



清华大学

Tsinghua University

基于海洋参数智能预测的荷载分析

Load Analysis Based on Intelligent Prediction of Ocean Parameters

2024. 06. 14 | 冯伟杰 郭金霄



Contents



研究背景

- 海洋参数智能预测
- 海上结构荷载分析

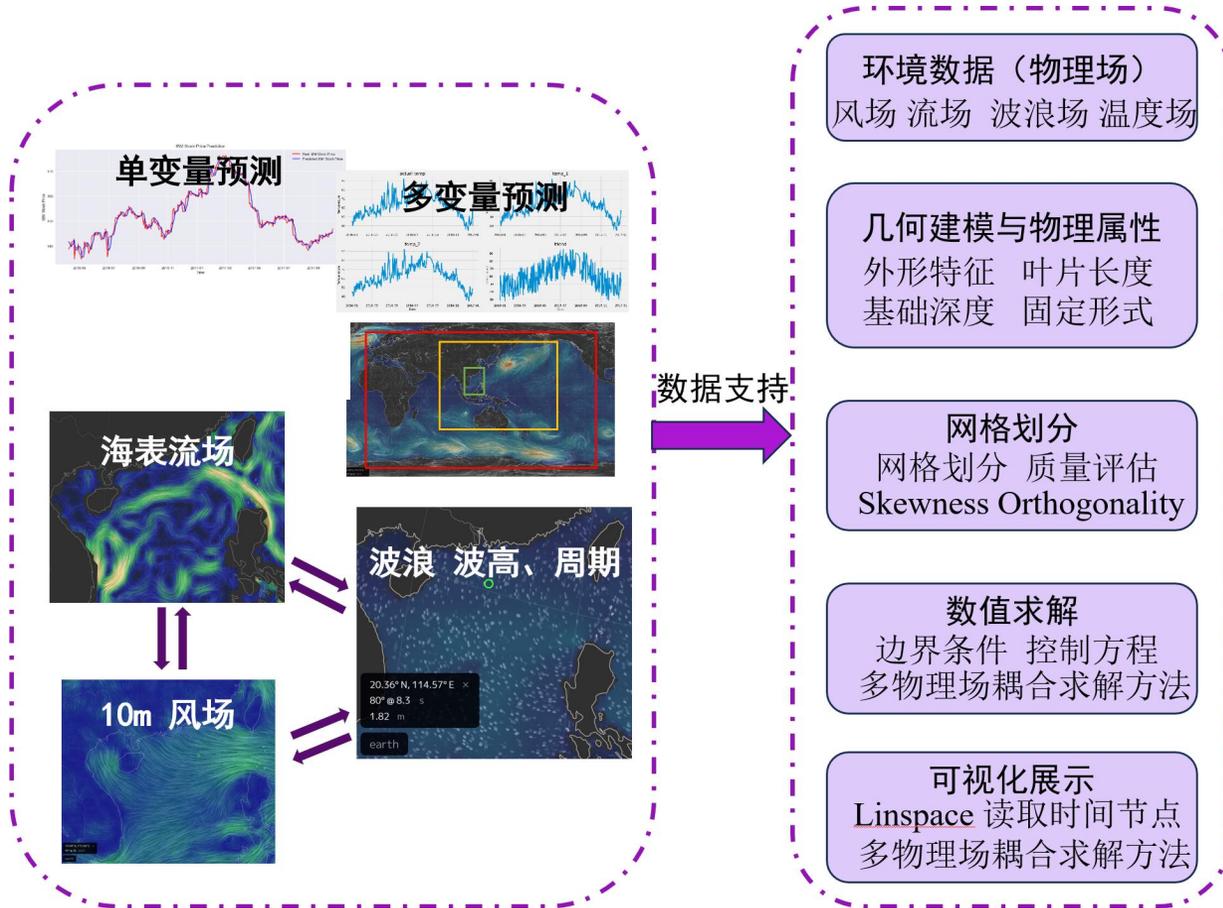


研究内容

- 气象预测
- 荷载分析



研究成果

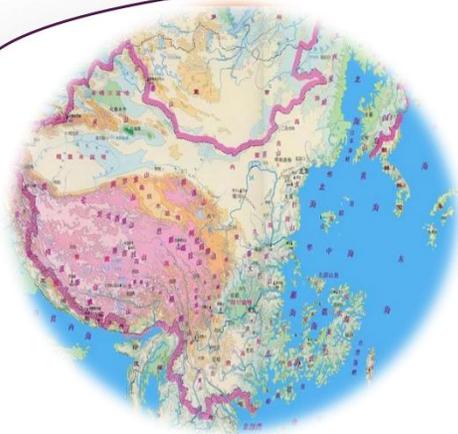




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01 研究背景

Research Background



21世纪，人类进入了大规模开发利用海洋的时期。**海洋**在国家经济发展格局和对外开放中的作用更加重要，在维护国家主权、安全、发展利益中的地位更加突出，在国家生态文明建设中的角色更加显著，在国际政治、经济、军事、科技竞争中的**战略地位**也**明显上升**。

研究背景

海上风力发电作为一种可再生能源，具有巨大经济潜力。**海上风机**需要面对复杂多变的海洋环境，包括风、浪、流等多种荷载的共同作用。研究荷载情况有助于确保风机在恶劣环境中的结构安全，避免灾难性故障和事故发生。



研究内容

研究成果

内容1：海洋环境气象数据的变异性



内容2：海上风机荷载计算的重要性





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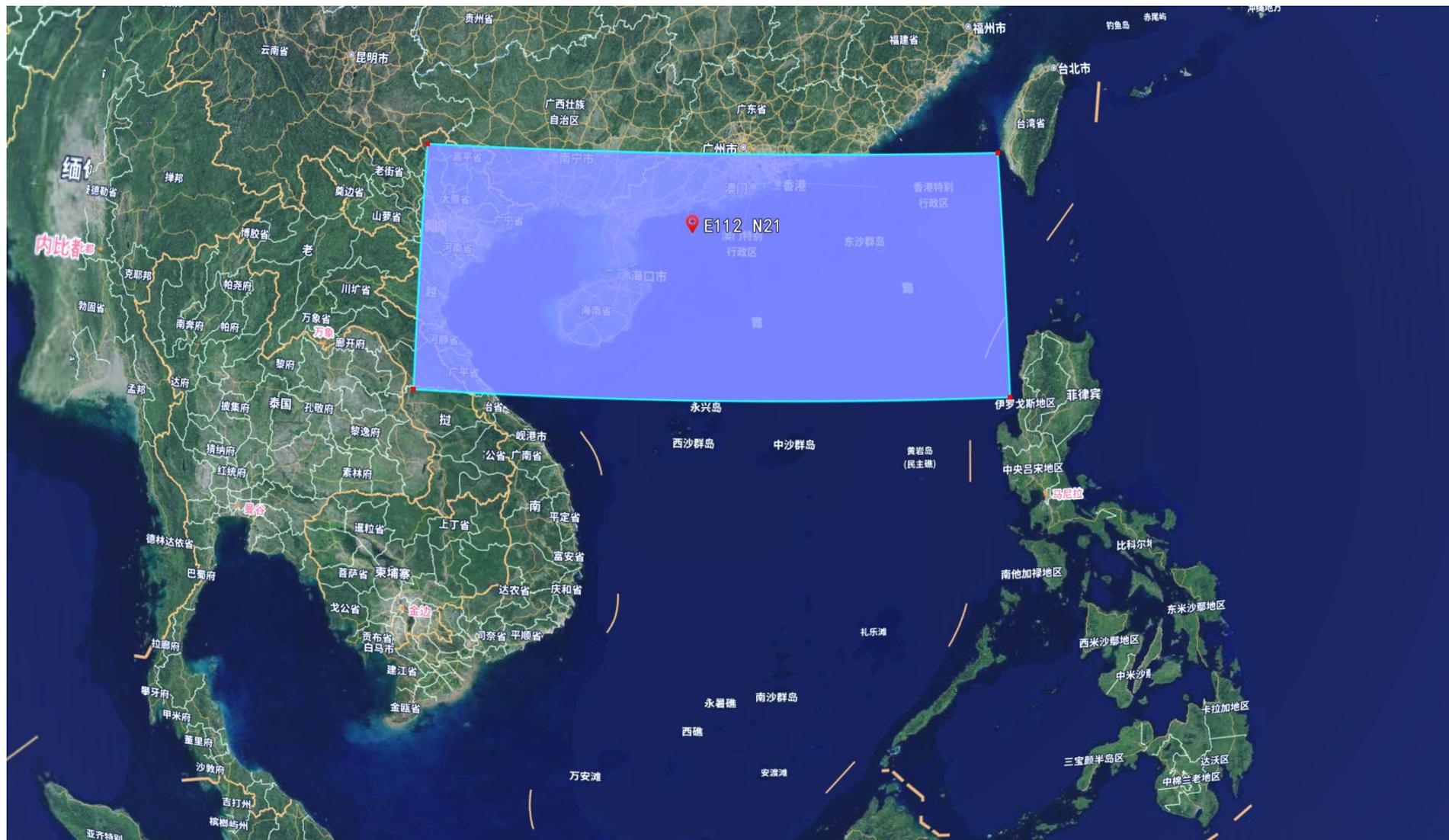
02 研究内容

