WRAP Regional Modeling Center Memorandum

Final Draft

Subject: Comparison of Plume Rise Estimates using the FEJF & the SMOKE-Briggs Approaches

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Introduction

Estimating the vertical distribution of smoke plumes from fire emissions is a challenging problem in emissions modeling and critical for evaluating the impacts of these sources on ambient air quality. Fire emissions estimates have traditionally been modeled as an areal average, either as a county average or a model grid cell average, in only the surface model layer. Observations of actual fire emissions show that fire plumes actually are lofted vertically several hundreds if not thousands of meters depending on the fire size, fuel conditions, and meteorology. In this task we compare two different algorithms for distributing fire emissions into the vertical layers of the air quality model. This section begins with descriptions of the fire events that we modeled to test these algorithms and the two approaches that we used to estimate the characteristics of the plumes from different fire events. We describe the concept of plume rise in the context of emissions modeling and described the technical details of the two algorithms that we tested. Finally we provide a discussion of the results from our analysis and discuss our plans for future work.

Description of FEPS and Scenarios Used

The Fire Emission Production Simulator (FEPS) (Anderson et al., 2004) is an MS Windows base graphical user interface (GUI) for specifying certain parameters that characterize the fire, and FEPS then produces output data for emissions, heat flux and plume rise height. The input parameters include data such as date, location, size, fuel type, burn type and other parameters. The FEPS program is fairly complex. It includes default values for most parameters, but it can also include menus to include from a large number of specific fuels types and burn types. The user can select event specific characteristics from those menus and/or override the default values with user specified data.

Our goal was to use FEPS to determine heat flux data, and we used default data for most parameters except for the fire date, location and size. We were also required to select certain values from default choices within menus, such as fire time and spread patterns. We were uncertain about the selection of these parameters as well as the fuels choices and this is a source of uncertainty in our analysis. It is possible that if an expert FEPS user entered the data into the FEPS GUI, they might obtain results that differ from our results. We also note that FEPS is not suitable for use in modeling a large number of fire events because entering data via the FEPS GUI is very labor intensive.

Plume Rise and Emissions Processing

The WRAP-RMC used emissions inventory data from the 2002 actual WRAP fire inventories to compare the effects of two different plume rise algorithms on the vertical distribution of fire plumes. Differences in the vertical distribution of emissions impact the dispersion of the emissions and the subsequent impacts on ground level air quality. We selected five fire events to evaluate the effects of the different plume rise algorithms on the vertical distribution of fire emissions estimated by SMOKE. The five events ranged in size from a few hundred to a few thousand acres and included wildfires, prescribed fires and wildland fire use events in Colorado, Oregon, and Arizona. For details on the fire events see Table 1. We held the daily emissions constant with the Base02a simulation and represent the Phase II emissions as they were provided to the WRAP-RMC by Air Sciences Inc (ARS). We used estimated hourly heat flux rates derived from FEPS in btu/h to calculate daily heat flux values for input to one of the plume rise algorithms. Additional details about fire modeling at the WRAP-RMC are available in Tonnesen et al. (2006).

Table 1. Fire events summary

Fire Type	State	Date	Fire Size (Acres)	Daily Emissions (tons/day)				Heat Flux (btu/day)
				CO	PM2.5	NOx	VOC	
WFU[1]	CO	July 14	850	3382.6	282.08	72.57	159.18	82,530,000,000
RX[2]	AZ	Nov. 7	2577	3988.1	332.58	85.56	187.68	268,320,000,000
WF[3]	AZ	June 30	9860	19804.3	1651.5	424.9	931.97	1,036,600,000,000
RX	OR	Sep. 24	1000	173.4	14.46	3.72	8.16	300,030,000
WF	OR	Aug. 3	7885	25,293.8	2,109.3	542.6	1,190.3	2,237,008,255,600

[1]WFU= wildland fire use [2]RX=prescribed fire [3]WF=wildfire

Plume rise is an emissions modeling concept for simulating the vertical distribution of emissions from large elevated point sources. The plume rise algorithm in SMOKE is based off the equations developed by Briggs (1984), and considers atmospheric stability, wind speeds, plume buoyancies, and the stack height relative to the vertical layer boundaries to distribute emissions plumes vertically across multiple model layers. Until recently, the default implementation of the Briggs algorithm in SMOKE was not applicable to fires because they lacked conventional stack parameter information, such as stack heights and diameters, and plume temperatures and velocities. The two plume rise approaches that we compared in this sensitivity circumvent this problem by either calculating the plume rise outside of SMOKE or by deriving the variables needed by the Briggs equation from fire-specific parameters.

WRAP-FEJF approach

The WRAP FEJF developed a work-around for the fire plume rise constraint in SMOKE using a methodology to pre-compute fire plume parameters (Air Sciences Inc., 2004). This method, herein referred to as the FEJF approach, categorizes five plume classes defined by increasing potential plume heights based on a range of possible fire size classes, with respect to virtual acre size. Virtual fire sizes are calculated using Equation 1 and are used to relate fuel loadings to a representative stack diameter for fire plumes. The normalizer in Equation 1 is derived from the National Fire Danger Rating System (Andrews and Bradshaw, 1997) for different types of fires.

$$\text{Virtual Acre Size} = \text{Actual Acre Size} * \sqrt{}\text{Fuel loading} / \text{Normalizer} \qquad \text{(Equation 1)}$$

For the different plume classes based on the virtual fire acreage, hourly plume top, plume bottom, and the fraction of the plume in layer 1 are derived using Equations 2, 3, and 4, respectively, where BE_{hour} is hourly buoyancy efficiency (unitless), BE_{size} is a fire size-dependent buoyancy efficiency (unitless), $Ptop_{max}$ is the maximum height of the plume top (meters), and $Pbot_{max}$ is the maximum height of the plume bottom (meters).

$$\text{Plume Top}_{hour} = (BE_{hour})^2 * (BE_{size})^2 * Ptop_{max} \qquad \text{(Equation 2)}$$

$$\text{Plume Bottom}_{hour} = (BE_{hour})^2 * (BE_{size})^2 * Pbot_{max} \qquad \text{(Equation 3)}$$

$$\text{Layer1 Fraction}_{hour} = 1 - (BE_{hour} * BE_{size}) \qquad \text{(Equation 4)}$$

The coefficients BE_{size}, $Ptop_{max}$ $Pbot_{max}$, and BE_{hour} in these formulae are provided in the FEJF Phase II fire report (Air Sciences, Inc., 2005). To calculate the hourly layer fractions for the emissions outside of layer 1, SMOKE uses the hourly plume top and plume bottom values and the full model layer heights to derive a layer distribution based on a weighted sigma pressure coordinate. For the layers that contain the plume top and plume bottom, SMOKE calculates a weighted layer fraction based on the fraction of the layer that contains the plume. For example, if the plume top falls at the exact midpoint of a layer, the weighted sigma pressure fraction is multiplied by 50% to find the fraction of emissions allocated to that model layer.

