Reliable Probability Forecast of Solar Flares using Deep Neural Networks

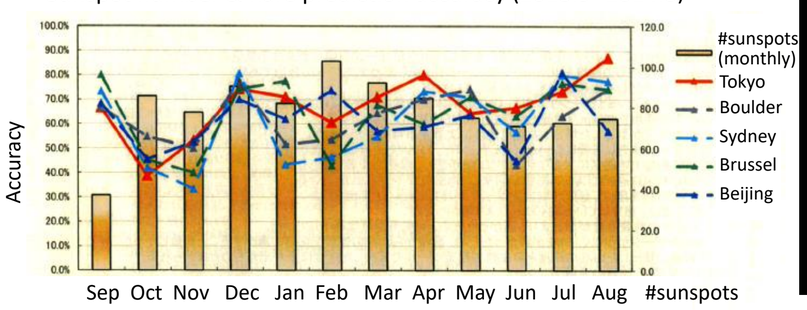
Naoto Nishizuka[1], Yuki Kubo[1], Komei Sugiura[2], Mitsue Den[1], Mamoru Ishii[1]
[1]National Institute of Information and Communications Technology, [2]Keio University

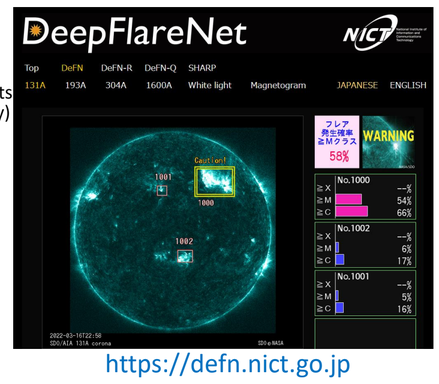
ABSTRACT

We developed two solar flare prediction models using DNNs, named Deep Flare Net (DeFN) and Deep Flare Net-Reliable (DeFN-R). These two are deterministic and probabilistic forecasting models and have been used in operational daily forecast. The models can predict the maximum classes of flares that occur in the following 24 hr. DeFN and DeFN-R are composed of multilayer perceptrons formed by batch normalizations and skip connections. By tuning optimization methods, DeFN and DeFN-R were trained and evaluated by the true skill statistic (TSS) and the Brier skill score (BSS), respectively. DeFN achieved TSS=0.80 for >=M-class flares, but it tends to overforecast. On the other hand, DeFN-R succeeded in improving the reliability. It achieved BSS=0.41 for >=C-class flares and 0.30 for >=M-class flares while keeping ROC curve almost the same. In this poster, we will discuss how to develop deterministic and probabilistic forecast models using DNNs.

1. Introduction

Sunspot number & flare prediction accuracy (2013.9 -2014.8)





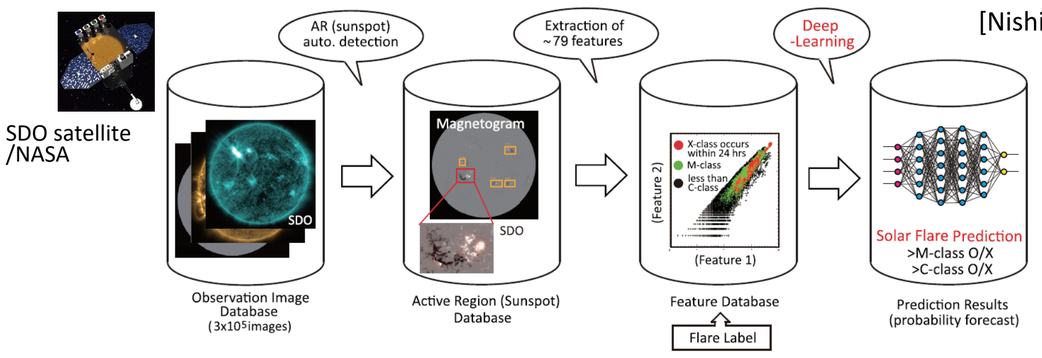
https://defn.nict.go.jp

- ISES/Regional Warning Centers provide daily forecasts, including solar flare predictions.
- It is essential to improve the **accuracy** and **efficiency** of manual forecasting.
- We developed a forecast model DeFN using DNNs, which became operational in 2019.
- While high TSS and **discriminant capability** are advantage of DeFN, low reliability is an issue for improvement (Gap with forecasters' requests). However, how to increase the **reliability** in DNN forecasting models is not well understood.
- Here we will introduce the DeFN-R model with improved reliability and explain methods to increase reliability.

