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Strength and Challenges of global model MPAS with regional mesh refinement for mid-latitude storm forecasting: A case study

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Introduction

- Mid-latitude storms have large impact on mid-latitude weather
- Fast travel speed + high wind speeds with impact on wind energy (e.g. grid performance & safety, shut-down of wind farms) → Forecasting of storm intensity & timings crucial
- Modeling strategies often involve limited area models (LAMs) & downscaling to accommodate large range of involved atmospheric scales of motions
- Impact of lateral boundary conditions (LBCs) in LAM impose challenges especially when large-scale information like storm structures need to be introduced via LBCs (spatial & temporal interpolation)
- Recent case study[a] investigated storm displacement and lack of deepening when storm is introduced close to LAM boundary corner in Weather Research and Forecasting (WRF) model
- Global Model for Prediction Across Scales (MPAS) with smooth mesh refinement:
  - Avoids issues with lateral boundary conditions (global model)
  - Smooth transition zone avoids sudden resolution jump and boundary corners

  → promising alternative for mid-latitude storm forecasting?

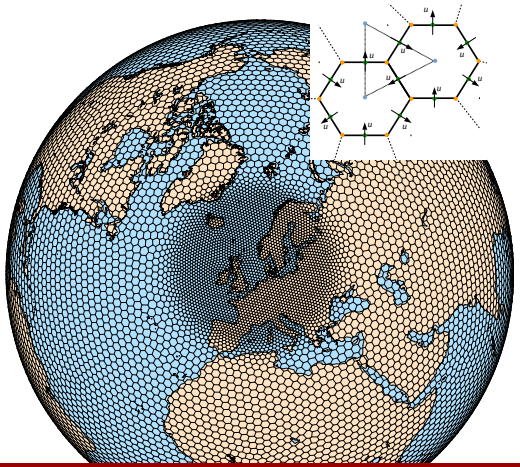
[a] Imberger, M., Larsén, X., Davis, N., & Du, J. (2020). Approaches toward improving the modelling of mid-latitude cyclones entering at the lateral boundary corner in the limited area model WRF. *Quarterly Journal of the Royal Meteorological Society, 146*(732), 3225–3244. https://doi.org/10.1002/qj.3843

Introduction

Leading Questions:

- To what extent can the global MPAS model with regional refinement represent key storm parameters like storm intensity, arrival time & duration?
- How does the absence of lateral boundary conditions in MPAS impact the forecast?
- How is the forecast affected by the transition zone and mesh refinement?

Introduction

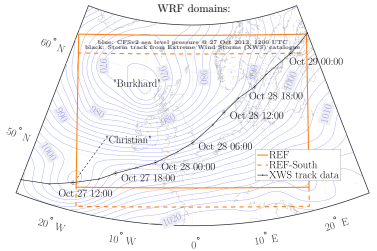


- Finite-volume atmosphere model
- Mesh discretization (horizontal): Spherical Centroidal Voronoi Tessellation (SCVT)
- SCVT allows design of regional mesh refinements with smooth transition zones (see figure)
- Height-based vertical coordinate
- MPAS physics are subset of WRF physics

Model Setup & Measurements

- Expansion of WRF simulations described in Imberger et al. (2020)
- Motivator for MPAS investigation
- Designed to highlight challenging situation of introducing large-scale storm structure via lateral boundary corner (corner issue) and its impact on storm structure
- Different scenarios performed (see table) to reduce / mitigate corner issue effect
- Initial conditions and LBCs coming from CFSv2[a] 6-hourly forecasts.

