Forest Fuel Parameterization and Large-Scale Fire Simulation Modeling Using High-Performance Computing in the Himalayas

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Abstract:

Large-scale forest fire modeling necessitates high-resolution spatial data and complex fuel parameterization, resulting in substantial computational demands. While significant progress has been made in countries such as the USA, Australia, and parts of Europe, particularly in region-specific fuel parameter development. Comparable studies for Indian forests remain limited. This research addresses that gap through extensive field investigations in the Sikkim Himalayas, leading to the generation of localized fuel parameters and their integration into high-resolution (1 m) fire simulations. We employed the Fire Dynamics Simulator (FDS), a Computational Fluid Dynamics (CFD)-based tool, to model forest fire behavior, executing simulations on a High-Performance Computing (HPC) platform. Pre-processing and formatting of input data were facilitated using open-source GIS software, ensuring compatibility with FDS requirements. Validation was performed by comparing simulated outputs with burnt area extents derived from post-fire satellite imagery. By integrating FDS, HPC and field investigations specific to Sikkim forests, this approach offers new insights into forest fire simulation tailored to the Sikkim context. Leveraging parallel computing enables faster simulation outputs, providing valuable support to decision-makers for more effective fire management and mitigation strategies.

Keywords: HPC, FDS, GIS, Forest fire, Remote Sensing.

1. Introduction:

Uncontrolled forest fires result in the loss of human lives, biodiversity, property and increase in environmental pollution. Although the majority of forest fires are of anthropogenic origin, lightening induced forest fires are also common (Clarke et al., 2019). Besides this climate change-induced warming forms conducive conditions for a spurt of forest fire (Miller et al., 2009, Kale et al., 2017). Globally numerous severe fires have been reported in Australia, the Euro-Mediterranean region, and the USA. Around 500000 ha area was burnt in Australia during 2019-2020 and around 12000000 ha area was burnt in USA in California and Western Nevada provinces between 1984-2006 (Boer 2020, Miller et al., 2009, Andrade 2022, Morante-Carballo 2022). Recently significant wildfires have been reported in different parts of Europe and showing increasing trend (Ganteaume et al., 2021).

Besides the challenges posed by raging wildfire to fire control authorities recently it has been reported that wildfire fire can be successfully controlled through coordinated efforts by the fire control authorities, local people, and technological interventions which focuses on proper resource management for wildland fire prevention and suppression based on region specific calibrated fire risk mapping along with fire spread model (Fernandez-Anez et al., 2021).

It is extremely important to detect, track and control the wildfire in good time so as to minimize the damages. Significant efforts have been made in detecting the wildfire by means of satellite remote sensing and operationalization of active fire detection has already been achieved. The 1 km spatial resolution MODIS sensor on board the Terra and Aqua satellites and 375 m spatial resolution VIIRS on board Suomi NPP satellite have played/are playing a key role in detecting the fire hotspots. Besides these geostationary satellites also provide regional information about the active fires. Such satellite provides the fire alerts at very short time interval for example INSAT 3D satellites provide info at the interval of 30 minutes. These satellites are extremely useful in detecting and tracking the large wildfire. This satellite however operates at coarser resolution and hence detection of small fires is difficult.

It is important to predict the spread of the wildfire over next time interval once its location is detected. Many wildfire simulation models are available which can estimate the fire spread faster than real time. Some of these models are WRF FIRE, WRF SFIRE, FARSITE and FLAMMAP. WRF SFIRE and WRF FIRE uses the inputs from the numerical weather prediction model i.e., WRF (Weather Research and Forecasting model) and are coupled with high resolution fire simulation models so that the feedbacks from the fire models are incorporated into the WRF model. These models generally work on the level set methods which makes them operationally feasible. The WRF SFIRE models have been successfully tested for their operational deployment in different parts of the world (Mandel 2014).

The models like FARSITE/FLAMMAP are based on the constant environmental conditions and although faster have limited questionable accuracy. Using FLAMMAP software Vilà-Vilardell et al. (2020) studied fire hazards of two valleys in Bhutan (Thimphu and Jakar) having blue pine forests.

BehavePlus is widely applied due to its ease of use, it overcomes the necessary black-box aspects of spatial systems. BehavePlus can be used to examine effect of fuel model, live fuel moisture, or canopy cover on modeled fire behavior (Andrews et al., 2005). Mangiameli et al. (2021) presented a new free and open-source system to simulate and predict the movement of the fire front using the Geographic Information System (GIS) and Rothermel surface fire spread model, modified by Albini. They describe the mathematical models used and provided a GIS design and its implementation. They have shown some results for the Etna volcano (Sicily, Italy).