We modified SMOKE to use these pre-computed hourly plume parameters and applied this approach to simulate the five fire events for this study.

SMOKE-Briggs Approach

The U.S. EPA, United States Forest Service, and the University of North Carolina Center for Environmental Modeling for Policy Development (CEMPD) collaborated in a modification to the plume rise calculation in SMOKE to accommodate fire sources that do not have typical stack parameters. This modification derives a plume buoyancy flux from the daily fire heat flux to prepare the fire information for input to the Briggs plume rise algorithm (Pouliot et al, 2005). To use the Briggs algorithm, we use Equation 5 to relate the daily heat flux, Q (btu/day), to the plume buoyancy efficiency, F (m^4/s^3), as follows:

$$F = Q * 0.00000258 \qquad \text{(Equation 5)}$$

Buoyant Efficiency (BE_{size}) and fire size are related using Equation 6:

$$BE_{size} = 0.0703 * \ln(\text{acres}) + 0.03 \qquad \text{(Equation 6)}$$

The smoldering fraction (S_{fract}) is then derived using Equation 7:

$$S_{fract} = 1 - BE_{size} \qquad \text{(Equation 7)}$$

The SMOKE-Briggs approach, herein referred to as the SB approach, uses the actual size of the fire as opposed to a virtual size on a daily, rather than hourly basis. The smoldering fraction is used to allocate emissions to the layers below the plume bottom. All of the emissions from the SB approach are allocated to the model layers using a weighting based on the sigma-pressure vertical coordinate. A key difference between the FEJF and SB approaches is that the SB approach uses the same predicted local hourly meteorological fields (wind, temperature and pressure) to calculate plume rise and layer fractions as is used to drive air quality model simulations.

Emission Modeling

We applied the FEJF and the SB plume rise approaches to the five fire events to compare how they affect the vertical distribution of the fire emissions. It should be noted that the coefficients and formulae used for the FEJF approach were derived using Western U.S. fuel loadings (vegetation dependant) and climatological data. While we did apply event specific fuel and heat flux information to both fire cases, the FEJF equations were validated using Western U.S. fire events and may not be completely suitable for fires in other regions of the world.

Invoking the FEJF approach in SMOKE requires using Equations 1 through 4 to pre-compute hourly plume parameters for each fire. Combined with daily estimates of the pollutant emissions from each fire, the plume data are used by SMOKE to calculate hourly layer fractions for allocating the fire emissions to the model layers. The SB approach requires providing daily acreage and heat flux data along with the daily pollutant inventories to SMOKE. SMOKE uses these data to derive the hourly layer fractions for distributing emissions to the vertical model layers. To quality assure these simulations, we configured the SMOKE program Smkreport to output hourly emissions reports by layer to compare the vertical distribution of the fire plumes.

Results

Figure 1 through Figure 10 compare the vertical layer structures of the two approaches used in this study. In both approaches we configured the model to distribute the emissions into 19 vertical layers at a 36-km horizontal grid resolution.

For each fire event there are two sets of plots; each set contains a pair of plots, one for the FEJF approach and one for the SP approach. The first plot in each set (Figures 1, 3, 5, 7, and 9) is a three dimensional bar chart that plots the hourly emissions in each layer as a function of time of day and vertical layer number. The second plot in each set (Figures 2, 4, 6, 8, and 10) is a combination of a stacked bar and line charts showing the hourly emissions magnitudes as a function of time of day. Each stack segment represents the distribution of emissions across the model layers at each hour. The line overlaid on these plots is plotted on the right axis and illustrates the height of the maximum layer for the emission plume at each hour.

There are three features of the plume characteristics that we will use to compare the two plume rise approaches: (1) maximum height of the plume; (2) the fraction of emissions allocated to the first model layer; and (3) the distribution of the plumes across all of the model layers. The calculated maximum plume height varies considerably between the two approaches. The FEJF approach calculates maximum plume heights 2-3 times greater than the SB approach, with the FEJF emissions allocated 5-8 layers higher than the SB approach.

The FEJF approach allocates a much larger percentage of emissions to layer 1 as compared to the SB approach. For the five fires in this study the FEJF approach allocated 35-51% of the total daily emissions to the first layer. By comparison, the SB approach allocated 0.2-12% of the total daily emissions to the first layer. Where the first layer receives the single largest fraction of emissions as compared to the rest of the model layers with the FEJF approach, for the SB approach, the top model layer receives the largest single fraction of emissions.

Plume distribution across the model layers is also vastly different between the two plume rise approaches. A notable trend in the FEJF approach is the layer discontinuity of the plume distribution between the first and elevated model layers. The figures show that on many of the hours in the simulations, layer fractions calculated using the FEJF approach jump from the first model layer across several layers to the upper model layers. For example, Figure 2 shows that on hour 14 the FEJF approach allocates about 30% of the emissions from the Colorado wildland fire use event to layer 1 and then the rest of the emissions to layers 14 through 18. This example illustrates that the emissions pass completely over layers 2 through 13 using the FEJF approach to calculate layer fractions. The SB approach does not create this layer discontinuity as all of the layers between the ground and the plume top receive emissions, with the allocation weighted by the sigma pressure coordinate.

The temporal and chemical distributions of the emissions do not differ between the two plume rise approaches. The diurnal temporal consistency is illustrated in the similarity of the time series and magnitudes of the emissions across the two approaches. The significant differences in the emissions modeling results are in the layer distribution and the maximum layer heights at each hour, reflected in the differences in the stack segments and the line overlays between the two approaches, respectively.

Conclusions

The two plume rise approaches that we studied produce vertical plume profiles that are vastly different. The FEJF approach calculates higher plumes with the majority of the emissions in the first model layer. The SB approach calculates plumes with the majority of the emissions near the top of the plume and with a continuous distribution of emissions from the ground to the plume top. Differences in the emissions allocation to the first model layer arise based in the assumption of the vertical extent of smoldering emissions. The FEJF approach assumes that all smoldering emissions remain in layer 1 and contains an explicit calculation for the fraction of emissions allocated to the first layer. With the SB approach, the smoldering emissions are assumed to be distributed across all of the layers beneath the plume bottom. These different assumptions about the smoldering emissions result in the continuity differences across model layers observed in the layer fractions calculated by the two approaches.

