SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Investigating the optimal configuration of the HARMONIE-AROME NWP model for hectometric-scale forecasting over Ireland
Computer Project Account:	spieclan
Start Year - End Year :	2021 - 2022
Principal Investigator(s)	Colm Clancy
Affiliation/Address:	Met Éireann Glasnevin Hill Dublin 9 D09 Y921 Ireland
Other Researchers (Name/Affiliation):	James Fannon and Eoin Whelan, Met Éireann

Summary of project objectives

The objective of this project was to explore the behaviour and the performance of the HARMONIE-AROME NWP model at hectometric-scale resolutions over Ireland; ideally to ultimately arrive at an optimal configuration for operational use.

Summary of problems encountered

No technical problems relating to the Special Project or HPC facility.

Experience with the Special Project framework

This was my first Special Project as Principle Investigator and I was very satisfied with the framework, particularly happy that the administrative aspects were straightforward and not overly-burdensome.

Summary of results

The simulations carried out with the project resources allowed us to identify optimal configurations of the HARMONIE-AROME model with sub-kilometre resolutions for use over Irish domains. The settings were quite region-dependent, with areas of more complex orography and extreme conditions not surprisingly requiring more care with dynamical settings.

Between the single forecasts and the longer cycling experiments, the following main points were noted:

- coupling cloud water and hydrometeors from the boundary files is particularly important on small domains,which are generally necessary at very high resolutions.
- it is important to have the domain as large as possible, such that the region of interest is far away from the domain boundaries.
- single precision option can yield runtime savings of approximately 40% for sub-kilometre resolution forecasts.
- an increase in vertical resolution from 65 to 90 levels appears to be beneficial overall, improving both MSLP and wind-speed scores over Ireland while also reducing fog prevalence over the small number of cases available in this study.
- it is favourable to use a geographically large domain at 750 m resolution, covering all of Ireland, as opposed to a smaller domain at 500 m resolution covering a particular region.
- it remains difficult to objectively assess the overall added value of the sub-kilometre model relative to the 2.5 km default at 90 vertical levels.

For a complete analysis and discussion of the results, we have appended an article to this report which was published in the ACCORD Newsletter in February 2022.

List of publications/reports from the project with complete references

Clancy C, Fannon J and Whelan E (2022). Hectometric-Scale Experiments at Met Éireann. ACCORD Newsletter 2, February 2022, 129-138. [Newsletter article, appended to this report]

Clancy C, Fannon J and Whelan E (2022). HARMONIE-AROME at Hectometric Scale. Met Éireann NWP Note 2022/02. [Internal technical report, available from Met Éireann]

Future plans

The results and experiences from this project will guide the development of a 750m forecasting setup which will begin as a parallel e-suite in Q3 2022, with an eventual operational implementation subject to satisfactory performance with full cycling. Applications for more Special Projects may be submitted in the future for addressing specific topics related to the further development of this system.

Hectometric-Scale Experiments at Met Éireann

Colm Clancy, James Fannon, Eoin Whelan

1 Introduction

This article summarises some of the key results from a series of experiments with HARMONIE-AROME at sub-kilometre horizontal resolutions, and with an increased number of vertical levels. This is a topic of considerable interest across the consortium with numerous recent contributions; for example Antoine et al. (2021), Chikhi et al. (2021), Suárez-Molina and Calvo (2021), Yang (2018).

Currently at Met Éireann, and elsewhere, operational suites use a horizontal resolution of 2.5 km and 65 vertical levels. In this work domains with 500 m and 750 m resolution were tested, along with the 90 levels from Météo France. Cycle 43h2.1.1 was used for all of these experiments. A more comprehensive technical note detailing this work is available from Met Éireann.

2 Experiment Configurations

An initial phase of experiments on Irish domains were carried out to test configuration settings. These consisted of single 36-hour forecasts beginning from 0000 UTC on the 22nd of February 2021. On the night of the 22nd/23rd, a low pressure system to the west of the country brought strong winds and heavy rain to the south-west of Ireland in particular.

2.1 Single Precision

Building upon work carried out at ECMWF and Météo-France, the option to run HARMONIE-AROME in single precision (SP) was made available as part of Cycle 43h2.1 (see Vignes, 2019; HIRLAM, 2020). This has been largely motivated by ECMWF's extensive research in this area, which has demonstrated that SP IFS offers a ∼40% runtime saving, relative to double precision (DP), with no significant degradation in forecast quality (Váňă et al., 2017), culminating in the migration to operational SP forecasts as part of ECMWF's Cycle 47r2 upgrade (Lang et al, 2021).

The SP option in HARMONIE-AROME had previously been investigated as part of pre-operational testing of Cycle 43h2.1 at Met Éireann (Bessardon et al., 2020), with initial results suggesting an approximate 30% forecast runtime saving and largely neutral impact on surface verification scores. Given this substantial saving, it was deemed appropriate to investigate using SP in this project. Early tests at 2.5 km and 500 m resolution showed savings of 30-40% in the runtimes and very similar results in the SP and DP simulations, with the SP forecasts exhibiting a small positive MSLP bias relative to DP. These results are consistent with previous studies (Feddersen, 2021). Therefore, it was decided to use SP by default[1] in all of the high-resolution experiments. No significant issues regarding the stability of the SP forecasts were encountered.