[a] NCEP Climate Forecast System Version 2 (CFSv2) 6-hourly Products, Saha et al., 2011



Scenarios:

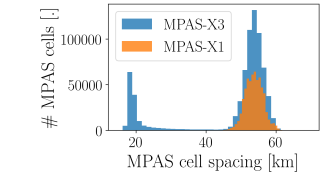
Identifier	Characteristics
REF	reference simulation (solid domain in Figure), 6-hourly lateral boundary condition (LBC) update
REF-South	like "REF" but with a southwards shifted domain (dashed domain)
NUD100km	like "REF" but with spectral nudging of $U,V,\ \theta$ above 100 km, above planetary boundary layer
HalfRelaxZone	like "REF" but with 50% relaxation zone width
2xRelaxZone	like "REF" but with doubled relaxation zone width
CFSv2-3h	like "REF" but with 3-hourly LBC update
CFSv2-1h	like "REF" but with hourly LBC update

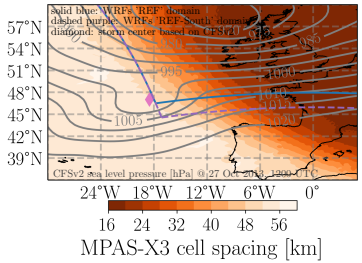
Figure & table with adaptions from Imberger et al., 2020

Model Setup & Measurements

Mesh Design:

- Variable-resolution mesh with circular mesh refinement from 54-km to 18-km (MPAS-X3)
  - Outer grid spacing closely follows resolution of CFSv2 forecast data (0.5°, initial conditions identical to WRF simulations)
  - Refinement zone grid spacing follows WRF grid spacing
  - Location of transition zone defined by south-west corner of WRF domain
- Quasi-uniform 54-km mesh (MPAS-X1) allows investigation of refinement zone impact on large scales.





Model Setup & Measurements

MPAS Scenarios:

- X1-CPKF and X3-CPKF apply same physics schemes as WRF (reference runs)
- -CP and -MESO scenarios used for exploring physics impact

Attribute	X1-CPKF	X1-CP	X1-MESO	X3-CPKF	X3-CP	X3-MESO
mesh	54 km	54 km	54 km	54-18 km	54-18 km	54-18 km
physics						
Cumulus	KF	GF	NT	KF	GF	NT
Microphysics	TMS	TMS	WSM6	TMS	TMS	WSM6
Land surface	Noah†					
Boundary layer	MYNN	MYNN	YSU	MYNN	MYNN	YSU
Surface layer	MYNN	MYNN	MM5	MYNN	MYNN	MM5
Long-/shortwave	RRTMG					

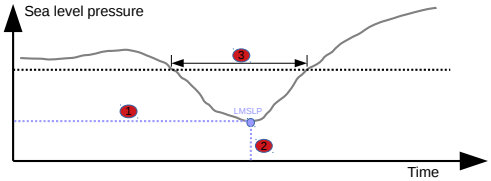
† Niu et al. (2011) and Yang et al. (2011)

Used abbreviations: GF: Scale-aware Grell-Freitas (Grell & Freitas, 2014), NT: New Tiedtke (Zhang & Wang, 2017; Zhang et al., 2011), TMS: Thompson non-aerosol aware (Thompson et al., 2008), WSM6: WRF Single-Moment 6-Class (Hong & Lim, 2006), MYNN: Mellor–Yamada–Nakanishi–Niino (Nakanishi & Niino, 2009), YSU: Yonsei University Scheme (Hong et al., 2006), MM5: Revised MM5 similarity scheme (Jiménez et al., 2012), RRTMG: Rapid Radiative Transfer Model for General Circulation Models (Iacono et al., 2008).

Model Setup & Measurements

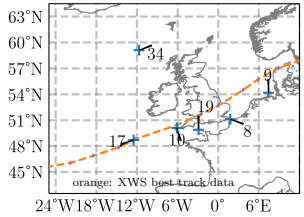
Key evaluation parameter:

1. **Storm intensity**: Magnitude of the local minimum sea level pressure (LMSLP).
2. **Storm arrival time**: defined as the time when models/observations see LMSLP, used to define time shifts in the storm forecast.
3. **Storm duration**: number of hours for which sea level pressure (SLP) remains below p_t = LMSLP + 10 hPa.