Research Content



研究区域: 南海北部 (E105-120 N17-23)

研究变量: 地表10米风 (U10、V10)、地表100米风 (U100、V100)、海表流场 (UV)、平均波方向 (mwd)、平均波周期 (mwp)、显著波高 (swh)



研究背景

研究内容

研究成果



数据来源: ERA5 hourly data on single levels from 1979 to 2023
(The fifth generation ECMWF reanalysis for the global climate and weather)

研究背景

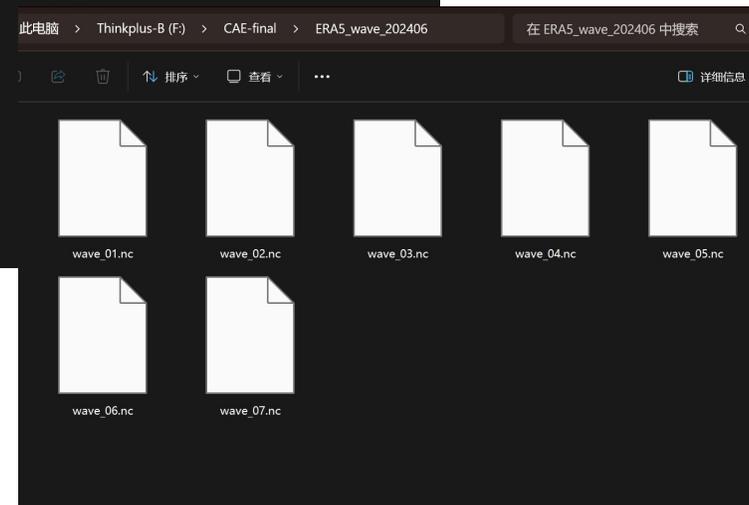
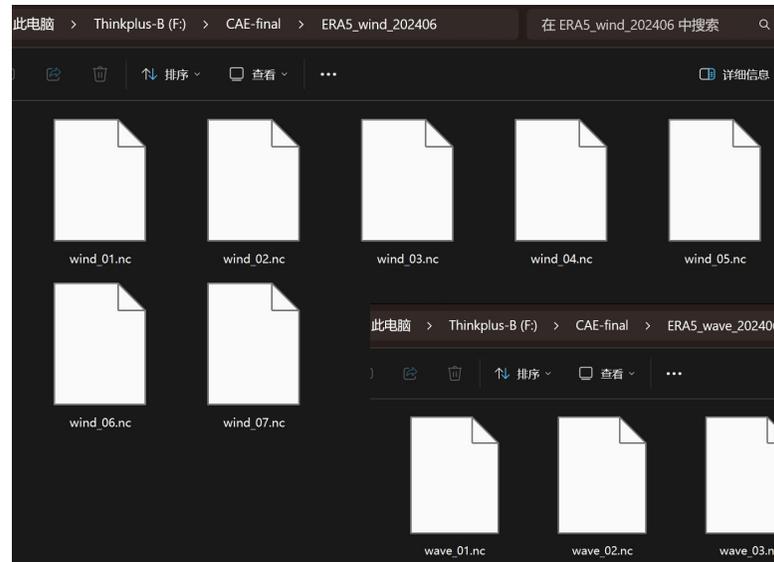
研究内容

研究成果

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e-levels
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```



ERA5数据每天更新，但有5-7天延迟。

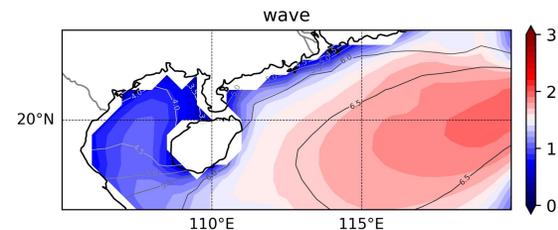
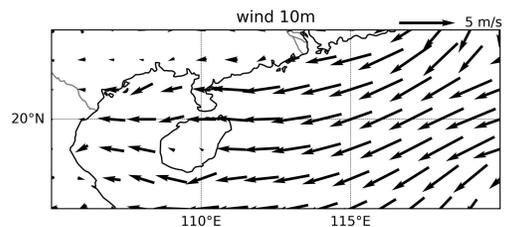
风场数据不能和波浪数据同时下载，不然会导致数据错误！

风场网格精度为0.25°，波浪场网格精度为0.5°，流场数据用月平均值。

用于训练时，总共下载的数据时间点有394464个（1979-2023年每小时）。



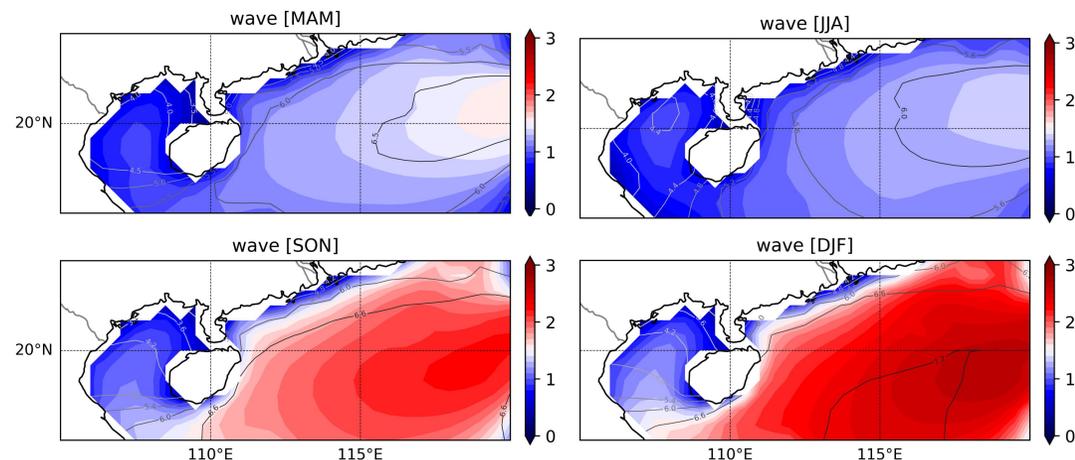
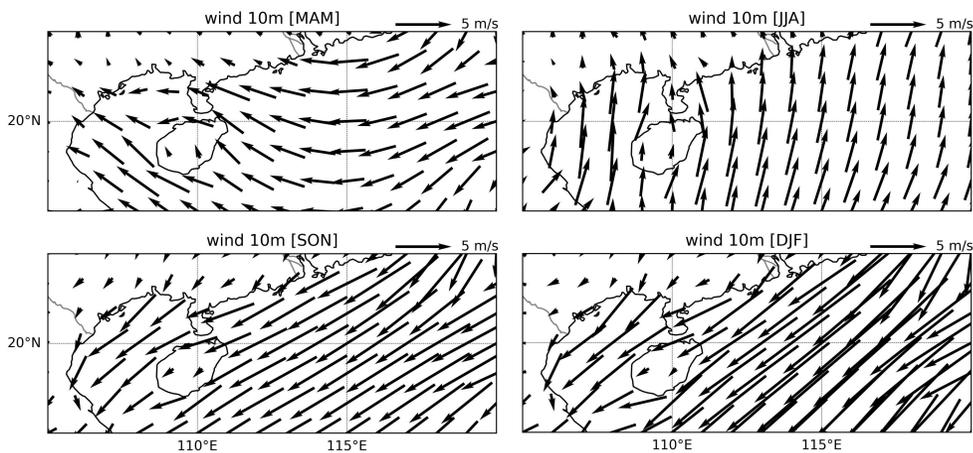
研究区域气候状态



研究背景

研究内容

研究成果





单变量区域二维模型搭建

使用了Transformer架构，进行归一化处理，然后通过 Multi-Head Attention 层，结合自注意力机制对输入进行加权组合。接着应用了 Dropout (0.1) 以防止过拟合。最后，使用残差连接来构建输出。

