

Response to comments of reviewer #1 (in italics – marked green in article with tracked changes):

This article provides a review of papers relating to long-term trend analyses that have been published between 2018-2022, focusing on research related to the Earth's mesosphere, thermosphere and ionosphere.

As in the case of the author's prior review papers, this latest manuscript serves as a good primer on the state of research relating to observed and modelled trends to date. The author has evidently put in a significant amount of effort to synthesize, organize and contextualize often very disparate research papers. Although not presenting original work, this manuscript provides a useful summary guide on the main progress made in the field, and it will be useful and helpful to a broader scientific audience. As such it is relevant for publication in ACP.

*Thank you.*

However, the article needs some work prior to publication. General and specific comments are listed below. Due to the nature of the article, that is, it is an extended literature review, I feel that the volume and type of edits needed, prompt me to return for "major revision" rather than simply for "minor revision". Some of these changes are quick changes, while others will require re-reading of cited papers in order to pull out additional necessary information. Once these changes and improvements are made, I recommend swift publication.

A general comment is that the manuscript text still needs some polishing and refinement in terms of language use and sentence structuring. Specific examples are provided below along with suggested changes. However, this is non-exhaustive. A strength of a review paper such as this would be to allow a reader to get an overview of a field of research, and to provide enough definitions and context to act as a standalone and informative piece. This review paper covers studies across a range of different foci; it would be helpful to define certain terms on first usage to make the paper more accessible to readers who may be experts on one part of the upper atmosphere, yet unfamiliar with another.

*Specific terms are now defined at the first usage.*

Some sections of the manuscript currently read far too much like a list and would benefit from some additional explanatory text to help the reader place the results into context, to understand the gist of any issues/caveats mentioned in the study, and to improve the flow of the article. The author must make sure to sufficiently detail the latitude location/range, time period and altitude range covered in each of the studies cited. This is not always consistently done.

*Some additional texts summarizing results of individual sections have been added. Missing time periods, altitudes and latitudes have been added as well.*

Specific comments/suggestions:

Line 13: change "reviews main progress in investigations" to "reviews THE main progress MADE in investigations". Similar editorial changes should be made throughout much of the

manuscript to improve the flow and readability. I'll include some suggestions below, but these are non-exhaustive.

Line 18-19: "The results on [...] detailed them further". This sentence is currently a little unclear and hard to understand. I suggest providing clarification here on what "but develop and detailed them further" refers to. Alternatively I would suggest changing this to "The results on temperature trends in the MLT region are generally consistent with THOSE FROM PREVIOUS STUDIES. HOWEVER, NEW SIGNIFICANT FINDINGS INCLUDE...".

Line 27: "evidence of clear" —> "evidence of A clear"

*Done.*

Line 28: "results in increasing" —> "results in AN increasing"

*Done.*

Line 29: need to define "foE" as first usage here.

*Done.*

Line 31: it would be perhaps useful to define the approximate latitude, as not all readers will be familiar with the latitude range that Europe extends across.

*Here I divide Europe into European high middle latitudes and low middle latitudes but it is based only on three stations, Juliusruh (55°N), Chilton (52°N) and Rome (42°N), so it is not possible to establish latitudinal extent of these two zones.*

Line 39: Define "foF2, hmF2, TEC and Te" as first usage here.

*I included: "...foF2 (critical frequency corresponding to the maximum electron density in the ionosphere) and its height hmF2, total electron content and electron temperature ...".*

Line 44: define time period of "Holocene".

*I copied this time period from line 665 and included here.*

Line 55: "affect also" —> "also affect"

*Done.*

Line 101: "in ionosphere" —> "in THE ionosphere"

*Done.*

Line 101: Define "middle atmosphere" here.

*Definition is given: "(stratosphere, mesosphere and mesopause region)"*

Line 108: please provide additional explanation of what “lower levels” refers to.

*I changed formulation to “... in lower levels below the F2 layer...”.*

Line 115-116: please provide additional explanation what “with some military consequences” refers to.

