Written Statement of

Craig B. Clements, Ph.D.

Director, Wildfire Interdisciplinary Research Center
Professor of Meteorology, Department of Meteorology and Climate Science
San José State University, San Jose, CA

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I am a Professor of Meteorology and Director of the Wildfire Interdisciplinary Research Center and Fire Weather Research Laboratory at San José State University. In this testimony I present briefly on the current needs in wildfire and fire weather research and the funding requirements for improving our state of knowledge in these fields. Additionally, I will address some aspects of current technologies and provide an example of how the private sector has successfully developed new tools for fire management agencies. I will close with a summary of recommendations.

Background and the changing wildfire environment

Wildfire globally is becoming more challenging compared to just a few decades ago with many fires becoming larger and more severe, particularly in the western US. This trend is projected to continue into the future due to a number of factors including changes to fire weather conditions that are caused by anthropogenic climate change (Stravos, et al. 2014; Barbero et al. 2015). Fire seasons are getting longer and fire danger and critical fire weather conditions are increasing globally as well (Jolly et al 2015; Abatzoglou et al. 2019). Studies have also shown that increased air temperatures and drying of the atmosphere due climate change are driving more critical conditions in the fire environment (Parks and Abatzoglou 2020). This leads to impacts on fuel moisture content (FMC) which is the amount of water or moisture within a plant. As FMC within a plant decreases, flammability of the plant increases leading to increased ignition probability and faster rates of fire spread. Live fuel moisture content and fire weather are key drivers to high-severity fires (Parks et al. 2018). In addition to the climate impacts on fuels, forest management has also played a role in the increase of large and higher severity fires in the western US. Over 100 years of fire exclusion resulted in increased tree density dead fuel accumulation, and decreased forest structure heterogeneity magnifying the wildfire problem (Collins et al. 2017). It is clear that there is a pressing and immediate need for more research to address the changing wildfire environment. For example, many studies attributing changes in wildfire severity to climate change employ empirical indices that account for atmospheric conditions conducive to fire weather, such as air temperature and low humidity (e.g., Abatzoglou et al. 2019). However, a more comprehensive attribution requires dynamical modelling of wildfires that accounts for the coupling between atmospheric conditions, ecological conditions, and the fire behavior itself (Lloyd and

Shepherd, 2020). Furthermore, as catastrophic wildfires become more common, there is a need for more research to help develop improved understanding of future wildfires and their behavior. This involves the development of improved real-time prediction and forecasting tools.

Current state of federal fire weather research and forecasting

While there are many research efforts within various federal agencies that focus on wildfire, I will focus my testimony on programs that are aimed at fire weather research and wildfire prediction, which are mainly within the U.S. Department of Agriculture U.S. Forest Service (USFS) and partners. Research at the USFS is primarily driven by user needs and is mostly application focused. However, to some degree basic wildfire research is also conducted within the various USFS research laboratories and research stations and through partnerships with academic institutions who typically focus on more fundamental research.

Federal wildfire forecasting and prediction is generally addressed by the USFS which leads the nation in development of tools for wildfire risk and fire danger assessment. The National Fire Danger Rating System (NFDRS) is a system that is used throughout the nation to predict fire danger based on the environmental conditions. Current efforts are being made to improve its algorithms, to advance fine-dead fuel moisture and live fuel moisture models, and simplify fuel classifications (https://www.firelab.org/project/national-fire-danger-rating-system). NFDRS relates environmental conditions to fire operations and is the core tool used by fire agencies around the country. However, NFDRS is produced only once per day and not at a high spatial resolution as needed for forecasting fire risk at the community scale. As a result, investor owned utilities (IOUs) in California have been forced to develop their own fire potential indices to meet their requirements of Public Safety Power Shutoffs so that de-energization of circuits can be limited to small areas. Increasing both the temporal and spatial resolution of fire danger forecasts will be an improvement to an already critical tool for fire management.

Another key contribution of USFS fire weather research has been the development of various fire weather indices that are used to assess and predict weather conditions conducive to large wildfires. Many of these indices are still in use today (Fosberg 1978; Haines 1988). More recently the Hot-Dry-Windy index was developed in partnership between three USFS research stations and Saint Cloud State University (Srock et al. 2018).