接下来是 Feed Forward 部分，也经过归一化处理，然后通过一个全连接层，使用 ReLU 作为激活函数，再次应用 Dropout，最后再通过一个线性变换得到输出。

损失函数：均方误差 (MSE)

优化器：Adam

评估指标：平均绝对误差 (MAE)

变量：U100

数据量：[14464, 25, 61] (大约600天)

输入步长:输出步长 = 168:24

训练集:测试集:验证集 = 0.80:0.15:0.05

batch_size = 32; epochs = 5

Layer (type)	Output Shape	Param #	Connected to	
input_1 (InputLayer)	[(None, 24, 1525)]	0	[]	
layer_normalization (LayerNormalization)	(None, 24, 1525)	3050	['input_1[0][0]']	
multi_head_attention (MultiHeadAttention)	(None, 24, 1525)	6250997	['layer_normalization[0][0]', 'layer_normalization[0][0]']	
dropout (Dropout)	(None, 24, 1525)	0	['multi_head_attention[0][0]']	
tf.__operators__.add (TFOpLambda)	(None, 24, 1525)	0	['dropout[0][0]', 'input_1[0][0]']	
layer_normalization_1 (LayerNormalization)	(None, 24, 1525)	3050	['tf.__operators__.add[0][0]']	
dense (Dense)	(None, 24, 256)	390656	['layer_normalization_1[0][0]']	
dropout_1 (Dropout)	(None, 24, 256)	0	['dense[0][0]']	
dense_1 (Dense)	(None, 24, 1525)	391925	['dropout_1[0][0]']	
tf.__operators__.add_1 (TFOpLambda)	dense_4 (Dense)	(None, 24, 256)	390656	['layer_normalization_5[0][0]']
layer_normalization_2 (LayerNormalization)	dropout_5 (Dropout)	(None, 24, 256)	0	['dense_4[0][0]']
multi_head_attention_1 (MultiHeadAttention)	dense_5 (Dense)	(None, 24, 1525)	391925	['dropout_5[0][0]']
dropout_2 (Dropout)	tf.__operators__.add_5 (TFOpLambda)	(None, 24, 1525)	0	['dense_5[0][0]', 'tf.__operators__.add_4[0][0]']
tf.__operators__.add_2 (TFOpLambda)	layer_normalization_6 (LayerNormalization)	(None, 24, 1525)	3050	['tf.__operators__.add_5[0][0]']
layer_normalization_3 (LayerNormalization)	multi_head_attention_3 (MultiHeadAttention)	(None, 24, 1525)	6250997	['layer_normalization_6[0][0]', 'layer_normalization_6[0][0]']
dense_2 (Dense)	dropout_6 (Dropout)	(None, 24, 1525)	0	['multi_head_attention_3[0][0]']
dropout_3 (Dropout)	tf.__operators__.add_6 (TFOpLambda)	(None, 24, 1525)	0	['dropout_6[0][0]', 'tf.__operators__.add_5[0][0]']
dense_3 (Dense)	layer_normalization_7 (LayerNormalization)	(None, 24, 1525)	3050	['tf.__operators__.add_6[0][0]']
tf.__operators__.add_3 (TFOpLambda)	dense_6 (Dense)	(None, 24, 256)	390656	['layer_normalization_7[0][0]']
layer_normalization_4 (LayerNormalization)	dropout_7 (Dropout)	(None, 24, 256)	0	['dense_6[0][0]']
multi_head_attention_2 (MultiHeadAttention)	dense_7 (Dense)	(None, 24, 1525)	391925	['dropout_7[0][0]']
dropout_4 (Dropout)	tf.__operators__.add_7 (TFOpLambda)	(None, 24, 1525)	0	['dense_7[0][0]', 'tf.__operators__.add_6[0][0]']
tf.__operators__.add_4 (TFOpLambda)	layer_normalization_8 (LayerNormalization)	(None, 24, 1525)	3050	['tf.__operators__.add_7[0][0]']
layer_normalization_5 (LayerNormalization)	global_average_pooling1d (GlobalAveragePooling1D)	(None, 1525)	0	['layer_normalization_8[0][0]']
	dense_8 (Dense)	(None, 128)	195328	['global_average_pooling1d[0][0]']
	dropout_8 (Dropout)	(None, 128)	0	['dense_8[0][0]']
	dense_9 (Dense)	(None, 4575)	590175	['dropout_8[0][0]']
	tf.reshape (TFOPLambda)	(None, 3, 1525)	0	['dense_9[0][0]']

=====
Total params: 28,947,265
Trainable params: 28,947,265
Non-trainable params: 0

研究背景

研究内容

研究成果

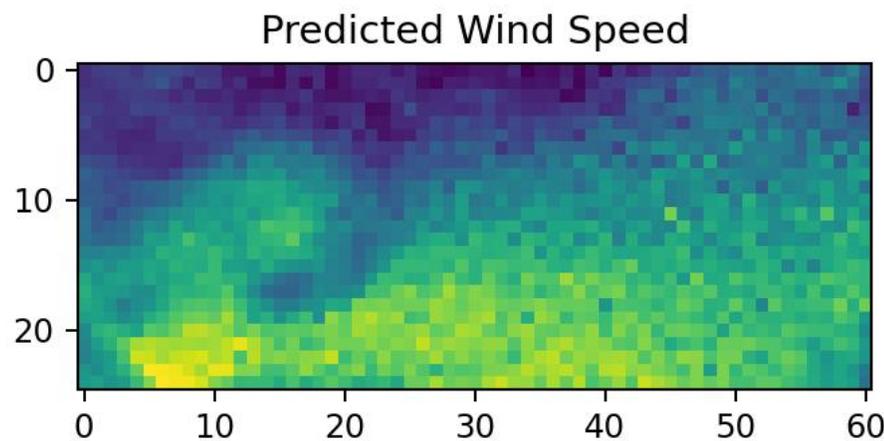
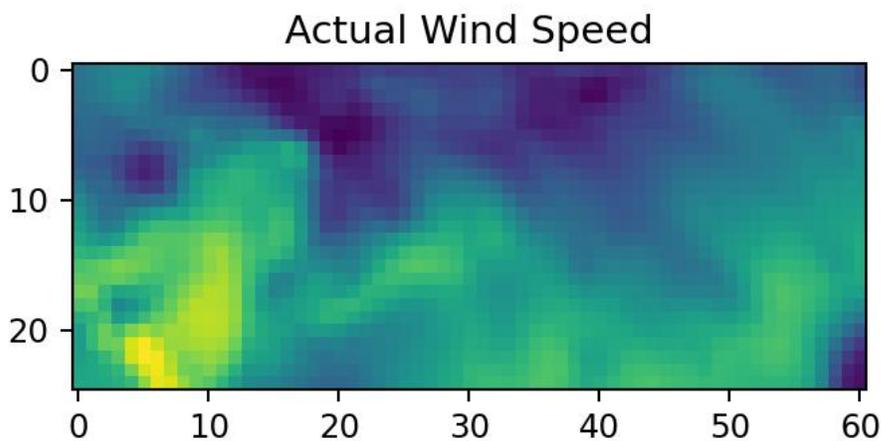
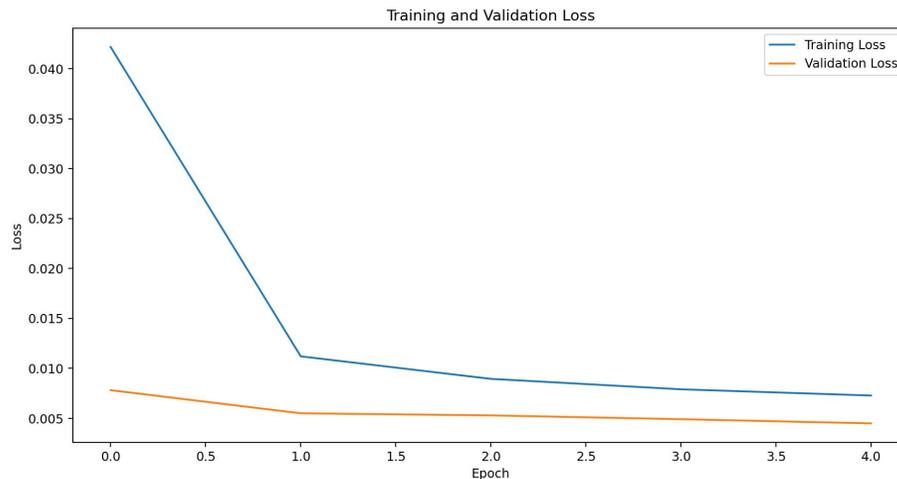


