FINAL REPORT

Title: Assessment of HRRR Model Forecasts of Convective Outflows in the Fire Environment

JFSP PROJECT ID: 17-1-05-1

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Abbreviations

AWS: Amazon Web Service
CFFDRS: Canadian Forest Fire Danger Rating System
CHPC: Center for High Performance Computing
CONUS: Contiguous United States
FBAN: Fire Behavior Analyst
FLAME: FireLine Assessment MEthod
GIS: Geographic Information System
GLM: Geostationary Lightning Mapper
HDW: Hot-Dry-Windy Index
HRRR: High Resolution Rapid Refresh model
IMERG: Integrated Multisatellite Retrievals for the Global Precipitation Mission
IMET: Incident Meteorologist
NCEP: National Centers for Environmental Prediction
NDFD: National Digital Forecast Database
NOAA: National Oceanic and Atmospheric Administration
OSG: Open Science Grid
VPD: Vapor Pressure Deficit
WFDSS: Wildland Fire Decision Support System
WFO: Weather Forecast Office

Abstract

This study evaluated the ability of the High Resolution Rapid Refresh (HRRR) modeling system to forecast the characteristics of mesoscale atmospheric boundaries arising from thunderstorm outflows, gust fronts, and downburst winds (referred collectively as convective outflows) within the contiguous United State and Alaska. Such convective outflows in the vicinity of wildfires can lead to rapid changes in fire behavior and growth that increase risks to firefighters. Our objective was to develop and evaluate diagnostic tools based on HRRR model output that could improve situational awareness within the operational fire weather community of the ability of the HRRR model to nowcast and forecast convective outflows at lead times of 18 hours or less.

Through the development of the only publicly-accessible archive of HRRR model output at the start of the project, we were able to apply novel data analytical methods applied to the HRRR fields at high temporal (hourly) and spatial (3 km resolution) resolution across the nation. A benefit of our creation of this archive was that over a thousand other researchers were able to access the HRRR model output for other operational and research applications, including initializing fine-scale models for simulating wildfire and other hazardous weather conditions. Beginning in late 2020, the NOAA Open Data Program has created similar archival capabilities using Google and AWS cloud resources. Hence, we, and other researchers, have a sustainable path to migrate existing codes that relied on our archive to those cloud environments.

In addition to the extensive online resources developed as part of this project (see http://hrrr.chpc.utah.edu), the results of our research have been disseminated through 4 peer-reviewed publications, over a dozen presentations at regional and national conferences, and direct discussions with Incident Meteorologists and Fire Behavior Analysts. This work confirmed our original hypothesis that the HRRR model and fire behavior tools that rely upon it are not able to provide highly specific forecast guidance on convective outflows in complex terrain. However, the HRRR can facilitate nowcasting at lead teams less than 6 h and does improve situational awareness for the potential for convection at lead times less than 18 hours, particularly in synoptic-mesoscale situations for which the model is well initialized as part of the model's data assimilation procedures. In addition, the GOES-Lightning Mapper sensors onboard GOES-16 and GOES-17 satellites were shown to be useful for evaluating the HRRR forecasts of lightning potential as a proxy for forecasts of intense convection.

GOES-16 and GOES-17 fire products for automated alerts to new fire starts have been successful enough in some parts of the country to suggest potential for earlier warnings of fire threats. However, assessment of the utility of the HRRR products in combination with other available resources as part of this study highlighted that automated alerts for action in the absence of well-designed fire metrics beyond those commonly used (e.g., fire danger, red flag) will require greater effort by trained personnel to understand local trends and thresholds applied to HRRR-derived or other model-derived products in order to minimize false positive and false negative errors. Such automated alerts, and the criteria they are derived from, will require extensive verification, calibration and validation. Criteria based on objective model guidance is useful for situational awareness, but is not of sufficient accuracy for actionable decisions.

Objectives

Our research focused on improving the information available to firefighting personnel from convective outflows on fire behavior and the ability of current weather prediction models to forecast them. The fundamental hypothesis for our research was that the High Resolution Rapid Refresh (HRRR) model of the National Centers for Environmental Prediction (NCEP) and fire behavior tools that rely upon it are not able to provide accurate, highly specific forecast guidance on convective outflows in complex terrain. We hypothesized that the HRRR could facilitate nowcasting at lead teams less than 6 h and improve situational awareness for the potential for convective outflows at lead times less than 24 h, particularly in certain synoptic-mesoscale situations.

To address those hypotheses, we focused on assessing HRRR model output for fire weather situations when operational models were more likely to provide useful forecast skill. While we did not expect high forecast accuracy for the timing, speed, and intensity of individual convective outflows in complex terrain, there was considerable potential to improve the operational use of high-resolution model output for convective outflow forecasting at lead times of less than 24 h, as well as how the risks associated with such events could be communicated operationally to the fire weather community.

The specific project objectives for this study were:

- utilize an extensive array of observational resources to identify and evaluate the characteristics of convective outflow events that had substantive impacts on wildfires in the CONUS and Alaska
- use those observational resources to evaluate the ability of the HRRR model to analyze and forecast those events
- assess the sensitivity on fire behavior and spread rate resulting from forecast uncertainty of convectively-driven outflows using a physically-based tool, Rate of Spread Ratio.

We addressed all four of the research needs identified for this task, restated here in the context of our research: (1) evaluate the ability of the HRRR modeling system to characterize the development, movement, and magnitude of convective outflows; (2) assess the HRRR forecast skill for basic fire behavior assessment; (3) demonstrate that model and tool validation is possible in complex terrain using information provided by incident meteorologists on site combined with an extensive array of surface observations, radar and satellite imagery, upper air soundings, and model analyses; (4) illustrate how the potential risks associated with convective outflows can be communicated effectively to the fire weather and fire management community.

We were most successful at meeting the research objectives by developing an archive of the HRRR model output that had not been available for operational or research users and assessing HRRR model skill. Graduate students Brian Blaylock and Taylor Gowan (McCorkle) evaluated utilizing HRRR model output for the contiguous U.S. and Alaska that led to four publications and 2 Ph.D. theses. CoI Ziel conducted analyses that contributed extensively to examining ways that the HRRR model output could be used operationally by fire-weather forecasters and fire behavior analysts. As the project unfolded, it was evident that less effort was needed to simulate convective case studies using the WRF model than had been planned.

Background

Convective outflows arising from thunderstorms, gust fronts, and downburst winds are common on many fires, which influence fire behavior and can lead to loss of life and extensive damage (Wildland Fire Associates 2013; Johnson et al. 2014). The potential impacts of such convective outflows on fire behavior are well known and the ability of NWS forecasters to provide general guidance in advance on their likelihood as well as nowcasts of their behavior are greatly appreciated within the fire community. Figure 1 summarizes the types of forecasts required to be issued by IMETs and WFO forecasters as a function of lead time. Diverse resources from many sources are available for lead times > ~24 h. *Our work focused on the needs of forecasters to have resources to improve forecasts and situational awareness of thunderstorm outflow probabilities at lead times of 12-24 h, short-term forecasts at lead times of 6-12 h, and nowcasts at lead times <~6 h.*

The ability of the operational High Resolution Rapid Refresh (HRRR) atmosphere modeling system for the contiguous United States (CONUS) and Alaska (Benjamin et al. 2016) to detect and forecast convective outflows were examined comprehensively in this study. The HRRR modeling system is the most relevant operational forecast system for detecting and forecasting convective outflows and providing that information with sufficient lead time for operational fire decision making. During the lifetime of this project, the HRRR evolved through three major development cycles and as of December 2020 is referred to as HRRRv4 with improved capabilities and additional wildfire smoke forecast products.

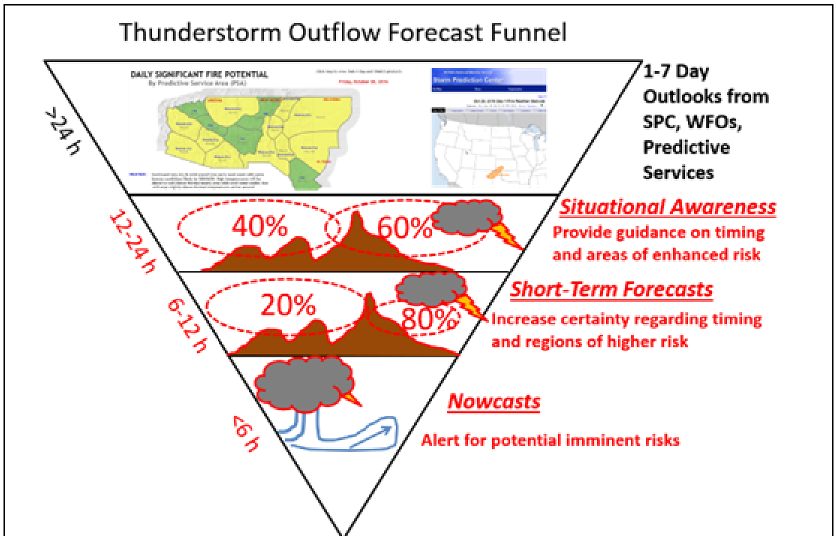

Figure 1. Guidance for the threat posed by convectively-driven outflows over a wide range of spatial scales and forecast lead times. Our work focused on improving the information available to forecasters for the components in red.

