D

Dry Thunderstorms

Nicholas J. Nauslar[1] and Benjamin J. Hatchett[2]
[1]NOAA/NWS/NCEP Storm Prediction Center, Norman, OK, USA
[2]Division of Atmospheric Sciences, Desert Research Institute, Reno, NV, USA

Synonyms

Dry lightning; High-based thunderstorms

Definition

Dry thunderstorms are defined as cumulonimbus clouds that produce cloud-to-ground lightning strikes with little to no precipitation reaching the ground. The “dry” in dry thunderstorms is relative as there is no standardized threshold for precipitation accumulation to classify a thunderstorm as being “dry.” The National Weather Service and peer-reviewed literature often use <2.5 mm (0.1 in.) and occasionally <6.35 mm (0.25 in.) to delineate dry thunderstorms Storm Prediction Center (SPC) (Nauslar et al. 2013).

Introduction

Dry thunderstorms, also referred to as dry lightning, produce cloud-to-ground (CG) lightning with little to no rainfall reaching the surface. While there is no fundamental difference between how typical thunderstorms and dry thunderstorms form, the distinction arises from the environments they develop in and the resultant precipitation totals. Dry thunderstorms form in environments that have marginally sufficient moisture and instability to support cumulonimbus development despite dry land surface and boundary layer conditions. Such marginal conditions make dry thunderstorms difficult to forecast given the uncertainty regarding convective initiation and storm coverage, especially at lead times of multiple days.

All thunderstorms are important to fire management during fire season, but dry thunderstorms carry extra significance given their predilection for igniting wildfires (e.g., Fuquay et al. 1979; Nauslar et al. 2013). Larger dry thunderstorm events where lightning is spread over a wide region (i.e., dry lightning busts (Nauslar et al. 2013)), have acute impacts on fire management, especially with regards to fire suppression efforts. These impacts underscore the importance of dry thunderstorms to the fire community. Dry thunderstorms, especially with implications to fire suppression, occur most often in western North America and Australia, although they can occur anywhere within the mid-latitudes (e.g., Rorig and Ferguson 1999; Changnon 2001; Kuleshov et al. 2002; Amatulli et al. 2007; Ganteaume et al. 2013; Associated Press 2017)

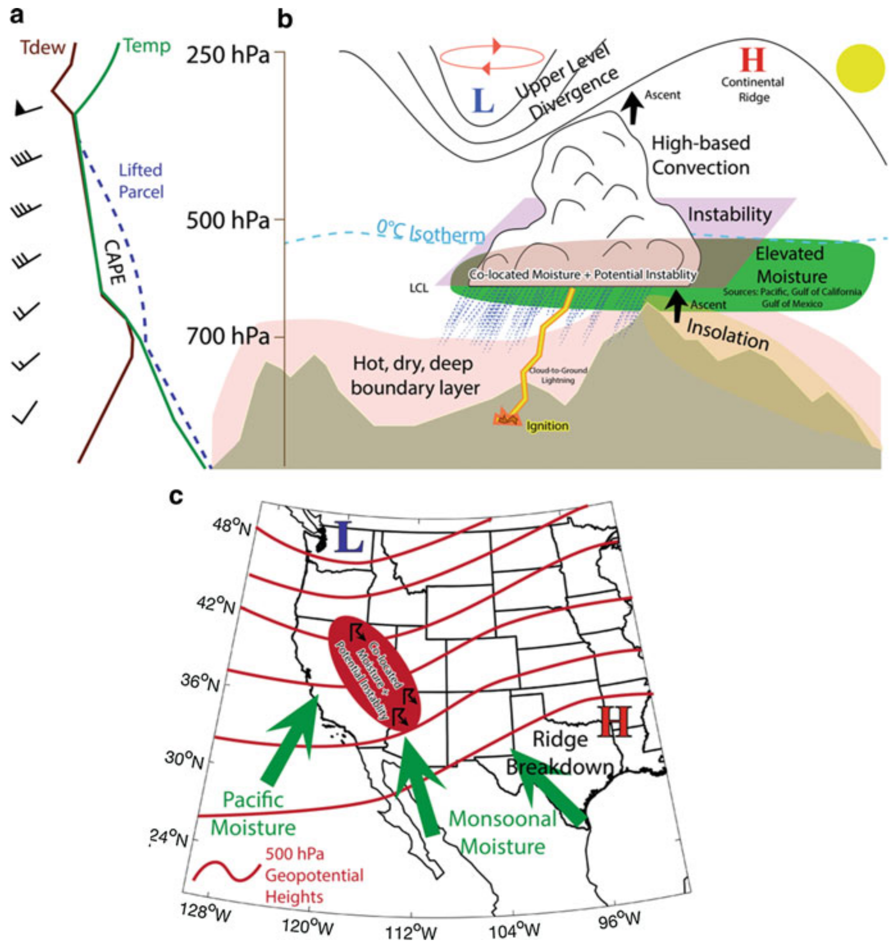
S. L. Manzello (ed.), *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires*,
https://doi.org/10.1007/978-3-319-51727-8_176-1