With the FEJF approach using a look-up table of maximum plume top and plume bottom heights as a function of fire size, the maximum height and vertical extent of the plumes are controlled by climatological parameters that may not be applicable outside of the Western U.S. The more generally applicable SB approach uses modeled local meteorology to calculate the maximum height and vertical extent of the plumes.

The WRAP-RMC is currently engaged in preparing other fire events to compare the effects of the two plume rise approaches. We are drafting a manuscript to publish the results of this work in a peer-reviewed journal.

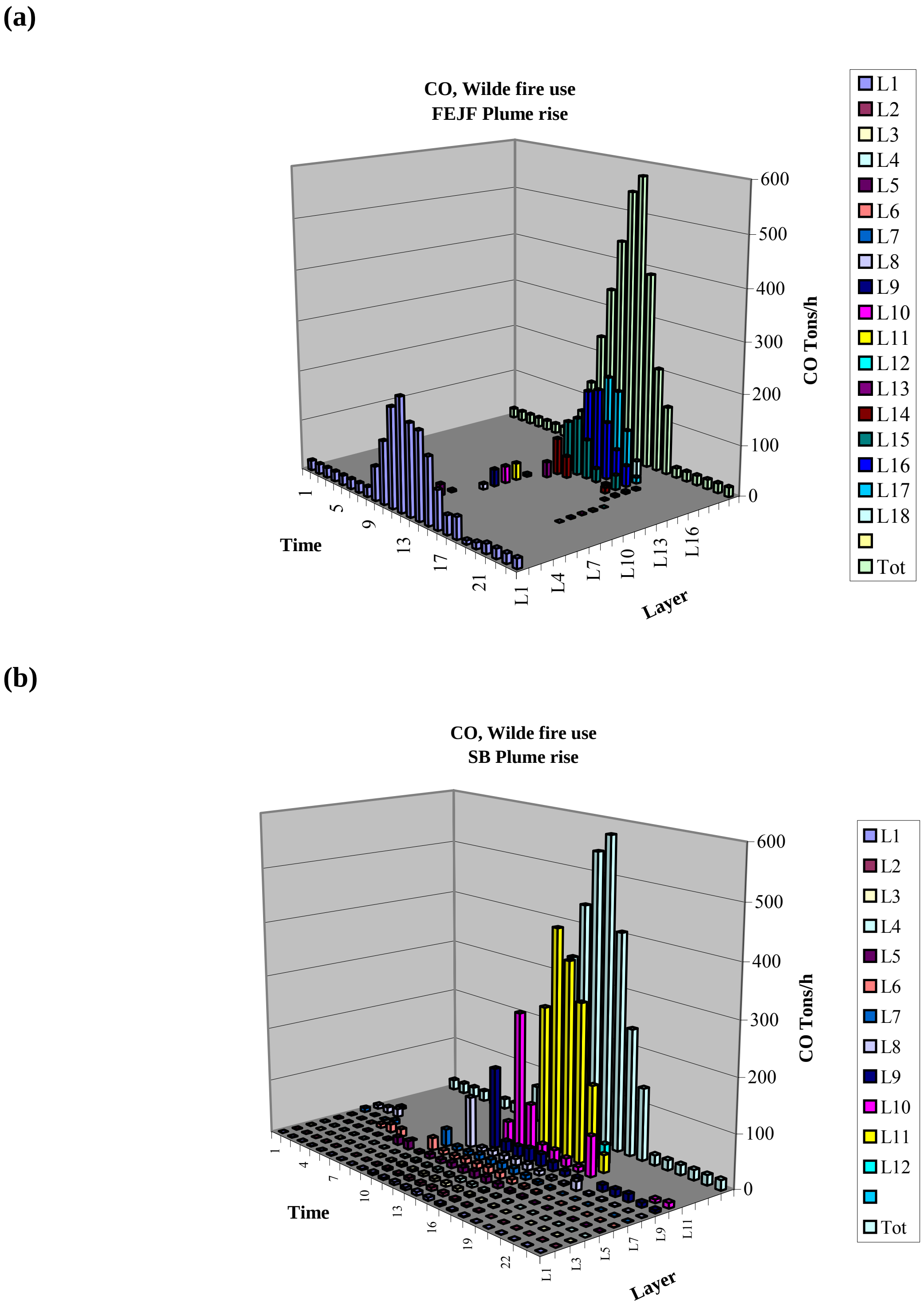
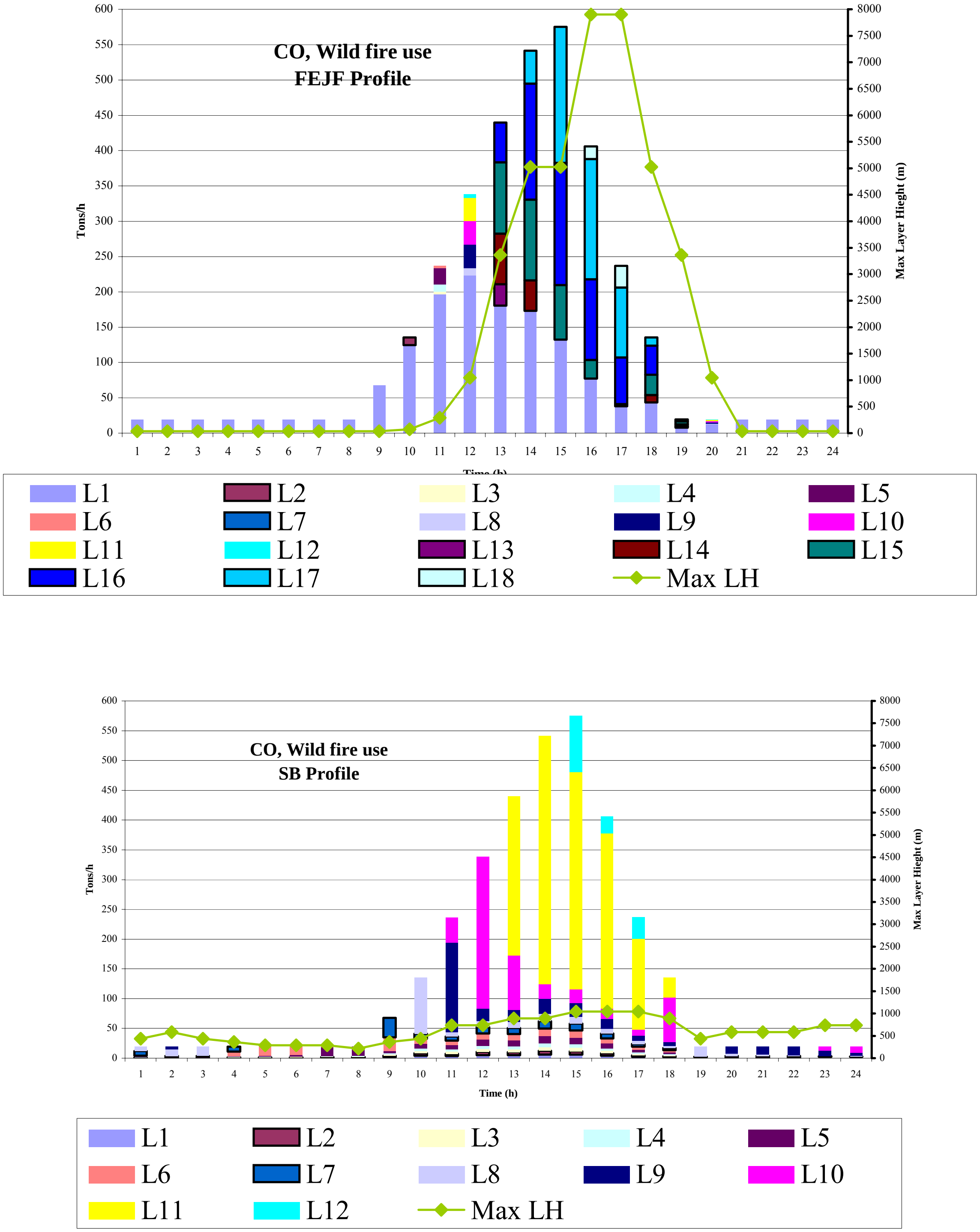


