Atmospheric Chemistry and Physics

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Solar-tidal Phase and Amplitude in Middle-atmosphere Winds Investigated From an Adaptive Rational Neural Operator, two Reanalyses and Meteor-Radar Observations

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Author Comment (AC2): Reply on Referee Comment RC2

Open discussion of egusphere-2026-4972, Atmospheric Chemistry and Physics

Response to Anonymous Referee #2 (RC2)

Dear Referee,

We thank Referee #2 for a careful and constructive review. We agree with the central point: in its present form, the manuscript does not say early or clearly enough which atmospheric-science question it addresses, it mixes atmospheric motivation with machine-learning (ML) detail, and several sentences are abstract to the point of being unclear. We will make a major revision along the lines the referee suggests. The revised manuscript will (i) state the atmospheric-science question first: how much of the observed solar-tidal wind amplitude and phase survives at about 80 km in ERA5 and MERRA-2, and in a forecast model trained on them, measured against meteor radars; (ii) separate the atmospheric science from the ML methodology, which will be presented as a tool in a dedicated Methods subsection, with technical detail moved to an Appendix and the Supplement; (iii) tighten the statements on

observations and on novelty and cite the earlier reanalysis–meteor-radar comparisons; and (iv) rewrite unclear passages in plain language. The referee's comments are reproduced below, followed by our response and the planned changes. Line numbers refer to the discussion paper.

General comments:

"I am not an expert on machine learning (ML) techniques and will thus limit my comments on the science, the organization of the manuscript and the general readability. I trust that other reviewers will comment on the ML aspects of the manuscript and will assume in the following that the ML algorithms follow accepted standards. The manuscript uses an ERA-5 reanalysis-trained ML approach to obtain tidal amplitudes and phases in the mesosphere. The latter are then statistically validated with three meteor radars from the Chinese Meridian Chain and MERRA-2. The ML-model produces some improvements but does not fully overcome the inherent tidal damping in less-data constrained regions of the reanalysis."

Response:

We agree with this summary, and we will make the last point a central message of the revised paper rather than a caveat. We have computed the tidal amplitudes and phases of the ATMNO forecasts themselves at the three radar sites (80 km, 11 July–31 December 2024). ATMNO reproduces the ERA5 tides closely (ATMNO/ERA5 amplitude ratios 0.88–1.17, phase differences within 0.35 h) and therefore shows the same underestimation as ERA5: ERA5 retains 18–33 % of the observed semidiurnal amplitude and ATMNO 20–31 %; for the diurnal tide the ranges are 17–88 % and 16–91 %. The model improves short-range forecasts relative to persistence while reproducing the tidal amplitudes of the reanalysis on which it is trained.

"Overall, the manuscript is very hard to follow (see the more details comments below) and does not clearly say upfront what science problem it is trying to solve. From my (atmospheric science) perspective, the manuscript is heavy on ML technical aspects with the advances in understanding the atmosphere not very clear. As a result, I felt somewhat lost in reviewing it and really struggled to identify the take-home message. I recommend a major revision to make the manuscript accessible to the broader middle atmosphere community. This could be done by more clearly separate (atmospheric) science and ML parts."

Response:

We thank the referee for this assessment and accept it. The revised manuscript will be reorganised as follows:

1. Introduction: atmospheric motivation only. This covers tides as the dominant short-period wind signal near 80 km; what is observed there (radars, lidars, satellites) and what only reanalyses provide (global, gridded, continuous winds); what is known about tides in reanalyses, including earlier radar comparisons; the specific question; and, in one short paragraph, why a reanalysis-trained forecast model is included.

2. Data and observations: ERA5, MERRA-2, meteor radars, including the upper-level damping in both reanalyses, collocation and quality control.

3. Methods: (a) harmonic (tidal) analysis applied identically to radar, reanalysis and model winds; (b) the forecast model as a tool, described in plain terms in one subsection, with architectural detail, baselines and training settings moved to an Appendix and the Supplement; (c) statistics.