Dry Thunderstorm Development

Thunderstorms and dry thunderstorms develop similarly through deep, moist convective processes. A parcel is lifted to the level of free convection (LFC) and realizes instability, and under conditions where sufficient atmospheric moisture exist, moist convection occurs. Enough instability must be present above the freezing level to allow vertical cloud development to encompass the main charging zone region (−10 °C to −20 °C) (Houze 1993; MacGorman and Rust 1998). Therefore, an LFC below the freezing level and an equilibrium level (i.e., level of neutral buoyancy) above the height of the −20 °C isotherm increases the likelihood for cloud electrification and thunderstorm development (Houze 1993; MacGorman and Rust 1998). The presence of convective available potential energy (CAPE) indicates positive buoyancy and the possibility of thunderstorm development if a lifted parcel becomes unstable.

As previously noted, the main difference between dry thunderstorms and typical thunderstorms is the environment that dry thunderstorms develop in. Dry thunderstorms often form in an environment that is marginally conducive for thunderstorms, typically on the fringes of the deepest moisture and strongest buoyancy and forcing for ascent (Nauslar et al. 2013). Mid-tropospheric moisture moving over a hot, dry, and well-mixed boundary layer creates a favored scenario for dry thunderstorm development (Fig. 1) (e.g., Hall 2007; Wallmann et al. 2010; Nauslar et al. 2013). During that scenario, temperature and dewpoint traces on the atmospheric sounding profile form an "inverted-V" (Fig. 1), illustrating a well-mixed, hot, and dry boundary layer with sufficient mid-tropospheric (700–500 hPa) moisture. High cloud bases are typical of dry thunderstorms with lifting condensation levels (LCLs) often ≥ 2500 m above ground level (AGL) with some instability (i.e., CAPE) in the middle troposphere. Boundary-layer circulations deepen as insolation increases and begin to lift parcels to the LCL and LFC resulting in thunderstorms. These circulations are augmented when topography is present as orographic lifting enhances thermal circulations with more parcels able to reach the LFC (e.g., Cotton et al. 1983; Tripoli and Cotton 1989). Synoptically-driven dynamical lifting associated with mid- and upper-tropospheric troughs can produce elevated convection (i.e., lifted parcels not originating from/near the surface) resulting in dry thunderstorm development (Favors and Abatzoglou 2013). Elevated thunderstorms during the warm season are often high-based and do not rely on diurnal circulations to generate vertical motions. This can lead to dry thunderstorms including nocturnal dry thunderstorms as elevated convection develops over a dry, stable boundary layer.

During the warm season across western North America, dry thunderstorms often form during the breakdown of the upper-tropospheric ridge, a known critical fire weather pattern (Werth et al. 2011; Nauslar et al. 2018. Deeper subtropical moisture associated with the North American Monsoon often stays along the southern periphery of the subtropical ridge over western North America where mid- and upper-tropospheric easterlies are present (e.g., Douglas et al. 1993; Higgins et al. 1997). Poleward moisture advection along the western edge of the ridge is common, but due to the complex terrain of the western CONUS, surface moisture advection often lags behind mid- and upper-tropospheric moisture advection (Fig. 1) (e.g., Carleton 1986; Favors and Abatzoglou 2013). The western and northern portions of the ridge are often favored for dry thunderstorm development as mid-tropospheric moisture streams over a hot, dry, and well-developed boundary layer (Favors and Abatzoglou 2013; Nauslar et al. 2013). As an upper-tropospheric trough approaches and interacts with the ridge, geopotential heights and temperatures aloft fall, which increases mid- and upper-tropospheric instability. As a result, the potential for thunderstorm development increases. Additionally, stronger mid- and upper-tropospheric winds increase storm motions (≥12 ms^{-1} (25 knots)), which limits precipitation accumulation at any given location, increasing the likelihood of dry thunderstorm occurrence. Dry thunderstorms occur infrequently when compared to typical



Dry Thunderstorms, Fig. 1 (**a**) Typical atmospheric sounding profile characteristic of dry thunderstorms; (**b**) and (**c**) vertical and planar schematics depicting an environment conducive for dry thunderstorms across the western United States

thunderstorms, but there is no established dry thunderstorm climatology.