Some other models such as Fire Dynamics Simulator (FDS) and FIRETEC provide greater details about wildfire behavior and are important for in-depth research related to wildfire science. Fire Dynamics Simulator (FDS) is a Computational Fluid Dynamics based model developed by the National Institute of Standards and Technology (NIST). It simulates fire propagation along with gases, flumes, and smoke. Navier-Stokes equations form the basis of FDS which in turn solves equations for low-speed, thermally driven flows emphasizing smoke and heat transport from fires. FDS is based on LES calculations and involves significant calculations which necessitate high-performance computing. The model provides significant details of wildfire dynamics over a terrain and have the flexibility to model the smoke.

The models require fire initialization, fuel and terrain parameters to be defined in a single .fds file. Many tools are available to convert the fuel and terrain parameters to FDS compatible formats. These include WFDS Input File Creator & Data Viewer (McNamara et al., 2016), BlenderFDS, an open QGIS plugin qgis2fds which exports terrains and fuel for wildfire simulation.

Wildland Urban Fire Dynamics Simulator (WFDS) is an extension of FDS for vegetation as fuels and has been used in different research studies. Various researchers have studied and emphasized importance of field derived fuel parameters as input to WFDS and FDS Mell et al. (2011) used WFDS for modeling the wildland-urban interface (WUI) in a residential area adjoining a forest. They emphasized the use of remote sensing data for fuel type mapping. They emphasized the use of LIDAR data for deriving vegetative fuels, structures, fire barriers, and topography. Overholt et al. (2014) studied the physical and burning characteristics of the prairie grass commonly named little bluestem. They experimented at different scales to parameterize WFDS concluding that Fuel Moisture Content (FMC) had significant impact on the fire spread rate compared to fuel loading and SAV ratio.

Moinuddin et al. (2017) used WFDS, for vegetation fire for studying surface to canopy propagation of wildland fire. They used a mesh size of 50 mm for modeling the burning of single Douglas fir tree and a semi-quantitative study for forest floor fire transitioning to a crown fire.

Soummar et al. (2022) tested vegetation fire data at a laboratory scale using the FDS model. They measured heat release rate (HRR) for fuel bed slopes at 0^0 and 30^0 with varying fuel loads of 0.6 and 0.4 kg.m-2. They used a computational domain with 7 × 3 × 3 m and ran the simulation using a desktop computer.

Using WFDS Kim et al. (2016) simulated various combinations of terrain slopes, stand ages and tree spacing to establish effective thinning guidelines for steep sloping terrains with dense and young growth pine stands in Republic of Korea. Forest fuel reduction by proper tree spacing simulated using WFDS can be studied prior to actually carrying out thinning exercise on ground.

Wildfire control can have two different perspectives i.e., preparedness for potential wildfire and managing the running wildfire. In the prior case, the information about the potential fire incidences is available well in advance so that authorities have sufficient time to allocate the resources judiciously at specified locations, whereas, in the latter, the information about the forest fire spread is available on real or near real-time basis which is useful in evacuating the people and livestock in good time.

Although significant research have been carried out in forest fuel characterization and making available the state of the art datasets including the satellite derived fuel and fuel moisture maps, state of the art operational software and so on and so forth, it is however, required to investigate the fire and smoke propagation by way of modeling at high resolution using the principals of computational fluid dynamics so as to have detailed qualitative and quantitative insights about the wildfire spread in natural terrain.

Figure 1. Grasses on steep slopes near Melli

The fuel is one of the most important inputs to run the fire spread simulation models. Although significant research has been carried out in different countries including the USA, Canada, and Australia and the fuel parameters database has been developed, however, for many other countries where wildfires are prominent the regional fuel data is not available. This restricts validation of the fire spread outputs provided by these models. This was one of the major motivations to carry out the present research.

The present research is aimed at 1. Estimating the regional fuel parameters 2. Simulation of wildfire using FDS in a High-Performance Computing environment using the indigenously collected fuel data.

