Remote sensing observations for monitoring and mathematical simulations of transboundary air pollutants migration from Siberian mass wildfires to Kazakhstan

I.V. Kaipov
National Center of Space Research and Technologies, 050011, str. Shevchenko, 15, Almaty, Republic of Kazakhstan

Abstract. Anthropogenic and natural factors have increased the power of wildfires in massive Siberian woodlands. As a consequence, the expansion of burned areas and increase in the duration of the forest fire season have led to the release of significant amounts of gases and aerosols. Therefore, it is important to understand the impact of wildland fires on air quality, atmospheric composition, climate and accurately describe the distribution of combustion products in time and space. The most effective research tool is the regional hydrodynamic model of the atmosphere, coupled with the model of pollutants transport and chemical interaction. Taking into account the meteorological parameters and processes of chemical interaction of impurities, complex use of remote sensing techniques for monitoring massive forest fires and mathematical modeling of long-range transport of pollutants in the atmosphere, allow to evaluate spatial and temporal scale of the phenomenon and calculate the quantitative characteristics of pollutants depending on the height and distance of migration.

1. Introduction
Massive forest fires are accompanied by a large release of pollutants into the atmosphere. Smoke from wildfires is an aerosol and a gas mixture of CO, CO\textsubscript{2}, NO\textsubscript{2}, SO\textsubscript{2}, water vapor and small particulate matter (soot, ash, tar droplets) and other product transformations of the combustible materials. In recent years, more attention has been attracted to the fires in the boreal zone of the northern hemisphere, which is connected with the development of satellite fire observing systems and the possibility of more reliable quantitative estimations of burned area and the associated emissions of combustion products. Boreal forest fires can consume large amounts of both aboveground and below-ground biomass (Ottmar and Sandberg, 2003; French et al., 2004).

Annually from 4.5 to 27 thousand fires occur in the forests of Siberia. The fires cover an area of 3.5 to 18 million hectares. Since the beginning of 1992 till the end of 2014 about 580 000 forest fires have taken place in Russia. Dynamics of forests burning in Siberia in recent years shows a steady growth trend as the number of fires and the areas damaged by them. According to satellite measurements, global emissions of CO are estimated at 1000-1400 million tons per year, where Asian’s input is about 509 million tons per year. (Petron G. et al., 2004)

With increasing frequency and scale of forest fires, their direct and indirect effects on ecosystems and human health aggravated. Therefore, it is important to carry out more precise study of the various aspects of this phenomenon. Complex use of earth remote sensing techniques for monitoring massive forest fires and mathematical simulation of pollutant transport in the atmosphere, based on meteorological parameters and processes of chemical interaction of impurities, gives the opportunity to evaluate spatial and temporal scale of the phenomenon and calculate the quantitative characteristics of impurities, depending on the height and horizontal distance from sources.

Currently, satellite systems have been successfully used for monitoring wildfires. Detection of fires is usually done with the help of infrared radiometers that are part of on-board space systems. One of the
most commonly used devices for fire detection are MODIS radiometers on board of TERRA and AQUA satellites and VIIRS instrument of SUOMI NPP satellite.

With regard to the numerical methods, the study of atmospheric chemical processes using numerical simulations have become more widely used because of the increased availability of atmospheric chemical models, high-performance computing resources, as well as more reliable wildfire emission data.

2. Model description
In this study regional hydrodynamic model (WRF-Chem) is used to simulate the pollutant transport in the atmosphere with chemical interactions and transformations. This is a model for research and weather forecasting (WRF) coupled with the chemical module Chemistry (Chem). WRF-Chem (Skamarocket et al. 2005; Grell et al. 2005) and allows to simulate emissions, transport and chemical transformation of gases and aerosols. Chemistry model is built into the numerical framework of weather forecasting. The interaction of chemical and meteorological models is carried out at each time interval. In addition, changing in gas and aerosol concentrations have feedback effects on meteorological parameters, in particularly, on radiation transfer and cloud formation. Fully integrated into the WRF, Chemistry module allows estimating pollutant transport on the same vertical and horizontal coordinates as meteorological parameters without any spatial and temporal interpolation.

