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Simulation of Flow Fields in Complex Terrain with RMAPS-LES Prediction System

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February 2024

Overview

1. Backgrounds and motivations
2. Overview of Model Setup
3. Analysis and verification of model results
4. Summary and ongoing work

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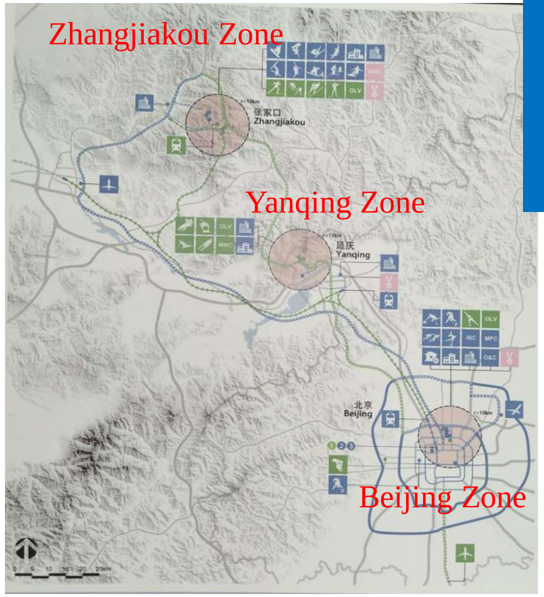
1. Background

Complex terrain
Large elevation drop

Alpine Skiing field



Bobsleigh/ Skeleton/Luge field

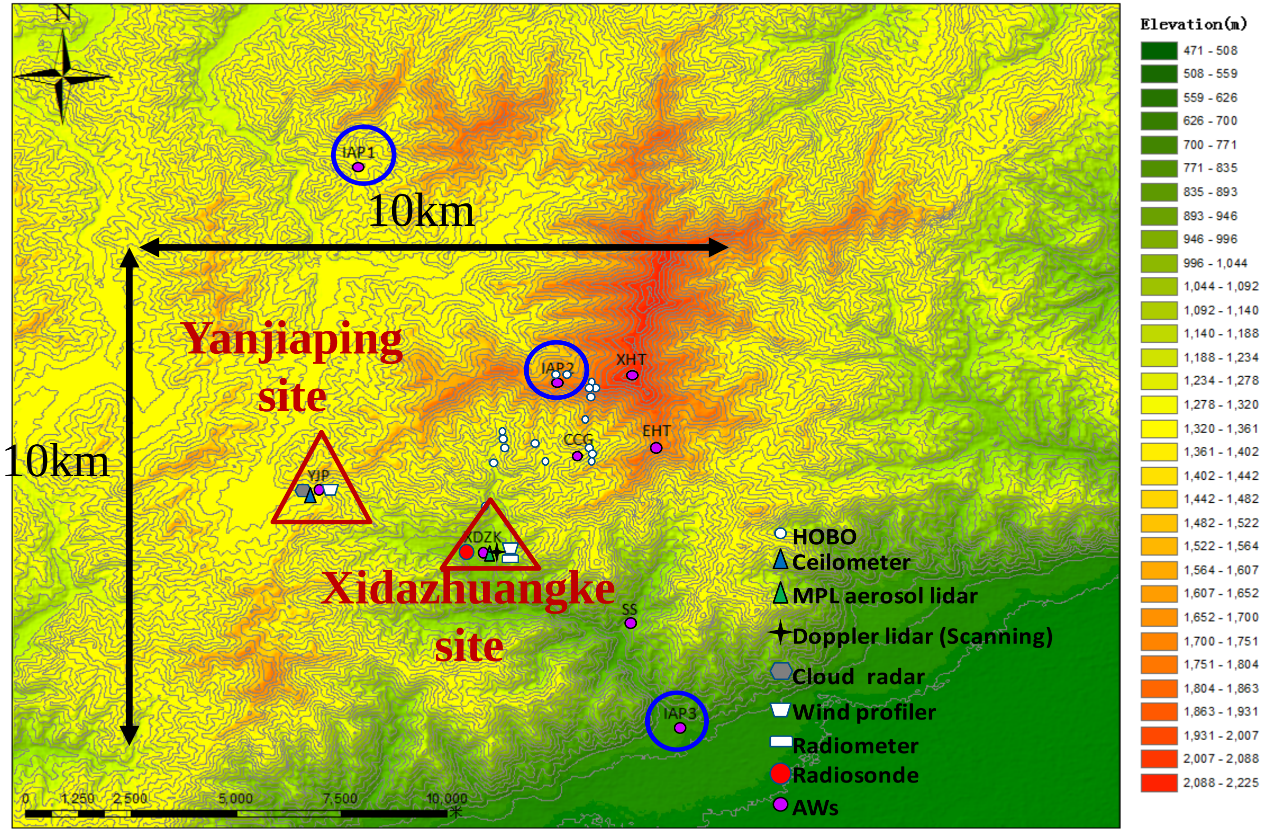
(1) The Olympic Cities

A total of 26 competition and non-competition venues were utilized during the 2022 Olympic and Paralympic Winter Games.

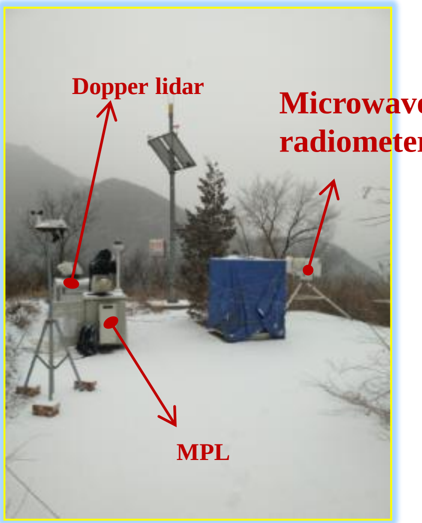
- **Zhangjiakou Zone**
  - Freestyle Skiing, Snowboard, Ski Jumping ; Biathlon, Nordic Combined, Cross-Country Skiing
- **Yanqing Zone**
  - Alpine Skiing, Bobsleigh / Skeleton and Luge
- **Beijing Zone**
  - Curling, Ice Hockey and Skating, big air

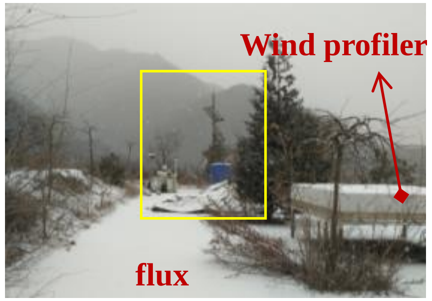
1. Background

- The near-surface wind field over complex terrain exhibits significant non-uniformity, primarily owing to the impact of topographical variations. Hence, conducting high-density observational experiments in these regions poses considerable challenges. Additionally, the representativeness of single-point observation is inherently limited. Due to the opportunity of the Winter Olympic Games, we conducted a winter field campaign in the Xiaohaituo mountain area within the Yanqing zone.



These observational data provide a good foundation for model assessment





- 14 AWSs
- 24 HOBOs(temperature and humidity observations)
- 2 suppersites
- Enhanced radio soundings, launched ever 3-h & over 7 days at Xidazhuangke suppersite.

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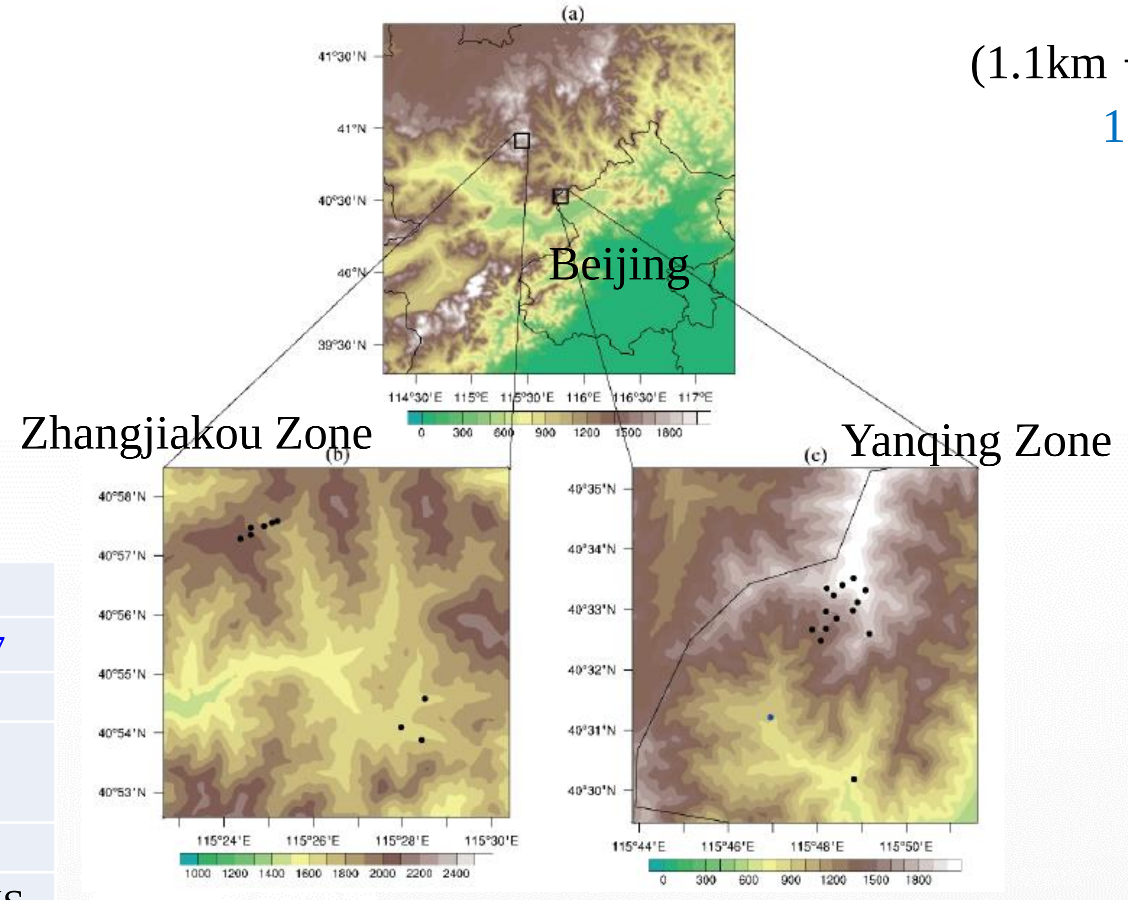
1. Overview of Model Setup

- **Model name: RMAPS-LES**
- **WRF version: WRF 3.9.1.1**
- **Geographic data: SRTM-1, 30m resolution**
- **Land use data：Globeland_30, 30m resolution**

	d01	d02	d03	d04
R&D Resolution (km)	1	0.333	0.111	0.037
Time step (s)	5	1	1/5	1/25
Operational forecast Resolution (km)	1.1	0.1		
Time step (s)	6	0.3		
Surface	MODIS	MODIS	MODIS	MODIS
Cumulus physics	0			
Longwave radiation	rrtmg scheme			
Shortwave radiation	rrtmg scheme			
Urban physics	BEP			
Microphysics	Thompson scheme			
PBL schemes	YSU/SH			
LES sub-stress model	**0**	**TKE 1.5**		
Surface-layer physics	Revised MM5 Monin-Obukhov scheme			
Land-surface physics	Noah-MP land-surface model			

