Towards Validating Wave-Ice Interactions in Climate Models Using In Situ Observations

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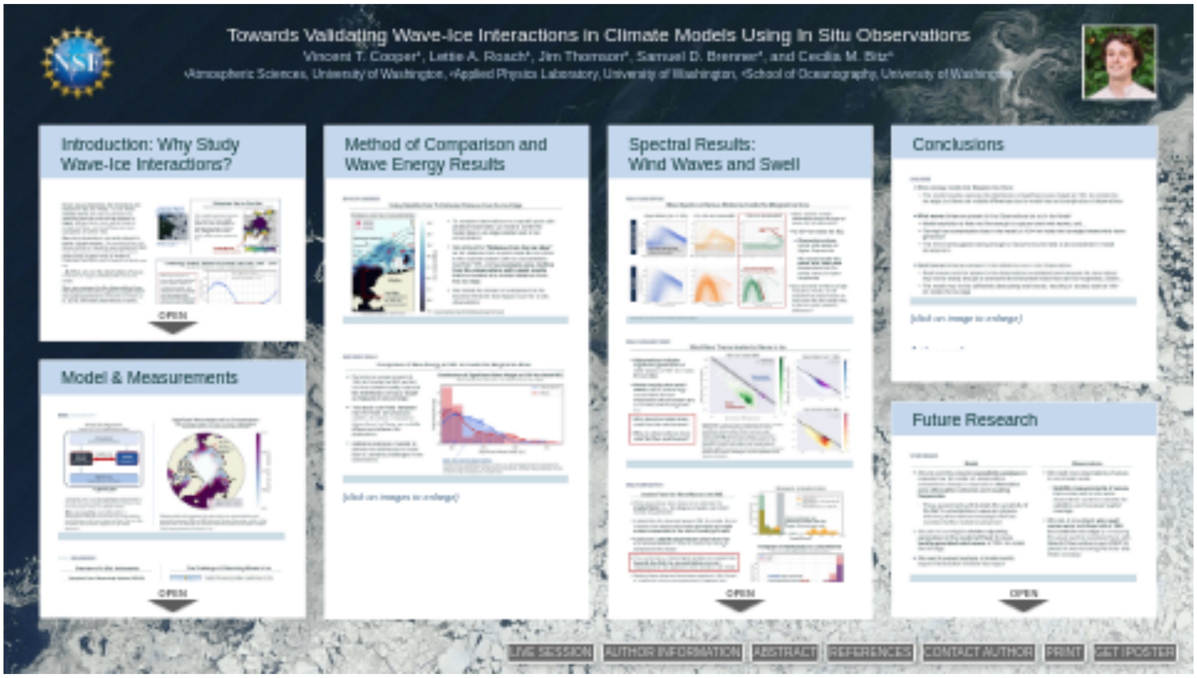
Abstract

The retreat of Arctic sea ice coincides with increased ocean surface wave activity, and wave-ice interactions are consequently poised to have a growing influence on the Arctic climate system. Recent field campaigns have focused on rectifying the scarcity of wave measurements inside the marginal ice zone, and work is now underway to incorporate wave-ice interactions in global climate models. Here, we apply a collection of in situ wave observations spanning multiple years in the Beaufort Sea and including wave activity beyond 100 kilometers inside the sea ice edge. To better understand waves in the presence of sea ice, we connect the in situ data with satellite-derived ice concentrations across the Arctic and compare the observations with a recent global climate model experiment that includes coupled interactions between waves and a sea ice floe size distribution. We present a series of comparisons focused on wave energy and wind-wave relationships in partial ice cover. These analyses provide a framework for assessing the impact of uncertainty in wave-ice physics on the marginal ice zone in new experiments in the coupled wave-ice model. Our work guides further model development and future observational campaigns.

