Understanding Santa Ana Winds and Fire Progression

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www.mtri.org
Background: What are Santa Ana Winds?

- A relatively ephemeral weather phenomenon, lasting from a few hours to 2-3 days\(^1\)
- Santa Ana season stretches from fall to spring
- Incorporates hot, high-speed offshore winds with very low relative humidity
- Affects the coastal southern California region, typically associated with driving many wildfires to catastrophic size

How are Santa Ana Winds quantitatively related to fire progression?

- Unknown!
  - Very little in the literature to suggest that we understand how Santa Ana winds directly affect fire progression rates

- Moritz et al. 2010
  - Showed that particularly large fires have a higher probability of occurring in areas of historically high fire risk (as indicated by an index derived from October Santa Ana events ‘95-’03), but did not link specific Santa Ana events to specific fires

- There is no standard definition of what combination of weather parameter thresholds define a Santa Ana wind event
  - Most definitions are based on pressure gradient differences, but we found three that are based on widely available and easily detectable weather parameters
# Santa Ana Criteria Used for Study

<table>
<thead>
<tr>
<th>Source</th>
<th>ID</th>
<th>Wind Direction</th>
<th>Wind Speed</th>
<th>Relative Humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Diego County</td>
<td>SA1</td>
<td>&gt;345° and &lt;115° true</td>
<td>&gt;3.8 m/s</td>
<td>&lt;30%</td>
</tr>
<tr>
<td>National Weather Service</td>
<td>SA2</td>
<td>---</td>
<td>&gt; 11.18 m/s sustained</td>
<td>&lt;15% for &gt;6 hours</td>
</tr>
<tr>
<td>Red Flag Day Criteria</td>
<td></td>
<td></td>
<td>&gt; 15.65 m/s frequent gusts</td>
<td></td>
</tr>
<tr>
<td>Sergius and Huntoon (1956)</td>
<td>SA3</td>
<td>0° to 90° true</td>
<td>≥8.93 m/s</td>
<td>&lt;40% at 1630 PST</td>
</tr>
</tbody>
</table>

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![Santa Ana Fire Danger Sign](image)
Study Outline

- Do burns occurring on days with Santa Ana wind conditions have a greater area than those that do not?

- How do Santa Ana definition parameters (relative humidity, wind speed, wind direction) relate to burn area per day?

- Are there other parameters (weather, topographic, fuels, etc.) that are better predictors of burn area per day?

- What suite of parameters best predicts burn area per day?
Datasets : Fire Progression Polygons

- MODIS-based, daily fire progression maps developed by Dr. Tatiana Loboda, University of Maryland
  - Model bounded by MTBS Landsat-derived fire perimeters
  - Burned area pooled by day and fire event

2003 Cedar Fire: >260,000 acres burned in 4 days
This study used 528 total burn area polygons grouped by fire and date.

The dataset comprises 163 distinct wildland fire incidents from 2001-2009 in southern California within 32.5 to 35.4° latitude and -116.0 to -120.6° longitude.

Individual fires in the dataset lasted anywhere from 1 to 44 days (mean 3.4 days).

Polygon burn area was non-parametrically distributed with a mean of 2081 ± 5055 ha (median = 635 ha).

The dataset was power transformed by 1/5 in order to approximate normality for the use of more powerful parametric tests.
Datasets: RAWS

- **Remote Automated Weather Stations (RAWS)**
  - RAWS is an interagency network comprising 2,200 stations located throughout the United States. Data is compiled and distributed by the National Interagency Fire Center (NIFC) in Boise, Idaho.

- **Advantages**
  - High temporal (hourly) resolution
  - Over 20 standardized weather variables available
  - Extensive network (82 units within study area)

- **Linking to fire progression dataset**
  - Linked by shortest straight-line distance
  - The mean distance from a burn area polygon to its assigned RAWS station was 8.5 ± 6.4 km.
**Methods: Detect Santa Ana events**

- **Santa Ana events as detected by RAWS**

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- Seasonal pattern compares well with Santa Ana events defined using mapped pressure gradients (Raphael 2003)

- Raphael found the # of Santa Ana events per month peaked at around 4 from November to January -> compares well sa2 & sa3

- This also illustrates that our sa1 criteria (San Diego County) is a much more lax definition than has been previously documented.
Study Outline

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- What suite of parameters best predicts burn area per day?
Do burns occurring on days with Santa Ana wind conditions have a greater area than those that do not?