Figure 1. Colorado wildland fire use emissions vertical distribution: (a) FEJF and (b) SB



(a)

(b)

Figure 2. Colorado wildland fire use emissions vertical distribution and maximum layer heights: (a) FEJF and (b) SB

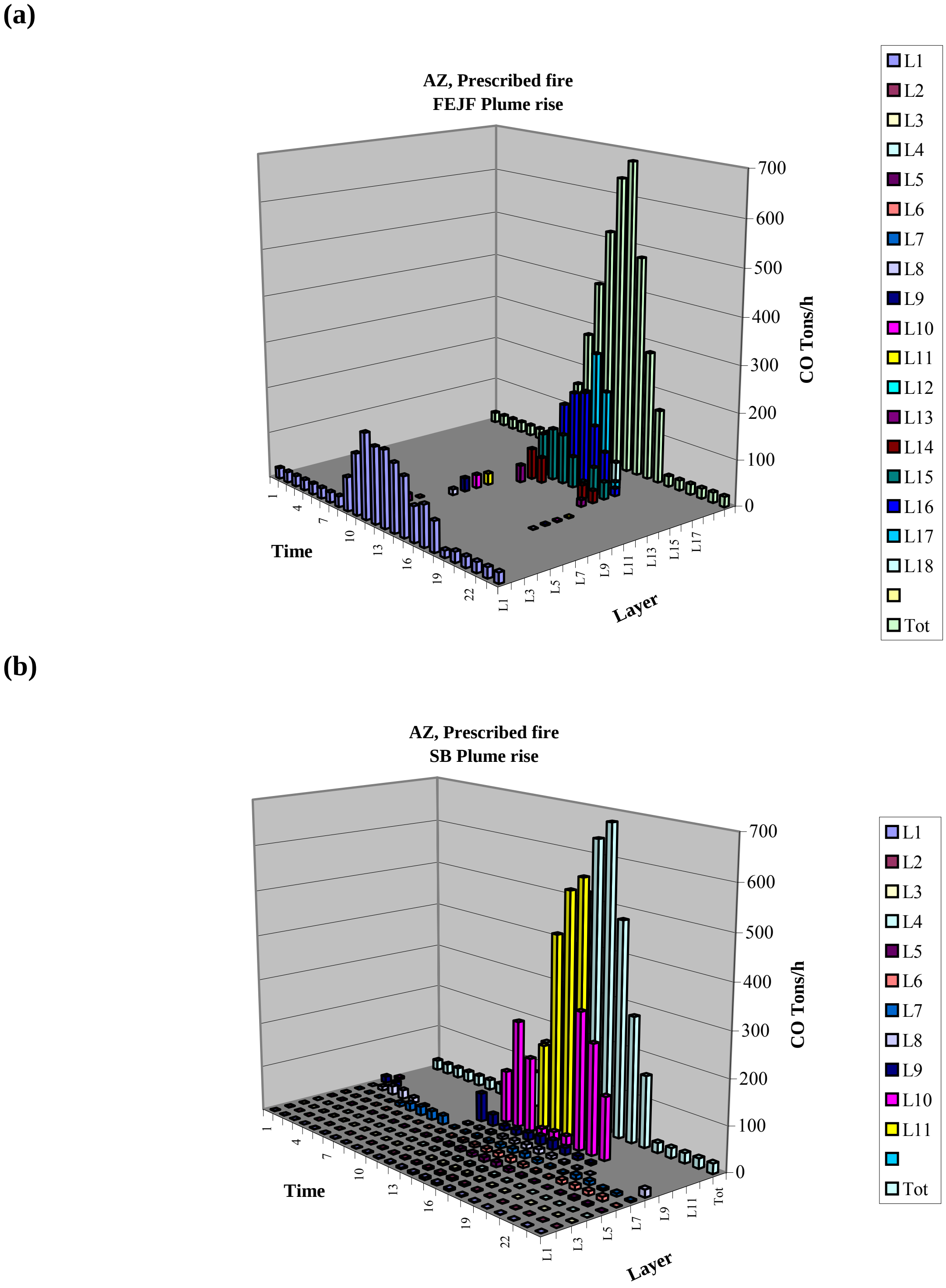


