Wildfire and Weather Radar: A Review

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Abstract Research in the pursuit of better understanding of fire behavior and fire-atmosphere interaction has frequently encountered a dearth of observational data, especially from events that cause most impact. Here we show that meteorological radar has been demonstrated as an effective tool for profiling the microphysics, thermodynamics, and fire behavior feedback of wildfire plumes, including for cases with deep and moist convection occurring in the fire plume. A synthesis of knowledge on the use of radar for the analysis of wildfire is presented, and the new term pyrometeor is introduced to describe the range of scatterers observed by radar, the reflectivity signature of which is determined by interacting processes of wildfire behavior and atmospheric convection. The reflectivity theories of pyrometeors are compared, and it is shown that there are gaps in knowledge on the size distributions of pyrometeors as well as the complex dielectrics. Observational case studies are compared across plume microphysics, plume thermodynamics and deep pyroconvection, and operational usage of radar to monitor wildfire. The dominant hypothesis of reflectivity is scattering from ash particles, though theories for scattering such as from larger debris exist, although evidence is limited for any hypothesis. Vortices have also been identified using Doppler velocity radar data, but there is limited understanding of their cause and influence on fire-atmosphere interactions. Recommendations are provided for methods and data sets to advance the application of radar for observing and understanding wildﬁre, including for plume microphysics and atmosphere-fire interactions.

Plain Language Summary This literature review covers the theory, laboratory, and observational uses of radar in the study of wildfires, providing the necessary background on “what” and “how” radar observes wildfire plumes and associated atmospheric processes. The understanding of theory alongside what has been observed can inform decision makers and future scientific study to better interpret weather radar observations of wildfire plumes and meteorology. It is intended that this will lead to an improved ability to prepare for, and manage, the hazards associated with wildfires.

1. Introduction
Wildfires represent significant natural hazards leading to loss of life and property from both direct and indirect effects, as well as causing significant economic and environmental impacts (Ashe et al., 2009; Bowman et al., 2017; Johnston et al., 2012; van der Werf et al., 2010). The effects of wildfires are being amplified by climate and land use change (Abatzoglou & Williams, 2016; Dowdy, 2018). The most severe effects result from large events that exhibit so-called “extreme” fire behavior, often involving fire-atmosphere coupling (Tedim et al., 2018). Research aimed to better understand the dynamics of wildfires and fire-atmosphere interaction is hampered by a dearth of observational data, especially from the most extreme events (Filkov et al., 2018). This review presents a synthesis of the history and capability of meteorological radar applied specifically to wildfire research. The aim is to determine from the literature: (1) characterization of the microphysics of targets observed by radar in wildfire plumes, (2) how radar observations can help describe and explain physical processes of wildfires and their plumes, and (3) how high temporal- and spatial-resolution information from radar can be practically used in future research of wildfire behavior and management.

A pyrogenic feedback process is one that originates from the wildfire, then feeds back to affect fire behavior, and may include pyrogenic winds, debris transport, lightning, or hydrometeors in the plume (Dowdy et al., 2017; LaRoche & Lang, 2017; Sullivan, 2017). These processes can be closely linked with fire behavior when deep and moist pyroconvection occurs (McRae et al., 2015). Deep pyroconvection is defined as where fire...
activity augments storm-scale convection (McCarthy et al., 2018). Gaps in knowledge relating to pyroconvection and interaction with fire behavior have significant implications for fire management when, for example, pyroconvection severely limits the effectiveness of fire suppression efforts. Understanding the interaction of wildfires with the atmosphere is therefore important for helping current and future preparedness for wildfires, their mitigation, and management.

Acquiring quantitative data on wildfires and wildfire-atmosphere interaction is challenging yet critical for enabling research to improve understanding and prediction of wildfires (Filkov et al., 2018). This lack of data limits the conceptual understanding of the processes that link wildfires to the atmosphere, as well as ability to calibrate and verify fire models, including fire spread and plume transport. Various approaches have been taken to the coupled modeling of wildfires with the atmosphere. However, this research is hindered by the lack of data to validate pyrogenic processes and deep pyroconvection on the scale at which they occur (Coen et al., 2013; Coen & Schroeder, 2015; Kochanski et al., 2013, 2016; Peace et al., 2015). Data sets on fire behavior and spread (e.g., isochrones and heat release rate) are also scarce from large events, as most data are collected from smaller experimental fires (Achtemeier, 2013; Filippi et al., 2013; Kochanski et al., 2012; Peterson et al., 2017). For smoke and pollution dispersion modeling, the injection height and concentration is critical but difficult to capture for wildfires (Goodrick et al., 2013; Kochanski et al., 2016; Price et al., 2016). Similarly, the nature, concentration, and trajectories of plume lofted combusting debris (known as firebrands) must also be modeled in order to resolve the behavior of wildfire in response to spotfires—ignitions ahead of the fire front. This may occur on scales of tens of kilometers ahead of the fire front (Cruz et al., 2012). All these processes require direct observation of wildfire plumes.

In situ observations of wildfires are difficult to gather, so remote sensing techniques are used. These include ground, airborne, and spaceborne active and passive sensing techniques. Satellite platforms have been extensively used in both research and operations for monitoring fires, stratospheric injection, aerosol, and air pollution (Al-Saadi et al., 2005; Kahn et al., 2008; Lentile et al., 2006; Martin et al., 2010). The challenges of spaceborne observations include the trade-off between resolution and orbit revisit time, as well as smoke and cloud clover, which can block thermally sensitive atmospheric radiation windows. Wildfire management often requires fire location at subdaily temporal resolution; these typically rely on satellite information as well as expensive airborne observation platforms (Robert et al., 2016). Ground-based active remote sensing can offer insights to fire behavior by directly observing the interaction between fire and atmosphere at high spatial and temporal resolutions (i.e., tens of meters and minutes).

Lidar and meteorological radar are two well-known ground-based remote sensing methods. Scanning lidar has been demonstrated to be an effective tool for capturing and analyzing the kinematics of fire plumes and moist pyroconvecive initiation. Figure 1 illustrates the advantages and disadvantages of different wildfire remote sensing techniques including radar and lidar.

The drawbacks of lidar include range (typically <10 km) and attenuation in moist convection (Banta et al., 1992; Clements, 2010; Lareau & Clements, 2016, 2017). At longer wavelengths than lidar, meteorological radar is well positioned for observation of the interactions of fire with the atmosphere albeit at coarser resolutions. Common meteorological radars fall into the ultrahigh frequency, UHF (914 MHz), L (1–2.6 GHz), S (2.6–3.95 GHz), C (3.95–8.2 GHz), X (8.2–12.5 GHz), Ku (12–18 GHz), Ka (26.5–40), and W bands (75–110 GHz). Depending on pulse length, beam width, and scan rate, meteorological radar is capable of a variety of resolutions ranging from meters to hundreds of meters while achieving unambiguous range into the hundreds of kilometers dependent on the pulse repetition frequency. Three-dimensional radar-derived volumes are constructed by stacking scan elevations, which is done operationally for radar networks in many countries every 4–10 min. Figure 2 shows an example of a sequence of scans of the Pinery fire, as observed from the Australian Bureau of Meteorology Buckland Park S-Band radar in Adelaide, Australia.

