

Final Report for Project **1476**

Project title: **CAIRT Gravity Wave Resolution Study**

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Report period: **Jan. 1, 2025 – Dec. 31, 2025**

## 1 Background

Project bb1476 supported the ESA Earth Explorer 11 mission proposal Changing-Atmosphere Infrared Tomography (CAIRT). To this end, simulations with the ICOSahedral Non-hydrostatic modelling framework (ICON) were conducted providing high-resolution upper atmosphere data. This project benefited from achievements of DKRZ project bm1233, where developments led to a setup with a model lid of 250 km and a horizontal resolution of 10 km (R2B8). To provide a feature-rich atmospheric scenario, we targeted a sudden stratospheric warming (SSW) event centered on Jan 1, 2019.

## 2 Simulation setup

To reproduce the historic atmospheric state as accurately as possible, the simulation contained three phases:

1. Oct 15–Nov 15: 20 km (R2B7) run nudged to IFS operational data
2. Nov 15–Dec 15: 10 km (R2B8) run nudged and initialized from (1)
3. Dec 15–Jan 15: R2B8 free run initialized from (2)

The nudging was applied between 2 and 45 km. Hourly output was produced for all runs for the relevant dynamic and thermodynamic variables.

## 3 Preliminary results

A main motivation for the simulation effort was to represent small-scale structures that arise from gravity wave (GW) dynamics, which become a dominant driver of atmospheric dynamics in the upper atmosphere. By comparing the three simulation setups described above, fig. 1 demonstrates a clear increase in the kinetic energy spectrum, in the relevant wavelength spectrum between 5000 km and 40 km. There are two distinct observations:

- (i) Between 5000 km and 800 km (synoptic and sub-synoptic scale) the free-running R2B8 simulation exhibits a substantially elevated kinetic energy spectrum following a power law with exponent -3. This indicates 2D turbulent dynamics.
- (ii) Between 500 km and 40 km (meso- and sub-meso scale) both, the nudged and the free-running R2B8 simulation, exhibit elevated spectral energy following a power law with exponent -5/3. This indicates 3D turbulent dynamics and gravity wave dynamics.

This comparison between the two available resolutions demonstrates the added value of the higher resolution in that both R2B8 simulations reproduce the canonically known sub-spectra for 2D and 3D turbulence [2].

Both, figs. 2 and 3, show a SSW signal in the stratopause region at about 50 km with an onset on Dec 22, 2018. Subsequently, the polar vortex is weakened until Jan 9, 2019. The weakening of zonal velocity between 25 km and 65 km (cf. fig. 2) on Dec 22, 2018, correlates with

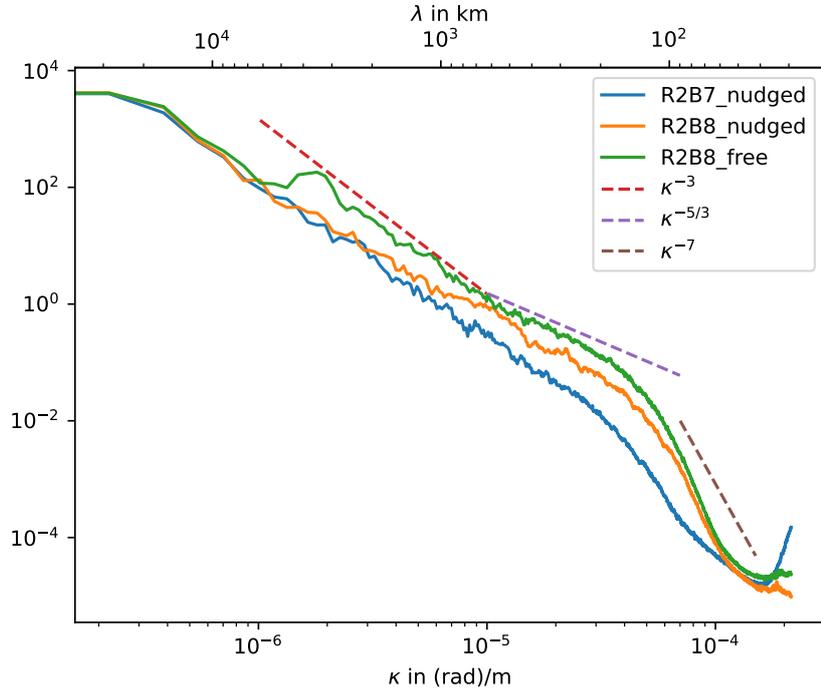


Figure 1: Kinetic energy power spectrum. Shown is the horizontal power spectrum of kinetic energy at 220 km height for Nov 11, 2018 (R2B7, nudged), Dec 15, 2018 (R2B8, nudged) and Jan 14, 2019 (R2B8, free running), each at 00:00:00 UTC.