An issue facing fire weather applications is the sheer volume of information that operational forecasters must consider from in-situ sensors, satellites, and numerical models. This project developed new methods to analyze Tbytes of HRRR model output efficiently that benefited not only our own research needs, but also those of over a thousand registered research users to the publicly-accessible HRRR archive at the University of Utah. Our work also involved developing and evaluating diagnostic products that could be used operationally in the fire weather community that are not available currently from the HRRR such as vapor pressure deficit and red flag potential. We also evaluated the use of the HRRR archive to inform forecasters whether current model forecasts of hazardous fire weather are unusual for specific locations within the CONUS compared to the conditions during recent years around the same time of year.

Materials and Methods

Fire weather forecasters and fire behavior analysts are faced with an overwhelming volume of information to consider from GIS and web sources, in-situ sensors, satellites, and numerical models. This project extended further into developing new methods for archiving and handling big data than originally expected as it became evident that operational personnel could benefit from machine learning applications applied to the HRRR model output.

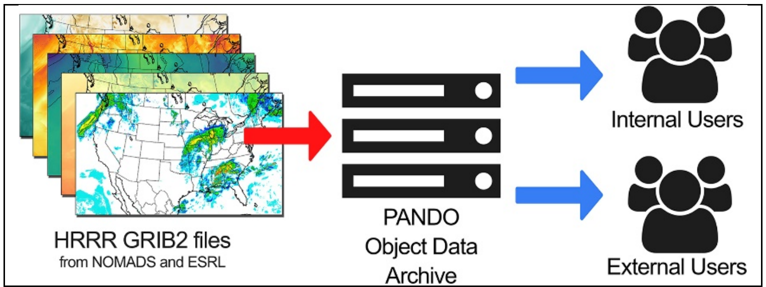

Figure 2. From Blaylock et al. (2017). A major outcome of this study was to illustrate how access to archives of operational model output was facilitated using a local data archive accessible for our own research and that of thousands of other researchers and operational users.

We demonstrated those applications in 4 publications that will be discussed in the Results section. Our work involved developing approaches to access the HRRR output files from NCEP, store the files locally, and provide that efficiently for this research project. A benefit to the broader operational and research community was that this storage system was available publicly and conveniently such that over a thousand external users have relied upon the data archive during the project period. Figure 2 reflects the sequence from HRRR file creation to local cloud storage, and availability of the data for our research needs and those of others. Figure 3 shows the growth to nearly160 Tbytes of satellite and model information for CONUS and Alaska available locally for project needs and ancillary benefits for other operational and research users.

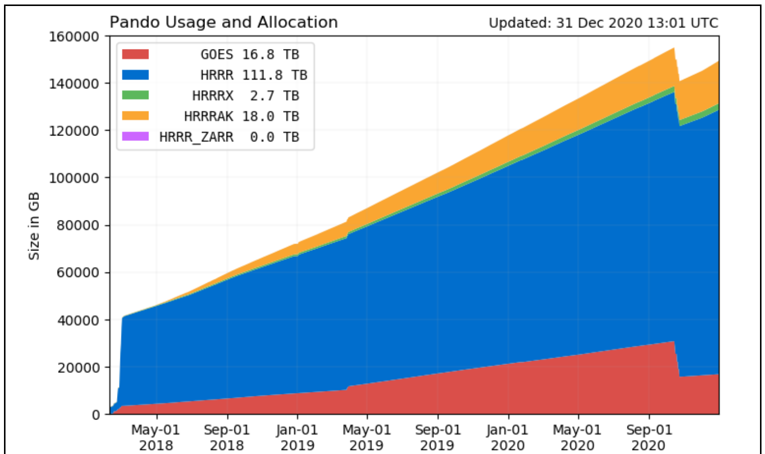

Figure 3. Increase in local storage of HRRR model output and GOES satellite imagery

Fortunately, the NOAA Big Data Program began supporting during 2020 access to the entire HRRR model archive via both the Google cloud and AWS cloud services. Hence, our efforts can be viewed now as a successful demonstration of research to operations that has developed a community of users familiar with the technology. We no longer need to commit to archive the bulk of this information in perpetuity and can focus on developing new methods to archive the data for machine learning applications of benefit to the operational weather community. That includes using an alternative file format, Zarr, that will be discussed in the Results section.

Numerous displays were developed and tested based on the HRRR output for fire weather applications that are available at https://hrrr.chpc.utah.edu including vapor pressure deficit and red flag potential indices.

Results and Discussion

Development of the HRRR Archive

As described by Blaylock et al. (2017), fire weather research is aided by synthesizing vast amounts of data that need archival solutions that are both economical and viable during and past the lifetime of the project. We have demonstrated the efficacy of both public cloud computing services (e.g., from Amazon, Microsoft, or Google) and private clouds managed by research institutions, such as the University of Utah. We illustrated the use of the cloud object store developed by the CHPC)at the University of Utah. We have archivied thousands of two-dimensional gridded fields (each one containing over 1.9 million values over the CONUS as well as separate grids over Alaska) from the HRRR data assimilation and forecast modeling system. The archive was used for retrospective analyses of meteorological conditions during high-impact fire weather events and assessing the accuracy of the HRRR forecasts. The archive is accessible interactively and through automated download procedures for researchers at other institutions that can be tailored by the user to extract individual two-dimensional grids from within the highly compressed files. Figure 4 highlights how the HRRR archive makes it possible to access and evaluate model output near wildfires.

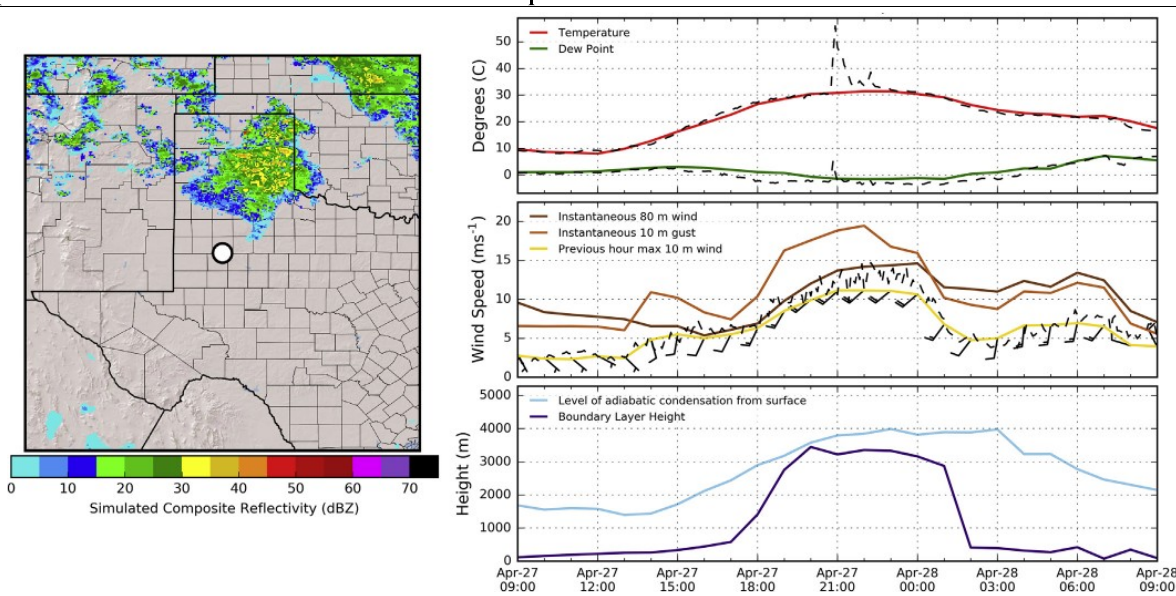

Figure 4. From Blaylock et al. (2017). (Left) HRRR simulated radar reflectivity (dBZ) at 2100 UTC 27 April 2017 at the time of a wildfire near O'Donnell, Texas (white circle). (Right) HRRR analysis of temperature (ºC), dew point temperature (ºC), 80 m wind speed (m s^{1}), 10 m gust (m s^{1}), 10 m maximum wind speed (m s^{1}), 10 m wind speed and direction (half and full barbs denote 2.5 and 5 m s^{1}, respectively and direction from which the wind blows denoted by the shaft), boundary layer height (m), and level of adiabatic condensation (m) between 0900 UTC 27 April 2017 and 900 UTC 28 April 2017 near O'Donnell, Texas (white circle on the left). Observed temperature, dew point temperature, and wind speed from the O'Donnell West Texas mesonet site are shown by dashed black lines in the upper two panels.