*Since authors do not specify military consequences, I deleted these words.*

Line 117: provide explanation of what “intensification of “meteorological control” refers to.

*Penetration of gravity waves from the troposphere into the ionosphere is one of the main channels of meteorological influences on the ionosphere; its intensification intensifies so called meteorological control of the ionosphere (additional to solar and geomagnetic activity control).*

Line 121: define “ionospheric slab thickness”.

*Definition is now included: “the ratio of TEC to the F2-layer peak electron density”*

Line 124-128: the use of “deals with” and “treats” is very informal. Suggestion to change these to words/phrases like “examines”, “describes”, “provides an overview of”, etc.

*Done.*

Line 137-138: unsure what the tense of this sentence is. Suggest either changing to “which leads to” or “which led to” depending on the intended tense.

*Corrected, “led” is correct.*

Lines 157, 163, 168 (and throughout the manuscript): please list the latitude of these listed places (i.e., Juliusruh, Pruhonice, Rome, Slough/Chilton, Boulder, etc.); it should not be assumed that a reader will necessarily know where these stations are.

*Coordinates of stations are added.*

Line 173: define “NmF2” as first usage.

*NmF2 is now defined – “(the maximum electron density in the ionosphere located at the maximum of F2 region)”*

Line 179: replace “Main progress was reached in...” with “SIGNIFICANT progress was MADE in...”

*Done “made”. I keep “Main” as it is what I want to say.*

Line 180: “removing/suppression of effect of solar cycle” —> “REMOVAL/suppression of THE effect of THE solar cycle”

*Your formulation is now used in the paper.*

Line 196: change “mostly” to “most” or perhaps “main”?

*Done.*

Line 227: suggest removing “carefully”. As it was not similarly used on line 221 for the Li et al. study, it could unintentionally suggest that the Venkat Ratnam et al study was “carefully merged” but the Li et al. study was perhaps carelessly merged?

*Done.*

Line 230: suggest changing “over more than 25 years” to “ACROSS more than 25 years”.

*Done.*

Line 240: define latitude of “Moscow region”.

*Done (around 55°N).*

Line 255: “on most heights by 1-2 K/decades” —> “AT most heights by 1-2 K/DECADE”

*Corrected.*

Line 257: define “NH” and “SH” here as first usages.

*Done.*

Line 262: “with mean value” —> “with A mean value”

*Done.*

Line 268-269: define altitude ranges of “lower mesosphere” and “upper mesosphere”.

*Unfortunately authors of this paper do not define the lower and upper atmosphere in terms of altitudes.*

Line 273: “20002-2020: —> “2000-2020”?

*You are right, 2002 is correct – corrected.*

Line 273: “20-110 km (middle atmosphere)” — unclear if this is Zhao et al. definition of middle atmosphere, but it is worth clarifying as this definition may differ from what others understand the altitude range of the middle atmosphere to comprise of.

*I deleted “middle atmosphere” as the definition by the given range of heights is sufficient.*

Line 287: “estimated -7.5 K” —> estimated TO BE -7.5 K”?

*Done.*

Line 289: provide latitude of Observatories de Haute Provence.

Done. “(44°N, 6°E)“

Line 293-294: Odd standalone sentence. Please better integrate this into the surrounding text to improve flow.

*Modified to: “The observational analyses have been accompanied and supported by model simulation analyses of long-term trends in the MLT region temperatures, which are reported below.*

Line 298: “reaching maximum of about” —> “reaching A maximum of about”

Done.

Line 298: state the “middle and lower thermosphere” definition that the authors used.

*Modified to “middle and lower mesosphere (~55-65 km)”, Thermosphere was misprint.*

Line 299: “near none” —> “near ZERO”

Done.

Line 300: suggest giving an example/s of the “dynamic effects” to help the reader understand why the temperature trend may be near-zero/slightly positive.