(1.1km ⟶ 100m)
1:11

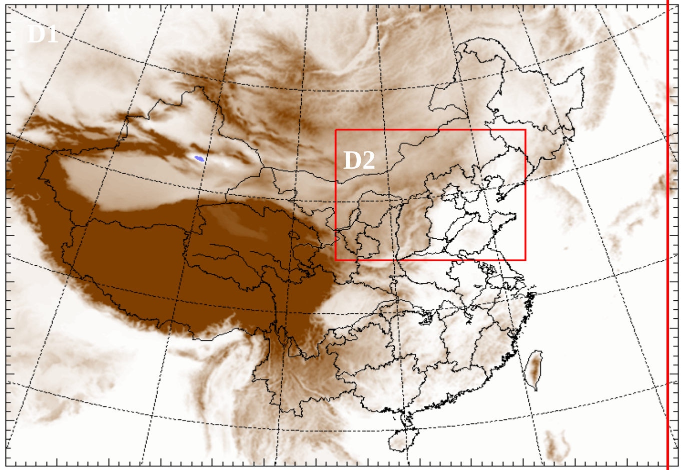


vertical levels: 82(Research), 37(Operation)

- P_top： 50hPa
- The resolution of the mid-low layer is improved
- Surface：0-20m
- Boundary layer: 18.5-206m
- Upper atmosphere: 214-508m

Rapid-refresh Multi-scale Analysis & Prediction System (RMAPS)_ST（Short Term）（CMA-BJ）R&D

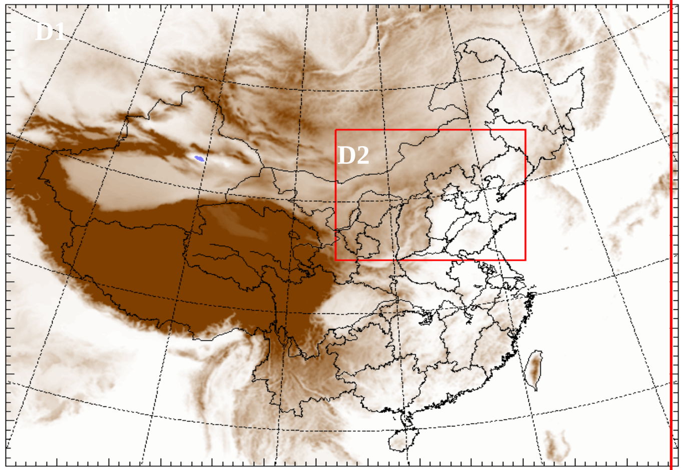
2017-2021



- **RMAPS-STv1.0**

D1：9km，649×500
D2：3km，550×424
Vertical layer: 51
Update frequency: 3-hour
The system got the operation approval by Department of Forecasting, CMA in 2017

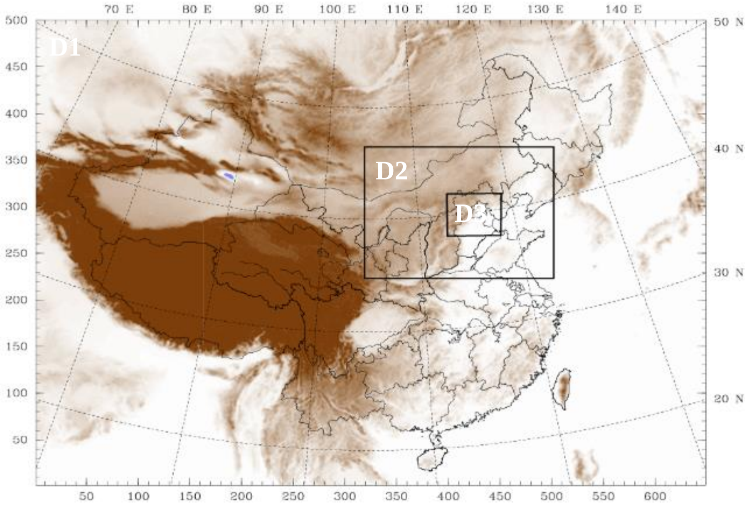
2020-2023



- **RMAPS-STv2.0**

D1：9km，649×500
D2：3km，550×424
Vertical layer: 59
Update frequency: 1-hour
The system got the operation approval by Department of Forecasting, CMA in June 2021

2021-



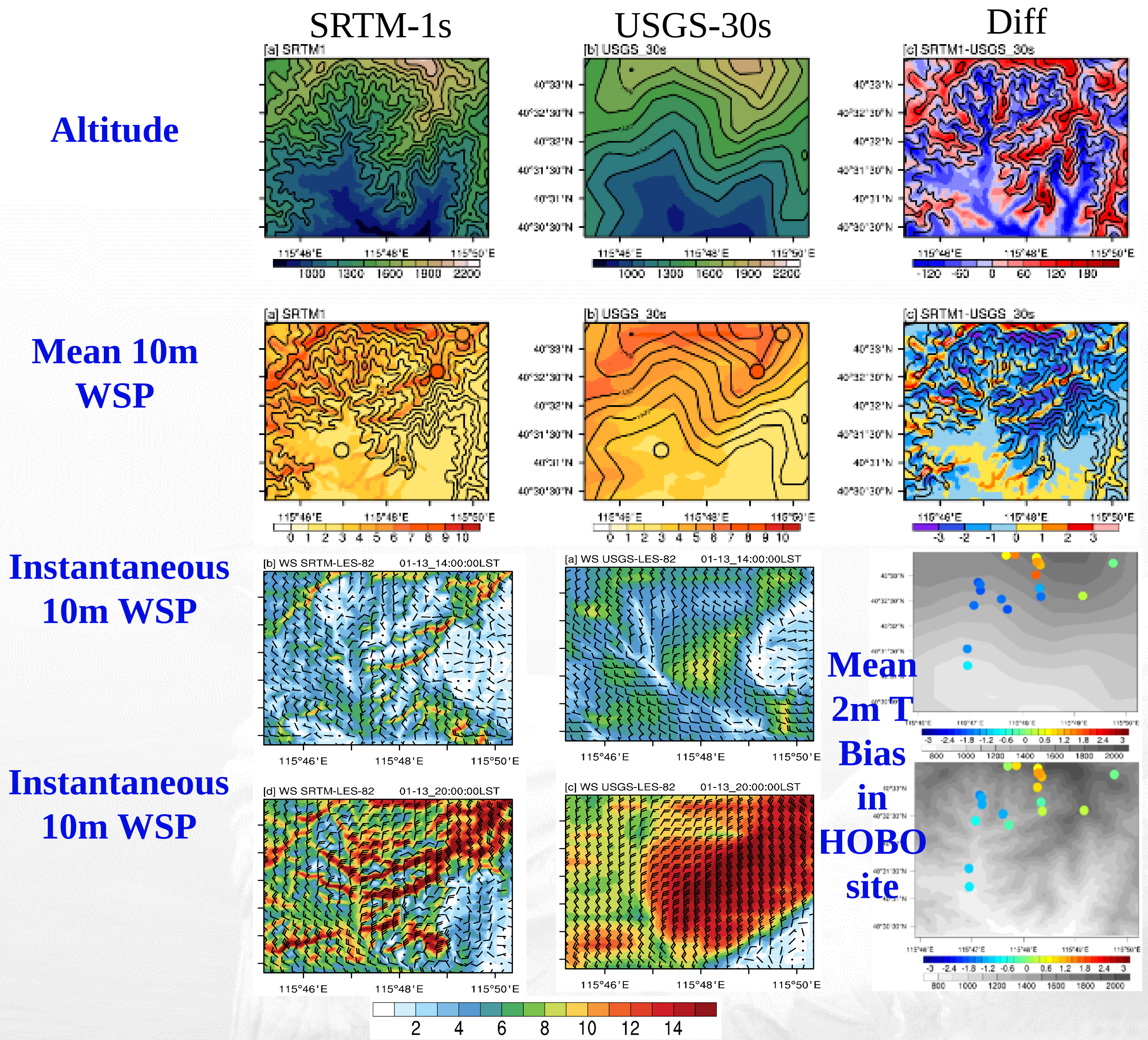
- **RMAPS-STv3.0**

D1：3km，1498×1945
Vertical layer: 61
D2 and D3 are not in yet
The system completed technical integration and ran in real time in May 2023;
Apply for the operation permit in November 2023

- **High resolution 3km in D1**
- **Inherit all the technologies of RMAPS-STv2.0**
- **8 new updates**
- **The computing demand increases significantly**

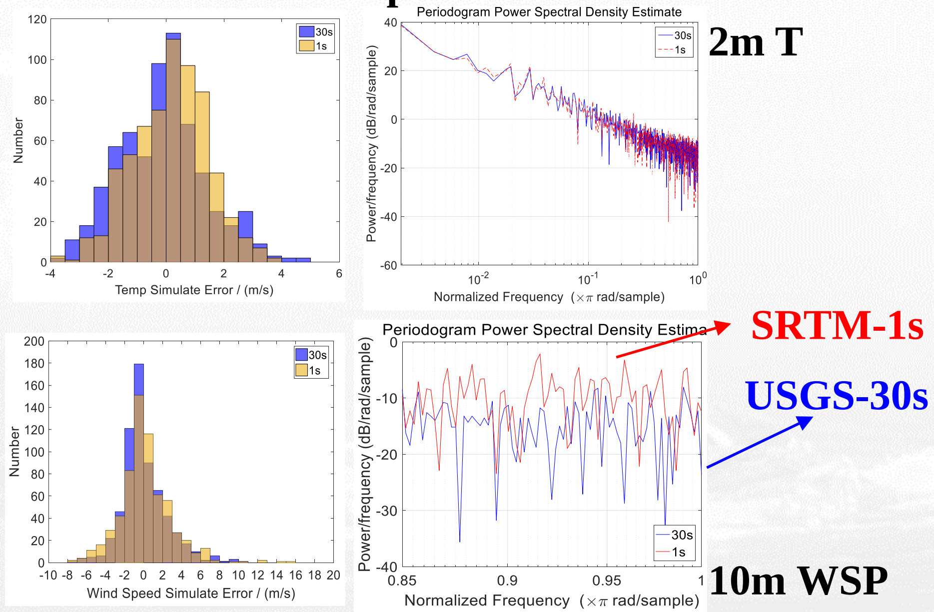
The initial and boundary conditions for the RMAPS-LES was derived from the forecast field of RMAPS-ST version.2 domain 2 which is a mesoscale area model(3km*3km) for short time. The RMAPS-ST assimilates several observational data including surface observation data, sounding data, AWS data, aircraft data, water data over Beijing, and radar wind and reflectivity data collected by 29 Doppler weather radars.

