FIRO: A Deep-neural Network for Wildfire Forecast with Interpretable Hidden States

Eduardo Rodrigues [1], Campbell Watson [2], Bianca Zadrozny [2], Gabrielle Nyirjesy [3]

[1]Microsoft Research, [2]IBM Research and [3]Columbia University

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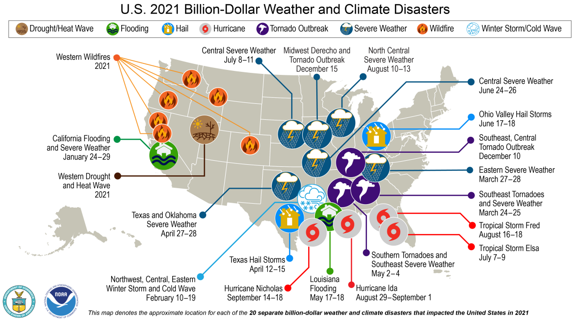
Wildfire: now and in the future



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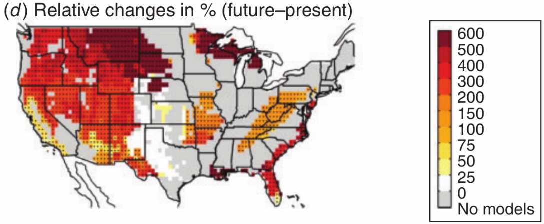
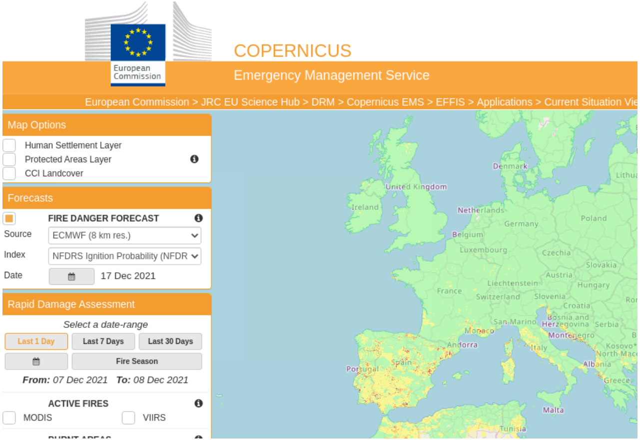
Climate change presents increased potential for very large fires in the contiguous United States



Wildfire - Background

- Wildfire risk forecast models are an important tool to tackle this problem
- They are driven by atmospheric forcing among other variables
- These models have been used by protection agencies worldwide
- Examples are:
  - the U.S. Forest Service National Fire-Danger Rating System (NFDRS)
  - the Canadian Forest Service Fire Weather Index Rating System (FWI)
  - the Australian McArthur (Mark 5) rating systems



Fire indices

NFDRS: National Fire-Danger Rating System provides *empirical* indexes for measuring fire potential in wildlands in the USA.

- Ignition component (IC) : Numerical rating of the probability that a fire that requires suppression action will result if a firebrand is introduced into a fine fuel complex
- Burning index (BI) : Metric of flame length in feet at the head of a fire
- Energy release component (ERC) : Potential available energy at the head of the fire
- Spread component (SC) : Forward rate of spread at the head of the fire in feet (1 ft 5 30.5 cm) per minute.

FWI: Canadian Forest Service Fire Weather Index Rating System

- Fire weather index (FWI) : Numerical rating of fire intensity. It is suitable as a general index of fire danger
- Fine fuel moisture code (FFMC) : Numerical rating of the moisture content of litter and other cured fine fuels
- Duff moisture code (DMC) : Numerical rating of the average moisture content of loosely compacted organic layers of moderate depth
- Drought code (DC) : Numerical rating of the average moisture content of deep, compact organic layers
- Initial spread index (ISI) : Numerical rating of the expected rate of fire spread
- Buildup index (BUI) : Numerical rating of the total amount of fuel available for combustion

Mark 5: Australian McArthur rating systems

- Fire danger index (FDI) : Numeric rating related to the chances of a fire starting, its rate of spread, its intensity, and its difficulty of suppression
- Keetch–Byram drought index (KBDI) : Metric of seasonal drought severity and fuel availability
- Drought factor (DF) : Metric of fuel availability as determined by seasonal severity and recent rain effects.