Within the Research and Applications Laboratory at the National Center for Atmospheric Research (NCAR) efforts have been made to extended the functionality of the Weather Research and Forecasting (WRF) community NWP model to enable in-line simulations of weather conditions and fire behavior. New developments leverage the WRF-SFIRE model (Mandel et al. 2011) and improve the fire spread representation, the fuel characterization (Jiménez et al. 2018), as well as satellite-derived fuel-moisture data, and spotting potential to better predict fire progression and where the spot-fires are likely to ignite. These developments are being included in the community WRF-Fire model. Additionally, a new satellite-driven fuel moisture prediction system has been developed for better fire spread forecasts (McCandless et al. 2020).

Wildfire and fire weather research gaps

To address the major gaps in our understanding of fire weather and fire behavior, we need to think about and treat wildfires like other natural disasters and severe weather threats. Fire weather is the severe weather of the western US, yet there are very few resources aimed at monitoring these events like those dedicated to severe thunderstorms and hurricanes.

Core deficiencies in our knowledge are related to how wildfires create their own weather and how these coupled processes manifest on the fire line. We have limited understanding of how fire-atmospheric interactions affect fire spread. This is an area of research that has not been well funded and requires improved modeling capability using next-generation coupled fire-atmosphere models (e.g., WRF-SFIRE) and new capabilities in field observations which are also lacking.

Current efforts used for forecasting wildfire behavior need to focus on further development of community coupled fire-atmosphere prediction systems such as WRF-SFIRE (Kochanski et al. 2015; Mandel et al. 2011,2014; Jiménez et al. 2018). This type of framework is community based allowing researchers from any institution to not only use the model but to also improve the model and share it with other users. This is in contrast to models that are kept in-house and within one agency, institution or national lab and are not available for other agencies or institutions to use, modify or contribute to. Community-based models provide buy-in from the entire community to further develop the model and make it better. For example, the Open Wildfire Modeling group (http://openwfm.org) facilitated development of the first community coupled fire-atmosphere model WRF-SFIRE, leveraging the community Weather and Research and Forecasting Model (Skamarock et al. 2019). This model has become a core fire forecasting system used by many institutions and agencies not only in the US, but around the world. Coupled fire-atmosphere models are the only models that can predict how a wildfire interacts with its environment and how the fire can change local weather conditions. Wildfire induced weather is responsible for some of the most extreme fire events in history, including the development of fire tornadoes (Lareau et al. 2018) which can form quickly and cause extreme rates of fire spread endangering firefighters and communities. Additionally, coupled fire-atmosphere models can predict smoke impacts at community scales more accurately than typical smoke prediction systems that run at course resolutions and are incapable of resolving small-scale processes critical in the context of plume dynamics and smoke dispersion.

In order to build better fire prediction tools, there is a critical need for new comprehensive observational datasets that include weather, plume dynamics and fire behavior observations (Clements et al. 2018). These data are rare, especially compared to the observational record for other atmospheric processes such as severe storms. This observational deficit stems from the logistical and safety challenges associated with sampling in the near-fire environment. One way to overcome these challenges is to capitalize on planned prescribed fires. For the last decade, prescribed fire experiments have focused on small, low-intensity fires in flat terrain and do not represent the high-severity wildfires of the western US. One exception to this is the Fire and Smoke Model Evaluation Experiment (FASMEE) (Prichard et al. 2019), which is an interdisciplinary and multi-agency program that is focusing on high-intensity prescribed fires to study fire behavior, smoke and plume dynamics, fire weather, fire ecology and fuels, and fire effects. A large coordinated effort is needed to address extreme wildfire with research needs at its core. This program will build on the decades of research focused by many national agencies on low-intensity prescribed fire. The FASMEE project is one of the higher priority projects in wildfire science today and should be a national priority.

Fire weather data collection needs

Collecting routine meteorological data on wildfire incidents is challenging because many wildfires typically occur in remote areas with the exception of those burning in the wildland urban interface (WUI). We have not invested in monitoring the fire environment as we have for other severe weather phenomena. Many regions in the western US lack a sufficient coverage of surface weather stations, but this is improving with new networks being established in the last few years. California is unique because it likely has the most dense weather station network in the world as the IOUs there each have invested heavily in creating a network of surface weather stations that are installed on utility infrastructure and within each utility's territory. While surface weather data are critical for assessing near surface fire risk (temperature, humidity, and wind), it is the atmospheric conditions above the surface that are important in understating how fires may evolve especially in mountainous terrain where the atmosphere is more complex and associated with rapid changes that can impact a fire's behavior in a matter of minutes (Werth et al. 2011; Lareau et al. 2018). Additionally, fuel moisture observations are critical for both fire risk and fire spread prediction. These data are sparse and this is a major limitation that requires new observations of both live and dead fuel moisture for wildfire prediction improvement.

