Experimental Results (2021), 2, e17, 1–7
doi:10.1017/exp.2021.6

CAMBRIDGE UNIVERSITY PRESS

EARTH AND ENVIRONMENTAL SCIENCE

SUPPLEMENTARY-RESULT

On the temporal evolution of turbopause altitude, 1996–2021, 70°N, 19°E

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(Received 17 February 2021; Revised 15 March 2021; Accepted 15 March 2021)

Abstract

Medium frequency radars with multiple receivers are able to track the movement of the interference pattern on the ground from echoes from irregularities in refractive index. In particular, refractive index in the mesosphere is determined by electron density – commonly known as the ionospheric D-region. Thus using this technique it is possible to determine winds in the height regime 70-90 km, depending on the degree of ionization throughout the year. In addition, by examining the fading times of the passage of these structures, it is possible to deduce metrics pertaining to neutral air turbulence. Here, we employ a well-established method to this effect. Thereafter, comparing the turbulent intensity to the kinematic viscosity of the neutral atmosphere, we determine the turbopause altitude. Above this height, atmospheric constituents behave independently, whereas below, all components are mixed. Contrary to earlier analyses, we present evidence the turbopause altitude has been constant since approximately 2004.

Keywords: turbopause; high-latitude; temporal evolution; medium frequency radar

1. Introduction

The turbopause is a demarcation between regions in the atmosphere characterised by different mixing processes. Below, the homosphere, turbulence dominates, whereas above, the individual constituents are distributed according to their respective scale heights. Since ionisation creates different species (such as atomic oxygen) at different heights, an elevated turbopause will result in mixing of these components downwards affecting the mesospheric chemistry such as hydroxyl. In turn, species such as water vapour and hydroxyl can be mixed to similarly elevated heights affecting the ion chemistry. For an introduction to the basics of turbulence applicable to this study, the reader is referred to Batchelor (1953). The method for extracting turbulence parameters from ground-based radar is described by Briggs (1980), and to facilitate this we employ data from the 2.78 MHz medium frequency radar (hereafter MFR) at Ramfjordmoen in northern Norway at 70°N, 19°E. The system has been described fully by Hall (2001). Hitherto, the most recent study of the available time-series is described by Hall et al. (2016); this furthermore contains an exhaustive reference list and is the *de facto* reference for the method and description of underlying physics for this study; Weinstock (1978) is an underlying study and deserves specific mention.

2. Method and results

The 2.78 MHz medium frequency radar MFR) at Ramfjordmoen (70°N, 19°E, Hall, 2001) transmits through a 4x4 crossed dipole array, and therefore illuminates structures in refractive index, dominated

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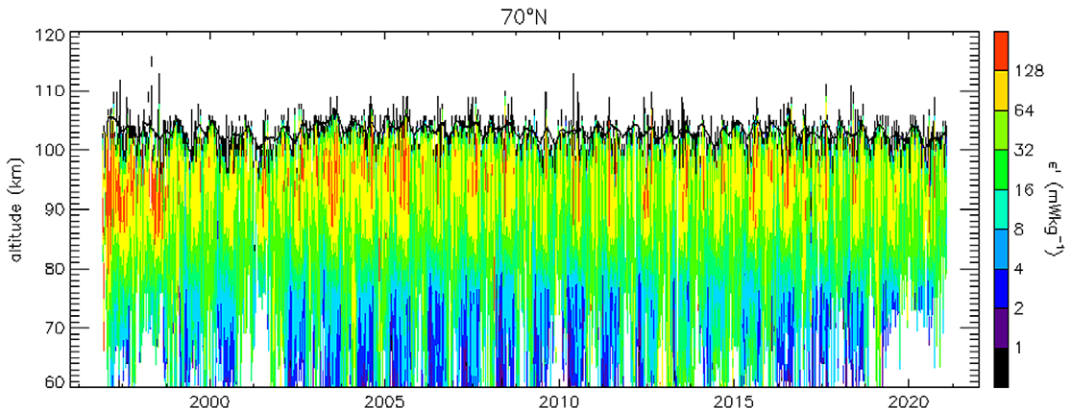

Figure 1. Turbulent intensity from Northern Norway (70°N, 19°E) (upper limits – see main text). Thick line shows turbopause.