*I added sentence: “This is likely due to dynamical effects associated with the mesospheric meridional circulation that is driven by the breaking of upward propagating gravity waves (Qian et al., 2019). “ There might be also one more contributor - the summer mesopause is the coldest part of the whole atmosphere and when temperatures are very cold, we can hardly expect further substantial cooling – but this is not mentioned in the paper..*

Line 309: define “middle atmosphere” used by Venkat Rattan et al. (2019).

*Sentence is broadened to “...the middle atmosphere (stratosphere, mesosphere and lower thermosphere) ...”.*

Line 313: “decade” —> “decadeS”

*Changed to “the last decade” – authors meant just the one decade, the last one. Sorry for inaccurate formulation.*

Line 328: “near altitude” —> “near AN altitude”

Done.

Line 340: Sentence beginning “Very important parameter...” needs rewording. Example could be: “Atmospheric waves, namely gravity waves, planetary waves and tides, are a very important vertical coupling mechanism between the upper atmosphere and ionosphere, and the lower atmosphere below.”

*Your formulation is now used in the paper.*

Line 356: suggest changing “(= polar mesospheric) clouds” as it looks too informal. Could change last part of sentence to “...related trends in polar mesospheric clouds (sometimes known as “noctilucent” clouds if observed during nighttime).” Or similar.

*I made the following modification: “...and related trends in noctilucent clouds, called also polar mesospheric clouds when they are observed from above by satellites.” The point is that the original name of this phenomenon is noctilucent clouds and authors of papers referred to by me also use term noctilucent clouds.*

Line 354: “near surface” → “near THE surface”.

*Done.*

Line 365-366: “with merged” → “with THE merged”

*Done.*

Line 366: “over” → “BETWEEN” or “ACROSS THE PERIOD”

Line 372-373: provide latitudes for “California, Hawaii and New Zealand”.

*Unfortunately authors of this paper (Nedoluha et al., 2022) did not present coordinates of stations used by them.*

Lines 377-378: Clarify what “Such a trend is within trends” means. Do you mean the trends from Nedoluha et al. (2022) are consistent with the findings of other independent studies?

*The sentence was modified to “Such a trend is within the range of trends and their uncertainties derived from measurements of other WVMS instruments.”*

Line 391: “of impact” → “of THE impact”

*Done.*

Line 393: Not critical, but I suggest that it may be helpful to a reader to state how increasing methane concentration results in an increase of water vapor. This is later stated in lines 470-472, but it would be more useful if explained here (i.e., earlier in the manuscript).

*I moved this explanation from original lines 470-472 to original lines 395-396.*

Line 402: “reported update” → “reported AN update”

*Done.*

Line 402: state latitude of “Moscow region”

*Done - around 55°N.*

Line 406: can you explicitly define “summer length”?

*Added in the text “(defined using spring and autumn wind reversal)”.*

Line 414: state latitude of “Zvenigorod”

*Coordinates of Zvenigorod are added (55.4°N, 36.5°E).*

Lines 421-422: “obtained after eliminating effects” → “obtained after eliminating THE effects”

*Done.*

Line 425: “over 2004-2020” → “BETWEEN 2004-2020” or “ACROSS THE PERIOD 2004-2020”

*Done, “between” is used.*

Lines 424-428: This paragraph needs further detail. Please explain some of the different definitions of “summer length” used by Jaen et al. (2022). Which definition of summer length resulted in a positive trend? Please further clarify what is meant by “break point and non-uniform trend of summer length”.

*First question – sentence was changed to “... a positive trend of summer length for the mesosphere only but no clear trend for the whole MLT region”.*

*Second question – I added at the end of that sentence “i.e. 1990-2008 a slight negative trend, break in 2008, and a positive trend in 2008-2020”.*

Line 436: “...increasing concentration of CO<sub>2</sub> is cooling...”. It is very important to specify at what altitude range that CO<sub>2</sub> acts as an IR cooling, as this otherwise runs the risk of being misquoted/misunderstood by those that may not understand that it acts as an important IR heater in the lower atmosphere.