Forecasting Dry Thunderstorms

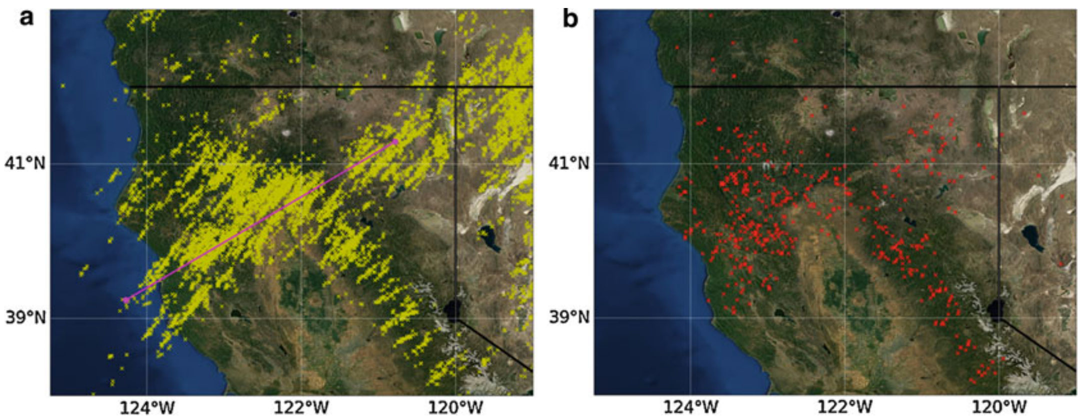
There are existing forecasting methods that help identify dry thunderstorm potential (e.g., Rorig et al. 2007; Wallmann et al. 2010; Nauslar et al. 2013). Each forecast method examines a combination of moisture, lift, and instability. Rorig et al. (2007) utilized 850 hPa dewpoint depressions and 850 hPa to 500 hPa temperature differences in their discriminant algorithm to determine dry thunderstorm probabilities. Wallmann et al. (2010) describes what they call the dry lightning procedure (DLP). The DLP identifies possible lifting mechanisms (e.g., dynamic tropopause and 850–700-hPa layer equivalent potential temperature (θ_e)) and quantifies instability in the mid- and upper-troposphere (e.g., MUCAPE and 500–300 hPa lapse rates ≥7.5 °C) and potential thunderstorm coverage (e.g., High-Level Total Totals (Milne 2004)). Nauslar et al. (2013) advances the DLP by utilizing vertical atmospheric cross-sections with equivalent potential temperature θ_e and mixing ratio or relative humidity to identify mid-tropospheric potential instability (e.g., Schultz et al. 2000). Nauslar et al. (2013) also examined ageostrophic motions within upper-tropospheric jet structure including the formation of mesoscale jetlets, which locally increase upper-tropospheric divergence (e.g., Hamilton et al. 1998; Kaplan et al. 1998). The National Weather Service Storm Prediction Center developed probabilistic dry thunderstorm guidance based on the North American Model and Global Forecast System model using a Perfect Prognosis technique (e.g., Bothwell 2009).

As with forecasting other types of impactful weather (e.g., severe weather), there are no set thresholds for variables or objective analyses that yield definitive answers on dry thunderstorm development. Fire meteorologists often use precipitable water thresholds between 10 and 20 mm (0.4–0.8 in.) as being favorable for dry thunderstorms, with any value lower than 10 mm unlikely to support deep, moist convection capable of producing CG lightning. Values above 20 mm indicate precipitation accumulation will likely exceed dry thunderstorm precipitation thresholds (2.5 or 6.35 mm). Additionally, various CAPE calculations (e.g., surface-based, mixed-layer, most unstable) and thresholds are utilized to ascertain convective and cloud electrification potential. Bright et al. (2005) theorized that $\geq$100 J/kg of CAPE in the mixed phase region through the charge reversal temperature zone (0 °C to $-$20 °C) is adequate for cumulonimbus electrification.

Impact on Wildfires

Dry thunderstorms can result in mass wildfire ignitions (i.e., lightning busts) that strain local, regional, and national firefighting resources. Dry thunderstorms are more efficient (i.e., CG lightning to wildfire ratio) in starting wildfires than typical thunderstorms, and fires ignited from dry thunderstorms are often more active initially as environments conducive for dry thunderstorms and fire spread are similar (e.g., Fuquay et al. 1979; Rorig and Ferguson 1999, 2002; Hall 2007). Strong thunderstorm outflow winds often develop from dry thunderstorms as downdrafts accelerate through evaporative cooling processes within the hot, dry, and unstable boundary-layer (i.e., downbursts, microbursts). Dry microbursts environments are characterized by mid-tropospheric moisture, a deep, dry adiabatic subcloud lapse rate, and low surface moisture, which are similar to dry thunderstorm environments (Wakimoto 1985). Microbursts occur when precipitation evaporates as it descends into a dry subcloud layer. As the air cools and becomes denser, it accelerates downward until it reaches the surface creating gusty and erratic winds (e.g., Fujita 1985; Wakimoto 1985). Strong thunderstorm outflow winds can create extreme and erratic fire behavior (e.g., Dude and Yarnell Hill fires) (Goens and Andrews 1998; ADFFM 2013).