Fire Weather Data Analytics

As described by Blaylock et al. (2018), efficient computational solutions are needed to process, archive, and analyze the massive datasets necessary for fire weather research. The OSG is a consortium of computer resources around the United States that makes idle computer resources available for use by researchers in diverse scientific disciplines. Our work demonstrated how the OSG can be used to compute a large set of empirical cumulative distributions from hourly gridded analyses of the HRRR model. These cumulative distributions derived from a 3-yr HRRR archive were computed for seven variables, over 1.9 million grid points, and each hour of the calendar year. The HRRR cumulative distributions were used to evaluate near-surface wind, temperature, and humidity conditions during two wildland fire episodes—the North Bay fires, a wildfire complex in Northern California during October 2017 that was the deadliest and costliest in California history up to that time, and the western Oklahoma wildfires during April 2018. The approach used here illustrated ways to discriminate between typical and atypical atmospheric conditions forecasted by the HRRR model. Such information is useful for model developers and operational forecasters assigned to provide weather support for fire management personnel.

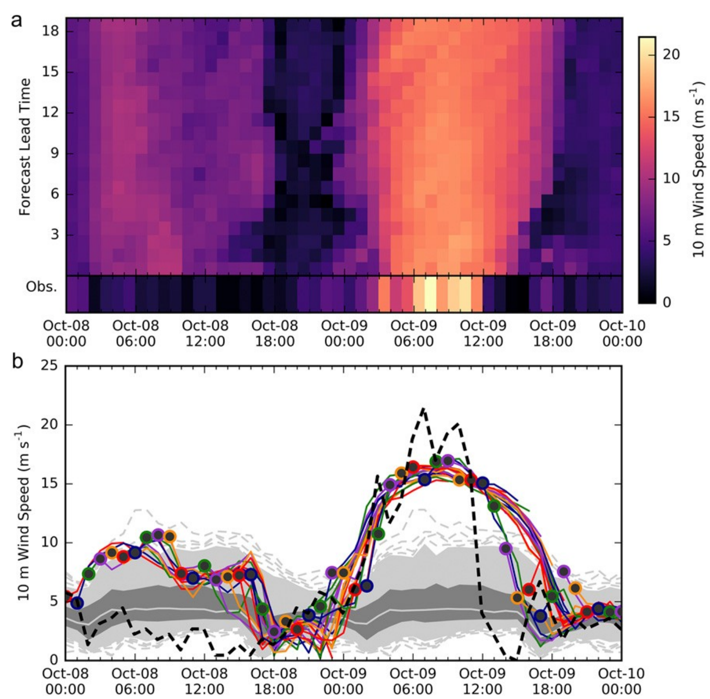

Figure 5. From Blaylock et al. (2018). Illustration of integration of real-time and statistical information for wildfire applications.

The upper panel of Figure 5 illustrates the run-to-run consistency from hourly forecasts of the HRRR l during the rapid growth of the October 2017 North Bay fires. The F00-F18 HRRR 10-m wind speeds are shaded for the Hawkeye, HWKC1, RAWS at each forecast lead time as a function of valid time. HWKC1 observed wind speeds during this period are shaded at the bottom. The lower panel shows the observed HWKC1 wind speeds (heavy dashed line), F00 HRRR wind speeds every hour (gray circles), and F01-F18 HRRR wind speed forecasts initialized every hour (colored lines). Percentiles of HRRR wind speed at HWKC1 are shown by the shading and light lines. This type of statistical information for situational awareness applications was created for every CONUS gridpoint. This would not have been possible at that time without the availability of the OSG computing resources that will be of use to other wildfire studies.

Skill of HRRR Convective Forecasts

Blaylock and Horel (2020) evaluated the ability of the HRRR model to forecast the location of convective storms, one of the key goals for this project. Since lightning is often present with intense convection, lightning observations from the GLM on GOES-East were used to evaluate the performance of the HRRR lightning forecasts during the 2018 and 2019 wildfire seasons. Case studies of individual events illustrate that the skill of the HRRR lightning forecasts varied from storm to storm as shown in Figure 6. Our results suggested that forecasters should use HRRR lightning forecasts to indicate general tendencies for the occurrence, region, and timing of thunderstorms in a broad region rather than expect high forecast accuracy for lightning locally.

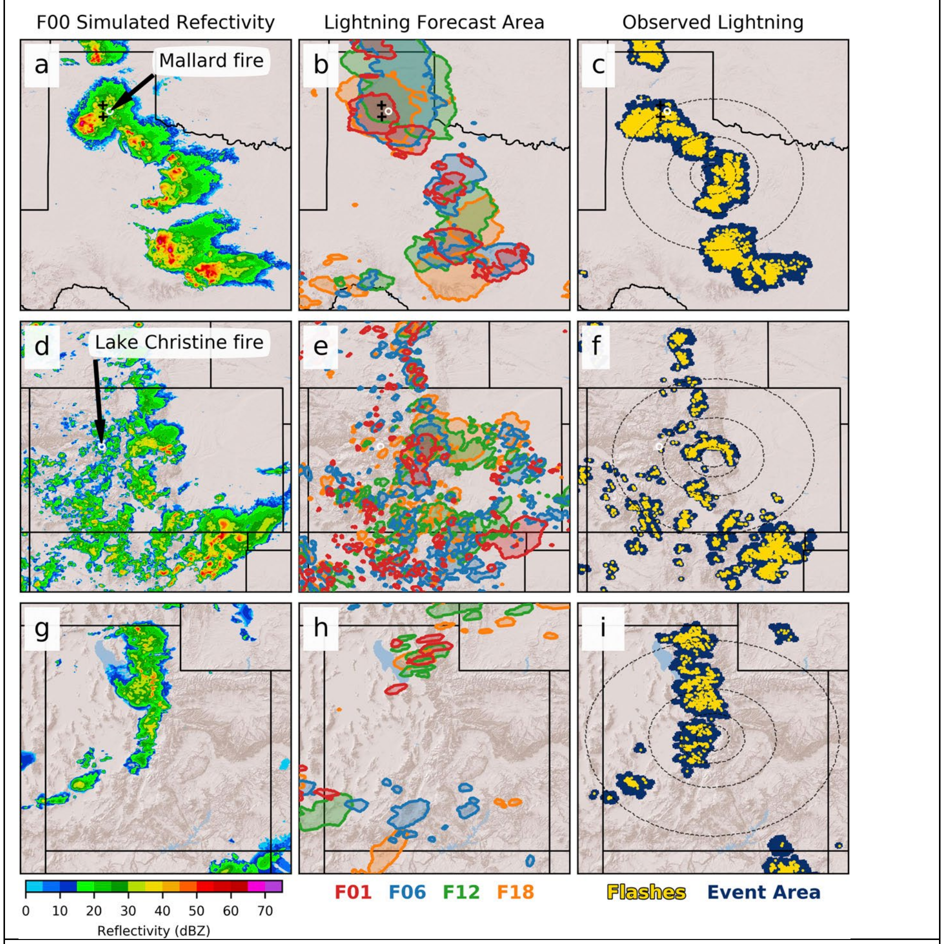

Figure 6. From Blaylock and Horel (2020). (a) HRRR analysis (F00) simulated composite reflectivity at 0200 UTC 16 May 2018 during the Mallard Fire in Texas. (b) Shading and contours enclosing HRRR-forecasted lightning threat during 0100–0200 UTC 16 May 2018 for forecast lead times of F01 (red), F06 (blue), F12 (green), and F18 (orange). (c) GLM events (dark blue) beneath GLM flashes (yellow dots) during 0100–0200 UTC 16 May 2018. (d)–(f) As in (a)–(c), but for 2000–2100 UTC 5 Jul 2018 during the Lake Christine fire in Colorado. (g)–(i) As in (a)–(c), but for 0500–0600 UTC 17 Jul 2018 during a thunderstorm in Utah.