- **sa1**: 2.8 x greater
- **sa2**: 2.3 x greater
- **sa3**: 2.2 x greater
Study Outline

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How do Santa Ana definition parameters relate to burn area per day?

- **Relative humidity**
  - As expected, relatively strong negative correlation
  - \( r = -0.449 \)
  - Of the three variations we used (mean daily, min. daily, and PST 1630), mean daily is slightly stronger

![Graph showing the relationship between mean relative humidity and area per day with a scatter plot and a regression line. The equation of the line is given: \( y = -0.01x + 2.23 \), with a p-value of 0.0000 and a correlation coefficient of -0.449.](image-url)
How do Santa Ana definition parameters relate to burn area per day?

- **Wind speed**
  - As expected, positive correlation
  - Of the three variations we used (mean, mean gust, mean peak), mean peak was the strongest
  - HOWEVER, correlation is unexpectedly weak:
    - Mean: not significant
    - Gust: $r = 0.17$
    - Peak: $r = 0.24$
Wind speed – examination of weak correlation:

- Does strength of correlation change when looking at subsets of burn area based on duration and temporal position?

- YES
  - Burn polygons that represent only the 1st day of a fire have a much higher correlation strength
    - Gust: $r = 0.35$
    - Peak: $r = 0.49$
  - This suggests that wind speed plays a key role in the establishment of a fire after ignition, but a very small role if any after established
How do Santa Ana definition parameters relate to burn area per day?

- Wind Direction
  - Since not a linear variable, the effects of wind direction on burn area were tested by comparison of means
  - The directions for which burn area was significantly greater align with those used to define Santa Ana winds

<table>
<thead>
<tr>
<th>Wind Direction</th>
<th>p-value</th>
<th>Mean ha within (n)</th>
<th>Mean ha outside (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 45°</td>
<td>0.0042</td>
<td>2583 (60)</td>
<td>2024 (467)</td>
</tr>
<tr>
<td>45 - 90°</td>
<td>0.0000</td>
<td>5989 (59)</td>
<td>1596 (468)</td>
</tr>
<tr>
<td>90 - 135°</td>
<td>0.2917</td>
<td>1242 (37)</td>
<td>2152 (490)</td>
</tr>
<tr>
<td>135 -180°</td>
<td>0.9982</td>
<td>768 (68)</td>
<td>2283 (459)</td>
</tr>
<tr>
<td>180 - 225°</td>
<td>0.9999</td>
<td>1421 (89)</td>
<td>2223 (438)</td>
</tr>
<tr>
<td>225 - 270°</td>
<td>0.8465</td>
<td>1672 (80)</td>
<td>2162 (447)</td>
</tr>
<tr>
<td>270 - 315°</td>
<td>0.8332</td>
<td>1462 (68)</td>
<td>2180 (459)</td>
</tr>
<tr>
<td>315 - 360°</td>
<td>0.0286</td>
<td>2154 (62)</td>
<td>2079 (465)</td>
</tr>
</tbody>
</table>
Study Outline

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- How do Santa Ana definition parameters (relative humidity, wind speed, wind direction) relate to burn area per day?

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- What suite of parameters best predicts burn area per day?
Are there other parameters that can better predict burn area per day?

- Attempted to identify and run linear regression on any variable that could have an effect for which data was available
  - RAWS units collect an assortment of weather parameters:
    - 10-hour fuel moisture
    - Fuel temperature
    - Precipitation
    - Air temperature
    - Dew point
  - Additional spatially derived parameters we decided to look at:
    - Topographic slope (derived from DEM)
    - Fuel loading (from Fuel Characteristic Classification System, FCCS)
    - Wildfire front length (spatially derived)
    - Population density and housing unit density (from 2000 Census)
Are there other parameters that can better predict burn area per day?

