INTERNATIONAL OCEAN VECTOR WINDS SCIENCE TEAM meeting

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Retrieving Wind Vectors from Buoy Wave Spectra using Deep Learning

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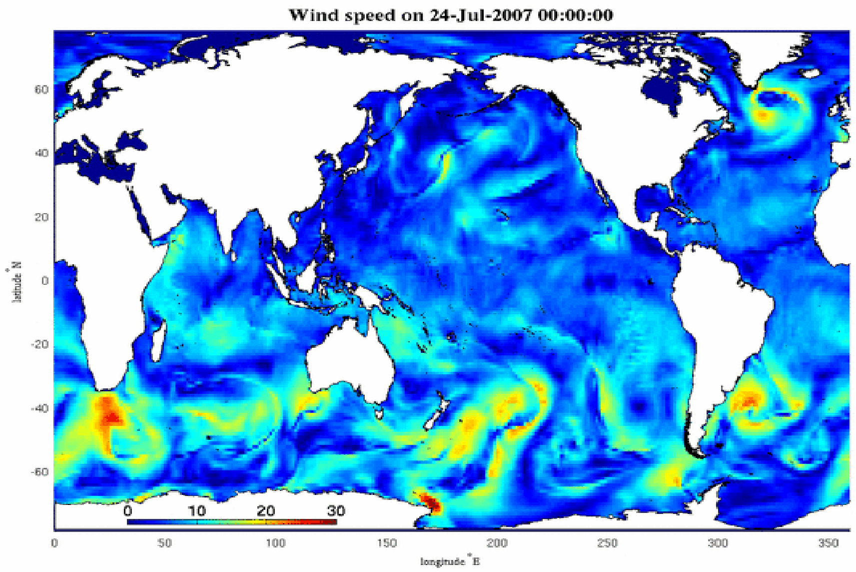
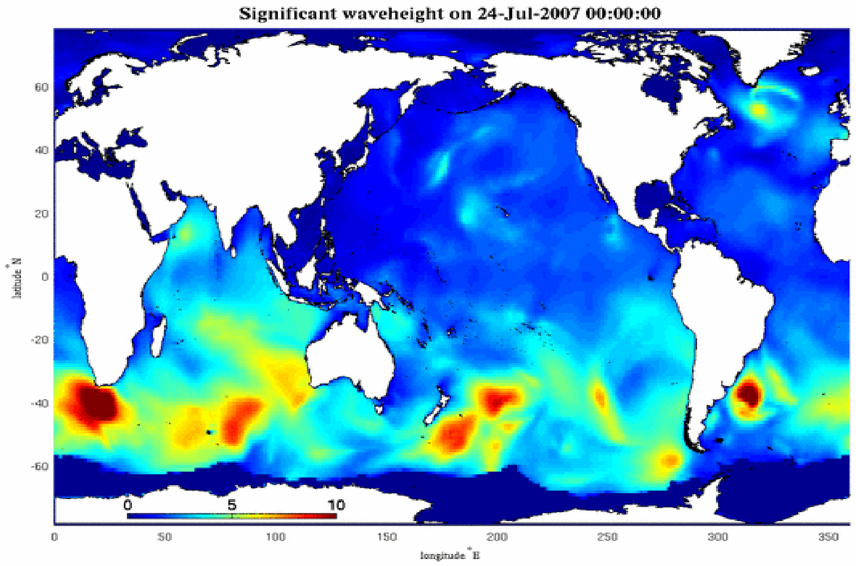
Introduction

Both sea surface wind & wave are import parameters of ocean dynamics

- Impacting almost all human activities in the ocean
- Disaster prevention – Tropical cyclone, huge waves
- Closely related to many ocean dynamic processes



The observation of sea surface wind & wave is useful for both scientific research & engineering practice.



The current wind/wave observation technology can be roughly classified as :

Remote Sensing & In-situ

Remote Sensing Observation of Ocean Wind/Wave

Remote Sensing of Sea Surface Wind

Sensor	Advantage	Disadvantage
Scatterometer	Wind Swath, Wind Vector, Good Accuracy	Saturation in High Wind, Low Resolution
Altimeter	Simultaneous Wind & Wave Information	Narrow Swath, No Wind Direction
SAR	Wind Vector, High Resolution, High Wind-Usable	Low Accuracy, Unstable Data Source
Radiometer	Wind Swath, ,Good Accuracy, High Wind-Usable	No Wind Direction (exp. WindSAT), Low Resolution

Scatterometer/radiometer are widely used (operational) in NWP assimilation/verification.

Remote Sensing of Waves (Wind-generated Surface Gravity Waves)

Sensor	Advantage	Disadvantage
Altimeter	High Accuracy, Simultaneous Wind & Wave	Narrow Swath， Only SWH
SAR	Simultaneous Wind & Wave, Swell Spectrum	Not Operational, Relatively Low Accuracy
SWIM	Simultaneous Wind & Wave (Directional Spectrum)	Accuracy of Wave Spectrum to be Evaluated

Altimeter SWH are widely used in wave model assimilation/verification.