While dry thunderstorms are important to fire management concerns, thunderstorms over dry fuels also ignite wildfires and complicate wildfire suppression efforts. Once fuel regimes dominated by forests with dense canopies (e.g., Pacific Northwest, Northern Rockies) fall below certain fuel moisture thresholds during the warm season, lightning, especially lightning followed by warm, dry, and windy conditions, can readily ignite wildfires with relative high efficiency (Wierzchowski et al. 2002; Evett et al. 2008; Ordóñez et al. 2012). Owing to this concern, some National Weather Service forecast offices issue Red Flag Warnings for abundant lightning over dry fuels (Hockenberry 2017). Red Flag Warnings for lightning are issued to alert firefighting personnel to the potential of widespread, numerous new ignitions (Hockenberry 2017). Densely forested areas at higher-latitudes and higher elevations, which have cold or temperate climates with warm and dry summers, are specifically susceptible (Köppen 1936; Conedera et al. 2006; Veraverbeke et al. 2017). Background climate conditions and weather during and after CG lightning play important roles in determining wildfire occurrence and spread (e.g., Bessie and Johnson 1995; Gedalof et al. 2005; Abatzoglou and Kolden 2013). A better meteorological understanding and predictive model for wildfires that includes weather and fuel information would immensely aid wildfire suppression strategy.



Dry Thunderstorms, Fig. 2 (**a**) Cloud-to-ground lightning (“x”, yellow) from 1200 UTC 20 June 2008–1200 UTC 22 June 2008 with cross-section transect (pink) for Fig. 3; (**b**) lightning ignited wildfires (“x” red) from 1200 UTC 20 June 2008–1200 UTC 24 June 2008

Case Study

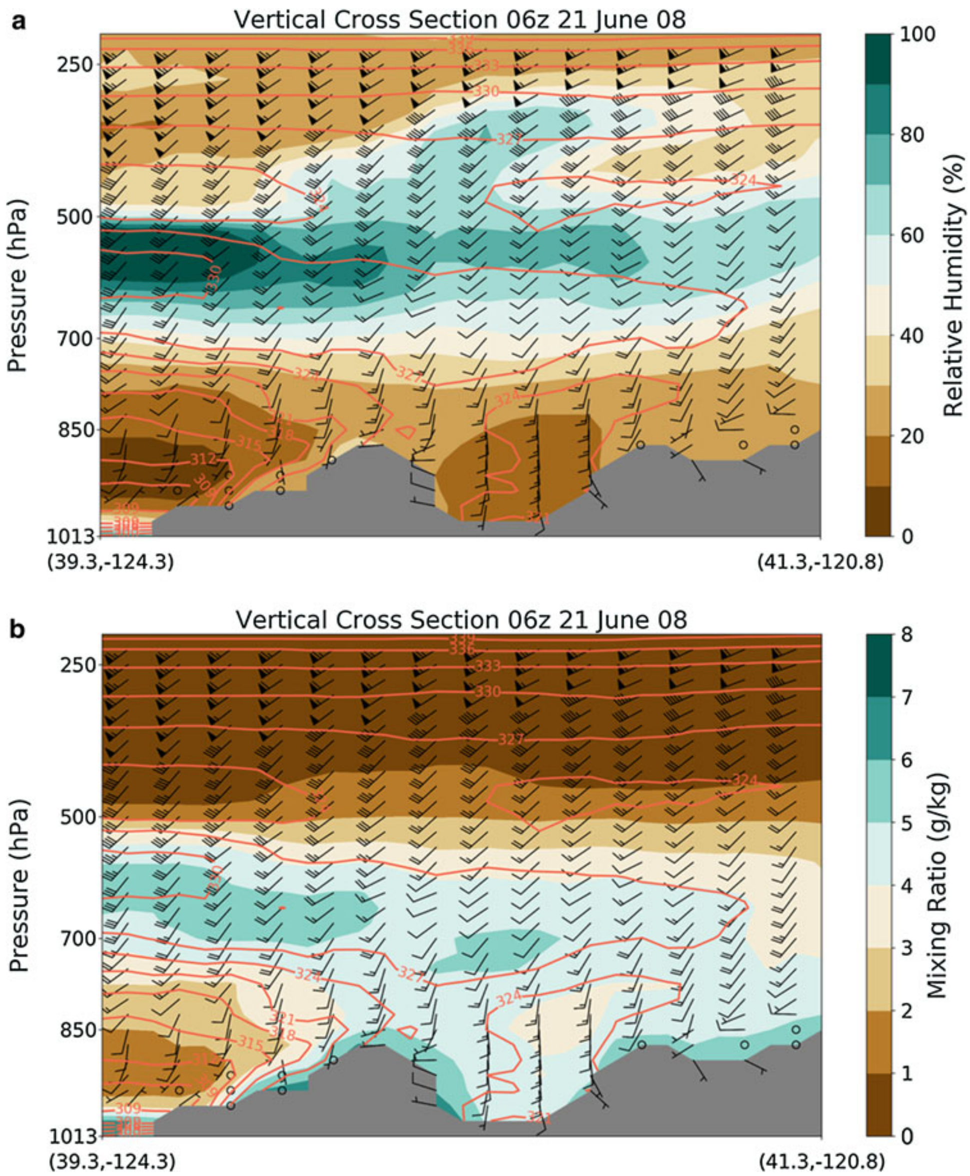
On 20–21 June 2008, more than 5000 lightning strikes from dry thunderstorms resulted in more than 500 wildfires across northern California and portions of the northwest Great Basin (i.e., southeast Oregon and northwest Nevada) (Fig. 2) (Wallmann et al. 2010; Nauslar et al. 2013). A weak, mid-tropospheric shortwave trough moved over the area and helped increase instability via mid-tropospheric moisture and steeper mid-tropospheric lapse rates (e.g., Figs. 3 and 4 from Nauslar et al. 2013). However, the number of ignitions was unexpected as the coverage and CG lightning production from thunderstorms exceeded predicted amounts.