For example, when skill was evaluated within small neighborhoods (30-km radius), mean skill dropped sharply after the first two hours of model integration in all regions and during all hours of the day. However, when evaluated within larger neighborhoods (60-km radius and larger), the skill in the western United States and northern Mexico remained high for all lead times in the late afternoon and early evening. This result is likely due to the model capturing the tendency for convection to break out over higher terrain during those hours.

Fire Weather Applications in Alaska

Gowan and Horel (2020) focused on evaluating methods to improve the spatial coverage of precipitation estimates across Alaska for fire weather applications. The Canadian Forest Fire Danger Rating System (CFFDRS) is used operationally by Alaskan fire managers to produce statewide fire weather outlooks and forecast guidance near active wildfires. The CFFDRS estimates of fire potential and behavior rely heavily on meteorological observations (precipitation, temperature, wind speed, and relative humidity) from the relatively small number of in situ stations across Alaska with precipitation being the most critical parameter.

The multi-satellite IMERG precipitation algorithm was evaluated during six fire seasons (1 June–31 August 2014–19). Near-real-time daily precipitation estimates from the IMERG algorithm were verified using 322 in situ stations across four Alaskan regions. For each region, empirical cumulative distributions of daily precipitation were obtained from station observations during each summer, and compared to corresponding distributions of interpolated values from IMERG grid points on a 0.1° × 0.1° grid. The cumulative distributions obtained from IMERG exhibited wet biases relative to the observed distributions for all regions, precipitation amount ranges, and summers. A bias correction approach using regional quantile mapping was developed to mitigate for the IMERG wet bias. The bias-adjusted IMERG daily precipitation estimates were then evaluated and found to produce improved gridded IMERG precipitation estimates (Figure 7).

This approach helps to improve situational awareness of wildfire potential across Alaska. This will be appropriate for other high-latitude regions where there are sufficient in situ precipitation observations to help correct the IMERG precipitation estimates.

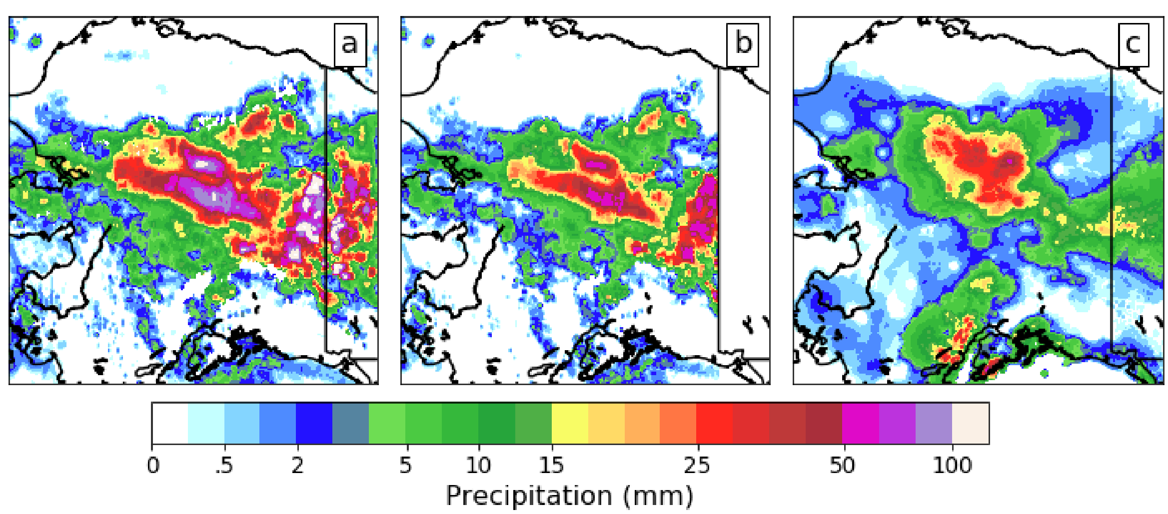

Figure 7. From Gowan and Horel (2020). 24-hour precipitation estimates valid for 22 June 2018 shaded according to the scale below as derived by a) original IMERG data, b) IMERG after quantile mapping, and c) the Alaska-Pacific River Forecast Center.

Applications of Fire Weather Information to Fire Behavior

As a nationally qualified Fire Behavior Analyst (FBAN), CoI Robert Ziel performed analysis of individual fires and coordination of analysis in support of incident prioritization several times each season. As a member of training cadres, he interacted with other analysts and meteorologists who work in similar capacities and environments.

During the 2017 season, Robert Ziel was assigned and reviewed the Lost Creek prescribed fire in the northern lower peninsula of Michigan, the Whitten Fire in eastern Montana, the Craig Mountain Complex along the Snake River in western Idaho, decision support for the national Wildland Fire Management, Research, Development and Application group, the Meyer Fire in southwestern Montana, and the Northern Rockies Geographic Area Decision Support Center (twice).

During the 2018 season, he was assigned to the Alaska Interagency Coordination Center in Fairbanks, the Lake Christine Fire in western Colorado, the Dollar Ridge Fire in northeast Utah, and the Cougar Fire in northern Idaho.

From these experiences, the following possible downdraft/outflow situations were identified:

- Lost Creek prescribed Fire in northern Lower Peninsula of Michigan on April 25, 2017
- Fire growth events in southwest Alaska on June 4, 2017
- Whitten Fire in eastern Montana on July 10, 2017
- Lake Christine Fire in western Colorado on July 4, 2018
- Dollar Ridge Fire in northeast Utah on July 4, 2018
- Upper Yukon fires in NE Alaska on July 7, 2019

In December, 2018, additional reports of outflow winds that impacted wildfire incidents were requested from the National Weather Service. With the assistance of Larry Van Bussum, the Incident Meteorologist (IMET) coordinator with the National Weather Service, the request went out to all IMETs.

Additional Identified Incidents and Situations:

- Brianhead Fire in north central Utah week of June 21, 2017
- Tubbs and Pocket Fires in California on October 9, 2017
- Knob Hill Fire in Arizona on February 27, 2018
- Faka-Union Fire in southwest Florida on March 3, 2018
- Tinder Fire in Arizona on April 30, 2018
- McDannald Fire in southwest Texas on May 1, 2018
- Mallard Fire in northwest Texas on May 11, 2018
- Horse Park Fire in Colorado on May 27, 2018
- Ute Park Fire in Colorado on May 31, 2018
- 416 Fire in Colorado on June 1, 2018
- Trail Mountain Fire in Utah on June 5, 2018
- Zitziana Fire in central Alaska on June 13 and 14, 2018
- Soldier Canyon Fire in south central New Mexico on June 21, 2018
- Weston Pass Fire in Colorado on July 5, 2018
- Spring Creek Fire in Colorado on July 3 and 5, 2018

- Deer Creek Fire in Utah on July 11, 2018.
- Carr Fire in Northern California on July 26, 2018
- Red Canyon Fire in Colorado on August 1 and 2, 2018
- Rabbit Foot Fire in Idaho on August 12, 2018?
- Ranch Fire in Northern California on August 19, 2018
- Camp Fire in Northern California on November 8, 2018

These situations were identified principally because they occurred on larger fires that had increased access to fire weather and fire behavior expertise. They provide opportunities to learn what the HRRR model can resolve in time and space and to learn how that information could be interpreted, communicated and acted upon.

The 2017 Witten Fire in eastern Montana provides examples of the forecasts, analyses, and communications typical for large wildfire incident management. Roles played by meteorologists and fire analysts are highlighted here. The potential benefit for short term, high (spatial and temporal) resolution forecasts is examined.

On July 10th, as part of an approaching cold front, a gust front passed over the Witten Fire area ~1700 MDT, bringing 30 mph winds onto open firelines where burnout operations were underway. Understanding how firefighters prepare for these situation and how new forecast models can better inform them is at the heart of this study.