National Weather Service Incident Meteorologists (IMETS) who are assigned to large wildfire incidents can request the deployment of portable, remote automated weather stations to provide surface weather observations, but these stations are generally limited to just a few and it takes a minimum of a few days after the incident management team is established. Additionally, IMETS are equipped with modern upper-air weather balloon sounding systems that allow the collection of vertical profiles of the atmosphere when time permits. Generally, the IMET is already heavily tasked with providing detailed weather forecasts to the Incident Management Team and this takes up a majority of their time (https://www.weather.gov/news/imet-articl). There is a need for increased fire weather observations at large wildfire incidents to provide critical data to IMETS for fire weather and fire behavior forecasts.

During the last few years, San José State University has made a concentrated effort to collect new observations of fire weather and fire behavior at active wildfire incidents (Clements et al. 2018; Brewer and Clements 2019). Because of the inherent dangers of the wildfire environment, research teams are required to possess fire-fighter qualifications through either state or federal agencies to access the fire line. Being the only academic meteorological research team in the US with these qualifications, we have deployed to nearly 40 wildfires in California with our mobile Doppler lidar and radar assets. These new tools have provided first insights into the dynamics of plume-dominated wildfires and fire-atmosphere interactions at the large scale (Lareau and Clements 2016; 2017). Still yet, these observations are very limited and we need to capitalize on these early efforts and create a concentrated program to sample critical fire weather during wildfire events. It is only then that we will have the data necessary to not only better understand extreme fire behavior, but also develop the next generation of forecasting models.

We do lack the appropriate observational tools for fire characterization and reconnaissance—knowing quickly and continuously where and how a wildfire is spreading is a major gap in both our forecasting and suppression capability. This is also creates a major gap in our scientific understating of extreme fire behavior. Fire managers need to make decisions in timely manner and having high-resolution and continuous observations of the fire front position is required to ensure not only public safety, but also that of firefighters. Additionally, next-generation models need high-resolution infrared observations in order to predict where the fire will be in the next few minutes, hours, or days. While there is much emphasis on fire detection, that is not as much of a concern as having continuous high temporal and spatial resolution observations allowing to characterize the fire, its temperature, flame lengths, heat release, spotting potential, and rate of spread. Improved fire characterization is a core need for all wildfire science fields. These observations can be made using both satellites and aircraft including drones, but must have high pixel resolution (tens of meters or less), high temporal resolution (< 15 minutes) and be multispectral so that images are not saturated.

A summary of fire weather research needs was presented during San José State University's Fire Weather Research Workshops in 2019 and 2021 (https://www.fireweather.org/2021-workshop), where over 400 attendees participated from around the world. The workshops focused on the state of knowledge of wildfire prediction and fire weather research, with a strong emphasis on models and tools that can be adopted operationally.

Wildfire community resilience

The social component can be one of the more intractable factors in wildfire management. The exploding residential population in the WUI and increasing wildfire impacts (e.g., smoke, evacuation) highlights a need to promote fire-adapted communities and increase the pace and scale of risk-averting activities, like fuels management or defensible space, across socially distinct populations sharing the same landscape. Fire professionals, emergency officials, and community leaders can struggle with disaster management within an administrative unit in the WUI, like a fire district or county, because new residents from more urban areas with less fire-education move into high-risk spaces. Furthermore, community contexts and capacities are going to vary, and our wildfire adaptation tools and policies need to be adaptable to local-level needs and capacities in order to promote fire adaptation across landscapes. Integrating social data into our planning, model development, and conversations with managers and community members can help illuminate gaps in our fire resilience programs, more accurately plan for and respond to wildfire events in areas with a residential population, and better understand barriers to increasing the pace and scale of fuels management in WUI contexts. New modeling tools on the other hand can be helpful in prescribed burn planning and identifying most fire-prone communities.