Summary

– Not unexpected results:
  • 10-hour fuel moisture, dew point, and precipitation all had negative correlations, all weaker in strength than relative humidity
  • Fuel temperature and air temperature had weak positive correlations
  • Topographic slope had very weak positive correlation
  • Wildfire front length had a very strong positive correlation (only after the first day of multiday fires, as expected)
  • Fuel loading positively correlated with area, especially after the first day of multiday fires

– Strange result:
  • Population density and housing unit density had relative strong ($r \sim 0.35$) positive correlation only for the first and last day of multiday fires
    – Possible explanations:
      » First day: Linked to anthropogenic causes of ignition in areas of higher population density?
      » Last day: Active containment disrupts typical “petering out” natural fire progression?
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Multivariate analysis – General Linear Model
– Iterated through all possible combinations of weather, topographic, etc. variables
– Included bimodal variables (1 = True, 0 = False):
  • Wind direction is NE
  • Burn day is 1\textsuperscript{st}
  • Burn day is last
  • Burn is part of multiday fire
  • Burn is coastal

What suite of parameters best predicts burn area per day?
What suite of parameters best predicts burn area per day?

- **GLM Results**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Coefficient</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative humidity (daily mean)</td>
<td>-8.89</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Peak wind speed (mean of hourly)</td>
<td>4.62</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>Wildfire front (length)</td>
<td>2.16</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Burn day is 1st</td>
<td>12.8</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Burn day is last</td>
<td>-3.33</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Intercept</td>
<td>21.9</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>

$r^2 = 0.509$
Three key points

– Area of burn polygons occurring under Santa Ana conditions is over twice as large as those occurring under non-Santa Ana conditions.

– Of the three Santa Ana classification parameters (relative humidity, wind speed, wind direction), relative humidity is the most consistently strong correlated with burn area (negative) while wind speed is strongly correlated only on the first day of a fire.

– No other weather variable was shown to be a consistently strong predictor of burn area. The suite of variables comprising the best fit generalized linear model for predicting burn area included relative humidity, peak wind speed, wildfire front length, and two day of fire event indicators (is first day of a fire event, is last day of a fire event).
Appendix: Limitations of RAWS

- RAWS unit data may misrepresent actual weather conditions for a burn area due to large distances separating the two.

- There was at least one instance of a fire (Reche 2001) for which the 2nd closest RAWS unit (16.2 km vs. 16.1 km in opposite direction) likely more accurately reflected the local weather conditions (as evidenced by local weather and news reports).
Appendix: Time lag effects

- Strength of correlation with burned area decreased with number of days before burning for all weather variables (figure below shows 4 examples).

- Separately, total precipitation summed over 1-7 days prior to burn did not improve the strength of correlation with burn area versus day-of total precipitation (7-day sum: $r=-0.193$, $p = 0.000$).
## Appendix: Independent Variables