单变量区域二维模型结果

研究背景

研究内容

研究成果



输出第6个步长



研究站点: 阳江海上风电场 (模拟 **E112 N21**)

研究变量: 地表10米风 (U10、V10)、地表100米风 (U100、V100)、
平均波方向 (mwd)、平均波周期 (mwp)、显著波高 (swh)



研究背景

研究内容

研究成果



多变量单站模型预测

构建CNN+LSTM混合模型。模型首先包含一个卷积层 (Conv1D)，用于在时间维度上提取特征。这里使用了64个滤波器，每个滤波器的窗口大小为3，激活函数为ReLU。然后通过池化层 (MaxPooling1D) 进行下采样，以减少特征数量。接着是两个LSTM层，在LSTM层之后使用了一个Dropout (0.2) 层，以减少过拟合。最后是两个全连接层 (Dense)，其中第一个全连接层的激活函数为ReLU。

损失函数：均方误差 (MSE)

优化器：Adam

评估指标：平均绝对误差 (MAE)

变量：所有7个变量

数据量：[394464, 7, 25, 61] (45年)

输入步长:输出步长 = 168:168

训练集:测试集:验证集 = 0.80:0.15:0.05

batch_size = 64; epochs = 1

Layer (type)	Output Shape	Param #
conv1d_1 (Conv1D)	(None, 166, 64)	256
max_pooling1d_1 (MaxPooling1D)	(None, 83, 64)	0
lstm_16 (LSTM)	(None, 83, 100)	66000
lstm_17 (LSTM)	(None, 100)	80400
dropout_8 (Dropout)	(None, 100)	0
dense_8 (Dense)	(None, 100)	10100
dense_9 (Dense)	(None, 168)	16968