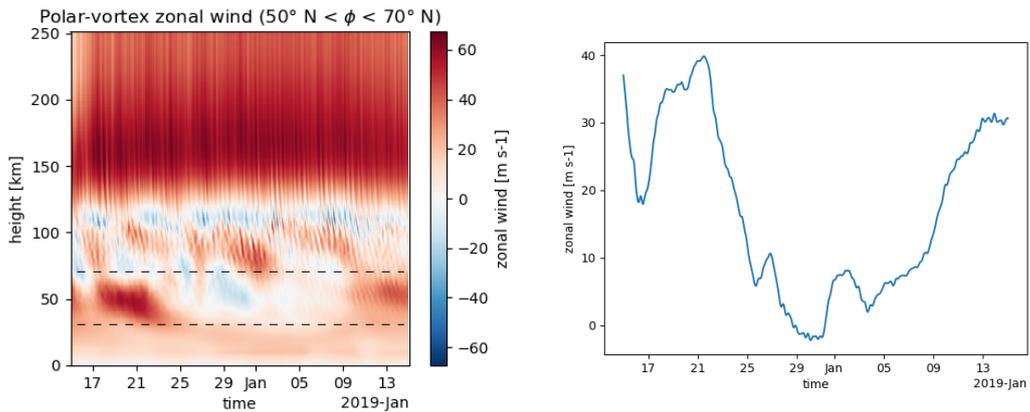


Figure 2: Average of zonal wind between 50°N and 70°N. The left panel shows the time evolution of the polar vortex zonal winds as function of height. The right panel shows the average over heights of 25–65 km as indicated by the area between the dashed lines in the left panel.

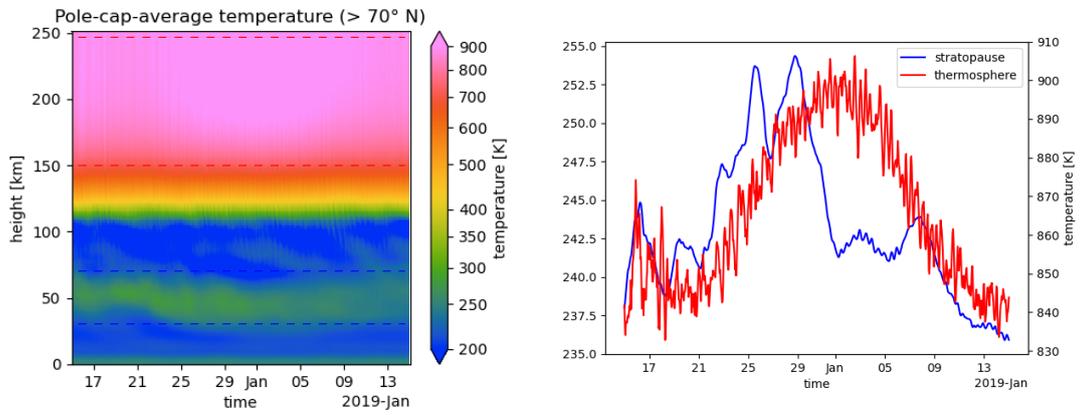


Figure 3: Left: Polecap average of temperature between 70°N and 90°N. Right: The averaged temperatures in the areas marked by dashed lines for the stratosphere and thermosphere, respectively.