Figure 3. Arizona prescribed fire vertical distribution: (a) FEJF and (b) SB

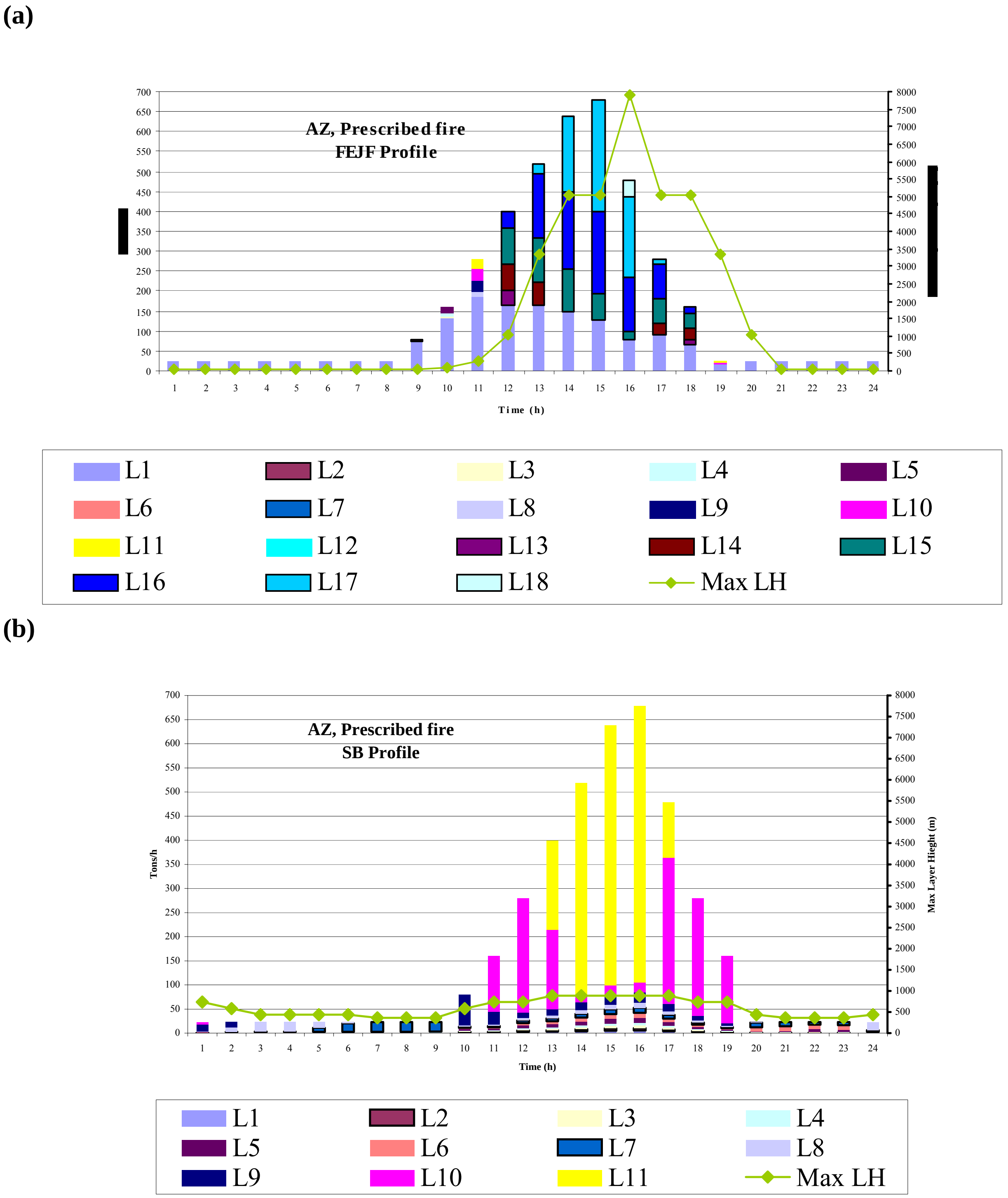


Figure 4. Arizona prescribed fire emissions vertical distribution and maximum layer heights: (a) FEJF and (b) SB