1. Overview of Model Setup: topography sensitivity experiment for d04 (37m)



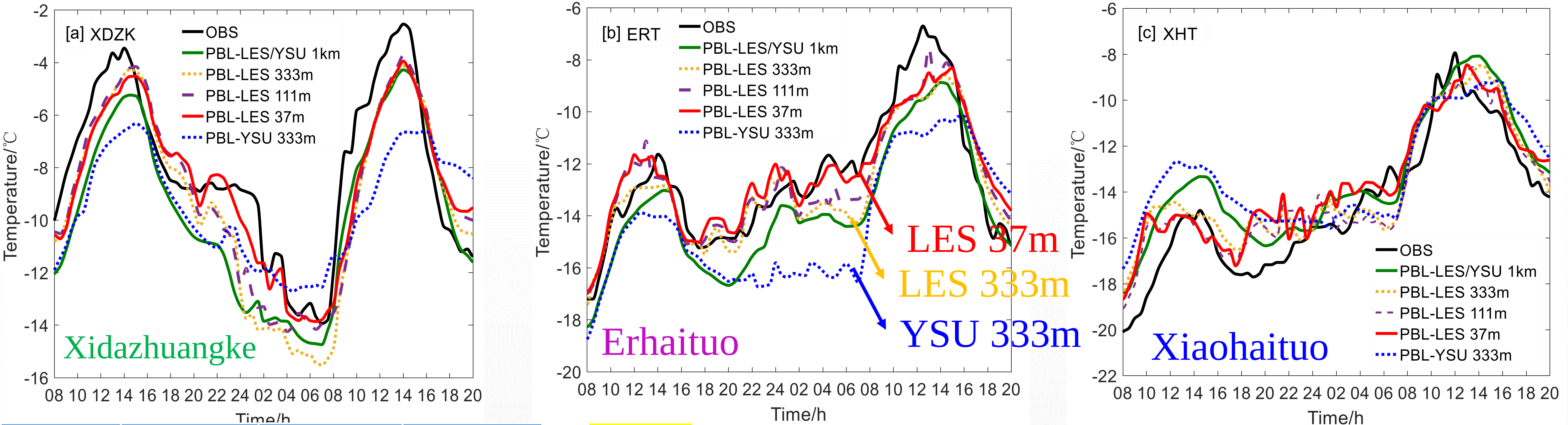
- Compared with the default 1km coarse resolution topo data USGS, high-resolution topo can reduce the systematic error of WRF that wind speed is overestimated at valley or plains and underestimated at hills.
- High-resolution topo can increase the TKE of wind speed, especially in the high-frequency region.
- High-resolution topo can effectively improve the simulation effect of surface wind and temperature.

Power spectrum



Liu et al., 2018,37(5), Plateau Meteorology (in Chinese)

1. Overview of Model Setup: topography and PBL treatments sensitivity experiment



	XDZK	EHT	XHT
LES 1km	RMSE=2.0 BIAS=-1.6	RMSE=1.5 BIAS=-1.2	RMSE=1.6 BIAS=1.2
LES 333m	RMSE=1.9 BIAS=-1.2	RMSE=1.1 BIAS=-0.5	RMSE=1.5 BIAS=0.8
LES 111m	RMSE=1.7 BIAS=-0.8	RMSE=1.1 BIAS=-0.2	RMSE=1.3 BIAS=0.6
LES 37m	RMSE=1.3 BIAS=-0.5	RMSE=0.9 BIAS=0.1	RMSE=1.3 BIAS=0.5
YSU 333m	RMSE=2.5 BIAS=-1.5	RMSE=2.5 BIAS=-2.0	RMSE=2.1 BIAS=1.4

LES 37m are the lowest, indicating the best performance.

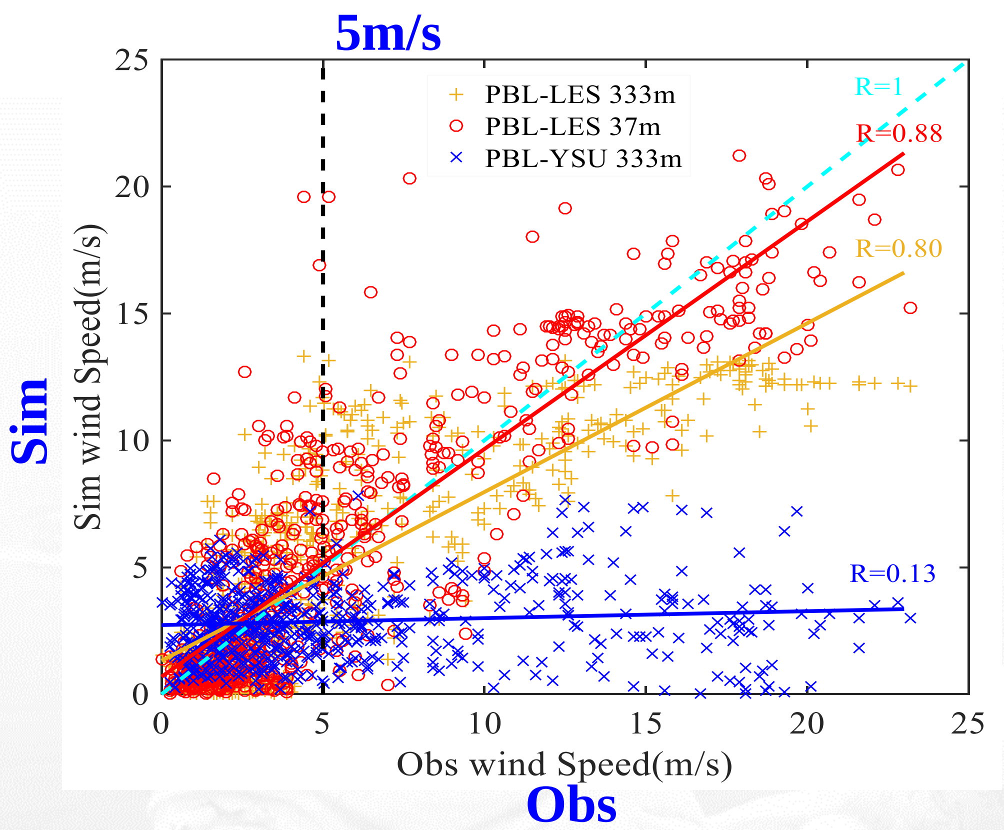
T_{2m}

1. YSU and LES reasonably captured diurnal cycle.
2. For the same resolution 333m：LES 333m exhibits better performance than YSU 333m — especially the Maximum and Minimum temperature.
3. For LES：higher resolution exhibits better accuracy.

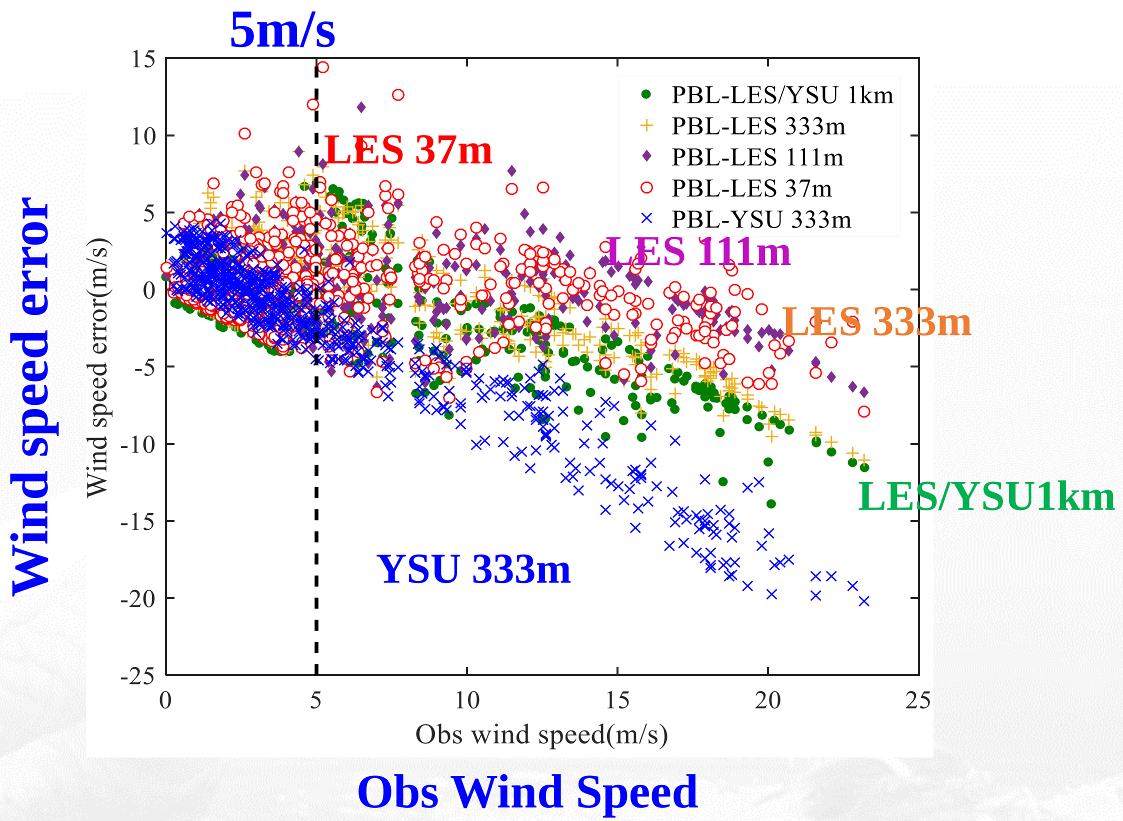
1. Overview of Model Setup: topography and PBL treatments sensitivity experiment

WSP_{10m}

Wind speed Scatter plot



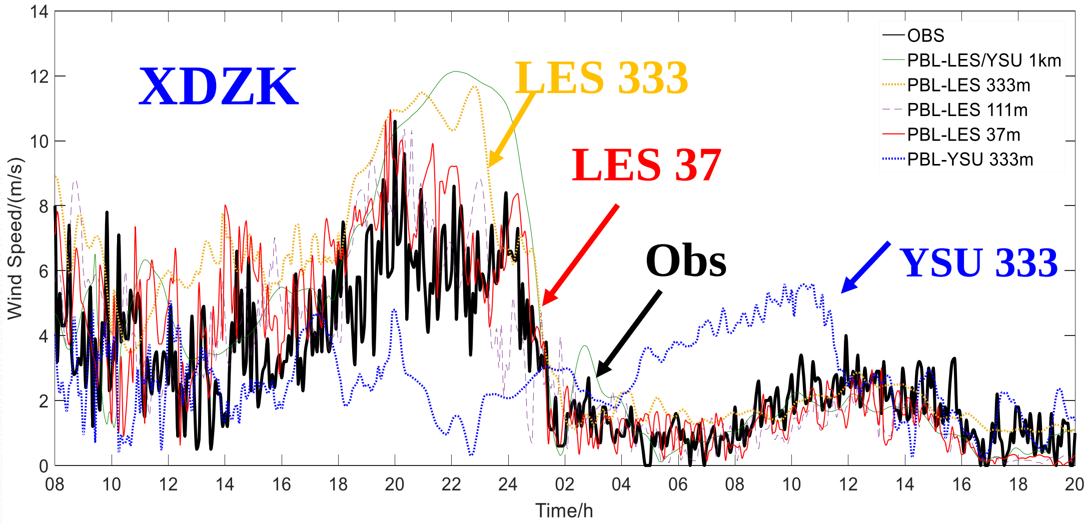
Simulation error Vs. wind speed



1. **LES 37m** performs better than **LES 333m** and **YSU 333m.**
2. **YSU 333m** exhibits substantial simulation error, particularly when wind is very strong.
3. **LES 37m** shows a good agreement with observations for wind speed **higher than 5 m/s.**