The scans of Pinery fire from the Buckland Park radar in South Australia (as shown in Figure 2) demonstrate the ability of radars to identify the evolution of wildfire plumes over time using predetermined scan patterns, which can be leveraged to aid operational response (Bureau of Meteorology, 2016). In the case of the Pinery fire, the scans every 6 min showed a close correspondence to the elliptical spread of the fire at the surface. Although the data contain appreciable clutter, the reflectivity from the burning and burnt debris of the fast-moving grass fire provided useful information for emergency managers where other spatiotemporal
intelligence was lacking. By contrast, research operations may use portable or fixed platforms to take customizable sector scans or cross-section scans with increased temporal resolution, that is, tens of seconds. Observations by radar depend on how the radar beam is scattered, the wavelength of the radar, the power and sensitivity of the radar, and how the radar beam is moved to construct a section or volume (i.e., the scan strategy). Typically, the radar beam is scattered by particles (such as rain droplets) in the atmosphere rather than clear air, which allows it to be used in the study of cloud particles. A model for reflectivity and other radar moments including Doppler velocity allows a high spatial and temporal resolution snapshot of the atmosphere that can be tailored to the weather phenomena or particles of interest.

This review examines the literature that has applied meteorological radar in the study of wildfire and frames the findings relevant to phenomena of fire-atmosphere interaction. In general, progress in the field of radar and wildfire research has been sporadic. Here we seek to synthesize understanding from the theoretical, laboratory, and modeling domains with observational work. To provide background, the theory of radar is covered, followed by those parameters known to affect radar reflectivity that are present in plumes above wildfires. The literature relevant to solid by-products secondarily produced by the chemical reaction of the wildfire and lofted into the atmosphere is then reviewed, along with the reflectivity models that have been derived experimentally and through numerical simulation. Observational case studies are split between plume microphysics, thermodynamics, and pyroconvection, as well as documented operational uses. Discussion is provided on the pressing challenges of the field, which also present novel avenues for future research. Where appropriate, comparisons are made to radar literature not specifically focused on wildfire, in particular volcanic ash studies.

**Figure 1.** Conceptual diagram of wildfire remote sensing methods, including spaceborne (satellite), airborne, lidar, and radar with basic characteristics, strengths, and weaknesses of each.
Figure 2. S-band radar Plan Position Indicator (PPI) observations of the Pinery fire in South Australia (25 November 2015). (a–h) The observations from the Buckland Park radar are shown in half hourly steps, though the radar operates on a 6-min scan cycle. Only the lowest elevation scan (0.5°) is shown. The reflectivity signature from the fire is delineated by the dashed red line.
2. Radar Theory and Wildfire Scatterers

The theoretical basis of meteorological radar and reflectivity is well understood for many meteorological phenomena (e.g., rain, hail, and snow) but less so for pyrogenic reflectivity (Fabry, 2015; Straka et al., 2000; Zrnić & Ryzhkov, 1999). Scattering media of two types exist in the atmosphere for radar wavelengths: clear air scattering (i.e., Bragg scattering) and particle scattering (Fukao & Hamazu, 2014a, 2014b; Ottersten, 1969). The reflectivity from particle scattering is generally studied for hydrometeors, and in the case of wildfires almost exclusively as particle based. Analysis of particle scattering for a given wavelength is based on Rayleigh and Mie scattering theory, where the particles are smaller than the wavelength for the former and equal or larger than the wavelength for the latter (Fabry, 2015). In particle-based (Rayleigh and Mie) scattering of a radar beam, reflectivity is normally expressed in rain-equivalent reflectivity factor (Z) using equation (1):

\[ Z = \frac{\lambda^4}{\pi^2 |K|^2 \eta} \]  

where \( \lambda \) is the wavelength of the radar and \( \eta \) is the radar cross section (RCS) per unit volume (Doviak & Zrnić, 1993). The dielectric constant (from which \( K \) is a function of) describes the complex permittivity of the scattering material in the RCS. In the context of hydrometeors, the RCS and dielectric factors are well known for a variety of microphysical conditions, with ongoing research continuing to improve understanding. It is an aim of wildfire radar research to establish the RCS and \( K \) for scatterers of pyrogenic origin, which can use other radar moments to constrain what is observed.

In addition to reflectivity, polarimetric radars are capable of providing information on wildfire plume characteristics. The simultaneous or alternative transmission of a horizontally and vertically polarized beam enables the calculation of a suite of metrics known as the polarimetric or dual-polarization moments (Kumjian, 2013). By calculating the difference and correlation between the voltage of the two channels, the differential reflectivity \( (Z_{\text{DR}}) \) and copolar correlation coefficient \( (\rho_{\text{hv}}) \) are output from dual-polarized radars. Additionally, the difference in phase shift of the return signal is described by the differential phase shift, or \( \psi_{\text{DP}} \). Using \( \psi_{\text{DP}} \), the specific differential phase \( (K_{\text{DP}}) \) can also be calculated, which halves the radar range derivative of \( \psi_{\text{DP}} \) to provide a measure of the \( \psi_{\text{DP}} \) per unit distance. Kumjian (2013) describes each of these dual-polarization moments, and their typical observations for hydrometeors (rain, hail, graupel, snow, and ice crystals), as well as shorter notes on nonmeteorological echoes in which fire observations are normally grouped. Examples of these parameters for hydrometeor returns include very high \( \rho_{\text{hv}} (0.85 \text{ to } 0.95) \) for rain droplets with increasing \( Z_{\text{DR}} \) for larger droplets, as compared to lower \( \rho_{\text{hv}} \) (0.85 to 0.95) for hail which has near-zero values in \( Z_{\text{DR}} \) due to the random tumbling on the hail stones. All values can vary for hydrometeors according to melting, freezing, and stabilizing of motion of particles, but consistent differences allow for effective distinguishing of particles, such as snow which will typically have notably higher \( Z_{\text{DR}} \) than other hydrometeors (in the range of 4–5 dB). There is therefore value in studying the RCS, reflectivity, and dual-polarization moments of pyrogenic radar targets where knowledge on the microphysics and thermodynamics is scarce to aid advanced signature interpretation, model validation, and operational guidance for wildfires.