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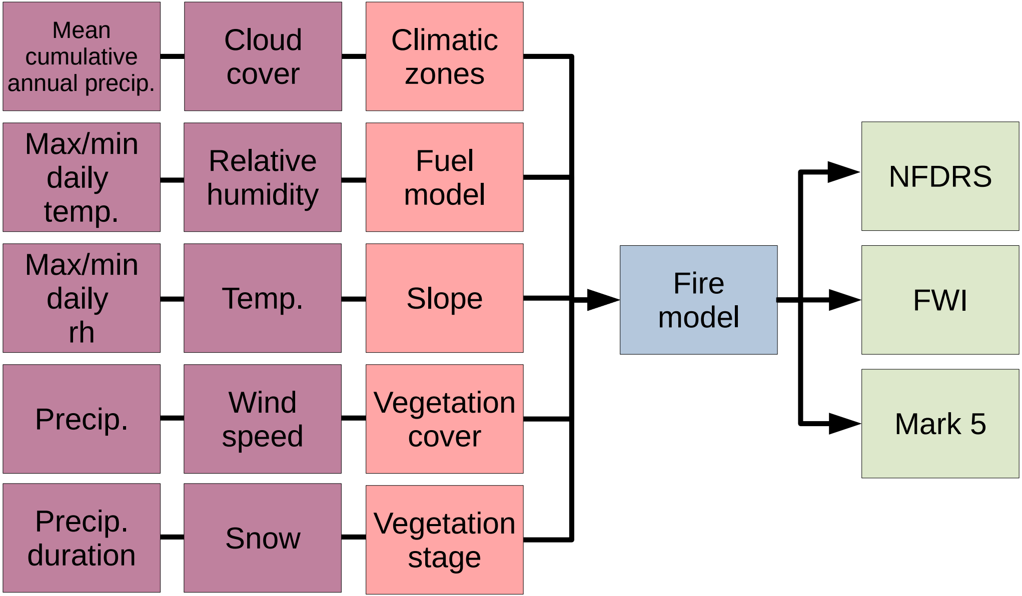
Input and output



Improve fire indices for specific regions - Fire Model DNN

- Fire risk indices have many empirically estimated parameters
- Their internal variables are also meaningful (e.g. moisture content, loadings of dead and live Fuels, terrain slope)
- We take a novel approach to remodel the indices (originally Fortran code) as a neural network
- The empirically estimated parameters can be learned in a (stochastic) gradient descent procedure (labels are actual observed fire events)
- The advantage of this approach is that the internal variables are interpretable, they are the same variables as the original index (instead of meaningless hidden variables)

The National Fire Danger Rating System: basic equations

Dead and Live Fuel Characteristic Surface-Area-to-Volume Ratios:

```
(dead) SGBRDE = (FIE * SG1) + (FLOE * SG10)
                + (FC100E * SG100)
                + (FI000E * SG1000)
(live) SGBRLE = (FWOODE * SGWOOD)
                + (FHERBE * SGHERB)
```

Characteristic Surface-Area-to-Volume Ratio:

```
SGBRTE = (FDEADE * SGBRDE)
         + (FLIVEE * SGBRLE)
```

Optimum Packing Ratio:

```
BETOPE = 3.348 * SGBRTE**(-0.8189)
```

Maximum Reaction Velocity:

```
GMAMXE = SGBRTE**1.5/(495.0
         + 0.0594 * SGBRTE**1.5)
```

Optimum Reaction Velocity:

```
GMAOPE = GMAMXE
     * (BETBAR/BETOPE)**ADE*EXP(ADE
     * (1.0 - BETBAR/BETOPE))
in which ADE = 133.0 * SGBRTE**(-0.7913)
```

Weighted Moisture Contents of Dead and Live Fuels:

```
(dead) WTMCDE = (F1E * MC1) + (F10E * MC10)
                + (F100E * MC100)
                + (F1000E * MC1000)
(live) WTMCLE = (FWOODE * MCWOOD)
                + (FHERBE * MCHERB)
```