1. Overview of Model Setup: topography and PBL treatments sensitivity experiment

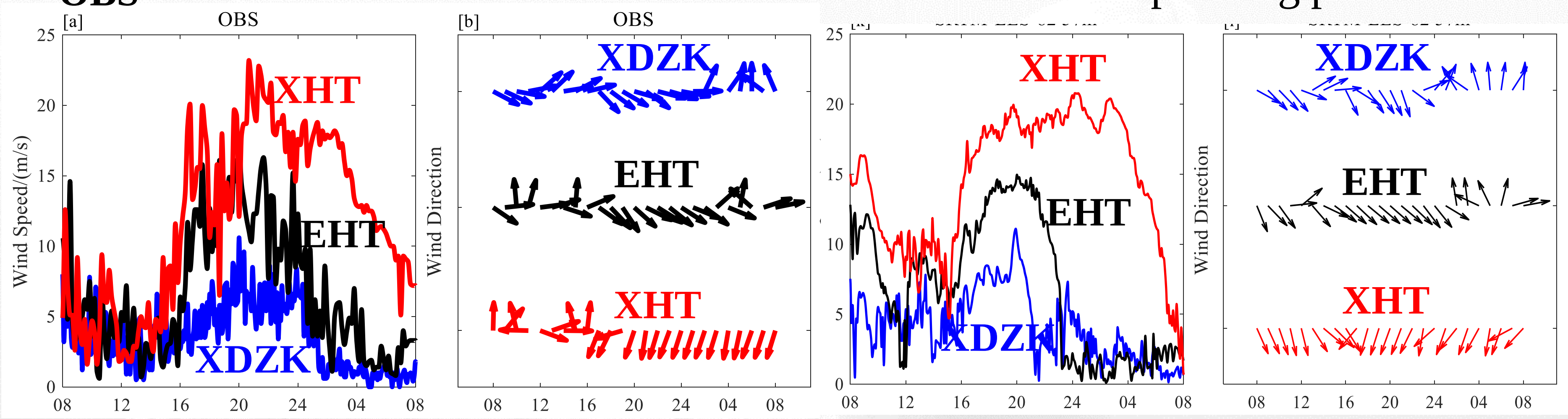
➢ **10m WSP** **in every 5 min**



- **It is apparent that fine grid LES model generally offer improved skills in simulating more accurate wind speed. Reasonably capture the microscale wind fluctuation. But LES 333m and YSU 333 failed.**

- **Possible factors for better sim of LES**
  - The high-resolution terrain forcing
  - Explicit PBL mixing
  - Upscaling processes with high-resolution model

OBS **37m**

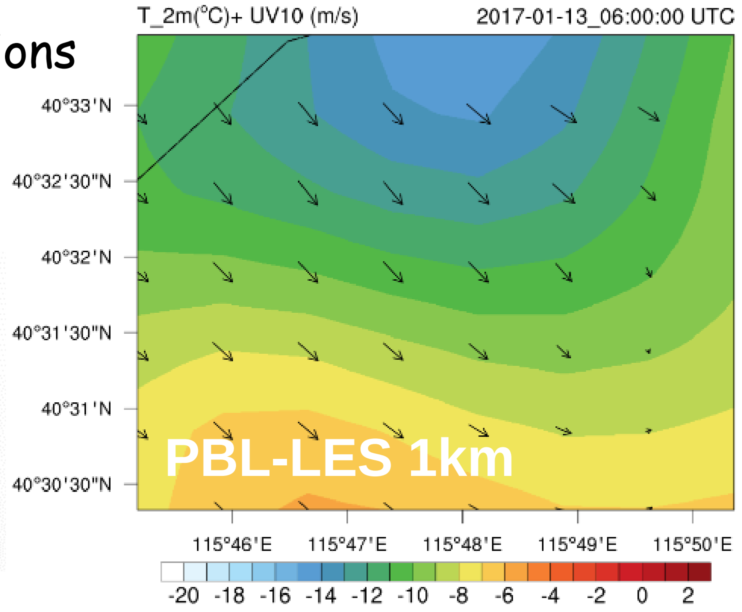


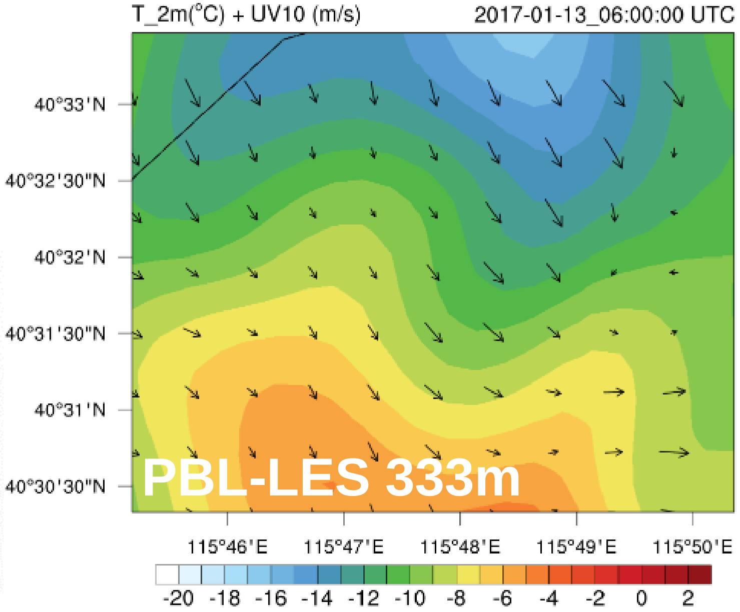
In general, the model shows more skills in modeling the spatial patterns of the wind than the absolute wind speed itself.

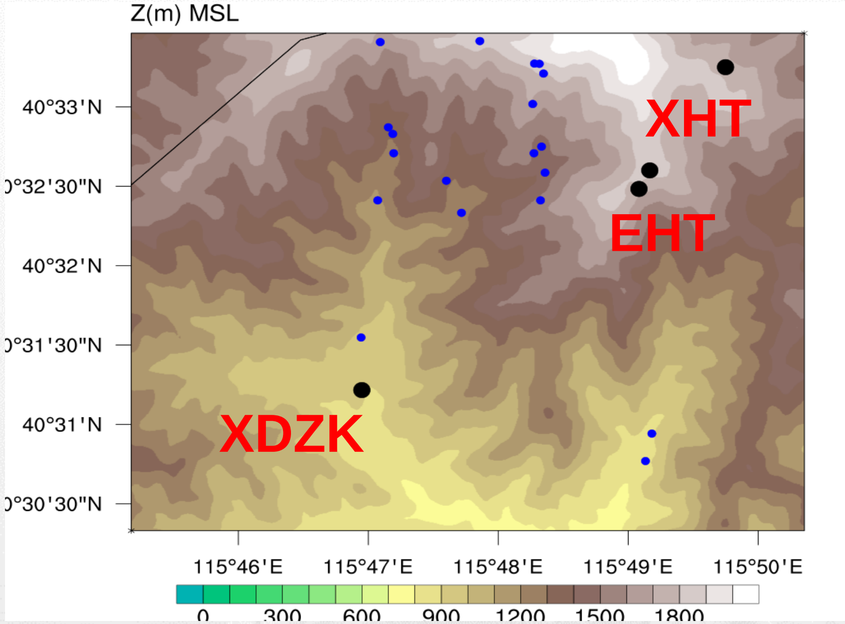
1. Overview of Model Setup: topography and PBL treatments sensitivity experiment

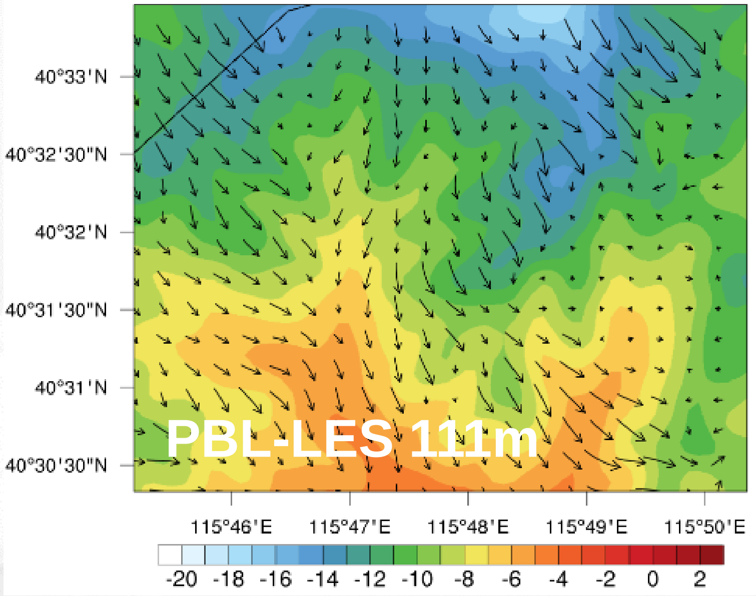
T2 Spatial patterns of different resolutions

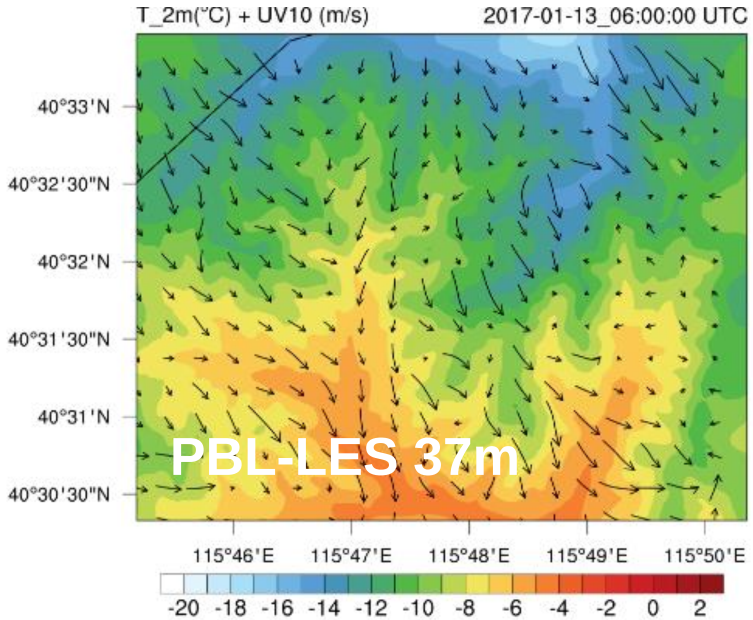
Higher resolution can more accurately depict the impact of topography on temperature simulations











Liu et al, 2020,JAMC

1. Overview of Model Setup: topography and PBL treatments sensitivity experiment

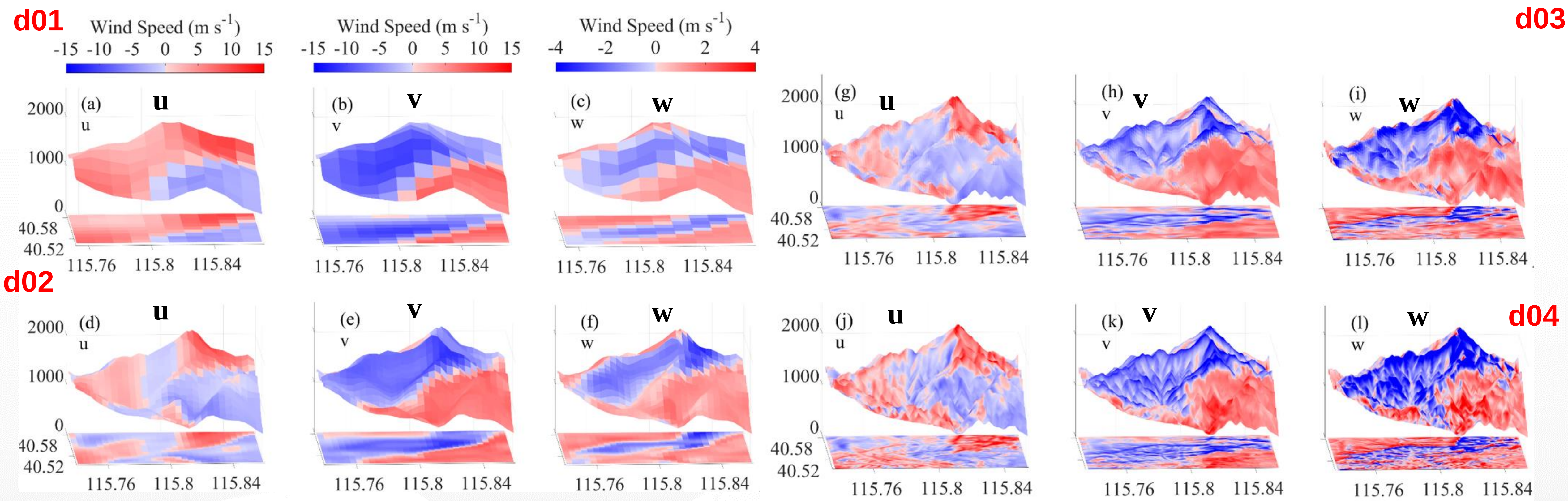


FIG. Snapshots of the simulated velocity components *u*, *v*, and *w* provide a 3D perspective (unit: m s^{-1}) in d01-d04 at the first model level (~13m) at 0400 UTC on 28 Jan 2018.