Tools for fire management

There is prevailing evidence that fire managers often utilize decision support tools to gut check or validate the tactics they already intend to take or implement due to years of experience. However, the tide is shifting. Many managers identify that models are increasingly useful to them when responding to events under a changing climate as years of expertise is beginning to be challenged by new environmental circumstances. The public demand for information during a wildfire event can also add additional stress to the fire management situation as agencies are expected to provide accurate and frequent information updates to a public that is attempting to time their evacuation to a variety of evacuation cues. Spatial data, models, and displays (e.g., dashboards, accessible websites) are important tools for both professional wildfire response under a changing climate and community/individual resident response during a wildfire event also under a changing climate. However, these tools must be integrated and adjusted to operational needs so that critical information can be extracted from multiple data sources and models easily and fast.

Wildfire research at academic institutions and the private sector

Traditionally, wildfire research at US academic institutions has been housed in forestry departments with a focus on fire ecology. There are a number of programs within engineering departments that study fire dynamics and combustion and some of these programs are focused on wildfire. In the last decade, much wildfire research in academia has focused on climate science and climate impacts on wildfire. There are few wildfire specific research programs at universities. Typically, only one or two faculty in any one department may have funded projects in wildfire research and many of these investigators are funded through specific directorates within the National Science Foundation focused only on a single aspect of wildland fire or through limited-scope Joint Fire Science Program grants. One gap in academia is the lack of programs focused on fire weather as most atmospheric science programs do not offer courses in fire weather or fire behavior. Exceptions to this are San José State University and the South Dakota School of Mines & Technology both of which offer specific courses in fire weather. Other programs occasionally offer fire weather as a special topics course.

In terms of technology development, few academic programs develop operational tools for wildfire applications as this typically remains within the scope of federal agencies. However, there are exceptions where model development at academic institutions is funded by federal partners and is then targeted for operational adoption. An example of this is the NASA Disasters Program which is funding operational deployment of coupled fire-atmosphere modeling for fire spread prediction and assimilation of satellite fire data. Another example is the Desert Research Institute partnership with the U.S. Forest Service to provide weather and climate data, both historical and operational, to inform various decision support systems.

Private industry, and in particular, the IOUs in California, are driving much of the wildfire science and technology development and is outpacing what is done at the federal level. This is due to the high demand placed on the utilities by regulatory agencies because of the inherent risks associated with utility infrastructure. These risks are driving innovation within all areas of the private sector and as a result the state of wildfire science has improved in just the last few years. For example, the California Department of Forestry and Fire Protection (CAL FIRE) have successfully adopted a new wildfire situational awareness and fire prediction system (https://technosylva.com/;https://www.wsj.com/articles/california-firefighters-tap-ai-for-an-edge-in-battling-wildfires-11601544600?reflink=desktopwebshare_permalink) that has also been implemented successfully in 9 other states. These technologies are being further improved by partnerships between universities and private industry.

Future efforts at universities need to focus on the interdisciplinary nature of wildfire. Not one department or college can address the wildfire problems facing the nation, but an interdisciplinary team that includes fire ecologists, engineers, meteorologists, and social scientists will be more successful. Interdisciplinary research centers are critically needed to advance our understanding of wildfire and push technology development forward. For example, a unique aspect of the Wildfire Interdisciplinary Research Center recently established at San José State University and something many academic institutions lack, is a strong social science component. Programs and products developed to assist in wildfire planning and management are often criticized for not matching the fine-scale nature of community or professional decision making, the tech savvy or access abilities of older WUI populations, or local needs. Integrating social science into the product development process, as well as integrating social science data into evacuation models and other tools, better allows for adopting the science innovations, and can provide a more realistic picture of our community needs and vulnerabilities and enhance our ability to promote local wildfire resilience and build up to the landscape level desired by national policies.

Needed federal investment to grow innovation

There is an immediate need for a national and sustainable fire weather research funding program. Most fire weather research is funded by smaller contracts with agencies such as the U.S. Forest Service and the occasional award through NSF's Division of Atmospheric and Geospace Sciences. To date, there has never been a dedicated program that funds both basic and applied research in fire weather and this is critically needed. User inspired research, a different approach than basic and applied, is of high value because it is undertaken with an objective of informing decision making at the outset by developing and weighing alternatives and formulating and implementing decisions. Investment should also be made in programs that are not only conducting cutting edge wildfire research but are also heavily investing in and have a record of preparing a diverse workforce and training the next generation of wildfire scientists.

