Forest Fire Impacts on the Global Energy Budget:

Optical Depth, Surface Temperature & Precipitation & Atmos. Chemical Composition

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Table of Contents

INTRODUCTION

Forests play a vital role in the Earth's energy budget by regulating the exchange of energy between the land and atmosphere (Bonan, 2008). Projections of future increases in the frequency and intensity of forest fires under climate change are of concern as these could threaten forest-atmosphere relationships and could significantly affect global climate (Westerling et al. 2011; Moritz et al. 2012; Barbero et al. 2015). This paper provides an assessment and understanding of fire's influence on the global energy budget and emphasizes the importance of a consistent and integrated understanding of fire effects. Forest fire's effects on (1) Optical Depth, (2) Surface Temperature, (3) Precipitation and Hadley Cell Circulation, and (4) Atmospheric Chemical Composition are analyzed separately and, thereafter, a conclusion is made about the overall effect of forest fires on the Earth's energy budget.

FOREST FIRES' IMPACT ON OPTICAL DEPTH

This section of the paper will discuss the impact of aerosols released by forest fires on both aerosol optical depth and cloud optical depth. Aerosol optical depth (AOD) refers to the measurement of the amount of particles in the atmosphere that absorb or scatter radiation, whereas cloud optical depth refers to the degree a cloud modifies the radiation passing through it (Glossary of Meteorology).

Chemical composition and diameter are important variables to consider when modeling AOD. Chemical composition determines the fraction of light absorbed versus reflected; whereas diameter often determines the wavelength of radiation absorbed (Mahowald et al., 2011). Thus, to model AOD, we must discuss two types of aerosols emitted by forest fires: organic carbon (OC) and black carbon (BC). Both of these carbonaceous aerosols consist of highly polymerized organic material with low hydrogen and oxygen content; however, BC strongly absorbs solar

radiation, whereas OC mainly scatters solar radiation (Liousse et al. 1996; Wolff and Klimish, 1982; Novakov, 1982). The diameter is important to discuss in relation to AOD because AOD is maximized when the wavelength of light is similar to the particle diameter; therefore, smaller aerosols (diameters ~ 0.1-1μm) tend to influence shortwave radiation, and larger aerosols tend to influence longwave radiation (Mahowald et al., 2011). Figure 6 within *Aerosol Impacts on Climate and Biogeochemistry* (Mahowald et al., 2011), shows that both POM and BC impact shortwave radiation AOD and do not impact longwave radiation AOD.

Figure 1 shows the change in shortwave AOD caused by fire aerosols from biomass burning for both AMIP and CMIP simulations using data of fire emissions from 2003-2011. AMIP simulations describe an atmospheric general circulation model constrained by sea surface temperature and sea ice (PCMDI). CMIP simulations are an analog to AMIP simulations and describe a coupled ocean-atmosphere general circulation model; which means, unlike AMIP simulations, it includes ocean-atmosphere feedback and thus can be used for climate change prediction (PCMDI). Figure 1 shows that both models produce a similar result with respect to the change in AOD caused by fire aerosols which implies that sea-surface temperature impact on global fire aerosol distribution is small (Jiang et al., 2020). At mid- and high-latitudes, the change in AOD induced by fire aerosols is approximately 0.03 for both models (Jiang et al. 2020). Figure 1 shows that forest biomes in equatorial regions have a greater change in AOD than forest biomes in mid- and high-latitudes; however, the greatest change of AOD in South America is above savanna and grassland biomes where humans have been clearing these biomes for agricultural purposes. For forest fires, most of the emissions come from the smoldering phase of burning which releases a higher OC/BC ratio, while savanna and grassland biomes produce emissions that have a lower OC/BC ratio (Jiang et al. 2016). Since BC absorbs solar radiation

instead of scatters like OC, we can conclude that the larger change in AOD above equatorial forest biomes compared to the change in AOD above mid- and high-latitudes is partially due to the burning of local savanna and grassland biomes.

Cloud optical depth is also important to consider due to its impact on the energy budget with respect to albedo, absorption, and emissivity. An increase in aerosols in the atmosphere can lead to a change in cloud optical depth and albedo because cloud droplets form preferentially on the surface of condensation nuclei such as aerosols; as condensation nuclei increase, the water spreads over more droplets thus decreasing the average particle radius and increasing optical depth (Hartman, 2012). Furthermore, because the water's surface area to mass ratio within the cloud has increased, the cloud becomes brighter and is able to reflect more solar radiation consequently decreasing shortwave absorption at the surface (Hartman, 2012). However, detailed research specifically relating forest fire aerosols and its impact on cloud optical depth is limited. This is likely due to complications of accurate cloud simulations in climate models (Zhang et al., 2005; Bender et al., 2006).

It is important to acknowledge although fire aerosols impact aerosol and cloud optical depth, an increase or decrease in both optical depths does not directly imply a net positive or negative radiative forcing by fire aerosols. The location of clouds above and below the aerosols as well as changes in land surface characteristics also need to be taken into consideration in order to reach a conclusion on fire aerosol forcing (Mahowald et. al 2011). In addition, effects on surface temperature and precipitation can produce feedbacks that may reduce or intensify fire aerosol forcing; thus, these are discussed in more detail in the following sections.