2. Study area:

Sikkim falls in the region of the biodiversity hot spot of the world. It is a small mountainous state in the eastern Himalayan region having a total geographical area of 7096 sq. km.). The vegetation types range from tropical Dry Deciduous Forests with Sal and its associates in the valleys of Teesta and Rangit to the Alpine Scrub and grassland at high altitudes. Rainfall starts in April and lasts up to September. March to May are the summer months and the

temperature hovers between 19°C to 28°C. These are the critical months for forest fire incidences and spread in Namchi district. During monsoon (from June to September), the region receives heavy rainfall which approximately ranges from 200 mm to 650 mm. and thus wildfires are suppressed in these months.

Steeply sloped terrains and abundant undisturbed surface fuels are highly prone to forest fire. Every year dry grasses, dead leaves, twigs, and dead tree trunks keep accumulating on the forest floor. It is observed that in few patches fire occurrence is a regular phenomenon. Wildfires in Sikkim are mainly anthropogenic.

We selected the part of the South-Sikkim (Melli region of Namchi district) to carry out forest fire spread simulation. The area comprises of long grasses along with scattered shrubs and Sal forests mostly on the steep slopes. These grasses are during the dry season (December to April) the moisture is low and grasses are prone to fire. Anthropogenic disturbance near roads sometimes acts as an ignition source. Shooting rock debris due to landslides or earthquakes can also cause sparks which may induce fire.

3. Methodology

In the present research FDS model has been used for the fire spread simulation using level set method. The model requires different inputs for fire spread simulation (Appendix 2).

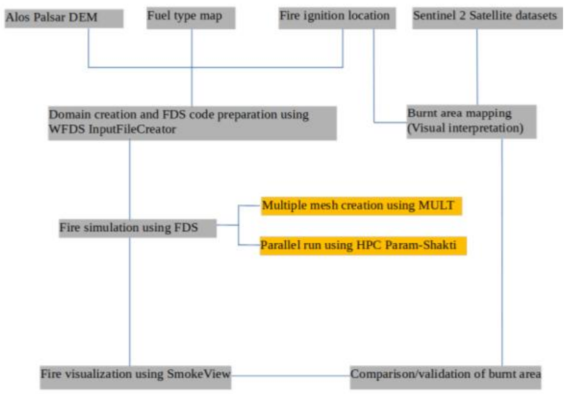

Figure 2. Flowchart of methodology

3.1 Data pre-processing

Various spatial and non-spatial datasets were converted to FDS code format using free and open-source software. DEM, fuel type maps, and ignition locations were processed using QGIS. Later the FDS code file was generated by integrating GIS datasets using a prototype software WFDS InputFileCreator developed by researchers (McNamara et al., 2016). Burnt areas were mapped using Sentinel 2 false color composite (FCC) comprising of NIR, Red and Green band. Figure 2 illustrates flowchart of methodology.

3.2 Terrain creation using DEM:

The study area terrain was created using ALOS Palsar Digital elevation model (DEM) data at 12.5 m resolution. The free DEM data was downloaded from (ALOS PALSAR – Radiometric Terrain Correction – ASF (alaska.edu)). The DEM data was extracted for the study area using QGIS raster tools.

3.3 Fuel type map

The existing LULC classified map was compared with the Anderson fuel model and accordingly different fuel classes were mapped (Anderson 1981). This was done by reclassifying the existing LULC map into appropriate fuel classes described by Anderson 1981 shown in Appendix 1.

The resultant fuel type map is used for assigning the fuel at each pixel. In the current study 1,2,3,8,10,14 Anderson fuel classes are used. The 13 Rothermel-Albini fuel models are aligned with the vegetation characteristics (Rothermel 1792, Albini 1976). The user can create their custom, distinctive vegetation model in the simulation.

3.4 Domain creation and FDS code preparation

A free software WFDS InputFileCreator (http://www.gmsgis.com/gis-model.html/) was used to convert the DEM, Fuel type, and ignition locations information to FDS code format. The tool facilitates the incorporation of spatial datasets into FDS code format. The software gives control over the specification of the domain and grid size in X, Y, and Z directions. Associated fuel types corresponding to each grid are attached in the output text file. In the current simulation grid size were 5 m, 5 m, and 1 m in X, Y, and Z directions respectively.

Running the FDS model using .fds file
FDS is a CFD tool for modeling fire-driven fluid flow. FDS solves a form of the Navier-Stokes equations numerically that is appropriate for low-speed (Ma< 0.3), thermally-driven flow, with a focus on smoke and heat transport from fires (McGrattan et al., 2020).