[1] Note that SP was used for Forecast, with other model components retained in DP. This is now available through the "dual" precision option in Cycle 43h2.2

2.2 Dynamics settings

The main aim of initial single-forecast testing was to find a stable configuration for a 500 m-resolution domain with 90 vertical levels. The quadratic or cubic grids were targeted: given their truncation of the spectral resolution, these have the advantage of both saving computational cost and potentially being more stable, albeit with a formal reduction in accuracy. In addition to the time-step, a key factor to be addressed is the appropriate level of diffusion necessary for higher-resolution forecasting: increasing diffusion helps to control noise. However, too much diffusion will over-smooth the solution and potentially counteract any benefits of increased resolution.

Concern for the dynamics at very high resolutions generally revolves around “complex orography” and “steep slopes”. Irish geography is fairly benign in these respects, and so testing may not push the dynamics to the limit. Put another way, a configuration that is found to be sufficient for Ireland may not be adequate for other regions. So in addition to the Irish tests with the 22nd of February 2021 case, experiments were run on 500 m-resolution domains over the Canary Islands and Greenland, using cases previously studied by DMI and AEMET. Unsurprisingly, a case of extreme wind over the south of Greenland during the 27th-28th of December 2017, with an observed mean wind-speed of 46 m/s, proved the greatest challenge for stability. This required a predictor-corrector scheme with a 10s time-step.

For the tests over the Canary Islands (25th-26th of February 2018), as well as all of the Irish domain experiments, a time-step of 15s was found to be sufficient for stability using the SETTLS scheme (default in the HARMONIE-AROME CSC) on both quadratic and cubic grids. Extensive testing of the spectral horizontal diffusion showed that the namelist settings REXPDH=4 and RDAMP*=1, on a cubic grid, were a sensible (perhaps over-cautious) choice. Full details of these experiments may be found in the technical note, available from Met Éireann.

2.3 Boundary coupling

When running a 2.5 km-resolution HARMONIE-AROME forecast with lateral boundary conditions (LBC) from the IFS, only the dynamics fields are used at all coupling times by default. The cloud water species - ice (I) and liquid (L) - as well as the hydrometeors - graupel (G), rain (R), snow (S) - are only coupled at the initial time. However it is possible to include them at all times, as long as they exist in the LBC files. Figure 1 shows the effect of the additional coupling of cloud water and hydrometeors in terms of 24-hour rainfall accumulation on the large IRELAND25 domain (the operational domain at Met Éireann until 2018). The impact of the change of coupling would seem to be insignificant, occurring (not surprisingly) close to the boundaries far from our region of interest, the island of Ireland.

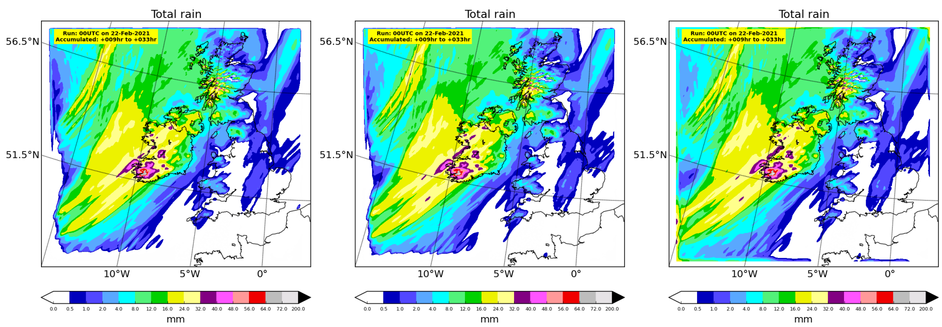

Figure 1: Forecasted 24-hour accumulated rainfall for the 22nd of February case using the IRELAND25 domain with (left to right) default IFS LBC coupling; coupling I/L; coupling all I/L/G/R/S.

It is a different matter when we have a geographically-small domain, unavoidable when we move to higher resolutions. An example is shown for the smaller 500×500 domain covering the east of Ireland at 500 m resolution in Fig. 2; for comparison the 2.5 km reference is shown zoomed into the region on the left panel. Now the dry regions "close" to the boundaries are much more significant, and the boundary spin-up is clearly an issue of concern: it would suggest that full coupling is essential for small domains.

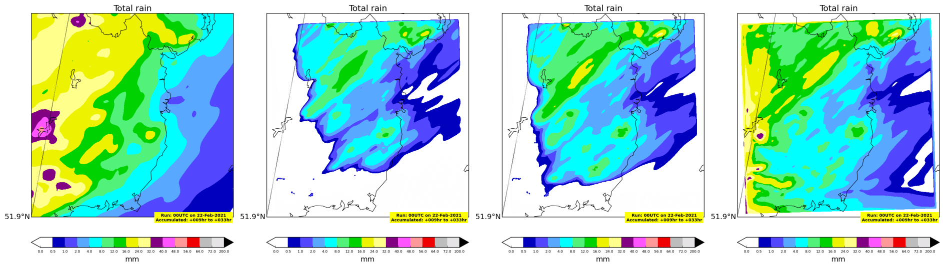

Figure 2: Forecasted 24-hour accumulated rainfall for the 22nd of February case. Left to right: 2.5 km forecast zoomed into the high-resolution domain region; 500 m domain with default IFS LBC coupling, with coupling of I/L, and with coupling of all I/L/G/R/S.

