Computer, how likely is it that I need my coat tomorrow?

How Bayesian Neural Networks can be used for probabilistic predictions of weather and climate

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Outline

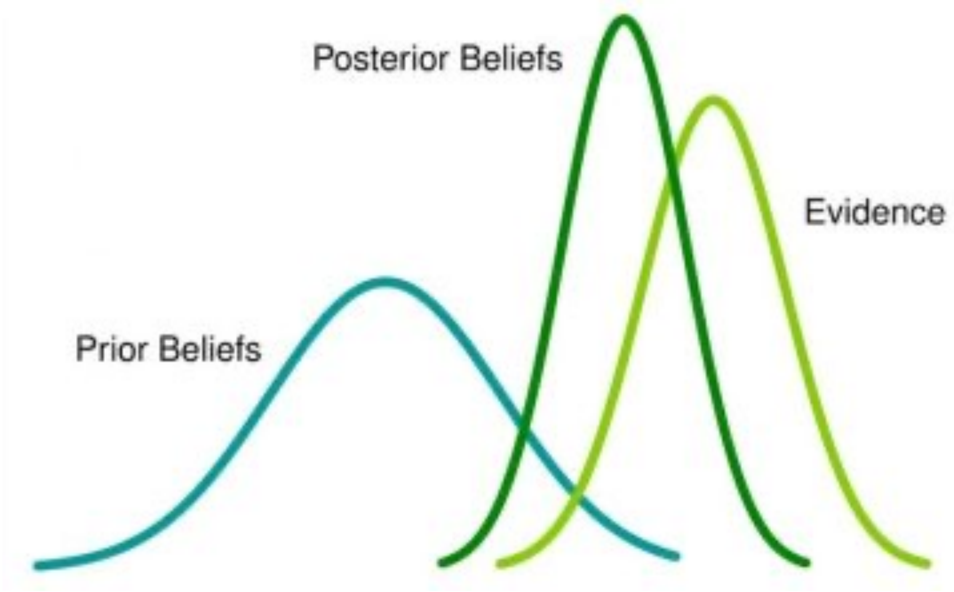
1. Bayesian Neural Networks

2. Applications to oceanography

3. Applications to post-processing of deterministic weather forecasts

Bayesian Neural Networks (BNNs)

Bayesian Inference

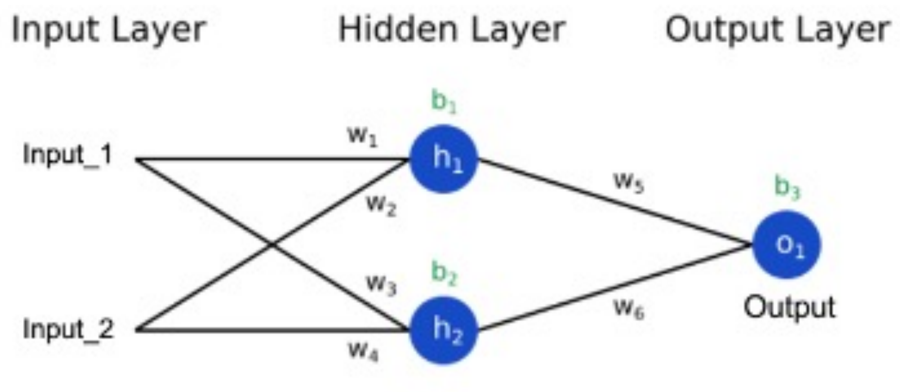


Bayes Rule

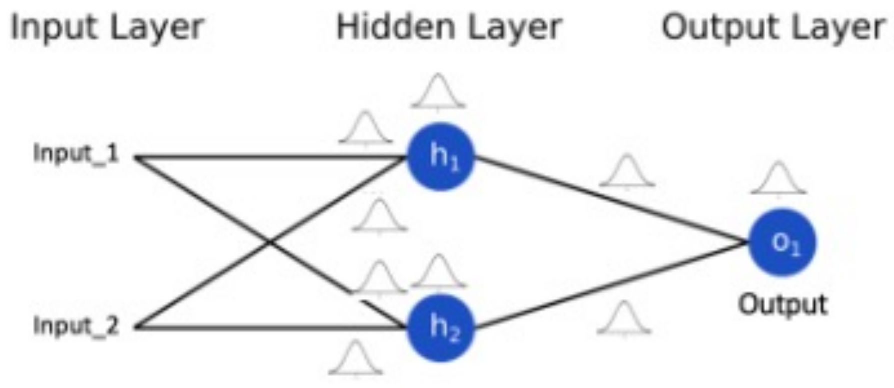
$$p\,(W|D_{tr}) = \frac{p(D_{tr}|W)p(W)}{p(D_{tr})}$$

where W are the network parameters, $D_{tr} = (x_n, y_n)$ the training data and $p(W)$ the prior distribution of the parameters.

Bayesian Neural Networks (BNNs)