- With the increasing of model resolution, more detailed topographic features are revealed, including the shape of the slopes and gullies.
- In d01, positive u and negative v values dominate the mountainous region. However, in the microscale d03 and d04, the wind components exhibit more turbulent structures. The ridge is oriented approximately along the southwest-northeast direction, perpendicular to the background mean flow. The prevailing flow and terrain forcing create a wake region on the lee slope of the ridge. Consequently, there are considerably more fine-scale wind structures in the wake region than in the other places.

1. Overview of Model Setup: Sub-grid stress model sensitivity experiment

- The NBA nonlinear backscatter model offers greater accuracy in simulating average meteorological elements and is better suited for characterizing small-scale turbulent structures, but which is time-consuming and not stable enough.

Sub-grid stress model	Vortex velocity	Energy closure
TKE 1.5	linear	Prognostic
Smagorinsky 3D	linear	Diagnostic
NBA	nonlinear	Diagnostic

linear

$$\tau_{ij} = -2K_m\tilde{S}_{ij},$$

nonlinear

$$\tau_{ij} = -2c_e l e^{1/2}\tilde{S}_{ij} - \left(\frac{27}{8\pi}\right)^{1/2} c_e^{3/2}\Delta^2\left[c_1\left(\tilde{S}_{ik}\tilde{S}_{kj} - \frac{1}{3}\tilde{S}_{mn}\tilde{S}_{mn}\delta_{ij}\right) + c_2\left(\tilde{S}_{ik}\tilde{\Omega}_{kj} - \tilde{\Omega}_{ik}\tilde{S}_{kj}\right)\right].$$

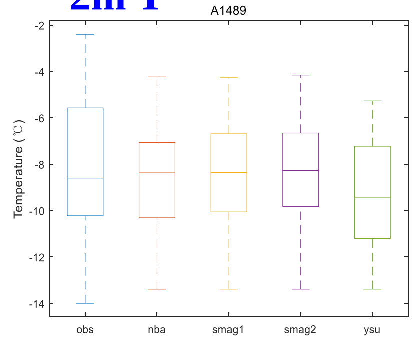
Predicted

$$c_\epsilon = 1.9c_k + (0.93 - 1.9c_k)\frac{l}{\Delta}$$

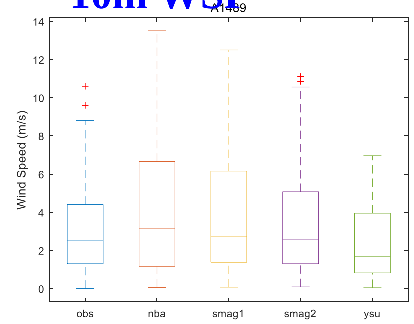
Diagnostic

$$e = \frac{c_k l^2}{c_\epsilon}\left[\tilde{S}_{ij}^2 - \left(1 + \frac{2l}{\Delta}\right)\frac{g}{\bar{\theta}}\frac{\partial\tilde{\theta}}{\partial z}\right]$$

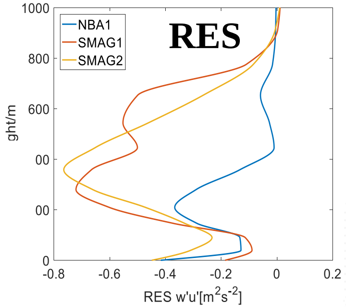
2m T

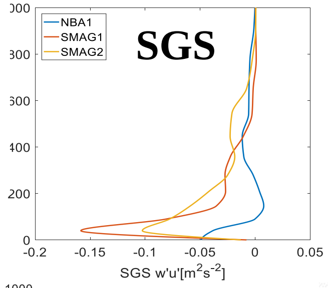


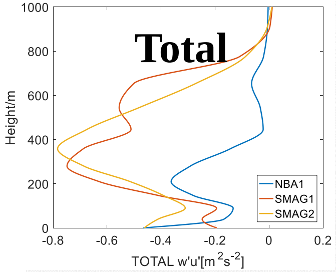
10m WSP



momentum flux profile

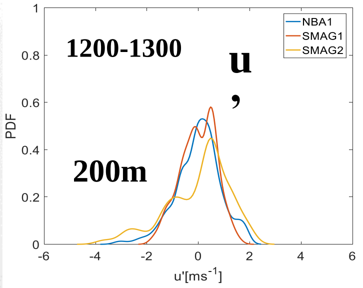


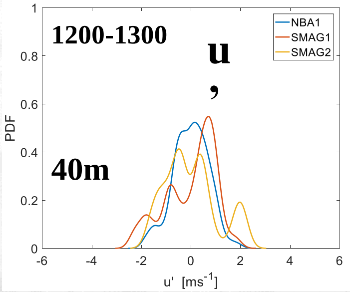


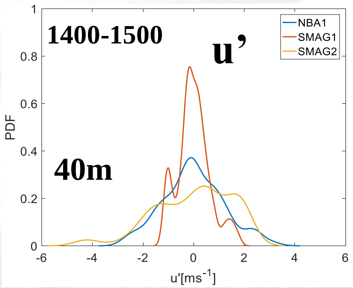


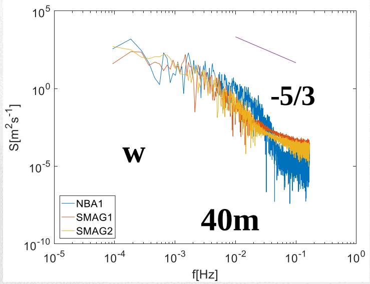
In the LES model, the sub-grid stress model is very important.
We compared three commonly used model:TKE1.5, SMAG, NBA, take comparative analysis of their PDF, momentum flux profile, power spectrum, and found that

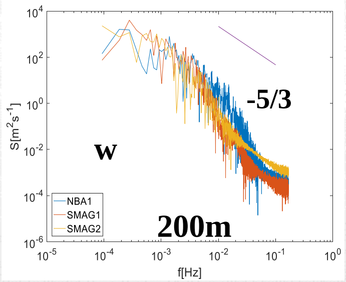
PDF







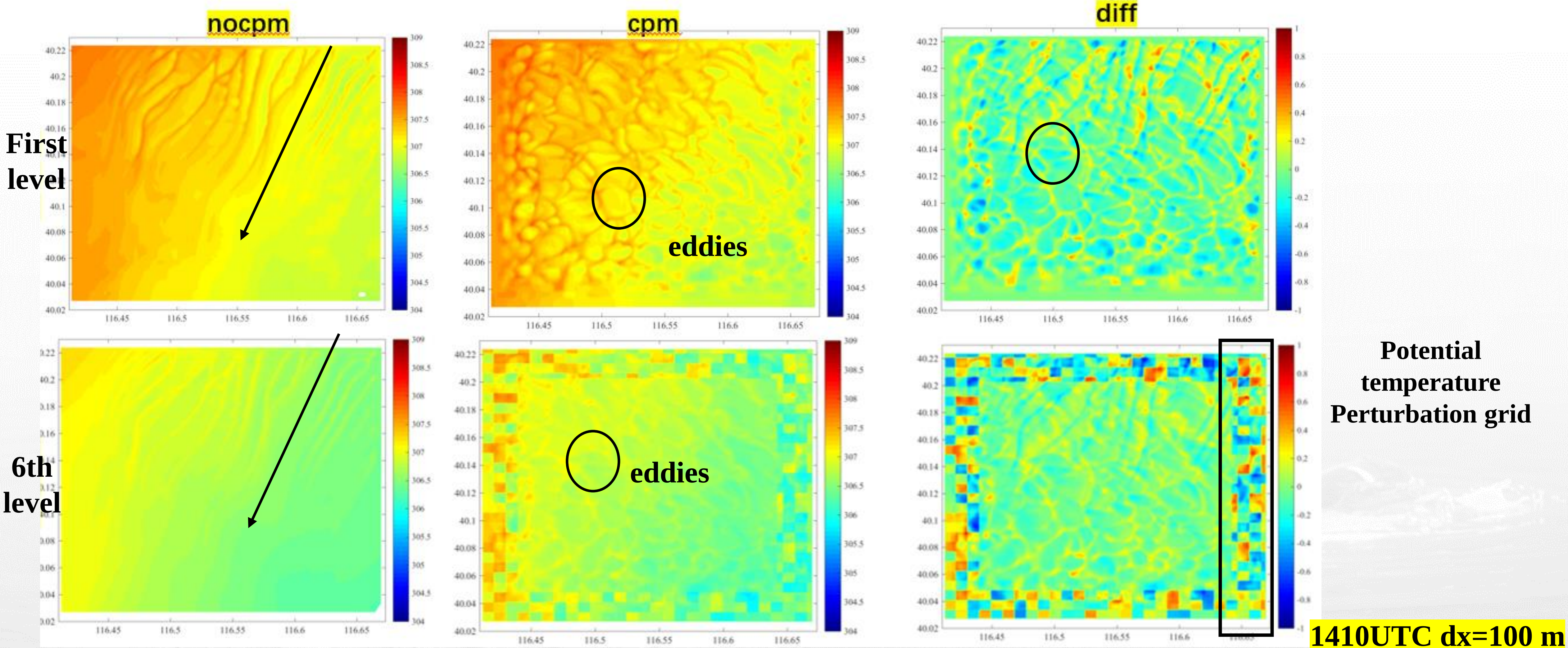




Power spectrum

1. Overview of Model Setup: Cell perturbation method(CPM)

- The "RMAPS-LES" utilized the generalized cell perturbation method (Domingo, 2014), which involves a novel stochastic approach utilizing finite amplitude perturbations of the potential temperature field applied within a specific region(8*8 cell) near the inflow boundaries of the LES domain. This method significantly reduced the distance required to achieve fully developed turbulence.