2.1. Radar Reflectivity From Wildfire Plumes

Determining the nature and distribution of pyrogenic scatters is an important step to realizing the full benefits of radar returns above wildfires and represents an open topic of research. As seen in equation (1), the radar scattering of any object will depend on its RCS \( (\eta) \). Baum et al. (2015) described three categories of factors that affect the RCS of pyrogenic scatterers: geometric properties including surface area, cross section, aspect ratio, and general shape (such as if the particle is plate-like, needle-like, and spheroidal-like); dynamic properties including its orientation during ascent and descent of the particle, as is significant in snowflake RCS (Matrosov, 1992); and electromagnetic properties, which are a function of the material molecular composition and the degree to which it polarizable, as well as the mass, moisture content, and porosity of the biomass material. Notably, these properties can be differentiated by the temperature history, as well as any ongoing combustion (flaming or smoldering) or cooling of the particle. Figure 3 shows these three categories for a pyrogenic radar target, represented as ash.
The plumes of wildfires are made up of a wide spectrum of by-products and debris theoretically important to radar reflectivity at different wavelengths. Beyond the geometry and size distributions, the dynamic components of scatterers have not been extensively investigated, and the electromagnetic properties of scatterers only studied in laboratory settings with limited diversity of burnt biomass materials. It is therefore important to consider these factors among all possible scatterers lofted in the plumes of wildfires.

2.2. Scatterers

Here we examine all observations in the literature of combustion by-products relevant to radar wavelengths, including coarse mode particle emissions, ash, firebrands, and extinguished and scorched debris. In order to clarify terminology, we introduce term "pyrometeor" to describe all debris of a pyrogenic origin encompassing sizes greater than and including ash of a millimeter in diameter. This enables differentiation between both solid and liquid phase smoke particulates, including of a coarse mode (up to 20 μm; e.g., too fine for significant radar wavelength scattering at common bands such as S, C, and X), as well as from traditional hydrometeors of all phases which are known to be present in deep pyroconvective plumes.

All in situ observations of wildfire by-products have come from field studies entailing biomass burning experiments, where the aim has been to observe aerosol-sized particulates. Reid et al. (2005) detail in their review of biomass burning emissions that coarse mode particle emissions in the diameter range of 2 to 20 μm represent up to 10% of emissions from fires, with an even lower and unquantified proportion of "giant ash particles" up to a millimeter in size being produced from very intense fires. In addition to the giant ash particulates, they reported that partially combusted foliage and ash landed up to 50 km from the wildfire source. Reid et al. (2005) also highlight that geometric, equivalent mass, and aerodynamic diameter for these ash particulates can vary by up to a factor of 2, which can be compounded by the aggregation of such debris.

**Figure 3.** The three categories of properties that affect the radar cross section of burnt or partially burnt vegetation ash and debris.

![Diagram](http://example.com/diagram.png)
This range is only based on observations from slash burning in the United States, with a likely significant difference occurring in burning of live forest fuels, as well as in other fuel types (e.g., grasslands) and tree species of different physical properties such as eucalyptus found throughout Australia.

In contrast to giant ash (hereafter referred as “ash”) pyrometeors for which little work is available, considerable research has been undertaken to examine the size and geometric distributions of larger vegetation debris transported in the plume in the form of firebrands (Filkov et al., 2017; Koo et al., 2010; Tohidifl et al., 2015). The motivation for this research has been to form better generation and transport models of these larger pyrometeors to estimate the threat of downwind ignitions from active fire areas. This topic has been addressed extensively in the review by Koo et al. (2010) and will not be addressed in depth here. In general, firebrands are typically on the order of centimeters in short- and medium-range spotting, where spot fires may ignite in the range of a distance of meters to a kilometer from the fire front (Manzello & Foote, 2014; Rissel & Ridenour, 2013; Sullivan, 2017). Flux densities have been proposed for smaller firebrands beneath the canopy by Thomas et al. (2017) but not in a diversity of fuels and fire intensities. Pyrometeors that may also travel tens of kilometers in advance of the fire front in long-range spotting (typically in Australian eucalypt fuels; Cruz et al., 2012) can be up to 4 m in length (Hall et al., 2015). While an extreme example pyrometeor size, this illustrates the wide distribution of sizes for pyrometeors with poorly understood density fluxes. The size distributions of much larger pyrometeors (including firebrands) will fundamentally affect the Rayleigh approximations of reflectivity factor as it is sensitive to the sixth power of scatterer diameter as is well understood for rainfall (Doviak & Zrnić, 1993). The broad lack of quantitative information in this respect has limited any inference of how these pyrometeors may affect radar scattering.

Beyond firebrand studies, there has been no investigation into the distributions or densities of extinguished or scorched canopy foliage transported downwind (Reid et al., 2005). Anecdotal evidence for this sort of debris exists, but only one study has considered this a candidate for scattering in radar wavelengths (Palumbo et al., 2013). Further complicating this is the possibility that millimeter-size soil particles, dust particles, and potentially even larger noncombustible materials have been noted to be entrained due to the strong inflow of fires (Radke et al., 1991; Reid et al., 2005; Reid & Hobbs, 1998).

In general, the lack of thorough in situ observations of pyrometeor size has restricted the interpretation of wildfire on radar in the literature to date. The theory most cited is that ash particles make up the majority of pyrometeors, but this neglects the full spectrum of lofted debris in wildfire given the material being combusted, especially close to the source that could act as both Rayleigh and Mie scatterers. As a result, the size distribution and origin of pyrometeors is poorly constrained and does not form a sound foundation for pyrometeor scattering theory.

### 2.3. Complex Dielectrics and Models of Reflectivity

The complex nature of combustion by-products lofted results in ambiguity not just in the size and form of pyrometeor RCS but also in how the material responds to the radiation at a molecular level. This is described by the complex dielectric properties of the material (described by the constant $K$ [equation (1)]) and is measured or modeled using the material’s dielectric permittivity ($\varepsilon$). To date, there has been very limited bridging between formulated models of reflectivity, complex dielectrics, and radar observations of pyrometeors. This manifests in challenges of modeling the radar reflectivity and opposing hypotheses for pyrometeors. In the absence of a generalized theory and model, the interpretation of radar observations can be tenuous for speculating on how phenomena and signatures relate to fire behavior.

A limited number of laboratory and modeling experiments have taken place to model the complex permittivity, RCS, and reflectivity of pyrometeors as summarized by Table 1. Melnikov et al. (2009) were the first to propose a reflectivity model for pyrometeors, following dual-polarization observations by Melnikov et al. (2008). They considered oblate and prolate spheroids as responsible for the RCS, although referring to the scatterers as smoke. They leveraged existing literature on dielectric permittivity and the hygroscopic nature of ash to constrain the absorbed (real) part of $\varepsilon$ to be in the range of 3 to 80, using a hypothesized value of 20 (Adams et al., 1996; Campbell & Ulrichs, 1969; Carrico et al., 2003; Cocker et al., 2001). This method allowed them to constrain the flutter angle of ash particles to 23.5° to 27.5° from a normal (horizontal) plane. They concluded that $\rho_{hv}$ could not depend on $\varepsilon$ and that in this scenario, the minimum $\rho_{hv}$ they could model was 0.56. As this was significantly higher than $\rho_{hv}$ observed from Melnikov et al. (2008), they stated that
the particles that scatter the 10-cm wavelength radiation cannot be plate-like, thus leaving needles as the best candidate for the geometry for scattering. Examining the relationship between the aspect ratio of their modeled particles and $\varepsilon$, they argued that the space of permittivity must reach $\varepsilon = 15$ to match the observations. However, their method introduced several unacknowledged assumptions about the consistency of $\varepsilon$, not only between different fires (for which fuels, intensity, and moisture contents will vary) but also within the event assuming that the debris density remained constant through time and space.