There is little need for duplication across agencies. A few federal agencies are already leading wildfire research efforts and spinning up new programs. But these are not well coordinated and not clear on how prioritization is determined or the extent that academic-government partnerships can be established. There are few true established partnerships today. These are important because as a step beyond the typical grant process, sustained partnerships allow for capacity building and interdisciplinary undertaking of the research. Leveraging already established programs will benefit the science community on a whole. There are already established federal programs that would benefit from increased investment including the interagency Joint Fire Sciences Program and the NASA Applied Science Wildland Fire Program, both of which have had their budgets drastically cut over the last few years. Increasing funding to these programs will provide more research opportunity to the wildfire research community. Additionally, the National Science Foundation could develop specific wildfire funding programs across directorates that would fund not only basic research but also provide more mechanisms for research within the social sciences. In order to further stimulate innovation in academia, increased federal investments need to be targeted for competitive grant programs that academic institutions can apply for. This investment needs to be separate from agency operational budgets.

Areas of improved coordination are also required to capitalize on current efforts being made within each agency. It is my understanding that coordination generally happens at a grassroots level where upper administrators are not aware of fostered collaborations. Partnerships are built on individual connections and common research interests with a goal of jointly building capacity and achieving actionable outcomes. In addition to partnerships, there are coordination efforts between agencies such as the 2012 Memorandum of Understanding between the U.S. Department of Agriculture U.S. Forest Service and the U.S. Department of Commerce National Oceanic and Atmospheric Administration that states both the USFS and NOAA have the authority to participate in collaborative research and development efforts in fire weather, fire behavior, fire danger, smoke and air quality forecasting, and fire-climate effects. The purpose of the MOU is to:

> "provide a framework for implementing and expanding existing research partnerships focused on weather and climate and their effects on fire potential, fire behavior, fire danger, and fire smoke products that support improved fire management and firefighting decisions. The parties recognize the importance of connecting improved weather elements such as numerical models, data assimilation, surface based observing platforms, telecommunications and aerial and satellite observations to improving operational forecasts in support of safe, reliable and sustainable USFS land management and firefighting operations."

This MOU directly addresses current research and development needs for improving wildfire and fire weather forecasting. However, no funding has been provided to support the research agenda outlined in this MOU. In order to leverage this coordination, federal investment must be allocated to these agencies to fund research outlined in the MOU. A mechanism for distributing funds to both agencies and external partners such as academic institutions will be needed to fast track this research.

Closing Remarks

It is clear that the coming decades will bring more catastrophic wildfire to the western US and managing this risk will require sustained investment in new science and technology. Wildfire and fire weather research requires more directed funding in order to address research gaps and encourage innovation within federal agencies and academic institutions. While this testimony is not exhaustive by any means, I have tried to illustrate priorities relative to fire weather research needs and potential areas for future investment. Below are a few key takeaways from this written testimony.

Summary of research needs and recommendations:

- Treat fire as a part of the earth system, and comprehensive coupled earth modeling approaches must be used to address issues related to wildfires and their impacts.
- Need improved understanding of how fire-atmosphere interactions impact fire behavior.
- Need further investment and development in operational coupled fire-atmosphere modeling systems (e.g., WRF-SFIRE). These tools should be operational across the US.

- Coordinated field measurement campaigns should focus on large high-severity fires (both prescribed fires and wildfires) to measure weather, plume dynamics, and fire behavior (e.g., FASMEE project).

- Enhance fire weather observations at wildfire incidents to support NWS IMETs and research.

- Improved fire characterization observations are needed at high spatial (< 50 meters) and temporal resolution (< 15 minutes) from both space and airborne platforms. Currently, these observations do not exist.

- Need higher temporal and spatial resolution forecasts of fire risk and this requires further investment in the National Fire Danger Rating System.

- Improve fuel moisture content observations for wildfire risk assessment and prediction.

- Establish a national and sustainable fire weather research funding program.

- Invest in already established wildfire engaged agencies rather than "reinvent the wheel."

- Increase federal investments targeted for competitive grant programs that academic institutions can apply.

- Provide funding to the USFS-NOAA MOU to support its research agenda and provide mechanisms for partners to engage in research.

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