4. Results, ordered by scientific question: (a) how much tidal amplitude and phase ERA5 and MERRA-2 retain at 80 km relative to the radars; (b) whether a model trained on the reanalysis reproduces this underestimation; (c) forecast skill against persistence and the radars; (d) ML-specific diagnostics (ablations, architecture comparison), shortened and partly moved to the Supplement.

5. Discussion: mechanism of the underestimation (upper-level damping and sparse assimilated observations), migrating versus non-migrating contributions, implications for users of reanalysis and for ML models trained on it, and limitations.

6. Conclusions: a short list of take-home messages written for the middle-atmosphere community.

"I also feel that the apparent use of LLMs to polish the text resulted in statements that are not easy to understand."

Response:

We thank the referee for raising this point. A language model was used only to polish the wording of text written by the authors; it generated no scientific content, data, analysis or interpretation. We agree that this editing produced compressed and abstract phrasing in several places, and we take responsibility for it. We will rewrite the abstract, the definitions and the passages identified by the referee in plain language, and define every technical term at first use.

Abstract:

"The last third of the abstract is hard to follow and should be reformulated to make it more clear what the main scientific finding/relevance of the manuscript is. For example, it is not clear to me what the last sentence is trying to say "… recovered frequencies give a representation that can be audited directly against observations." Overall, the abstract does not give a good summary of what the manuscript is about and what atmospheric science problem it is attempting to solve."

Response:

We apologise that the abstract did not make the scientific question and the main findings clear, and we thank the referee for pointing this out. In the revised manuscript the abstract will be rewritten so that it (i) opens with the atmospheric question: how much of the observed solar-tidal wind amplitude and phase at about 80 km is present in ERA5 and MERRA-2, and whether a forecast model trained on ERA5 reproduces the same underestimation; (ii) states the data and method in plain sentences: hourly winds from three meteor radars of the Chinese Meridian Project compared with collocated reanalysis winds, and the forecast model evaluated against the same radars; (iii) gives the main quantitative findings: the fractions of the observed semidiurnal and diurnal amplitudes retained at the three stations, the phase differences, the contrast between ERA5 and MERRA-2, and the forecast skill relative to persistence and to the other architectures; and (iv) ends with the implication: the tidal amplitudes of a reanalysis bound what a model trained on it can reproduce near 80 km, so radar winds are needed to evaluate both. The last sentence of the present abstract and the pole statistics will be removed. The rewritten abstract will be provided with the revised manuscript.

Introduction:

"The introduction should be re-organized. It is quite difficult to follow because it changes back-and-forth from an atmospheric science motivation to details of machine-learning technique. It should be made clear what problem the manuscript is trying to solve before jumping into the methodology."

Response:

We agree with the referee and thank them for the suggestion. The present Introduction alternates between atmospheric motivation (paragraphs at lines 24–32 and 67–78) and ML technique (lines 43–66 and 79–85). In the revision, the Introduction will contain only the atmospheric motivation, the relevant observational and reanalysis literature, and the question stated above. The neural-operator,

state-space and Takenaka–Malmquist literature will be condensed and moved to the Methods subsection that describes the forecast model.

"Paragraph around line 35. It needs to be more clearly explained what the meaning of data-driven weather prediction is. Readers not familiar with the listed systems/models cannot easily understand this and I suggest to explicitly state that they are AI-driven. Some readers may also call numerical weather forecast "data-driven" because data are used to initialize the models. I'm a bit surprised to not see NVIDIA's Earth2Studio listed here, which even allows users to add their own data."

