Graphics Processing Unit (GPU) Implementation Methodology of AERMOD model

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***Abstract*— Air pollution is one of the major problems the world is facing today. Air pollution is caused due to release of dangerous chemical substances such as carbon monoxide, CFC (Chlorofluorocarbon), carbon dioxide, hydro carbon, sulfur dioxide, etc in to the atmosphere. These substances are produced by various anthropological activities such as usage of vehicles, factory activities, etc. There is a need to assess the air quality to prevent the ill effects of pollutants on the environment. Air Quality Modeling (AQM) is an attempt to predict or simulate the ambient concentrations of contaminants in the atmosphere. These models are used primarily as a quantitative tool to correlate cause and effect of concentration levels found in an area. There are numerous models proposed in this regard. This paper proposes a methodology for GPU implementation of American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD) to evaluate the pollutant dispersion in atmosphere.**

Index Terms---Air pollution, carbon monoxide, CFC (Chlorofluorocarbon), carbon dioxide, hydro carbon, sulfur dioxide, Air Quality Modeling (AQM), GPU, AERMOD model.

I. Introduction

Air pollution modeling is essential in order to check the quality of air that we breathe and to prevent various ill effects caused due to pollutants that are exposed to atmosphere. Along with harming human health, air pollution also causes some serious effects on the environment. It causes ozone layer depletion. Another major effect of air pollution is the global warming where the increased emission of green house gases result in more heat trapped by earth's surface leading to increase in surface temperature of the earth. These effects make the process of air pollution modeling a must to determine the concentration of pollutants in the atmosphere at each instant and the need to control them.

II. LITERATURE

The basic air pollution dispersion models are Box model, Gaussian model, Eulerian model, Lagrangian model and dense gas model. The other models that are in use by various organizations are as follows.

A. AERMOD model

AERMOD is a steady-state Gaussian plume model. This model assumes the concentration distribution to be Gaussian in both vertical and horizontal in stable boundary layer (SBL), while in the convective boundary layer (CBL), the horizontal distribution is assumed to be Gaussian, but the vertical distribution is described with a bi-Gaussian probability density function (pdf) [1]. AERMOD also combines geophysical data such as terrain elevations and land use with the meteorological data to derive boundary layer parameters such as Monin-Obukhov length, friction velocity, mixing height, stability class, turbulence, etc [2]. Applications have been developed to run the model by making use of the concept of cluster of CPU's and enhancing the performance by reducing the time to compute the results [3].

B. CALPUFF model

CALPUFF is a non-steady state Lagrangian puff dispersion model distributed by Atmospheric Studies Group at TRC Solutions [4]. It can simulate the dispersion of buoyant puff or continuous point and area pollution sources as well as the dispersion of buoyant, continuous line sources. CALPUFF is particularly recommended for long-range simulations and studies involving the assessment of the visual impact of plumes. This version of CALPUFF is appropriate for both long-range and short-range simulations [2].

C. BLP (Buoyant Line and Point Source dispersion model)

This model is developed to simulate the dispersion of pollutants by aluminum reduction plants and other industrial sources in the atmosphere. In this model the effect of plumes generated is relevant [5]. It generates short term concentration output on a maximum of 100 points at ground level but can average these values on a monthly or yearly horizon. Through files input and output operations take place [6].

D. CALINE Series Models

Various air quality models are developed by the California Department of Transportation (Caltrans) to monitor the quality of air being affected by the pollutants released by vehicles. Prominent among them are CALINE4, CAL3HQC, and CAL3HQCR.

CALINE4 is a line source air quality model based on the Gaussian diffusion equation. It employs a mixing zone concept to characterize pollutant dispersion over the roadway. This model was proposed to assess air quality impacts near transportation facilities. The model can accurately predict concentration of nitrogen dioxide ($N0_2$), carbon monoxide (CO) and suspended particle concentrations.

CAL3HQC is a roadway model that predicts air pollutant concentrations near highways and arterial streets due to emissions from operating motor vehicles and idling vehicles. This model also estimates traffic queue lengths at roadway intersections. It is a combination of the CALINE3 line source dispersion model and an algorithm that estimates the length of the queues formed by idling vehicles at signalized intersections.