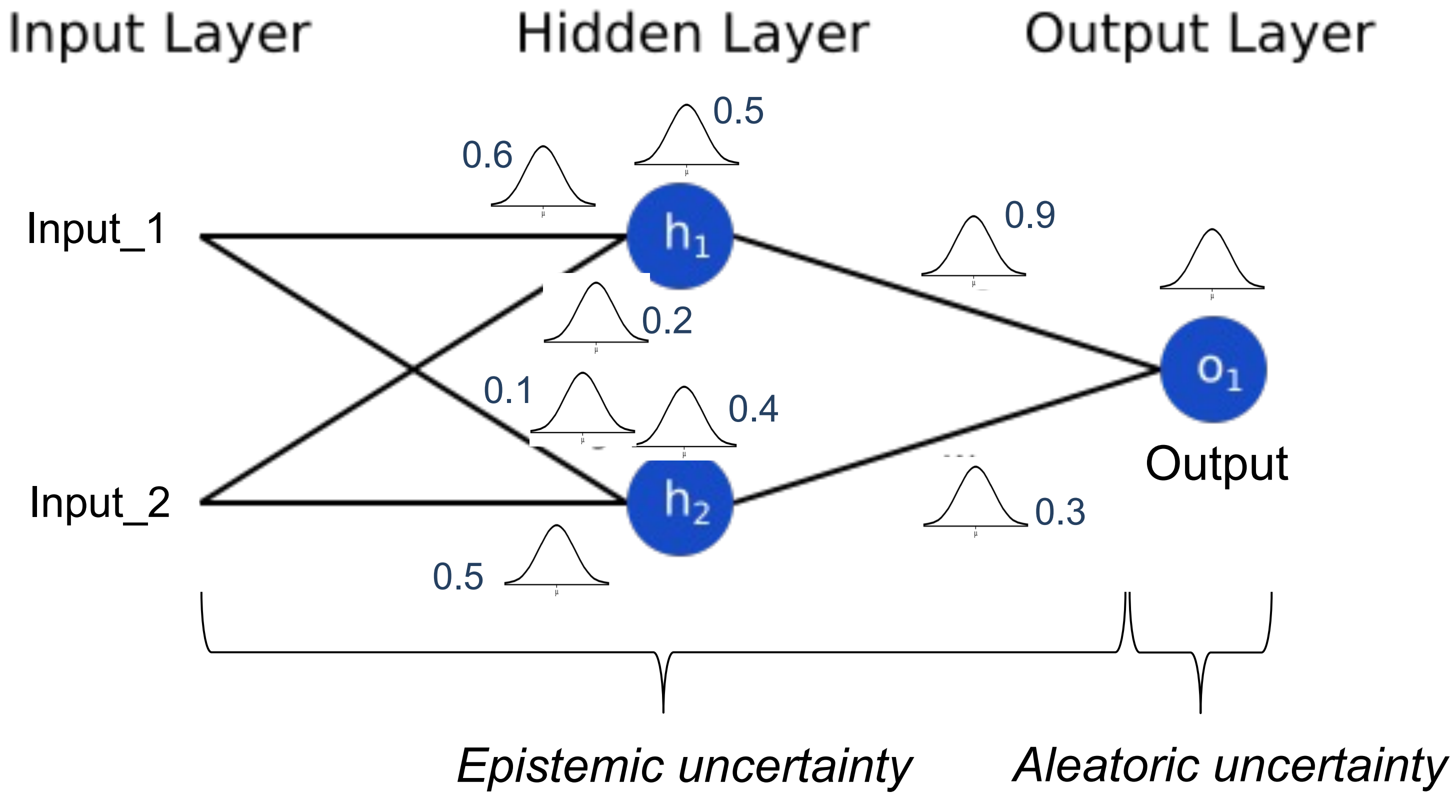
(a) Classical deterministic Neural Network. Weights and biases are point estimates.



(b) Bayesian Neural Network (BNN). Weights and biases are distributions.

Bayesian Neural Networks (BNNs)

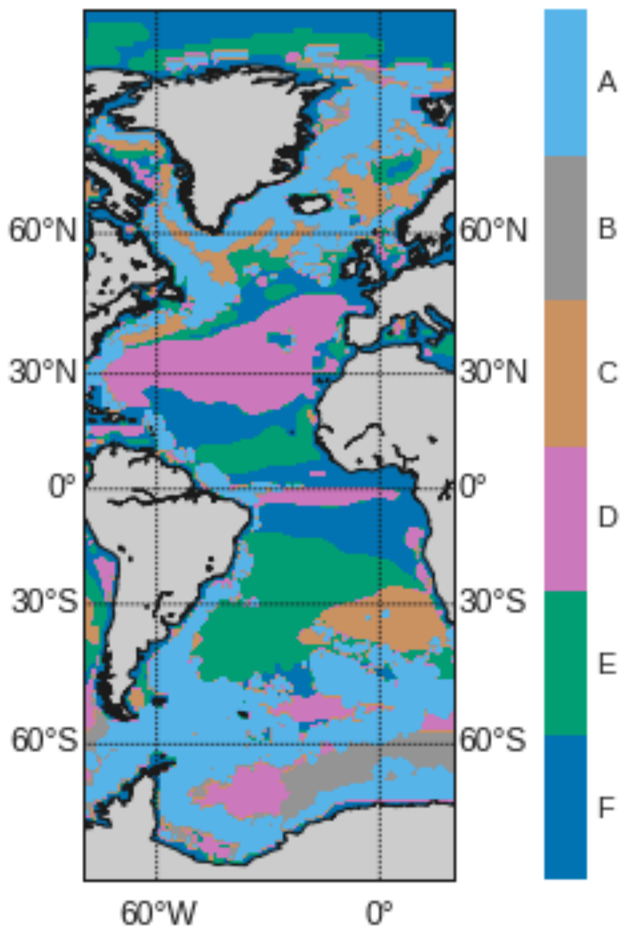
1) Make it easy to generate an ensemble by repeated sampling
2) Probabilistic output instead of deterministic one



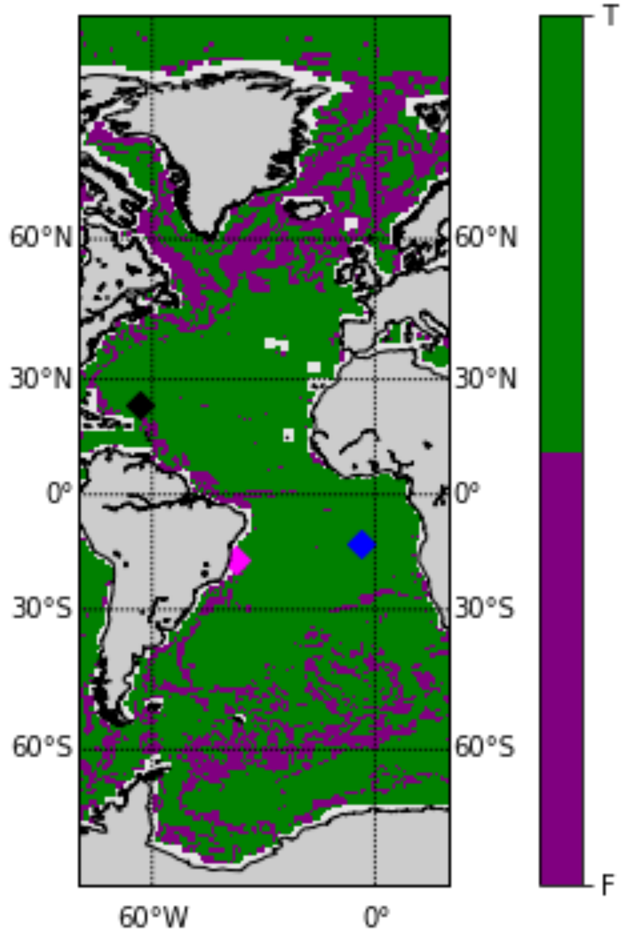
https://www.tensorflow.org/probability/overview