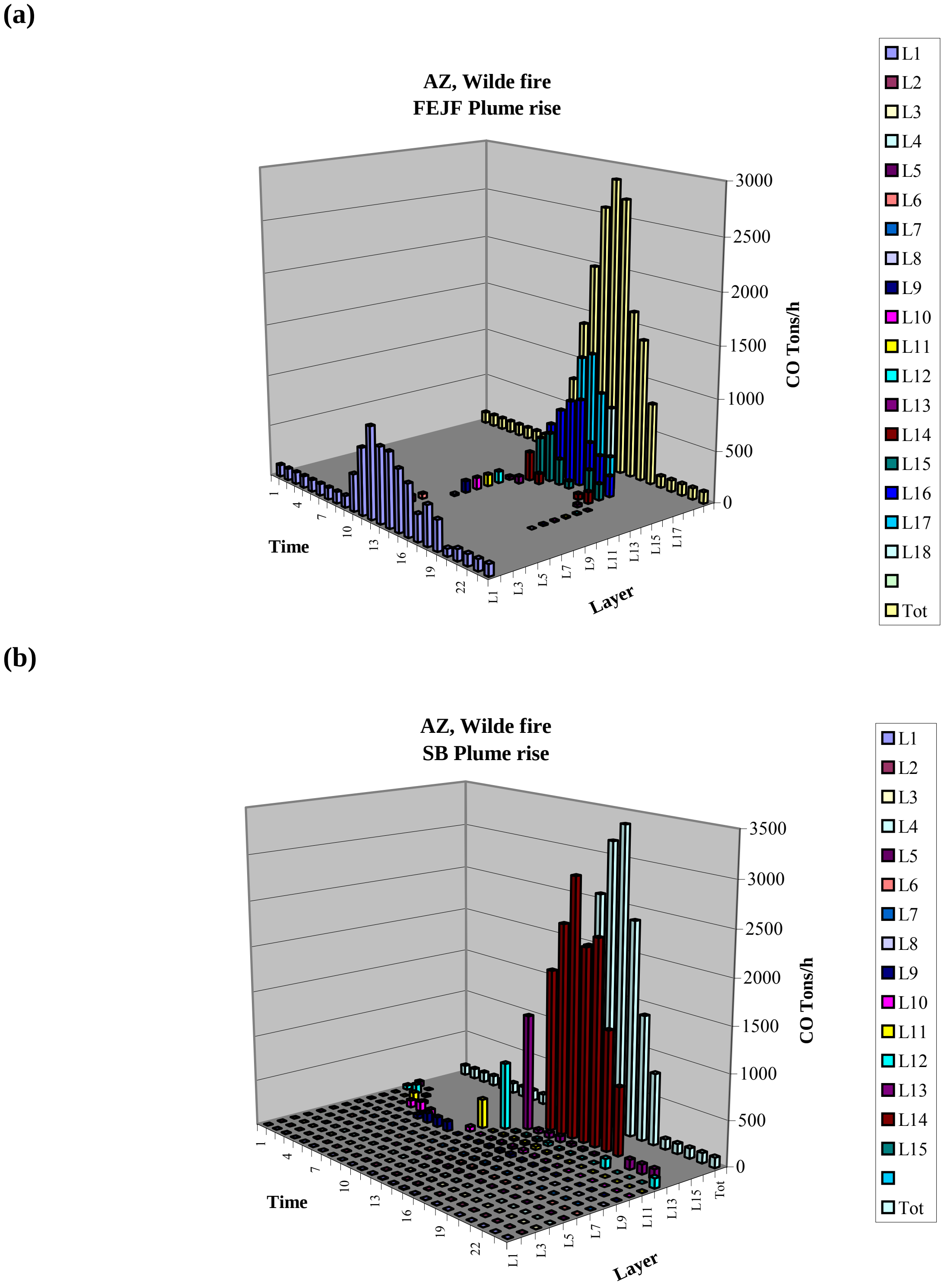


Figure 5. Arizona wildfire vertical distribution: (a) FEJF and (b) SB

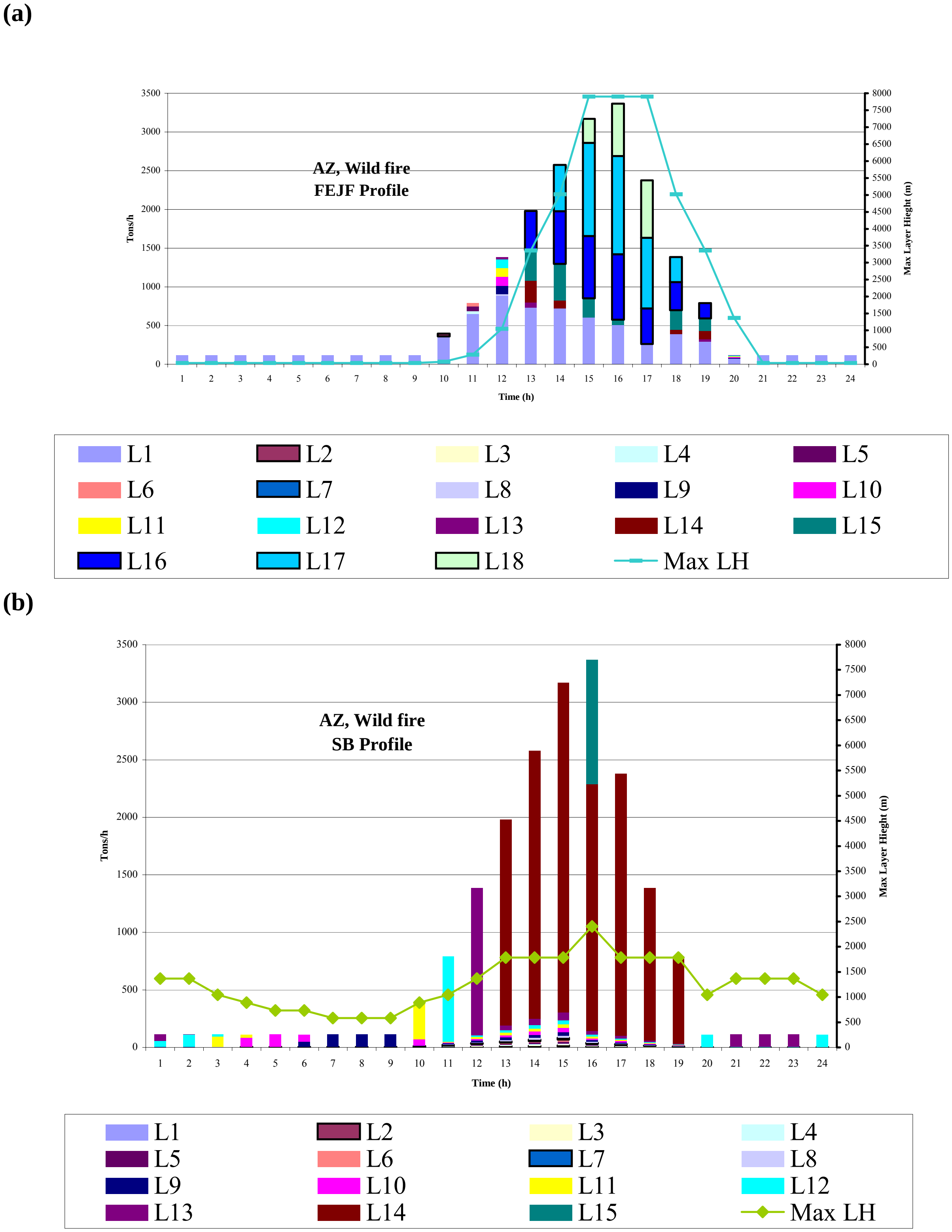


Figure 6. Arizona wildfire emissions vertical distribution and maximum layer heights: (a) FEJF and (b) SB