Model Setup & Measurements

Measurements: Sea level pressure from buoy observations from EMODnet[a]



Station identifier	platform code	location	Availability rate (coverage)	p_t [hPa]
17	62029	48.7°N 12.5°W	every 60 min (100%)	1000.1
34	64045	59.1°N 11.7°W	every 60 min (100%)	-[†]
10	62107	50.1°N 6.1°W	every 60 min (100%)	992.4
19	62103	49.9°N 2.9°W	every 60 min (98.4%)	995.2
8	62304	51.1°N 1.8°E	every 60 min (100%)	995.1
9	'UFSDeutscheBucht'	54.17°N 7.45°E	every 60 min (100%)	986.8

[†] not included in storm duration time analysis

Table adapted from Imberger, 2020

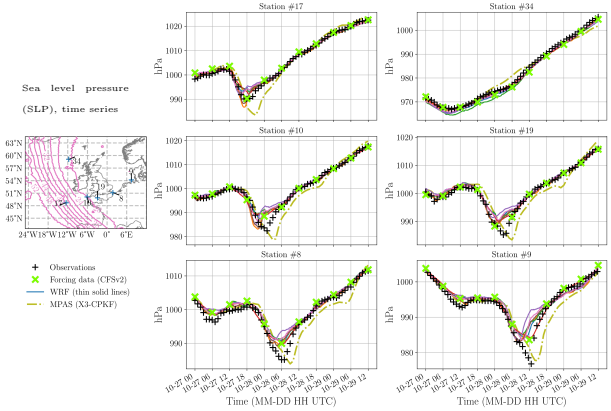
\+ comparison with **CFSv2 6-hourly forecast**

- Initial and boundary conditions for WRF
- Initial conditions for MPAS
- Spatial distribution & time series of sea level pressure

[a] European Marine Observation and Data Network (EMODnet) - Physics, https://www.emodnet-physics.eu/Portal, Novellino et al., 2015

Results

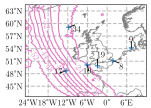
MPAS comparison with WRF | Impact of MPAS mesh refinement | Impact of MPAS physics

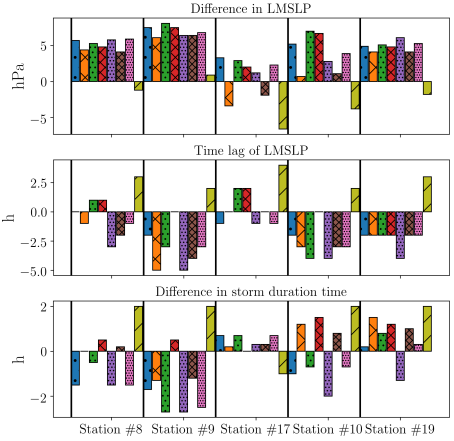


- WRF results dominated by lateral boundary conditions (LBCs)
  - Positive steering before/after local minimum sea level pressure (LMSLP)
  - Temporal interpolation & storm representation in CFSv2 forcing data prevent sufficient deepening
  - Spread biggest in storm vicinity
- MPAS' LBC independence allows detection of LMSLP, deviations after passing the LMSLP

Results

Difference between modeled and observed storm parameters (model minus observation)

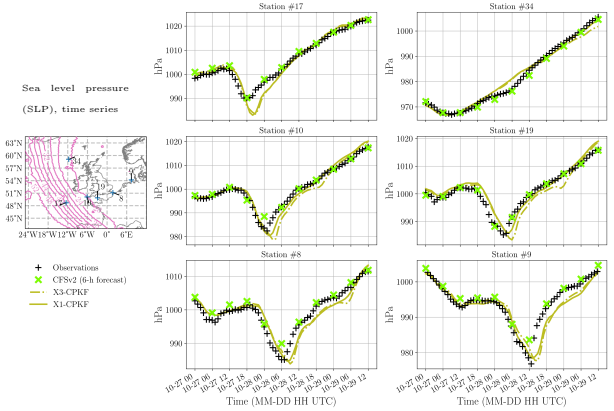




- WRF generally underestimates storm intensity while MPAS shows generally better agreement especially at easternmost measuring locations
- MPAS sees storm arrival time too late while WRF sees the storm too early at most locations
- MPAS overestimates storm duration, performance of WRF scenario dependent