CAL3HQCR is a developed version of CAL3QHC. In this version we can process up to a year of hourly meteorological, vehicular emissions, and traffic volume and signalization data in one model run. In addition, 1-hour and running 8-hour averages of CO or 24-hour and annual block averages of PM can be calculated [3].

E. CTDMPLUS model

The Complex Terrain Dispersion Model plus Algorithms for Unstable Situations (CTDMPLUS) is a refined air quality model used in all stable conditions for complex terrain applications. This model is the result of long-term effort by the U.S. Environmental Protection Agency to develop improved plume models for elevated point sources in complex terrain settings [7]. It estimates hourly averaged concentrations of plume material on or near user-selected terrain features about which the model stimulates the flow distortion. Flow in the upper layer has sufficient kinetic energy to pass over the top of the hill, while streamlines in the lower layer are constrained to flow in a horizontal plane around the hill. Two separate components of CTDMPLUS compute ground-level; concentrations resulting from plume material in each of these flows [8].

III. Model Description

The modeling system of AERMOD consists of one main program (AERMOD) and two pre-processors (AERMET and AERMAP). AERMET calculates the boundary layer parameters such as friction velocity (u_*), Monin-Obukhov length (L), convective velocity scale (w_*), temperature scale (θ_*), mixing height (z_i), and surface heat flux (H) making use of surface parameters in the form of albedo, surface roughness and Bowen ratio, plus standard meteorological observations (wind speed, wind direction, temperature, and cloud cover), for use by AERMOD. The meteorological INTERFACE, internal to AERMOD, uses these parameters and generates vertical profiles of wind speed (u), lateral and vertical turbulent fluctuations (Fv, Fw), potential temperature gradient ($d\theta/dz$), and potential temperature. In addition, AERMET passes all meteorological observations to AERMOD. The American Meteorological Society/Environmental Protection Agency Regulatory Model Improvement Committee (AERMIC) terrain pre-processor uses gridded terrain data to calculate a representative terrain-influence height (h_c) also referred to as the terrain height scale. The terrain height scale h_c, which is uniquely defined for each receptor location, is used to calculate the dividing streamline height. The gridded data needed by AERMAP is selected from Digital Elevation Model (DEM) data. AERMAP is also used to create receptor grids. The elevation for each specified receptor is automatically assigned through AERMAP. For each receptor, AERMAP passes the following information to AERMOD: the receptor's location (x_r, y_r), its height above mean sea level (z_r), and the receptor specific terrain height scale (h_c) [1].

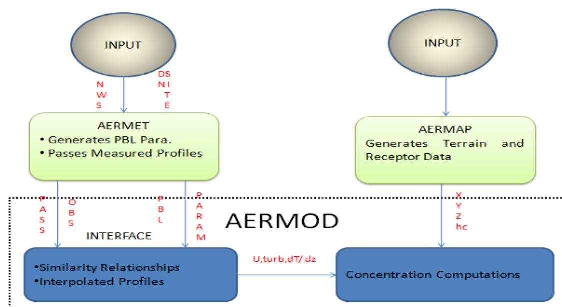

Figure1. Dataflow diagram of AERMOD model

IV. IMPLEMENTATION

A. Estimation of BLP

The surface parameters that are extracted by AERMET by means of several NCDC (National Climatic Data Center) formats contain hourly measurements of the same. Next the data from all the files are merged in to a single ASCII file in which each block of data contains all of the observations for a 24-hour period. If any input data is physically missing for the hour appropriate values are assigned to the missing meteorological variables. The final stage of processing reads the merged file along with site specific characteristics that define underlying surface to output two files. One file contains the boundary layer parameters and the second file contains one or more levels of winds, temperature and standard deviation of fluctuating components of wind [9]. Surface parameters such as albedo (reflectivity from earth's surface), Bowen ratio (surface moisture), wind speed, wind direction, cloud cover, temperature are extracted by the AERMET processor. Using these values the AERMET processor calculates the planetary boundary layer (PBL) parameters.