FOREST FIRES' IMPACT ON SURFACE TEMPERATURE

Recent satellite evidence suggests that forest cover loss is associated with a warming of Earth's surface at a global average (Anderson, 2011). This is because forests have well-established biophysical climate feedbacks that play a critical role in global **surface energy budget** regulation. To explore the relationships between fire-induced forest loss and Earth's surface temperature, we evaluate forest fire effects on each component of the energy budget equation. We can estimate fire-induced change in global average surface temperature by calculating the changes in the energy fluxes on the right hand side of the land surface energy balance equation (Xu, 2015):

$$ULW = \sigma T_s = NSW + DLW - SH - LH - G \qquad (1)$$

upward longwave radiation (ULW); Stefan-Boltzmann constant (σ); surface temperature (T_s); surface net shortwave radiation (NSW); downward longwave radiation (DLW); sensible heat flux (SH); latent heat flux (LH); ground heat flux (G)

This section begins by providing scientific support for the impact of fires on global energy budget terms. Thereafter, rationales behind such impacts are discussed. The section concludes by relating the information included herein back to the surface energy budget equation (Equation 1) to support the conclusion that forest fires increase global surface temperature.

Before discussing factors which contribute to changes to the terms in the energy budget equation, we sought out scientific evidence to support our conclusion. The most important terms influencing surface temperature changes are surface net radiation and latent heat flux. A study (Li et. al., 2017a) found that, for the 20th century average, fire-induced changes in terrestrial ecosystems decrease surface net radiation**(A)** and latent heat flux**(B)** by 1.08 Wm^{-2} and 0.99 Wm^{-2}, respectively, and have limited influence on sensible heat flux (−0.11 Wm^{-2}) and ground heat flux (+0.02 Wm^{-2}) thus producing a total increase in global land annual mean surface

temperature by 0.18 °C. The following section investigates how fire impacts latent heat flux and net surface radiation.

Among the energy fluxes in Equation 1, our first discussion is of latent heat flux. Fire generally decreases **latent heat flux(B)** mainly due to fire-induced damage in vegetation canopy (Li and Lawrence., 2017b). The canopy damage decreases vegetation transpiration and canopy evaporation due to decreased leaf area, fewer stomata, less canopy interception and water storage, and increases in soil evaporation thus exposing more of the soil to the air and sunlight. Changes in vegetation canopy are immediate and are short term effects which begin to subside in the years following a forest fire. This analysis is supported by a complementary study (Li and Lawrence, 2017b) which concludes that the reduction in latent heat is mainly attributed to fire-induced damage of the vegetation canopy.

Fire-induced changes in **surface net radiation(A)** are complex and involve a multitude of terms in the energy balance equation. The Stefan–Boltzmann's law describes that net radiation is the balance between the inputs and outputs of longwave and shortwave radiation and is controlled partly by surface albedo and clouds (Hartman, 2012).

First, we need to discuss the positive feedback loop between fires and **longwave radiation** which contribute to an overall increase in surface temperature. Immediate fire-induced increases in surface temperature enhance upward longwave radiation from the surface which then returns to the surface as downward radiation from the atmosphere, providing energy to further warm the land surface (Kato, 2013). Such a change is a slow and long term response to forest fires.

Next we discuss the impact of albedo and clouds on shortwave radiation which contributes to the change in surface net radiation and surface temperature. As discussed in the

optical depth paragraph, forest fires have a significant effect on net shortwave radiation. The reduced **surface net shortwave radiation** is co-caused by fire-induced lower surface albedo and higher coverage of low-level and mid-level clouds. Fire increases the surface **albedo**, in most regions due to the darker soil color, with respect to vegetation albedos, which become exposed as a result of reductions in vegetation coverage (Lawrence and Chase, 2007). Fire increases low and mid-level **cloud** coverage which reflect less solar radiation and thus intensifies the incident solar radiation and consequently reduces surface net shortwave radiation (Jiang, 2016). Together these factors result in a net decrease in surface net radiation.

It should be noted that the changes discussed herein differ significantly at the local and temporal scale. For example, tropical forest fires have a smaller long term influence on local surface temperature because of lower local evaporative cooling (Liu et al., 2019). At high latitudes, shortwave absorption is expected to increase and decrease in summer and winter respectively due to seasonal albedo fluctuations. The response time of individual variables also differ. For example, land cover changes associated with fires will subside in the years following a fire at the local scale, whereas positive feedbacks such as those discussed in relation to temperature and upward and downward longwave radiation may persist for decades after a fire (Kato, 2013). The biophysical feedback discussed herein presents only a framework for assessing the surface radiative impacts caused by fire that can be applied to a range of fire disturbances, but not all.

In summary, fires increase surface temperature in equation (1) in this way:

$$\sigma T_s(\Uparrow) = ULW(\Uparrow) = NSW(\Downarrow) + DLW(\Uparrow) - SH(\Downarrow) - LH(\Downarrow) - G(\Uparrow)$$

Fires generally decrease latent heat flux (LH) mainly due to fire-induced damage in vegetation canopy (Li and Lawrence, 2017). Surface warming increases upward surface

longwave radiation(ULW), increases downward longwave radiation, and reduces net shortwave radiation (NSW) (Kato, 2013). Together these influences increase average global surface temperature as indicated through an analysis of the surface energy budget equation.

FOREST FIRES' IMPACT ON PRECIPITATION & HADLEY CELL CIRCULATION

The net increase in fire aerosols from forest fires has also resulted in significant climate impacts in the form of precipitation and Hadley Cell circulation (Jiang et al. 2020). Most of the effects on the climate can directly be traced back to the positive feedback mechanisms caused by aerosols emitted from forest fires and can be analyzed in the theoretical components of Earth and atmospheric science, the radiative effect and total response, the fast response, and finally climate feedback and tropical circulation change.