above the radar by corresponding structures in electron density (*i.e.* the ionospheric D-region). The geographic location is beneath the auroral oval and therefore a degree of ionisation extending to as low as 70 km altitude is not uncommon. Reflections from these structures give rise to an interference pattern on the ground which is subsequently recorded by simple equi-spaced inverted-V antennas connected to the receivers. Cross-correlations between signals from these receivers provide information on horizontal winds that cause the reflecting structures to drift through the radar beam. Autocorrelations indicate backscattered power. The backscattered power, however, fades with time as the scatterers change shape and/or become less distinct as they drift through the radar beam. Several mechanisms might cause this fading, but a common prime one is considered to be neutral turbulence (*e.g.* Briggs, 1980). Thus, by determining the characteristic fading times of the autocorrelations, it is possible to estimate turbulent intensity - or in fact an upper limit for it (since other mechanisms may be present) – which is parametrised by the energy dissipation rate, ε' (the prime being used to differentiate between this determination and the actual dissipation rate, ε). At the same time, kinematic viscosity increases with altitude due to decreasing density, and at a certain height, energy dissipation due to viscosity, ε_{min}, equals that due to neutral turbulence; this can be thought of when inertial forces equal viscous forces, *i.e.* when the Reynolds number R_e is unity. This condition, the intersection of the ε_{min}, and ε, profiles defines the turbopause. The reader is referred to Fukao et al. (1994), Hall et al. (2016), Weinstock (1984) and references therein for an in-depth description of turbulent energy dissipation rate estimation and thereafter turbopause identification.

The results are shown in Figure 1. Turbulent intensity is indicated below the turbopause in the vicinity of 105 km. The distinct seasonal variation is due to gravity wave saturation and breaking being more evenly distributed though the mesosphere in winter, whereas breaking is more concentrated immediately above the mesopause in summer when temperature gradients are steep. Again the atmospheric physics is fully described in references to be found in Hall et al. (2016). Figure 2. Illustrates the turbopause altitude alone, here with a 30-day smoothing applied to enhance clarity. Earlier analyses of this dataset had identified possible trends; two possible candidates, identified by simple inspection are highlighted (1996–2001 and 2001–2005), but if we consider the entire series from 1996 to 2021, there is no convincing trend to be seen, although the determined value of 0.68 km decade^{-1} does indeed exceed the 2-σ uncertainty. For the individual segments and the entire series, the 95% confidence limits (Working & Hotelling, 1929) are indicated by dotted hyperbolae.

3. Conclusion

While earlier examinations of data from the Ramfjordmoen MFR suggested trends which could be attributed to climate change in the underlying neutral atmosphere, this latest review of the entire

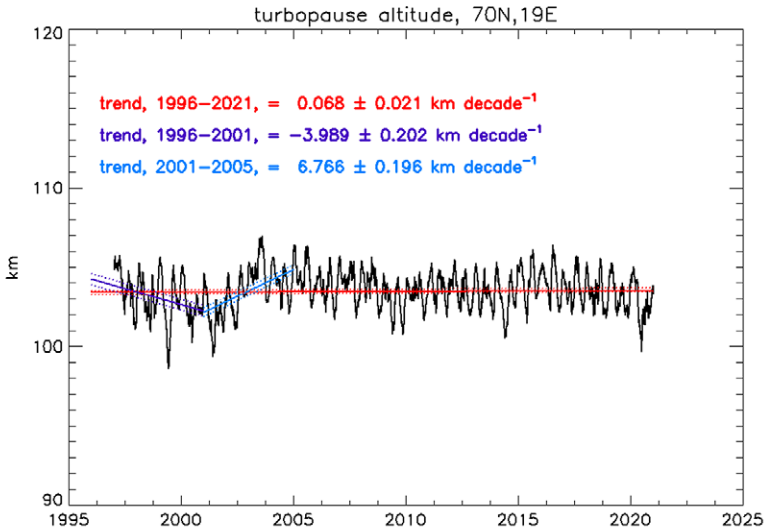

Figure. 2. Turbopause estimate over Northern Norway (70°N, 19°E). Purely from visual evaluation, two periods of change are identified: 1996–2001 and 2001 to 2005, and trendlines are fitted to these and to the entire period. Trends are indicated in the annotation on the plot and dotted hyperbolae indicate the 95% confidence limits.

timeseries from 1996 to 2021 (time of writing) suggests stability of the turbopause altitude with little significant variation, *viz.* 1.7 km over the last quarter of a century. In some ways, the result is surprising: kinematic viscosity and therefore the minimum energy dissipation sustained by the atmosphere, ε_{min}, is proportional to temperature$^{2/3}$ (*e.g.*https://en.wikipedia.org/wiki/Viscosity and Fukao et al., 1994); ε' is proportional to tempertature$^{-1/2}$ (Weinstock, 1978). Combined, these dependencies imply that increasing temperatures will tend to depress the turbopause and *vice versa.* However, the turbopause is located in a region of transition between summer and winter mesopauses, and therefore steep negative and positive temperature gradients. The recent stability of the turbopause is therefore simply reported here and relationships to upper atmosphere temperature trends left to deeper investigation.

Acknowledgments. The medium-frequency-radar (MFR) providing results for this study is partly owned by The University of Saskatchewan, Canada. In particular the authors thank Chris Meek for original provision of software and thereafter constant monitoring of the radar resulting in a nearly uninterrupted timeseries.

Funding information. This research employed resources provided solely by UiT – The Arctic University of Norway.

Conflict of interest. The authors declare no conflicts of interest.