=====
Total params: 173,724
Trainable params: 173,724
Non-trainable params: 0

研究背景

研究内容

研究成果



多变量单站模型模拟结果

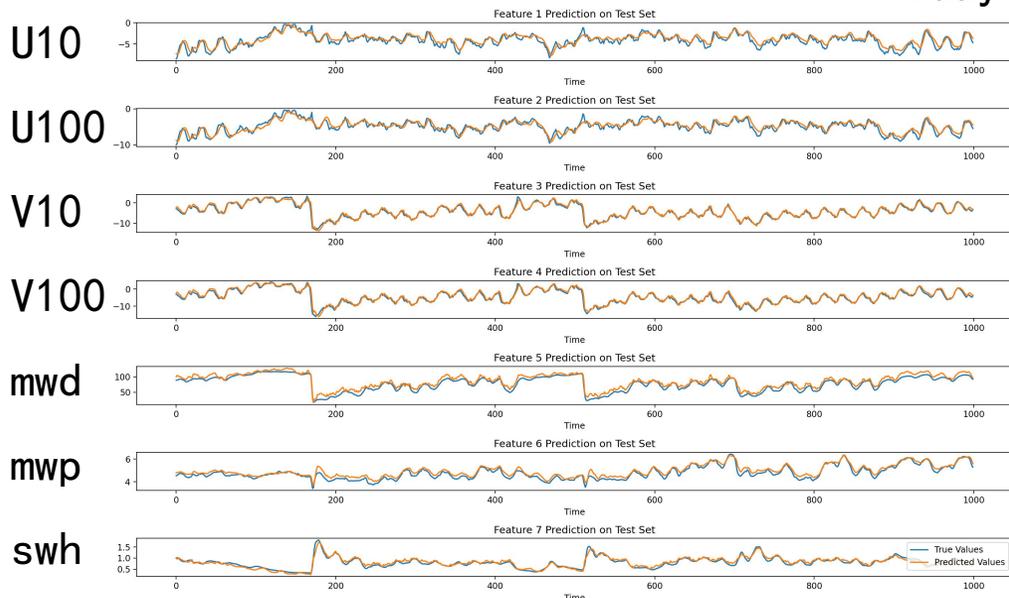
随机取1000个验证集预测四个时间点变化的结果

研究背景

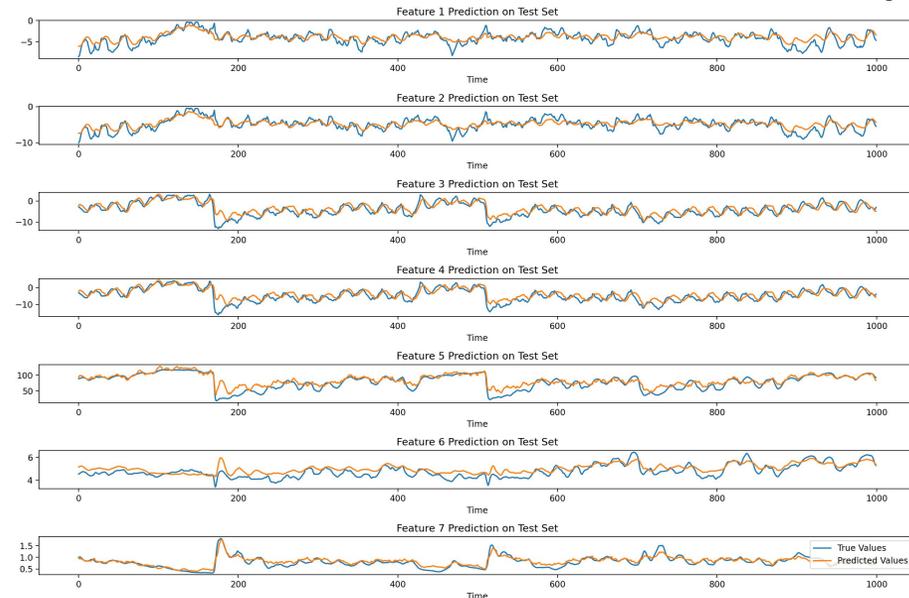
研究内容

研究成果

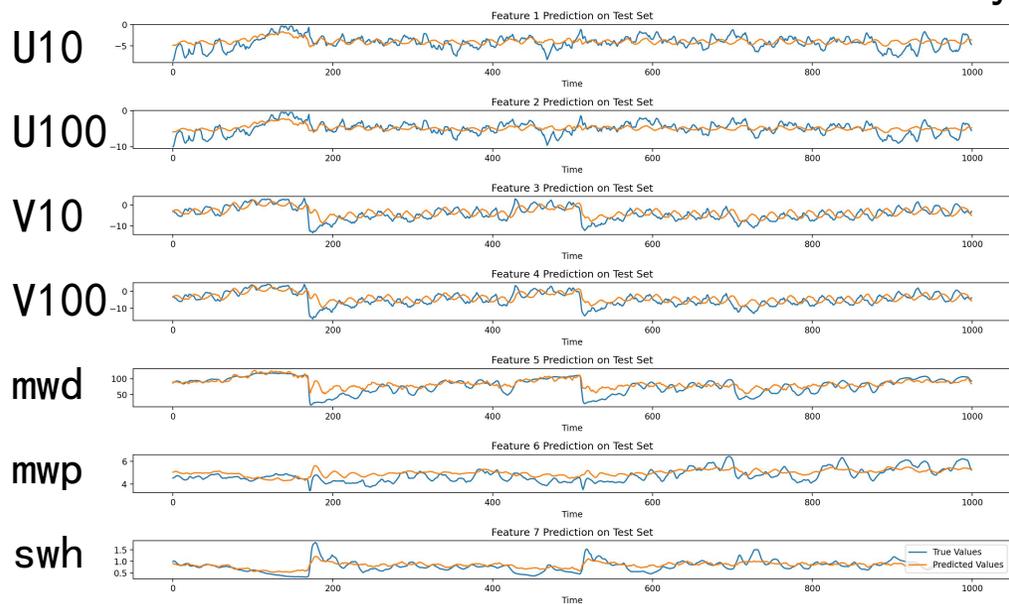
1day



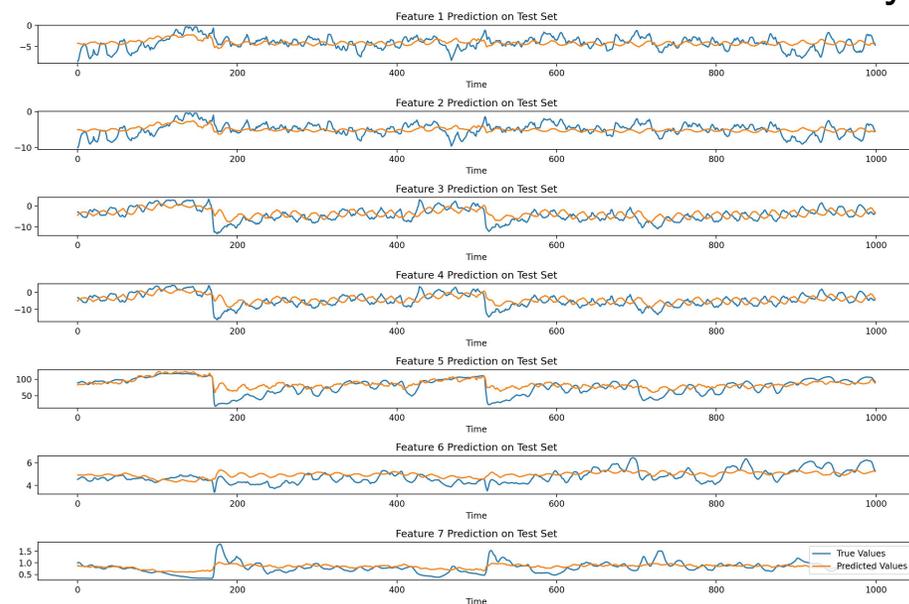
3day



5day

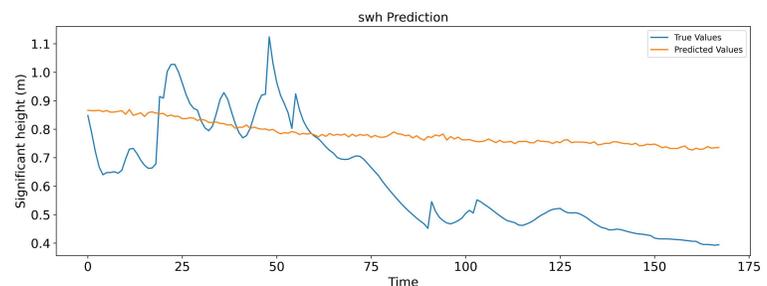
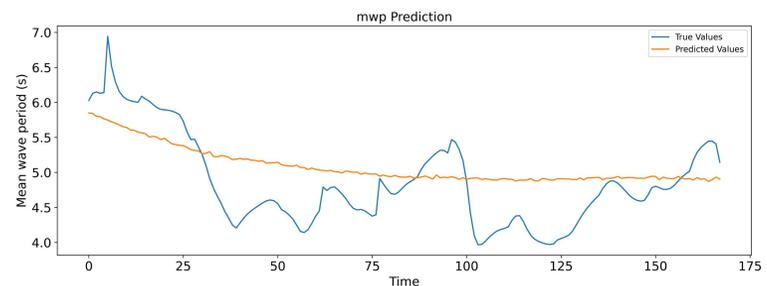
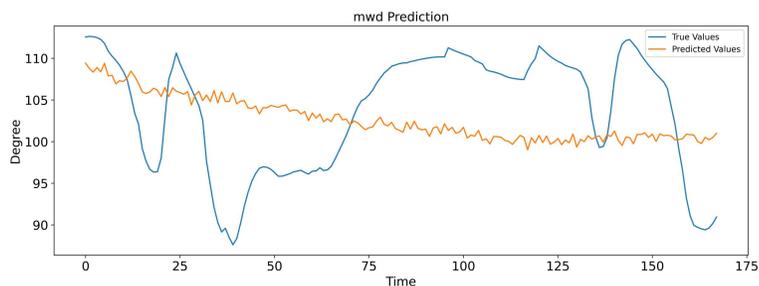
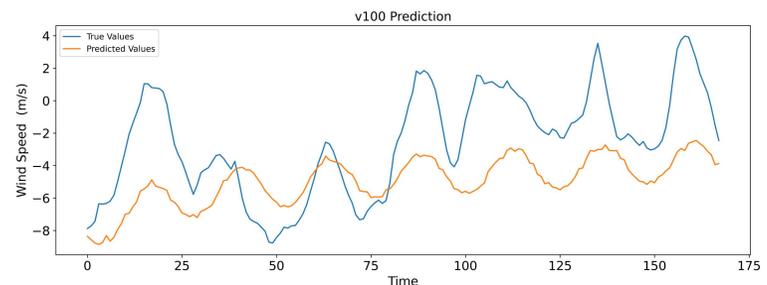
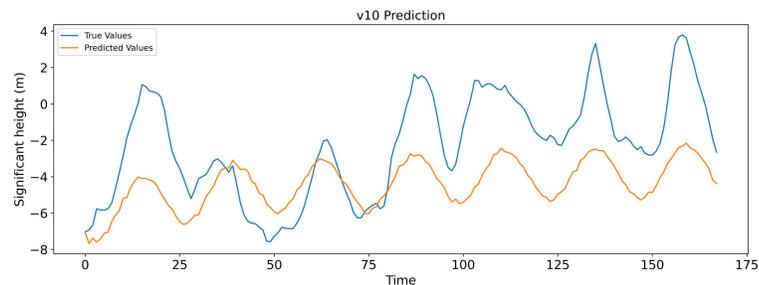
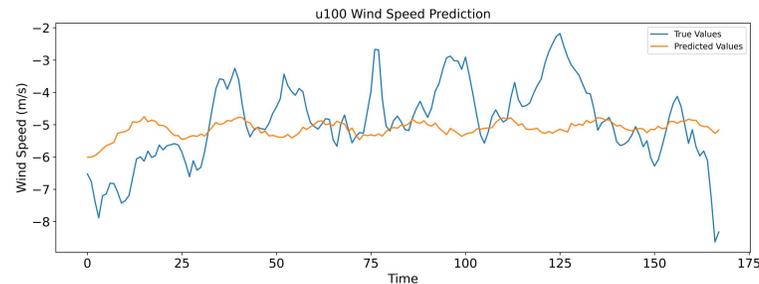
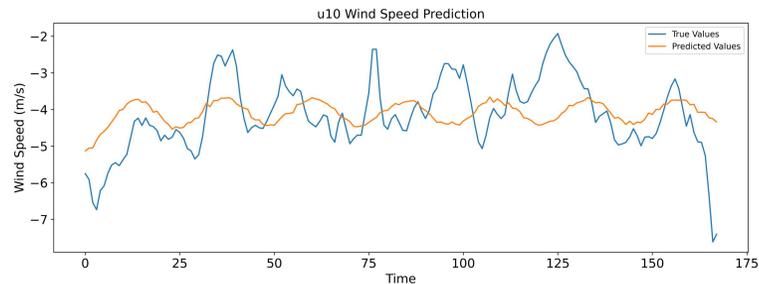