2.4 Domain size

Results in the previous section showed the sensitivity of rainfall amounts to the LBC coupling. Figure 3 shows snapshots of total cloud cover forecasts at 500 m resolution where all experiments use the default coupling, but the domain size is progressively increased. The domain in the third panel, where we begin to see some convergence in the predicted cloud structure, has horizontal dimensions 720×600. When run in single precision, a simulation on this domain costs roughly the same as double precision simulation on a 500×500 domain (the left panel of Fig. 3).

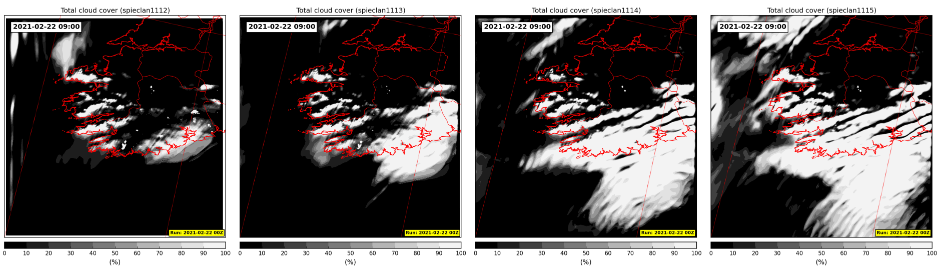

Figure 3: Forecasted total cloud cover during the 22nd of February case, 500 m resolution using IFS LBC with default coupling. Domain size increases from left to right, with the region shown corresponding to the smallest 500×500 domain on the left.

3 Results of Cycling Experiments

Longer cycling experiments were run in order to generate verification statistics on accuracy, and to test for any nonlinear instabilities which might arise. Simple upper-air blending was used, rather than any more complicated data assimilation. Three-hour cycling was used, with a 33-hour forecast at 0000 UTC and a 24-hour forecast at 1200 UTC. Two test periods were considered: the 3rd to 16th of February 2020, which contained Storms Ciara and Dennis, and the 10th to 24th of April 2021, a calmer, more stable period with a number of fog events.

3.1 Domains at 500 m

A number of 500 m-resolution domains were initially chosen for longer cycling tests. These are shown in Fig. 4. The two smaller domains have dimension 720×600, following the results shown in Section 2.4 above. As was seen there, larger domains are preferable, and so a third 500 m domain, of size 1200×1200 was also tested (red domain in Fig. 4). Due to the cost of this large domain, the experiment was run for just 7 days for the February case only, from the 3rd to 10th of February 2020. Full IFS LBC coupling (i.e. I, L, G, R, and S) was used.

Results can be compared for stations in the overlapping region of the three domains visible in Fig. 4. Scores of MSLP and 10 m wind-speed were found to be quite comparable. For 2 m temperature bigger differences were seen, with stations near the domain boundaries showing very different cloud cover (as seen in Fig. 3) and dominating the errors.

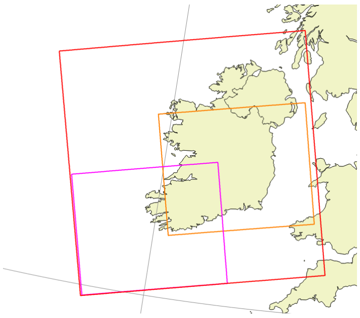

Figure 4: Larger test domains, of dimension 720×600 (SWIRL500W2, purple, and EIRL500W2, orange) and 1200×1200 (LIRL500, red).

The domain size and boundary effects are most clearly visible in precipitation forecasts. Figure 5 shows time-series for the three experiments. While no experiment is perfect, the green curve (EIRL500W2 domain in Fig. 4) stands out from the 10th of February, when it seems to significantly miss the observed precipitation. Figure 6 shows sample maps of 12-hour accumulations during this period, along with the observed amounts. Again, we see clearly how the EIRL500W2 domain is suffering near its south-west boundary.

Note that in all of these experiments IFS LBC were used with full coupling of I/L/G/R/S. We can instead nest within a 2.5 km HARMONIE-AROME forecast, also with I/L/G/R/S coupling. Figure 7 compares the total

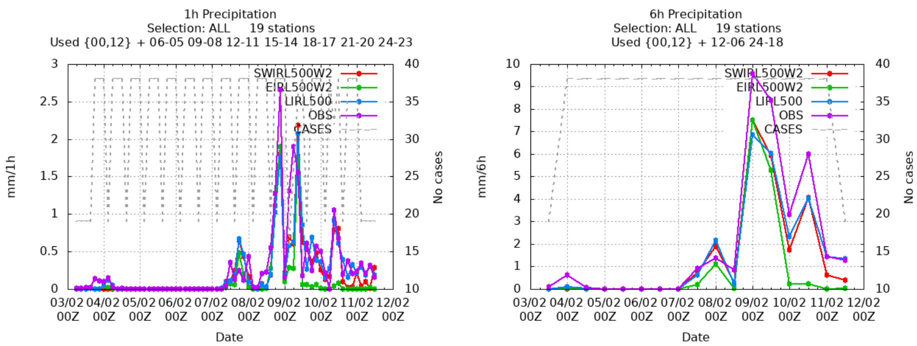

Figure 5: Averaged time-series for 1-hour (left) and 6-hour (right) precipitation for 500 m experiments during February 2020. The experiments use the domains shown in Fig. 4.