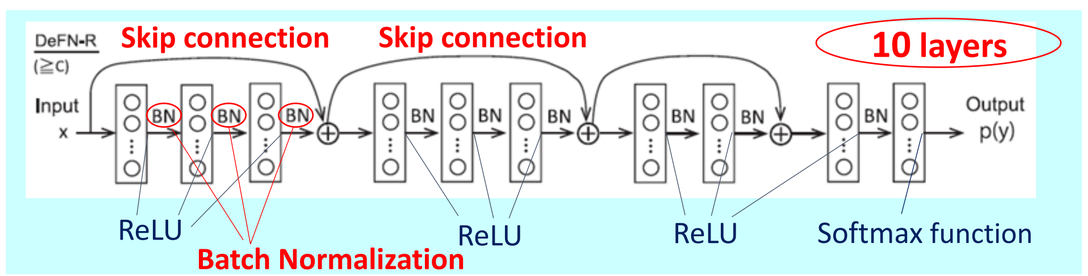
2. Deep Flare Net-Reliable (DeFN-R)

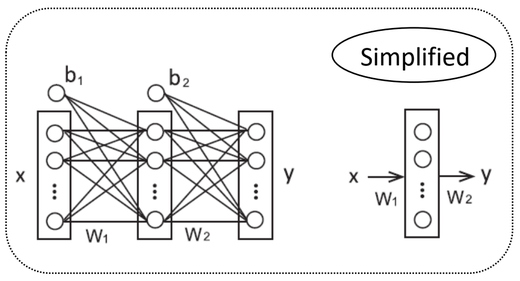
We developed a solar flare prediction model using DNNs with improved reliability. The model was trained using the Brier Skill Score (BSS) as an indicator while adjusting the loss function.

[Nishizuka et al. 2018 ApJ]



The original DeFN structure was modified through trial and error to increase BSS.





- ReLU (Activation function : non linear)
- Skip connection (Residual Net)
- Batch Normalization (BN)
- Weighted cross entropy (loss function)

$$J = \sum_{n=1}^{N}\sum_{k=1}^{K} w_k y_{nk}^* \log p(y_{nk}).$$

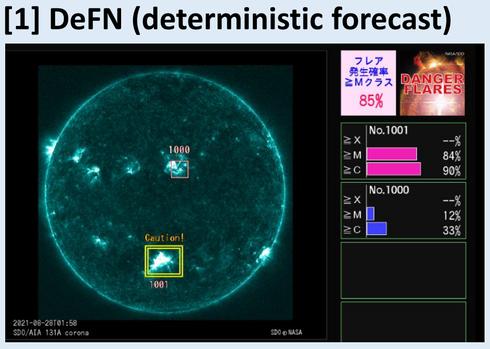
n: #samples
label y_n^*=(1,0), or (0,1)

weight w_k = (1,50)M, or (1,12)C **for DeFN**
→ w_k = **(1,1)** **for DeFN-R !!**

Which do you like to use, DeFN or DeFN-R?

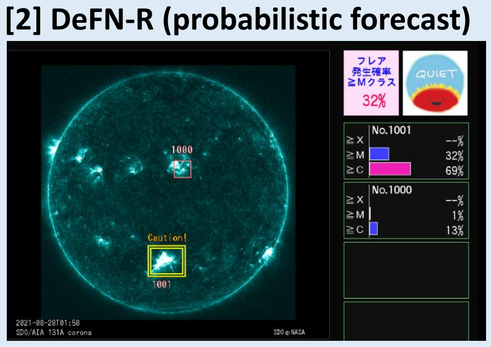
Comparison of the two models at the same time (you can also see the today's forecast by the two models at https://defn.nict.go.jp)

[1] DeFN (deterministic forecast)



For those who are concerned about leakage.
50% means the climatological event rate.

[2] DeFN-R (probabilistic forecast)



For those who would like to know the actual occurrence probability or to select the threshold.

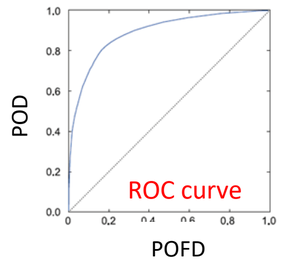
3. Verification methods

(1) Discriminant capability of deterministic forecasts

● **True Skill Statistic (TSS)**

$$TSS = \frac{TP}{TP+FN} - \frac{FP}{FP+TN} = POD - POFD$$

※ Perfect forecast is 1.



Prediction \ Observation	flare	no
flare	TP	FP
no	FN	TN

ROC curve represents changes in TSS when changing the threshold of probabilistic forecasts. The closer to the upper left, the better the accuracy.

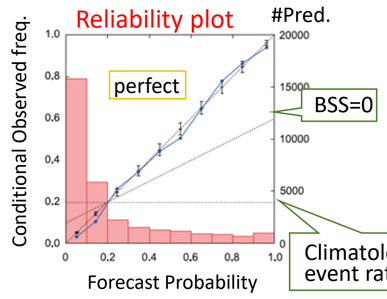
(2) Reliability of probabilistic forecasts

● **Brier Skill Score (BSS)**

$$BSS = \frac{BS - BS_c}{0 - BS_c}$$ climatology

$$BS = \sum_{n=1}^{N}(p(y_n) - y_n^*)^2,$$ Pred. Obs. 1 or 0

※ Perfect forecast is 1. Climatological forecast is 0. BS is like a squared error.