3.5 Governing Equations

The FDS software has been developed by the National Institute of Standards and Technology (NIST). It is based on the LES technique which solves a system of equations for thermally driven flow. The equations for conservation of mass, species, momentum, and energy are (McGrattan et al., 2013):

$$\partial_t \rho + \nabla \cdot \rho u = \dot{m}_b''' \tag{1}$$
$$\partial_t(\rho Y_\alpha) + \nabla \cdot \rho Y_\alpha u = \nabla \cdot \rho D_\alpha \nabla Y_\alpha + \dot{m}_\alpha''' + \dot{m}_{b,\alpha}''' \tag{2}$$
$$\partial_t(\rho u) + \nabla \rho u u + \nabla p = \rho g + f_b + \nabla \tau_{ij} \tag{3}$$
$$\partial_t(\rho h_s) + \nabla \cdot \rho h_s u = D_t p + \dot{q}''' - \dot{q}_b''' - \nabla \cdot \dot{q}'' + \varepsilon \tag{4}$$

where, $\dot{m}_b''' = \sum_\alpha \dot{m}_{b,\alpha}'''$, is the production rate of species, ρ is the density, u= (u, v, w) is the velocity field, p is the pressure field, g is the acceleration due to gravity, τ_{ij} is the viscous stress tensor, h_s is the enthalpy, and f_b is the external force. Y_α, D_α, and $\dot{m}_{b,\alpha}'''$ are the mass fraction, the diffusion coefficient, and the mass production rate of the α-th species per unit volume, respectively. The term $\dot{q}'''$ represents the heat release rate per unit volume from a chemical reaction, $\dot{q}_b'''$ represents the energy transferred to evaporating droplets, and $\dot{q}''$ represents the conductive and radiative heat fluxes. $\partial_t = \partial/\partial t$ is the partial derivative with respect to t and $D_t = (\partial|\partial t + u \cdot \nabla)$ is the total derivative with respect to t. There are two other equations in the system, namely, the pressure equation:

$$\nabla^2(p/\rho) = -\partial_t(\nabla \mathbf{u}) - \nabla \cdot (\mathbf{f}_b/\rho) \tag{5}$$

which is obtained from Eq. (3) by taking divergence and the equation of state:

$$p = \rho RT/W. \qquad (6)$$

Where R, T, and W are the universal gas constant, temperature, and molecular weight of the gas respectively.
There are six equations with six unknowns in the system: ρ, p, u, and T. The system of equations is solved by applying a low-pass filter using the LES technique in which the small-scale eddied that passes through the grid is modeled and the large-scale eddied are computed. This low-pass filter width is taken to be the cube root of cell volume (McGrattan et al., 2013, Meher et al., 2017).

FDS is based on the finite difference method which implements a predictor-corrector scheme explicitly and is second-order accurate in space and time. It is not suitable for complex shaped geometries as it uses rectilinear meshing but it helps in faster computational. The FDS version 6.7.5, developed by the National Institute of Standards and Technology (NIST) has been used in this study (Meher 2017, McGrattan et al., 2013).

For simulating wildland fire spread in FDS three methods are available. The first method is using a particle model. In this method the vegetation is represented by a collection of Lagrangian particles that are heated via convection and radiation.

The boundary fuel model approach is the second approach. In the boundary fuel model, the ground vegetation is represented as a porous solid with a thickness equal to the height of the vegetation. For the Boundary Fuel Model, the ground vegetation is modeled as a porous border made up of layers of dry plants, layers of moisture, layers of air, and layers of hard ground (Perez-Ramirez 2017).

The level set model approach is the third technique. There is an empirical model incorporated into FDS based on level sets for simulations of wildland fires spanning broad areas that cannot be gridded finely enough to predict fire spread using a physics-based model (Bova et al., 2015).

In the level set model, the level set function is activated by setting LEVEL SET MODE to one of 1, 2, 3, or 4 on the MISC line. In this research, level set mode 4 is turned on. The relationship between wind and fire is complete. When the fire front reaches a particular surface cell, it burns for a finite duration with a heat release per unit area that is set as part of the fuel model (McGrattan et al., 2020).

By selecting the appropriate method (Level set, Boundary fuel, Lagrangian particle) fuel parameters are defined for each fuel type. The Lagrangian particle method is computationally demanding and requires longer processing time and larger computational resources. The level set method is computationally less intensive and can be used for larger areas. The current experiment is for Sikkim terrain which is undulating and the altitude variations are high. Therefore, Level set method was used. The parameters are referenced from existing literature and field observations (Appendix 4). Level set mode 4 was used for the simulation. In level set mode 4 the wind and fire are fully-coupled. When the fire front arrives at a given surface cell, it burns for a finite duration and with a heat release per unit area provided as part of the fuel model (McGrattan et al., 2013).