Applications to oceanography problems

BNN predictions



Correct dynamical ocean regime map



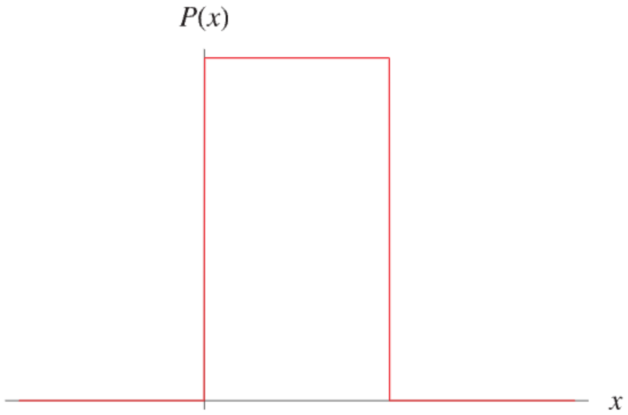
Accuracy of BNN predictions

Motivation

In a changing climate, the underlying physics of a problem may alter, leading to changes in ocean regimes.

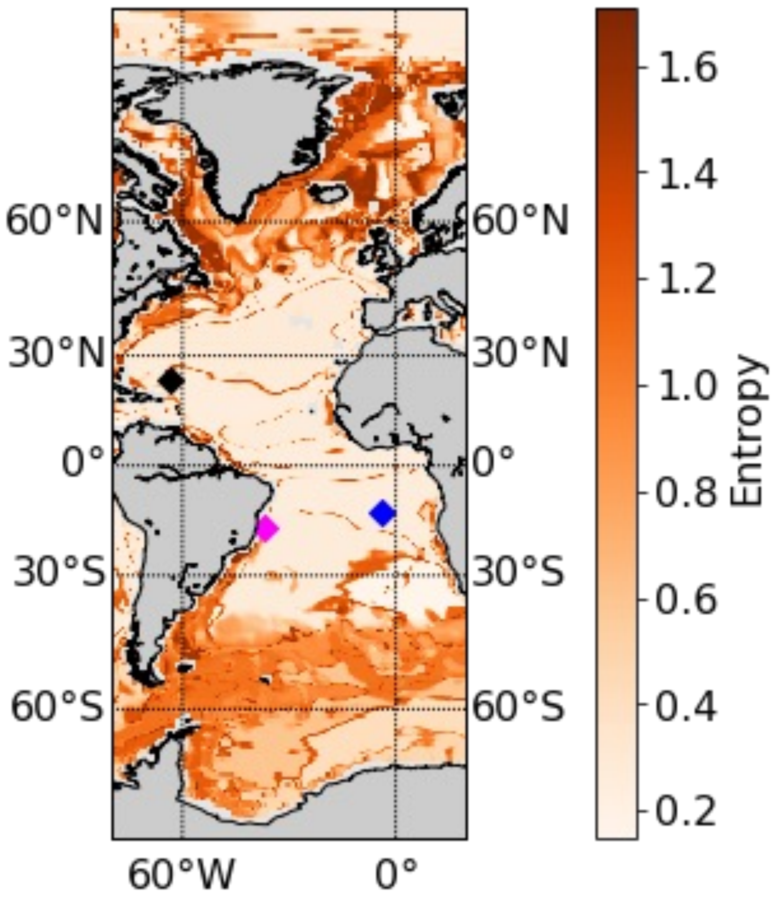
It is important to understand whether neural networks trained on historical ocean data is still fit-for-purpose on future data, or whether the data is out-of-sample.

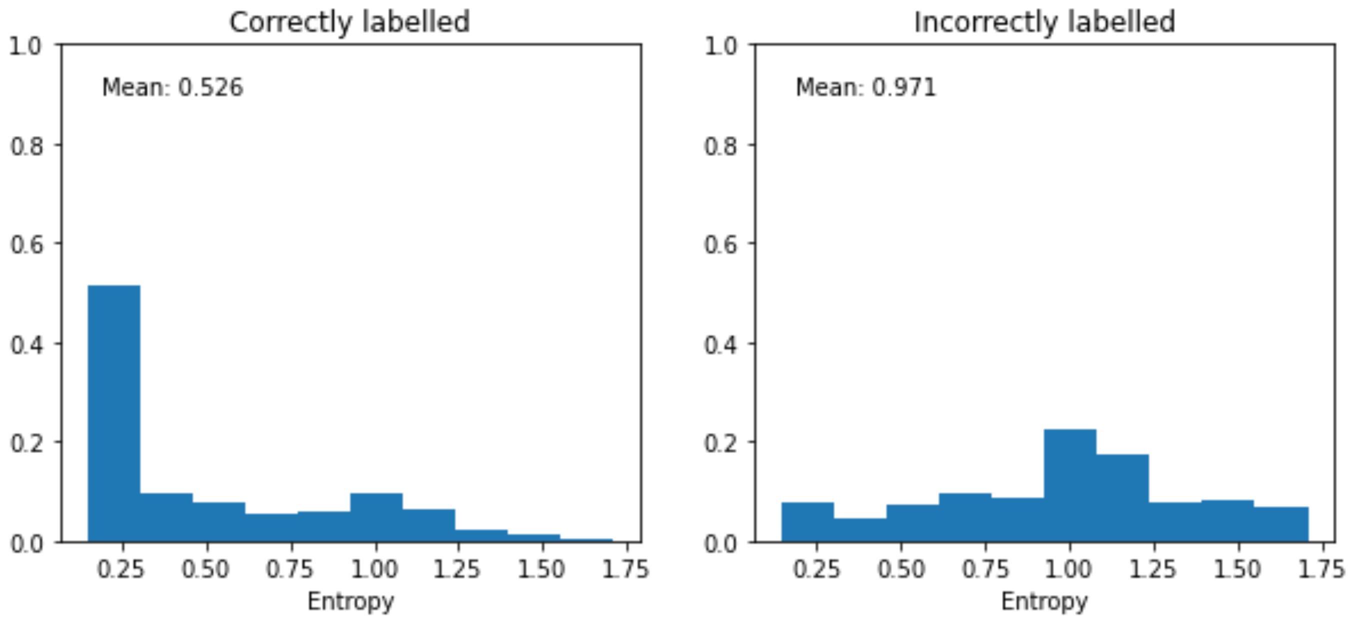
If the test-data is truly a different distribution from the trained data then a BNN will predict a uniform distribution, in other words it will say ‘**I don’t know’**