The work of Baum, Thompson, et al. (2011) was the first of a series of studies whose aim was to construct theoretical, laboratory, and simulation baselines to form a scattering model of Australian flora ash as detailed in Table 1. The authors examined powdered ash using the Nicholson-Ross-Weir method. The models were not immune from attenuation and transfer issues and assume size distribution with a mixing law, a limitation as compared to the method of Melnikov et al. (2009), which used observations to constrain the findings. However, the experiments were able show the relationships of exposed temperature and moisture content as significant, with less significance on difference between Australian species. The most comprehensive attempt at a scattering model for pyrometeors was proposed by Baum et al. (2015). The key advance was to incorporate the dynamic components into simulation, being ascent or descent of the particles. They considered ash to be random and chaotic in ascent due to the highly turbulent environment, and two modes of dynamic behavior in descent, including fluttering and tumbling (Andersen et al., 2005a, 2005b; Smith, 1971; Willmarth et al., 1964). They observed that the distribution of eucalypt ash in descent phase has a standard

<table>
<thead>
<tr>
<th>Model</th>
<th>Pyrometeors</th>
<th>Methodology</th>
<th>Methodology</th>
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<tbody>
<tr>
<td>Melnikov et al. (2009)</td>
<td>Reported as &quot;smoke,&quot; described as needle-like pyrometeors.</td>
<td>Mapped scatter model parameters of prolate spheroids as per Zrníć and Ryzhkov (2004) to match observations of Melnikov et al. (2008). This included observed ranges of $Z_{eq}$ (2.7 to 2.9), $n_{vess}$ (0.32 to 0.34), and $n_{vess}$ ($-10^6$ to $-6$).</td>
<td>Employed a mixing law (as per Sihvola 2000) to allow fragile ash samples to be tested for dielectric properties in an X-band waveguide experiment. Assumed spherical particles. Showed little difference between the plant species tested.</td>
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<tr>
<td>Baum, Thompson, et al. (2011)</td>
<td>Powdered ash from species of Eucalypt (at oven dry and 30% fuel moisture content), Bracken Fern, Casuarina, Wattle, and Cypress</td>
<td>Built on Baum, Thompson, et al. (2011) with the addition of combining ash at different temperature and ash-to-air volume fraction across samples.</td>
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<td>Baum, Thomson, et al. (2011)</td>
<td>As per Baum, Thompson, et al. (2011), experimenting with different heat exposures</td>
<td>Measured complex permittivity and then modeled for volumetric backscattering capacity with respect to radar cross section for different wavelengths. Demonstrated the strong potential for high-frequency radar (millimeter wavelength; e.g., W-band at 95 GHz)</td>
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<td>Baum et al. (2014a)</td>
<td>Ash of Messmate Stringybark (Eucalyptus obliqua) with varying exposed temperatures.</td>
<td>Proposed generalized model for complex permittivity according to temperature for X and Ka band wavelengths. Demonstrate statistical dependence of the complex permittivity on exposed temperature associated with porosity and equivalent mass loss.</td>
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<td>Baum et al. (2014b)</td>
<td>Ash of Messmate Stringybark (Eucalyptus obliqua) with varying moisture content.</td>
<td>Modeled reflectivity in a full electromagnetic solver framework demonstrating sensitivity to fuel moisture content. Argued that the permittivity would require moisture contents in ash as high as 30%, which they state as unlikely based on the observed moisture absorption rate of eucalypt ash particles exposed to different temperatures (between 150 and 400 °C, based on Ghorbani et al., 2012).</td>
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<td>Baum et al. (2015)</td>
<td>Ash of Messmate Stringybark (Eucalyptus obliqua).</td>
<td>Examined the effect of geometric, dynamic, and electromagnetic properties of eucalypt ash discussed in previous studies, proposing several theoretical and statistical models for the RCS of the ash.</td>
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Note: radar cross section.
deviation of 38.98°, higher than that of snowflakes, and higher than that proposed by Melnikov et al. (2009). They also highlight that the broadside of a pyrometeor should align to the direction of fall when in descent mode, which could explain the results of Melnikov et al. (2009) regarding the conclusion of needle-like scatterers, presumably North American pine species. At low scan angles of a radar and with a dominant descent mode of flapping, a radar will effectively see the targets as needle like. No studies have examined the cross correlation between the factors that affect the RCS of any pyrometeors, such as the relationship between the dynamic mode determining orientation and aspect ratio. It is reasonable to infer that the use of more radar observations could enable better derivation of the dielectric for ash for a comprehensive model, with the benefit of the added information on moisture for studying the thermodynamics of fire-atmosphere interaction.

Understanding the RCS of pyrometeors includes understanding of all the processes which should affect the material properties (and thus radar reflectivity). However, there have only been two methods attempted at resolving the RCS. Of the work published on these methods, electromagnetic properties of ash have received the most attention with only one attempt to incorporate dynamic and geometric factors affecting the RCS. None have used constraints from observations of an actual size distribution of pyrometeors. No study of larger pyrometeors has been considered in the context of theoretical work even though similar dynamic modes of ascent and descent exist in firebrand transport (Sullivan, 2017). Combined, these ambiguities and lack of constraints on a scattering model restrict the interpretation of radar signatures of wildfires in other research, as well as in operations.

3. Observational Case Studies

3.1. History of Wildfire and Radar Observations

There have been remarks and studies on the observation of wildfire plumes by radar in the literature since the technology was first applied to meteorology. Unlike other fields of atmospheric science using radar (i.e., in the study of precipitation, wind, and cloud microphysics), application toward targets of pyrogenic origin has been sporadic, with a number of papers reporting the use of radar in a supplementary capacity to study deep pyroconvection. However, few of any fire and radar papers have focused on understanding the relationships between radar scatterers and frequencies. This gap in knowledge could lead to significant advances across fields if filled.

The first report on the sensitivity of radar to pyrogenic scatterers was by Jones (1950), where remarks were made on observations of a smoke plume and capping cumulus cloud produced from a fire burning bales of cork. Similar notes were made by Hiser (1961) and Birch (1968), prior to when Lhermitte (1969) obtained radar observations at close range during the Project Flambeau experimental fires (Countryman & Storey, 1969). Turbulent flow within the plume was first described by Lhermitte (1969) through observations of the Doppler spectra from experimental fires conducted as a part of military research into the bulk interaction of many individual fires. No details were provided on the nature of scanning that occurred, but the findings raised the possibility of the quantitative ability of radar spectra in the context of wildfire and combustion science.