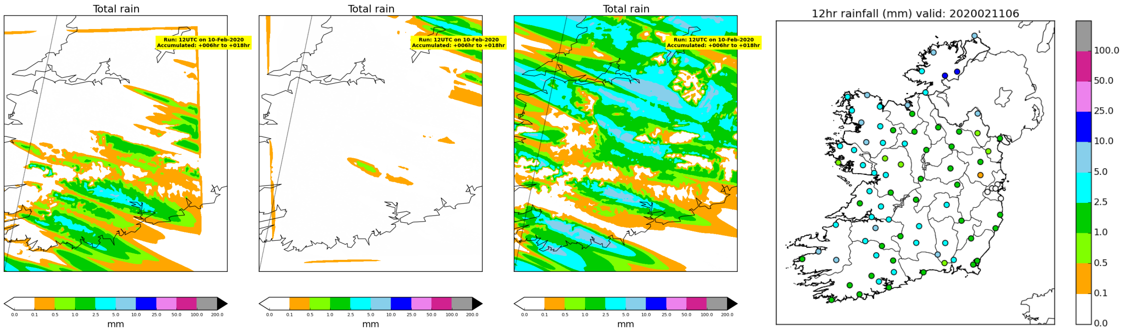

Figure 6: Forecasted 12-hour accumulated precipitation valid at 06 UTC on the 11th of February 2020, using the 12 UTC cycle on the 10th. The snapshots (from left) show the overlap regions from experiments with domains SWIRL500W2, EIRL500W2 and LIRL500; all shown in Fig. 4. Right: observations.

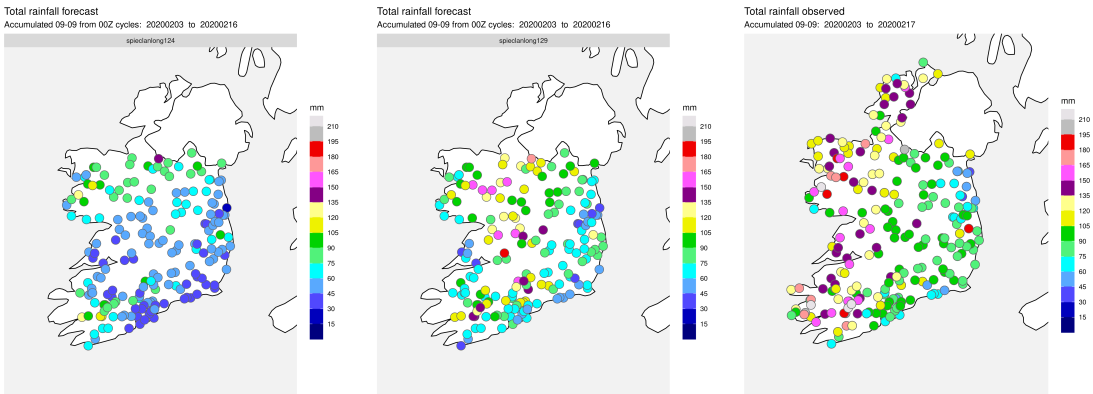

Figure 7: Accumulated rainfall for the February test period, using the +9 to +33 hour forecasts from the 0000 UTC cycles to sum the daily 09-09 amounts. Experiments at 500 m resolution on EIRL500W2 domain (see Fig. 4) using LBC from IFS (left) and HARMONIE-AROME (middle). Right: observed accumulations.

forecasted rainfall accumulations over the two-week February period between experiments with LBC from IFS and HARMONIE-AROME. While all the boundary regions in the nested experiment (middle panel) are still too dry compared with observed amounts, they show significant improvement from when IFS LBC are used.

3.2 Comparison of various resolutions

As illustrated in Sections 2.4 and 3.1, the domain size can have a major impact on the performance of the sub-kilometre resolution simulations, particularly in relation to precipitation. This highlights the need for a "large" domain, in the geographic sense, i. e. we want our region of interest to be far away from the boundaries. The use of the large LIRL500 domain in Fig. 4, however, is prohibitively expensive from an operational perspective. As a compromise, we also consider a 800×800 domain with 750 m resolution, IRL750, which matches the same region as LIRL500. Previous testing at Met Éireann has suggested a 30s time-step is sufficient for stability at this resolution, compared to a 15s time-step at 500 m, which ultimately results in the 750 m runs costing approximately 80% of the smaller-domain 720×600 500 m simulations.