Entropy

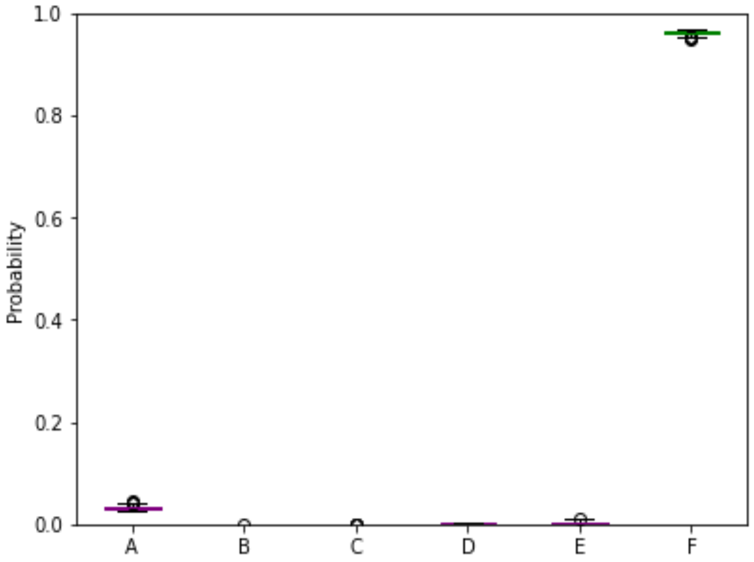
Entropy is a measure of uncertainty and can be used to determine how trustworthy the results are



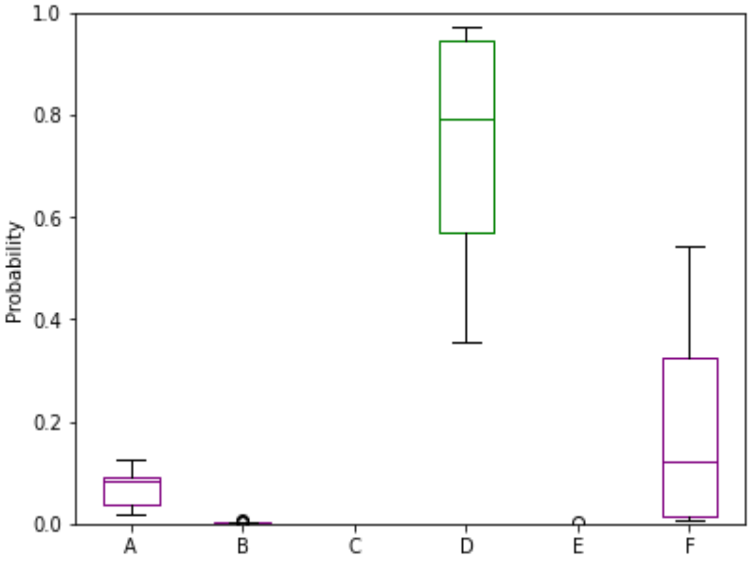


The entropy of BNN predictions is higher for incorrect predictions than correct predictions.

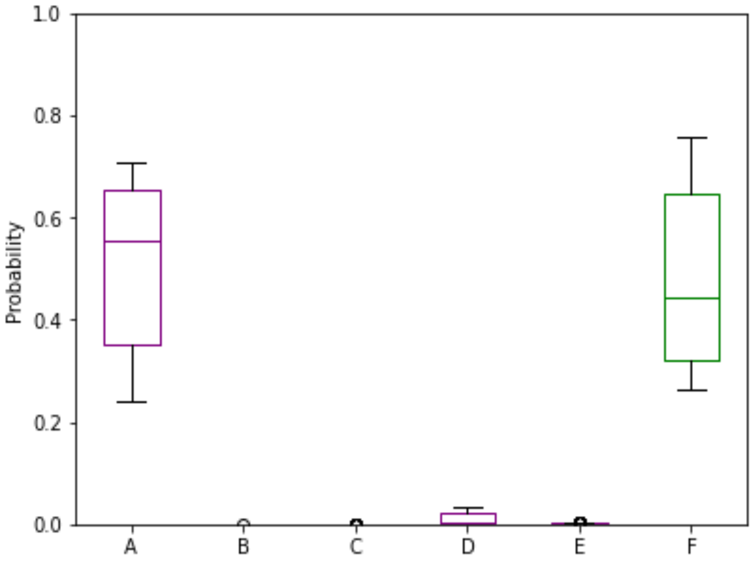
Predictions – Box and whisker plots



Correct regime predicted with high certainty



Correct regime predicted with some epistemic certainty



Incorrect regime predicted with high aleatoric and epistemic uncertainty

Predictions with low aleatoric and low epistemic uncertainty are more trustworthy.