Theoretically, a forcing in the atmosphere will cause feedback. In this scenario, the addition of fire aerosols leads to a decrease in the surface latent heat flux into the atmosphere from the tropics, which balances strong atmospheric black carbon absorption. This positive feedback further leads to less moisture and convection occuring at the Intertropical Convergence Zone (ITCZ) or the Equator, which disrupts the air rising near the Equator flowing towards the North and South Poles; this consequently weakens Hadley Cell circulation and causes an imbalance in precipitation in the tropics over the Northern and Southern hemispheres (Hartmann 2016). The weakening of Hadley Cells will lead to a reduction of warm cloud formation in the Northern Hemisphere, causing less convective precipitation while simultaneously increasing the precipitation in the tropics of the Southern Hemisphere. In addition, we can predict that the Southern Hemisphere will counteract the change to maintain equilibrium and sustain the ocean current caused by the Hadley Cells by increasing the precipitation in its tropical ocean regions.

Based on atmospheric models, there are also several different atmospheric effects caused by the addition of boreal forest fire aerosols into the atmosphere that affect precipitation. One of the major models is the estimation of the aerosol radiative effect and fast response. This model predicts **the climate adjustment caused by the aerosols before substantial changes to the global annual surface temperature**, which provides more insightful data and conclusions on the relationship between aerosol addition and precipitation as precipitation will only be affected by radiation changes. Overall, the model concluded that global annual surface precipitation will slightly decrease by 0.06 mm day^{-1} with a margin of error of 0.01 (Jiang et al. 2020). However, the precipitation reduction was irregular, and there were significant variations across the planet. In deep tropical oceans such as the equatorial Atlantic Ocean, east Pacific Ocean, and Maritime Continent, there was a substantial decrease in precipitation, along with smaller decreases in the middle to high latitudes in the Northern Hemisphere. Simultaneously, there were increases in the tropics in the Southern Hemisphere (Figure 2) (Jiang et al. 2020). However, there is no certain conclusion that can be made for the ITCZ, as there are different precipitation patterns along eastern and western latitudes. A model that utilizes slow response and analyzes the effects of surface temperature changes and Hadley Cell circulation provides a more realistic and comprehensive picture of precipitation at the Equator.

The slow response model **takes precipitation into account along with radiation and thus air circulation**, which can help determine the role that Hadley cell circulation plays in a feedback mechanism. Thus, the slow response model occurs over a longer time period. The model reflected similar results to the fast response model with more certainty for the ITCZ. The global annual precipitation decreased by approximately 0.03 mm day^{-1} with a margin of error of 0.029 (0.05 mm day^{-1} with a margin of error of 0.01 for fast response.) The small precipitation

reductions in the surface temperature remained constant in the Northern Hemisphere (Jiang et al. 2020). However, there were substantial differences in precipitation along the ITCZ and the Southern Hemisphere as shown in Figure 3 (Jiang et al. 2020).

Other slow response models provide insightful information on precipitation changes. Along the ITCZ, there was a spatial pattern of large precipitation decreases. Precipitation also decreased over tropical forest regions in South America, Africa and equatorial Asia. There were also slightly smaller decreases in the Northern Hemisphere and increases between 5 and 10 degrees north (and between 5 and 10 degrees south) (Tosca 2013). Over the main burning regions of Africa and South America, precipitation decreased .24 with a margin of error of 0.05 mm day^{-1} and 0.08 with a margin of error of 0.005 mm day^{-1} respectively. The combination of decreased temperatures, atmospheric heating and aerosol-cloud indirect effects reduced convection at the Equator and weakened the Hadley circulation (Tosca 2013). The weakened Hadley Cells can most likely be directly attributed to the significant climate changes as the Southern Hemisphere is usually more resistant to changes caused by temperature due to the higher specific heat capacity of water.

From the fast response and slow response model, there are strong indications that forest fire aerosols create a positive feedback mechanism as the changes in the deep tropical regions continue to remove moisture and convection at the ITCZ, further weakening Hadley Cells and causing significant impacts on the precipitation distribution as demonstrated by Figure 4.

FOREST FIRES' IMPACT ON ATMOSPHERIC CHEMICAL COMPOSITION

Another important impact of forest fire to consider is that forest fire emissions change the chemical composition of the atmosphere and might possibly lead to change in the Earth's energy budget. CO_2, CH_4, N_2O, and aerosols are of most interest in this section.

Table 1 shows the average chemical composition of the atmosphere. The relative mixing ratio for each component can be calculated assigning a value of 1 to that of SO_2. The relative mixing ratio of other components are 1.95×10^6 for CO_2, 9×10^3 for CH_4, and 1.62×10^3 for N_2O.

As an example, Table 2 shows the emission data from the forest fires during July 2000 in Greece (Lazaridis, M., et al. 2008). Since the mixing ratio is proportionate to the volume the gases are occupying, by assuming that the gases behave like an ideal gas, we can calculate the mixing ratio of the elements by dividing the emitted mass of a gas component by its molecular weight from Table 1. Using the same method, if the relative mass ratio of the emitted SO_2 is set to 1, the relative mixing ratio of CO_2, CH_4 and N_2O are 2.94×10^3, 4×10^1, and 3.5×10^{-1} respectively. The mixing ratio values of CO_2, CH_4, and N_2O are much smaller in the emitted gases than in the atmosphere, which changes the composition of the atmosphere through mixing.