Elevated moisture and instability over a dry lower-troposphere led to dry thunderstorm development across northern California (Fig. 3). Elevated thunderstorms continued overnight, thus de-coupled from any terrain or boundary layer circulations associated with insolation. However, deep boundary-layer mixing with orographic lift did aid in the development of dry thunderstorms during the event. The operational North American Model (NAM) 0000-0600 UTC 21 June 2008 analysis soundings across the region show little instability with all MUCAPE values below 400 J/kg across northern California (Fig. 4). Perhaps the most obvious signal for dry thunderstorm potential is evident in the NAM vertical cross-sections that show collocated mid-tropospheric moisture and instability (Fig. 3) (Nauslar et al. 2013). Storm motions were also estimated to be 12–20 ms^{-1} (25–40 knots), which further limited precipitation duration and totals. The vertical cross sections and model soundings depict elevated instability above a very dry lower-troposphere with fast storm motions, which is a prototypical dry thunderstorm structure (Figs. 3 and 4) (Wallmann et al. 2010).

Several hundred wildfires were ignited during this event, and these fires eventually burned more than 600,000 acres with the largest fires in northern California where fuels were the driest (Wallmann et al. 2010). These wildfires strained local, regional, and national fire suppression resources and caused smoke management issues across the region for several weeks. Wallmann et al. (2010) and Nauslar et al. (2013) provide a more comprehensive analysis of this event and detail forecast procedures that would have better predicted the event.

Summary

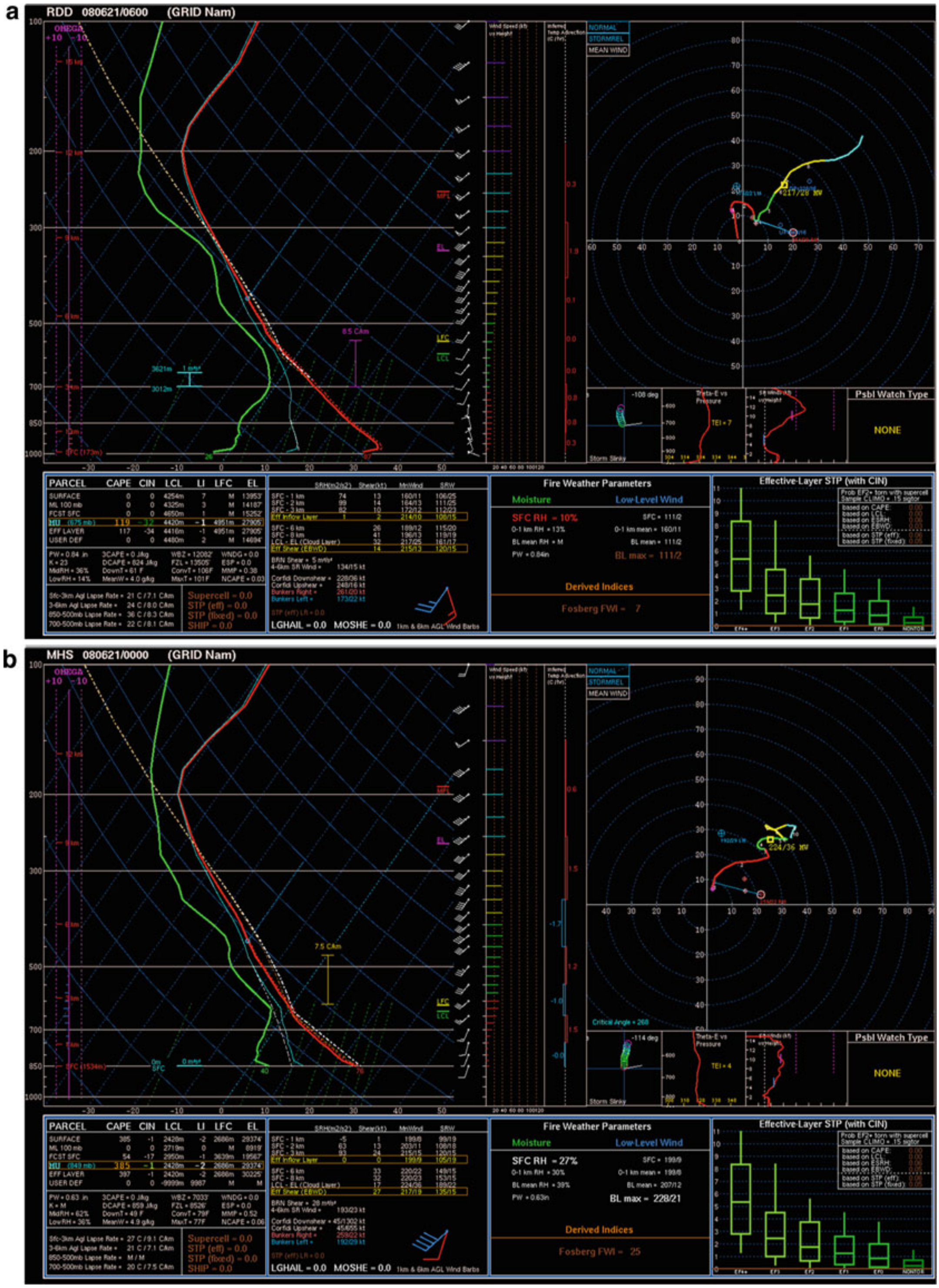
Dry thunderstorms are an important part of fire weather and greatly impact fire management and suppression. In the United States, lightning-ignited wildfires only account for 16% of all wildfires, but about half of the acres burned