Predictions with high aleatoric and high epistemic uncertainty suggest BNN not fit for purpose for this datapoint

Applications to post-processing of deterministic weather forecasts

Methodology

Aim: Improve accuracy of forecast

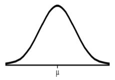
Method: Use a neural network to predict the forecast error (=Forecast – Analysis)

Post-processed forecast = Forcast – Forecast Error Prediction

Aim: Add uncertainty information to a deterministic forecast, for example, if an ensemble forecast is too costly

Method: *Use a Bayesian Neural Network to predict the distribution of the forecast error*

Post-processed probabilistic forecast = Deterministic forecast - Probabilistic Forecast Error



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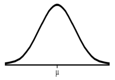
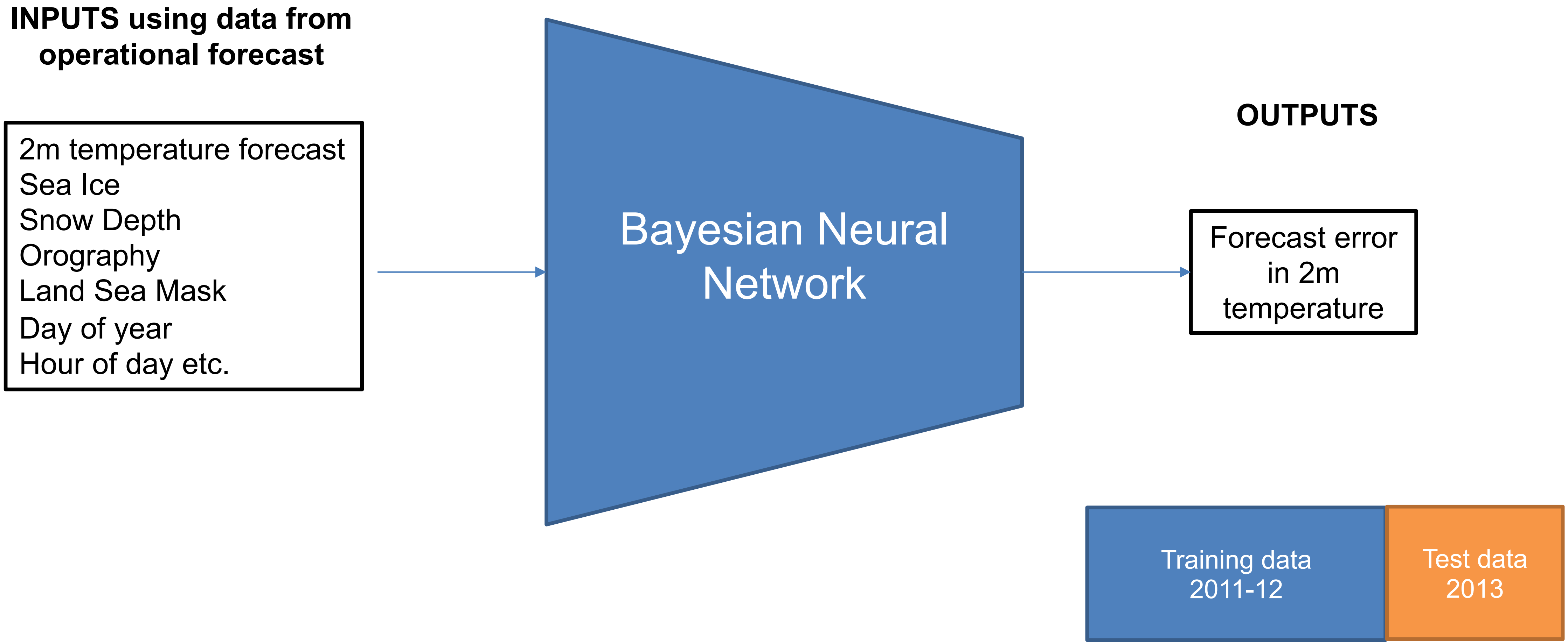
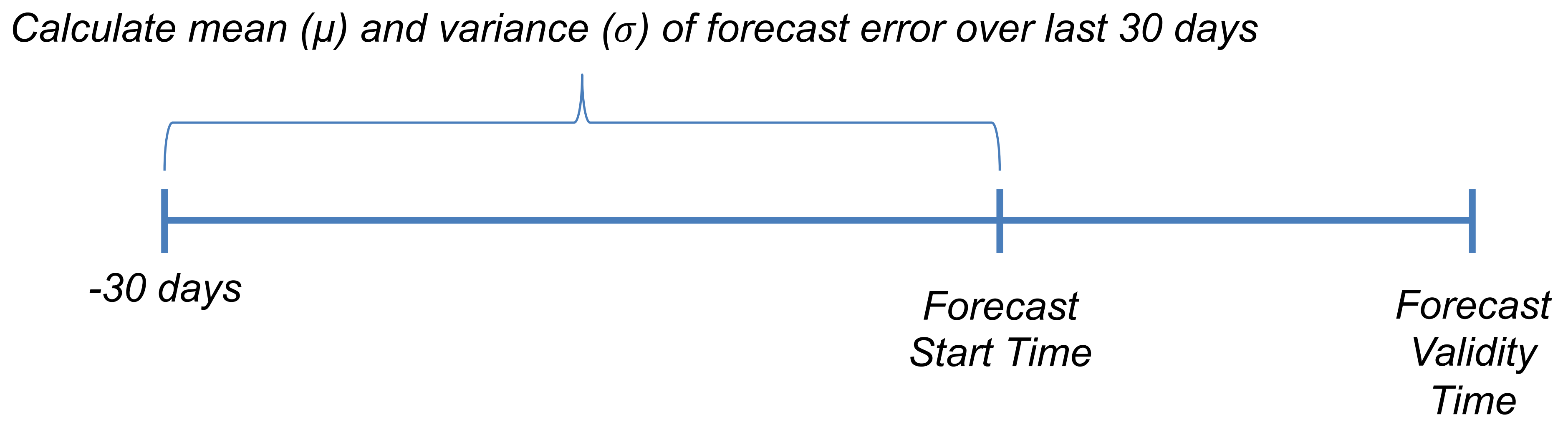