In Table 3, we introduce the emission factor (EF) which is defined as a mass of gaseous compounds released per mass of dry fuel consumed (Urbanski, S. P., et al. 2009). EF can be considered the expected value of potential emissions of gaseous particles. In addition, Figure 5 shows the global mean RF (Radiative Forcing) of agents. According to the data associated with the figure from the IPCC Fourth Assessment Report (AR4), the net RF from CO_2, CH_4, and N_2O are $1.66 \pm 0.17\ Wm^{-2}$, $0.48 \pm 0.05\ Wm^{-2}$, and $0.16 \pm 0.02\ Wm^{-2}$ respectively (Forster P., et al. 2007). Moreover, RF due to direct effects from aerosols is $0.50 \pm 0.40\ Wm^{-2}$. Two indirect effects from aerosols have RF of -0.70[-1.1,+0.4] Wm^{-2} for increase in cloud albedo and +0.10 $\pm 0.10\ Wm^{-2}$ for decrease of surface albedo due to black carbon landing on snow (Forster P., et al. 2007). EF values in Table 3 for each agent was calculated simply by averaging the values of EF for different types of forests. Assuming that global average EF is similar to that of Greece in

Table 1, EF of PM_{10} was calculated by multiplying EF of CO_2 from Table 3 and PM_{10} emission from Table 2 divided by CO_2 emission from Table 2. EF of PM_{10} is approximately $8.5\text{g}\,kg^{-1}$.

To compare the effectiveness of each agent regarding RF, we will define a parameter named RF sensitivity, which is the absolute value of RF divided by EF. The RF sensitivity of CO_2, CH_4, N_2O, and PM_{10} are $1.01\times10^{-6}Wm^{-2}$, $1.22\times10^{-4}Wm^{-2}$, $7.06\times10^{-4}Wm^{-2}$, and $7.06\times10^{-5}Wm^{-2}$. The agents are sensitive to amount of emission per unit mass in a descending order of N_2O, CH_4, PM_{10}, and CO_2. Therefore, CO_2, CH_4, and N_2O have positive RF while PM_{10} has negative RF. Nevertheless, RF sensitivity alerts caution on N_2O, CH_4, and PM_{10} more than the emission of CO_2 because of the larger net radiative effect those chemicals can bring to the Earth's energy budget.

Understanding briefly the net radiative forcing effects of each chemical component in the atmosphere, tracking the particles over time is essential to see how the transport of gaseous compounds from forest fire can spread and impact the global energy budget. Figure 6 is a time series of Sulfate, Organic Carbon, Elemental Carbon, and $PM_{2.5}$ of the Quebec forest fire episode in 2002, measured in Philadelphia (Begum, B. A., et al. 2005). The forest fire in Quebec lasted from July 6th to July 9th (Jeong, C., et al. 2004). In Figure 6, all agents started decreasing on July 7th and had a sudden rise starting approximately 8am. Then again the particle concentration decreases and goes up again and reaches its maximum. The two peaks might be due to difference in speed of diffusion. According to a dynamical equation of motion for atmospheric particles, the RMS (Root Mean Square) speed of an idealized gaseous particle is:

$$v_{rms} = \sqrt{\frac{3RT}{M}} \quad (2)$$

Where R is the universal gas constant, T is the temperature in Kelvin, M is molecular weight (Benson, H., 1995). According to equation (2), The rms speed of a particle is inversely proportional to the square root of the molecular weight of a particle. From this, we can conclude that PM_{10} particles arrived later than the $PM_{2.5}$. In a remote location during or after forest fire episodes, particles with higher mass travel slower, therefore, could possibly provide constant feedback of particulate matter to remote locations which might cause negative radiative forcing.

CONCLUSION

Understanding the threats posed by projected increases in the frequency and intensity of global forest fire occurrences from climate change (Westerling et al. 2011, Moritz et al. 2012, Barbero et al. 2015) is critical to properly prepare and react to subsequent changes to our global climate. This paper has analyzed and explained forest fire effects on (1) Optical Depth, (2) Surface Temperature, (3) Precipitation and Hadley Cell Circulation and (4) Atmospheric Chemical Composition. First, we determined that aerosols released by forest fires increase the aerosol optical depth in the atmosphere. In addition, with an increase in aerosol optical depth and cloud optical depth, shortwave radiation is impacted due to increased absorption of solar radiation in the atmosphere and increased brightness or reflection of clouds. Next, we found that forest fires increase the annual mean surface temperature primarily through reductions in surface net radiation and latent heat flux terms at the local scale which result in global implications to the energy budget. Moreover, we concluded that the release of fire aerosols alter normal precipitation distributions across the planet. Directly, it changes the balance of precipitation patterns. Overall, there is significant change at the Equator, where the relatively substantial decrease in precipitation will lead to the weakening of the Hadley cell circulation and create a positive feedback mechanism. Finally, forest fires change the atmospheric chemical composition

which might impact the Earth's energy budget. CO_2, CH_4, and N_2O have positive radiative forcing. In contrast, PM_{10} has negative radiative forcing. Tracking of the chemical agents mentioned is important. In addition, there might be a second feedback of particulate matter to remote locations due to difference in molecular mass of the gaseous chemicals.

While the fire impacts to (1) Optical Depth, (2) Surface Temperature, (3) Precipitation and Hadley Cell Circulation, and (4) Atmospheric Chemical Composition were discussed separately, they share net effects and concerns. Introducing CO2 and other particles into the atmosphere will raise average Earth temperatures (Ekwurzel, 2017). Similarly, shifts in precipitation mass and patterns will shift surface temperatures and vice-versa as warmer air can hold more water (Tosca, 2013). Fire-induced changes to aerosol and cloud optical depth through interactions between cloud droplet and smoke particles can also modify precipitation and Hadley cell circulation (Andreae and Rosenfeld, 2008), as can smoke-induced changes to atmospheric chemical composition (Tosca, 2013). These changes are a cause for concern because rising temperatures and precipitation will impact economies, agriculture and weather patterns (Scott, 1990). Rising temperatures pose a threat to ecosystems and species unable to quickly adapt such as coral reefs and arctic areas. Rising precipitation poses similar threats to ecosystems as well as increasing the likelihood of flooding and other severe weather events. Because of the interdependence of the four factors discussed above, a comprehensive analysis of the effects of forest fires on the global energy budget would be insufficient without discussing each. No single term, (1) Optical Depth, (2) Surface Temperature, (3) Precipitation, or (4) Atmospheric Chemical Composition, is of greatest importance and each must be considered for proper management of forest fire projections.