1. *Surface Heat Flux (H)*

The surface sensible heat flux is dependent upon net radiation and bowen ratio (which gives us the estimate of atmospheric moisture) .The surface heat flux is calculated using the equation

$$H = \frac{0.9\, R_n}{(1 + 1/B_0)}. \quad (1)$$

, where and B_0 is the Bowen ratio and R_n is the net radiation.

2. *Monin-Obukhov length (L)*

It is defined as the height at which the turbulence is generated more by buoyancy than by wind shear. It is calculated using the equation

$$L = -\frac{\rho c_p T_{ref} u_*^3}{kgH} \quad (2)$$

, where ρ is the density of air, c_p is the specific heat of air at constant pressure, T_{ref} is the ambient temperature representative of the surface layer and u_* represents friction velocity.Infact u_* and L are calculated iteratively until L changes by 1%.

3. *Friction velocity(u_*)*

It is the measure of surface stress reflecting the effects of surface roughness and wind velocity which are given as input to AERMET processor.

$$u_* = \frac{ku_{ref}}{\ln(z_{ref}/z_o) - \Psi_m\{z_{ref}/L\} + \Psi_m\{z_o/L\}} \quad (3)$$

, where k is the von Karman constant, u_{ref} is the win speed at reference height, z_{ref} is the reference measurement height for wind in surface layer, z_0 is the roughness length and L is the Monin-Obukhov length.

4. *Convective velocity Scale (w_*)*

It is the measure of turbulence in the convective boundary layer and is given by the equation [1]

$$w_* = \left(\frac{gHz_{ic}}{\rho c_p T_{ref}}\right)^{1/3} \quad (4)$$

, where g is acceleration due to gravity, H is the sensible heat flux, z_{ic} is the convective mixing height, ρ is the density of air, c_p is the specific heat of air at constant pressure and T_{ref} is the ambient temperature representative of the surface layer.

5. *Temperature scale (θ_*)*

It is given by the equation

$$\Theta_* = -\frac{H}{\rho c_p u_*} \quad (5)$$

, where H, ρ, c_p, u_* represent sensible heat flux, density of air, specific heat of air at constant pressure and friction velocity respectively.

6. *Mixing height (z_i)*

It is the height above the ground level at which relatively vigurous vertical mixing occurs. In convective boundary layer the mixing height is dependent upon both convective mixing(z_{ic}) and mechanical mixing(z_{im}) whereas in stable boundary layer mixing height depends on only mechanical turbulence.

a) *Convective mixing height (z_{ic})*

It is calculated using the early morning potential temperature and time varying surface heat flux. Given by equation

$$z_{ic}\theta\{z_{ic}\} - \int_0^{z_{ic}} \theta\{z\}dz = (1+2A)\int_0^t \frac{H\{t'\}}{\rho c_p}dt' \quad (6)$$

, where θ is the potential temperature , A is set equal to 0.2 and t is the hour after sun rise.

b) *Mechanical mixing height (z_{im})*

During morning when the convective mixing layer is relatively small the turbulence mainly occurs due to mechanical mixing.Given by the equation

$$z_{im}\{t+\Delta t\} = z_{im}\{t\}e^{(-\Delta t/\tau)} + z_{ie}\{t+\Delta t\}\left[1 - e^{(-\Delta t/\tau)}\right] \quad (7)$$

, where z_{ie} is the unsmoothed mechanical layer height, z_{im} {t} is the previous hour's smoothed value

The mixing height for convective and stable boundary layers is given as follows [1].

$$\begin{aligned} &z_i = MAX[z_{ic};\, z_{im}] && for\ L < 0\ (CBL) \\ &z_i = z_{im} && for\ L < 0\ (SBL) \end{aligned} \quad (8)$$

B. *Profiling*

The above calculated BLP parameters are then passed to AERMOD interface which contains a set of routines to compute vertical profiles of wind direction, wind speed, temperature, potential temperature gradient, horizontal and vertical turbulences using appropriate profiling equations. The AERMOD interface compares the height at which the meteorological variable must be calculated for any one of the six variables with the height at which the measurements were made and if it is below the lowest measurement and above the highest measurement the interface calculates the appropriate value from selected PBL profiling relationships. This approach makes use of information contained in both measurements and similarity parameterizations [1].