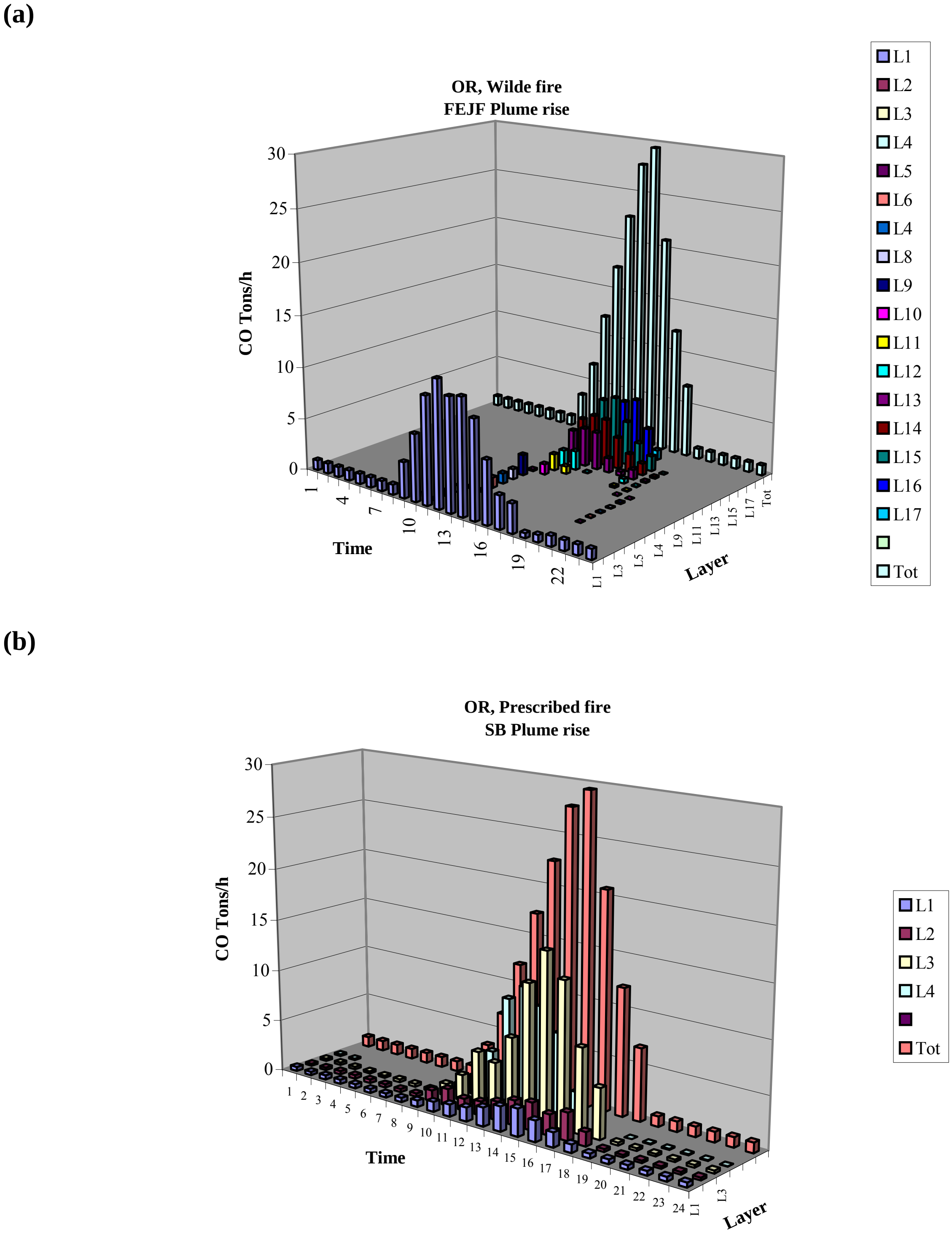


Figure 7. Oregon prescribed fire vertical distribution: (a) FEJF and (b) SB

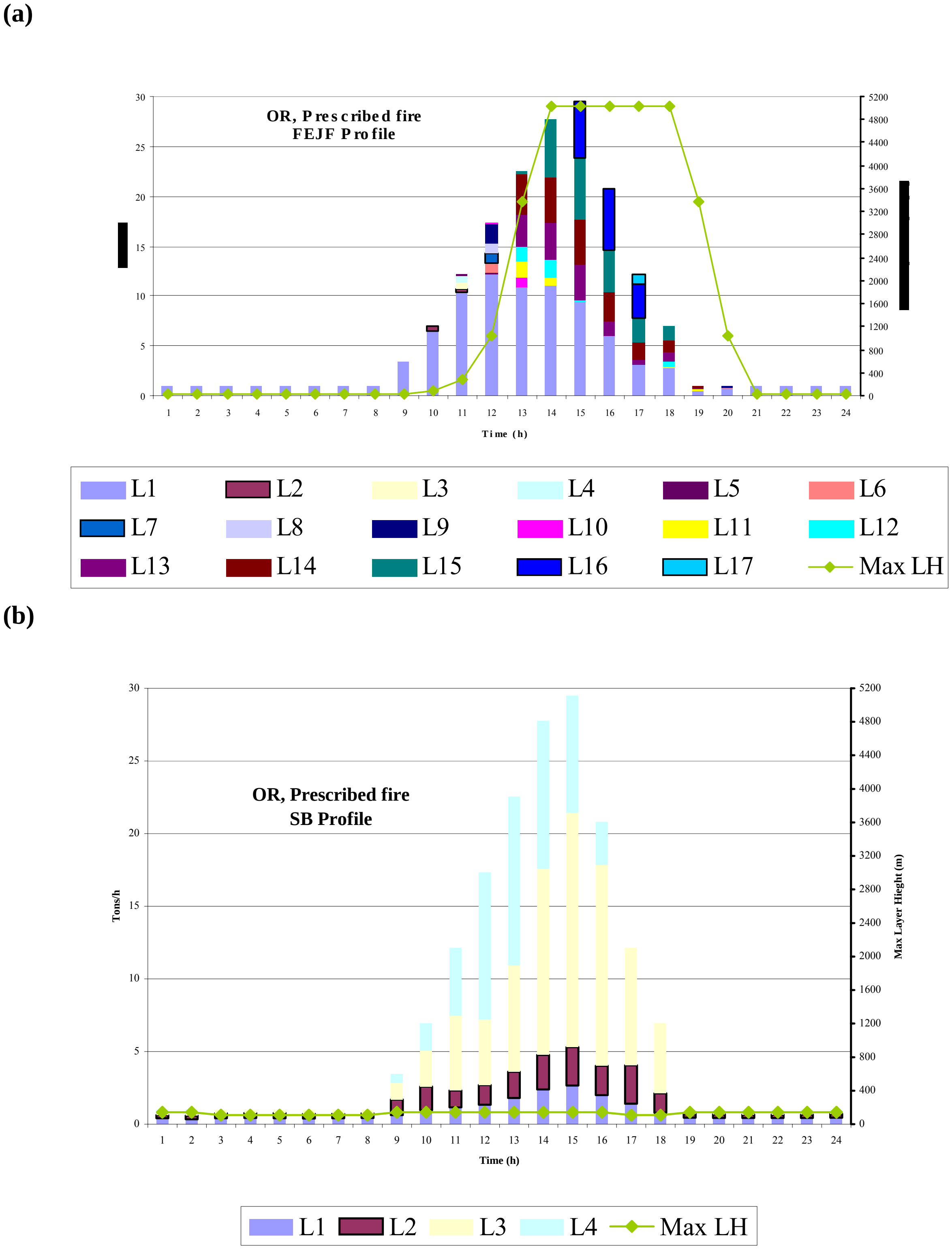


Figure 8. Oregon prescribed fire emissions vertical distribution and maximum layer heights: (a) FEJF and (b) SB