Response:

We thank the referee; we agree that the term is ambiguous. We will write "machine-learning (AI) weather prediction" and define it explicitly: models such as FourCastNet, Pangu-Weather, GraphCast, GenCast and ECMWF's AIFS are neural networks trained, mostly on the ERA5 reanalysis, to map the atmospheric state at one time to the state a few hours later, without explicitly solving the equations of motion; physics-based numerical weather prediction also uses observations, but only to initialise a model that integrates those equations. We will cite Ben Bouallègue et al. (2024) for an operational assessment of such systems and Lang et al. (2024) for AIFS, which is trained on ERA5 and ECMWF operational analyses. We thank the referee for pointing to NVIDIA Earth2Studio. It is an open-source Python framework for running and comparing pre-trained AI weather and climate models with a variety of data sources, rather than a forecast model itself; we will mention it as tooling of this kind (NVIDIA, 2026).

"Paragraph around line 45. ERA5 is discussed in the context of ML approaches but ERA5 is a numerical weather forecasting system. So, I do not fully understand the take home message of the paragraph. Also, what is a "uniform basis"?"

Response:

We thank the referee for the question. ERA5 is a reanalysis produced with ECMWF's numerical forecast model (IFS) and 4D-Var data assimilation; it is not an ML method. It appears in this paragraph only because we analysed the frequency spectrum of the ERA5 winds that are later used to train the model. A "uniform basis" meant a standard Fourier basis: a set of sines and cosines whose frequencies are equally spaced, so that spectral resolution is spread evenly over the frequency axis. The paragraph will be rewritten to say only what is needed: a small fraction of frequencies (1.3–3.6 % of the frequency

modes) carries 80 % of the variance in the ERA5 winds, and the 24, 12 and 8 h harmonics fall on Fourier frequencies of a 48 h window sampled every 3 h. It will be moved to the Methods subsection on the forecast model.

Conclusions (but really throughout the manuscript):

"Sentences like "Suppressing tide-frequency components at inference time nonetheless degrades skill less than energy-matched non-tidal interventions do, so the poles are best understood as a frequency-auditable coordinate system embedded in a distributed predictor rather than as carriers of individual tides." are very hard to understand. I really urge the authors to make their work more accessible."

Response:

We agree with the referee and thank them for pointing this out. The sentence will be rewritten in plain language, and the terms "frequency-auditable coordinate system" and "carriers of individual tides" will be removed from the Conclusions, the Discussion (line 476) and the closing paragraph (lines 593–595). The intervention experiment of Supplement Sect. S4 will be repeated with the tidal components identified from the spectra of the layer's basis functions, and its result will be stated in one plain sentence: the change in forecast error when these components are suppressed during forecasting, compared with suppressing a comparable amount of non-tidal signal. More generally, we will go through the manuscript sentence by sentence, avoid compound abstract nouns, define terms at first use, and place one plain-language statement of the main result at the start of each Results subsection.

Specific comments:

"Line 10. "reanalysis is in practice the only systematic source for studying and predicting this layer". I disagree with this statement. There are plenty of radar, lidar, satellite measurements in the MLT. If this statement refers to global winds, then say so. Even then, reanalysis is heavily constrained by the underlying model."

Response:

We thank the referee for this correction; the sentence will be revised. Winds in the upper mesosphere are measured routinely by meteor and MF radars and by Doppler lidars, and from space by, for example, TIMED/TIDI (e.g. Gauthier et al., 2025) and ICON/MIGHTI (Englert et al., 2017);

temperatures are observed by TIMED/SABER and Aura/MLS. Revised text: "Above the lower stratosphere, wind observations are local (radars, lidars) or sparse in time and altitude (satellites), so reanalyses are the only source of global, gridded and temporally continuous wind fields between 20 and 80 km. At their uppermost levels these fields are determined largely by the forecast model and by the damping applied near the model top rather than by assimilated observations."

"Line 11. What are "canonical" solar-tidal harmonics?"

Response:

We thank the referee for the question. We meant the diurnal (24 h), semidiurnal (12 h) and terdiurnal (8 h) solar tides. The word "canonical" will be removed, and the three tides will be named explicitly.

"Line 12. Why do satellite tides weaken "too rapidly"? They are direct measurements why reanalyses are models constrained with data."