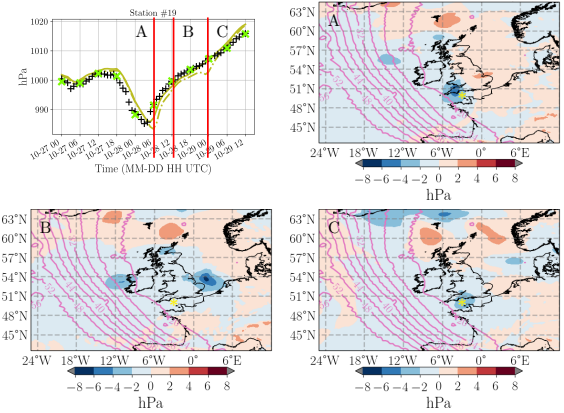
Results

MPAS comparison with WRF | Impact of MPAS mesh refinement | Impact of MPAS physics



- Additional time shift and lower LMSLP when refinement zone is active
- High agreement of quasi-uniform and variable-resolution results in transition zone (Station #17)
- Variable-resolution configuration shows artificial drop in SLP over English channel stations (#10,#19,#8) after 28 Oct 2012, UTC 1800

Results

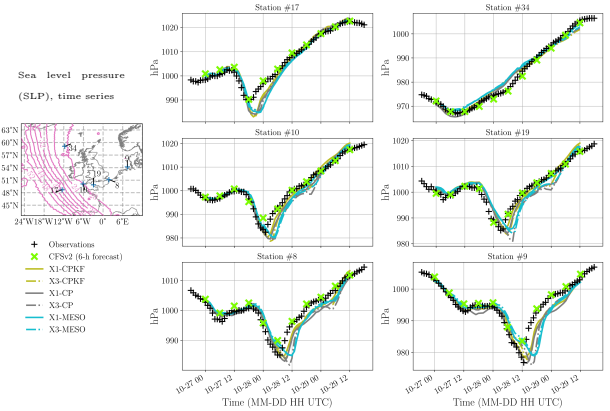


MPAS Sea level pressure difference (variable-resolution minus quasi-uniform), pink contours: isolines of mesh refinement, yellow star: station #19

- Refined simulation creates artificial low-pressure system moving from Ireland south-eastwards over Cornwall (responsible for artificial pressure drop at C)
- Additional time lag in storm arrival time (positioned further west) in refined simulation

Results

▸ MPAS comparison with WRF ▸ Impact of MPAS mesh refinement ▸ Impact of MPAS physics

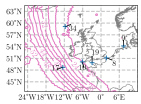


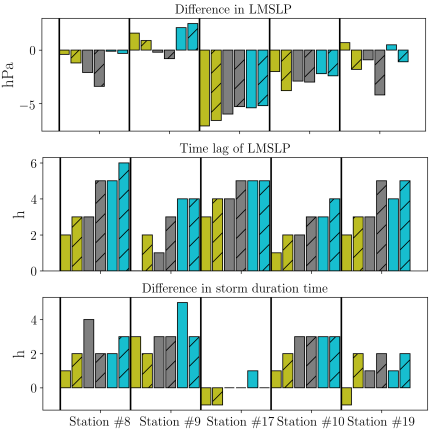
- Configuration differences mainly around the storm arrival time and within 24 hours afterwards.
- Presence & absence of artificial low-pressure system in X1- & X3- scenarios suggests combined impact of mesh refinement and physics on its creation
- Switch from Kain-Fritsch (-CF) to scale-aware Grell-Freitas scheme (-CP) increases difference between quasi-uniform and variable-resolution counterpart