<u>Evaluate analyses conducted, forecasts produced, and communications provided for cases</u>

- Forecasts Produced

Nearly all forecast products provided by the National Weather Service are derived from its NDFD. Tables of hourly surface weather data are provided to spatial models. Narrative forecasts are formatted from it. These narrative products are produced in the morning and afternoon, with updates provided for important forecast updates.

```
Fire Weather Planning Forecast for SCen and SErn Montana...UPDATED
National Weather Service Billings MT
908 PM MDT Sun Jul 9 2017

 ...Fire Weather Watch in effect from Monday afternoon through Monday
    evening for portions of South Central Montana... and portions of
    Southeast Montana...

 .DISCUSSION...
 Overnight recoveries may continue to
 be poor to moderate over the Custer and Northern Cheyenne/Ashland
 Ranger Districts. Another round of thunderstorms is expected
 Monday evening thanks to a frontal passage. These storms could
 extend farther east than today`s round and include both strong
 erratic winds and some hail. There is indication of a strong wind
 shift over east central Montana toward evening which has prompted
 us to issue a fire weather watch for Musselshell and Northern
 Rosebud. Behind Mondays system, look for somewhat higher humidity
 values on Tuesday, but northwesterly gusts above 30 mph are
 possible over the eastern plains. BT/STP

 MTZ131-101015-
 Northern Cheyenne Indian Reservation/Ashland Ranger District
 Custer Natl Forest-
 908 PM MDT Sun Jul 9 2017

 .MONDAY...
 * Sky/weather...........Mostly sunny.
 * Max temperature.......95-100.
 *   24 hr trend.........1 degree warmer.
 * Min humidity..........14-19 percent.
 *   24 hr trend.........2 percent wetter.
 * Wind (20 ft)
 *  Slope/valley.........Southwest winds 5 to 15 mph.
 *  Ridgetop.............Southwest 5 to 15 mph.
 * LAL...................1...no thunderstorms.
 * CWR...................Zero.
 * Haines index..........4.

 .MONDAY NIGHT...
 * Sky/weather...........Partly cloudy. Isolated rain showers and
   thunderstorms in the evening.
 * Min temperature.......60-65.
 *   24 hr trend.........4 degrees cooler.
 * Max humidity..........75-80 percent.
 *   24 hr trend.........21 percent wetter.
 * Wind (20 ft)
 *  Slope/valley.........West winds 5 to 15 mph.
 *  Ridgetop.............West 5 to 15 mph.
 * LAL...................2...1 to 8 strikes/15 min/cell.
 * CWR...................Less than 10 percent.
```

FIRE BEHAVIOR FORECAST

FORECAST NUMBER: 1	**OPERATIONAL PERIOD:** 7/10/17 0700-2000
FIRE NAME: Tongue River Complex	**DATE/TIME ISSUED:** 7/9/2017 @ 2300
UNIT: Northern Cheyenne Agency	**SIGNED:** ____________ **Typed/printed:** Robert Ziel (Zeke)

WEATHER SUMMARY

Fire Weather Watch in effect from Monday afternoon through Monday evening for portions of South Central Montana and portions of Southeast Montana

Mostly sunny. No significant thunderstorms expected with LAL of 1.
Max temp 95-100, Min RH 14-19%, Winds SW 5-15 on ridges, west 5-15 slope/valley.
Haines down to 4 (from 5 on Sunday).

Yesterday at MTNCA Port 1 at approx. 4114 ft : temp 98, RH 14%, Wind 8G20 NNW to SW late.

FIRE BEHAVIOR

GENERAL:
Grass and sage with needle litter under pine and Juniper carrying fire under light winds. With late afternoon and evening winds, increased flame length, torching and spotting will threaten creek and river bottoms. Flames of 2-4 ft in surface fuels can increase dramatically to 10-15 ft flames, spread rates of ½ mph, and torching and spotting of ¼ mile..

Grasses not fully cured in many places, slowing spread somewhat in the open. Under these hot and dry conditions, expect spread to increase significantly with the anticipated wind increases late in the afternoon.

Local thresholds for extreme fire behavior: Temps over 90, daytime RH less than 25%, poor overnight RH recovery (<35%), Eye level winds over 8mph, 1 hr fuel moisture under 5%

SPECIFIC:
Div A (Witten N Ops): Cook Creek seems to be holding on the north side, but there is more pine and juniper cover across it that could support significant spread to the NE if it crosses the creek.

Div J (Witten SE): Heavy fuels ahead of main fire keep focus on burnout and possibility of intense burning and torching/spotting behavior in the afternoon with wind switch to the west and NW.

Div Z (Witten SW): Fire was active along much of the perimeter in the division with burnout operations and active fire. Southwest winds should help operations for the early part of the burn period, but wind switch to West and NW make spread near the break with J a concern.

Div M (Lee): Burnout operations and holding actions are helping prospects for success. Wind directions SW to NW should be favorable for holding yesterday's actions, but there is more heavy fuel to the north and east of the fire.

AIR OPERATIONS: Mostly sunny with light winds Sunrise 0528, Sunset 2056 at Lame Deer.

SAFETY

Flashy grass fuels have some green in them, but will carry very rapid spread and intense flames under wind. Fire Weather Watch points out evening winds that are a problem in this area. Pay attention to wind directions in the forecast and be prepared for strong winds in the afternoon and evening.

Figure 8. Narrative Weather Forecast (left) and Fire Behavior Forecast (right) for July 10 2017

In the Witten example for July 10th, fire weather and fire behavior forecasts (Figure 8) were prepared the night before and distributed at the first morning operational briefing after the incident management team's arrival. Concerns for frontal passage were well documented.

- Analyses Conducted

The WFDSS analysis tools are generally chosen for assessment of active wildfire incidents throughout the US (Noonan and Opperman, 2015). Only a single forecast WFDSS Short Term analysis, with little specific information about the fire, was conducted for growth anticipated for July 9th. Non-spatial analyses using the same fire models are conducted with either offline software or fireline references. Without effective internet, these non-spatial analyses were used for a fire behavior forecast prepared late on July 9th for the July 10th operational period.

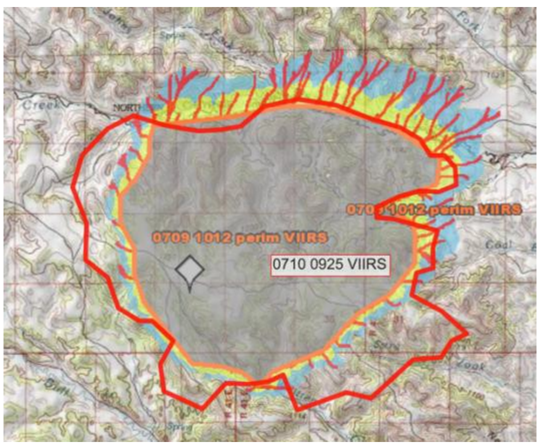

Figure 9. WFDSS Short Term Fire Behavior for July 9. It utilized remotely sensed perimeter from VIIRS AF detections and the fuelscape as mapped by LANDFIRE.

Fuel Model 2, Timber (grass and understory)

SPREAD Ch/hr	Effective Windspeed(EWS), mph *Use 20ft/FCST wind only if EWS = MFWS and assumes unsheltered wind adjustment (0.4)													
*FCST/20ft	NWNS-0	Back - ½	Flank - 1	7	13	20	27	33	40	47	53	60	67
EWS				2	4	6	8	10	12	14	16	18	20
1-hr Moisture, %; (Herbaceous moist. 120%-80%) 1	3-4	4-5	6-7	12-14	36-41	71-82	118-136	176-202	245-281	324-371	412-473	511-586	619-710
3	3	3-4	5	10-11	28-32	56-64	93-106	138-158	192-220	253-290	323-370	400-458	484-555
5	2-3	3	4-5	8-10	24-27	48-55	79-91	118-135	164-188	217-248	277-316	343-392	415-475
7	2	3	4	8-9	22-25	44-50	73-83	108-123	150-171	198-226	253-288	313-357	379-432
9	2	2-3	3-4	7-8	20-23	40-46	66-76	99-113	138-157	182-207	232-264	287-327	348-396
11	2	2	3	6-7	17-20	34-39	57-65	85-97	118-134	155-177	198-226	245-280	297-339
13	1	1-2	2	4-5	12-14	24-27	40-45	60-68	83-94	110-124	140-159	173-196	210-238
15	0	0-1	0-1	0-2	0-4	0-9	0-13	0-13	0-13	0-13	0-13	0-13	0-13
17	0	0	0	0	0	0	0	0	0	0	0	0	0

Low	Moderate	High	Very High	Extreme

Figure 10. Fire Spread Table for Fuel Model 2 (timber- grass and understory) from Fire Behavior Reference Guide. Utilized 1-hr of 3%, Windspeed of 15 mph.