C. Terrain Data Computation

It is used to process the terrain data in conjunction with a layout of receptors and sources to be used in AERMOD files. Terrain data in USA is available in the form of computer terrain elevation data files. AERMAP produces terrain base elevations base elevations for each receptor and source and a hill height scale value (the terrain height and location that has the greatest influence on the dispersion for each receptor) for each individual receptor.

AERMAP needs two types of input data. The first type of input file defines the source and receptor locations. The second type of input is the computer files of terrain data. There are 3 distinct data formats available in the USA that produce the terrain data they are the DEM format (Data Elevation Model) ,SDTS format (Spatial Data Transfer Standard), NED format (National Elevation Dataset).Out of the 3 formats AERMAP processes only the DEM format which follows the USGS "Blue book" standard. Other formats can be converted to DEM format. Each DEM file covers a section of land based on latitude and longitude co-ordinates. These data are available in various internet sites.

When a DEM file breaks through the 10 degree slope from receptor additional DEM files are required and the domain need to be extended to include that node .Considering such situations the base elevations of source and receptors and hill height scale calculated from AERMAP are given as an input to AERMOD [10].

D. Concentration estimation in AERMOD

The general concentration equation is given by

$$C_T\{x_r, y_r, z_r\} = f \cdot C_{c,s}\{x_r, y_r, z_r\} + (1-f)C_{c,s}\{x_r, y_r, z_p\} \quad (9)$$

, where $C_T\{x_r, y_r, z_r\}$ is the total concentration, $C_{c,s}\{x_r, y_r, z_r\}$ is the contribution from horizontal plume state, subscript c and s denote under convective and stable conditions, $C_{c,s}\{x_r, y_r, z_p\}$ is the contribution from terrain following state, f is the plume state weighting function, $\{x_r, y_r, z_r\}$ is the co-ordinate representation of receptor (z_r is the relative stack base elevation).$z_p = z_r - z_t$ is the receptor height above local ground and z_t is the terrain height at a receptor. In flat terrain z_t reduces to 0 and $z_p = z_r$.

General form of the concentration equation

$$C\{x, y, z\} = (Q/\tilde{u})\, P_y\{y; x\}\, P_z\{z; x\} \quad (10)$$

, where Q is the source emission rate, $\acute{u}$ is the effective wind speed and p_y *and* p_z are probability density functions which describe the lateral and vertical concentration distributions respectively.

1) Concentration calculation in CBL

The total concentration C_c in CBL is formulated as

$$C_c\{x_r, y_r, z_r\} = C_d\{x_r, y_r, z_r\} + C_r\{x_r, y_r, z_r\} + C_p\{x_r, y_r, z_r\} \quad (11)$$

, where C_d, C_r *and* C_p are the contributions from direct, indirect and penetrated sources respectively. The total concentration for the terrain following state has the same form of equation but z_r is replaced by z_p.

2) Concentration calculation is SBL

The total concentration in C_s can be calculated by

$$C_s\{x_r, y_r, z\} = \frac{Q}{\sqrt{2\pi}\tilde{u}\sigma_{zs}} \cdot F_y \cdot \sum_{m=-\infty}^{\infty}\left[\exp\left(-\frac{(z - h_{es} - 2mz_{ieff})^2}{2\sigma_{zs}^2}\right) + \exp\left(-\frac{(z + h_{es} + 2mz_{ieff})^2}{2\sigma_{zs}^2}\right)\right], \quad (12)$$

, where z_{ieff} is the effective mechanical mixed layer height, $\sum_{ZS}$ is the total vertical dispersion in the SBL and H_{ES} is the plume height references [1].

V. PROPOSED GPU IMPLEMENTATION

With the advent of high performance computing these days, computations can be done faster with better efficiency and get the results in quick time. For this purpose this paper illustrates the use of GPU, so that hourly calculation of all the parameters leading to the calculation of pollutant concentration can be done in parallel using GPU.