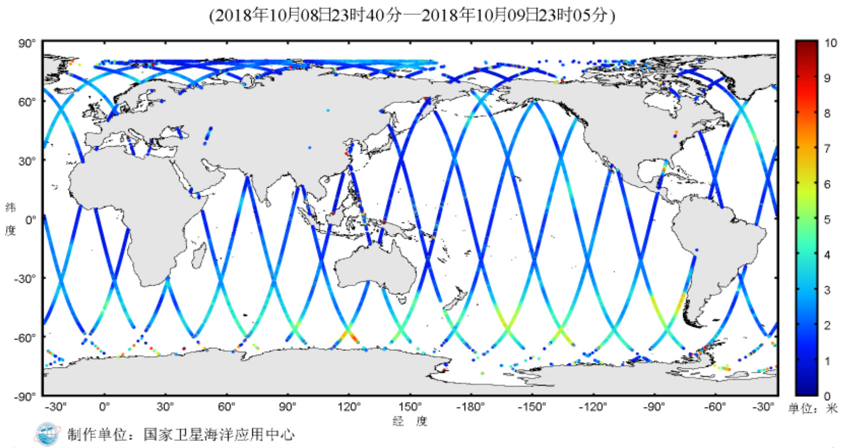
Introduction

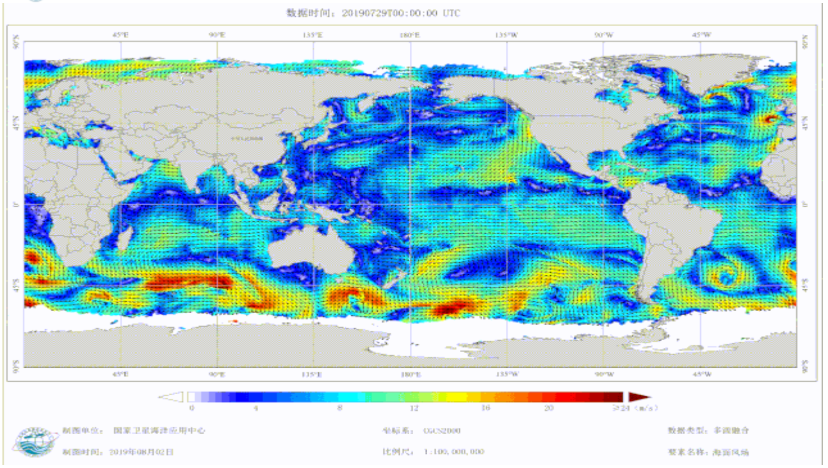
In-situ Observation of Ocean Wind/Wave

- ➢ RS cannot obtain good-quality directional wave spectra at this stage
- ➢ RS cannot continuously observe a fix point
- ➢ Low resolution → Low accuracy at coastal areas

In-situ method is still irreplaceable for wind/wave observation

- ➢ **Continuous** observations at selected points
- ➢ **More** parameters with **better** accuracy
- ➢ RS data is often **evaluated/validated** against them





In-situ observation of wind/wave are often made by meteorological buoys with both wind and wave sensors.

Introduction — In-situ Observation of Ocean Wind/Wave

Problem of large meteorological Buoy:
EXPENSIVE

- Meteorological Platform + Mooring
  - → High manufacturing cost
  - → Large buoy size
    - ➞ High deployment/maintenance cost (needing a dedicated ship/voyage)

Large buoys are sparsely distributed even near the coasts of developed countries

- A contradiction of stability requirement between wave and wind observations:

For wind observation: Buoys need to be **stable**
(otherwise, the measurement height will vary)

For wave observations: Buoys need to be **unstable**
(to respond to the wave motion)

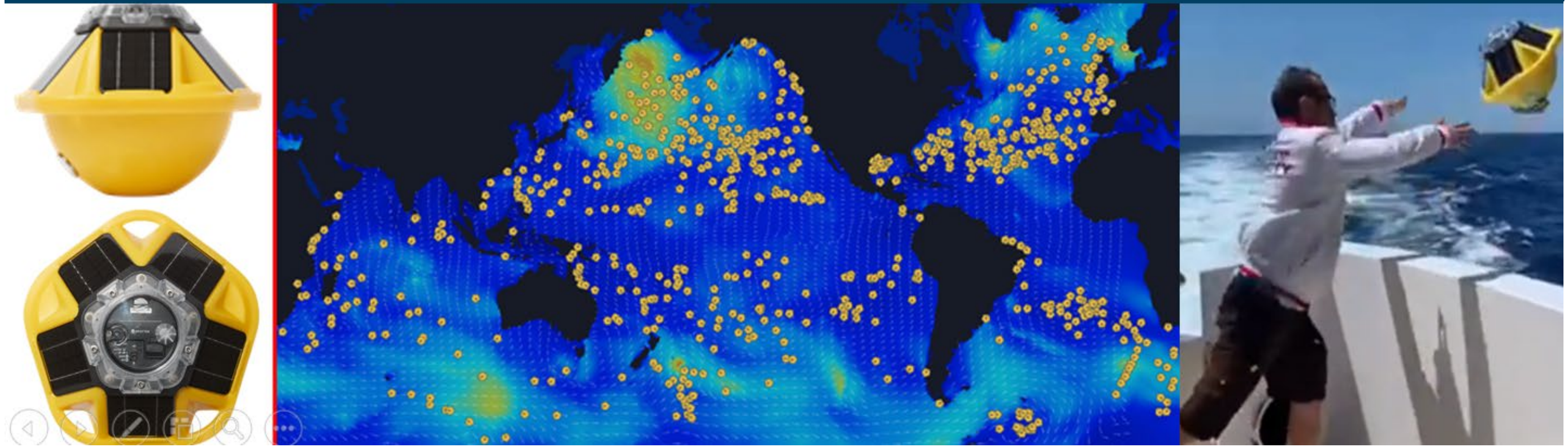
Introduction

In-situ Observation of Ocean Wind/Wave

Wave measurements from small wave drifters

- Low cost | Light | User friendly | Quick deployment
- Can be deployed by all types of ships (even small boats)
- Can be deployed "in pass"
- Can well respond waves, but difficult to setup a anemometer

Spotter buoys from SOFAR (~$5000)



Introduction In-situ Observation of Ocean Wind/Wave

Proxy wind observation from waves

Wind-wave relationship in the equilibrium range can be used to estimate wind speed and direction
(Voermans et al. 2020 JGR)


JGR Oceans

RESEARCH ARTICLE
10.1029/2019JC015717

Key Points:
- Wind properties are estimated based on a f^{-4} spectral dependence in the equilibrium range
- Wind speed and direction can be estimated based on wave