Dry Thunderstorms, Fig. 3 (**a**) Vertical cross-section across northern California (see transect line in Fig. 2a) with equivalent potential temperature (contoured, pink), relative humidity (color-filled, %), and winds (barbs, knots); (**b**) Same as (**a**) but with mixing ratio (color-filled, g/kg)

(Balch et al. 2017). While CG lightning from any thunderstorm can ignite wildfires, dry thunderstorms and the environment they typically form in are often more efficient for igniting and spreading wildfires. Dry thunderstorms are not unique to the United States or even North America as they occur in multiple regions across the world (e.g., portions of Australia and Europe).

The distinguishing characteristic of dry thunderstorms is the minimal amount of precipitation reaching the surface from the cumulonimbus cloud, which is product of the environment. Dry thunderstorms develop in three different regimes: (1) sufficient mid-tropospheric moisture above a dry, unstable boundary layer with strong insolation often aided



Dry Thunderstorms, Fig. 4 (**a**) North American Model (NAM) analysis sounding at 0600 UTC 21 June 2008 for Redding, CA; (**b**) NAM analysis sounding at 0000 UTC 21 June 2008 for Mt. Shasta, CA by terrain circulations or a surface boundary (e.g., surface pressure trough, dryline); (2) a mid-tropospheric shortwave trough with mid-tropospheric moisture produces elevated convection over a dry boundary layer; and (3) a combination of the first two regimes.

Forecasting dry thunderstorms remains challenging given the marginal convective environment in which they develop. Wallmann et al. (2010) and Nauslar et al. (2013) detail dry thunderstorm forecasting techniques, while others rely on algorithms (e.g., Rorig et al. 2007; Bothwell 2008a,b, 2009). Many operational fire meteorologists rely heavily on experience and pattern recognition when forecasting dry thunderstorms and their impacts on wildfire ignition and spread. Research has demonstrated that lightning-ignited wildfires are a function of fuel conditions and atmospheric moisture (e.g., Wierzchowski et al. 2002; Evett et al. 2008; Ordóñez et al. 2012; Parisien et al. 2012). However, there needs to be a greater effort to translate research findings into operations while understanding the underlying difficulties of forecasting the intricate relationships among the contributing factors to wildfires. Examination of dry-thunderstorm research in an operational setting, similar to what is done for severe weather during the Spring Experiment in the Hazardous Weather Testbed (Clark et al. 2012), would help address current limitations in fire weather and dry thunderstorm forecasting.

Cross-References

▶ Ignition Component
▶ Slope Winds

References

Abatzoglou JT, Kolden CA (2013) Relationships between climate and macroscale area burned in the western United States. Int J Wildland Fire 22:1003–1020

ADFFM (Arizona Department of Forestry and Fire Management) (2013) Yarnell Hill Fire serious accident investigation report. September 23. Phoenix, AZ

Amatulli G, Peréz-Cabello F, de la Riva J (2007) Mapping lightning/human-caused wildfires occurrence under ignition point location uncertainty. Ecol Model 200(3–4):321–333. https://doi.org/10.1016/J.ECOLMODEL.2006.08.001

Associated Press (2017) 62 killed in Portugal forest fires, many dying in their cars as flames weep road. Los Angeles Times. Accessible: http://www.latimes.com/world/la-fg-portugal-forest-fires-20170617-story.html