Response:

We apologise for the ambiguous wording. "Their" referred to the reanalyses, not to the satellite observations: compared with TIMED/SABER temperatures, diurnal-tide amplitudes in reanalyses are up to 30–50 % smaller in the upper stratosphere and lower mesosphere (Sakazaki et al., 2012), and the agreement among reanalyses and with SABER weakens further in the upper stratosphere and mesosphere (Sakazaki et al., 2018). Revised text: "Comparisons with satellite temperature observations show that reanalyses underestimate tidal amplitudes in the upper stratosphere and lower mesosphere, and agree less well with each other and with the observations higher up (Sakazaki et al., 2012, 2018)."

"Line 13. "How much tidal wind amplitude survives near the mesopause has not been measured against ground-based observations…" This is not correct, i.e., meteor radar tides are routinely measured near the mesopause. If this statement refers to altitudes below 80 km, then it needs to be clearly stated."

Response:

We thank the referee for this correction; the sentence will be revised. Meteor-radar tides near the mesopause are measured routinely, and reanalysed or analysed tides have been compared with them before. Korotyshkin et al. (2019) found, in a one-year (2016) comparison with the Kazan (56° N, 49°

E) meteor radar, that ERA5 semidiurnal tidal amplitudes are significantly underestimated at the top model levels. McCormack et al. (2017) and Stober et al. (2020) validated winds and tides of the high-altitude NAVGEM-HA analysis against meteor radars between about 75 and 95 km. Hindley et al. (2022) used 2016–2020 meteor-radar winds over South Georgia to test a climatological WACCM simulation, and found eastward wintertime winds of up to 40 m s^{-1} at 85–105 km in the radar observations where WACCM had westward winds of up to 20 m s^{-1}. These studies will be cited, and the statement will be rewritten as: "Earlier comparisons have shown that ERA5 underestimates the semidiurnal tide at its top levels (Korotyshkin et al., 2019). Here we quantify, at three meteor-radar sites spanning 23° of latitude, the fraction of the observed diurnal, semidiurnal and terdiurnal wind amplitude and phase that is present in ERA5 at its uppermost level (about 80 km), and we test whether a forecast model trained on ERA5 reproduces the same underestimation."

"Line 18. Are all digits significant? This applies to other numerical values that are stated throughout the manuscript."

Response:

We thank the referee for raising this. They are not: the 95 % block-bootstrap intervals of the differences between models are about 0.03 m s^{-1} wide, so the third decimal of an RMSE carries no information. In the revised manuscript, wind errors and tidal amplitudes will be given to one decimal in the text and to two decimals in the tables, percentages will be rounded to integers unless a difference below 1 % is the point being made, angles and phases will be given to one decimal, and confidence intervals will be given to the same precision as the estimates. All numbers in the text, tables and figures will be checked against this rule.

"Line 25. Winds to not organize vertical coupling through gravity-wave breaking. Winds influence where GWs break but I wouldn't call this "organize"."

Response:

We agree with the referee and thank them for the correction. The sentence will be revised to: "The background winds in this layer determine which gravity waves can propagate upward and at which altitudes they break and deposit momentum (critical-level filtering; Lindzen, 1981; Fritts and Alexander, 2003). Together with solar tides, planetary waves, the quasi-biennial oscillation and sudden stratospheric warmings, these processes couple the lower and upper atmosphere."

"Line 30. "operational systems treat much of the region as a sponge-damped model top" References needed."