Overview

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3. Overview of RMAPS-LES Application
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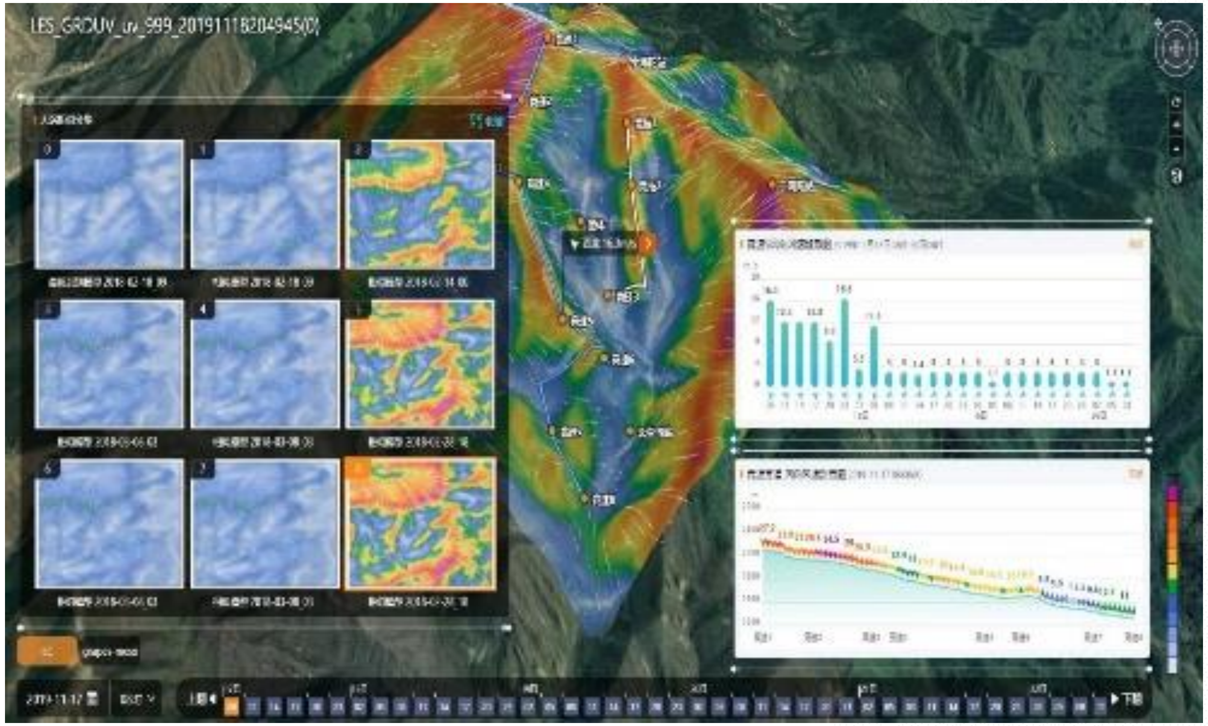
Refined Assessment of Wind Environment over Winter Olympic Competition Zones

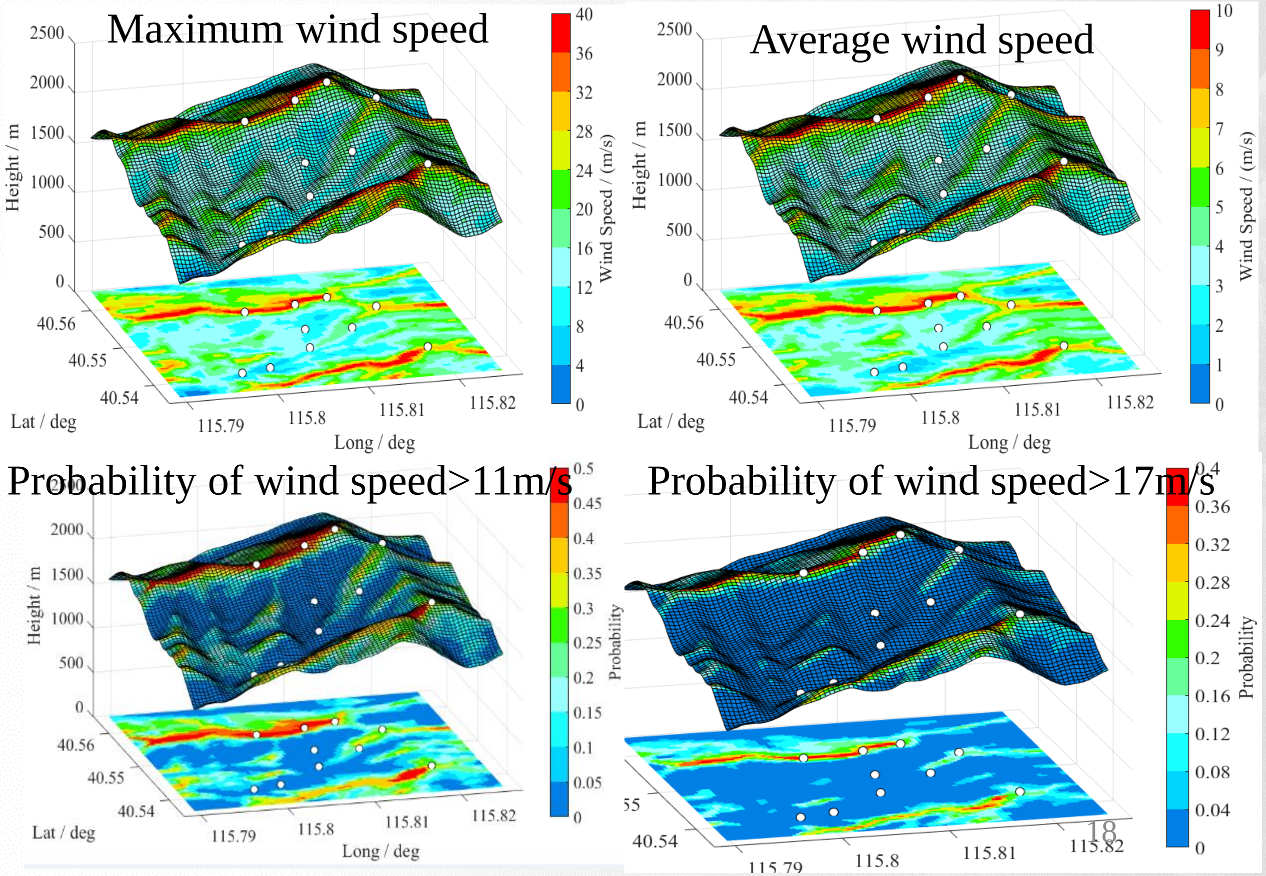
① **Firstly: The weather during the winter competition periods from 2009 to 2021 (every February and March) are classified into 93 types by Lamb-Jenkinson (L-J) atmospheric circulation classification scheme.**

② **Secondly: RMAPS-LES(37m) is used to simulate the wind field for the typical cases of each type.**

③ **Finally: based on the simulation results, a ten-year winter wind environment assessment is carried out to provide detailed spatial distribution characteristics of the wind field, and the risk probability of exceeding the wind speed thresholds of the sport events.**



Example image of Winter Olympics service website



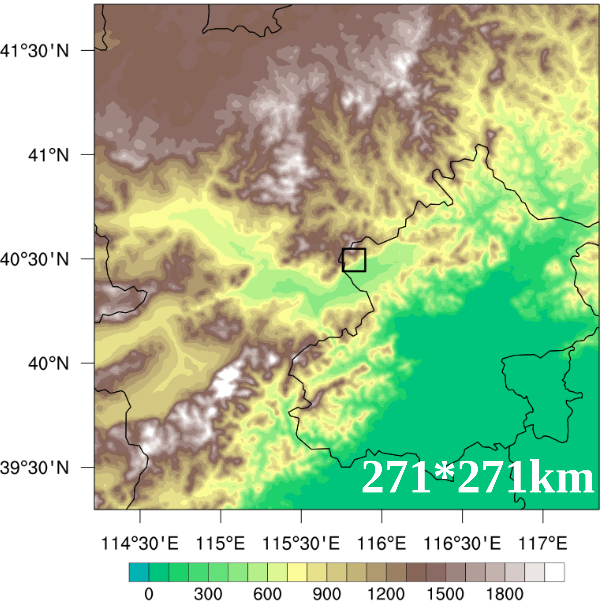
Real-time 100 m resolution RMAPS-LES for Winter Olympic Games

Two domains

D01-1.1km

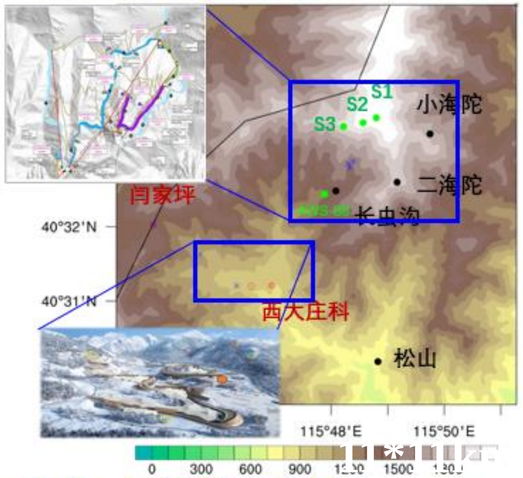
1:11

D02-100 m



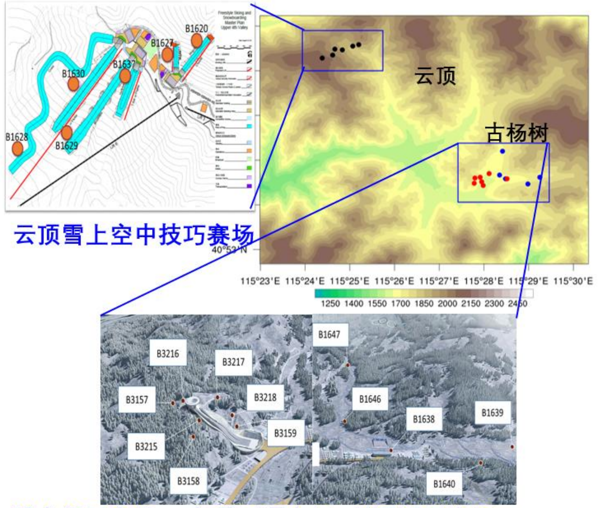
Yanqing zone

高山滑雪赛场场馆



雪车、雪橇赛场场馆

Zhangjiakou zone



云顶雪上空中技巧赛场

跳台滑雪赛场 + 冬季两项赛场+越野滑雪赛场

Main features

- 100m Higher horizontal resolution
- Fine-scale topo and LU/LC data

- LES with sub-grid stress model
- Scale adaptive sub-grid terrain correction
- Cell perturbation method
- Local optimization

- Correction at key stations

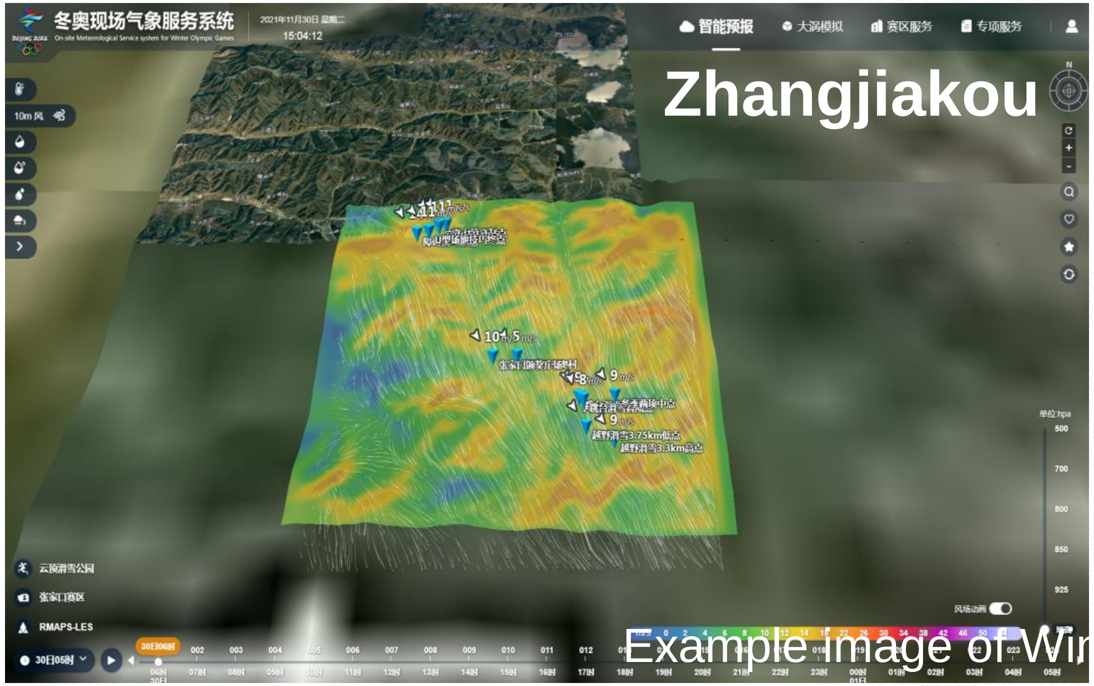
Forecast process (for one zone)