Reid and Vines (1972) were the first to investigate the dynamic properties of plumes above wildfires, noting their differences to thunderstorms on radar. The methodology underpinning the paper was a technique of manual analysis comparing with photogrammetry to assign “turrets” to the pulses of the plume above the fire in radar signatures. The use of this terminology is broadly equivalent to the description of thunderstorms as “cells” (Byers & Braham, 1949) in cases where thunderstorms appear on radar as temporally evolving well-defined entities. Reid and Vines (1972) make the case of the term turrets as the appropriate description and framework for the pulses of the plumes in cross flow as they appear in radar signature (Morton, 1956; Morton & Ibbetson, 1996). Annotations of the observed plume showed a pileus cloud, indicative of deep convection, though the terminology of deep pyroconvection was not used at this point. As Potter (2012) highlighted, the turret tracking framework presented in these studies has enabled some of the only quantitative plume horizontal and vertical velocity measurements in the literature to date.

Following Lhermitte (1969) and Reid and Vines (1972), the literature followed a largely application-based approach to the use of radar. Closely linked with the application is the scan strategy employed, typically
horizontal cross sections known as plan position indicator scans stacked into a volume. Less common and more applicable for research are vertical cross sections known as range-height indicator scans. While there have certainly been papers addressing multiple aspects of wildfire plume signatures on radar, there have been distinct outcomes that can be divided between the microphysics of the plume, plume thermodynamics and deep pyroconvection, and the use of radar operationally for wildfire.

### 3.2. Wildfire Plume Microphysics

As the study of cloud processes can be conducted on the microphysical scale of the individual particulates or hydrometeors (as opposed to that of the whole cloud), the same topic has been addressed by multiple papers on radar and wildfire (on the scale of pyrometeors). The hypothesis of ash as scatterers recurred across multiple papers making observations of plume microphysics, though different methods have raised alternate hypotheses and firm evidence is not present for any.

Studying plume microphysics with radar began with Banta et al. (1992) who reported observations alongside theory on plume microphysics. The authors put forward that the observed reflectivities between 10 and 20 dBZ were far too high for micrometer-sized particles, and that ash and debris in the range of 1 mm to 1 cm were much more likely to be the scatterers observed. They noted the circular polarization observations of 0 dBZ, indicative of flat or needle-like targets, measured as the difference of received reflectivity from the simultaneous left- and right-hand polarized transmitted beams. Their findings cited the anecdotal reports of pine needles and needle-like fibers during airborne observation campaigns (Eagan et al., 1974; Radke et al., 1978, 1991). It was shown that even a low concentration of macro-sized (>1 cm) needle-like scatterers could produce the observed reflectivity. This initial finding has shaped much of the literature subsequent to it around scattering mechanisms, despite the lack of quantitative evidence for it. Matching in situ scatterers of this macrosize to observed reflectivity has yet to be revisited, and subsequent literature has usually failed to highlight the sensitivity of stated reflectivity to the unknown dielectric constant of pyrometeors.

The analysis of microphysics can be enhanced by the incorporation of multiple radar wavelengths. Rogers and Brown (1997) used observations at a fire at a paint factory in Montreal collected by three radars: a scanning S-band as well as vertically pointing X-band and UHF radars. The finding of interest was that the longer-wavelength UHF radar observed 20- to 30-dBZ greater equivalent reflectivity factor than the X-band radar. Meanwhile, a lidar ceilometer in the same location observed no backscatter, a difference similar to that noted observed with other meteorological phenomena with both Raman lidar and ceilometer (Geisinger et al., 2017; Madonna et al., 2009). The authors theorized that this was a result of scattering from particles greater than 1 cm in size or as a result of Bragg scattering from the refraction of heat and turbulent mixing on the plume boundaries. Rogers and Brown (1997) detailed the assumptions of using a dielectric constant of equivalent to water in the radar equation. A specific note on the comparability of this event to others observed in the literature was that it was a chemical fire (latex and alkyd paints, liquid tars, mineral oil among others in lesser quantity). The smoke composition was, as a result, different to that of other published observations, which have been of wildfires burning in forest or grassland environments. The work remains the only multiwavelength radar analysis of combustion by-products.

Extending the analysis, Erkelens et al. (2001) examined the correlation between the reflectivity of the UHF and X-band radar in the Rogers and Brown (1997) observations. They theorized that coherent particle scattering from the variability of the fire debris itself may cause a dominant mode of scattering. In other words, the turbulent mixing causes gradients of debris sufficient to form the reflectivity observed in the study, not the Bragg scattering from the turbulence itself. The case made by Erkelens et al. (2001) is, however, constrained to the comparison of the X-band and the less common 33-cm UHF wavelength for which no other observations of fire have been made.

Another study of a structural fire was the dual-polarization observations of Jones et al. (2009) from an apartment fire in Huntsville, Alabama. They eliminate aerosol-size smoke (less than 10 µm) as a candidate scatterer by deriving —66 dBZ as the maximum possible reflectivity based on published aerosol size distribution in smoke (Hand et al., 2005; Jayaratne & Verma, 2001). At significantly below the sensitivity of the C-band radar observations they study, they conclude that particle-based scattering from ash and debris causes the reflectivities observed. The authors argue that this regime is the most probable scenario given the strong
sensitivity to the largest particle in a given volume based on the Rayleigh approximations, but acknowledge that coherent scattering from the turbulent plume (including Bragg scattering) could still be significant.

Hufford et al. (1998) argued that the pyrometeors to which the radar is sensitive are more likely to be larger firebrand materials. By making the case of firebrands as pyrometeors they make the case for an operational usefulness of this reflectivity for predicting rates of spotfires on the fireground. While the theory does not broadly align with the rest of the literature, it cannot be ruled out while the size distribution of pyrometeors remains unknown, especially for the most intense of forest fires (Finney & McAllister, 2011).

Rosenfeld et al. (2007) were the first to employ automated echo top time series analysis in their investigation of pyroCb microphysics, from the Chisholm firestorm in Alberta, Canada. An intense reflectivity core (>40 dBZ) observed by Rosenfeld et al. (2007) occurred near the surface and coincidentally above a rain gauge with negligible rain recorded, suggesting that the radar scatterers in this case were ash and similar debris, and as such the results align with that of Banta et al. (1992). The authors analyze the height of the maximum return in time series, as well as snapshots at 8, 20, 30, and 40 dBZ to compare against satellite data with little detail on the assumptions involved with modes of reflectivity in the pyroCb.