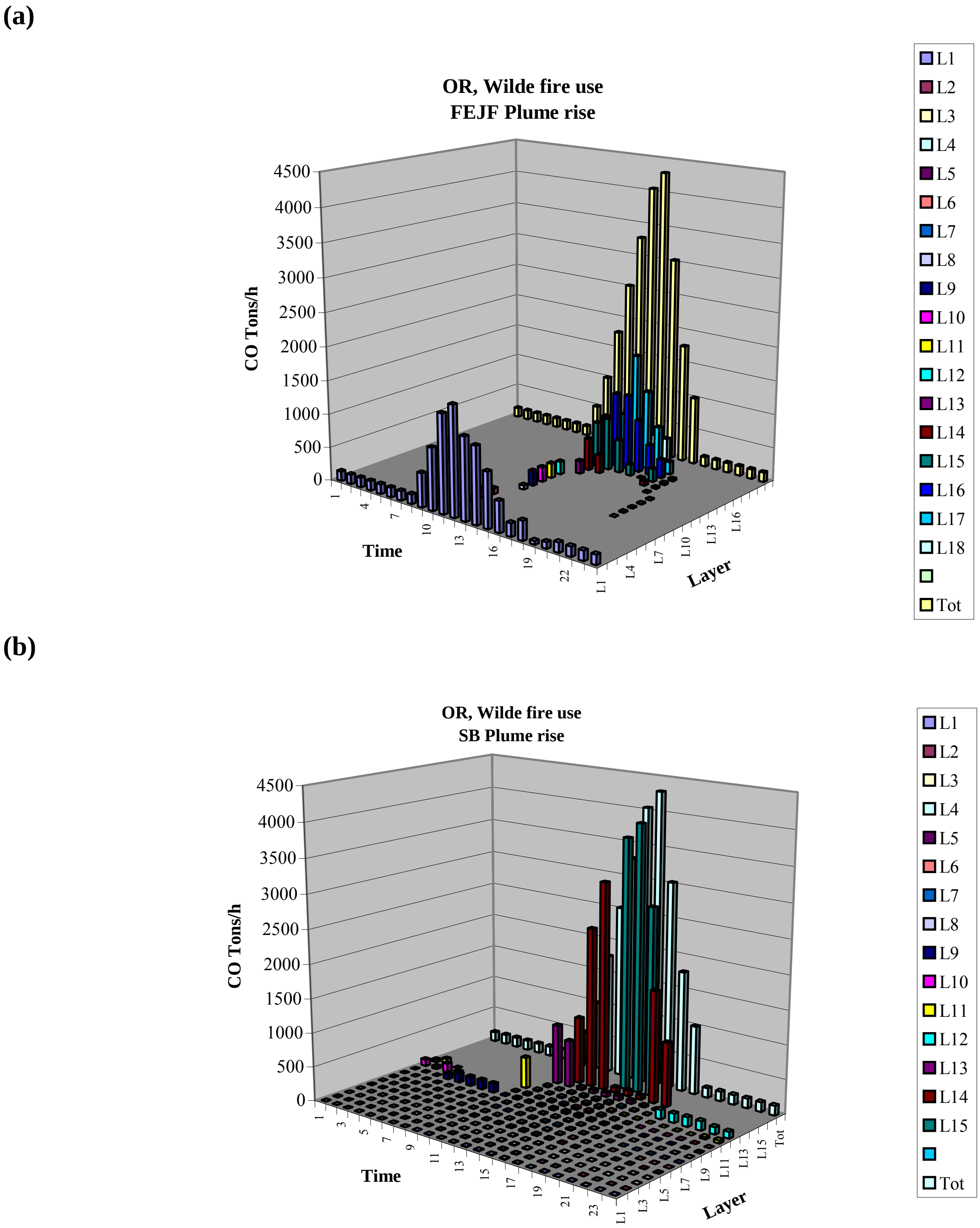


Figure 9. Oregon wildfire vertical distribution: (a) FEJF and (b) SB

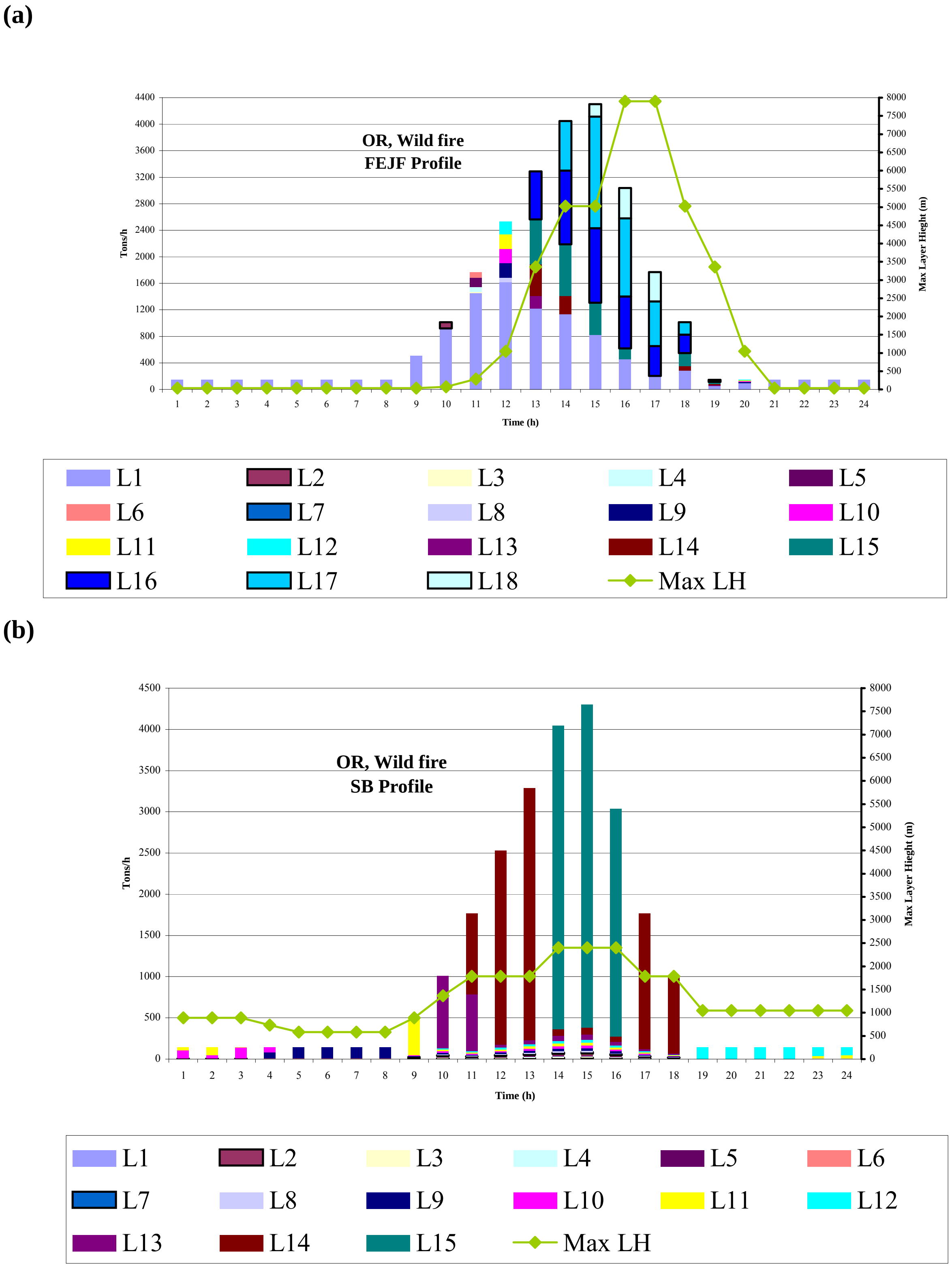


Figure 10. Oregon wildfire emissions vertical distribution and maximum layer heights: (a) FEJF and (b) SB