Towards Validating Wave-Ice Interactions in Climate Models Using In Situ Observations



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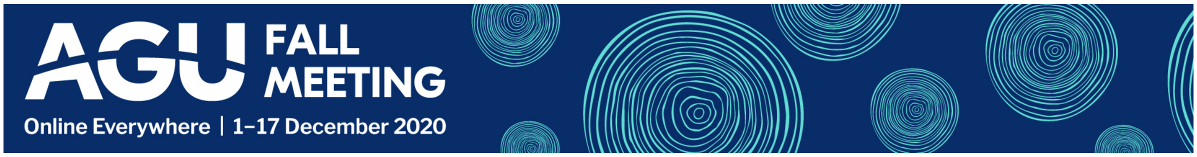
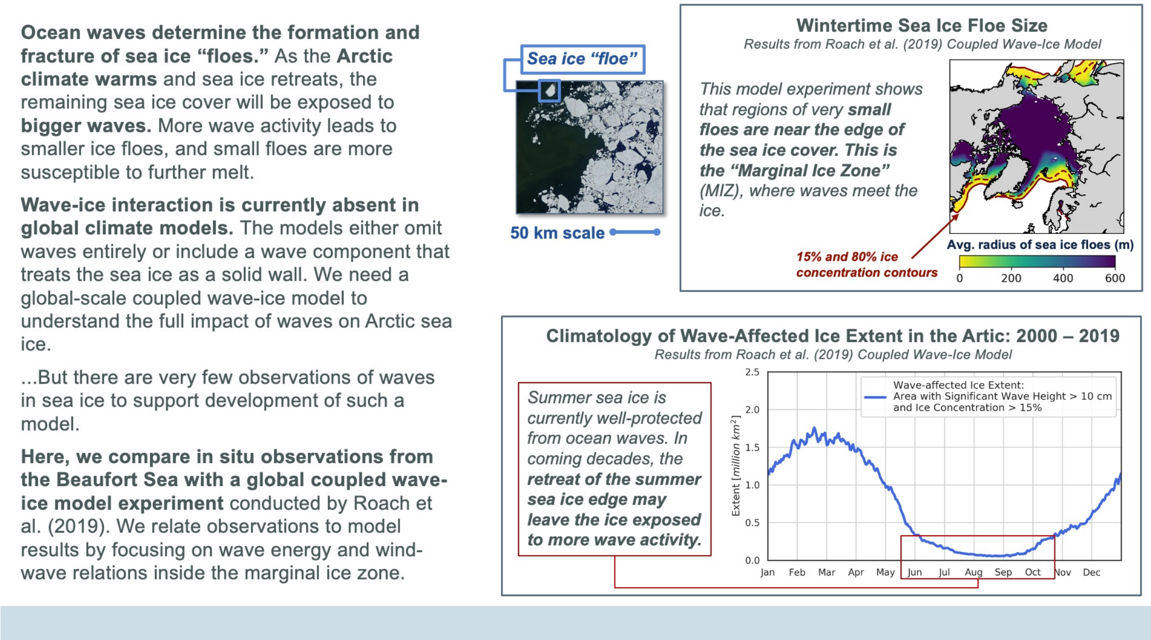


INTRODUCTION: WHY STUDY WAVE-ICE INTERACTIONS?



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[VIDEO] https://www.youtube.com/embed/LtfPJHJe5u8?rel=0&fs=1&modestbranding=1&rel=0&showinfo=0

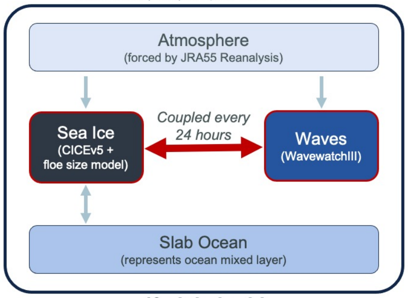
See video (30 seconds) for examples of waves in Arctic sea ice. Footage by Edward Blanchard-Wrigglesworth.

MODEL & MEASUREMENTS

MODEL & MEASUREMENTS

Model Configuration

Roach et al. (2019) Coupled Wave-Ice Model



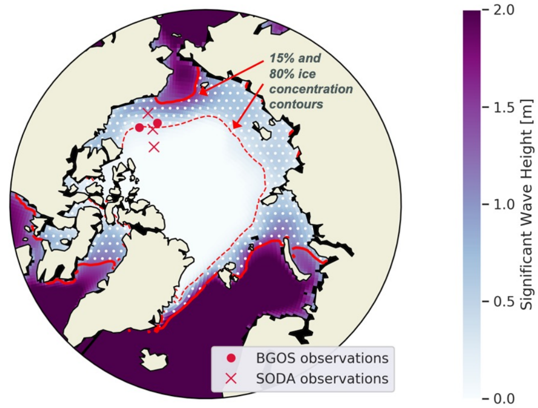
1° global grid

The Roach et al. (2019) experiment was the first to include two-way coupled interactions between sea ice and ocean waves in a global model.