Methodology



All results shown in this part are for 2m temperature

Sliding window benchmark

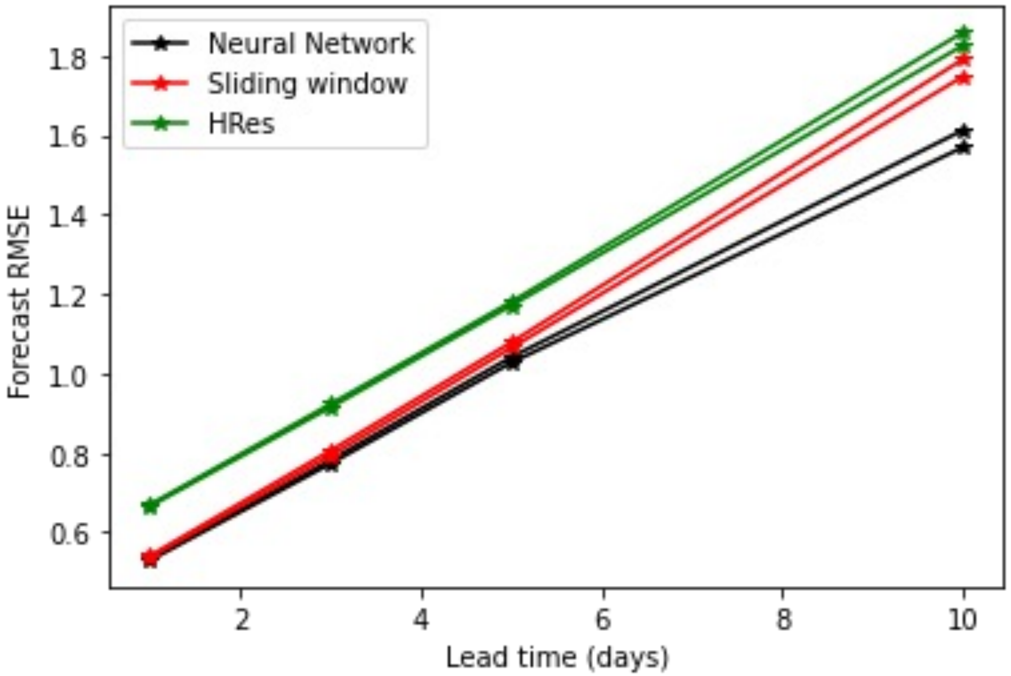


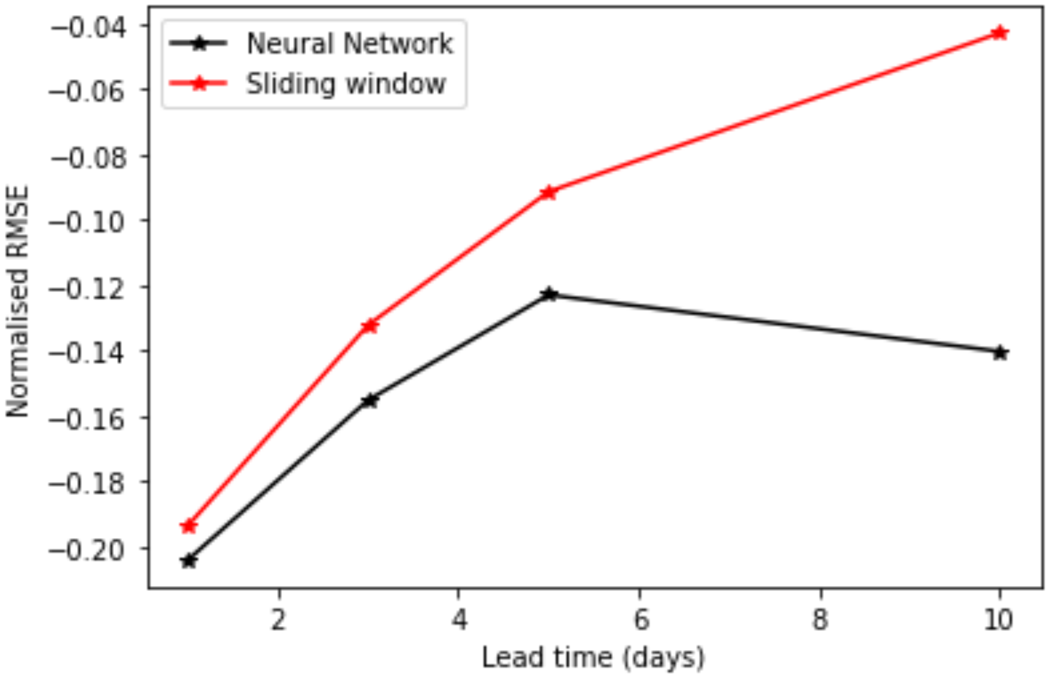
$$New\ Forecast\ Error_j = \left(Forecast_j - Analysis_j\right) - \mu_{j-30}$$