WRF model is a numerical weather prediction (NWP) and an atmospheric simulation system. The WRF Software Framework (WSF) provides the infrastructure that accommodates the dynamics solvers, physics packages that interface with the solvers, programs for initialization, WRF-Var, and WRF-Chem. ARW Solver includes fully compressible equations with Euler non-hydrostatic and run-time hydrostatic options. Microphysics schemes ranging from simplified physics to mixed-phase physics are suitable for numerical weather prediction. ARW solver uses a time-split integration scheme. Low-frequency (meteorologically significant) modes are integrated with the use of a third-order Runge-Kutta (RK3) time integration scheme, while the high-frequency acoustic modes are integrated over smaller time steps to maintain numerical stability. Model that couples with API enables WRF to be coupled with other models such as ocean and land models using ESMF and MCT.

WRF-Chem has a modular structure providing the users an opportunity to select various gaseous and aerosol chemical schemes. The set consists of the following mechanisms: RADM2 which includes 59 chemical compounds and 157 reactions; RACM - 73 compounds and 237 reactions; CBM-Z - 73 compounds and 237 reactions; SAPRC99 - 79 compounds and 235 reactions; MOZART - 85 compounds and 196 reactions. In addition, the model allows adding new chemical mechanisms or modifying an existing one, using the Kinetic Pre-Processor Interface (KPP). The following aerosol modules are available in WRF-Chem: GOCART; MADE-SORGAM; MAM; MOSAIC. It should be noted that most of the researchers use for their works the RADM2 gas phase chemical mechanisms that originally were developed for the Regional Acid Deposition Model, version 2 (RADM2, Chang et al., 1991) for gaseous compounds in combination with an aerosol module MADE-SRGAM. The smoke plume rise associated with biomass burning is parameterized using a simple one-dimensional time-dependent entrainment plume model (Freitas et al., 2006). The scheme was developed for usage in low resolution global atmospheric chemistry models, but also can be used at higher resolutions.

The system is ideal for exploring the mutual influence of chemical and meteorological processes. Many implementations, combined with different schemes of aerosol and water chemistry, enable to use them in a number of applications, ranging from air quality modeling at the regional level to the estimation of the impact of natural and anthropogenic emissions on the climate.

In the past ten years a significant progress has been made in characterizing the initial emissions of trace gases and particles from open biomass burning and their post-emission evolution. One of the main differences between running with and without chemistry is the inclusion of additional data sets describing the sources of chemical species. In this paper Fire Inventory from National Centre of Atmospheric Research (FINN NCAR) model is used to estimate emissions from wildfires sources. The model provides high-resolution estimation of emissions from the open burning biomass sources and has been specially designed to prepare an input data for hydrodynamic transport models that take into account the chemistry of the atmosphere. The model makes it possible to estimate the daily volume of emission with a horizontal resolution of approximately 1 km. The product differs from other inventories because it provides a unique combination of high temporal and spatial resolution, global coverage, and estimations for a large number of chemical species. FINN emission estimations are based on the framework described by Wiedinmyer et al. 2006; 2011. FINN uses satellite observations of active fires and land cover, together with emission factors and estimated fuel loadings to provide daily, highly-resolved open burning
emissions estimations for usage in regional and global chemical transport models. In recent years, FINN emissions have been used in many various modeling studies that simulate the chemical and climate impacts from fires. By using FINN emissions within the WRF-Chem model Jiang et al. (2012) explored the impacts of fire plumes on ozone chemistry during a wildfire event in Idaho and Montana during August 2007. WRF-chem simulated the immediate addition fire emissions combined with the changes in photolysis rates, boundary layer height, and biogenic emissions. The results highlighted the importance of including the radiative impacts of fire plumes. Martin et al. (2013) used FINN emissions in conjunction with satellite observations to explore the importance of fire smoke impact on air quality and regional climate in Colorado.

3. Case study and input data
The WRF-Chem model was used to simulate trans boundary transfer of smoke plums episodes, from 28 June to 9 July 2012, when massive forest fires on the territory of Siberia were observed.