Informing the more recent studies of plume microphysics has been the use of dual-polarization radar moments. The consensus with such polarimetric radar results is now that the scatterers within fire plumes are dominantly ash (Jones & Christopher, 2010a, 2010b; Lang et al., 2014; Lareau & Clements, 2016; Melnikov et al., 2008, 2009). The dual polarization in the work of Melnikov et al. (2009), Lang et al. (2014), and Lareau and Clements (2016) has consistently pointed to poor correlation in voltage between the vertical and horizontal channels in the correlation coefficient ($\rho_{hv} < 0.6$) and strong differential reflectivity ($Z_{DR} > 5$) for the visible smoke regions of plumes in the S-band frequency. These parameters also matched the dual-polarization observations of Jones et al. (2009) in the plume above a residential structure fire, implying less of a relationship to the fuel type of a fire. Above the condensation level in the context of a pyroCb, decreasing (increasing) $Z_{DR}$ ($\rho_{hv}$) with height and with proximity to the edges of the deep convective cloud was shown to be associated with lightning generation (Lang et al., 2014). An extension of this work by LaRoche and Lang (2017) showed this occurring in a sample of 10 fires, where ice riming as observed in dual polarization consistently preceded lightning formation as the ash volume transitioned to a level in the pyrocumulus where glaciation occurred. The study of pyrocumulonimbus (pyroCb) microphysics is perhaps a more constrained approach to studying plume microphysics, where traditional cloud microphysics can be used to determine known hydrometeor types. Profiling the microphysics of plumes below the condensation level is certainly a challenge, but worthwhile given the interdisciplinary applications with combustion science. As with hydrometeors, understanding these microphysical regimes is also critical to understanding processes occurring at the scale of whole plumes and clouds.

Different perspectives on theory and speculation on scattering mechanisms have been presented in the observational literature, including ash or firebrands as particle scatterers, density gradients in pyrometeors resulting in coherent scatter, and temperature gradients causing Bragg scattering. Ash has received by far the most attention as a hypothesis, with recent papers further informed by dual polarization aiding this theory, with smaller aerosol-sized particles (normally considered “smoke”) not normally treated as a viable scatterer for most studied radar wavelengths. No observational studies have set out with specific aims on the ability of radar for examining plume microphysics. While it is unlikely that these theories of scattering in wildfire plumes are mutually exclusive, interpretation of wildfire and associated atmospheric processes must be informed by one or more of these theories.

### 3.3. Plume Thermodynamics and Deep Pyroconvection

There have only been a limited number of studies investigating plume thermodynamics directly, with most papers leveraging plume height assessment in time series combined with other information on the wildfire or local meteorology. Vortices represent the key dynamic feature for measuring the intensification, structure, and level of hazard in severe thunderstorms (Lemon & Doswell, 1979; Markowski & Richardson, 2009), but the significance of their presence in wildfire and pyroCb is not clear in both research and operations (Potter, 2012). Structural analysis of thunderstorms involves the identification of hydrometeor phases and reflectivity cores. Given an assumption of particle scattering from pyrometeors and complex dielectrics near that of water, density structures in rain-equivalent reflectivity signatures should be determined by fire behavior.
through time, plume dynamics, and detrainment of the pyrometeors. There have been efforts to connect observed fire behavior with changes and signatures in radar imagery, but quantification in this regard has been limited. To use radar observations quantitatively, the radar data are typically processed to a map or time series of maximum height.

Several types of vortices have been interpreted from radar signatures in the literature. Banta et al. (1992) showed plume bifurcation in a bent-over plume in Colorado (USA) with two counterrotating horizontal vortices. Murdoch et al. (2016) analyzed the impact of a horizontally aligned longitudinal vortex on burn severity patterns in the Bastrop Complex wildfire (Texas, USA), aligning with previous work in simulation that showed such vortices to be a determining mesoscale factor in extreme fire weather conditions (Engel et al., 2013). The mobile X-band radar observations of McCarthy et al. (2018) leveraged a range-height indicator scan strategy to show coupling of crown fire in localized areas to turrets and shear generated vortices in the plume updraft during the Mt. Bolton wildfire (Victoria, Australia). In the same study, plan position indicator observations from the Apsey West prescribed fire (Queensland, Australia) quantified vortices from a single rotating vertical vortex above the gridded aerial ignition fire (as seen in Figure 4b). In these studies, the analysis of vortices has been qualitative, and the interpretation could be aided by the methodologies used to analyze severe thunderstorm evolution.

While the occurrence of pyroCb has received increasing attention in recent years, quantitative radar interpretation of these storm events has focused on echo top time series. The echo top analysis technique first used by Rosenfeld et al. (2007) has been employed in several other deep pyroconvection studies, including as a means for combing time series analysis of the plume with other indicators of fire meteorology and behavior (Fromm et al., 2012; McRae et al., 2015). Despite the limitations (Lakshmanan et al., 2012), echo tops have allowed for effective trigger analyses (McRae et al., 2015), spatiotemporal tracking of pyroconvective features, and interevent comparison (Dowdy et al., 2017) and are more quantitative than height determined manually, usually from cross sections (Bannister, 2014; Cruz et al., 2012; Fromm et al., 2006; Jones & Christopher, 2009, 2010a; Luchs & Pendergrast, 2012; McRae et al., 2013). Other studies have leveraged radar to illustrate the extent of the atmospheric coupling of wildﬁres (Cruz et al., 2012; Fromm et al., 2006, 2012; McRae et al., 2013, 2015). For example, Fromm et al. (2006) and McRae et al. (2013) both examine the Canberra (Australia) conflagration and pyroCb of 2003, which inferred a pyrogenic tornado, though the lack of Doppler data prohibited the identification of vortices, limiting the analyses of storm evolution. Peace et al. (2018) analyzed the growth and structural aspects of two pyrocumulonimbus events during the Waroona bushfire (Western Australia). Analysis of the evolution with radar included initiation along a sea-breeze boundary, surface and elevated core formation, downdraft core formation, and vertically aligned vortex imbedded within a pyroCb as shown in Figure 4.

Wildfires can be affected by and generate vortices, and case studies have used radar signatures to infer single rotating plumes, bifurcated plumes with counterrotating vortex pairs, shear-generated vortices in updrafts, a rotating updraft in a pyroCb, and horizontally aligned vortices impacting fires. However, the connections made between these features and observed fire behavior have been qualitative. Quantitative analysis has instead incorporated echo tops to study the temporal evolution of plumes and pyroCb, aiming to determine triggers and feedback with fire behavior.

3.4. Operational Usage of Radar in Wildfire

Only a small number of studies have evaluated the operational usefulness of radar data for monitoring wildfires, though these studies highlight its key value as a tool and potential for expansion in operations. It has been linked to step changes and growth rates in fire behavior, fire location, and tracking and possibly observing trends and rates of fire propagation by firebrands through spotting.

