b]Swedish Meteorological and Hydrological Institute, SE-601 76 Norrköping, Sweden

Received 28 November 2003; received in revised form 26 November 2004; accepted 9 December 2004

Abstract

The Multiple-scale Atmospheric Transport and CHemical modelling system (MATCH)—driven by meteorological data from the ECMWF—has been applied to a model domain covering Southeast Asia to complete a simulation extending over the full year of 2000. The current paper presents an evaluation of the model performance using archived chemical and meteorological data collected in the region during the year 2000. The calculated sulphate concentrations (on atmospheric aerosols and in precipitation) compare reasonably with observations while the atmospheric SO_2 mixing ratios show worse correspondence. This latter mismatch is attributed to local variations in the measured SO_2 concentrations that are not resolved in the regional model and possible miss-location of the emissions in our model. It can also be pointed out that different laboratories measuring SO_2 at the same site occasionally report SO_2 concentrations that differs by an order of magnitude or more.

The seasonal variations of the modelled species are less than initially expected but generally in accordance with the measurements available. Most of the Malaysian cities have comparatively low concentrations of sulphate in precipitation. This is supported both by the model results and by independent measurements. From the model simulations and the measurements, it is concluded that the sulphur deposition is still relatively low (i.e. $<0.5\,g$ sulphur $m^{-2}\,year^{-1}$) in most of rural Malaysia. This is also the case in Myanmar, Laos, central Vietnam, Kampuchea and southern Thailand. The situation in the vicinity of the large cities in the region is, however, much worse and the deposition is similar, or larger, than estimated critical loads.

Keywords: Acid deposition; Air pollution EANET; Malaysia; MATCH; Thailand

1. Introduction

Atmospheric pollution is a serious problem in many regions of the globe with high population densities and rapidly growing economies, such as, e.g. Southeast Asia. Various pollutants are associated with different environmental problems. Long-lived species like CO_2 and CFCs are linked with the climate change issue and the destruction of the stratospheric ozone layer. Medium reactive species like the oxides of sulphur and nitrogen, ammonia, ozone and VOCs are typically associated with acidification, eutrophication or other deteriorating effects on soil or living matter. Close to the emissions, the concentration of certain pollutants may become so high that the health and wellbeing of humans and other living organisms are threatened, as well as serious

*Corresponding author. Tel.: +46 11 4958582; fax: +46 11 4958001.
E-mail address: magnuz.engardt@smhi.se (M. Engardt).

1352-2310/$ - see front matter
doi:10.1016/j.atmosenv.2004.12.031

impacts on constructed materials. Species related to health problems in cities include NO_2, atmospheric aerosols (PM2.5 and PM10), ozone, PAHs, etc.

Following an initiative from The Swedish International Development Cooperation Agency (Sida), and a request from the Environmental Studies Division of MMS (Malaysian Meteorological Services), a collaborative research project is ongoing between Malaysian and Swedish scientists. The main objectives of the work are capacity building for scientists in Southeast Asia, and, of course, acquiring a better understanding of transport and deposition processes in the tropical environment. This project focuses on the use of a *regional* transport model. Regional modelling, in this context, means calculating fluxes and concentrations of chemical species with atmospheric residence times of days to weeks and corresponding transport distances of hundreds to thousands of kilometres. Typical examples of regional problems are acid deposition and increased tropospheric ozone, both of which have plagued Europe and North America during the last few decades. The transport model, now installed and operated at MMS, is also intended to be used by scientists and policy makers in the region to study other features in the atmosphere, such as the haze periods resulting from particles emitted during forest fires, and transboundary transport of anthropogenic pollutants.

The initiated modelling activity builds upon the measurements already performed by MMS and various other agencies at a number of monitoring stations in Malaysia and around Southeast Asia. The EANET (Acid Deposition Monitoring Network in East Asia) plays a central role here in its attempts to create a harmonised and quality controlled data base on measurements performed at various stations throughout East and Southeast Asia (for more info, see webpage: www.adorc.gr.jp). The present work would not have been possible without the utilisation of the data published by EANET, as well as from other sources of published and unpublished measurements from the Southeast Asian region.

The current paper gives an overview of the three-dimensional tracer model employed and presents results from a 1-year simulation performed for Southeast Asia, focussing on anthropogenic sulphur. Available data—mainly sulphate in precipitation and atmospheric SO_2—from several monitoring stations are compared with calculated results and uncertainties in the comparison are discussed. The present paper is a continuation and refinement of the initial work by Engardt and Leong (2001). We have now increased the resolution of the model and focus on the seasonal variation of the tracer burden in the region. The objectives are both to demonstrate the performance of the tracer model and the uncertainties in the results, as well as estimate the current sulphur load in Southeast Asia through combining measured data and model results. Many countries in the region are undergoing large economical and structural changes and a detailed mapping of atmospheric concentrations and surface depositions is essential to assess the current state of the environment. The oxides of sulphur (SO_2 and sulphate) are relatively straightforward to include in a model; the emission estimates are typically the most reliable of all anthropogenic pollutants and the chemistry and deposition processes are reasonably well known. At the same time, these species have been responsible for many of the environmental problems in Europe, America and East Asia. Anthropogenic SO_2 emissions, finally, can relatively be easily reduced, if deemed necessary.

2. Description of the model

Multiple-scale Atmospheric Transport and CHemical modelling system (MATCH) is a Eulerian *off-line* model for simulating emission, transport, deposition and chemical conversion of atmospheric pollutants. The model is a flexible framework and includes a number of different advection schemes and optional parameterisations of physical processes in the atmosphere. It has a variable horizontal and vertical resolution that is set by the driving data (meteorology, emissions, etc.), and several different chemical transformation and deposition modules that can be selected by the user, depending on application and type of input data available. In the present study we use MATCH version 3.8.3.

To drive our *off-line* model we use 12 months of meteorological data from ECMWF's (European Centre for Medium-Range Weather Forecast) global weather forecast and analysis system, covering the year 2000. We utilise short forecasts (6, 12 or 18 h) available every 6 h, interpolated to $0.5^\circ \times 0.5^\circ$ horizontal resolution (ca. $50\,km \times 50\,km$). In the vertical, our model domain extends up to ca. 11 km, divided into 30 layers. The MATCH model use the terrain following "η-coordinates" of ECMWF; the lowest model layer has a thickness of ca. 20 m, increasing to $\sim$400 m at 5 km and $\sim$700 m at 11 km. We use meteorological information from the 43 lowest layers (which corresponds to 98% of the atmospheric mass) to re-calculate the vertical velocity in MATCH to ensure mass consistency in the domain (see Heimann and Keeling, 1989 for details). Vertical mass fluxes enabling rapid vertical tracer redistribution in sub-grid convective clouds is calculated in our model from the convergence of water vapour following the scheme of Tiedtke (1989). The influence on the near-surface concentration of tracer in this study is, however, only marginal.

The horizontal advection of the trace species in MATCH is calculated using a mass-preserving, fifth-order-polynomial, integrated flux scheme, similar but