Wave-ice coupling: wave attenuation in Wavewatch depends on the sea ice concentration, ice thickness, and size of sea ice floes. Sea ice floe formation and fracture depend on the wave spectrum.

Significant Wave Height and Ice Concentration: Climatological Mean for Oct. and Nov. (2000-2019)

Results from Roach et al. (2019) Coupled Wave-Ice Model



Stippled white dots represent the area where ice concentrations are generally between 15% and 80% during October-November, which is the period when the BGOS and SODA instruments were most able to obtain valid measurements of waves in ice.

MODEL & **MEASUREMENTS**

Overview of In Situ Instruments

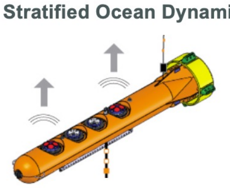
Beaufort Gyre Observing System (BGOS)

Adapted from Thomson (2020)

Two subsurface **BGOS** moorings in the Beaufort Sea measured ocean surface waves with the Nortek Acoustic Wave and Current (AWAC) instrument (boxed in red).

Data from 2012 were initially reported in *Thomson and Rogers (2014);* here, we employ an extended dataset with observations spanning 2012-2018 (*Thomson 2020).*

Stratified Ocean Dynamics of the Arctic (SODA)

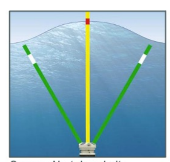


Adapted from Lee et al. (2016)

Three subsurface **SODA** moorings in the Beaufort Sea measured ocean surface waves with the Nortek Signature-500 acoustic instrument.

Data analysis is ongoing and was last updated in June 2020 (Brenner et al. 2020).

The Challenge of Observing Waves in Ice



Source: Nortek website

Inside the sea ice edge, roughness on the bottom of ice floes can mask out the wave signal that would normally be identified by the moorings' acoustic instruments, especially when waves are small.

When the mooring is in partial ice cover, **the wave signal must be sufficiently energetic relative to noise and ice roughness** to yield a valid wave measurement.

Summary of Observations

					Count of Wave Obs. (1)	
Data set	**Instrument**	**Time Period**	**Latitude**	**Longitude**	**0-100 km**	**100+ km**
BGOS-A	AWAC	2012-2018	75° N	150° W	11	29
BGOS-D	AWAC	2013-2018	74° N	140° W	6	2
SODA-A	Signature500	2018-2019	73° N	148° W	24	16
SODA-B	Signature500	2018-2019	75° N	146° W	35	10
SODA-C	Signature500	2019	78° N	139° W	0	16
Total					**76**	**73**

(1) Count of Wave Observations: this represents the number of valid wave measurements in partial ice cover (grouped by distance inside the ice edge) that are used for comparisons with model output. Model data are based on 6-hr intervals; the measurements are averaged to 6-hour intervals for comparability (despite sampling at a higher frequency), i.e., there is a maximum of one observational datapoint per 6 hours in the "count" above.

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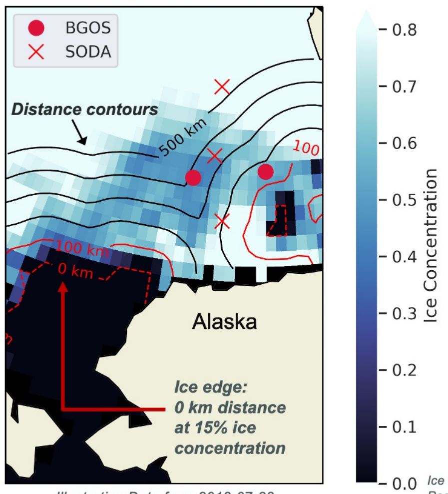
METHOD OF COMPARISON AND WAVE ENERGY RESULTS

