Operational Solar Flare Predictions and Evaluations using Deep Flare Net

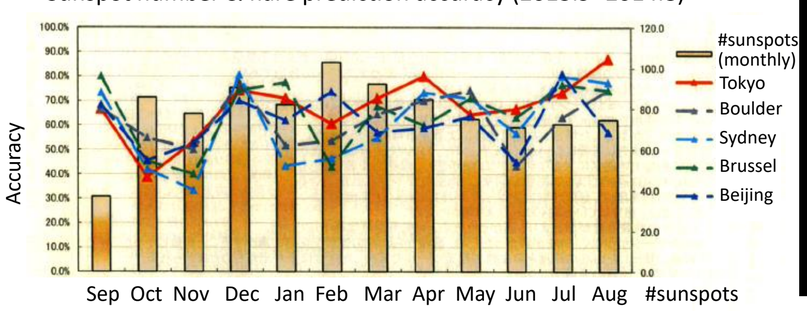
Naoto Nishizuka[1], Yuki Kubo[1], Komei Sugiura[2], Mamoru Ishii[1] , Takuya Tsugawa[1]
[1]National Institute of Information and Communications Technology, [2]Keio University

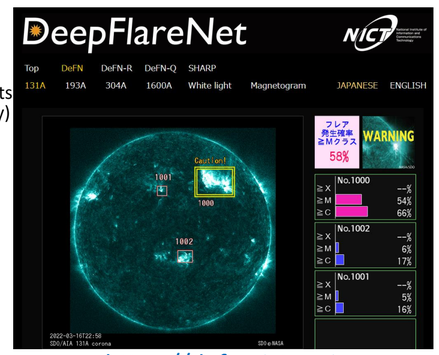
ABSTRACT

We have developed an operational solar flare prediction model using deep neural networks (DNNs), Deep Flare Net (DeFN), which is used in daily space weather forecast meetings in NICT. The DeFN model can predict the largest level of flares occurring within the next 24 hr. We used magnetograms and EUV images taken by SDO. DeFN can automatically detect active regions, extract 79 physical features, and input them into DNNs to predict flares. We evaluated the prediction results by TSS, and DeFN achieved TSS=0.80 (0.63) for >=M(C)-class flares, which is better than human forecasting. Furthermore, DeFN has been operated since 2019 and used for daily forecasting. We evaluated the operational prediction results for 2019/1-2020/7, and we found that DeFN achieved TSS=0.82 for >=C-class flare predictions. Recently, we have evaluated the prediction results again for 2019/1-2023/6, and DeFN achieved TSS=0.70 (0.72) for >=M(C)-class flare predictions. In this presentation, we would like to introduce our DeFN model and operational results for five years.

1. Introduction

Sunspot number & flare prediction accuracy (2013.9 -2014.8)