The nomenclature used to describe the input of the fire spread rate estimation of burning grass with no wind and no slope is VEG LSET ROS 00. The definition of VEG LSET HT is the height of the grass or fuel. The VEG_LSET_SIGMA is the surface area to volume ratio (sigma) and VEG_LSET_BETA= Packing ratio (beta). ROS influences the burn severity and spread of fire. The dryness of the fuel and wind velocity also contribute to the fire spread rate. ROS observed from existing references of CS64 (Australian grass experiment) and studies carried out on Bluestem grasses were referred (Overholt et al., 2014). There are no ready references available for Indian regions for grasses rate of spread. Sati et al. (2016) reported a spread rate of 0.888 m/s in Chir pine and pine-oak mixed forests of Tehri, Pithoragarh, and Uttarkashi in Uttarakhand state. During fieldwork, locals and forest officials mentioned a spread rate of approximately 2 m/s. Laboratory studies as well as destructive sampling and in-field validation studies for various fire parameters are the need of the hour for forest fire fuel parameters in India. The height of the grass was 1- 2 meter (field observation of authors). The surface area to volume ratio (sigma) was estimated from sample field observations. The packing ratio for the grass was 0.0012. Parameters were referred from Overholt et al. (2014), Bova et al. (2015), and field observations by authors.

Various researchers have estimated SAV values following different methodologies, Buffacchi et al. (2020) did a comparative study for SAV values along with a new method of estimating SAV for Brazilian Amazon litter. SAV estimation was carried out based on the field-based observations for different fuel types based on the methodology as proposed by Bufacchi et al., 2020. Six sample plots were laid in various fuel types. Litter was collected from each plot in 5 quadrates of 1 m x 1 m. Three leaves (Large, medium, and Small) from each plot were selected for measurements (Figure 3 a and 3 b). The calculated SAV values are presented in Appendix 3. The values are derived for the first time for forest fuels in Sikkim. The SAV values are in agreement with other international literature (Appendix 3).

Figure 3 a. Quadrate size for field data collection

Figure 3 b. Leaves collected for a 1 x 1 m quadrate

3.6 Wind direction and velocity

The prevailing wind direction in South Sikkim for fire day was considered (https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/gangtok_india_1271631). 1.41 m/s wind speed (Gust) 10 m above ground was used for simulation. Wind data was downloaded from National Centre for Medium-Range Weather Forecasting (NCMRWF) In the level set 4 methods the wind and fire are fully coupled. Once the fire front arrives at a given surface cell, it burns for a finite duration and with a heat release per unit area provided as part of the fuel model. (McGrattan et al., 2013)

3.7 Multiple mesh creation for HPC simulation

Large spatial domains and finer grids involve significant computation resources. MULT functionality in FDS allows breaking the bigger domain into small parts and assigning them to individual processors/nodes. This allows the utilization of parallel processing on the high-performance computing (HPC) platform which improves the performance and reduces the computational time. This requires the use of HPC resources. PARAM-Shakti HPC machine was used for fire simulation modeling. 16 nodes were used for performing fire simulation of 500 m x 500 m x 725 m domain.

The supercomputer PARAM Shakti is based on a heterogeneous and hybrid configuration of Intel Xeon Skylake processors, and NVIDIA Tesla V100. The system was designed and implemented by HPC Technologies team, Centre for Development of Advanced Computing (C-DAC). It consists of 2 Master nodes, 8 Login nodes, 10 Service/Management nodes and 442 (CPU+GPU) nodes with total peak computing capacity of 1.66 (CPU+GPU) PFLOPS performance. The cluster consists of compute nodes connected with Mellanox (ERD) infiniBand interconnect network. The system uses the Lustre parallel file system.

3.8 Post processing

Fire visualization using SmokeView:

Smokeview is bundled with FDS and can be downloaded from the NIST website. The output of the FDS model is visualized using SmokeView software developed by NIST. Smoke plumes can be visualized at various time intervals. The software provides a facility for dynamic visualization, and time step-wise increment of various parameters like RoS, flume, HRRPUA, etc. Wind vectors that evolved during the simulation can also be viewed using Smokeview.