APPENDIX A - Tables and Figures

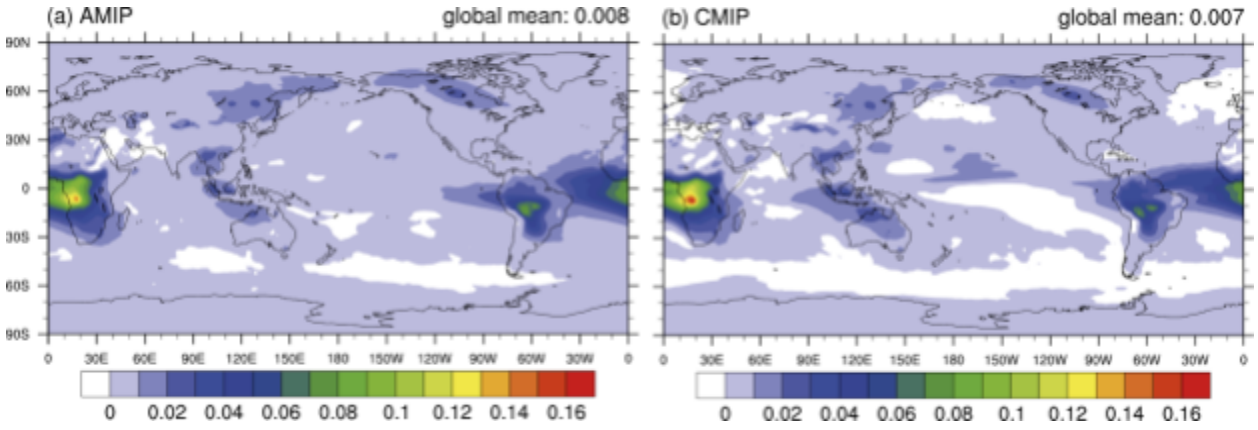

Figure 1: Change in AOD at 550 nm induced by fire aerosols in (a) AMIP- and (b) CMIP-type simulations. (Jiang et al. 2020)

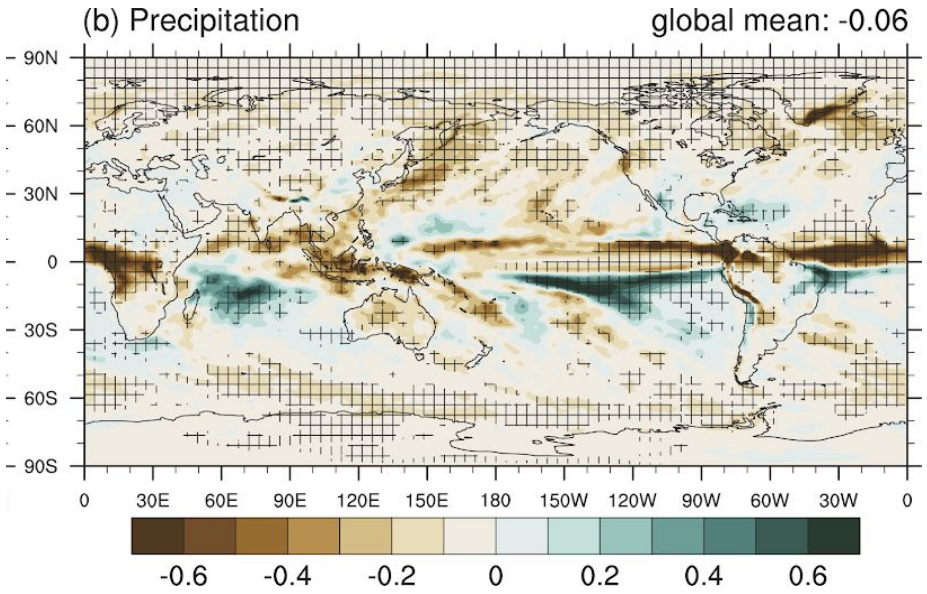

Figure 2: Fast Response Precipitation Graph, From: "Impacts of Wildfire Aerosols on Global Energy Budget and Climate: The Role of Climate Feedbacks" 2020, Accessed 29 Nov. 2020.