Moisture Damping Coefficients of Dead and Live Fuels:

```
(dead) ETAMDE = 1.0 - 2.0 * DEDRTE
                + 1.5 * DEDRTE**2.0
                - 0.5 * DEDRTE**3.0
(live) ETAMLE = 1.0 - 2.0 * LIVRTE
                + 1.5 * LIVRTE**2.0
                - 0.5 * LIVRTE**3.0
```

in which
DEDRTE = (WTMCDE/MXD)
LIVRTE = (WTMCLE/ MXL)
ETAMDE and ETAMLE cannot be less than zero or greater than 1.0

Reaction Intensity:


```
IRE = GMAOPE * ((FDEADE * WDEDNE * HD
   * ETASD * ETAMDE) + (FLIVEE * WLIVNE
   * HL * ETASL * ETAMLE))
```

Residence time of the Flaming Front:

```
TAU = 384.0/ SGBRT
```

The surface area weighted surface area-to-volume ratio, SGBRT, is used rather than the mass weighted form (SGBRTE). The mass weighted residence time produced unrealistic results.

Energy Release Component:

```
ERC = IRND(0.04 * IRE * TAU)
```

The 0.04 scaling factor has the units ft^2/ Btu. As such, a unit value of ERC is equivalent to 25 Btu of available energy per square foot.

Burning Index

The BI is numerically equivalent to 10 times the predicted flame length, in feet. The equation developed by Byram (1959) is used with some liberties, enabling us to use parameters that are outputs from Rothermel's fire spread model.

Byram's equation:

```
FL = 0.45 * I**0.46 (ft.)
```

in which I is the fireline intensity, Btu/ft-sec
but I = IRE * D/60.0, Btu/ft-sec
in which D = ROS * TAU, ft
so I = (ROS/60.0) * IRE * TAU, Btu/ft-sec
but ROS = SC and IRE * TAU = 25.0 * ERC
therefore FL = 0.45 * ((SC/60.0) * (25.0 * ERC))**0.46
and FL = 0.301 * (SC * ERC)**0.46

Burning Index:

```
BI = IRND(3.01 * (SC * ERC)**0.46)
```

If the fuels are wet or covered by snow or ice at observation time, the BI is set to zero.

Models of Fire Occurrence

Ignition Component

The IC consists of two parts: (1) the probability that a firebrand will produce a successful fire start in dead, fine fuels, P(I); and (2) the probability that a reportable fire will occur, given an ignition P(F/ I).

P(I) is a function of the amount of heat required to produce an ignition (QIGN) which, in turn, is a function of the 1-hour fuel moisture, MC1. P(I) is scaled such that it is 100 when MC1 = 1.5 percent and zero when MC1 = 25.0 percent. Three scaling factors are used for this purpose:

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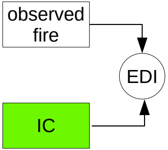
Weighted Moisture Contents of Dead and Live Fuels:

Make parameters learnable



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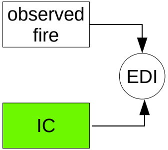

IC = IRND(0.10 * P(I) * P(F/I))

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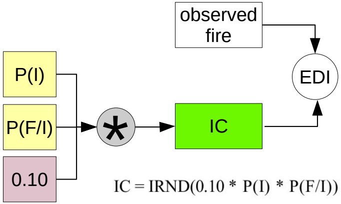

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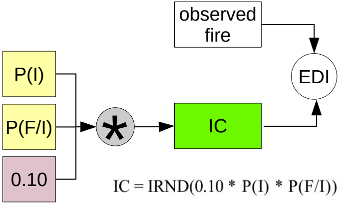
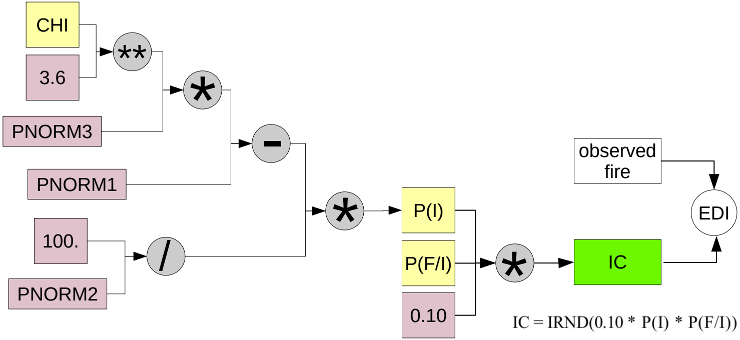