$$Forecast\ error\ distribution_j \approx N(\mu_j, \sigma_j)$$

RMSE

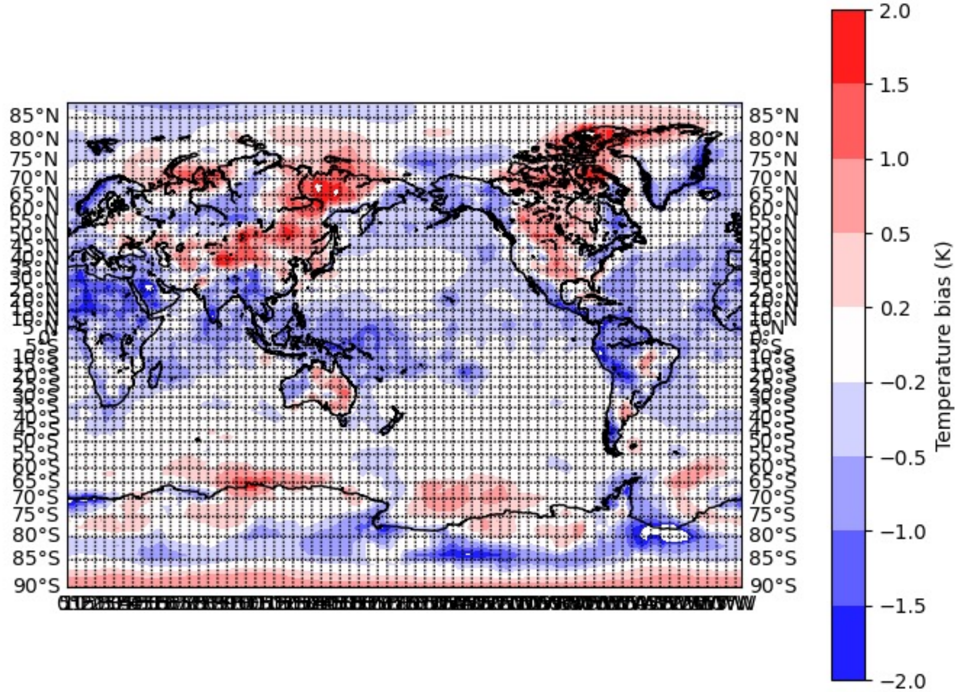
Accuracy improvement from post-processing ECMWF's high-resolution forecast



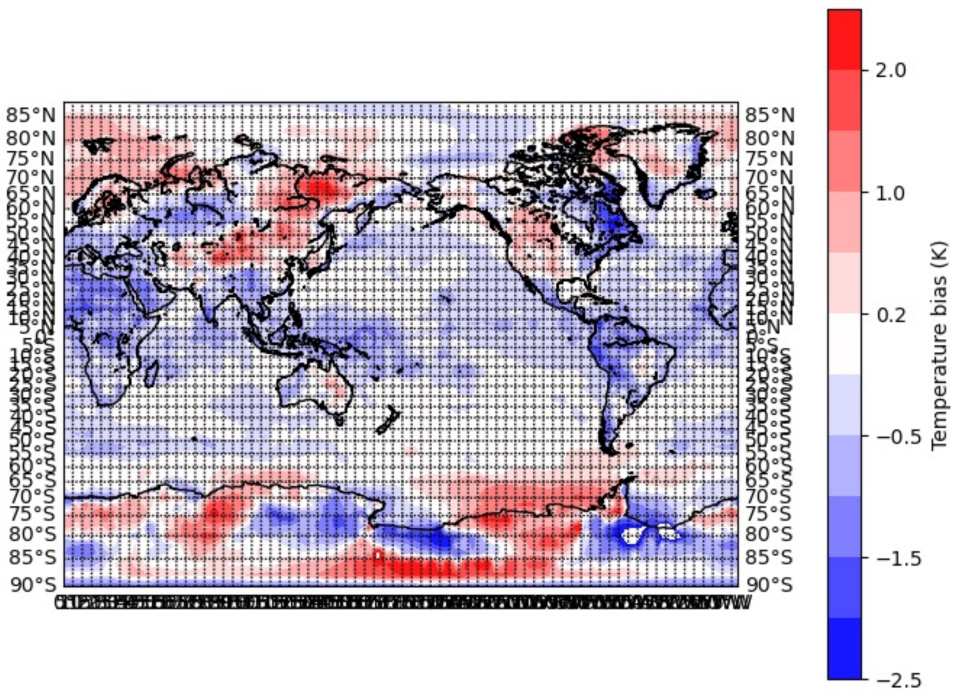


$$\text{Normalised RMSE} = \frac{New\ RMSE\ - High\ Res\ RMSE}{High\ Res\ RMSE}$$

Predictions



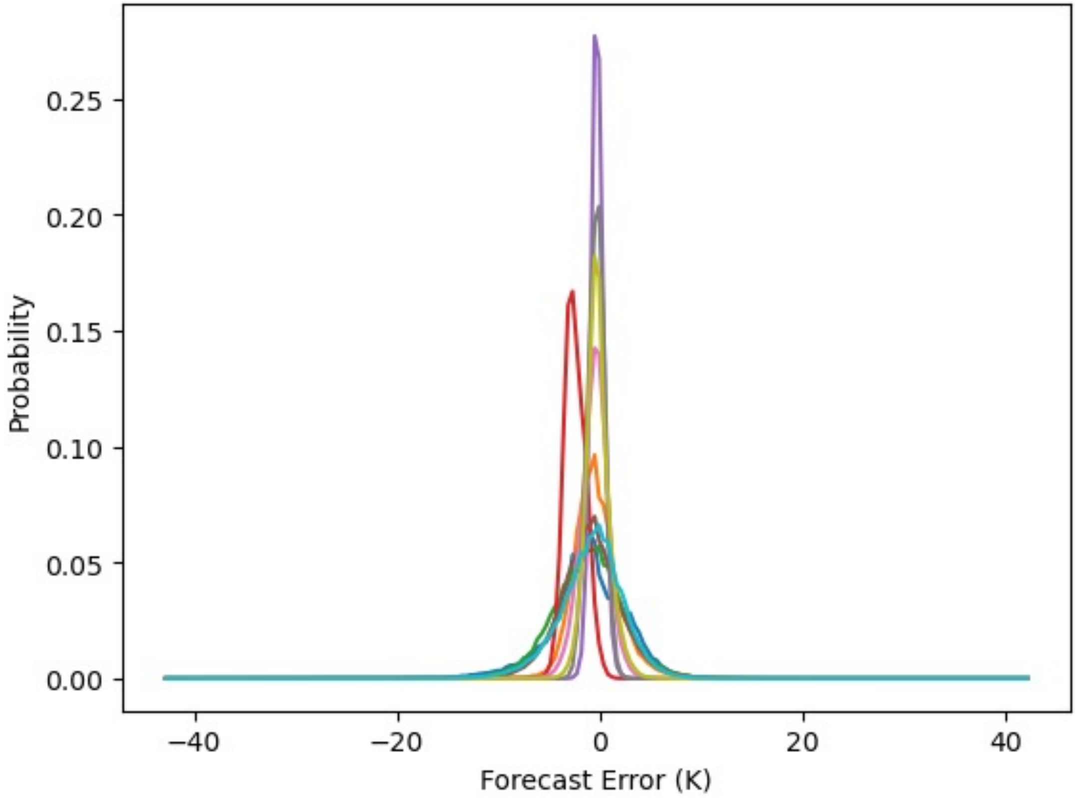
Real Forecast Bias (averaged over entire year)