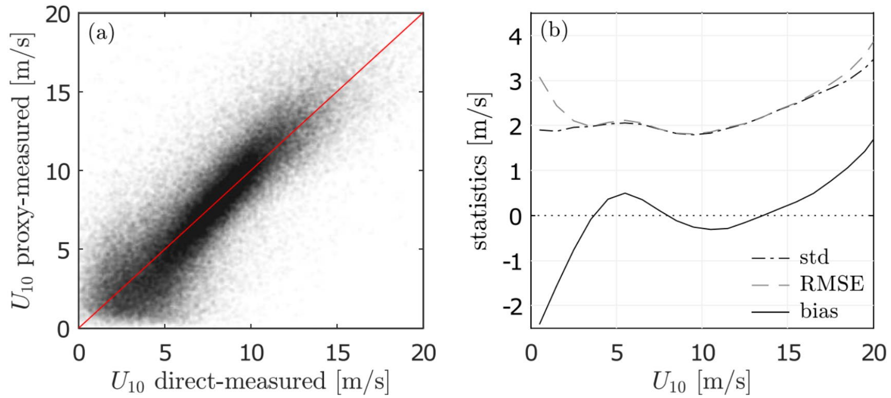
Estimating Wind Speed and Direction Using Wave Spectra

J. J. Voermans[1], P. B. Smit[2], T. T. Janssen[2], and A. V. Babanin[1,3]

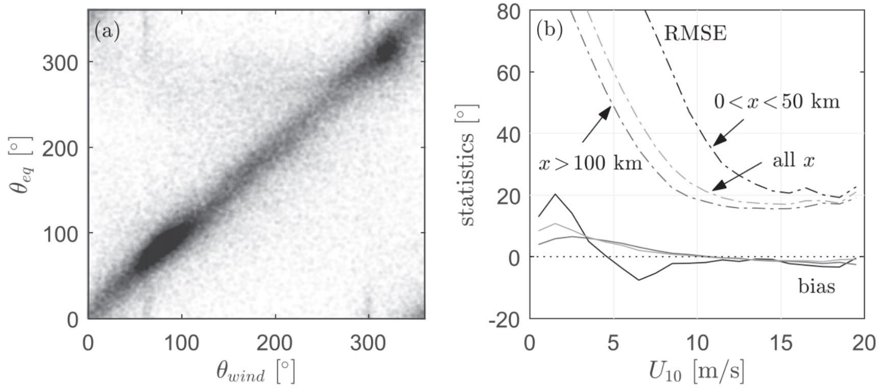
[1]Department of Infrastructure Engineering, University of Melbourne, Melbourne, Victoria, Australia, [2]Sofar Ocean Technologies, San Francisco, CA, USA, [3]Laboratory for Regional Oceanography and Numerical Modeling, Qingdao National Laboratory for Marine Science and Technology, Qingdao, China

$$E(f) = E_0 f^{-4} \text{ with } E_0 = \frac{4\beta I u_* g}{(2\pi)^3} \quad f > 1.3 f_p$$

Wind Speed RMSE: ~2.5 m/s
Wind Direction RMSE: ~25° (>7 m/s)



Compared to satellite scatterometer:
Wind Speed RMSE: 1~1.5 m/s
Wind Direction RMSE: 15°~18°
13°~15° (>7m/s)



Can not be used in operational observations
BUT GOOD IDEA!

In-situ Observation of Ocean Wind/Wave

- Some potential error sources：

1. Some energy maybe in saturation range → A better way to find equilibrium range?
2. Wave spread is assumed to be constant → A changeable wave spread coefficient?
3. Same weight for different frequencies → Considering different frequencies separately?

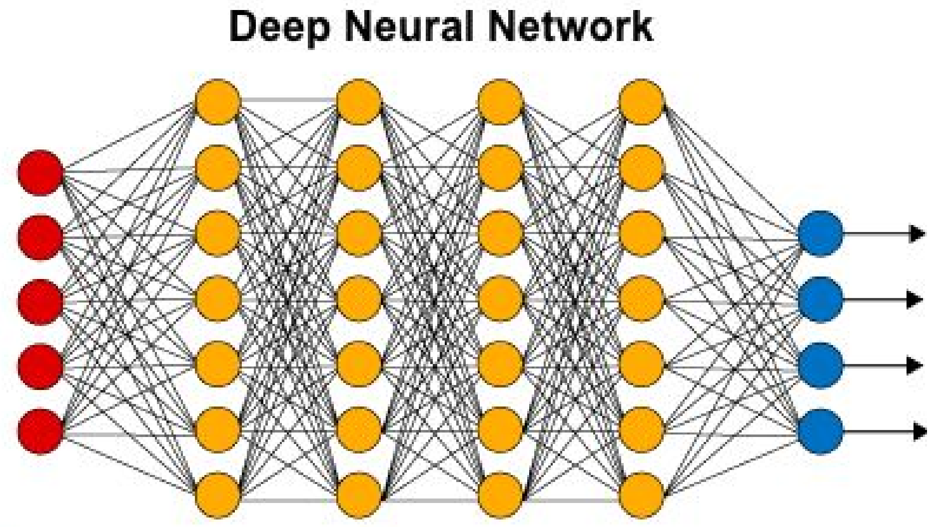
OR

Digging the relationship between wind and wave from the observational data?

Regression problem: **Wave spectra →** ***U*** **/** ***θ***

Multivariate regression：

A new opportunity from machine learning



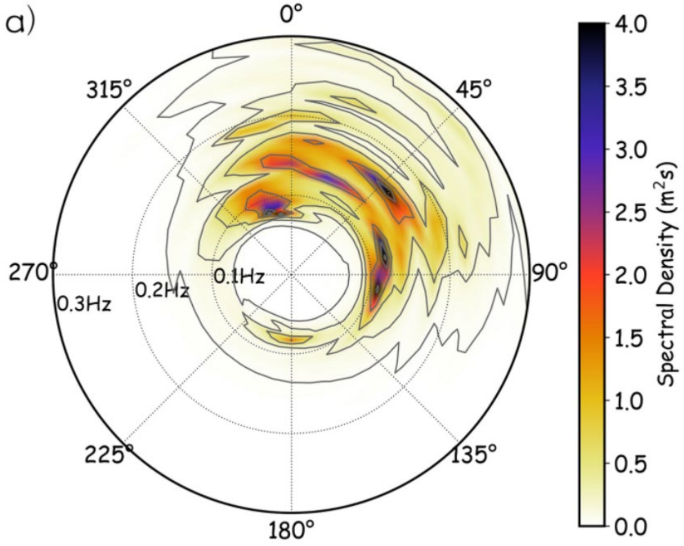
Data

Model inputs and outputs

- **Simultaneous observations of wind vector & wave spectra**

  ~100 NDBC buoys，5 years（2014-2018)