Results

MPAS comparison with WRF | Impact of MPAS mesh refinement | Impact of MPAS physics

Difference between modeled and observed storm parameters (model minus observation)





- Later storm arrival time in variable-resolution configurations at most stations (independent from physics)
- Impact of model physics vs. mesh refinement less clear for storm intensity and storm duration

Conclusion and Further Work

Conclusion:

- Lack of steering from CFSv2 via LBC allowed MPAS to sufficiently develop storm & outperform WRF
- Tight control of WRF by boundary conditions showed beneficial effects after storm passes location.
- Introduction of large-scale features in refined region remains challenging also with smooth transition zone (additional westward shift of storm in variable-resolution configuration)
- Combined effect of mesh refinement and model physics responsible for introduction of artificial low-pressure system
- quasi-uniform configurations indicate overall better performance on key indicators, however SLP focus does not reveal potential benefits on smaller-scale storm features (wind fields, voriticity).

Future Work:

- Expand analysis to smaller-scale storm features and other storm cases
- Investigate impact of transition zone width
- Exploration of data assimilation in MPAS to mitigate model drifts

References I

Presented results are mainly based on:

Imberger, M. (2020). *Advanced meteorological modelling across scales* (Doctoral dissertation 0104(EN)). Denmark, DTU Wind Energy. https://doi.org/10.11581/dtu:00000091

Full list of references:

Grell, G. A., & Freitas, S. R. (2014). A scale and aerosol aware stochastic convective parameterization for weather and air quality modeling. *Atmospheric Chemistry and Physics*, *14*(10), 5233–5250. https://doi.org/10.5194/acp-14-5233-2014

Hong, S.-Y., Noh, Y., & Dudhia, J. (2006). A New Vertical Diffusion Package with an Explicit Treatment of Entrainment Processes. *Monthly Weather Review*, *134*(9), 2318–2341. https://doi.org/10.1175/MWR3199.1

Hong, S.-Y., & Lim, J.-O. J. (2006). The WRF single-moment 6-class microphysics scheme (WSM6). *Journal of the Korean Meteorological Society*, *42*(2), 129–151. http://www.mmm.ucar.edu/wrf/users/docs/WSM6-hong_and_lim_JKMS.pdf

Iacono, M. J., Delamere, J. S., Mlawer, E. J., Shephard, M. W., Clough, S. A., & Collins, W. D. (2008). Radiative forcing by long-lived greenhouse gases: Calculations with the aer radiative transfer models. *Journal of Geophysical Research: Atmospheres*, *113*(D13). https://doi.org/10.1029/2008JD009944

Imberger, M. (2020). *Advanced meteorological modelling across scales* (Doctoral dissertation 0104(EN)). Denmark, DTU Wind Energy. https://doi.org/10.11581/dtu:00000091

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Jiménez, P. A., Dudhia, J., González-Rouco, J. F., Navarro, J., Montávez, J. P., & García-Bustamante, E. (2012). A Revised Scheme for the WRF Surface Layer Formulation. *Monthly Weather Review*, *140*(3), 898–918. https://doi.org/10.1175/MWR-D-11-00056.1

Nakanishi, M., & Niino, H. (2009). Development of an improved turbulence closure model for the atmospheric boundary layer. *Journal of the Meteorological Society of Japan. Ser. II*, *87*(5), 895–912. https://doi.org/10.2151/jmsj.87.895

References II

Niu, G.-Y., Yang, Z.-L., Mitchell, K. E., Chen, F., Ek, M. B., Barlage, M., Kumar, A., Manning, K., Niyogi, D., Rosero, E., Tewari, M., & Xia, Y. (2011). The community noah land surface model with multiparameterization options (noah-mp): 1. model description and evaluation with local-scale measurements. *Journal of Geophysical Research: Atmospheres*, *116*(D12). https://doi.org/10.1029/2010JD015139