Data availability. Data-files are available at http://radars.uit.no/mfrdata/YYYY/rtwYYYYDDD.dat, where YYYY is the year and DDD the day-number, e.g, http://radars.uit.no/mfrdata/2020/rtw2020354.dat. After 2021, the format changes to http://radars.uit.no/mfrdata/YYYY/rtwYYYYMMDD.dat, the date being specified by YYYYMMDD, denoting year, month and day-of-month. The files are binary and users are invited to contact the author for assistance with software. The site was accessed on 10th February 2021.

Author contributions. The MWR system is operated by CMH, and jointly owned by UiT – The arctic University of Norway, Nagoya University (SN) and The University of Saskatchewan.

References

Batchelor, G. K. (1953). *The theory of homogeneous turbulence* (pp. 197). Athenaceum Press Ltd.

Briggs, B. H. (1980). Radar observations of atmospheric winds and turbulence: A comparison of techniques. *Journal of Atmosspheric and Terrestrial Physics*, **42**, 823–833. https://doi.org/10.1016/0021-9169(80)90086-0

Fukao, S., Yamanaka, M. D., Ao, N., Hocking, W. K., Sato, T., Yamamoto, M., Nakamura, T., Tsuda, T., & Kato, S. (1994). Seasonal variability of vertical eddy diffusivity in the middle atmosphere, 1. Three-year observations by the middle and upper atmosphere radar. *Journal of Geophysics Research*, **99**, 18973–18987. https://doi.org/10.1029/94JD00911.

Hall, C. M. (2001). The Ramfjordmoen MF radar (69_°N, 19°E): Application development 1990–2000. *Journal of Atmospheric and Solar-Terrestrial Physics*, **63**, 171–179. https://doi.org/10.1016/S1364-6826(00)00144-9.

Hall, C. M., Holmen, S. E., Meek, C. E., Manson, A. H., & Nozawa, S. (2016). Change in turbopause altitude at 52° and 70°N. *Atmospheric Chemistry and Physics*, **16**, 2299–2308. https://doi.org/10.5194/acp-16-2299-2016.

Weinstock, J. (1978). Vertical turbulent diffusion in a stably stratified fluid. *Journal of the Atmospheric Sciences*, **35**, 1022–1027. https://doi.org/10.1175/1520-0469(1978)035<1022:VTDIAS>2.0.CO;2.

Weinstock 1984: Gravity wave saturation and eddy diffusion in the middle atmosphere, *JATP*, **46**, 1069–1082, 1984.

Working, H., & Hotelling, H. (1929). Application of the theory of error to the interpretation of trends. *Journal of the American Statistical Association*, **24**, 73–85. https://doi.org/10.1080/01621459.1929.10506274.

Cite this article: Hall CM, Nozawa S (2021). On the temporal evolution of turbopause altitude, 1996–2021, 70°N, 19°E *Experimental Results*, 2, e17, 1–7. https://doi.org/10.1017/exp.2021.6

Peer Reviews

Reviewing editor: Dr. Jacob Carley

NOAA Center for Weather and Climate Prediction, NCEP/Environmental Modeling Center, 5830 University Research Cour, College Park, Maryland, United States, 20740

This article has been accepted because it is deemed to be scientifically sound, has the correct controls, has appropriate methodology and is statistically valid, and has been sent for additional statistical evaluation and met required revisions.

doi:10.1017/exp.2021.6.pr1

Review 1: On the temporal evolution of turbopause altitude, 1996-2021, 70°N, 19°E

Reviewer: Dr. Xuguang Cai

NCAR, High Altitude Observatory, Boulder, Colorado, United States, 80307-3000

Date of review: 03 March 2021

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Conflict of interest statement. Reviewer declares none

Comments to the Author: This experiment can be an important contribution to the Aeronomy community, I am looking forward to seeing the following work to be published as a whole paper

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Score Card

Presentation

4.0 /5

Is the article written in clear and proper English? (30%)	4/5
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Analysis

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Does the discussion adequately interpret the results presented? (40%)	4/5
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doi:10.1017/exp.2021.6.pr2

Review 2: On the temporal evolution of turbopause altitude, 1996-2021, 70°N, 19°E

Reviewer: Dr. Selvaraj Dharmaligam

Date of review: 14 March 2021

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Conflict of interest statement. Reviewer declares none

Comments to the Author: Hall and Nozawa are presenting the results on the temporal evolution of turbopause altitude. They have calculated the turbulence intensity from MF radar. Experimental design (very importantly integration time) and turbulence method (identify the Bragg wavelength in the inertial sub-range) is necessary to be described. Fukao et al 1994 does not have the section on identification of the turbopause. Method on the identification of turbopause is need to be described. How does the author could distinguish the turbopause between the no/low-TKE dissipation rate and no-signal since the identified turbopause lies very close to the no-signal regime.

Score Card

Presentation

4.0 /5

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Analysis

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