As rapid escalation of fire behavior has been shown to be closely correlated with the onset of pyroCb captured by radar (Dowdy et al., 2017; McRae et al., 2015), increasing size and reflectivity in a signature will indicate step changes and diurnal patterns in fire behavior. Duff et al. (2018) found that quantifying the volume occupied by the radar beam over a reflectivity threshold in the vicinity of wildfires acted as a robust indicator of growth in wildfire area. The most skill ($R^2 = 0.64$) in estimating the area change was found with a threshold of 10 dBZ; however, the assumptions of scattering theory, particularly important at lower signal strengths, were not stated.
Figure 4. Vortex signatures identified above forest fires (a–f) from the Waroona fire on the Perth (serpentine) radar at 3:24 UTC and (g–i) from the Apsey West prescribed burn at 4:40 UTC. (a)–(c) show the reflectivity as a Plan Position Indicator (PPI), reconstructed Range Height Indicator (RHI), and combined oblique view, respectively, during a stage of the fire when it coupled with a pyrocumulonimbus. (d)–(f) show the same scans in Doppler velocity. Along the bottom, (g)–(i) show PPIs from three tilts of the radar at 4, 6, and 8 from the UQ-XPOL radar. The burn containment line is indicated in pink in the bottom panel. The Waroona fire panels are adapted with permission from Peace et al. (2018), and the Apsey West panels are modified from McCarthy et al. (2018).
Bannister (2014) conducted a detailed analysis of radar and wildfire evolution as described by operational reports of Kilmore East fire during the Black Saturday fires of 2009 in Victoria, Australia. The authors concluded that radar is capable of making real-time identification of fire location, as well as documenting escalating fire intensity. Radar was reported to be used in this capacity again during the Pinery fire (South Australia), where these techniques were used by meteorologists and fire authorities to estimate the timing of such a change, as well as infer fire location from the reflectivity signature (Bureau of Meteorology, 2016). The fine-line boundary discussed in this report is visible in the lowest scan elevations in Figure 2 and can be seen impacting the fire at 4:30 UTC (Figure 2f).

Differential reflectivity and high spectral width were used by Palumbo (2016) for plume tracking of wildfire using a phased-array X-band system, demonstrating proof of concept for five fires in South Australia. The tracking method is capable of determining the direction of pyrometeor advection (and, by analogy, fire spread direction), but no direct comparison to fire spread was made. Similarly, Jones and Christopher (2010a) modified a storm tracking algorithm to track debris from grassfires to gauge the escalation of individual fires. Palumbo (2016) suggested that foliage (burnt or partially burnt) make up the dominant scatterer, while Jones and Christopher (2010a) interpret the scatterers as similar size debris from grassfires.

If smoldering or flaming firebrands are at least partially and discriminatorily present in radar signatures as Hufford et al. (1998) suggest, it would represent a valuable application of remote sensing operationally. This possibility has yet to be examined in detail but has potential for aiding fire management. Another untested use case for operations is the use of radar reflectivity as a proxy for wildfire aerosol smoke pollution. Price et al. (2018) compare the areal footprint of reflectivity signatures above wildfires and prescribed burns to gauge their relative impact on air pollution, but the findings are limited by the use of an arbitrary cutoff of 1 dBZ in rainfall equivalent reflectivity factor. Radars with different frequencies, beam width, power, and range to targets made use of such a threshold in this study. Findings from plume microphysics studies suggest that aerosol-sized smoke has a decreasing capability to cause observable reflectivities when their size is around or below 10 μm; however, their signatures can be operationally useful for this purpose in the absence of other real-time data.

Another apparent application of radar for wildfire has been informing firefighter safety by detecting and warning of convective outflows. Two notable uses of radar in this capacity are apparent in the forensic use of radar in the Yarnell Hill fire (Arizona, USA) fatality investigations (Arizona Department of Forestry and Fire Management, 2013) and the reconstruction of the outflow impacting the Waldo fire in Colorado, USA (Johnson et al., 2014). The analysis by Johnson et al. (2014) of the Waldo fire leveraged manual interpretation of radar fine-line boundary for positioning of the convective outflow, as well as plume growth as analyzed by reconstructed range-height indicators and echo tops. Similar analysis has been applied to analyze the gravity currents of sea breezes, which are known to have a similar but perhaps less intense effect on wildfires (Hanley et al., 2013). Fine-line boundaries associated with a dramatic change in air density are also typically observed in southern Australia from the leading edge of cold fronts, which bring strong wind speed and direction changes affecting fire behavior (Bannister, 2014; Crook & Sun, 2002; Garratt, 1988; May et al., 1990).

While radar has long been a decision support tool for meteorologists, there is a specific use case of radar data for fire managers by directly collecting intelligence for firefighter safety in meteorological hazards, as well as for support of incident decision making in changing fire intensity and location especially in the absence of other real-time data. Studies focusing on operational capability of radar have shown that it is an effective monitoring tool for pyroCb initiation, fire area growth, and wind change impacts; however, a framework combining fire location and direction inference, along with profiling firebrand potential, has yet to be proposed.

4. Current Challenges and Future Research Directions

While there are multiple technical challenges in the study and use of radar in wildfire, they present avenues of development in the field that, if addressed, should bring improved quantification to the data scarce field of wildfire dynamics and behavior. Namely, these are (1) developing a comprehensive model of pyrometeor microphysics, (2) leveraging existing work from the use of weather radar to monitor volcanic ash plumes, and (3) developing analysis techniques of wildfires in radar data for analyzing fire-atmosphere feedback and plume dynamics.
There are multiple interacting factors that determine the size distributions, complex permittivity, and RCS of pyrometeors, which are illustrated in Figure 5.

Extensive work has profiled the distribution of biomass burning by-products up to the scale of ash and independently on larger firebrands, but no size-agnostic sampling of pyrometeors in or from plumes has ever occurred. Biomass burning aerosol and smoke studies have not been able to resolve ash particles, and firebrand studies do not sample below the size of ash (Eagan et al., 1974; El Houssami et al., 2016; Radke et al., 1978, 1991; Reid et al., 2005; Reid & Hobbs, 1998; Rissel & Ridenour, 2013; Thomas et al., 2017; Tohidi et al., 2015). Future observations should focus on the full pyrometeor size distributions at multiple distances and elevations from the source, requiring novel field and experimental design. The use of higher-frequency weather radars combined with radiometers would be more adapted to the smaller sizes of particles such as aerosol-sized smoke and water vapor, relating to key questions of initiation of pyroCb clouds (Bryan et al., 2017). Further evidence is required to support the hypotheses of ash pyrometeors as dominant scatterers, which introduces several other factors into the physical processes that affect the RCS. Baum, Thomson, et al. (2011) and Ghorbani et al. (2012) showed that increasing the exposed temperature significantly reduces the complex permittivity relevant to the RCS of ash. If this finding is validated, radar may be able to provide a temporally continuous record of wildfire temperature and thus fire intensity, yet is a theory difficult to corroborate with observation. Only Melnikov et al. (2009) have examined the viability of a polarimetric-based radar reflectivity model. Further, no microphysical studies outside of observation have addressed moisture absorbed into the pyrometeor material, aggregation of material, or nucleated around it. Nucleation on wildfire aerosols or pyrometeors was observed by Lang et al. (2014) in showing the polarimetric characteristics of the particles transitioning into “dirty” hydrometeors in a pyroCb (processes 5 and 6 in Figure 5), later reinforced to be significant in pyrogenic lightning formation across multiple events by LaRoche and Lang (2017). Nucleation around such particles means that a core and shell model of scattering or a variant of it may apply in this context (Fabry & Szymer, 1999; Rasmussen & Heymsfield, 1987). Studies linking observations and laboratory experiments with simulations are missing in the field of fire and radar.
with several unexplored methodologies. Future work should certainly adopt the broadly successful approaches to hydrometeor research, where extensive field campaigns (such as MC3E, IPHEX, and OLYMPEx) have leveraged multiwavelength and multiphysical radars to detail cloud microphysics (Chandrasekar et al., 2015; Houze et al., 2017; Jensen et al., 2016). A common feature of such field campaigns is the leveraging of spaceborne meteorological radar, and in particular the Global Precipitation Mission for which no studies have been published on their application to directly observing wildfire plumes. The lack of targeted studies and coordination across the sporadic studies of wildfire and radar has limited the advances in the science, which has influenced its uptake operationally. This is in comparison to the use of radar in volcanology, which has received far more attention and coordination.