Table 1 describes experiments for comparison for the February 2020 test period. In addition to the 2.5 km references, and the 750 m mentioned above, the 500 m domain is kept but only when nested within a reference

Table 1: Details of cycling experiments. The 2.5 km domain, IRELAND25, can be seen in Fig. 1. The sub-kilometre resolution domains are shown in Fig. 4: IRL750 matches the region of LIRL500. Full coupling of the LBC cloud and hydrometeors is used for the sub-kilometre experiments. For the spectral diffusion, all experiments use RRDXTAU=123 and REXPDH=4. The 2.5 km experiments (*) use the HARMONIE-AROME default of RDAMP=20 for all variables except for RDAMPPD=200000. The higher-resolution use the same RDAMP on all. ECOCLIMAP SG is used in all experiments.

Exp	Domain	Resolution	Vertical	Time-step	Grid	RDAMP	LBC
104	IRELAND25	2.5 km	65	75	Q	20*	IFS
106	IRELAND25	2.5 km	90	75	Q	20*	IFS
144	IRL750	750 m	90	30	C	10	IFS
149	IRL750	750 m	90	30	C	10	HAR
129	EIRL500W2	500 m	90	15	C	1	HAR

HARMONIE-AROME. As discussed in Section 3.1, this mitigates the problem of dry boundaries somewhat.

Point verification of these experiments for a selection of near-surface parameters is shown in Fig. 8. It is immediately evident that increased horizontal resolution does not necessarily yield better results, in terms of these metrics anyway. On the other hand, looking at 10 m wind-speed (bottom row of Fig. 8) suggests that the increase in number of vertical levels has a large impact. From the time-series (lower right panel), we can see that this impact comes particularly from the higher wind-speeds, which tend to be over-predicted by the 65-level experiment (in red).[2] Once we increase to 90 levels (green), many of the remaining results are comparable with those experiments at sub-kilometre horizontal resolution. The results also appear to suggest that it is preferable to choose the 750 m resolution on the larger domain, rather than a smaller domain at 500 m.

In terms of precipitation, there is a notable increase in the total rainfall accumulation over the February 2020 period when coupling the IRL750 run to HARMONIE-AROME LBCs as opposed to IFS (see Fig. 9), in line with the behaviour over the EIRL500W2 domain observed in Section 3.1. Rainfall totals are also increased slightly when switching from 65 to 90 levels at 2.5 km resolution. A study of the MÉRA reanalysis (Whelan et al., 2018) found a general dry bias in the mountainous west of the country, so an increase here is welcome.

It can be seen in Fig. 8 that HARMONIE-AROME coupling tended to increase the wind-speed bias and RMSE due to an over-prediction of the strongest wind-speeds in particular. However, it should be noted that this may be an inherited bias from the host model which had 65 vertical levels.

3.3 Impact on fog

The impact of increased vertical and horizontal resolution on HARMONIE-AROME fog forecasts over Ireland was also assessed for cases of interest in the two test periods, yielding four fog cases in total (06/02/2020 and 13-15/04/2021). For each case the 1200 UTC forecast on the preceding day was considered in the analysis. As discussed in the previous Newsletter (Clancy et al,. 2021), operational HARMONIE-AROME guidance at Met Éireann frequently over-predicts fog over Ireland and the surrounding seas.

Focussing on the April 14th case, sample cloud base height forecasts comparing 65 and 90 vertical levels, with 2.5 km resolution, are given in Fig. 10. The default 65 level simulation indicates substantial regions with low cloud base (<100m, given by red in the maps) in the midlands/north of Ireland and in the Irish sea. These low visibility regions are significantly reduced in size in the 90 level run, with the sample cloud cross-sections indicating a notable reduction in the sea fog in particular. The corresponding 0600 UTC IR MSG satellite image and observations are shown in Fig. 11 for comparison; while some fog is present, it is not as widespread as suggested by HARMONIE-AROME, although it appears that the increase in vertical resolution helps to remove

[2]Note that the lowest model level is approximately 12 m and 5 m for 65 and 90 vertical levels, respectively. As 10 m wind speed is a diagnostic field, i.e. extrapolation/interpolation to 10 m must be carried out, it may be worth considering these differences when interpreting the results at different vertical resolutions.