  ~1,600,000 records



- **Model INPUT: Wave spectra**

  Buoy cannot measure directional spectra directly,

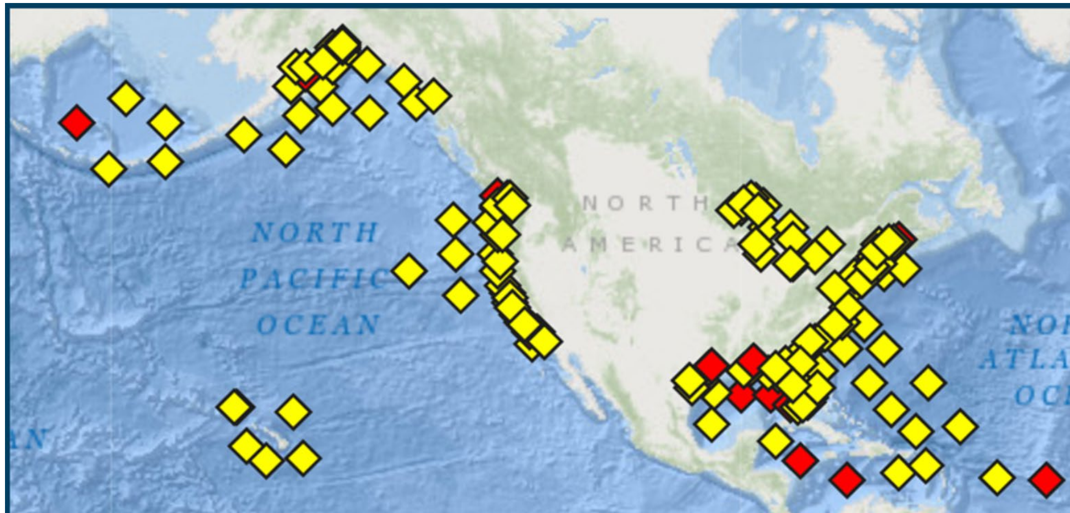
  but can measure "First-5"

  $E / \alpha_1 / \alpha_2 / r_1 / r_2$ of 0.02–0.485 Hz (47 frequency bands)

- **Model OUTPUT：Wind speed/direction**

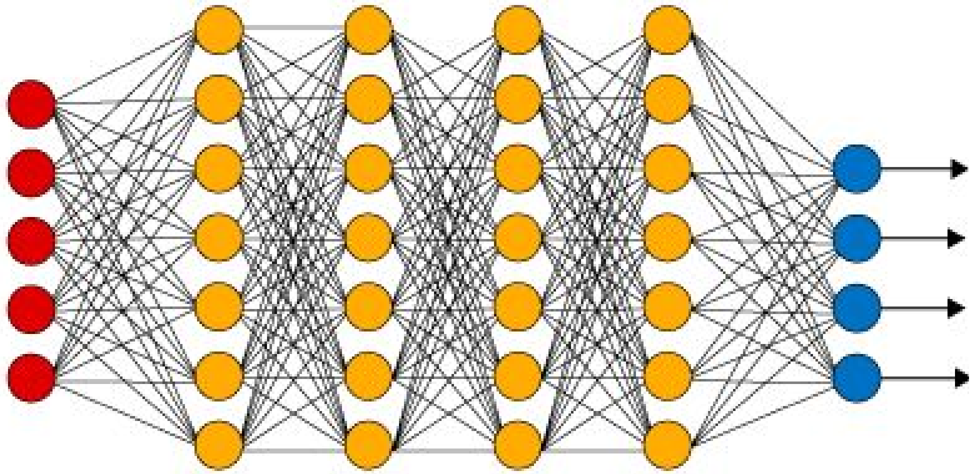
  3-5m wind → 10m (Log profile)

  Buoy U10 is widely used in the Cal/Val of remote sensing data



Method Modelling

- Building the model "violently"



$$\mathrm{Loss}_{U_{10}} = \mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2},$$

$$\mathrm{Loss}_{\mathrm{Dir}} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[(\sin(y_i) - \sin(x_i))^2 + (\cos(y_i) - \cos(x_i))^2\right]}.$$