*I added “at heights above ~50 km is radiative cooling” to make it clear. Thank you.*

Line 439: “partially maybe due to insufficient...” → “LIKE due to THE insufficient”

*Your suggestion has slightly different meaning than what I want to say, therefore I keep my original formulation.*

Line 444: “near none” → “near ZERO”

*Done.*

Line 445: again suggest giving a few examples of what these “dynamic effects” may be.

*I added at the end of this sentence “(winds and atmospheric wave activity)”.*

Line 449: Final sentence beginning “Summing up we may say that long-term trends...” needs rewording. Currently it is too informal and quite vague. Suggest at least rewording the beginning to “In summary, it is clear that long-term trends...”. It would be helpful to the

reader to state 1-3 clear ways (examples) in which “our knowledge broadened and it is more detailed”.

*I added at the end of this sentence “e.g. trends are now better quantified, model-derived trends are in agreement with observational trends, and some hemispheric asymmetry of temperature trends was found”.*

Line 452: “Other important group” —> “ANOTHER important group”. This sentence needs strengthening/rewording. Presumably winds and atmospheric waves are the “dynamical parameters”? One could reword to something like: “Dynamical parameters, such as winds and atmospheric waves, play a critical role in the MLT region.”

*Your formulation is now used in the paper. Thank you.*

Line 456: “The limited activity in the area of” —> suggested clarifying that this limited activity refers to the amount of published papers on this topic between 2018-2022.

*I added at the end of this sentence “in 2018-2022”. However, the activity in investigating trends in tides was limited also before this period.*

Lines 467-468: Suggest rewording sentence beginning “Water vapor trends...” to “Water vapor trends in the mesosphere are generally positive; it is only in the equatorial region that there are very little or near-zero trends.”

*Your suggested formulation is now used in the paper.*

Line 469: provide latitude of Switzerland.

*Geographic coordinates of these measurements are given at original page 387 in a paragraph about water vapor concentration measurements by radiometer in Switzerland near Bern.*

Line 470: “with unknown” —> “with AN unknown”

*Done.*

Line 479-480: Sentence beginning “Midlatitude partial..” requires an earlier definition of what is meant here at lines 424-428.

*Break point and non-uniform trend are now explained earlier as you require.*

Lines 493-395: provide more context of what “their method might be questioned” means.

*This would require almost one special paper. Some reasons of critics of methods of Mikhailov are given in the paper by Zhang et al. (2018) cited in my paper. Another problem is foF1 and trial to derive almost everything in the ionosphere from this parameter, which is available only in summer with data gaps due to screening by the sporadic-E layer and which is in ionospheric community considered to be less reliable than other ionospheric parameters; and there are also other reasons like uncertainties in reaction rates.*



Line 500: “in the deep solar” —> “DURING the deep solar”

*Done.*

Line 496: provide more details. Satellite drag data from where?

*Added in the text “from a broad range of altitudes in the thermosphere”.*

Lines 501-503: provide more details about the Mlynczak et al. (2022) study. What altitude range? What latitude range?

*Added in the text “(heights of ~48-105 km, low and middle latitudes)”.*

Lines 506-511: what latitude range? Is this a globally averaged simulation?

*This is global simulation – added “global” in the text.*

Lines 512: state what altitude range is used by Liu et al. (2020).

*Heights (100-400 km) are added.*

Line 517-523: what altitude range? Define latitudes of all stations, but particularly Sodankyla as it hasn't formerly been mentioned. What time range was covered by the six solar cycles? Can you elaborate on what the impact of not considering particle precipitation could be?

*Heights, geographic coordinates and covered period have been added. Nobody knows sufficiently how can be the impact of not considering particle precipitation.*

Line 533: “since review” —> “since THE review”

*Done.*

Line 535-538: what time period and altitude range was covered by this study?

*I added period (1960-2010) and typical heights of the E-region maximum (~110-115 km).*

Line 539: define station latitudes, particularly for Wakkanai. This is defined later in the paragraph (line 545) but it would be more useful near the start. Also include the time period covered by the study.

*Geographical coordinates of all four stations and analyzed period (1960-2010) were added.*

Line 546-548: Unclear what is meant by this sentence. Please reword and clarify.