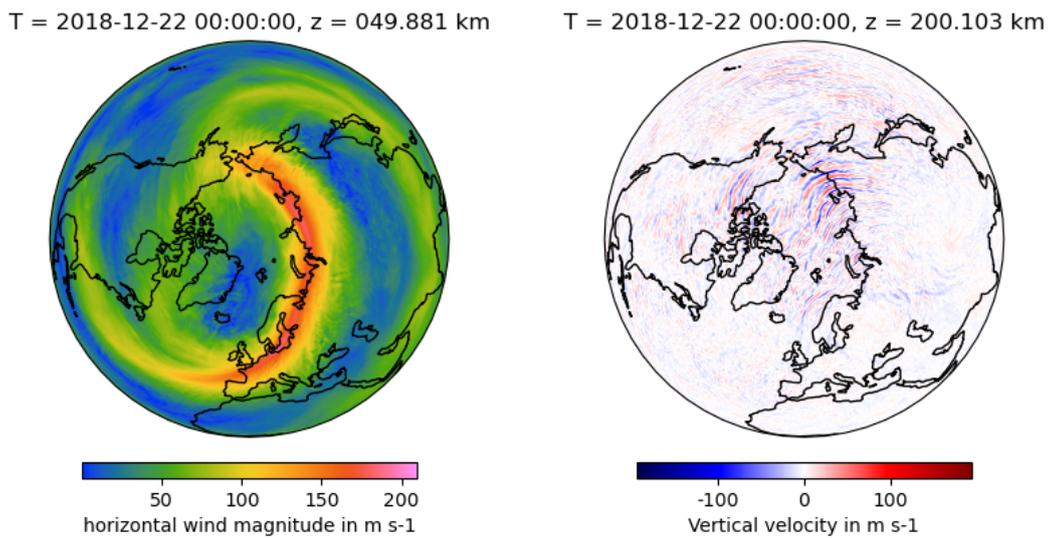


Figure 4: Simultaneous snapshots of horizontal wind at 50 km and vertical wind at 220 km.

an increase in temperature in the same region. Furthermore, the thermosphere above 150 km follows this trend (cf. fig. 3).

The value of explicitly resolving GWs at R2B8 is seen in fig. 4: The polar vortex centered at the stratopause at 50 km generates GW patterns in the thermosphere that align closely with the stratospheric jet pattern. They are likely generated by jet instabilities.

## 4 Additional analysis

We assessed how well CAIRT would observe the atmosphere after accounting for the substantial differences between modeled and measured states. This included explicit treatment of observing geometry, radiative transfer, volume averaging in the retrieval process, and scan-induced blurring. To achieve this, we:

1. Extracted and prepared high-resolution model fields, including both simulations produced within this project and earlier datasets such as the DYAMOND global storm-resolving runs, ensuring coverage of key dynamical regimes
2. Generated synthetic radiances and retrieval products to quantify the effects of sampling, line-of-sight integration, radiance averaging and retrieval assumptions on CAIRT’s ability to resolve fine-scale thermal and compositional structure, with particular focus on gravity waves
3. Delivered processed datasets and performance metrics into the CAIRT Report for Selection [1], providing evidence to support instrument specification and demonstrating scientific readiness
4. Conducted validation and sensitivity analyses to benchmark results against existing satellite observations and assess the influence of model and radiative-transfer uncertainties on performance estimates

## 5 Data archiving statement

The data produced within the project bb1476 will be used by project bm1233. Hence, it will not be archived for now. Long-term storage resources are therefore not necessary.

## 6 Publications

Besides the CAIRT Report for Selection, our results will enter a future publication about the SSW event. The study will be completed and reported in the context of bm1233.

## References

- [1] *Earth Explorer 11 Candidate Mission CAIRT Report for Assessment Issue Date: 15/09/2023 Ref: ESA-EOPSM-CAIR-RP-4372*. URL: [https://esamultimedia.esa.int/docs/EarthObservation/EE11\\_CAIRT\\_Report\\_for\\_Assessment\\_v1.0\\_15Sept23.pdf](https://esamultimedia.esa.int/docs/EarthObservation/EE11_CAIRT_Report_for_Assessment_v1.0_15Sept23.pdf).
- [2] Ka Kit Tung and Wendell Welch Orlando. “The  $K^{-3}$  and  $K^{-5/3}$  Energy Spectrum of Atmospheric Turbulence: Quasigeostrophic Two-Level Model Simulation”. In: *Journal of the Atmospheric Sciences* 60.6 (Mar. 2003), pp. 824–835. ISSN: 0022-4928, 1520-0469. DOI: [10.1175/1520-0469\(2003\)060<0824:TKAKES>2.0.CO;2](https://doi.org/10.1175/1520-0469(2003)060<0824:TKAKES>2.0.CO;2); 2. URL: [http://journals.ametsoc.org/doi/10.1175/1520-0469\(2003\)060%3C0824:TKAKES%3E2.0.CO;2](http://journals.ametsoc.org/doi/10.1175/1520-0469(2003)060%3C0824:TKAKES%3E2.0.CO;2) (visited on 11/13/2025).