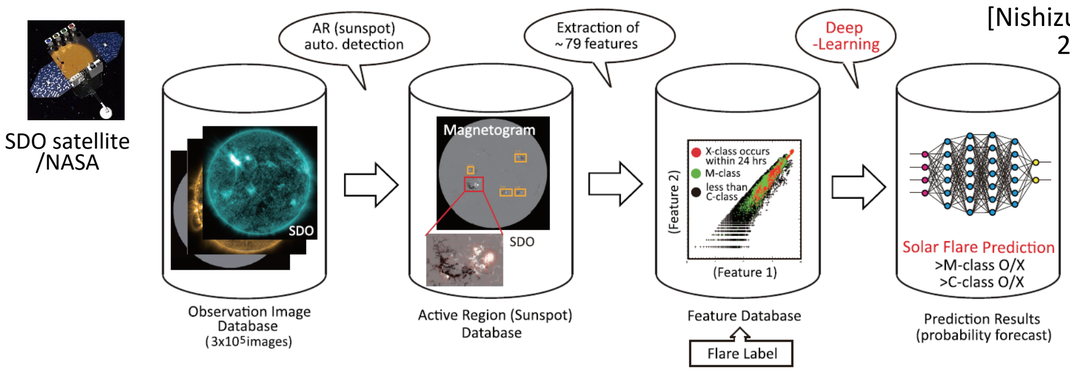
https://defn.nict.go.jp

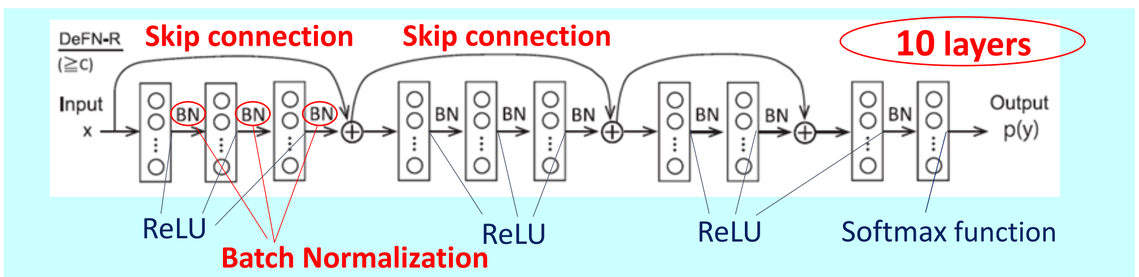
- ISES/Regional Warning Centers provide daily forecasts, including solar flare predictions.
- It is essential to improve the **accuracy** and **efficiency** of manual forecasting.
- We developed a forecast model DeFN using DNNs, which became operational in 2019.
- There are few operational models of solar flare predictions using DNNs, and operational results have not yet been analyzed. **The relationship between prior and operational evaluation accuracy is unknown but is important for model training**.
- Here we will introduce the operational DeFN model and its forecast results and evaluations during 2019/1-2023/6.

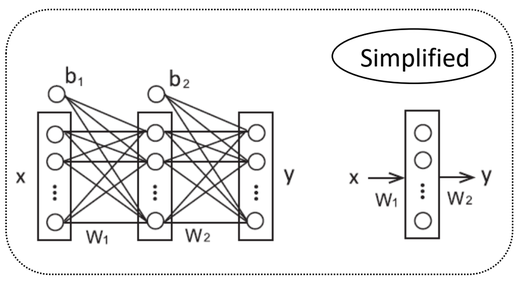
2. Deep Flare Net (DeFN) model

We developed a solar flare prediction model using DNNs. The model was trained using the True Skill Statistics (TSS) & Brier Skill Score (BSS) as indicators while adjusting the loss function.

[Nishizuka et al. 2018 ApJ]







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

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

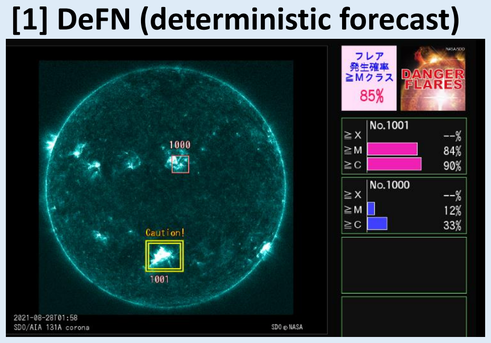
n: #samples
label y_n*=(1,0), or (0,1)

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?

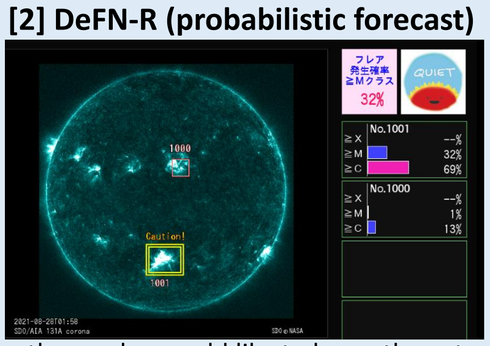
Comparison of the two models at the same time (you can also see the today's forecast by the two models at https://defn.nict.go.jp)

[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.

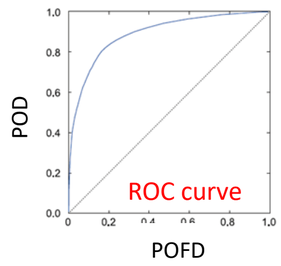
3. Verification methods

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.

● **Evaluation results of DeFN**

We evaluated DeFN using datasets in 2010-2014 for training and the one in 2015 for testing. (We adopted the **chronological split** for operational evaluations.)