IC = IRND(0.10 * P(I) * P(F/I))

P(I) = (CHI**3.6 * PNORM3 - PNORMI) * 100.0/PNORM2

PNORM1 = 0.00232
PNORM2 = 0.99767
PNORM3 = 0.0000185

Make parameters learnable



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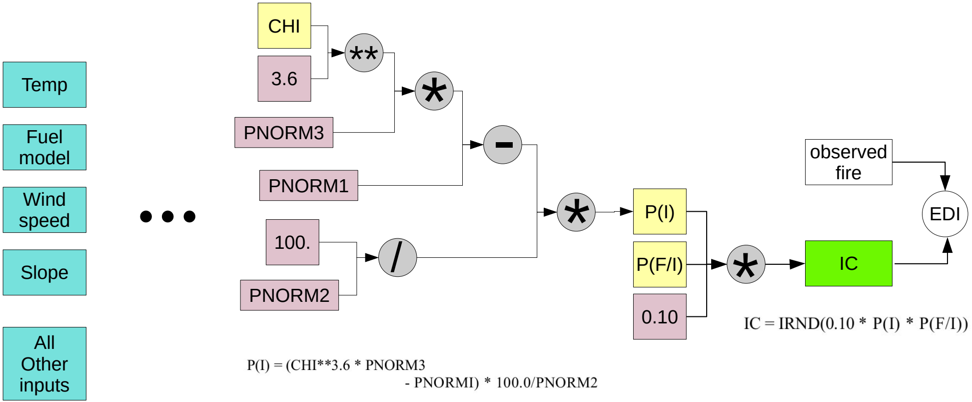

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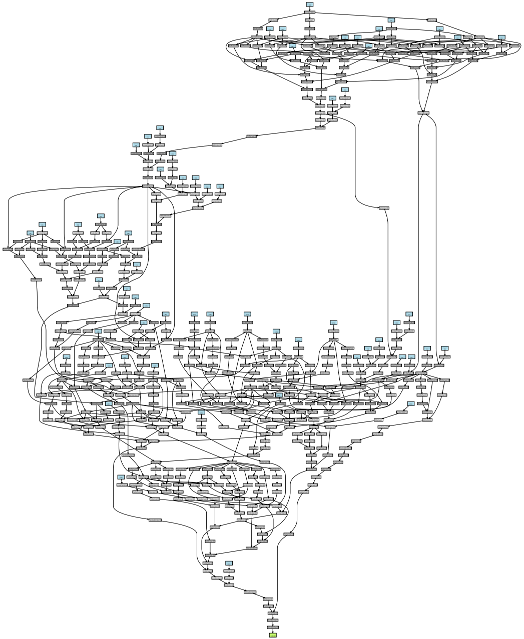


Making hard branches (and a few more things) smooth

For example, IC is set to zero if the expression:

$$((344. - \text{QIGN})/10.)^{3.6} * \text{PNORM3}$$

is equal or less than PNORM1. We have a pattern like:

```
if X < A then
    return Y
else
    return Z
```

which becomes the smooth:

$$\sigma\left(\left(X - A\right) * \alpha\right) * \left(Z - Y\right) + Y$$

An internal variable in the NFDRS model is $P(F/I)$, which stands for the probability of a reportable fire and is defined as:

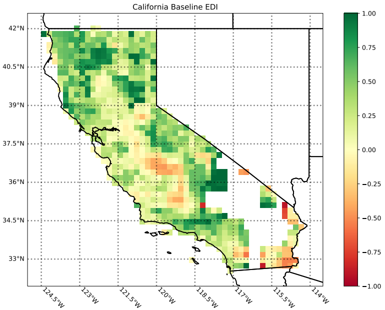
$$\text{P(F/I)} = \sqrt{\text{SCN}}$$

where SCN is normalized rate of spread. Consider a weight w downstream in the model. In order to compute an update to w so as to minimize the loss $\mathcal{L}$, one would need to compute the derivative of P(F/I) with respect to SCN:

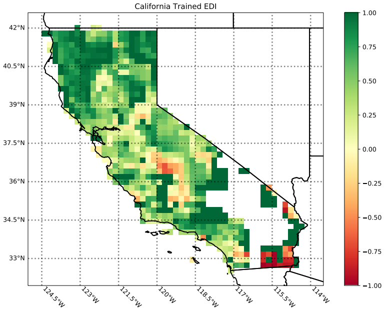
$$\frac{\partial \mathcal{L}}{\partial w} = \frac{\partial \mathcal{L}}{\partial \text{P(F/I)}} \frac{\partial \text{P(F/I)}}{\partial \text{SCN}} \frac{\partial \text{SCN}}{\partial w}$$

which exists but is infinity when SCN is zero, but physically it can indeed be zero. To avoid the derivative to blow up we clip the gradients.

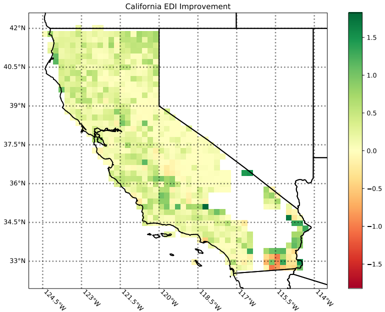
Results - California



IC index performance of the original NFDRS system



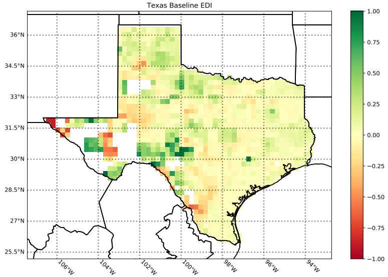
IC index performance after training (some of the parameters)



difference between trained and untrained

EDI measures the skill of the index. It ranges from -1 to 1 and 1 corresponds to a perfect score

Results - Texas



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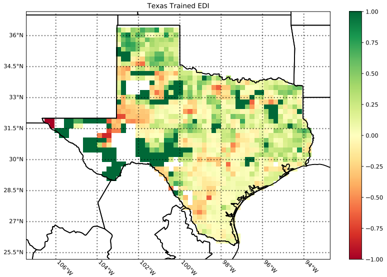

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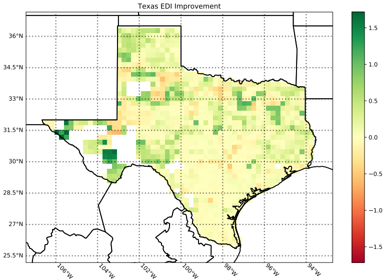

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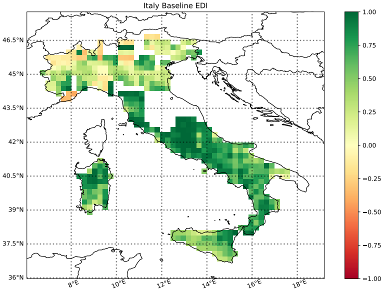
Sample result - Italy



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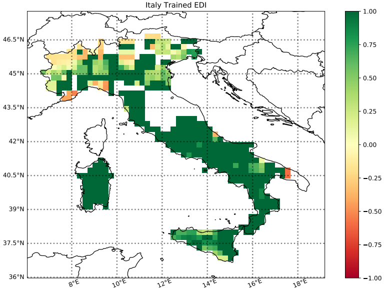

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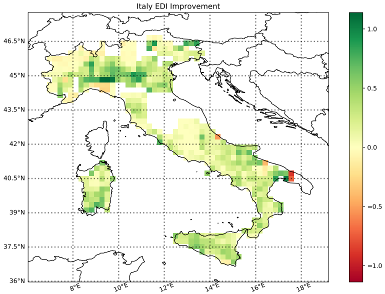

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The model can improve further by making more parameters learnable (i.e. make more parts of the model differentiable)

Final Remarks

- Fire indices are used worldwide to estimate fire risk
- These indices have interpretable internal variables whose relationships are established through fixed parameters
- We recasted an existing fire index as a neural network in which the weights are the index parameters
- This approach has three advantages: (1) we start from a proven fire index, and (2) parameters can be adjusted to the current climate and location, and (3) internal variables have meening