3.9 Validation

Sentinel 2 satellite datasets at 10 m spatial resolution were downloaded from EarthExplorer (https://earthexplorer.usgs.gov/). All bands of Sentinel 2 satellite scene data for 29th April 2020 were downloaded. The bands were stacked using QGIS software. Fire locations obtained from NASA FIRMS archives were overlaid on the satellite dataset (Figure 4). This helped in identifying the burnt area. The burnt area was digitized using the visual interpretation method.

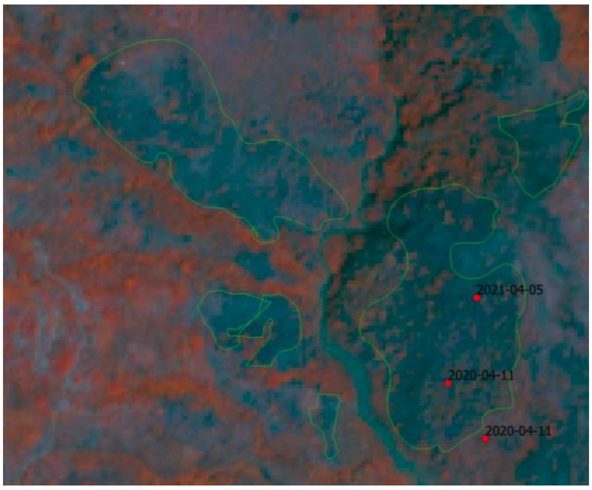

Figure 4. Sentinel 2 data (FCC 843) of 29th April 2020 overlaid with NASA FIRMS fire points

4. Results and Discussion:

4.1 SAV estimation

In Appendix 3 SAV estimations by various researchers is presented along with the present work. The SAV values are in agreement with other reported literature. This research work was experimental setup which were further improved in later studies by Kale et al. (2024) for Sikkim.

4.2 Scale up analysis

The fire spread simulation were carried out using different mesh and domain sizes resulted in different processing times (Appendix 5). It was observed that the computing time for the simulation decreases as the grid size increases from 1 m to 5 m. The number of processors and the simulation time were kept constant for these simulations.

It was observed that as the number of processors increased processing time reduces, however, beyond a certain point even when the number of processors is increased processing time does not increase Table 1 and (Figure 5). The graph shows linear scalability up to 200 processors, beyond which it declines due to an increase in communication time between processors. Comparing 625 processors to 80 processors, the scale-up study yielded speed up to 6.7X. The plot shows that the time speed up of the processor decreases at 625 processors, plainly indicating that adding more processors after this point will not help the simulation run faster. This study's objective is to determine the highest CPU power that can be used to increase simulation speed.

Mesh size (meter)	Domain size	Total mesh count (grid size)	Simulation time (sec)	Processing time (sec)	No. of processors
(1x1x1)	500x500 x725 meter	90 million	100	30361	80
				20303	125
				11180	200
				9906	250
				6275	400
				5286	500
				4521	625

Table 1: The Scale-up study of the Melli region Sikkim

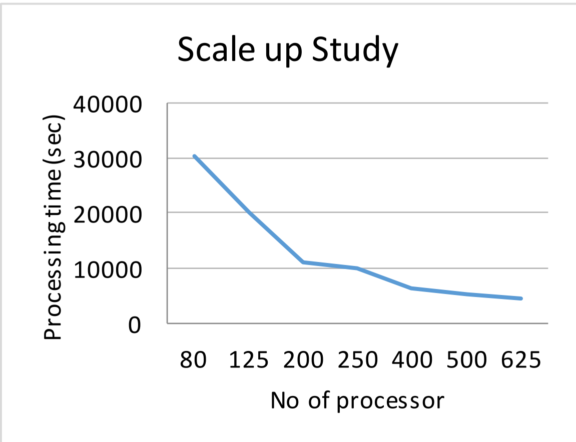

Figure 5. Scale up study graph

The Melli region area is addressed to an FDS simulation for Sikkim vegetation fuel types. In the X, Y, and Z directions, the terrain measures 634395, 634895, 3000836, 3001336, 423, and 1148 accordingly (500m x 500m x 725m). The overall mesh size is 181,250,000 (181 million) approx. The total number of processors required to run the simulation is 625, with 16 nodes. A real fire lasts for 800 seconds. The required simulation wall clock time in this situation is 10 hours.

Appendix 4 enlists various fuel parameters for different fuels along with the values used and references. In figure 6 a and b Smoke and Plume visualization for Melli region is shown. Figure 7 shows the shape of the burnt area in Melli viewed using Smokeview.