Volcanic ash microphysics and the thermodynamics of volcanic plumes have a number of similarities with pyrogenic ash, debris, and clouds, and the cross application of radar methodologies from volcanology to wildfire has never been addressed. Understanding of the scattering mechanisms for volcanic ash and the spatiotemporal evolution of radar moments within a volcanic plume could be leveraged to improve our understanding of weather radar applied to wildfire plumes. Use of ground-based microwave weather radar to study volcanic ash plume dynamics, quantify particle size distributions, and mitigate impacts of volcanic ash clouds has seen an increased interest over the last decade, most of which was highlighted in the review on this topic by Marzano et al. (2013). A complete microphysical scheme including particle size distribution, dielectric properties, and terminal velocities to characterize volcanic ash proposed in radar volcanology has enabled operational volcanic ash retrieval algorithms (Madonna et al., 2010; Marzano et al., 2013; Montopoli et al., 2014; Vulpiani et al., 2016). In particular, T-matrix approaches and lidar and radar comparison techniques used in radar volcanology have yet to be tested in radar wildfire literature (Madonna et al., 2013; Marzano, Barbieri, et al., 2006; Marzano, Vulpiani, & Rose, 2006; Marzano et al., 2015). In a similar regard, the study of dust and sand storms with radar has applied techniques relevant to wildfire study and detection with radar, such as examining the relationship of backscatter to quantified visibility and the dependency of reflectivity on particle electrostatic change (Dong et al., 2014; Goldhirsh, 1982; Zhou et al., 2005). As the generation of pyrometeors is highly stochastic, methodologies cannot be directly adapted to wildfire. However, adapting these methodologies to wildfire in future studies could be aided by characterization of condensation and freezing levels, probabilistic approaches based on decreased likelihood of larger pyrometeors to occur further aloft from the fire source, and a thorough analysis of radar dual polarization moments with other moments of Doppler velocity. The usage of radar in wildfire has been outpaced by that of volcanology and far more coordination in the radar community is required to address these challenges. Capabilities of detailed microphysics and particle size quantification incorporated into operational algorithms would enable broader use of the technology in the science of wildfire.

Independent of advances that could emerge from better understanding of the scattering properties of pyrometeors, there is significant work to be done in forming frameworks for analyzing radar data in an operational capacity. Reid and Vines (1972) presented the turret tracking method, determining proxies for vertical and horizontal velocities. In subsequent papers an automated approach was opted for in echo top time series, but at a cost of information on the pulsing nature of plumes in cross-flows (Dowdy et al., 2017; Fromm et al., 2012; McRae et al., 2015; Morton, 1956; Morton & Ibbetson, 1996; Rosenfeld et al., 2007; Tohidi & Kaye, 2016). Vortex features of different scales and forms have been observed in the Doppler imagery captured by radars. While vortices are both cause and effect of visibility and the dependency of fire behavior, in the context of deep pyroconvection the relationships remain unclear (Tohidi et al., 2018). There would therefore be utility in adapting these concepts and analyses, as well as collecting further data and examples so that a coherent literature and training guidance can be arrived at for such signatures as is the case for thunderstorms (Bluestein, 2013; Fukao et al., 2014). Further, the field of severe thunderstorm research has the potential to provide significant insights, where numerous methods of thermodynamic and debris transport analyses exist, much like how approaches can be borrowed from volcanology (Bodine et al., 2014, 2016; Broeke & Jauernic, 2014; Snow et al., 1995; Snyder & Rydzhkov, 2015). The adaptation of these methods to wildfire should be informed by targeted field campaigns using various remote sensing platforms (radar and lidar active sensing as well as airborne and spaceborne platforms) with more focus on transition of research to operations (Bluestein, 1999; Houze et al., 2017; Lareau & Clements, 2016; McCarthy et al., 2018). A framework for analysis of wildfire with radar data would be best delivered as science-based tools that meet the unique needs of intelligence gathering for wildfires.
5. Conclusions

Radar has an important role to play in addressing knowledge gaps for dangerous fire conditions. Primarily, it can help fill a significant knowledge gap by enabling fine-resolution temporal information of fire dynamics and coupling to the atmosphere. The literature on wildfire and radar to date can be regarded as addressing one of three key themes which build on each other. The first is characterization of microphysics, which has been done both observationally and experimentally in laboratory and numerical simulation contexts. Next is how radar can be used to analyze the processes of wildfire-atmosphere interaction, which has been exclusively in the observational literature. The third is how the wealth in the spatiotemporal data sets could see more practical usage in the research and operational communities.

The theory and findings on plume microphysics has led to several hypotheses of scattering mechanisms, for which ash as the dominant speciation of particle scatterer is the most cited, however weakly supported. The key gap in knowledge in this is evidence of the nature and size of the particles themselves which is largely anecdotal but with the potential to substantially impact the reflectivity factor, as well as unclear complex dielectrics essential for resolving a physically meaningful reflectivity factor. Theory has suggested that aerosol-sized smoke particles are unlikely to cause significant reflectivities. Interpretations of fire-atmosphere processes rely on the outcome of the microphysical studies, where the patterns interpreted rely on what reflects or refracts the radar beam. The most common usage of radar in wildfire recently has been in echo top time series and maps to study the growth and decay of pyroCbs. Interpretations of radar signatures have led to several interesting findings around vortices and structural elements of pyroCbs, but no standards exist for such features leading the interpretations subjective. Partially due to this subjectivity and significant gaps in knowledge in the microphysics, operational tools have focused on interpreting location and relative change in reflectivity to infer fire behavior from the data. Additionally, fine-line boundaries of wind changes and convective outflows have played a role in assisting firefighter safety decisions.

Building off previous experimental observations, proof-of-concept studies, and volcanology, there is now demonstrated potential of portable and network radars for monitoring local to mesoscale convective interactions over wildfires, providing value for both research and operational activities. Advances could be yielded from a generalized microphysics model of wildfire plumes, as well the literature in the similar domain of radar and volcanology. Mindful of the known risks to life and property directly resulting from deep pyroconvection and convective outflows there is significant room for radar use in fire to move from research to operations. Thus, there is a strong case for radar becoming a key asset to increase wildfire preparedness and response, thereby benefiting communities and improving firefighter safety.

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