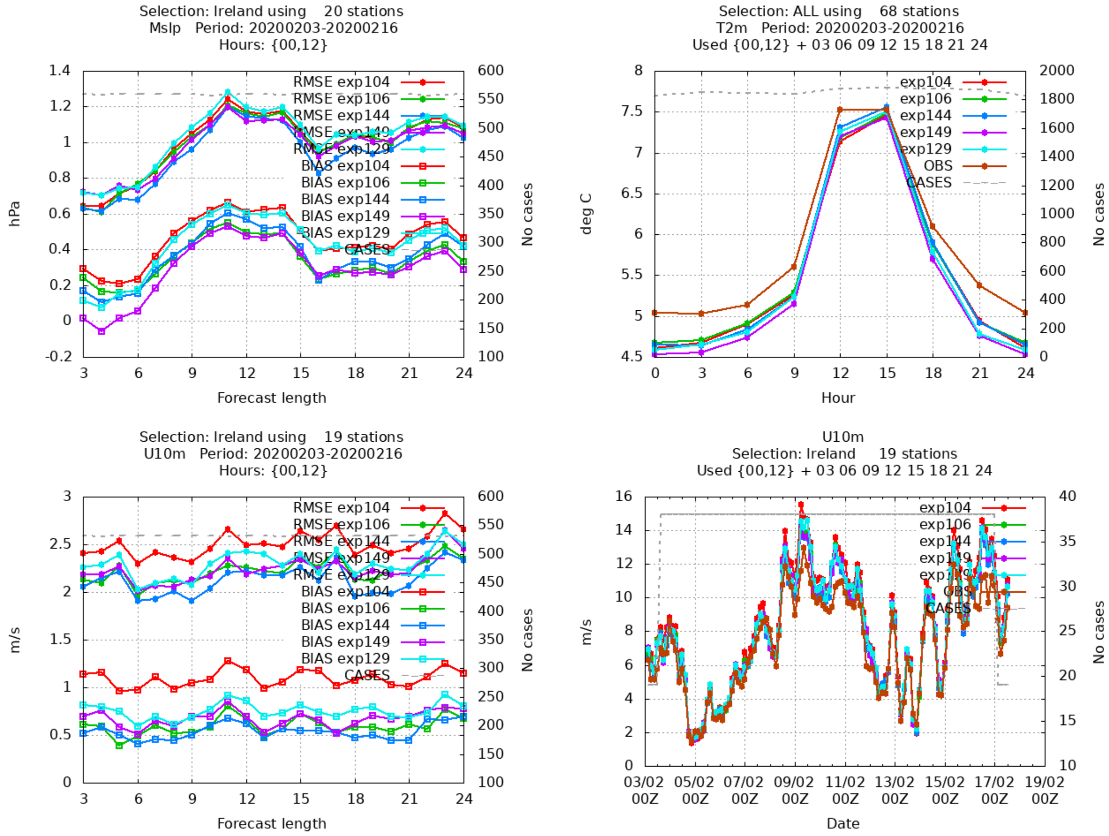

Figure 8: Point verification of the experiments listed in Table 1. Top: MSLP RMSE/bias (left) and 2 m temperature daily cycle (right). Bottom: 10 m wind-speed, RMSE/bias (left) and averaged time-series (right)

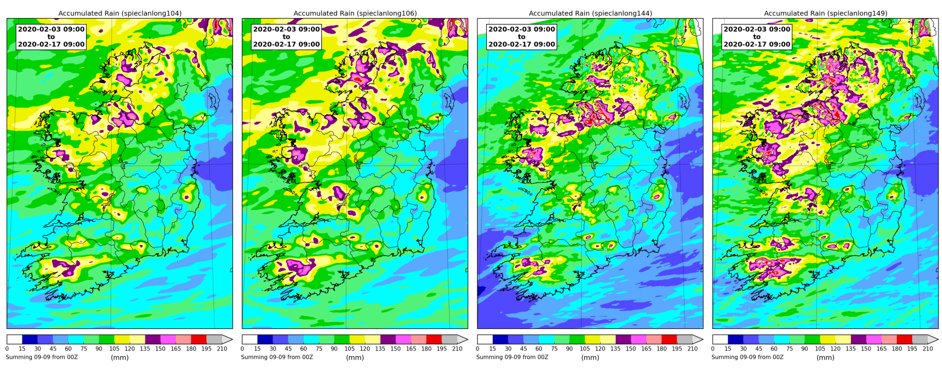

Figure 9: Accumulated rainfall for the February period, using the +9 to +33 hour forecasts from the 0000 UTC cycles to sum daily 09-09 amounts. Left to right: experiments 104, 106, 144, and 149, as described in Table 1.

some of the erroneously-forecasted fog. This reduction in fog extent in the 90 level runs is consistent across each of the four fog cases considered. Both land and sea fog appear to be reduced by the increase in vertical resolution, particularly the latter.

The role played by increased horizontal resolution has also been assessed for the 750 m and 500 m resolution