To confirm the burnt area, manual digitization was carried out using standard FCC data. Figure 6b shows a GIS image spread across a topographical surface. The results for the FDS simulation are in good agreement with the burned area. For the first fire point, there is a 70% agreement between the simulated findings and the satellite based burned area. The observed smoke release rate was also greater than the values for the parameters of the Rothermel-Albini fuel model that were given in the FDS user guide.

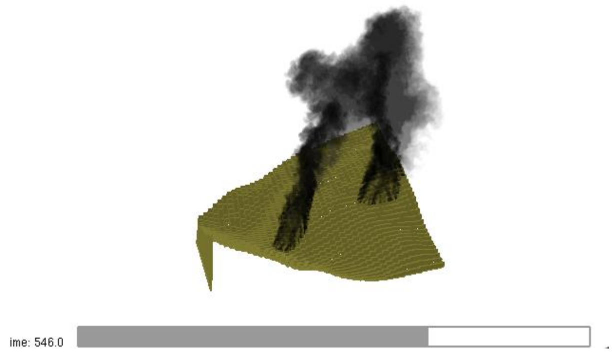

Figure 6a. Smoke and plume visualization using Smokeview for Melli simulation

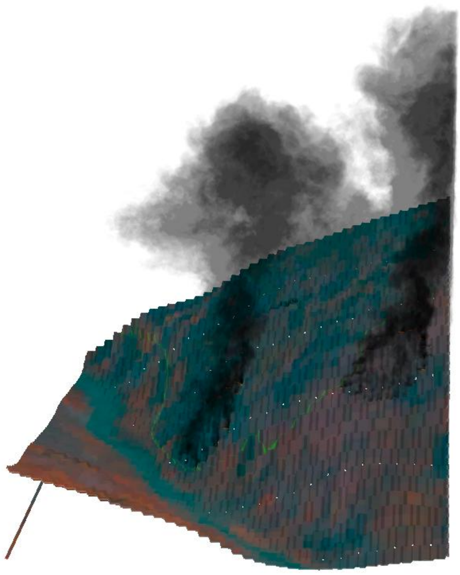

Figure 6b. Smoke and plume visualization using Smokeview for Melli simulation raped on satellite FCC

Sentinel 2 standard FCC data for April 29, 2020 (ESA, 2021) was used to map the burnt area using the visual interpretation technique. Burnt area polygon of 23.45 acres was digitized. The satellite based burnt area and the results of the FDS simulation were overlaid for accuracy.

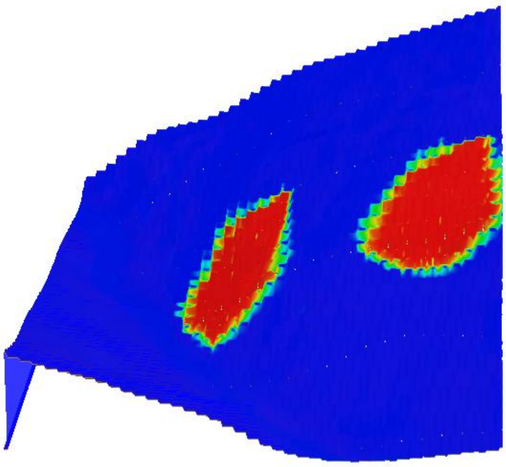

Figure7. Fire spread in the study area

5. Conclusion:

This study focuses on the use of FDS, a CFD based simulation modeling software for vegetation fires using HPC platform. The study concludes that area specific field-derived fuel parameters for forest fuels in India are required for proper simulations as they affect the ROS, plume, and heat release per unit. FDS can be used for CFD-based modeling of forest fires with proper parameterization and validation. It gives robust visualization capabilities using the accompanying Smokeview package. Plume and Heat release can be properly visualized.

There is scarcity of literature for forest fire parametrization studies in the study area. The study attempted to derive SAV and ROS from field observations for Sikkim Himalayan region. The derived values are in agreement with reported literature. More such field studies are needed for fuels in Indian region to improve the forest fire simulation science which is in nascent stage. In the present study, an attempt has been made to estimate SAV values for a few fuel types in Sikkim. Area specific fuel parameter values improve the accuracy of outputs. This is the first of its kind study in the country where FDS and HPC are being used for forest fire simulation modeling.

With currently available HPC platforms, simulations with huge computational requirements can be distributed using parallel computing platforms and the results can be presented in near real time. Such pre-fire simulations help fire managers to simulate the possible effects of management measures well in advance to make more efficient decisions. Field derived fuel specific parameters can be tested using FDS model for incorporating in various fire simulation models.