These forecast tools and results portray detail not fully representing the input factors as the fire burned throughout the day on July 9th and 10th. As snapshot-in-time tools, based on expertise applied with great uncertainty in initial assessment, these prediction details cannot be accepted as is. Updates to critical factors, such as wind shifts, need to be integrated as they are known and can be anticipated throughout the day.

- Communications Provided

Meteorologists are tasked with reviewing, and interpreting model forecast outputs and adjusting NDFD outputs for individual situations in time and space. Early morning conversations between the fire analyst or incident commander and meteorologist identify key updates to these forecasts to highlight in the morning briefing. Communications throughout the day are based on timing concerns and situation changes.In this case, red flag conditions were reinforced, highlighting frontal passage, thunderstorms and high winds. These updates were provided to all fireline supervisors at the morning operational briefing. With limited internet and cell service, fire analyst again requested an update to the expected incoming weather and advised fireline supervisors of impending thunderstorm and gust front events in the afternoon. Late afternoon communications reinforced the imminent changes.

<u>Conduct fire behavior analyses utilizing currently available tools along with interpretations of HRRR outputs to determine how results may be different</u>

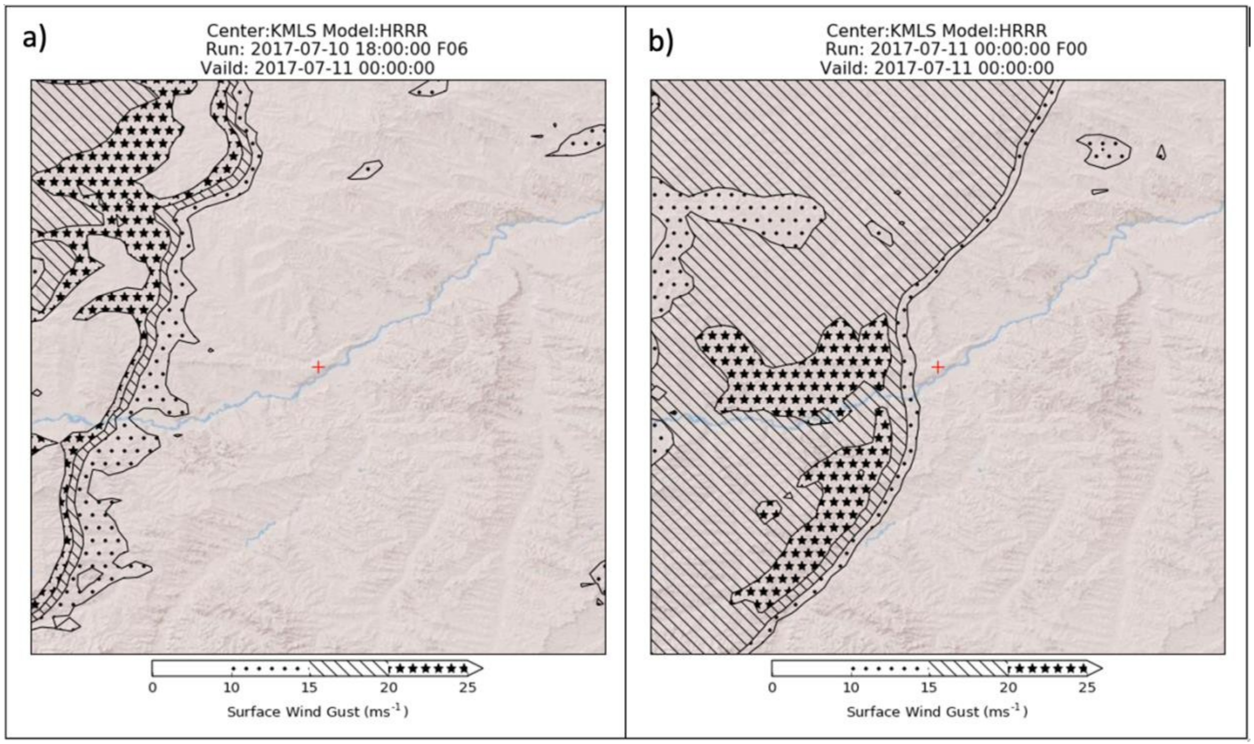

Figure 11. Reformatted HRRR output for the Witten Fire area on July 10, showing position of gust front. Image on left (a) is a 6-hr lead time forecast. Image on right (b) is a nowcast of the frontal passage. Red cross hair is the Witten Fire location.

Figure 11 effectively shows how, even at high temporal and spatial resolutions, that the understanding of input wind factors changes over short periods of time. In this Witten Fire example, the “convective outflow” was forecasted well in advance and observed progressing toward the fire area. The details become more accurate and precise as the lead time decreases and input details become clearer. Once the front arrived, on-scene reports suggested that the wind speed was 40 mph out of the NW at its peak, and the Nearby RAWS station reported sustained winds increasing from 7 to 28 mph and changing direction from W to NW between 1600 and 1700.

Despite all this detailed forewarning, fire operations were still actively burning out on exposed firelines as the front passed. Firefighters were threatened by windthrow as well as intense burning and visibility limitations. Escape to safe areas was dependent on effective movements at critical times.

The Witten Fire example is one where situation, science, expertise, and judgement combined to identify the potential, understand its significance, monitor its development, and communicate necessary alerts in advance of the gust front that arrived late in the afternoon. However, timely and appropriate decisions, effective communication of those decisions, and well implemented response by fireline personnel also play key roles in the success of these warnings. Outcomes can be impacted by performance from any of these roles and responsibilities.

Evaluate ability of the HRRR to produce meaningful fire behavior interpretation in situations where outflow winds may be significant

Weather events and phenomena such as gust fronts, downdrafts and outflow winds can produce critical fire weather conditions. However, they do not alone constitute sufficient cause for concern and alert ahead of and during the life of wildfire incidents. Fuel character, availability and flammability are traditional factors that are not evaluated in the most atmospheric models. The project considered different indicators and approaches to informing and enhancing interpretation of these wind events as critical fire weather warning situations. These indicators can be derived directly from the HRRR model inputs and derived outputs.

- Vapor Pressure Deficit (VPD) and the Crossover Concept

Fuel availability and fuelbed flammability are limited by fuel moisture. Fuel moisture at any point in time is influenced by atmospheric moisture and the exchange between them. VPD (Seager et al 2015) reports the difference between how much moisture the atmosphere can hold and how much it actually does. Monitored for years to understand growing conditions for agriculture and greenhouse products, VPD is increasingly being used to evaluate wildfire fire potential. While both dew point (DP) and relative humidity (RH) provide measures of atmospheric moisture, it is difficult to compare their values over time and space because of ambient temperature variability. VPD effectively allows objective comparison between measurements both temporally and spatially, with optimal growing conditions found generally between 8 and 14 hPa.

The Crossover Concept (Lawson and Armitage 2008), as detailed for the Canadian Forest Fire Danger Rating System (CFFDRS), similarly combines ambient temperature with DP or RH to identify a threshold for potentially severe fire weather.

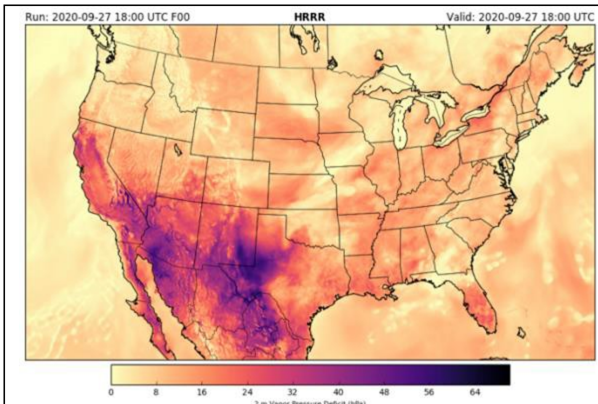

Figure 12. Vapor Pressure Deficit from HRRR Model at 1800 UTC Sept. 27, 2020.

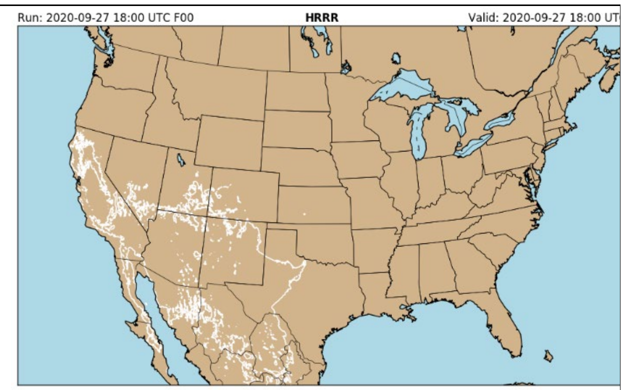

Figure 13. Crossover contour, where temperature (C) equals relative humidity at 1800 UTC Sept 27, 2020. Within the contour, temperature exceeds relative humidity, suggesting potentially severe fire potential.