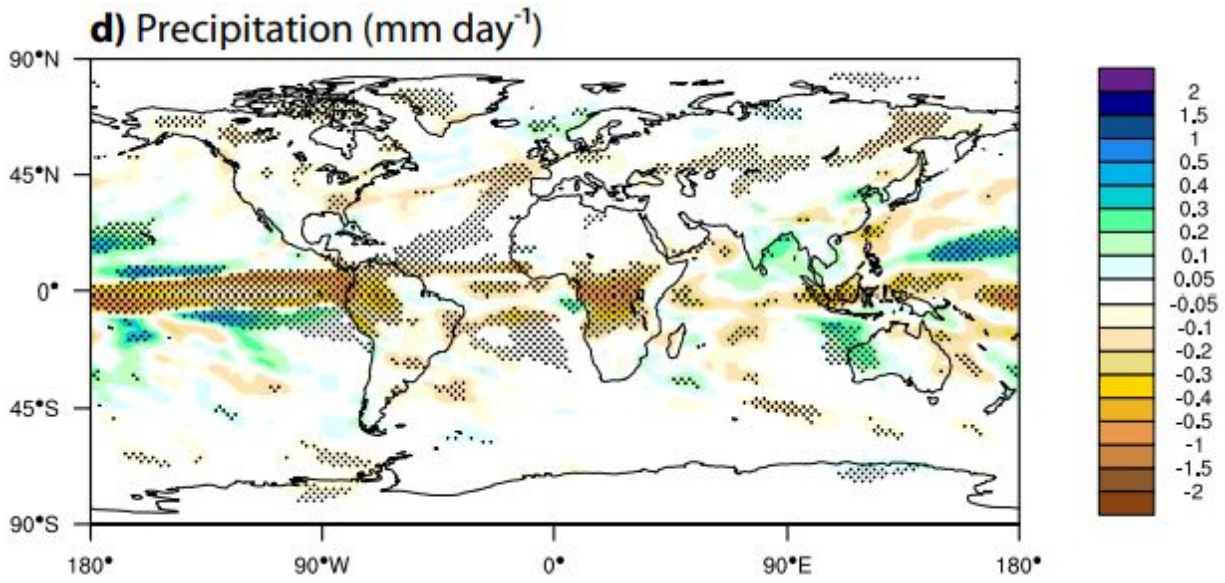

Figure 3: Slow Response Precipitation Graph from: "Impacts of Wildfire Aerosols on Global Energy Budget and Climate: The Role of Climate Feedbacks" 2020, Accessed 29 Nov. 2020.

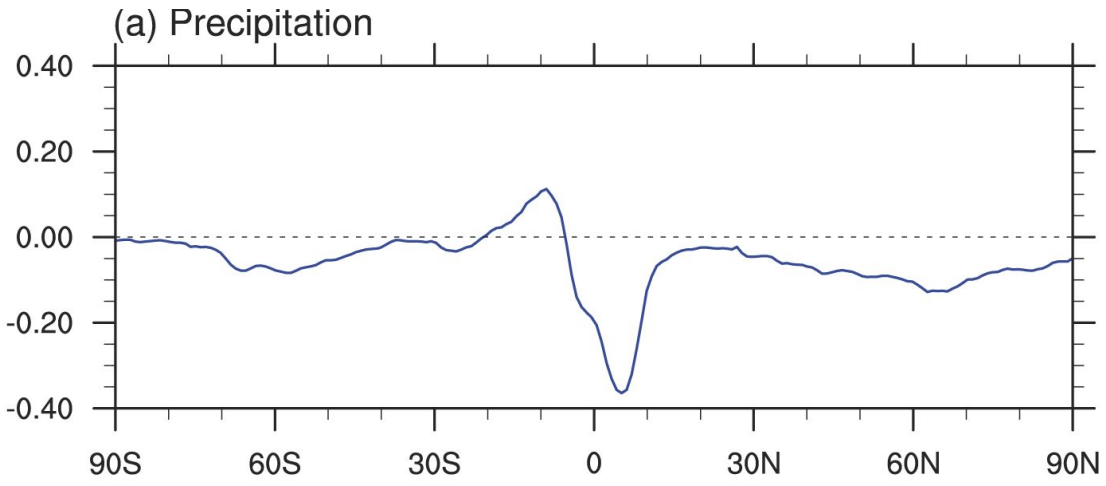

Figure 4: Fast Response Precipitation Graph, From: "Impacts of Wildfire Aerosols on Global Energy Budget and Climate: The Role of Climate Feedbacks" 2020, Accessed 29 Nov. 2020.

Constituent	Chemical formula	Molecular weight ($^{12}C = 12$)	Fraction by volume in dry air
Total atmosphere		28.97	
Dry air		28.96	100.0 %
Nitrogen	N_2	28.01	78.08 %
Oxygen	O_2	31.99	20.95 %
Water vapor	H_2O	18.02	Variable
Carbon dioxide	CO_2	44.0	391 ppmv*
Methane	CH_4	16.04	1.8 ppmv*
Ozone	O_3	47.99	Variable
Nitrous oxide	N_2O	44.01	324 ppbv*
Carbon monoxide	CO	28.0	120 ppbv
Hydrogen	H_2	2.02	500 ppbv
Ammonia	NH_3	17.0	100 ppbv
Nitrogen dioxide	NO_2	46.0	1 ppbv
Sulfur dioxide	SO_2	64.1	200 pptv
Hydrogen sulfide	H_2S	34.1	200 pptv
CFC-12	CCl_2F_2	120.9	528 pptv*
CFC-11	CCl_3F	137.4	238 pptv*

Table 1: Chemical composition of the atmosphere (Hartman et al., 2016).

	Pollutant	Emissions (t)
Carbon compounds	CO_2	2,201,836
	CO	157,789
	CH_4	10,820
	NMHCs	14,178
	Total C mass	676,240
Nitrogen compounds	NO_2	5,410
	NH_3	1,217
	N_2O	270
	Total N mass	6,762
Sulfur compounds	SO_2	1,082
Particulate matter	TSP	12,773
	PM_{10}	11,496

Table 2: Chemical composition of emitted gaseous compounds from forest fires during July 2000 in Greece (Lazaridis et al. 2008).

Species	Temperate forest	Temperate rangeland	Tropical savannas	Tropical forest	Boreal forest
			EF ($g\,kg^{-1}$)[b]		
Carbon dioxide (CO_2)	1619±112	1684±45	1661±66	1604±50	1604±119
Carbon monoxide (CO)	89.6±13.2	69±17	75±20	117±19	105±45
Methane (CH_4)	3.41±0.90	2.31±1.08	2.7±1.1	6.7±1.1	4.5±2.3
Nitrogen oxides (as NO)	1.7		2.3±1.0	1.77	1.1–3.3
Nitric oxide (NO)			1.1	0.74–1.8	1.5–2.3
Nitrous oxide (N_2O)	0.16	0.32	0.12–0.18		0.14–0.41
Sulfur dioxide (SO_2)			0.43		
$PM_{2.5}$	11.7±5.0	9.7±4.3	4.4	8.5	1.5–7.2

Table 3: Emission Factor (g emission/kg fuel burned) from wildfires. "d" indicates the particle diameter (Urbanski et al. 2009).