Forecast Correction (averaged over entire year)

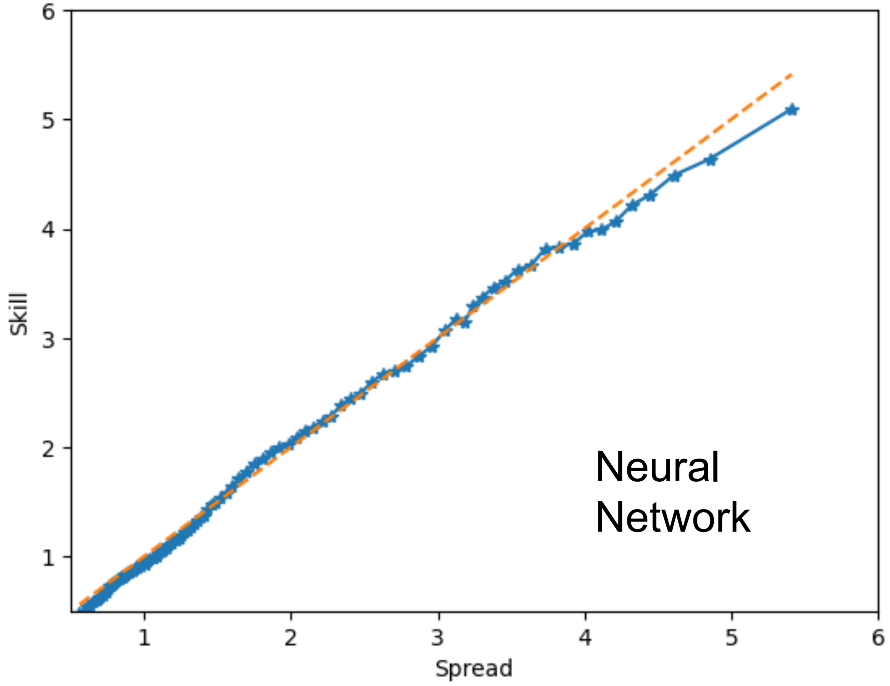
Probabilistic Predictions – Neural Network

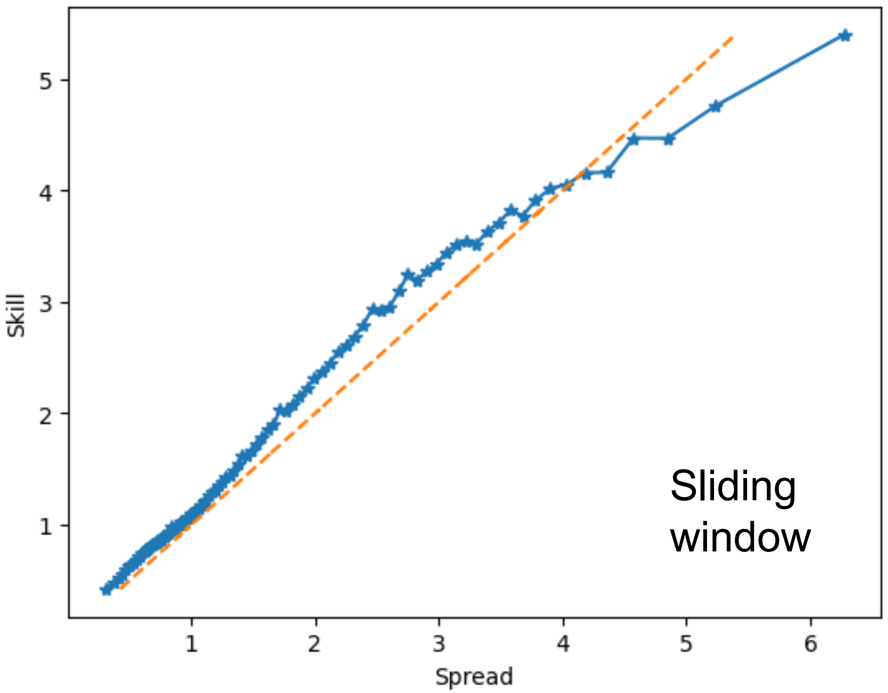
Instead of predicting a deterministic value, a Bayesian Neural Network predicts a distribution, as shown below



Spread/Skill ratio

A forecast is considered to be reliable if the forecast variance [spread] is equal to the forecast error [skill]





Conclusion

Conclusion

Key conclusion: Bayesian Neural Networks can make accurate and reliable probabilistic forecasts from deterministic information and they can significantly add value

- BNNs provide much more information about their predictions than a standard neural network, which makes them vastly more useful for scientific applications
- Uncertainty analysis provided by the BNN can help to understand if it’s predictions on this data are trustworthy and thus fit for purpose
- BNNs can produce reliable probabilistic forecasts of surface variables without requiring information from ensembles. This is particularly useful in cases where ensembles are too expensive to run

Clare, M. C., Sonnewald, M., Lguensat, R., Deshayes, J., & Balaji, V. (2022). Explainable artificial intelligence for bayesian neural networks: toward trustworthy predictions of ocean dynamics. *Journal of Advances in Modeling Earth Systems*, *14*(11), e2022MS003162.

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Key References

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