Both indices recognize diurnal differences, and attempt to reflect them with reduced bias so that interpretations of burning thresholds can be applied regardless of the time of day.
Additional detail about them, their relation to temperature and RH factors, and comparison between them can be found in the NWCG Fire Behavior Field Reference Guide.

- Resolution of Red Flag Warnings

One of the ways that the National Weather Service identifies and warns about potential for critical fire weather events is their program for Red Flag Warnings. The objective criteria vary widely across the country, respecting differences in fire occurrence, fire behavior, and values at risk.

Typically, there is some combination of atmospheric humidity and windspeed thresholds, an example represented by the rectangular area shown in Figure 8. In this representation, the minimum combination of 7 m/s windspeed and 25% relative humidity is used to bound the rectangle that exceeds the thresholds. For “Red Flag Potential”, the threshold is utilized to identify a zero line, from which departures can be identified. The result (Figure 15) on September 27, 2020 shows significance in areas where fires were burning actively in California among others.

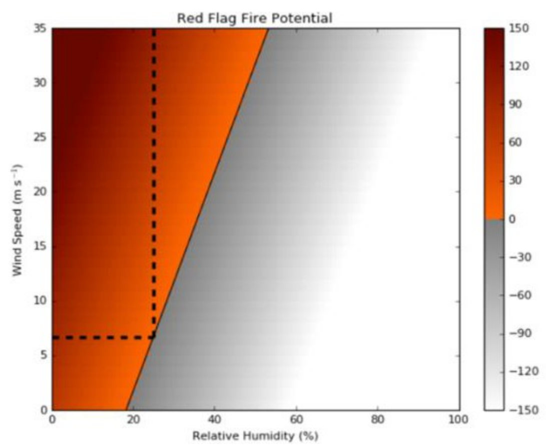

Figure 14. Red Flag Potential, referencing typical Red Flag criteria as a rectangle within the shaded range.

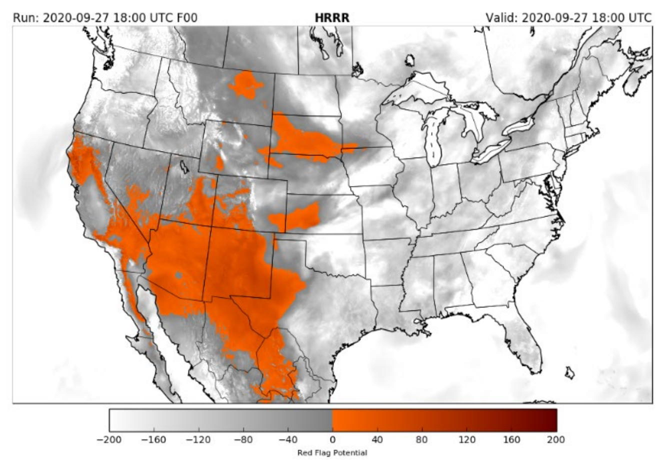

Figure 15. Example Red Flag Potential for 1800 UTC September 27, 2020 from the HRRR.

Given the potential utility of VPD and the ongoing consideration of improvements to the Red Flag Warning program, the introduction of the Hot-Dry-Windy (HDW) Index offers a new method for depicting these factors (Srock et al 2018). The developers of the HDW Index have constructed a website (https://www.hdwindex.org/index.html) for access and utilization of forecast HDW interpretations. It provides an ensemble forecast of single daily HDW values across a low-resolution Global Ensemble Forecast System grid of 0.5 degrees. The developers chose a low- resolution system to simplify climatology referencing, speed the integration of ensemble forecasts and output production, and to discourage its misuse in tactical application.

Implementing HDW with the project’s system for resolving HRRR forecasts and deriving wildfire hazard interpretations at high temporal and spatial resolution is under development at the time of this report. An important outcome of this approach, utilizing high resolution outputs of coarse index formulations to automate the identification of specific situations, and to alert and inform decision makers at local levels of potentially extreme problems.

- <u>FireLine Assessment MEthod (FLAME) Fire Spread Model (Bishop 2007)</u>

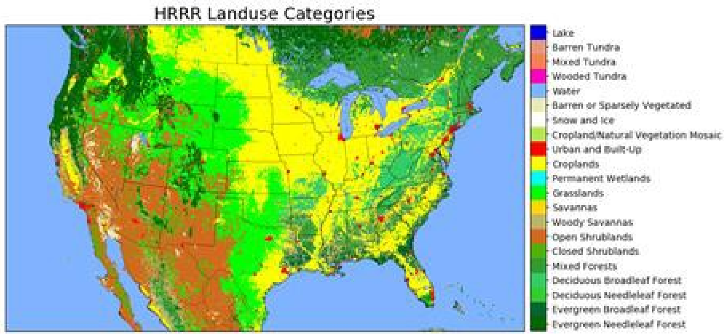

Figure 16. HRRR Land Use categories

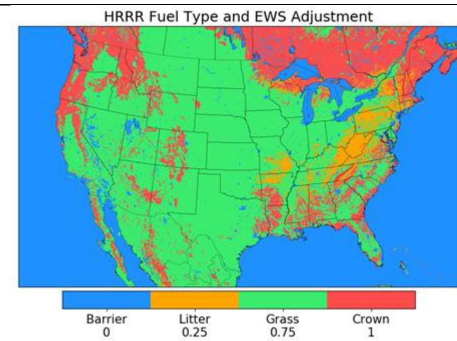

Figure 17. HRRR FLAME Fuel Type classifications and Effective Windspeed adjustments

Like all atmospheric models, the HRRR includes land surface information, including vegetation type, to inform and influence model outputs from their interactions. One of our project's objectives was to determine if this vegetation information information could aid in interpreting the fire potential as influenced by wind variation and concentration. Both vegetation (300+) and fuelscape (53+) depictions in LANDFIRE (https://landfire.gov/) datasets offer detailed classifications not discernable within the HRRR system that discriminates only 18 different vegetative classes. The FLAME system generalizes fuels into three categories; grass, litter, and crown fuel types that make it easier to reclassify the HRRR landuse categories into fuels. It assumes that the landscape is generally flammable, making wind and fuel the independent variables for estimating fire spread.

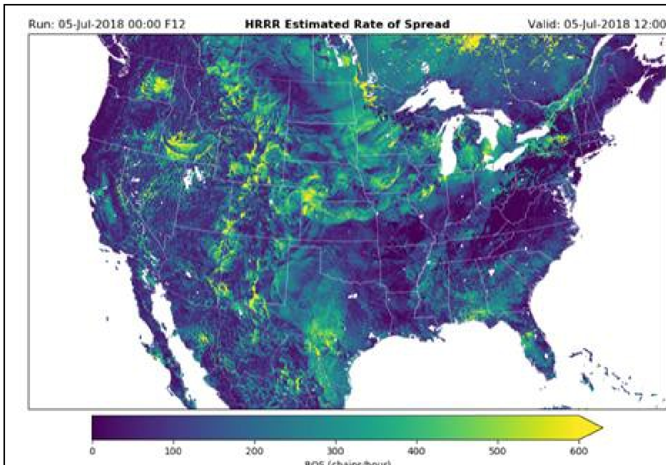

Figure 18. HRRR FLAME Model Estimated Rate of Spread utilizing for July 5, 2018 at 0z.

HRRR Land Use (Figure 16) were reclassified as FLAME system fuel types and associated wind reductions (Figure 17). This spatial depiction was combined with HRRR surface wind forecasts to produce Rate of Spread at high resolution as shown in Figure 17.

While this resulting depiction of spread rates is interesting, it was found wanting in important aspects. With no real integration of variations in fuel availability and flammability, such as could be offered by VPD and other more cumulative factors, it produced far too many warning locations and situations to be useful as an automated tool. Integrating additional factors is possible.

However, other more sophisticated atmosphere-fire models seem to be better environments for application.