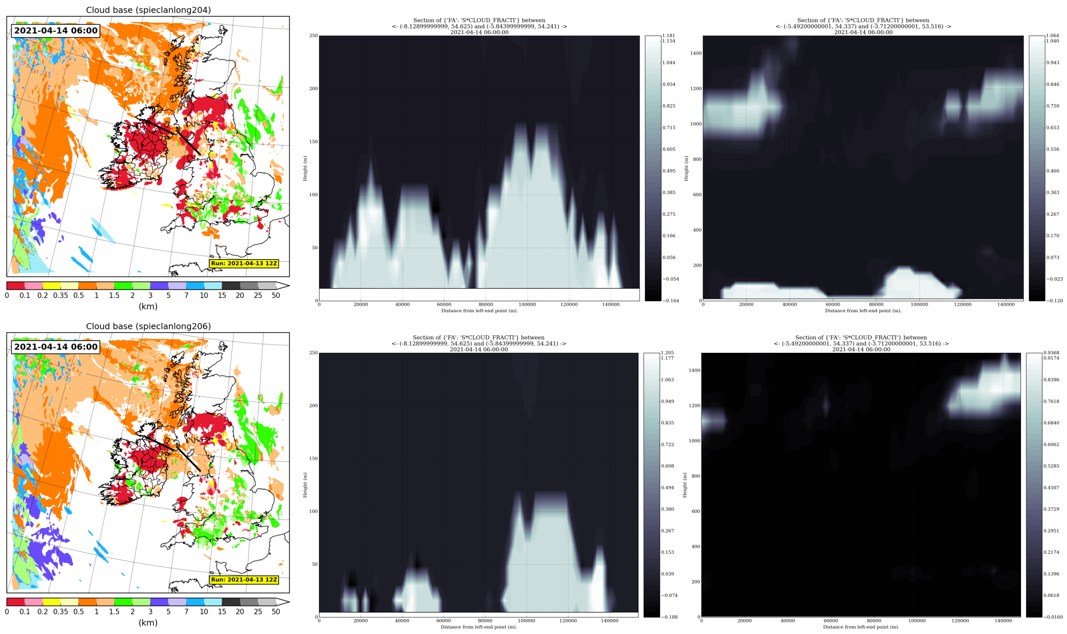

Figure 10: Left: Cloud base height forecasts over the IRELAND25 domain valid at 0600 UTC on April 14th 2021, using the 1200 UTC forecast on April 13th. Two transects, one over land and sea, are indicated by the black lines. Corresponding cloud cross-sections for (middle) the transect over Ireland, between 0 and 250 m above the surface, and (right) the transect over the Irish Sea, between 0 and 1500 m above the surface. The 65 and 90 level experiments are above and below, respectively, with configurations given by 104 and 106 in Table 1.

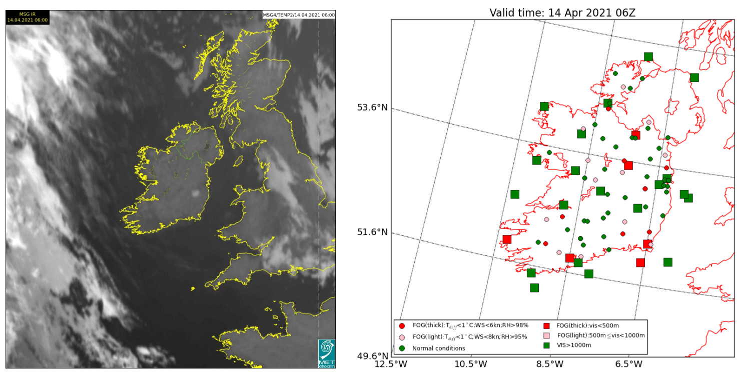

Figure 11: MSG IR satellite image (left) and observations (right) valid at 0600 UTC on April 14th 2021.

experiments. Total fog frequency is compared by constructing visibility distributions over the entire forecast length, as illustrated in Fig. 12, for all cases available. Here the 2.5 km and 750 m runs have been regridded onto the EIRL500W2 grid using the "regrid" transformation in harp's "read_forecast" function, and all gridpoints over land and sea are considered in the histograms. Mixed behaviour can be observed over the four cases, with the higher-resolution runs leading to slightly less, similar, or significantly more fog relative to the 2.5 km run with 90 levels. It is also interesting to note the impact of switching from the smaller EIRL500W2 domain to the larger IRL750 domain, which tends to reduce fog frequency overall, again highlighting the importance of domain size effects.

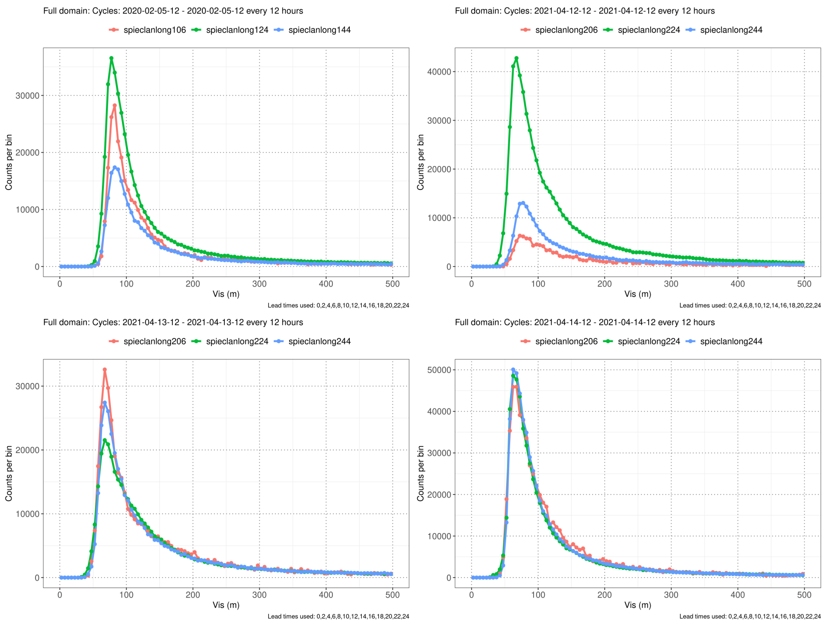

Figure 12: Visibility histograms from the 1200 UTC forecasts on (from top left to bottom right) 5th February 2020 and 12th-14th April 2021. The red, green, and blue lines represent 2.5 km, 500 m, and 750 m resolution experiments, respectively. Experiment configurations are the same as 106, 129, and 144 in Table 1, respectively, except that full coupling with IFS LBCs are used for the EIRL500W2 run. Lead times 0-24, in steps of 2 hours, are used to construct the distributions, which are zoomed into the the lowest visibility range.