METHOD OF COMPARISON

Using Satellite Data To Estimate Distance from the Ice Edge

Distance and Ice Concentration



Illustrative Data from 2018-07-23

Ice Concentration from NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration (Meier et al. 2020)

- To compare observations at a specific point with gridded model data, we need to control for model bias in ice edge position and in ice concentration
- We defined the **"Distance from the Ice Edge"** as the distance from a point inside the ice cover to the nearest location with ice concentration less than 15%, and **we compare wave metrics from the observations with model results that are located at a similar Distance from the Ice Edge**
- We limited the domain of comparison to the Beaufort-Chukchi Sea Region near the in situ observations

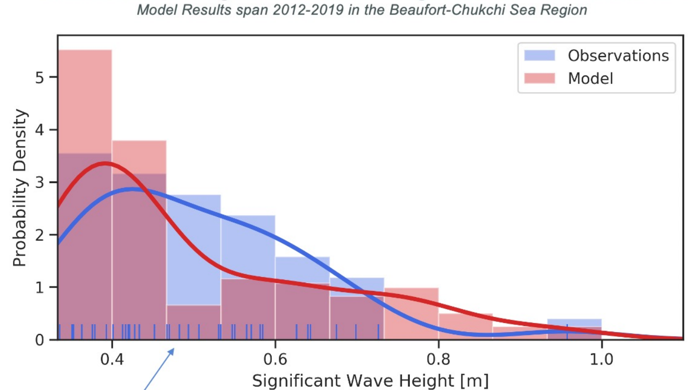
WAVE ENERGY RESULTS

Comparison of Wave Energy at 100+ km Inside the Marginal Ice Zone

- Focusing on waves present at 100+ km inside the MIZ, we find that **the model broadly captures the distribution of wave height** (a measure of wave energy)
- This result is an initial indication that the model can produce a realistic simulation of wave-ice interactions, but there are notable differences between the distributions
- Additional analysis is needed to attribute the differences to model bias vs. sampling challenges in the observations

Distribution of Significant Wave Height at 100+ km Inside MIZ

Model Results span 2012-2019 in the Beaufort-Chukchi Sea Region



Blue lines denote observations

Domain shown is limited to waves > 33 cm, i.e., waves large enough to overcome the signal-to-noise threshold for all instruments considered. Smaller waves detected only by a subset of the moorings are excluded here.

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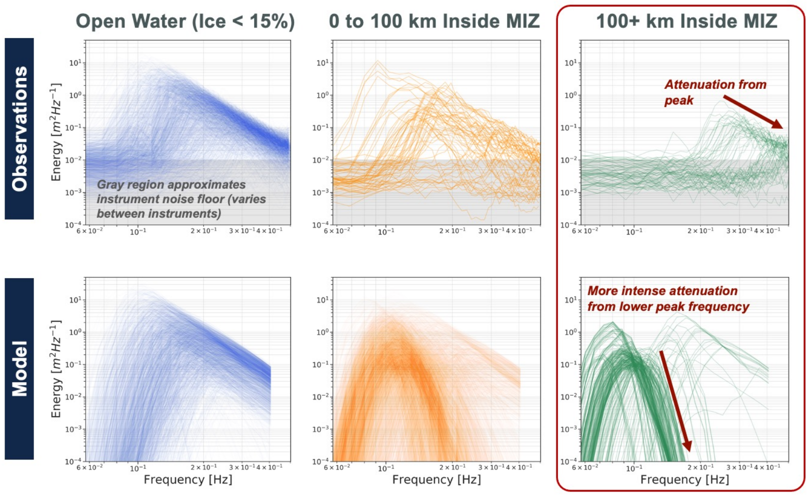
SPECTRAL RESULTS: WIND WAVES AND SWELL

RESULTS: WAVE SPECTRA

Wave Spectra at Various Distances Inside the Marginal Ice Zone



- Wave spectra contain information about the type of wave and its attenuation
- **At 100+ km inside the MIZ:**
  - **Observations show waves with *peaks at higher frequencies***
  - **The model mostly has waves with *lower peak frequencies*** that lose energy rapidly at higher frequencies
- Sea ice tends to filter out high frequency waves, so we expected the observations to look more like the model: why is there a such a distinct difference?