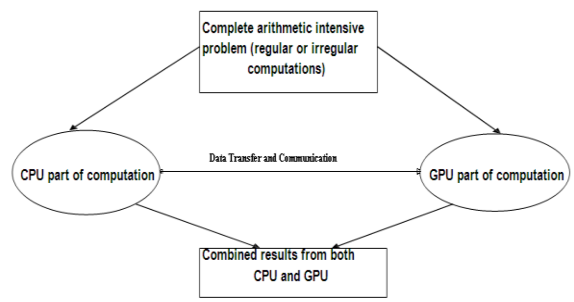

Figure2. Dataflow between CPU and GPU

This paper proposes a model such that GPU can be used in AERMOD model so that the time needed to compute the results is decreased and the performance can be enhanced. The proposed algorithm is given as follows:

- Firstly the hourly calculation of planetary boundary layer parameters is computed in GPU in parallel i.e. hourly computations are done by many threads in parallel
- After calculating the boundary layer parameters the vertical profiles of wind direction, wind speed, temperature, and potential temperature gradient, horizontal and vertical turbulences are computed

for each hour in parallel in GPU by passing the boundary layer parameters.

- The calculated boundary layer parameters, the computed vertical profiles of parameters, the hill height scale and the base elevation calculated through terrain data files are then passed to AERMOD to compute concentration of pollutants and other parameters at each receptor. These values can be computed in parallel using GPU by passing all the calculated parameters to achieve better results in less time.

Hence by using the GPU in each part of computations, a reduction is observed in the time for computation of parameters and enhances the performance of the application.

VI. PERFORMANCE ANALYSIS

The performance of the application is accelerated using GPUs. The performance analysis of the application is done based on the size of the input data and the execution time. As the number of hours under consideration increases the input data size also increases which results in more execution time.

The performance is analyzed by increasing the input data size. It is observed that the execution time increases exponentially as the data size increases. Figure 3 shows the performance of the application using sequential and GPUs. We can observe that the execution time increases exponentially with the increase in input data size.

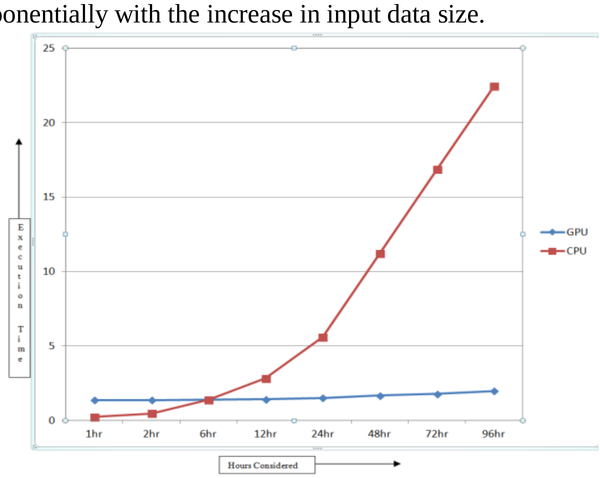

Figure3. Input Data Size Vs Execution Time

The analysis shows good speedup when GPU is used. When the data size is too small, CPU is better than GPU since more time is taken for data copy operations in GPU. But when the data size increases GPU works much faster than sequential execution. Thus GPU implementation of the application gives better performance when the data size is huge.

VII. CONCLUSION

Air pollution modeling is very much important given the fact that factors that worsen the quality of atmosphere are in rise. The evaluation of the parameters is implemented so far in CPUs. This paper proposes a methodology to implement the AERMOD model on GPU to get further improvement in the performance of the applications. Main components of AERMOD model that are suitable for the data parallelism are chosen for the GPU implementation. A further improvement in the performance of the application is expected by optimizing the code to parallelize more data. Also the time to transfer data from CPU to GPU and vice versa is expected to reduce using streams.

It is also planned to extend the GPU implementation of AERMOD model to GPU clusters to further improve the performance of the application. As the model is basically designed with U. S. terrain data etc., the authors plan to enhance the AERMOD model to Indian Scenarios and also specific to different industries and different properties of the pollutants.

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