Input:
47 frequencies×5 parameters
235 neurons

Hidden:
3 layers
×64 neurons

Division:
Training 50%
Testing 50%

Activation:
ReLU

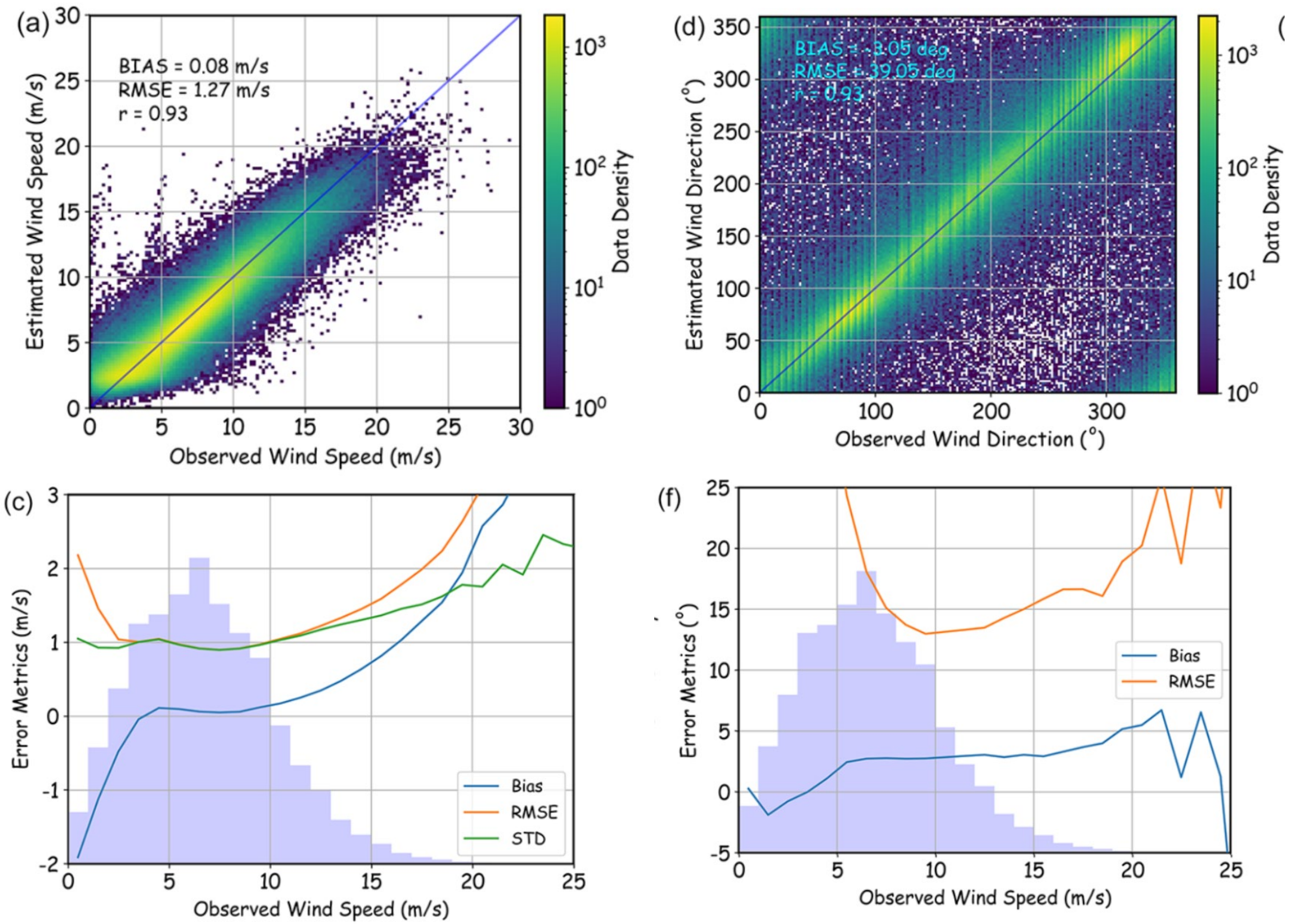
Optimizer:
Adam

Batch:
2048

Early Stopping

Results

- **Results for the "violent" model**



U_{10} RMSE:

~2.5 m/s (Voermans et al. 2020)

~1.3 m/s (this study)

1~1.5 m/s (scatterometer)

θ RMSE (U_{10}>7m/s)

~25° (Voermans et al. 2020)

~16° (this study)

13~15° (scatterometer)