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Source</th>
<th>Stat. Param</th>
<th>Mean</th>
<th>med</th>
<th>std</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>relative humidity (daily mean)</td>
<td>%</td>
<td>RAWS</td>
<td>^0.2</td>
<td>32</td>
<td>25 ± 22</td>
<td>Mean of hourly mean relative humidity measurements</td>
<td></td>
</tr>
<tr>
<td>relative humidity (daily minimum)</td>
<td>%</td>
<td>RAWS</td>
<td>^0.2</td>
<td>19</td>
<td>13 ± 16</td>
<td>Min. of hourly mean relative humidity measurements</td>
<td></td>
</tr>
<tr>
<td>relative humidity (at 1630 PST)</td>
<td>%</td>
<td>RAWS</td>
<td>^0.2</td>
<td>25</td>
<td>20 ± 19</td>
<td>Relative humidity measurement taken at 1630 PST</td>
<td></td>
</tr>
<tr>
<td>wind speed (daily mean)</td>
<td>m/s</td>
<td>RAWS</td>
<td>^0.2</td>
<td>2.8</td>
<td>2.3 ± 2.4</td>
<td>Mean of hourly mean wind speed measurements</td>
<td></td>
</tr>
<tr>
<td>wind speed (daily max)</td>
<td>m/s</td>
<td>RAWs</td>
<td>^0.2</td>
<td>5.7</td>
<td>4.9 ± 3.8</td>
<td>Maximum of hourly mean wind speed measurements</td>
<td></td>
</tr>
<tr>
<td>gust (daily mean of hourly)</td>
<td>m/s</td>
<td>RAWS</td>
<td>^0.2</td>
<td>5.9</td>
<td>4.8 ± 4.0</td>
<td>Mean hourly of max. 3 sec.mean over 2 minute period</td>
<td></td>
</tr>
<tr>
<td>peak wind speed (daily mean of hourly peaks)</td>
<td>m/s</td>
<td>RAWS</td>
<td>^0.2</td>
<td>14</td>
<td>11 ± 11</td>
<td>Mean of hourly peak wind speed measurements</td>
<td></td>
</tr>
<tr>
<td>dew point (daily mean)</td>
<td>°F</td>
<td>RAWS</td>
<td>^1</td>
<td>43</td>
<td>44 ± 12</td>
<td>Mean of hourly mean dew point measurements</td>
<td></td>
</tr>
<tr>
<td>fuel temperature (daily mean)</td>
<td>°F</td>
<td>RAWS</td>
<td>^1</td>
<td>75</td>
<td>76 ± 10</td>
<td>Mean of hourly mean fuel temperature measurements</td>
<td></td>
</tr>
<tr>
<td>temperature (daily mean)</td>
<td>°F</td>
<td>RAWS</td>
<td>^1</td>
<td>72</td>
<td>74 ± 10</td>
<td>Mean of hourly mean air temperature measurements</td>
<td></td>
</tr>
<tr>
<td>precipitation accumulation (hourly mean)</td>
<td>in.</td>
<td>RAWS</td>
<td>^0.2</td>
<td>5.6</td>
<td>2.2 ± 7.4</td>
<td>Mean of hourly precip. accumulation measurements</td>
<td></td>
</tr>
<tr>
<td>10-hour fuel moisture (daily mean)</td>
<td>%</td>
<td>RAWS</td>
<td>^0.2</td>
<td>7.4</td>
<td>6.0 ± 5.3</td>
<td>Mean of hourly 10-hour fuel moisture MORE</td>
<td></td>
</tr>
<tr>
<td># hours that met SA1 criteria</td>
<td>hr</td>
<td>RAWS</td>
<td>NP</td>
<td>2.3</td>
<td>0 ± 5.4</td>
<td># hours in the day that meet criteria specified by SA1</td>
<td></td>
</tr>
<tr>
<td>2000 population density</td>
<td>p/mi²</td>
<td>CENSUS</td>
<td>NP</td>
<td>47</td>
<td>3 ± 118</td>
<td>Mean US CENSUS 2000-derived population density</td>
<td></td>
</tr>
<tr>
<td>2000 housing unit density</td>
<td>h/mi</td>
<td>CENSUS</td>
<td>NP</td>
<td>16</td>
<td>2 ± 50</td>
<td>Mean US CENSUS 2000-derived housing unit dns.</td>
<td></td>
</tr>
<tr>
<td>Wildfire front (length)</td>
<td>km</td>
<td>Fire Prg.</td>
<td>NP</td>
<td>10</td>
<td>2 ± 18</td>
<td>Length of wildfire front at the start of the day</td>
<td></td>
</tr>
<tr>
<td>Slope</td>
<td>°</td>
<td>NED</td>
<td>None</td>
<td>19</td>
<td>19 ± 7</td>
<td>NED 1/3 arc second (10m)-derived slope</td>
<td></td>
</tr>
<tr>
<td>Fuel loading</td>
<td>tons/ac</td>
<td>FCCS</td>
<td>^0.2</td>
<td>42</td>
<td>43 ± 11</td>
<td>Area-weighted mean fuel loadings</td>
<td></td>
</tr>
</tbody>
</table>