7day





多变量单站模型模拟结果



研究背景

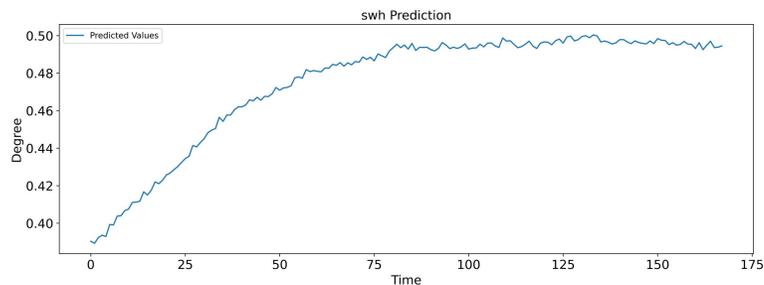
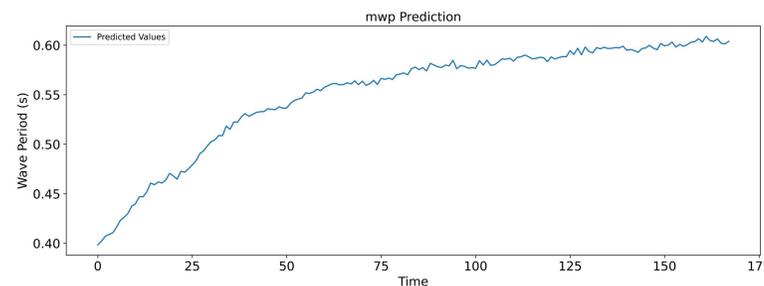
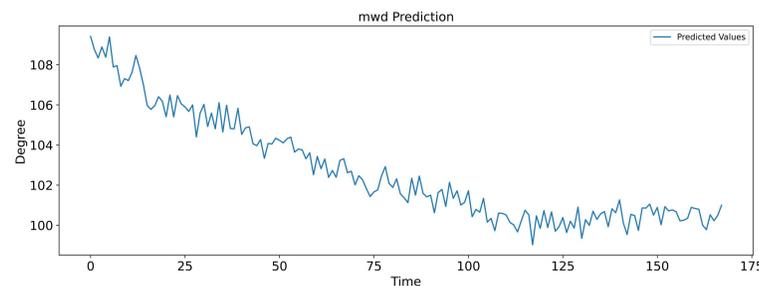
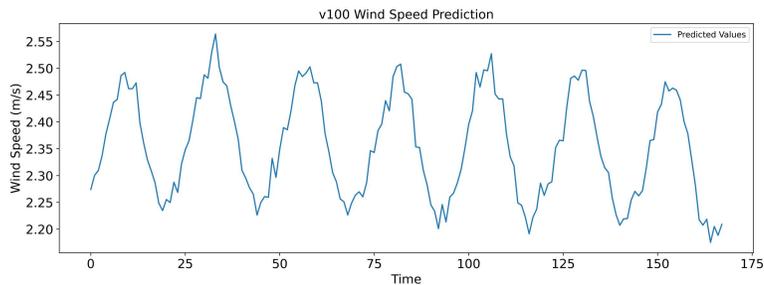
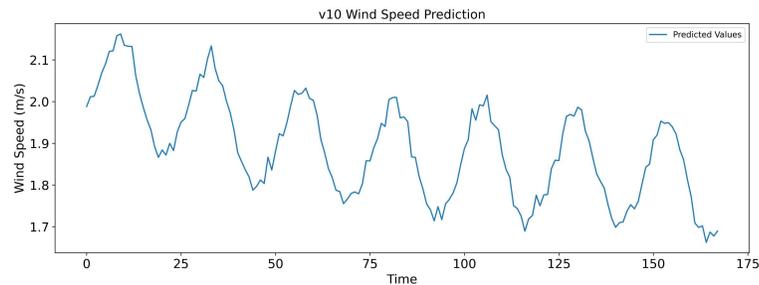
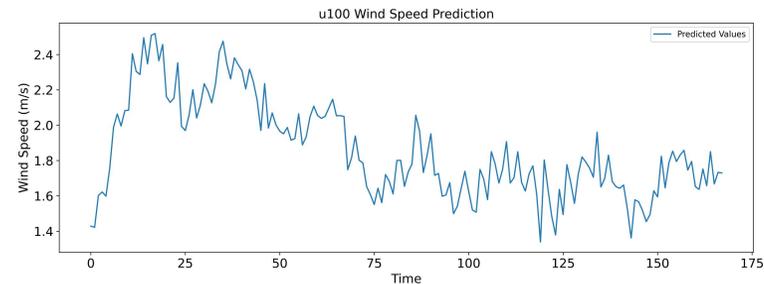
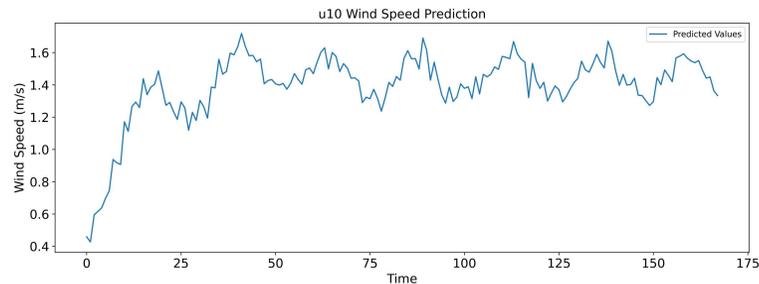
研究内容

研究成果

随机取一个验证集
预测168h变化结果



多变量单站模型预测结果



研究背景

研究内容

研究成果

2024年6月8日至6月14日

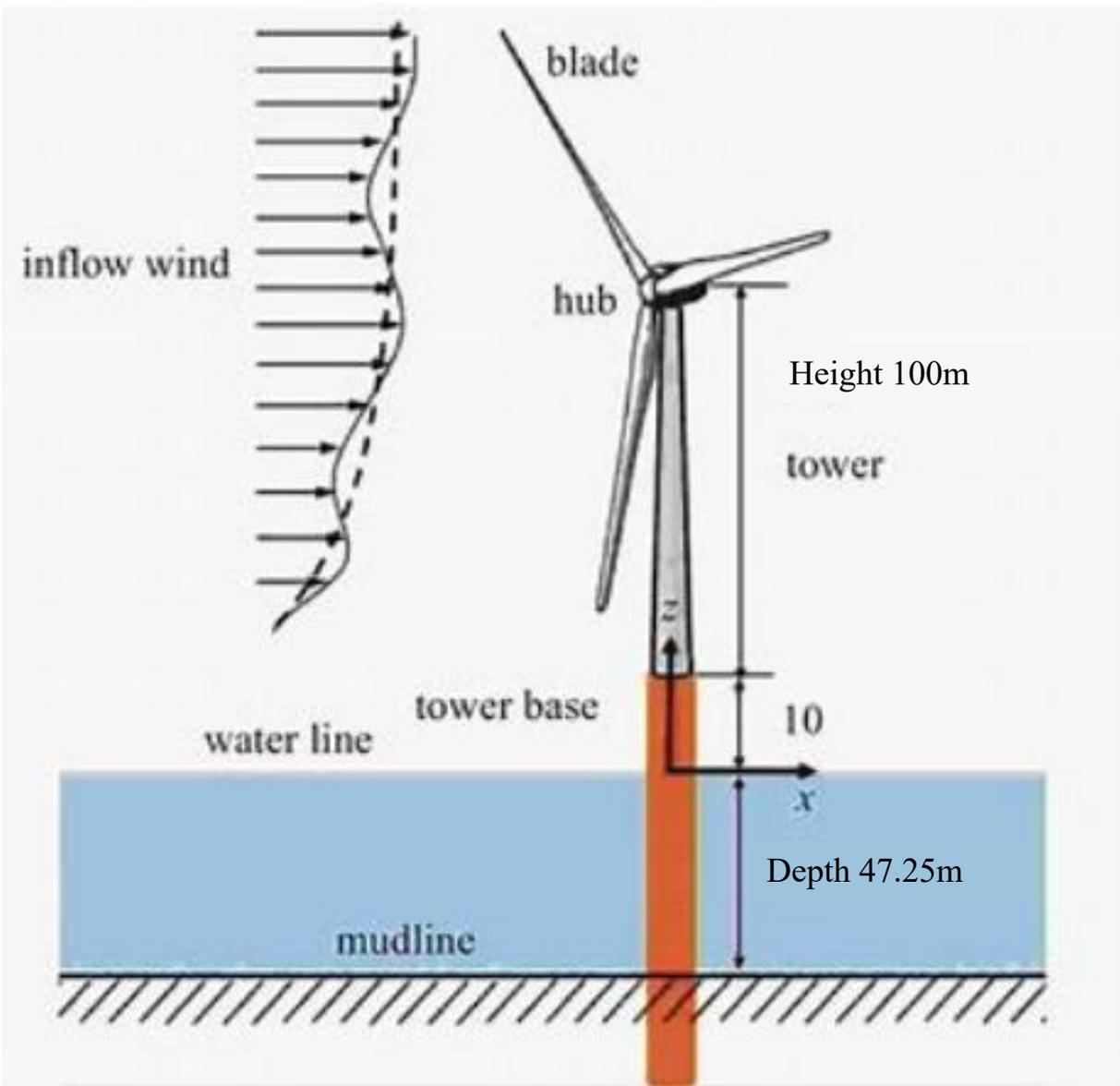


物理模型抽象

研究背景

研究内容

研究成果



海上风机模型工况简化图

- **创建网格节点** `np.linspace`
 - 物理量 `z_grid` `x_grid` `y_grid`
- **提取气象数据**
 - **已知节点数据**
 - Wind*4 10m和100m风速
 - Wave*3 周期、波高、角度
 - Current*2 10m流速
 - **未知节点插值**
 - 插值函数 `interp1d`
 - 插值赋值节点
- **定义荷载计算函数**
 - 风和流的荷载 $F = 0.5\rho_{air}C_dAV^2$
 - 浪荷载计算 $F = 0.5\rho_{water}D u |u|C_d$
- **存储数据 DataFrame**
 - 循环建立 DataFrame
 - 数据存储和呈现