≧M-class

Prediction \ Observation	flare	no
flare	963	4382
no	54	25937

TSS= **0.80**

≧C-class

Prediction \ Observation	flare	no
flare	4967	4420
no	1171	20778

TSS= 0.63

[Nishizuka+2018 ApJ]

DeFN achieved TSS=0.80, which is better than human forecast, though FP is large.

4. Results of Operational Predictions & Evaluations

● **Prediction results in operations (2019/1～2020/7)** [Nishizuka+2021 EPS]

≧M-class

Prediction \ Observation	flare	no
flare	0	25
no	0	491

TSS= **none**

≧C-class

Prediction \ Observation	flare	no
flare	26	24
no	4	463

TSS= 0.82

DeFN has been operated since 2019 and used for daily flare predictions in NICT.

DeFN achieved the expected performance for >=C-class flares.

● **Prediction results in operations (2019/1～2023/6)** [Nishizuka+2023 ASJ conf.]

≧M-class

Prediction \ Observation	flare	no
flare	483	979
no	65	4484

TSS= 0.70

≧C-class

Prediction \ Observation	flare	no
flare	1454	202
no	432	2923

TSS= 0.72

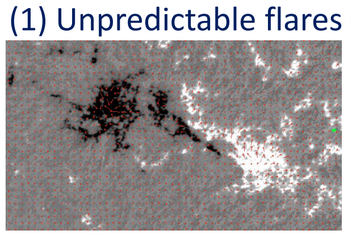
Due to missing of sunspot detection by threshold of 140G.

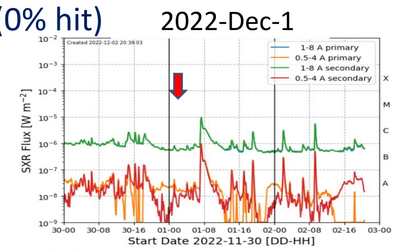
Even for 4.5 years operations, we found that DeFN achieved the expected performance for >=M/C-class flares.

If we limit the case when sunspots were detected, TSS becomes >=0.80 for >=C-class flares.

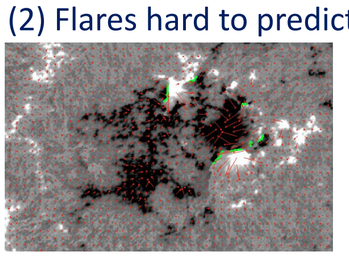
Failure Analysis

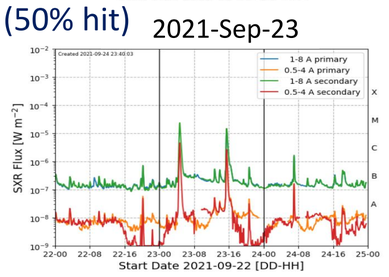
(1) Unpredictable flares (0% hit) 2022-Dec-1





(2) Flares hard to predict (50% hit) 2021-Sep-23





10% of M-class flares occur in ARs where the magnetic field gradient along magnetic neutral line is small.
→
Hard to predict using photospheric info. **Filament eruptions** or **triggers in the corona** are important?

Impulsive M,X-class flares are hard to predict, because the energy storage is local and in short time.
→
Prediction results varies in time. **Prediction of sunspot evolution** is necessary?

5. Conclusion

We developed Deep Flare Net, which has been operated for 5 years and used for daily forecasts in NICT. We found that DeFN achieved expected performance of TSS for ≧M(C)-class flare predictions, as a result of operational prediction evaluations during 2019/1-2023/6. We executed failure analysis and found that some C-class flares were missed when they occurred in ARs <140 G. Some M-class flares were missed when they occurred in ARs without sharp magnetic neutral lines. It is also found that impulsive X,M-class flares does not show clear features of energy storage and hard to predict. Based on these analysis, we would like to update DeFN using new features and techniques.

(References)
- Nishizuka et al. 2018, ApJ, 858, 113 "Deep Flare Net (DeFN) Model for Solar Flare Prediction"
- Nishizuka et al. 2021, EPS, 73, 64 "Operational solar flare prediction model using DeFN"