4 Summary

The suite of higher horizontal and/or vertical resolution experiments discussed in this article has highlighted a number of important aspects to consider when developing a prospective sub-kilometre scale HARMONIE-AROME model for operational guidance. LBC coupling and the domain size are both found to have a strong influence on forecast performance, particularly in relation to precipitation. The increase in vertical resolution to 90 levels appears to be beneficial overall, improving both MSLP and wind-speed scores over Ireland while also reducing fog prevalence over the small number of cases available in this study.

While our results indicate that it is preferable to use a large 750 m resolution domain as opposed to a smaller domain at 500 m, it is difficult to draw conclusions on the overall benefit of the 750 m runs relative to the 2.5 km reference at the same vertical resolution. In terms of point verification at least, increasing horizontal resolution does not simply lead to better averaged scores. However, there are of course limitations to using point verification at such resolutions, and objective assessment using spatial methods will be considered further. Preliminary results using CRPS scores over a common neighbourhood for the 2.5 km and 750 m simulations, based on the methodology described in Mittermaier (2014), are found to generally corroborate the point verification results.

Forecasts on domains of much higher resolution are likely to be of more obvious benefit for extremes, rather than for general conditions. Additional efforts will therefore be made to next assess the performance of the high-resolution models in extreme weather events, with initial work suggesting roughly similar wind-speed and precipitation forecasts for the 750 m and 2.5 km runs during Storms Ciara and Dennis in February 2020.

One should also keep in mind that Ireland is relatively flat with little complex orography, particularly in the east of the country, and as such the benefit of increased resolution to capture local orographic features may be minimal. This is in marked contrast with sub-kilometre experiments over Greenland and the Faroe Islands carried out at DMI, in which the high-resolution model demonstrates a clear value over its 2.5 km counterpart for storm forecasting in regions of complex orography (Yang, 2019).

Finally, we note some technical issues encountered during this work. Tests with small domains to the south-west of Ireland (such as the purple in Fig. 4) failed in the Prepare_pgd stage when attempting to use ECOCLIMAP SG; version 2.5_plus had to be used instead. This was traced to an interpolation issue when a domain does not have "enough" land points, and is currently under investigation within the community.

The use of single precision was discussed in Section 2.1. In general this was successful and yielded satisfactory results. However, one problem encountered here related to nesting within another AROME experiment: it was found that the host experiment had to be in double precision. This issue remains to be investigated.

5 Acknowledgements

Computing resources for this work were provided through a Special Project at ECMWF.

6 References

Antoine S., R.Honnert and Y.Seity, Improvement of fog forecast at hectometric scales in AROME, ACCORD Newsletter 1, October 2021.

Bessardon G., C.Clancy, C.Daly, R.Darcy, E.Gleeson, A.Hally and E.Whelan, Met Éireann Updates, ALADIN-HIRLAM Newsletter 14, January 2020.

Chikhi W., A.Ambar and M.Mokhtari, Testing visibility diagnostics in AROME at high resolution, ACCORD Newsletter 1, October 2021.

Clancy C., E.Gleeson, and E.McAufield, Met Éireann's Physics Testing in HARMONIE-AROME CY43, ACCORD Newsletter 1, October 2021.

Feddersen H., Running HarmonEPS ensemble members in single precision. 1st ACCORD All Staff Workshop 2021. http://www.umr-cnrm.fr/accord/IMG/pdf/feddersen_accord_asw2021_singprecmbrs.pdf

HIRLAM, Harmonie 43h2.1 Release Notes, 2020. https://hirlam.org/trac/wiki/ReleaseNotes/harmonie-43h2.1

Lang S.T.K., A.Dawson, M.Diamantakis, P.Dueben, S.Hatfield, M.Leutbecher, T.Palmer, F.Prates, C.D.Roberts, I.Sandu and N.Wedi, More accuracy with less precision, Q.J.R. Meteorol. Soc., 2021

Mittermaier, M., A Strategy for Verifying Near-Convection-Resolving Model Forecasts at Observing Sites, Weather and Forecasting, 29(2), 185-204, 2014

Suárez-Molina D. and J.Calvo, Very high-resolution experiments at AEMET, ALADIN-HIRLAM Newsletter 16, February 2021

Váňă F., P.Düben, S.Lang, T.Palmer, M.Leutbecher, D.Salmond, and G.Carver, Single Precision in Weather Forecasting Models: An Evaluation with the IFS, Mon. Wea. Rev., 145(2), 495–502, 2017

Vignes O., Single precision in cycle 43. Joint 29th ALADIN Workshop & HIRLAM ASM 2019. http://www.umr-cnrm.fr/aladin/IMG/pdf/sp_cy43_olev_asm2019.pdf

Whelan E., E.Gleeson, and J.Hanley, An Evaluation of MÉRA, a High-Resolution Mesoscale Regional Reanalysis, J. Appl. Meteor. Climatol., 57, 2179–2196, 2018

Yang X., Sub-km HARMONIE and on-demand setup for storm forecast, ALADIN-HIRLAM Newsletter 10, Jan 2018

Yang X., TAS, an operational forecast model at hectometric scale, ALADIN-HIRLAM Newsletter 12, Jan 2019