Balch JK, Bradley BA, Abatzoglou JT, Nagy RC, Fusco EJ, Mahood AL (2017) Human expansion of the fire niche. Proc Natl Acad Sci 114(11):2946–2951. https://doi.org/10.1073/pnas.1617394114

Bessie WC, Johnson EA (1995) The relative importance of fuels and weather on fire behavior in sub-alpine forests. Ecology 76:747–762

Bothwell PD (2008a) Predicting the location and intensity of lightning using an experimental automated statistical method. In: Third conference on meteorological applications of lightning data. Amer. Meteor. Soc., New Orleans, 6 pp

Bothwell PD (2008b) Evaluation of experimental/automated lightning forecasts for western U.S. fire season and significant lightning outbreaks in the eastern U.S. In: 2nd international lightning detection conference, April 24–25, Tucson, AZ. Vaisala, Inc, Tucson, 8 pp

Bothwell PD (2009) Development, operational use, and evaluation of the perfect prog national lightning prediction system at the Storm Prediction Center. Preprints, Fourth conference on the meteorological applications of lightning data, Phoenix, AZ, Amer. Meteor. Soc., 6.2. Available online at ams.confex.com/ams/89annual/webprogram/Paper150697.html

Bright DR, Wandishin MS, Jewell R, Weiss SJ (2005) A physically based parameter for lightning prediction and its calibration in ensemble forecasts. 85th AMS annual meeting, American Meteorological Society - Combined Preprints 1993, pp 5699–5709

Carleton AM (1986) Synoptic-dynamic character of "bursts" and "breaks" in the southwest U.S. summer precipitation singularity. J Climatol 6:605–623

Changnon SA (2001) Thunderstorm rainfall in the conterminous United States. Bull Am Meteorol Soc 82:1925–1940. https://doi.org/10.1175/1520-0477(2001)082<1925:TRITCU>2.3.CO;2

Clark AJ, Weiss SJ, Kain JS, Jirak IL, Coniglio M, Melick CJ, Siewert C, Sobash RA, Marsh PT, Dean AR, Xue M, Kong F, Thomas KW, Wang Y, Brewster K, Gao J, Wang X, Du J, Novak DR, Barthold FE, Bodner MJ, Levit JJ, Entwistle CB, Jensen TL, Correia J (2012) An overview of the 2010 hazardous weather testbed experimental forecast program spring experiment. Bull Am Meteorol Soc 93:55–74. https://doi.org/10.1175/BAMS-D-11-00040.1

Conedera M, Cesti G, Pezzatti G, Zumbrunnen T, Spinedi F (2006) Lightning-induced fires in the Alpine region: an increasing problem. For Ecol Manag 234. https://doi.org/10.1016/j.foreco.2006.08.096

Cotton WR, George RL, Wetzel PJ, McAnelly RL (1983) A Long-Lived Mesoscale Convective Complex. Part I: The Mountain-Generated Component. Mon Wea Rev 111:1893–1918. https://doi.org/10.1175/1520-0493(1983)111<1893:ALLMCC>2.0.CO;2

Douglas MW, Maddox RA, Howard K, Reyes S (1993) The Mexican monsoon. J Clim 6:1665–1677

Evett RR, Mohrle CR, Hall BL, Brown TJ, Stephens SL (2008) The effect of monsoonal atmospheric moisture on lightning wildfire ignitions in southwestern North America. Agric Forest Meteorol 148:1478–1487

Favors JE, Abatzoglou JT (2013) Regional surges of monsoonal moisture into the southwestern United States. Mon Weather Rev 141:182–191. https://doi.org/10.1175/MWR-D-12-00037.1

Fujita TT (1985) The downburst: microburst and macroburst. SMRP research paper 210, University of Chicago, 122 pp. [NTIS PB85-148880]

Fuquay DM, Baughman RG, Latham DJ (1979) A model for predicting lightning fire ignition in wildland fuels. USDA forest service research paper INT-217. Intermountain Forest and Range Experiment Station, Ogden, 22 pp

Ganteaume A, Camia A, Jappiot M, San Miguel-Ayanz J, Long-Fournel M, Lampin C (2013) A review of the main driving factors of forest fire ignition over Europe. Environ Manag 51(3):651–662. https://doi.org/10.1007/s00267-012-9961-z

Gedalof Z, Peterson D, Mantua N (2005) Atmospheric, climatic, and ecological controls on extreme wildfire years in the northwestern United States. Ecol Appl 15:154–174

Goens DW, Andrews PL (1998) Weather and fire behavior factors related to the 1990 Dude Fire near Payson, Arizona. In: Proceedings: 2nd symposium on fire and forest meteorology. American Meteorological Society, Boston, pp 153–158

Hall BL (2007) Precipitation associated with lightning-ignited wildfires in Arizona and New Mexico. Int J Wildland Fire 16:242–254