Response:

We thank the referee; references will be added and the sentence rephrased as a statement of fact. ERA5 is produced with IFS cycle 41r2 on 137 levels up to 0.01 hPa (about 80 km) (Hersbach et al., 2020). In this configuration, a stratospheric sponge (enhanced horizontal diffusion) starts at 10 hPa, and an additional mesospheric sponge acts on the divergence from 1 hPa to the model top (ECMWF, 2016, Part III, Sect. 2.2.11). MERRA-2 also has its top at 0.01 hPa (Gelaro et al., 2017) and increases the horizontal divergence damping coefficient in its top nine layers, at pressures below about 0.24 hPa (Fujiwara et al., 2017), who also note that such sponge layers can introduce spurious behaviour in the middle-atmospheric dynamics of reanalyses. Revised text: "In ERA5 and MERRA-2, the layer above about 1 hPa (about 48 km) lies within, or close to, numerical damping layers that absorb upward-propagating waves near the model top at 0.01 hPa (ECMWF, 2016; Fujiwara et al., 2017; Gelaro et al., 2017; Hersbach et al., 2020)." The same references will support the corresponding statements at lines 103–104 and 360.

"Line 40. This (temporal variance) statement ignores gravity waves."

Response:

We agree with the referee. The statement applies only to the 3-hourly, 1° ERA5 fields that we analyse. In the real atmosphere, gravity waves, with periods from minutes to hours, contribute a large part of the wind variance in the mesosphere and lower thermosphere (Fritts and Alexander, 2003; e.g. Hindley et al., 2022). Most of this variance is not resolved by 3-hourly sampling (the shortest resolvable period is 6 h), by a 1° grid or by a reanalysis that is damped near its top. Revised text: "In the 3-hourly, 1° reanalysis winds used here, most of the resolved temporal variance is concentrated at tidal and planetary-wave periods; gravity waves, which contribute substantially to the observed wind variance in the mesosphere, are largely unresolved at this sampling." We will also make clear in Sect. 4.7 that the radar winds include gravity-wave variance that neither the reanalysis nor the model can represent (see also lines 535–537).

"Line 115. What's the radar longitude?"

Response:

We thank the referee; the coordinates will be given in full: Mohe (53.5° N, 122.3° E), Beijing-Shisanling (40.3° N, 116.2° E) and Wuhan (30.5° N, 114.6° E) (e.g. Wang et al., 2024b). We will also give the ERA5 grid points used for collocation.

"Line 117. What is "platform error code 1"?"

Response:

We thank the referee for the question. In the wind products supplied by the data centre, hourly records with missing or invalid values are marked with the platform error code 1; these records were excluded before any analysis. The revised text will say this in plain words and give the fraction of records excluded at each station.

"Line 127. What is HxW?"

Response:

We apologise for the undefined notation. H × W denotes the number of grid points in latitude (H = 61, 0–60° N) and longitude (W = 79, 65–143° E) at 1° spacing. This will be stated where the notation is introduced.

"Line 130. Units?"

Response:

We thank the referee; units will be added: levels at 20, 30, 40, 50, 60, 70 and 80 km; T = 16 time steps of 3 h, i.e. a 48 h input window; winds in m s^{-1}; directions in degrees.

"Line 131. Atan2?"

Response:

We thank the referee for the question. atan2(v, u) is the two-argument arctangent, which returns the angle of the wind vector in the correct quadrant (range −180° to 180°). The text will be corrected and clarified. The network outputs the zonal (u) and meridional (v) wind components at each level (14 output channels), and wind speed $s = \sqrt{u^2 + v^2}$ and direction are derived from them. As written, $\theta = \mathrm{atan2}(v, u)$ is the mathematical angle of the vector measured anticlockwise from east, i.e. the direction towards which the wind blows; the meteorological direction from which the wind blows is $(270^\circ - \theta) \bmod 360^\circ$. The direction error used in all scores is the angle between the predicted and

observed wind vectors, computed from their normalised dot product (Sect. 3.7), and therefore does not depend on this convention.

"Line 135. How's the normalization done? The given information is insufficient for a reader who's not an expert in ML."