Novellino, A., D'Angelo, P., Benedetti, G., Manzella, G., Gorringe, P., Schaap, D., Pouliquen, S., & Rickards, L. (2015). European marine observation data network - EMODnet physics. *OCEANS 2015 - Genova*, 1–6. https://doi.org/10.1109/OCEANS-Genova.2015.7271548

Saha, S., Moorthi, S., Wu, X., Wang, J., Nadiga, S., Tripp, P., Behringer, D., Hou, Y.-T., Chuang, H.-y., Iredell, M., Ek, M., Meng, J., Yang, R., Mendez, M. P., van den Dool, H., Zhang, Q., Wang, W., Chen, M., & Becker, E. (2011). Ncep climate forecast system version 2 (cfsv2) 6-hourly products. *Research Data Archive at the National Center for Atmospheric Research, ComputationalInformation Systems Laboratory*. https://doi.org/10.5065/D61C1TXF last accessed: 20 January 2017

Thompson, G., Field, P. R., Rasmussen, R. M., & Hall, W. D. (2008). Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. part ii: Implementation of a new snow parameterization. *Monthly Weather Review*, *136*(12), 5095–5115. https://doi.org/10.1175/2008MWR2387.1

Yang, Z.-L., Niu, G.-Y., Mitchell, K. E., Chen, F., Ek, M. B., Barlage, M., Longuevergne, L., Manning, K., Niyogi, D., Tewari, M., & Xia, Y. (2011). The community noah land surface model with multiparameterization options (noah-mp): 2. evaluation over global river basins. *Journal of Geophysical Research: Atmospheres*, *116*(D12). https://doi.org/10.1029/2010JD015140

Zhang, C., & Wang, Y. (2017). Projected Future Changes of Tropical Cyclone Activity over the Western North and South Pacific in a 20-km-Mesh Regional Climate Model. *Journal of Climate*, *30*(15), 5923–5941. https://doi.org/10.1175/JCLI-D-16-0597.1

Zhang, C., Wang, Y., & Hamilton, K. (2011). Improved Representation of Boundary Layer Clouds over the Southeast Pacific in ARW-WRF Using a Modified Tiedtke Cumulus Parameterization Scheme*. *Monthly Weather Review*, *139*(11), 3489–3513. https://doi.org/10.1175/MWR-D-10-05091.1

2-min pitch: Mid-latitude storm forecasting for wind energy applications

[1]

[2]

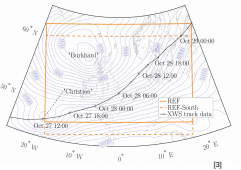
mid-latitude storm

(complex)

Established concept:

Limited area model

(+ nesting)



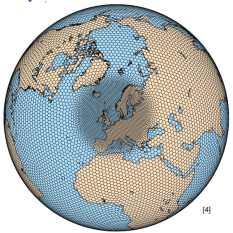
[3]

Weather Research & Forecasting model, WRF

Alternative:

Global Model

\+ smooth mesh refinement


[4]

Model for Prediction Across Scales, MPAS

→ To what extent can the global MPAS model with regional refinement represent key storm parameters?

→ How does the absence of lateral boundary conditions affect the forecast?

→ How is the forecast affected by the transition zone and mesh refinement?

[1]: HR Wallingford https://www.hrwallingford.com/edge/supporting-safe-operations-accurate-marine-weather-forecasts
[2]: NASA Worldview Snapshots https://wvs.earthdata.nasa.gov/
[3]: Adapted from Imberger, M., Larsén, X., Davis, N., & Du, J. (2020). Approaches toward improving the modelling of mid-latitude cyclones entering at the lateral boundary corner in the limited area model WRF. *Quarterly Journal of the Royal Meteorological Society, 146*(732), 3225–3244. https://doi.org/10.1002/qj.3843
[4]: Adapted from Imberger, M. (2020). *Advanced meteorological modelling across scales* (Doctoral dissertation 0104(EN)). Denmark, DTU Wind Energy. https://doi.org/10.11581/dtu:00000091