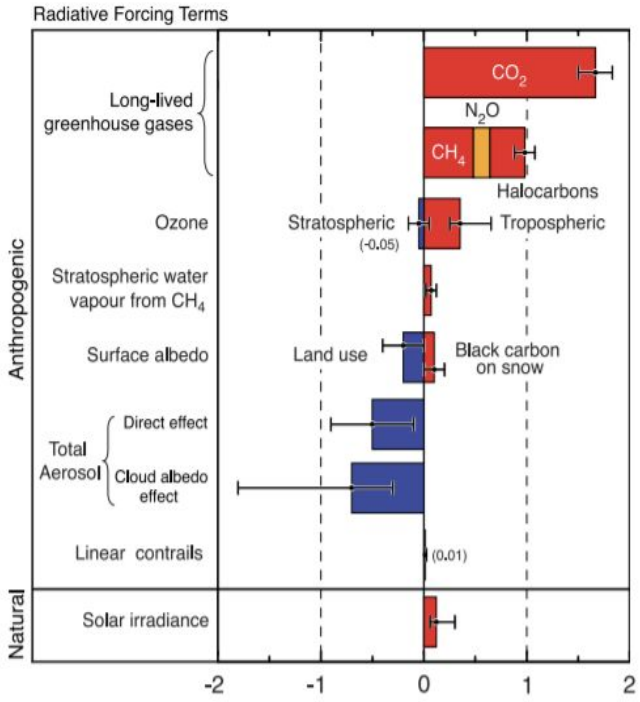

Figure 5: Global mean Radiative Forcing of climate between 1750-2005. (Forster et al. 2007).

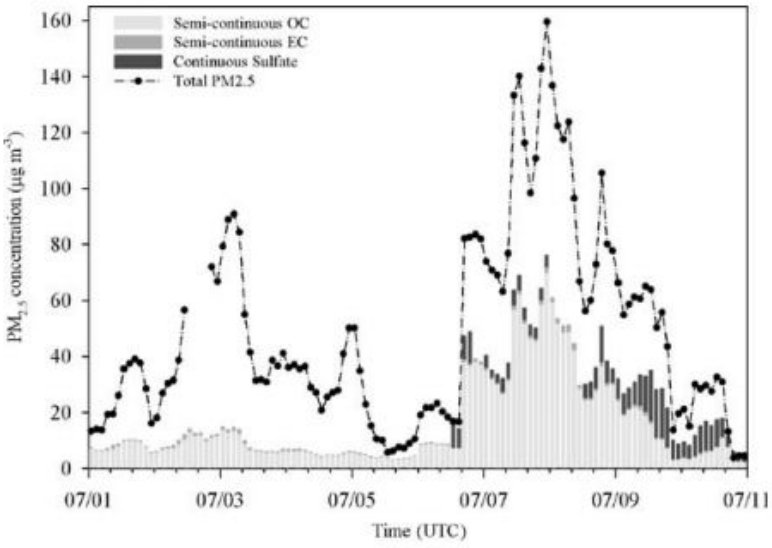

Figure 6: Time series of Sulfate, OC (Organic Carbon), EC (Elemental Carbon), and PM2.5 of the Quebec forest fire episode in 2002 (Begum,et al. 2005)

APPENDIX B - Limitations

The limitations to our analysis of the impacts of forest fires on the global energy budget must be acknowledged. We present a very superficial framework for assessing impacts due to fires globally. Because forest fire impacts vary greatly based on local factors (Liu, 2019), different locations may experience different effects than those discussed in the sections above. These local factors can include timescale and modeling.

Fire impacts also vary by timescale. For example, changes in vegetation canopy and albedo will subside in the years following fires at the local scale; whereas positive feedback loops and altered atmospheric chemical composition could persist for decades or more (Ekwurzel, 2017). Some of these differences between fast and slow responses have been addressed within each section.

Models also often fall short of making accurate assessments of fire effects. Fire's impact on Earth system models vary significantly based on how regional, seasonal, spatial and other factors are considered, leading to simulations which may not be consistent with observations (Andela, 2017).

The biophysical diagnostics that we present should only be used as a superficial prognostic of forest fires' feedbacks on Optical Depth, Surface Temperature, Precipitation and Chemical composition. These can serve the additional purpose of increasing confidence in or identifying necessary improvements within fire and climate prediction models. Further study and observation are required to lower uncertainties before fires impact on the global energy budget can be reliably quantified and understood.

APPENDIX C: Works Cited

Andela, N. et al. (2017) 'A human-driven decline in global burned area', *Science*, 356(6345), pp. 1356–1362. doi: 10.1126/science.aal410

Anderson, R. et al. (2011). Biophysical considerations in forestry for climate protection. In: *Front. Ecol. Environ.* 9, 174–182.

Andreae, M. O. and Rosenfeld, D. (2008). Aerosol cloud precipitation interactions. Part 1. The nature and sources of cloud-active aerosols, *Earth Sci*. Rev., 89, 13–41.

Barbero, R., et al. (2015). Climate change presents increased potential for very large fires in the contiguous United States. *International Journal of Wildland Fire*. 24:892–899.

Begum, B. A. (2005). Evaluation of the potential source contribution function using the 2002 Quebec forest fire episode. Atmospheric Environment. doi:10.1016

Bender, F., H. Rodhe, R. Charlson, A. Ekman, and N. Loeb (2006), 22 views of the global albedo—comparison between 20 GCMs and two satellites, *Tellus*, 58, *A*, 320–330.