Science Delivery

The resources developed and research undertaken as part of this project has been made available through many avenues:

- The extensive volume (150+ Tbytes) of HRRR model output and satellite imagery is accessible now on AWS and Google cloud servers as part of the NOAA Open Data Program. Our archive filled a gap during the past 4 years for the HRR model output that was used by over a thousand registered operational and research users. Over the next year, those users will be encouraged to transition to using the capabilities we pioneered using the AWS and Google cloud archives. The paper describing the HRRR archive by Blaylock et al (2020) has already been cited in over 40 other research works.
- An large set of web tools were developed to analyze and display output from the HRRR model for fire weather applications (https://hrrr.chpc.utah.edu) including the HRRR Custom Surface Maps: http://home.chpc.utah.edu/~u0553130/Brian_Blaylock/hrrr_custom.html . Some of those will continue to be available subject to available compute resources at the University of Utah typically within the most recent year. However, support to provide web access to HRRR model output for prior years is not sustainable by us due to the storage costs required and no funding to do so.
- As indicated in Appendix B:
  - Four papers were published directly relevant to the operational fire weather community with one more nearing completion
  - Graduate student Brian Blaylock completed the requirements for the Ph.D.
  - Graduate student Taylor Gowan (McCorkle) completed the requirements for the M.S. degree and will complete her Ph.D. thesis during early 2021
  - Ten presentations at national conferences and regional wildfire workshops in Alaska were made by the University of Utah research team
- CoI Robert Ziel interacted extensively with National Weather Service and Predictive Service meteorologists, as well as Fire Behavior Analysts, to determine how best to apply improved analysis/interpretation to messaging for fire management community. For example participation in the following meetings:
  - NWS Red Flag Warning Workshop, Boise, Idaho, May 8, 2018
  - Fire and Forest Meteorology Symposium, Boise, Idaho, May 15-17, 2018
  - NWS Fire Weather Summit, Boise, Idaho, September 18-20, 2018
  - 6th Fuels and Fire Behavior Conference, Albuquerque, New Mexico April 29-May 3, 2019
  - Alaska Fire Science Consortium Fall Fire Science Workshop, October 2019
  - Report to the Fire Behavior Subcommittee
  - Report on QPE Bias Correction at the 2019 Fall Fire Science Workshop in Fairbanks, AK

Conclusions and Implications for Future Research/Policy

Transfer of research methods and results to operations is a difficult process to implement effectively. Our experience from a prior JFSP project and this study is that the research is more effective if it aligns closely with what an operational agency is already in the process of implementing. We would not be able to expand our archive adding hundreds of Gbytes of model output daily after the end of this project. However, the NOAA Open Data Program is now archiving the HRRR model output that reduces the need for our archive such that we and other researchers can migrate codes easily to access the data from those resources.

We began the project expecting the HRRR model to not be effective at forecasting specific outbreaks of convective outflows with high fidelity at long lead times- no deterministic operational convective allowing model is expected to do so at the present time by us or likely within the broader research community as well. We were stymied in some respects by not being able to objectively contrast outflow boundaries arising from convection as there is insufficient wind data to do so, especially in remote locations of highest interest for wildfires. We relied upon satellite estimates of lightning as a proxy for assessing the ability of the HRRR model to forecast the occurrence of intense convection rather than outflows. It was instructive to assess the utility of the GLM products from GOES as well as the forecast skill of the HRRR model. Hence, our conclusion (Blaylock et al. (2020): "Our results suggest that forecasters should use HRRR lightning forecasts to indicate general tendencies for the occurrence, region, and timing of thunderstorms in a broad region rather than expect high forecast accuracy for lightning locally,"

Use of GOES-R fire products for the automated alert to new fire starts has been successful enough in some parts of the country to highlight the potential for earlier warnings of threats in the fire environment when rapid response is called for. However, automated alerts for action using discrete interpretation of pre-disposing factors in the absence of active fire (fire danger, red flag) could require greater effort in understanding local trends and thresholds to minimize false positive and false negative errors. Ultimately these alerts, and the criteria they are derived from, will require verification, calibration and validation even once implemented operationally. Coarse criteria can be useful for awareness, but probably not for action.

Who has access to these alerts and how many times will the alerts need to be passed along before reaching the decision-maker with responsibility for protecting the values at risk? Many of these situations occur on individual incidents, if not particular situations within them. How skillfully will the interpretation be communicated along its passage? And how compromised will the communication network be from multiple competing incidents and alerts?

There are critical losses reported from wildfires each year. Some losses were not warned sufficiently or on time. But other important examples demonstrate the roles of the message, the messenger, and the recipient response in the successful protection of values. The human element in all this cannot be understated until the human is excluded from the responsive decision and action.

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Appendix B: List of Technical Publications, Presentations, Web Resources

Articles in peer-reviewed journals

Gowan, T., and J. Horel, 2020: Evaluation of IMERG-E Precipitation Estimates for Fire Weather Applications in Alaska. Wea. Forecasting, 35, 1831–1843. https://doi.org/10.1175/WAF-D-20-0023.1

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Graduate Thesis

Blaylock, B., 2019: *High-Resolution Rapid Refresh Model Data Analytics for Wildland Fire Weather Assessment.* Ph.D. Thesis. University of Utah. 147 pp.

McCorkle (Gowan), T., 2018: *An Evaluation of the Experimental High-resolution Rapid Refresh - Alaska Modeling System During Winter.* M.S. Thesis. University of Utah. 90 pp.

Gowan, T., 2021: *Data Analytics Applied to Near-Real Time Satellite Estimates and High-Resolution Model Output for Research and Forecasting Applications.* Ph.D. Thesis. University of Utah. 120 pp.

Conference Abstracts

Blaylock, B., 2017: Communicating Fire Weather Risks at Short Lead Times using the High-Resolution Rapid Refresh (HRRR) Forecast Modeling System. *2017 Conference on Fire Prediction Across Scales* Columbia University. Poster

Blaylock, B., and J. Horel, 2018: High Resolution Rapid Refresh Model Analytics in a High Performance Computing Environment. *Fourth Symposium on High Performance Computing for Weather, Water, and Climate* Austin, Texas

McCorkle, T., J. Horel, and B. Blaylock, 2018: Communicating Fire Weather Risks at Short Lead Times Using the High-Resolution Rapid Refresh Forecast Modeling System. 98th Annual AMS Meeting. Austin, Texas. https://ams.confex.com/ams/98Annual/webprogram/Paper326251.html

Blaylock, B., and J. Horel, 2019: High-Resolution Rapid Refresh Model Data Analytics Derived on the Open Science Grid to Assist Wildfire Weather Assessment. 35th Conference on

Environmental Information Processing Technologies Phoenix, Arizona

Blaylock, B., and J. Horel, 2018: Evaluating HRRR Model Performance at Wildfires. *12th Fire and Forest Meteorology Symposium* Boise, Idaho

McCorkle, T., and J. Horel, 2018: Validation of GPM IMERG Precipitation Data for Fire Weather Applications in Alaska. *12th Fire and Forest Meteorology Symposium* Boise, Idaho

Gowan, T., 2019: Utilizing Remotely-Sensed Data Products and Modeling Tools for Fire Weather Applications in Alaska. *NCAR Information Seminar.* 26 June 2019, Boulder, CO

Gowan, T., 2019: Utilizing Multi-Satellite Precipitation Estimates for Fire Weather Applications. AFSC Fall Fire Workshop. 9 October 2019, Fairbanks, AK

Horel, J., 2019: Enhancing Access to Observations and Model Output for Mountain Weather Applications (Invited). American Geophysical Union Annual Meeting. San Francisco, CA. •

Gowan, T., and J. Horel, 2020: Evaluation of Near Real-Time IMERG Precipitation Estimates for Fire Weather Applications in Alaska. 19th Conference on Mountain Meteorology. Recorded Presentation. Handout (13.6 MB)

Website development

https://hrrr.chpc.utah.edu has extensive documentation regarding the objectives, methods, data, and outcomes from this study. During the project, all of the following analytical tools were operational. Most of them are no longer maintained except for example the HRRR Custom Maps remains functional and relevant for fire weather applications.

- HRRR Point Forecast
- HRRR Fires Forecast
- HRRRx vs. HRRR Maps
- HRRR Error Maps
- HRRR Percentile Demo
- HRRR Yesterday
- HRRR Events

Appendix C: Metadata

As proposed originally for this project, the metadata for the HRRR data archive completed as part of this project is referenced by a Digital Object Identifier in the University of Utah's Research Data Repository: https://hive.utah.edu/: https://dx.doi.org/10.7278/S5JQ0Z5B