Bad wind direction for U_{10}<5m/s

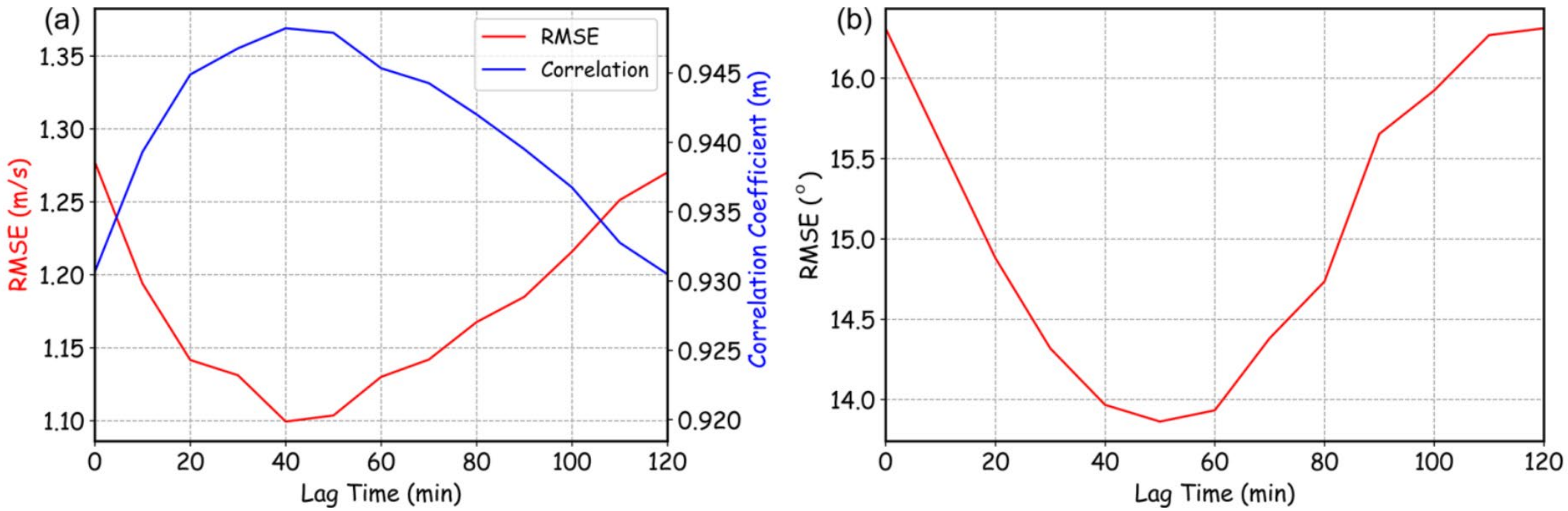
High winds are underestimated

A good result applicable for engineering application

Results

Delay in the signal

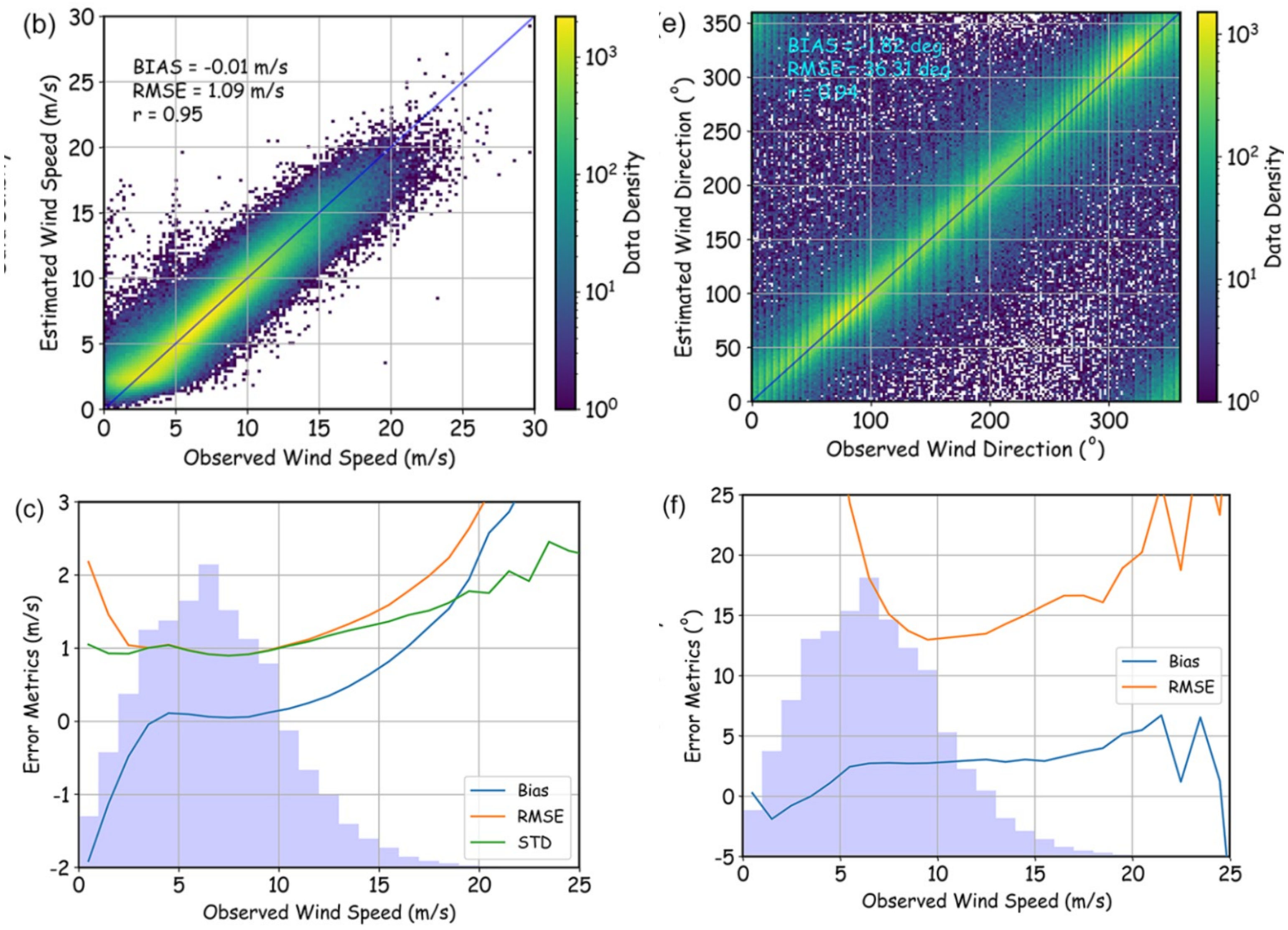
- Even for equilibrium range, the waves need time to "fully" respond to wind
- A shifting correlation is computed between model output and observed wind to find the "delay" response of waves.



- Different delay for different wind & wave spectra (related to the wave growth)
- Statistically, DNN-retrieved winds are the best correlated to observed winds 30~60 min before

Results

Delay in the signal



U_{10} RMSE:

~2.5 m/s (Voermans et al. 2020)

~1.1 m/s (this study)

1~1.5 m/s (scatterometer)

θ RMSE (U_{10}>7m/s)

~25° (Voermans et al. 2020)

~14° (this study)

13~15° (scattrometer)

Still:

Bad wind direction for U_{10}<5m/s

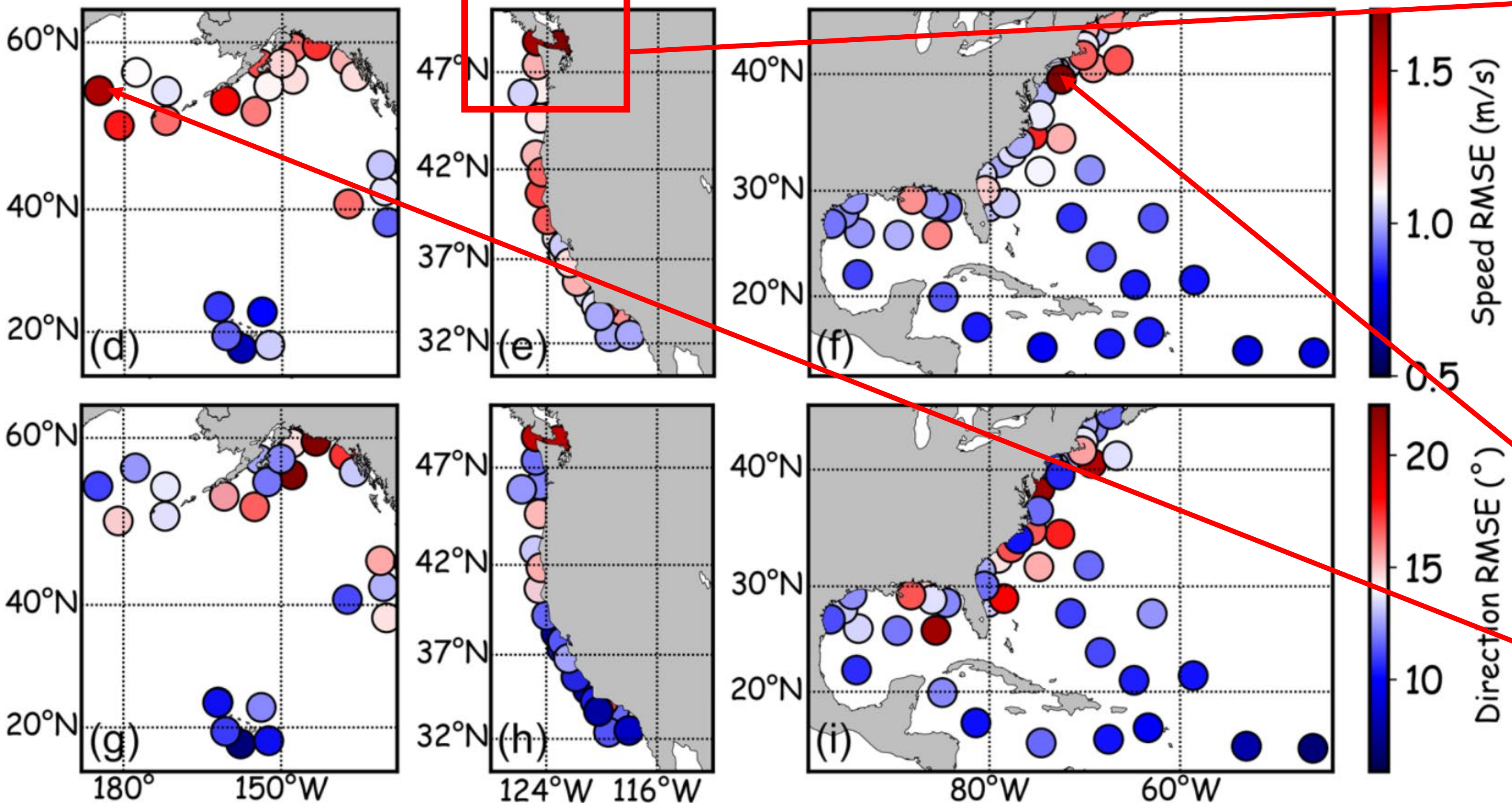
High winds are underestimated

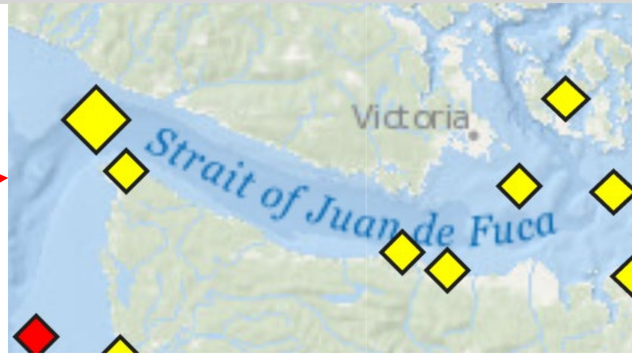
If a 30-min data delay is acceptable for an application, a better result can be obtained.

- **Case study**

ID 46987
RMSE: 1.7 m/s

ID 46988
RMSE: 1.8 m/s





Currents change the dispersion relation (wave's response is in wave number spectra)