Benson, H. (1995). Chapter 20/Kinetic Theory. In (Revised ed., p. 467). John Wiley & Sons.

Bonan, G. (2008). Forests and climate change: forcings, feedbacks, and the climate benefits of forests. In: *Science* 320, 1444–1449 .

Ekwurzel, B., et al. (2017). The rise in global atmospheric CO2, surface temperature, and sea level from emissions traced to major carbon producers. *Climatic Change* 144, 579–590. https://doi.org/10.1007/s10584-017-1978-0

Forster, P., 2007: Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Glossary of Meteorology. American Meteorological Society, https://glossary.ametsoc.org/wiki/Welcome.

Hartmann, Dennis L. *Global Physical Climatology*. Elsevier, 2016.

Jeong, C., Lee, D., Kim, E., & Hopke, P. K. (2004). Measurement of real-time PM2.5 mass, sulfate, and carbonaceous aerosols at the multiple monitoring sites. *Atmospheric Environment, 38*(31), 5247-5256. doi:10.1016/j.atmosenv.2003.12.046

Jiang Y, et al. (2016). Impacts of global wildfire aerosols on direct radiative, cloud and surface-albedo forcings simulated with CAM5. In: *Atmos. Chem. Phys.* 16 14805–24

Jiang, Y., et al. (2020) Impacts of Wildfire Aerosols on Global Energy Budget and Climate: The Role of Climate Feedbacks. In: *J. Climate*, **33**, 3351–3366, https://doi.org/10.1175/JCLI-D-19-0572.1.

Kato S et al. (2013). Surface irradiances consistent with CERES-derived top-of-atmosphere shortwave and longwave irradiances. In: *J. Clim.* 26 2719–40

Lawrence, P. and Chase, T. (2007). Representing a MODIS consistent land surface in the community land model. In: *J. Geophys. Res* 112 G01023
Lazaridis, M., et al. (2008). Contribution of forest fire emissions to atmospheric pollution in Greece. Retrieved December, 2020. doi:10.1007/s11869-008-0020-0

Li, F., et al. (2017a). Impact of fire on global land surface air temperature and energy budget for the 20th century due to changes within ecosystems. In: *Environ. Res. Lett*. 12, 044014; corrigendum 12, 069501.

Li, F. and Lawrence, D. (2017b). Role of fire in the global land water budget during the 20th century through changing ecosystems. In: *J. Clim.* 30 1893–908

Liu Z., Ballantyne A.P., and Cooper L.A. (2019). Biophysical feedback of global forest fires on surface temperature. *Nat. Commun*. 10(1): 214.

Liousse, C., J. E. Penner, C. C. Chuang, J. J. Walton, H. Eddleman, and H. Cachier. (1996). A global three‐dimensional model study of carbonaceous aerosols, *J. Geophys Res.*, 101, 19,411–19,432.

Mahowald, N., Ward, D. S., Kloster, S., Flanner, M. G., Heald, C. L., Heavens, N. G., Hess, P.G., Lamarque, J., and Chuang, P. Y. (2011). Aerosol Impacts on Climate and Biogeochemistry. In: *Annu. Rev. Environ. Resour.* **36**, 45-74.

Moritz, M., et al. (2012). Climate change and disruptions to global fire activity. In: *Ecosphere*. 2012;3:1–22.

Novakov, T. (1982). Soot in the atmosphere, in Particulate Carbon: Atmospheric Life Cycle, pp. 19-37, Plenum, New York.

NRC (National Research Council): Committee on Air Quality Management in the United States, Board on Environmental Studies and Toxicology, Board on Atmospheric Sciences and Climate, Division on Earth and Life Studies. Air quality management in the United States. (2004). Washington, DC: National Academies Press. *Program for Climate Model Diagnosis & Intercomparison(PCMDI)*, Lawrence Livermore National Laboratory, https://pcmdi.llnl.gov/index.html.

Scott, M., et. al. (1990). Consequences of climatic change for the human environment. Climate Research, 1(1), 63-79. Retrieved December 5, 2020, from http://www.jstor.org/stable/24863378

Tosca, M. G., J. T. Randerson, and C. S. Zender. (2013). Global impact of smoke aerosols from landscape fires on climate and the Hadley circulation. In: *Atmos. Chem. Phys.*, **13**, 5227–5241, https://doi.org/10.5194/acp-13-5227-2013.

Trenberth, K. E., J. T. Fasullo, and J. Kiehl. (2009). Earth's Global Energy Budget. In: *Bull. Amer. Meteor. Soc.*, 90, 311–324, https://doi.org/10.1175/2008BAMS2634.1.

Urbanski, S. P., et al. (2009). Chapter4. Chemical Composition of Wildland Fire Emissions. In Developments in Environmental Science (Vol. 8, pp. 79-107). Elsevier B.V. doi:10.1016

Westerling, A., et. al. (2011). Climate change and growth scenarios for California wildfire. In: *Climatic Change*. 2011;109:S445–463.

Wolff, G.T., and Klimisch, R.L., (Eds.), Particulate Carbon: Atmospheric Life Cycle, 411 pp., Plenum, New York, 1982

Xu, Z. et al. (2015). Investigating diurnal and seasonal climatic response to land use and land cover change over monsoon Asia with the Community Earth System Model. In: *J. Geophys. Res. Atmos.* 120 1137–52

Zhang, M. H., et al. (2005), Comparing clouds and their seasonal variations in 10 atmospheric general circulation models with satellite measurements, *J. Geophys. Res.*, 110, D15S02, doi:10.1029/2004JD005021.