![Image](https://worldview.earthdata.nasa.gov/)

**Figure 1.** Images from the Moderate Resolution Imaging Spectroradiometer (MODIS) of NASA’s Terra and Aqua satellites, 3 July– 6 July, 2012 (screenshots from website https://worldview.earthdata.nasa.gov/)

TERRA and AQUA satellites detected massive forest fires in western Siberia (Fig.1). The red dots show the fire areas, obtained by MODIS radiometer in the infrared band. Smoke plumes from fires cover large areas and have several hundred kilometers of linear scale.

The domain of investigation was defined taking into account the spatial scale of phenomenon as well as the need to avoid the orographic heterogeneity in border regions. The model domain is shown in Figure 2.

![Image](https://worldview.earthdata.nasa.gov/)

**Figure 2.** Model domain used in case study simulations

The domain consists of a 27-km grid resolution, with 360 × 200 grid points. Vertical sigma levels were more frequently set near the surface. The initial and boundary conditions of meteorological parameters for the selected WRF-Chem modeling domain were interpolated from ERA-INTERIM reanalysis dataset produced by the European Centre for Medium Range Weather Forecasts (ECMWF).
ERA-INTERIM configuration has a spectral T255 horizontal resolution, which corresponds to approximately 79 km spacing on a reduced Gaussian grid. The vertical resolution is 60 model layers with the top of the atmosphere located at 0.1 hPa. (D.P. Dee et al, 2001).

Sources of emissions from wildfires were estimated using special fire_emiss utility which converted the FINNv1.5 model outputs with MOZART4 chemical mechanism to use a within WRF-Chem simulations.

Synoptic processes (1-4 July, 2012) caused a strong northern, north-eastern winds with speed about 30 - 50 km / h (8-14 m / s) at 700 hPa and 36 - 64 km / h (10-18 m / s) at 500 hPa levels and rapid and extensive transfer of air masses from the areas of the West Siberian Plain to the territory of the northern, central and southern Kazakhstan (Figure 3).

4. Result
WRF-Chem can simulate dozens of organic and inorganic species, this study focused on carbon monoxide (CO) as a gas phase tracer of the biomass burning plumes. Twelve days WRF-Chem simulations (28 June–9 July, 2012) were run in the case study. The results of CO transport and dispersion simulations over the territory of Kazakhstan in the near surface layer of the atmosphere are shown on Figure 4.

The model depicts an increase of 0.3-1.8 ppmv in CO mixing ratios. Figures 4 (a,b,c) shows smoke plume transport to the south, southeast directions. Sources of the smoke from Siberia were also seen both in the satellite image and the model output. The model adequately reflects the meteorological processes (wind speed and direction).

![Figure 3. Synoptic process over the West Siberian Plain and Kazakhstan (1, 4 July 2012)](image)

![Figure 4. 2D plots of WRF-Chem’s carbon monoxide emission and transport simulation over Kazakhstan](image)
The WRF-Chem model CO mixing ratio outputs were compared with the satellite monitoring data, at 700 hPa, simulation data in the same range as the AIRS product, similar the scope and contours of the smoke plume.

![WRF-Chem output](image1.png) ![AIRS product](image2.png)  
**Figure 5.** The WRF-Chem model CO mixing ratio (a), hyper spectrometer AIRS product (b)

Smoke plumes also detected by MOPITT tool (satellite TERRA), which measures the mixing ratio of CO at various altitudes. At the Earth's surface and at 700 hPa (about 3 km) marked the increasing of CO mixing ratio, note that the order of magnitude coincides with the data of numerical experiments.