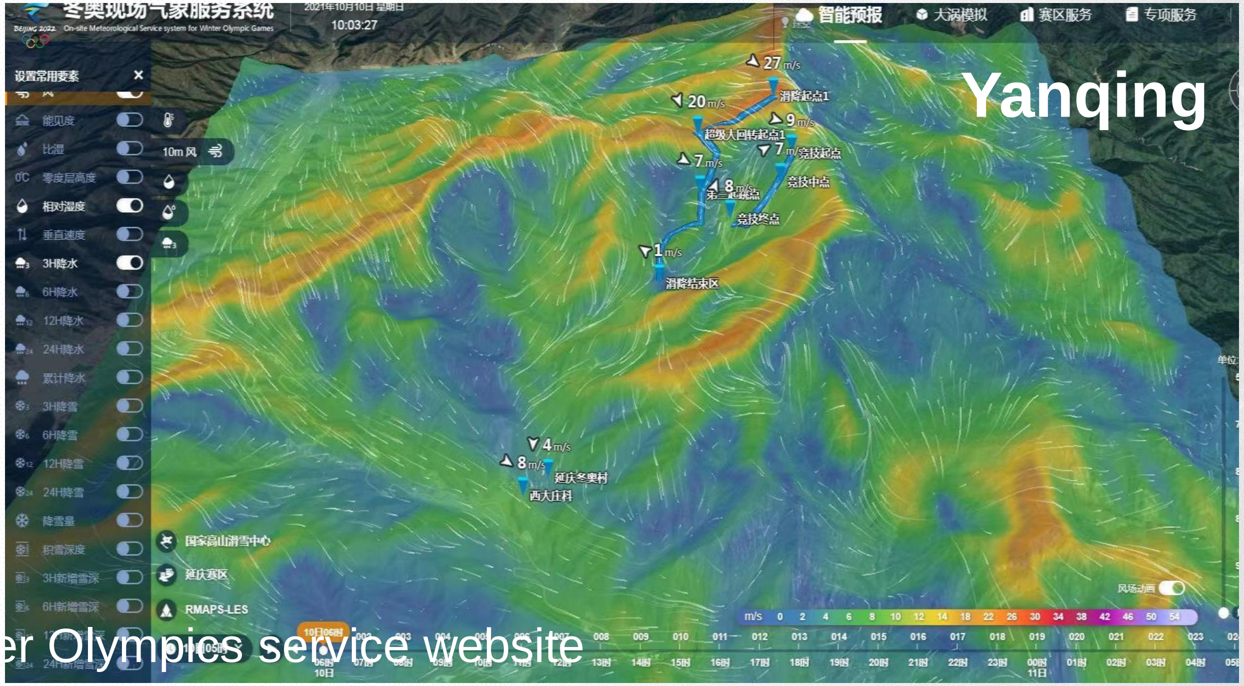
- ◆ Start twice a day:
  - 0900LST (0100BJT)
  - 2100LST (1300BJT)
- ◆ Run time： 2.5-3 hours
- ◆ Computing resource： 3 cores * 36 threads =216 threads
- ◆ Storage ：50G /day

Real-time 100 m resolution RMAPS-LES for Winter Olympic Games

□ **The site and grid products are produced and pushed in real-time to the service website for visual display**

products	Name	Meteorological elements	update frequency	Time	IP	Service
Site products	18AWS time series Xml file	10m WSP/WSD，2m T、2m RH、Surface T、P0、snowfall、precipitation、cloud cover	12h	02:00/14:00 UST	172.18.9.133	data
Grid products	Two/three-dimensional NC file	10m WSP/WSD，2m T、2m RH、Surface T、P0、snowfall、precipitation、cloud cover at surface, 925/700/500hPa	12h	02:00/14:00 UST	172.18.9.133	data





Example image of Winter Olympics service website

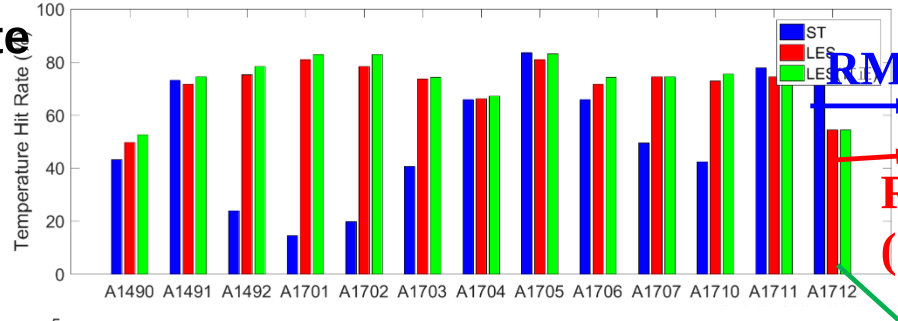
Real-time 100 m resolution RMAPS-LES for Winter Olympic Games

04. Feb-20.Feb.2022
14 AWS

2m T

Hit Rate

52%
71%
73%



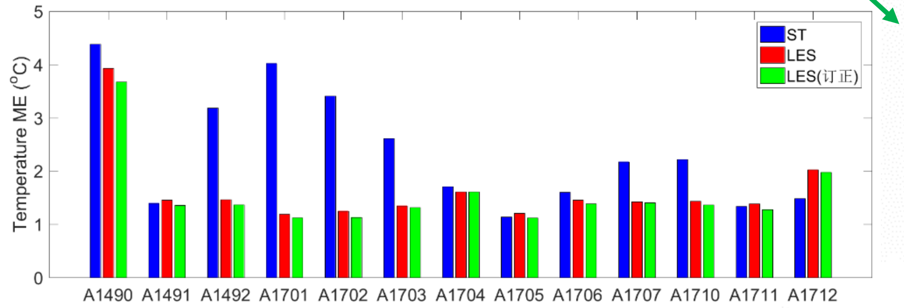
RMAPS-ST(3km)

RMAPS-LES (100m)