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Appendix 1: Corresponding LULC class with respect to Anderson classification of fuels

LULC Class	Anderson fuel class
Agriculture plantation, Cropland, Barren rocky, Grassland & Grazing land	1
Scrub land Dense	2
Scrub land Open	3
Forest	8
Forest plantation	10
Hamlets and dispersed households, built up (Rural), Built up (Urban), Lakes / Ponds, Mixed settlement, Peri-urban, Reservoir / Tanks, River / Stream / Drain, Sandy areas, Snow/Glaciers, Transportation, Village, Gullied / ravenous	14

Appendix 2: Various datasets and tools used along with references

S.N.	Data and tools used	Resolution	Purpose	Reference
1	Fire ignition location		To determine the fire spread initiation location	https://firms.modaps.eosdis.nasa.gov/download/
2	Elevation	12.5 m	To characterize the terrain	https://search.asf.alaska.edu/#/
3	Fuel map	10 m	To define different fuel categories	Digitization on satellite datasets and field work
4	Fuel parameters		Controlling the spread of wildfire based on the fuel variability	Field sample plots and published literature
5	Wind velocity and direction	1.41 m/s	wind speed (Gust) 10 m above ground	(https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/gangtok_india_1271631).
6	WFDS Input File Creator & Data Viewer		To create FDS input files from Geographic Information System (GIS) data sets and to integrate FDS simulation outputs in GIS	(McNamara et al., 2016) Free Software (gmsgis.com)
7	Smoke view		Output visualization	

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Appendix 3: Comparison of SAV (m−1) estimated by various researchers for different litter or leaf species, last four lines refer to data estimated by this work

Litter/leaf type	Rothermel	Scott and Burgan	Brown	Fernandes and Rego	Hachmi et al.	Bufacchi et al.	Overholt et al.	Cheney et al.	Clark et al.	This work
Fine hardwood litter	8202									
Broadleaf litter (low load)		5925								
Broadleaf litter (moderate load)		6352								
Broadleaf litter (very high load)		5686								
Aspen (Populus tremuloides Michx.) leaves			13980							
Eucalyptus (Eucalyptus obliqua L'Herit.) leaves			6180	5690	6922					
Quercus suber L.					8887					
Brazilian Amazon litter (leaves only)						12680				
Brazilian Amazon litter (twigs only)						770				
Grass (little blue stem)							9270			
Eriachne burkittii (kerosene grass)								9770		
Themeda Australis (kangaroo grass)								12240		
Tall grass									4921	
Brazilian Amazon litter (leaves and twigs)						8460				
Forest										4086
SLDense										9123
SLOpen										6997
ForestPL										7198
Grass										2650

Appendix 4: References for various fire simulation parameters

Parameter	Meaning / Explanation	Relevance to Sikkim	Reference
Surface area / Volume ratio (m -1)	It is the ratio of objects surface area to volume which significantly affects the burning.		
	Grassland	2650	+ Derived by authors from field and laboratory investigations
	Forest	4086	
	Scrub land Open	6997	
	Scrub land Dense	9123	
	Forest Plantation	7198	
C H O values	Gas and liquid species values	C=6, H=10, O=5*	McGrattan et al. (2013)
Rate of spread (RoS)	Rate of spread in m/s	0.002*	McGrattan et al. (2013)
Soot yield	Soot yield as kg/kg	0.01*	McGrattan et al. (2013)
Heat of combustion	Energy release per unit volume (kJ/m3)	18607*	McGrattan et al. (2013)
Wind velocity	Hourly wind speed (Gust) 10 m above ground	1.413361 m/s**	**RDS NCMRWF
Packing ratio	It is the bulk crib mass per unit volume divided by the density of the wood	0.0012	McGrattan et al. (2013)

Appendix 5: Grid sensitivity study of the Melli region Sikkim

Sr. No.	Mesh size (meter)	Domain size (meter)	Total mesh count (grid Size)	Simulation time (seconds)	Processing time (seconds)	No. of nodes	No. of processors
1	(1x1x1)	500 x 500 x 725	90 million	100	34880	3	100
2	(2x2x1)	500 x 500 x 725	29 million	100	3105	3	100
3	(5x5x1)	500 x 500 x 725	4.7 million	100	950	3	100

This contribution has been peer-reviewed. The double-blind peer-review was conducted on the basis of the full paper.
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