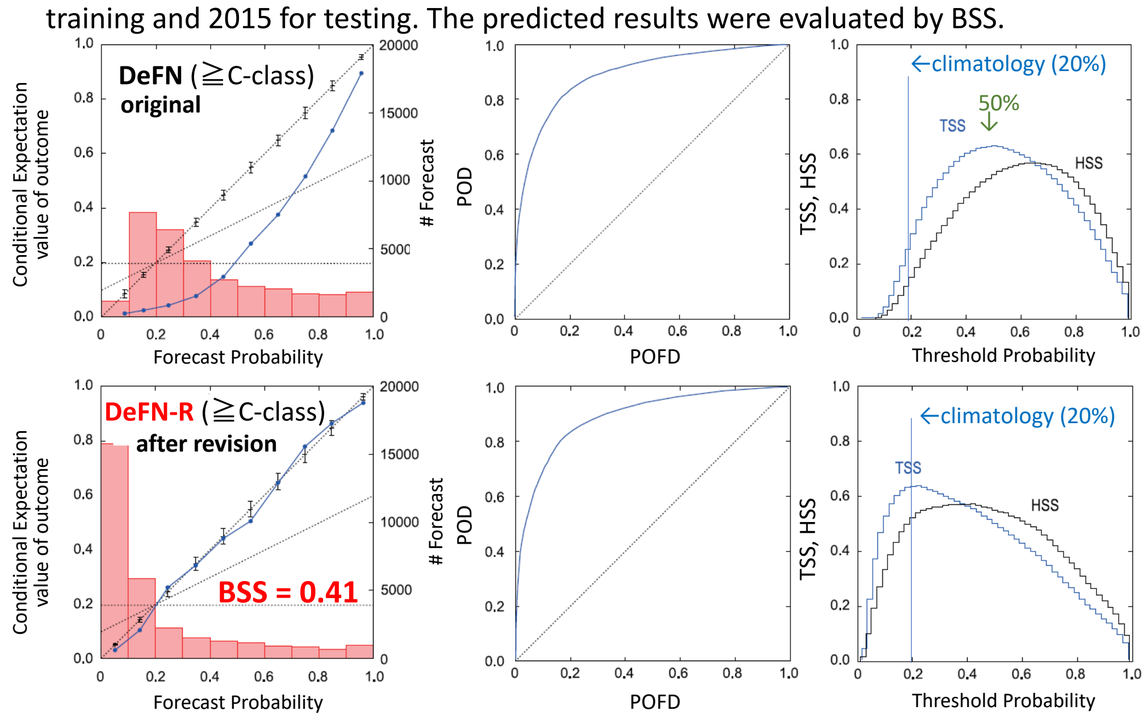
Highly reliable means to be on the diagonal in the left panel.

※ Climatology
= averaged occurrence rate

4. Results of Predictions & Evaluations

[Nishizuka+2020, ApJ, 899, 150]

We divided the database into two by a climatological split: the one in 2010-2014 for training and 2015 for testing. The predicted results were evaluated by BSS.



- The reliability plot was greatly improved while keeping the ROC curves nearly the same.
- We achieved BSS=0.41 (≧C-class flare), 0.30 (≧M-class flare)
  cf) NOAA (human): BSS=0.28 (≧C), 0.26 (≧M) NWRA (statistical): BSS=0.37 (≧C), 0.26 (≧M)
- When improving the reliability, TSS peaks at the climatological event rate.

5. Discussion & Conclusion

- We developed a probabilistic forecasting model of solar flares occurring in the next 24 h, by revising the deterministic forecasting model. We named the model DeFN-R.
- **How to increase the reliability in forecasting models** is not well understood. Here, by trial and errors, we succeeded in improving the reliability (BSS=0.41) while keeping the ROC curves almost the same.
- It is found that adding weights to the loss function (the inverse of the occurrence rate) improves TSS by adjusting the **prior probability distribution** of flare occurrence in the deterministic model (DeFN), but the predicted probability is no longer the actual probability frequency.
- When the weights are removed from the loss function, the predicted probability represents the actual probability frequency, improving the reliability (which is not always the case in general).
- It is mathematically shown that the reliable forecasting models shows that TSS peak at the climatological event rate (Kubo et al. 2017 JSWSC), which is confirmed by the analysis.
- DeFN and DeFN-R can be used for different purposes. DeFN is a deterministic forecast model, which shows high discriminant performance but overforecasts. For those who are concerned about leakage.
- DeFN-R is a probabilistic forecasting model, whose output is the actual probability frequency. Users can select the probability threshold by themselves, depending on their purposes.

(References)

- Nishizuka et al. 2020, Astrophysical Journal, 899, 150 "Deep Flare Net Reliable (DeFN-R) "
- Nishizuka et al. 2021, EPS, 73, 64 "Operational solar flare prediction model using DeFN"