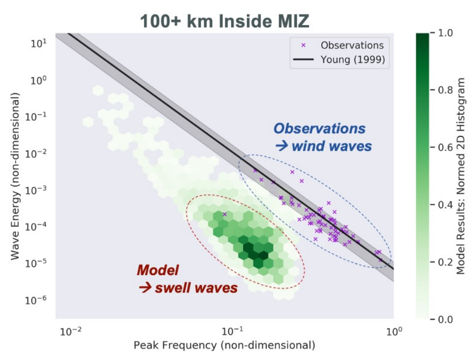
Model Results span 2017-2019 in the Beaufort-Chukchi Sea Region

RESULTS: WIND-WAVE THEORY

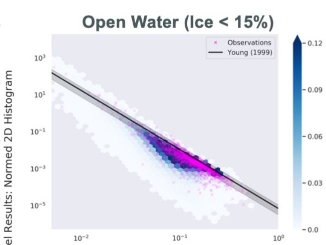
Wind-Wave Theory Applied to Waves in Ice

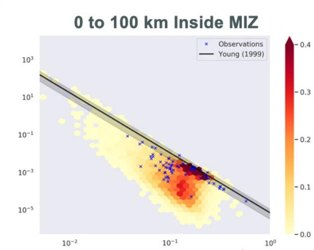
- **Observations indicate significant generation of wind waves** at 100+ km inside the ice edge
- **Model results show swell waves**, which have energy concentrated at lower frequencies and are better able to survive travel through sea ice

- **Why does the model show *swell* but few *wind* waves?**
- **Why do observations show *wind* but few *swell* waves?**



Black line: Linear fit with uncertainty bounds of wave energy vs. peak frequency power-law for wind-generated, fetch-limited waves (*Young 1999*).
Color shading (green/blue/orange): normed 2-D histogram of model results from 2017-2019 in the Beaufort-Chukchi Sea region near observations.
Scatter plot ("x" marks): in situ observations of waves paired with JRA55 reanalysis of wind speeds at the relevant location.

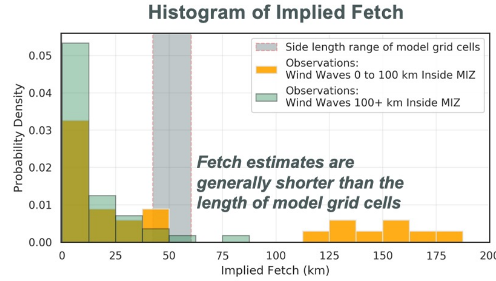


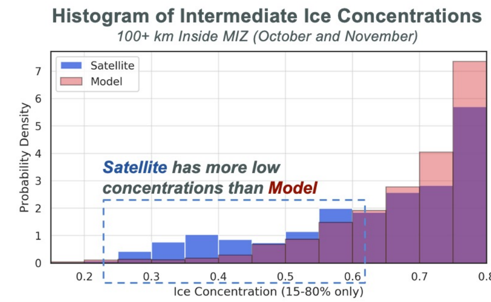


RESULTS: IMPLIED FETCH

Implied Fetch for Wind Waves in the MIZ

- Wind-wave theory also allows us to estimate the ***implied fetch***, i.e., the distance of water over which waves are generated
- Implied fetch for observed waves 100+ km inside the ice indicates that **waves are locally generated at length scales comparable to the size of model grid cells**
- Additionally, **satellite observations show more low ice concentrations** at 100+ km inside the ice edge compared to the model
- The combination of **short fetch scales** and **model bias towards too-high ice concentrations** appears responsible for the absence of wind waves in the model
- Testing these observed wind wave spectra in the *Horvat & Tziperman* (2015) parametrization suggests that **locally-generated wind waves are strong enough to fracture sea ice** and will be important to consider in future model development