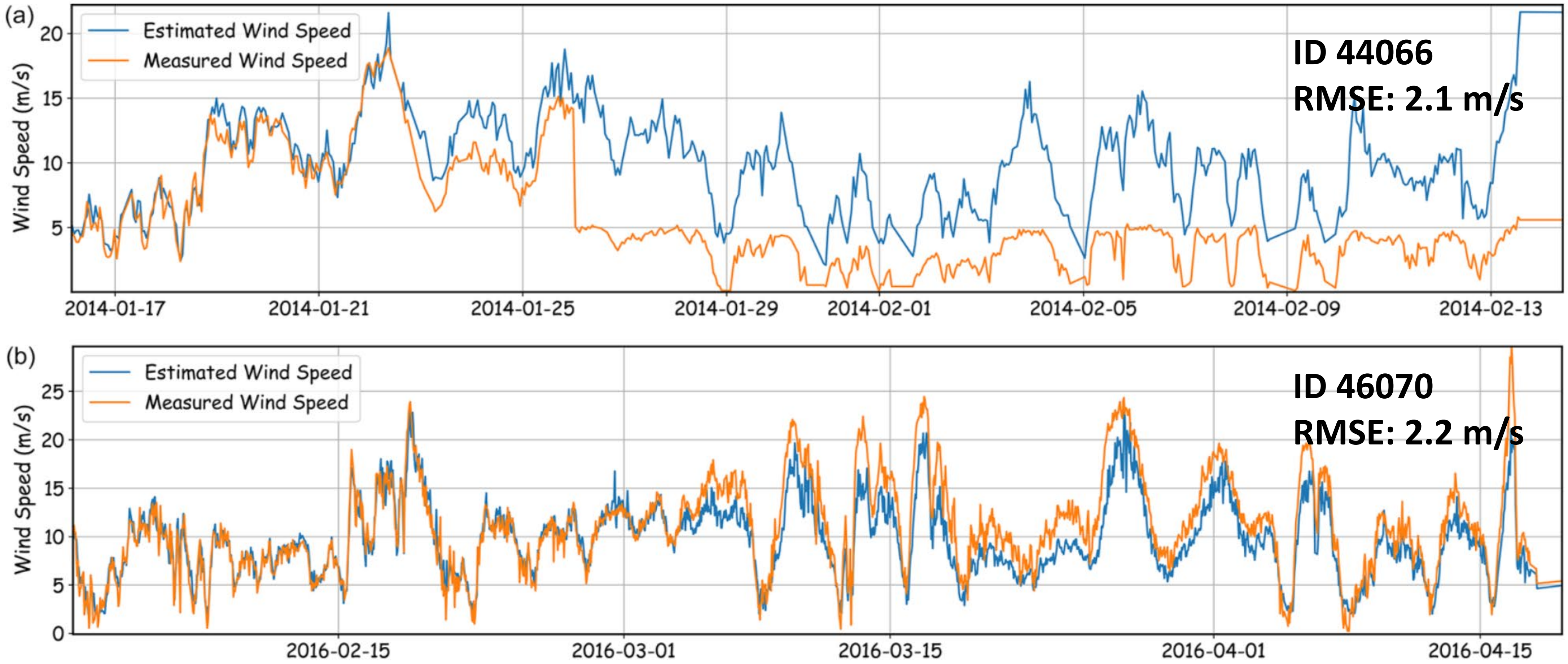
ID 44066
RMSE: 2.1 m/s

ID 46070
RMSE: 2.2 m/s

Error increases with wind speed

Results

➢ Case study



After QC: 1.1 m/s

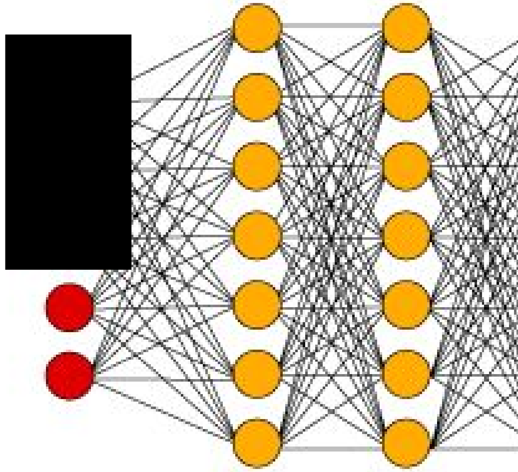
After QC: 1.25 m/s

Even for a platform with both wind/wave measurement, this model can be used to monitor the quality of wind/wave data.

Discussion

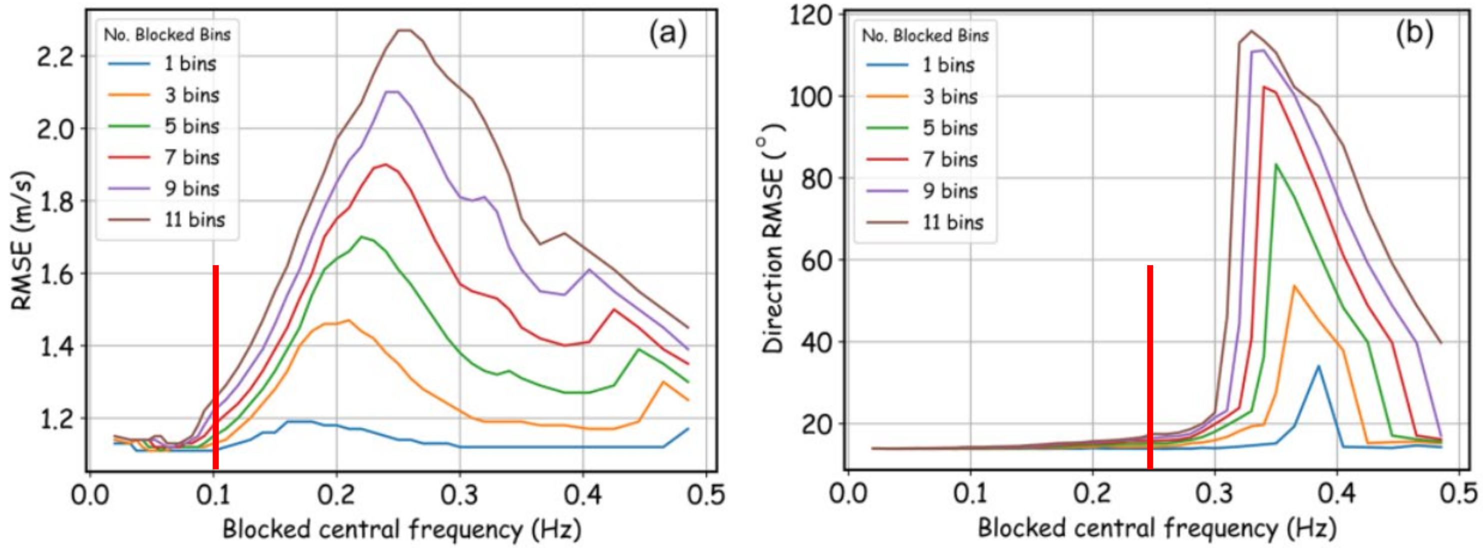
➢ Ablation test

Removed Variable	E	α_1	α_2	r_1	r_2
RMSE (U10, m/s)	**3.75**	1.17	1.14	**1.47**	1.19
RMSE (θ, °)	**17.3**	**111.9**	**16.2**	14.3	14.4



$$E(f) = E_0 f^{-4} \text{ with } E_0 = \frac{4\beta I u_* g}{(2\pi)^3} f > 1.3 f_p$$

Ablation frequencies



Important Inputs:

U_{10}:
E & r_1 @0.1Hz↑

RMSE: ~1.1 m/s

θ:
E, α1, & α2 @0.25Hz↑

RMSE: ~14° (>7m/s)

Summary

- **A DNN-based model to retrieve wind speed & direction from wave spectra**
- **The accuracy of the model is good (close to the level of scatterometer)**

  U_{10} RMSE: ~1.3 m/s (realtime) ~1.1 m/s (30min delay)

  θ RMSE(U_{10}>7m/s): ~16° (realtime) ~14° (30min delay)
- **The model can also be used for the QC of wave-wind joint observations**

Future application & improvement

- **The model can help wind-sea-swell partition when wind info is not available**
- **The model can work better for wave drifters: currents have less impact on the dispersion relation in the drifter coordinate**

Thank you!

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H. Jiang*, Wind Speed and Direction Estimation from Wave Spectra using Deep Learning, *Atmospheric Measurement Techniques*, 2022
W. Meng, S. Li, X. Wang, H. Jiang*, Wind-sea and Swell Separation of 1D Wave Spectrum by Deep Learning, *Ocean Engineering*, 2023