![MOPITT tool product](image3.png)  
**Figure 6.** MOPITT tool product - CO mixing ratio at surface (ppbv)

One of the goal of this study is to evaluate the height of migration and the vertical distribution of carbon monoxide. Figure 7 (a) shows the CO mixing ratio at near surface (ppmv), July 6, 2012 21:00:00. Black line indicates the trajectory of CALIPSO satellite. As on board lidar sensing data (figure 7 (b) and WRF-Chem simulation results (figure 7(c) show that the height of smoke migration is about 5 kilometers. In Figure 7(d) vertical section of smoke (black color) and continental emission (red color) along with the CALIPSO satellite trajectory are presented.
Figure 7. Horizontal (a) and vertical (b, c, d) section of smoke plume

The numerical results were compared with ground-based observations data of monitoring station "Borovoye". Location of station is shown on map with red dot (Figure 8(a)). The model describes well the diurnal variation of ozone concentration (b). It can be seen that the numerical calculations give excessive concentrations of CO (c) and NO2 (d), however, collects diurnal variation. Red lines - the results of WRF-Chem simulation, blue columns – observed data.

Figure 8. Location of ground monitoring station “Borovoye”(a), (b, c, d) - diurnal variation of O3, CO and NO2 concentration (µg/m³), time interval - 3 hours
5. Conclusion

In this case study NCAR FINN biomass burning emissions model outputs were used and can be based on near real-time remote sensing fire products or historic fire data to determine fire emissions and plume rise characteristics (Freitas et al., 2005, 2007; Longo et al., 2010). Qualitatively, similar results were seen in WRF-Chem outputs and remote sensing data. According to remote sensing and simulation data the height of smoke plume migration is about 5 km. The combination of remote sensing and mathematical simulation methods is a powerful tool to describe transfer and chemical transformation processes of atmospheric impurities and to predict the behavior of natural and anthropogenic disasters related to the emissions of pollutants.

Reference

[1] Chang Y Y, Cronan J E, Li S J, Reed K, Vanden Boom T and Wang A Y 1991 Locations of the lip, poxB and ilvBN genes on the physical map of Escherichia coli. J.Bacteriol. 173 5258-4259
[2] Freitas A et al Haem oxygenase/carbon monoxide-biliverdin pathway down regulates neutrophil rolling, adhesion and migration in acute inflammation. Br. J. Pharmacol. 2006 149 345-354
[3] French N H F, Goovaerts P, Kasischke E S 2004 Uncertainty in estimating carbon emissions from boreal forest fires. J. Geophys. Res. 09 D14S08, doi: 10.1029/2003JD003635
[4] Grell GA, Peckham SE, Schmitz R, McKeen SA, Frost G, Skamarock WC and Eder B. Fully coupled “online” chemistry within the WRF model. Atmos. Environ. 2005 39 6957–75
[5] Jiang X C Wiedinmyer, Carlton A G Aerosols from fires: an examination of the effects on ozone photochemistry in the Western United States. Environmental Science & Technology 46(21), 442-460 doi:10.1021/es301541k
[6] Ottmar R.D, Sandberg D V, Prichard S J, and Riccardi C L 2003 Fuel Characteristic Classification System Presentation at the 2nd International Wildland Fire Ecology and Fire Management Congress 16-20 November 2003, Orlando, FL.
[7] Petron G et al. // Geophysical Research Letters 2004 V.31. L21107. doi: 10.1029/2004GL020560.

[8] Skamarock W C, Klemp J B, Dudhia J, Gill D O, Barker D M, Wang W and Powers J G 2005 A Description of the Advanced Research WRF Version 2. NCAR Technical note NCAR/TN-468+STR.

[9] Val Martin M, Heald C L, Ford B, Prenni A J, and Wiedinmyer C A decadal satellite analysis of the origins and impacts of smoke in Colorado, Atmos. Chem. Phys. 13 7429-7439, doi:10.5194/acp-13-7429-2013, 2013.

[10] Wiedinmyer C, Akagi S K, Yokelson R J, Emmons L K, Al-Saadi J A, Orlando J J and Soja A J "The Fire Inventory from Ncar (Finn): A High Resolution Global Model to Estimate the Emissions from Open Burning." Geoscientific Model Development 4, no. 3 (2011): 625-41. (http://www.geosci-model-dev.net/4/625/2011/gmd-4-625-2011.html)

[11] Wiedinmyer, Christine, Brad Q, Chris G, Angle B, Don M, Zhang X Y, Susan O'Neill and Kristina K W "Estimating Emissions from Fires in North America for Air Quality Modeling." Atmospheric Environment 40, no. 19 (2006): 3419-32.