波浪荷载求解模型

相对深度	极浅水波 $d/L < 1/25$ 或 $1/20$	浅水波 $1/20$ 或 $1/25 < d/L < 1/2$	深水波 $d/L > 1/2$
波高轮廓	$\eta = \frac{H}{2} \cos(kx - \omega t) = \frac{H}{2} \cos(\theta)$		
波速	$C = \frac{L}{T} = \sqrt{gd}$	$C = \frac{gT}{2\pi} \tanh kd$	$C = C_0 = \frac{L}{T} = \frac{gT}{2\pi}$
波长	$L = T \sqrt{gd} = CT$	$L = \frac{gT^2}{2\pi} \tanh kd$	$L = L_0 = \frac{gT^2}{2\pi} C_0 T$
波群速	$C_g = C \sqrt{gd}$	$C_g = \pi C = \frac{1}{2} \left[1 + \frac{4\pi d/L}{\sinh(4\pi d/L)} \right] C$	$C_g = \frac{C}{2} = \frac{gT}{4\pi}$
质点水平速度	$u = \frac{H}{2} \sqrt{\frac{g}{d}} \cos \theta$	$u = \frac{\pi H \cosh k(d+z)}{T \sinh kd} \cos \theta$	$u = \frac{\pi H}{T} e^{kz} \cos \theta$
质点垂向速度	$w = \frac{\pi H}{T} \left(1 + \frac{z}{d} \right) \sin \theta$	$w = \frac{\pi H \sinh k(d+z)}{T \sinh kd} \sin \theta$	$w = \frac{\pi H}{T} e^{kz} \sin \theta$
质点水平加速度	$a_x = \frac{\pi H}{T} \left(\sqrt{\frac{g}{d}} \right) \sin \theta$	$a_x = \frac{2\pi^2 H \cosh k(d+z)}{T^2 \sinh kd} \sin \theta$	$a_x = 2H \left(\frac{\pi}{T} \right)^2 e^{kz} \sin \theta$
质点垂向加速度	$a_z = -\frac{2H\pi^2}{T^2} \left(1 + \frac{z}{d} \right) \cos \theta$	$a_z = -\frac{2\pi^2 H \sinh k(d+z)}{T^2 \sinh kd} \cos \theta$	$a_z = -2H \left(\frac{\pi}{T} \right)^2 e^{kz} \cos \theta$
质点水平位移	$\xi = -\frac{HT}{4\pi} \sqrt{\frac{g}{d}} \sin \theta$	$\xi = -\frac{H \cosh k(d+z)}{2 \sinh kd} \sin \theta$	$\xi = -\frac{H}{2} e^{kz} \sin \theta$
质点垂向位移	$\epsilon = \frac{H}{2} \left(1 + \frac{z}{d} \right) \cos \theta$	$\epsilon = \frac{H \sinh k(d+z)}{2 \sinh kd} \cos \theta$	$\epsilon = \frac{H}{2} e^{kz} \cos \theta$
压强	$p = \rho g(h - z)$	$p = -\rho g z + \frac{\rho g H \cosh k(d+z)}{2 \cosh kd} \cos \theta$	$p = \rho g \eta e^{kz} - \rho g z$

研究背景

研究内容

研究成果

- 小尺度结构的波浪力计算
- Morrison 公式
- 将作用在细长柱体单位长度上的波浪力分解为

$$f = \frac{\rho D}{2} u |u| C_D + \rho \frac{\pi D^2}{4} \dot{u} C_M$$

- 水流速度来自波浪理论
- C_d 和 C_m 称为阻力系数和附加水质量系数，来自工程经验



荷载计算技术路线图

输入
结构和环境的基础信息
智能预测的气象数据

网格划分
纵向节点: 1000 个 | 三维-二维抽象 z_grid

单元数据读取
已知节点数据: 按index属性 | 未知节点: 线性插值

各个单元荷载
分荷载计算原理 | 各单元荷载求解

耦合及可视化
u v方向矢量相加 | DataFrame

输出
荷载计算文件
可视化计算结果

离散化

模型化

智能化

可视化

对应课程板块

研究背景

研究内容

研究成果

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time Index -47.25m 02602602455205205f78078078041041043013013065615615618218218270820820823423423460260260862862861231231233
0 0.005957 0.009379 0.005666 0.005023 0.004057 0.002803 0.001469 0.001671 0.003725 0.006342 0.009343 0.0127 0.016403 0.020811 0.025366 0.030031 0.034796 0.039561 0.044326 0.049091 0.053856 0.058621 0.063386 0.068151 0.072916 0.077681 0.082446 0.087211 0.091976 0.096741 0.101506 0.106271 0.111036 0.115801 0.120566 0.125331 0.130096 0.134861 0.139626 0.144391 0.149156 0.153921 0.158686 0.163451 0.168216 0.172981 0.177746 0.182511 0.187276 0.192041 0.196806 0.201571 0.206336 0.211101 0.215866 0.220631 0.225396 0.230161 0.234926 0.239691 0.244456 0.249221 0.253986 0.258751 0.263516 0.268281 0.273046 0.277811 0.282576 0.287341 0.292106 0.296871 0.301636 0.306401 0.311166 0.315931 0.320696 0.325461 0.330226 0.334991 0.339756 0.344521 0.349286 0.354051 0.358816 0.363581 0.368346 0.373111 0.377876 0.382641 0.387406 0.392171 0.396936 0.401701 0.406466 0.411231 0.415996 0.420761 0.425526 0.430291 0.435056 0.439821 0.444586 0.449351 0.454116 0.458881 0.463646 0.468411 0.473176 0.477941 0.482706 0.487471 0.492236 0.497001 0.501766 0.506531 0.511296 0.516061 0.520826 0.525591 0.530356 0.535121 0.539886 0.544651 0.549416 0.554181 0.558946 0.563711 0.568476 0.573241 0.578006 0.582771 0.587536 0.592301 0.597066 0.601831 0.606596 0.611361 0.616126 0.620891 0.625656 0.630421 0.635186 0.639951 0.644716 0.649481 0.654246 0.659011 0.663776 0.668541 0.673306 0.678071 0.682836 0.687601 0.692366 0.697131 0.701896 0.706661 0.711426 0.716191 0.720956 0.725721 0.730486 0.735251 0.740016 0.744781 0.749546 0.754311 0.759076 0.763841 0.768606 0.773371 0.778136 0.782901 0.787666 0.792431 0.797196 0.801961 0.806726 0.811491 0.816256 0.821021 0.825786 0.830551 0.835316 0.840081 0.844846 0.849611 0.854376 0.859141 0.863906 0.868671 0.873436 0.878201 0.882966 0.887731 0.892496 0.897261 0.902026 0.906791 0.911556 0.916321 0.921086 0.925851 0.930616 0.935381 0.940146 0.944911 0.949676 0.954441 0.959206 0.963971 0.968736 0.973501 0.978266 0.983031 0.987796 0.992561 0.997326 1.002091 1.006856 1.011621 1.016386 1.021151 1.025916 1.030681 1.035446 1.040211 1.044976 1.049741 1.054506 1.059271 1.064036 1.068801 1.073566 1.078331 1.083096 1.087861 1.092626 1.097391 1.102156 1.106921 1.111686 1.116451 1.121216 1.125981 1.130746 1.135511 1.140276 1.145041 1.149806 1.154571 1.159336 1.164101 1.168866 1.173631 1.178396 1.183161 1.187926 1.192691 1.197456 1.202221 1.206986 1.211751 1.216516 1.221281 1.226046 1.230811 1.235576 1.240341 1.245106 1.249871 1.254636 1.259401 1.264166 1.268931 1.273696 1.278461 1.283226 1.287991 1.292756 1.297521 1.302286 1.307051 1.311816 1.316581 1.321346 1.326111 1.330876 1.335641 1.340406 1.345171 1.349936 1.354701 1.359466 1.364231 1.369001 1.373766 1.378531 1.383296 1.388061 1.392826 1.397591 1.402356 1.407121 1.411886 1.416651 1.421416 1.426181 1.430946 1.435711 1.440476 1.445241 1.450006 1.454771 1.459536 1.464301 1.469066 1.473831 1.478596 1.483361 1.488126 1.492891 1.497656 1.502421 1.507186 1.511951 1.516716 1.521481 1.526246 1.531011 1.535776 1.540541 1.545306 1.550071 1.554836 1.559601 1.564366 1.569131 1.573896 1.578661 1.583426 1.588191 1.592956 1.597721 1.602486 1.607251 1.612016 1.616781 1.621546 1.626311 1.631076 1.635841 1.640606 1.645371 1.650136 1.654901 1.659666 1.664431 1.669196 1.673961 1.678726 1.683491 1.688256 1.693021 1.697786 1.702551 1.707316 1.712081 1.716846 1.721611 1.726376 1.731141 1.735906 1.740671 1.745436 1.750201 1.754966 1.759731 1.764496 1.769261 1.774026 1.778791 1.783556 1.788321 1.793086 1.797851 1.802616 1.807381 1.812146 1.816911 1.821676 1.826441 1.831206 1.835971 1.840736 1.845501 1.850266 1.855031 1.859796 1.864561 1.869326 1.874091 1.878856 1.883621 1.888386 1.893151 1.897916 1.902681 1.907446 1.912211 1.916976 1.921741 1.926506 1.931271 1.936036 1.940801 1.945566 1.950331 1.955096 1.959861 1.964626 1.969391 1.974156 1.978921 1.983686 1.988451 1.993216 1.997981 2.002746 2.007511 2.012276 2.017041 2.021806 2.026571 2.031336 2.036101 2.040866 2.045631 2.050396 2.055161 2.059926 2.064691 2.069456 2.074221 2.078986 2.083751 2.088516 2.093281 2.098046 2.102811 2.107576 2.112341 2.117106 2.121871 2.126636 2.131401 2.136166 2.140931 2.145696 2.150461 2.155226 2.160001 2.164766 2.169531 2.174296 2.179061 2.183826 2.188591 2.193356 2.198121 2.202886 2.207651 2.212416 2.217181 2.221946 2.226711 2.231476 2.236241 2.241006 2.245771 2.250536 2.255301 2.260066 2.264831 2.269596 2.274361 2.279126 2.283891 2.288656 2.293421 2.298186 2.302951 2.307716 2.312481 2.317246 2.322011 2.326776 2.331541 2.336306 2.341071 2.345836 2.350601 2.355366 2.360131 2.364896 2.369661 2.374426 2.379191 2.383956 2.388721 2.393486 2.398251 2.403016 2.407781 2.412546 2.417311 2.422076 2.426841 2.431606 2.436371 2.441136 2.445901 2.450666 2.455431 2.460196 2.464961 2.469726 2.474491 2.479256 2.484021 2.488786 2.493551 2.498316 2.503081 2.507846 2.512611 2.517376 2.522141 2.526906 2.531671 2.536436 2.541201 2.545966 2.550731 2.555496 2.560261 2.565026 2.569791 2.574556 2.579321 2.584086 2.588851 2.593616 2.598381 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清华大学
Tsinghua University