LES error correction

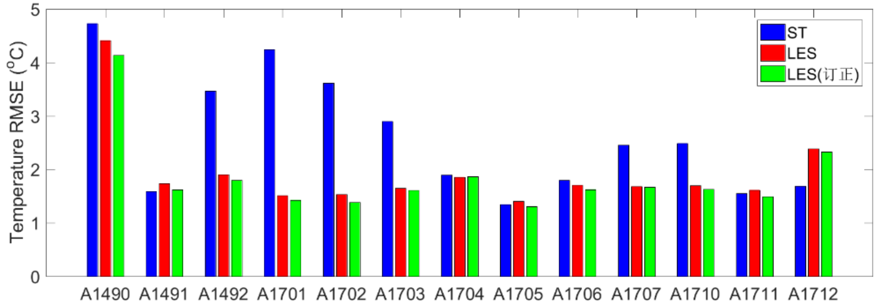
MAE

2.36
1.62
1.55



RMSE

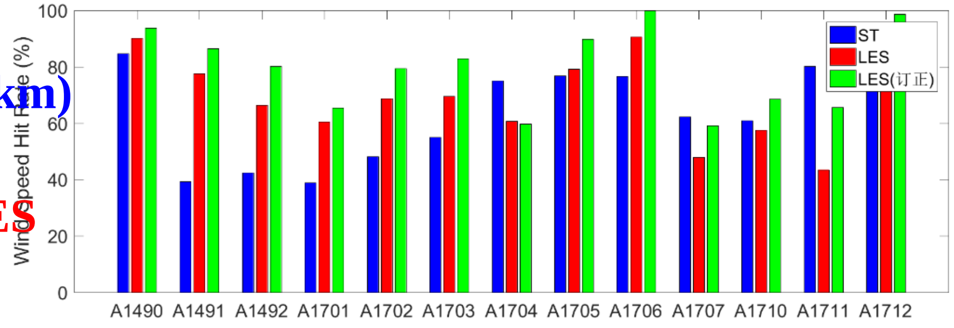
3.17
2.44
2.32



10m WSP

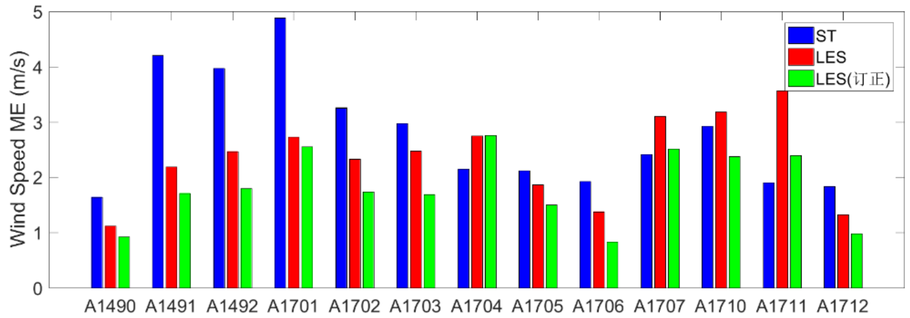
Hit Rate

63%
70%
79%



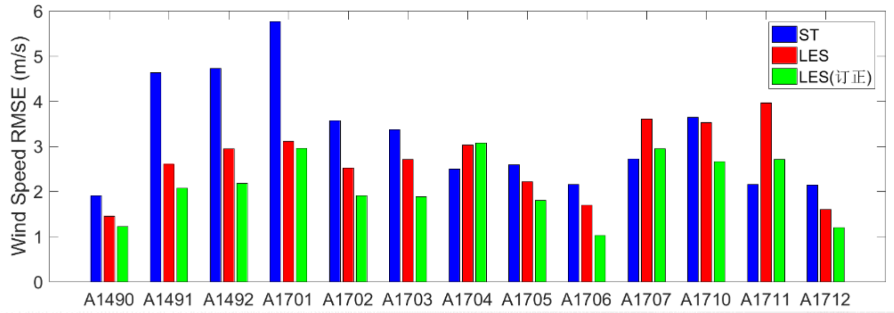
MAE

2.79
2.34
1.83



RMSE

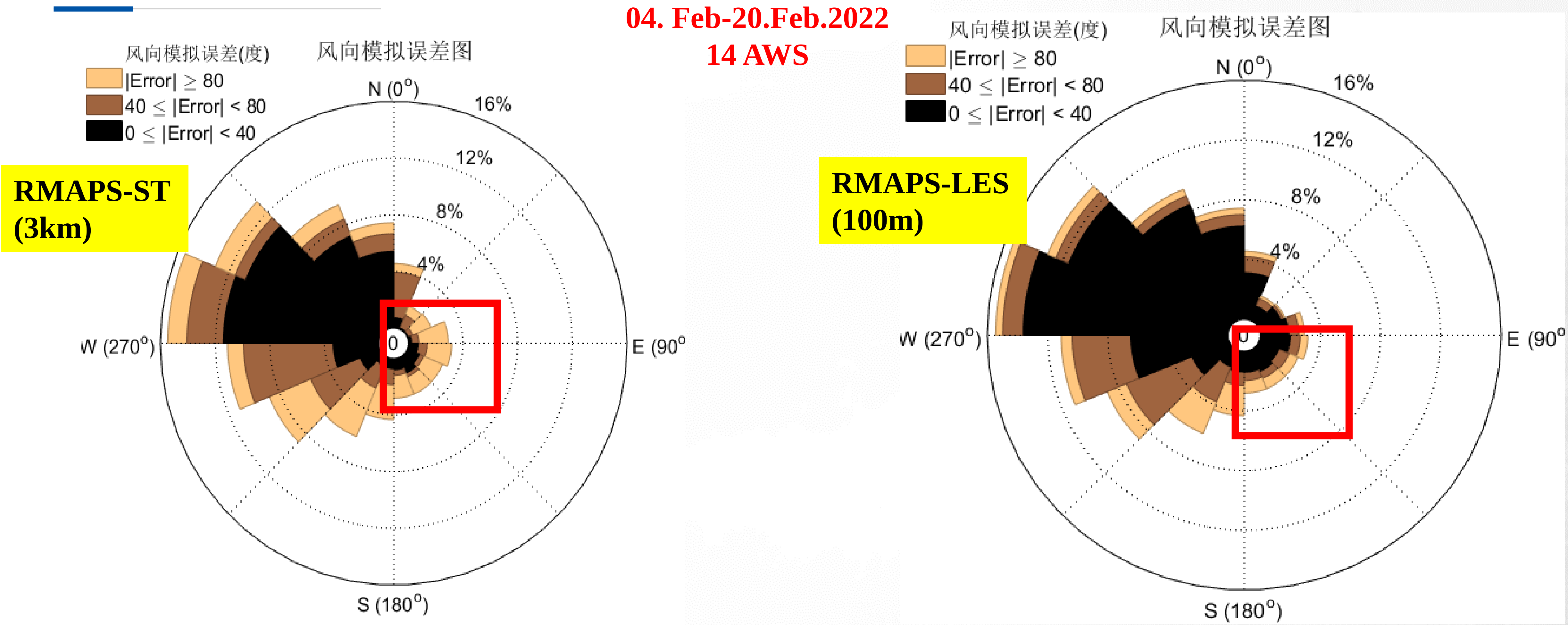
3.64
3.06
2.46



2m T： LES has a good results, with a hit rate over 70% and a MAE within 2 °C. After correction, there is a slight improvement.

10m WSP: LES also has a good effect on wind speed, with a MAE of 2.34 m/s, a RMSE of 3 m/s, and a hit rate of 70%. The correction effect of wind speed is better than temperature, with a 9% increase in hit rate.

Real-time 100 m resolution RMAPS-LES for Winter Olympic Games



- Figure shows the rose plot of wind direction error, which provides a clearer view of the differences between the mesoscale area model and 100m LES model in each direction. Not only in the western and northern prevailing wind direction, but also in the northeast and southeast where is opposite to the dominant winds, the errors (greater than 80 °) of RMAPS-LES is significantly reduced.
- MAE of 10m WD was 44.43 ° (decreased by 30.33%), RMSE was 57.61 ° (decreased by 20.80%), and the hit rate HR increased from 53% (CMA-BJ) to 68% (increased by 28.30%).

Overview

1. Backgrounds and motivations
2. Overview of Model Setup
3. Overview of RMAPS-LES Application
4. Summary and ongoing work

Summary and ongoing work

- The Mesoscale-LES coupled model serves as a valuable tool for studying microscale flow over complex terrain and supports the micro-siting of turbines and weather instruments.
- It shows potentials for operational forecasting practice at~100m grid spacing. However, its stability remains a challenge, as it is prone to collapse.
- Model evaluate would benefit from Intensive observation programs over complex terrain.
- In the future, RMAPS-LES will be utilized for wild-fire simulation and prediction.

Simulation of Flow Fields in Complex Terrain with RMAPS-LES Prediction System

Thank you for the attention!

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References

- Liu, Y., Y. Liu, D. Muñoz-Esparza, F. Hu, C. Yan, and S. Miao. Simulation of Flow Fields in Complex Terrain with WRF-LES: Sensitivity Assessment of Different PBL Treatments. J. Appl. Meteor. Climatol., 2020. 59, 1481–1501.
- LIU Yujue, MIAO Shiguang, HUANG Qianqian, LI Yuhuan, ZHANG Yizhou,2023.Evaluation and Analysis of Meteorological Service for Beijing Winter Olympic Games Supported by RMAPS-LES Prediction System[J].Meteor Mon,49(6):733-744.(In Chinese)
- Liu Yujue, Huang Qianqian, Zhang Hanbin, et al. Refined assessment of wind environment over Winter Olympic competition zone based on large eddy simulation. J Appl Meteor Sci, 2022, 33(2): 129-141. (In Chinese)

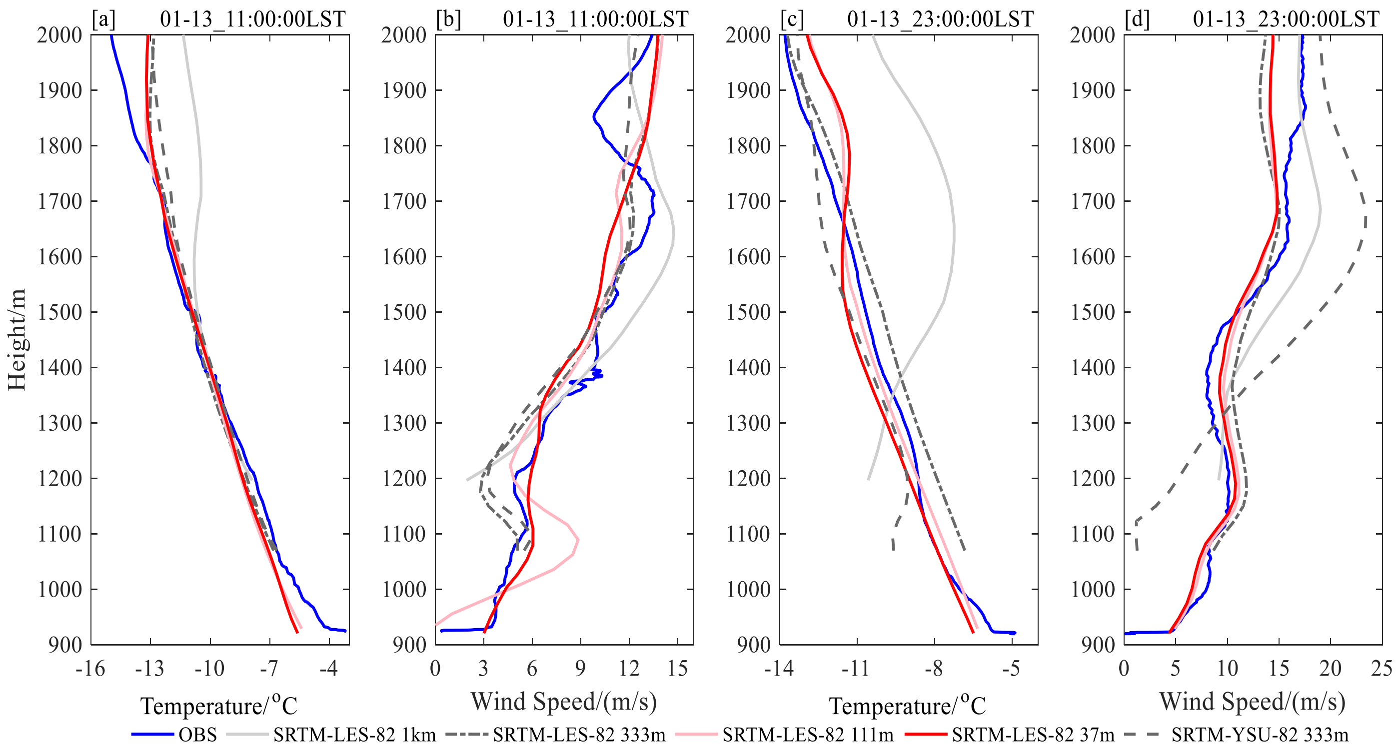
Introduction to MOUNTAOM

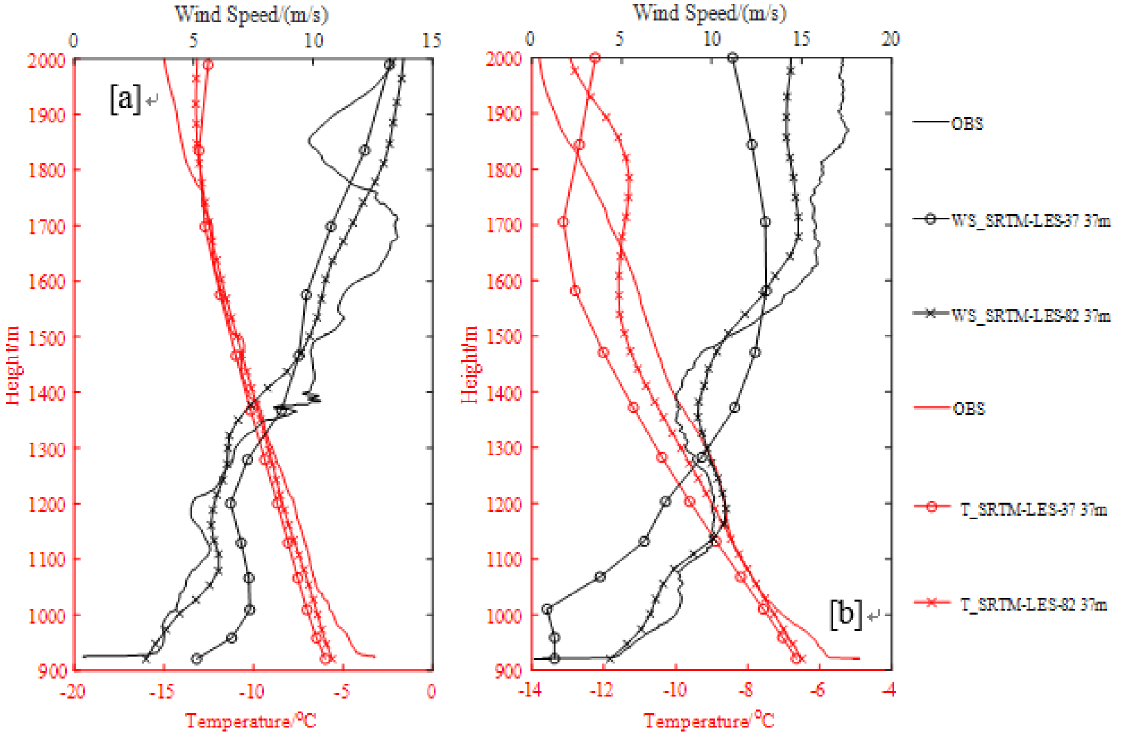
- Project **M**ountain **T**errain **A**tmospheric **O**bservations and **M**odeling (**MOUNTAOM**) is funded by the Beijing Science & Technology Planning Project of the Beijing Municipal Science & Technology Commission (BMSTC).
- Its goal is to improve understanding of PBL characteristics and meteorological conditions in the complex terrain area where venues for Beijing 2022 Winter Olympics will be located via field studies and numerical modeling
- With the aim of improved abilities of weather forecasting for the Beijing 2022 Winter Olympics, from January to March of 2017, a comprehensive field campaign was conducted by IUM and IAP in collaboration with BJWMO in the Xiaohaituo Mountain area, the venue for the Bobsleigh, Skeleton, Luge, and Alpine Skiing events.

2、敏感性试验-垂直分辨率

➢ profiles

Different horizontal resolutions **Different vertical resolutions**





- In addition, vertical resolution also has a direct impact on the distribution of verticalfeatures;
- For vertical winds and temperature profiles, increasing horizontal and vertical resolution can improve the description of wind shear structures and temperature distribution in vertical profiles