Response:

We thank the referee and will explain this in plain terms in the revised text. Neural networks train more reliably when their inputs have comparable magnitudes, whereas wind magnitudes differ strongly between 20 and 80 km. For each level and each wind component separately, we therefore subtract the median and divide by the interquartile range (the difference between the 75th and 25th percentiles): $x' = (x - \text{median})/\text{IQR}$. The median and IQR are used instead of the mean and standard deviation because they are less affected by extreme values; this is the RobustScaler of scikit-learn (Pedregosa et al., 2011). Both statistics are computed from the training period only and are then kept fixed for the validation and test periods, so that no information from the test period enters the model. All predictions are transformed back to m s^{-1} before evaluation.

"Line 137. What are the physical bounds?"

Response:

We thank the referee; the bounds are $|u| \leq 250\ \text{ms}^{-1}, |v| \leq 250\ \text{ms}^{-1}$ at all levels, applied before normalisation; they lie well outside the range of winds in ERA5 at 20–80 km and affect fewer than 0.1 % of values. The revised text will state these values.

"Line 503. "The physical mechanism is not obscure." What does this mean?"

Response:

We apologise for the unclear sentence. It was meant to say that the likely cause of the underestimation is known, but it did not say so clearly. It will be replaced by a direct statement: "We attribute the underestimation mainly to the numerical damping applied near the model top. In the IFS version used for ERA5, a stratospheric sponge begins at 10 hPa (about 30 km) and an additional mesospheric sponge acts from 1 hPa (about 48 km) up to the model top at 0.01 hPa (about 80 km) (ECMWF, 2016), so our 70 and 80 km levels lie in the most strongly damped layers. The small number of wind observations assimilated above the stratosphere probably contributes as well, since it leaves

the model's representation of the tides largely unconstrained (Fujiwara et al., 2017)." The remainder of the paragraph (the comparison with MERRA-2) will be retained.

We thank Referee #2 again. These comments will make the paper considerably clearer for the middle-atmosphere community.

References

Ben Bouallègue, Z., Clare, M. C. A., Magnusson, L., Gascón, E., Maier-Gerber, M., Janoušek, M., Rodwell, M., Pinault, F., Dramsch, J. S., Lang, S. T. K., Raoult, B., Rabier, F., Chevallier, M., Sandu, I., Dueben, P., Chantry, M., and Pappenberger, F.: The rise of data-driven weather forecasting: a first statistical assessment of machine learning-based weather forecasts in an operational-like context, B. Am. Meteorol. Soc., 105, E864–E883, https://doi.org/10.1175/BAMS-D-23-0162.1, 2024.

ECMWF: IFS Documentation CY41R2 – Part III: Dynamics and numerical procedures (Sect. 2.2.11, sponge at model top), ECMWF, Reading, UK, https://doi.org/10.21957/83wouv80, 2016.

Englert, C. R., Harlander, J. M., Brown, C. M., Marr, K. D., Miller, I. J., Stump, J. E., [et al.; complete author list]: Michelson Interferometer for Global High-resolution Thermospheric Imaging (MIGHTI): instrument design and calibration, Space Sci. Rev., 212, 553–584, https://doi.org/10.1007/s11214-017-0358-4, 2017.

Fujiwara, M., Wright, J. S., Manney, G. L., Gray, L. J., Anstey, J., Birner, T., Davis, S., Gerber, E. P., [et al.; complete author list]: Introduction to the SPARC Reanalysis Intercomparison Project (S-RIP) and overview of the reanalysis systems, Atmos. Chem. Phys., 17, 1417–1452, https://doi.org/10.5194/acp-17-1417-2017, 2017.

Gauthier, A., Borries, C., Kozlovsky, A., Janches, D., Brown, P., Vida, D., Jacobi, C., Murphy, D., Tsutsumi, M., Gulbrandsen, N., Nozawa, S., Lester, M., Kero, J., Mitchell, N., Moffat-Griffin, T., and Stober, G.: TIMED Doppler Interferometer measurements of neutral winds at the mesosphere and lower thermosphere and comparison to meteor radar winds, Ann. Geophys., 43, 427–440, https://doi.org/10.5194/angeo-43-427-2025, 2025.