Hamilton DW, Lin Y-L, Weglarz RP, Kaplan ML (1998) Jetlet formation from diabatic forcing with applications to the 1994 Palm Sunday tornado outbreak. Mon Weather Rev 126:2061–2089

Higgins RW, Yao Y, Wang XL (1997) Influence of the North American Monsoon system on the U.S. summer precipitation regime. J Clim 10:2600–2622

Hockenberry HE (2017) Fire weather Services Product Specification. National Weather Service Instruction 10-401. Accessible: http://www.nws.noaa.gov/directives/sym/pd01004001curr.pdf

Houze RA Jr (1993) Cloud dynamics. International Geophysics Series, Academic Press, Waltham

Kaplan ML, Lin Y-L, Hamilton DW, Rozumalski RA (1998) The numerical simulation of an unbalanced jetlet and its role in the Palm Sunday 1994 tornado outbreak in Alabama and Georgia. Mon Weather Rev 126:2133–2165

Köppen W (1936) Das geographische System der Klimate. In: Köppen W, Geiger R (eds) Handbuch der Klimatologie, 1C:1-44. Verlag von Gebrüder Borntraeger, Berlin

Kuleshov Y, de Hoedt G, Wright W, Brewster A (2002) Thunderstorm distribution and frequency in Australia. Aust Meteorol Mag 51:145–154

MacGorman DR, Rust WD (1998) The electrical nature of storms. Oxford University Press, New York

Milne R (2004) A modified total totals index for thunderstorm potential over the Intermountain West. NOAA/NWS WR Tech. Attach. 04–04, www.wrh.noaa.gov/media/wrh/online_publications/TAs/ta0404.pdf

Nauslar NJ, Kaplan ML, Wallmann J, Brown TJ (2013) A forecast procedure for dry thunderstorms. J Operational Meteor 1(17):200–214. https://doi.org/10.15191/nwajom.2013.0117

Nauslar NJ, Hatchett BJ, Brown TJ, Kaplan ML, Mejia JF (2018) Impact of the North American Monsoon on wildfire activity in the southwest United States. Int J Climatol 1–16. https://doi.org/10.1002/joc.5899

Ordóñez C, Saavedra A, Rodríguez-Pérez JR, Castedo-Dorado F, Covián E (2012) Using model-based geostatistics to predict lightning-caused wildfires. Environ Model Softw 29:44–50

Parisien M-A, Snetsinger S, Greenberg JA, Nelson CR, Schoennagel T, Dobrowski SZ, Moritz MA (2012) Spatial variability in wildfire probability across the western United States. Int J Wildland Fire 21:313–327

Rorig ML, Ferguson SA (1999) Characteristics of lightning and wildland fire ignition in the Pacific Northwest. J Appl Meteorol 38:1565–1575. https://doi.org/10.1175/1520-0450(1999)038<1565:COLAWF>2.0.CO;2

Rorig ML, Ferguson SA (2002) The 2000 fire season: lightning-caused fires. J Appl Meteorol 41:786–791. https://doi.org/10.1175/1520-0450(2002)041<0786:TFSLCF>2.0.CO;2

Rorig ML, McKay SJ, Ferguson SA, Werth P (2007) Model-generated predictions of dry thunderstorm potential. J Appl Meteorol Climatol 46:605–614. https://doi.org/10.1175/JAM2482.1

Schultz DM, Schumacher PN, Doswell CA, (2000) The Intricacies of Instabilities. Mon Wea Rev 128:4143–4148. https://doi.org/10.1175/1520-0493(2000)129<4143:TIOI>2.0.CO;2

Tripoli GJ, Cotton WR (1989) Numerical study of an observed orogenic mesoscale convective system: Part 1. Simulated genesis and comparison with observations. Mon Weather Rev 117:272–304

Veraverbeke S, Rogers BM, Goulden ML, Jandt RR, Miller CE, Wiggins EB, Randerson JT (2017) Lightning as a major driver of recent large fire years in North American boreal forests. Nat Clim Chang 7:529. https://doi.org/10.1038/nclimate3329

Wakimoto RM (1985) Forecasting dry microburst activity over the high plains. Mon Weather Rev 113:1131–1143. https://doi.org/10.1175/1520-0493(1985)113<1131:FDMAOT>2.0.CO;2

Wallmann J, Milne R, Smallcomb C, Mehle M (2010) Using the 21 June 2008 California lightning outbreak to improve dry lightning forecast procedures. Weather Forecast 25:1447–1462. https://doi.org/10.1175/2010WAF2222393.1

Werth PA, Potter BE, Clements CB, Finney M, Goodrick SL, Alexander ME, Cruz MG, Forthofer JA, McAllister SS (2011) Synthesis of knowledge of extreme fire behavior: Volume I for Fire managers. United States Department of Agriculture Volume PNW-GTR-85

Wierzchowski J, Heathcott M, Flannigan MD (2002) Lightning and lightning fire, Central Cordillera, Canada. Int J Wildland Fire 11:41–51