SUPPLEMENTARY: WIND-WAVE THEORY

Additional Detail: Wind-Wave Theory Methods

- In the marginal sea region of the observations considered here, fetch is generally the limiting variable for wave generation (*Hasselmann et al., 1973*; *Thomson & Rogers, 2014)*
- We apply the theory of fetch-limited wind waves (*Young, 1999)* to evaluate the types of modeled and observed waves in partial ice cover
- First, we use the 10-meter wind speed (U_{10}) from JRA55 reanalysis at the location of the relevant wave data to transform Significant Wave Height (H_s), Peak Frequency (f_p), and Fetch (x) to their non-dimensional counterparts *(E, F,* and *X,* respectively):

$$E = \left(\frac{gH_s}{4U_{10}^2}\right)^2 \qquad F = \frac{f_p U_{10}}{g} \qquad X = \frac{gx}{U_{10}^2}$$

- *E* vs. *F* for wind-generated waves should follow the power-law relationship implied in *Young (1999)*:

$$E = (6.9 \pm 3.8)\times 10^{-6}\, F^{-3.2}$$

- Power-law relationships relating *E* and *F* with *X* enable extrapolation of an implied fetch, *x*, for the waves that follow the wind-wave theory:

$$E_{max} = (7.5 \pm 2.0)\times 10^{-7}\, x^{0.8}$$

$$F_{min} = (2.0 \pm 0.3)\, x^{-0.25}$$

(click on images to enlarge)

CONCLUSIONS

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- **Wave energy inside the Marginal Ice Zone**
  - The model broadly captures the distribution of significant wave height at 100+ km inside the ice edge, but there are notable differences due to model bias and sample size of observations

- **Wind waves in ice** are present in the *Observations* but not in the *Model*
  - Model resolution is likely not fine enough to capture short wind waves, and…
  - Too-high ice concentration bias in the model at 100+ km inside the ice edge hinders wind wave generation
  - The wind waves appear strong enough to fracture ice and need to be considered in model development

- **Swell waves in ice** are present in the *Model* but not in the *Observations*
  - Swell waves could be absent in the observations considered here because the wave signal may not be strong enough to overcome the instrument noise floor and ice roughness, and/or…
  - The model may not be sufficiently attenuating swell waves, resulting in excess swell at 100+ km inside the ice edge

(click on image to enlarge)

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FUTURE RESEARCH

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Model

- We are currently preparing **sensitivity analyses** to evaluate how the model vs. observations comparisons change in response to **alternative wave attenuation schemes and coupling frequencies**
  - These experiments will illustrate the sensitivity of the MIZ to uncertainties in wave-ice physics, informing observational campaigns that can constrain further model development
- We plan to investigate **whether adjusting parameters in the model will lead to more locally-generated wind waves** at 100+ km inside the ice edge
- We need to expand analysis of model results beyond the Beaufort-Chukchi Sea region

Observations

- We need more observations of waves in ice at basin scale
  - **Satellite measurements of waves** that overlap with in situ wave observations would be valuable for validation and increased spatial coverage
- We plan to investigate **why swell waves were not observed at 100+ km inside the ice edge** by comparing the wave spectra considered here with Beaufort Sea surface buoys (SWIFTs) placed in sea ice during the Arctic Sea State campaign

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ABSTRACT

The retreat of Arctic sea ice coincides with increased ocean surface wave activity, and wave-ice interactions are consequently poised to have a growing influence on the Arctic climate system. Recent field campaigns have focused on rectifying the scarcity of wave measurements inside the marginal ice zone, and work is now underway to incorporate wave-ice interactions in global climate models. Here, we apply a collection of in situ wave observations spanning multiple years in the Beaufort Sea and including wave activity beyond 100 kilometers inside the sea ice edge. To better understand waves in the presence of sea ice, we connect the in situ data with satellite-derived ice concentrations across the Arctic and compare the observations with a recent global climate model experiment that includes coupled interactions between waves and a sea ice floe size distribution. We present a series of comparisons focused on wave energy and wind-wave relationships in partial ice cover. These analyses provide a framework for assessing the impact of uncertainty in wave-ice physics on the marginal ice zone in new experiments in the coupled wave-ice model. Our work provides insights to guide both further model development and future observational campaigns.

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