Hindley, N. P., Mitchell, N. J., Cobbett, N., Smith, A. K., Fritts, D. C., Janches, D., Wright, C. J., and Moffat-Griffin, T.: Radar observations of winds, waves and tides in the mesosphere and lower thermosphere over South Georgia island (54° S, 36° W) and comparison with WACCM simulations, Atmos. Chem. Phys., 22, 9435–9459, https://doi.org/10.5194/acp-22-9435-2022, 2022.

Korotyshkin, D., Merzlyakov, E., Sherstyukov, O., and Valiullin, F.: Mesosphere/lower thermosphere wind regime parameters using a newly installed SKiYMET meteor radar at Kazan (56° N, 49° E), Adv. Space Res., 63, 2132–2143, https://doi.org/10.1016/j.asr.2018.12.032, 2019.

Lang, S., Alexe, M., Chantry, M., Dramsch, J., Pinault, F., Raoult, B., Clare, M. C. A., Lessig, C., Maier-Gerber, M., Magnusson, L., [et al.; complete author list]: AIFS – ECMWF's data-driven forecasting system, arXiv [preprint], https://doi.org/10.48550/arXiv.2406.01465, 3 June 2024.

Lindzen, R. S.: Turbulence and stress owing to gravity wave and tidal breakdown, J. Geophys. Res., 86, 9707–9714, https://doi.org/10.1029/JC086iC10p09707, 1981.

McCormack, J., Hoppel, K., Kuhl, D., de Wit, R., Stober, G., Espy, P., Baker, N., Brown, P., Fritts, D., Jacobi, C., Janches, D., Mitchell, N., Ruston, B., Swadley, S., Viner, K., Whitcomb, T., and Hibbins, R.: Comparison of mesospheric winds from a high-altitude meteorological analysis system and meteor radar observations during the boreal winters of 2009–2010 and 2012–2013, J. Atmos. Sol.-Terr. Phy., 154, 132–166, https://doi.org/10.1016/j.jastp.2016.12.007, 2017.

NVIDIA: Earth2Studio: open-source deep-learning framework for exploring, building and deploying AI weather/climate workflows [code], https://github.com/NVIDIA/earth2studio, last access: 3 November 2026, 2026.

Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O., Blondel, M., Prettenhofer, P., Weiss, R., Dubourg, V., Vanderplas, J., Passos, A., Cournapeau, D., Brucher, M., Perrot, M., and Duchesnay, E.: Scikit-learn: machine learning in Python, J. Mach. Learn. Res., 12, 2825–2830, https://jmlr.org/papers/v12/pedregosa11a.html, 2011.

Sakazaki, T., Fujiwara, M., Zhang, X., Hagan, M. E., and Forbes, J. M.: Diurnal tides from the troposphere to the lower mesosphere as deduced from TIMED/SABER satellite data and six global reanalysis data sets, J. Geophys. Res., 117, D13108, https://doi.org/10.1029/2011JD017117, 2012.

Sakazaki, T., Fujiwara, M., and Shiotani, M.: Representation of solar tides in the stratosphere and lower mesosphere in state-of-the-art reanalyses and in satellite observations, Atmos. Chem. Phys., 18, 1437–1456, https://doi.org/10.5194/acp-18-1437-2018, 2018.

Stober, G., Baumgarten, K., McCormack, J. P., Brown, P., and Czarnecki, J.: Comparative study between ground-based observations and NAVGEM-HA analysis data in the mesosphere and lower thermosphere region, Atmos. Chem. Phys., 20, 11979–12010, https://doi.org/10.5194/acp-20-11979-2020, 2020.

(Already cited in the discussion paper: Fritts and Alexander, 2003; Gelaro et al., 2017; Hersbach et al., 2020; Wang et al., 2024b.)

Yang Wu, Qixiang Liao, Zhihui Li and Zheng Sheng, on behalf of all co-authors