03 研究成果

Research Result

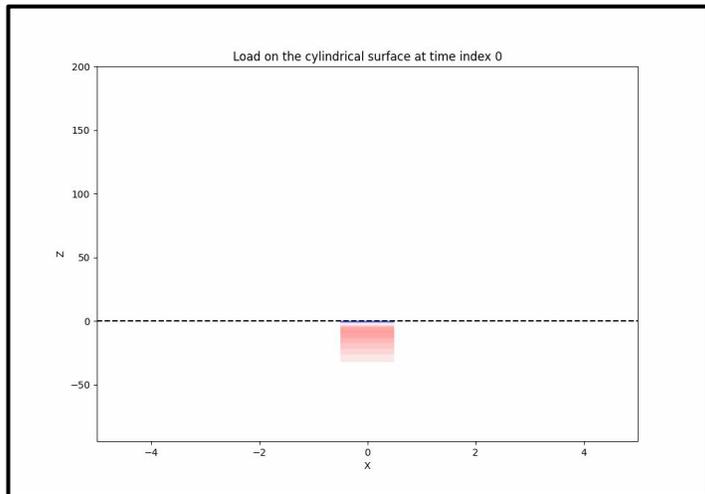


荷载计算结果展示

研究背景

研究内容

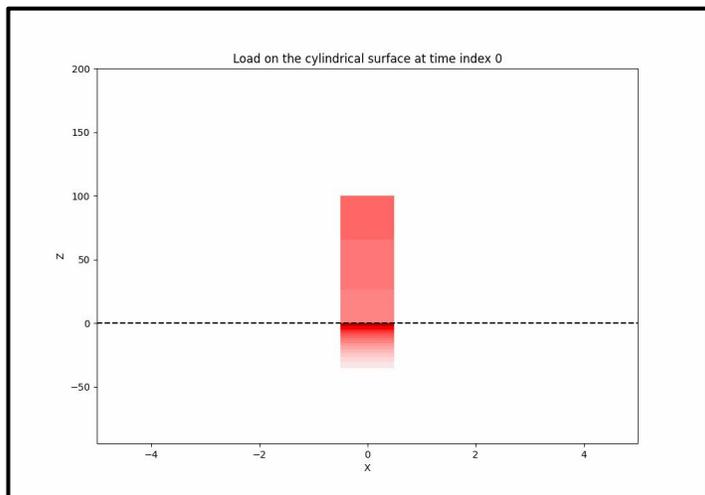
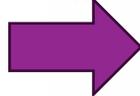
研究成果



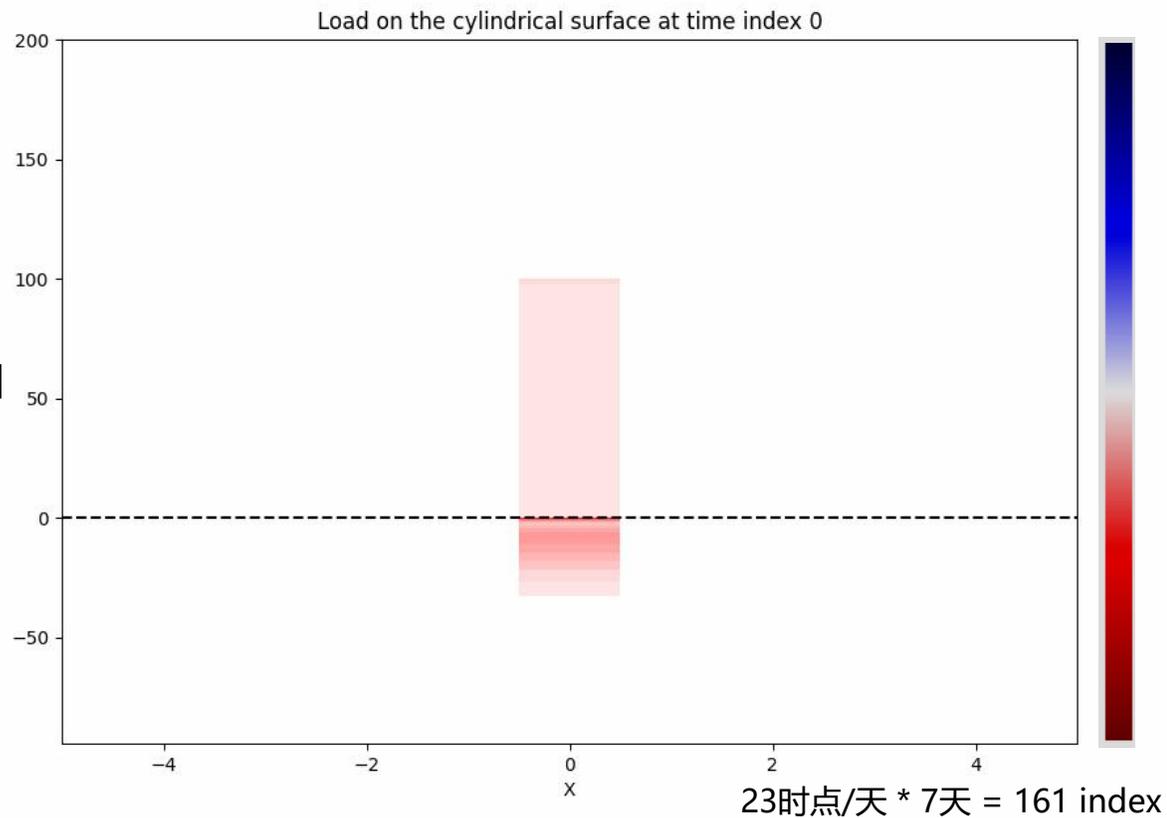
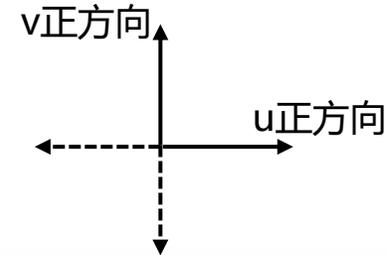
风浪流在u方向的分布耦合力(N/m)



矢量相加



风浪流在v方向的分布耦合力(N/m)



风浪流沿柱高的分布耦合力(N/m)



清华大学

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谢谢聆听~

名字	分工情况
冯伟杰	各类气象的变量预测
郭金霄	海洋风机的荷载求解