*I apologize. This sentence was re-formulated: This finding according to Danilov and Konstantinova (2019) provides evidence supporting the impact of meridional transport of NO from auroral zone on the observed trends in foE.*

Line 588-590: Need to reword/restructure the sentence “As for hmF2” as unclear what is meant by the second half of the sentence. Do you mean that the average trend in hmF2 was

comparable to the trends observed in middle-upper atmosphere CO<sub>2</sub> and also that observed in the Earth's magnetic field?

*I re-formulated this sentence into hopefully more clear statement: As for hmF<sub>2</sub>, the average trend is -1.06 km/decade; the roles of CO<sub>2</sub> and Earth's magnetic field in this trend are comparable (Yue et al., 2018).*

Line 620:621: restate the sentence beginning "Some problems.." It would be helpful to the reader if you give examples of what some of these problems were.

*This sentence was changed to "Some problems with foF<sub>2</sub> and hmF<sub>2</sub> in were indicated in solar cycle 24 (e.g. Haro Barbas et al., 2022), and around the solar cycle minimum 23/24 (e.g., Danilov and Konstantinova, 2020c)."*

Line 633: define mesopause altitude used here.

*Changed to "mesopause (~85-90 km) the cooling"*

Line 636-637: elaborate on how the behavior of NO and O(<sup>3</sup>P) differs from that of CO<sub>2</sub>.

*The sentence was modified to "... likely due to the stronger solar cycle variation of NO and O(<sup>3</sup>P) infrared irradiance compared to that of CO<sub>2</sub>, which results in a relatively larger role of CO<sub>2</sub> in the solar activity minimum conditions."*

Line 643: "as in historical period" —> "COMPARED TO THE historical period". Also please define what "historical period" is being referred to.

*Replaced by "compared to the period 1950-2007".*

Lines 654: suggest changing "violent oscillations" to "SIGNIFICANT oscillations", or perhaps "DRAMATIC oscillations".

*The term "violent oscillations" was used by authors of original paper, therefore I keep it.*

Line 668: "during several last decades" —> "during the last several decades".

*Done.*

Line 691: suggest changing "suffers with the" to "EXPERIENCES the"

*Done.*

Line 700: define Te and Ti here. I note that you later define them on lines 701-702, but it would be helpful to do so on their first usage.

*Done.*

Line 721: briefly explain what "vertical E x B drift" is for those that may be unfamiliar.

*Brief explanation is given.*

Line 737: unclear what “higher under low than under high levels” means. Please clarify.

*Clarified.*

Lines 763-764: make sure that the tense of “contractions” and “was” is consistent. Suggest either changing to “contraction” and “was”, or alternatively to “contradictions” and “were”.

*Done.*

Line 773: “near none” —> “near ZERO”

*Done.*

Line 775: “develop and detailed them further” —> “WERE DEVELOPED and detailed further”.

*Corrected.*

Line 805: “Important part of long-term trend investigation is specification of roles of individual trend drivers” —> “AN important part of THE investigation of long-term trends is THE specification of THE roles of individual trend drivers.”

*Corrected.*

Line 818: “from surface” —> “from THE EARTH’S surface”.

*Done.*

Line 828: “removing/suppression of effect of solar cycle” —> “THE REMOVAL/suppression of THE effect of THE 11-YEAR solar cycle”.

*Corrected.*

Line 834: “Despite of evidence progress, various challenges and open problems remain.” —> “Despite evident progress having been made, it is clear that various challenges and open problems still remain.”.

*Your formulation is now used in the paper.*

Line 835: “in activity” —> “in THE activity”.

*Done.*

Line 836: “which are very” —> “which are A very”

*Done.*

Line 845: “understood and related” —> “understood, and related”

*Not changed – spellcheck did not accept comma*

Line 847: “needs to be more specified” —> “needs to be BETTER specified”.

*Done.*

Line 848: “not mutually sufficiently consistent” —> do you mean “still not in consistent agreement with one another”?

*Your formulation is now used in the paper.*

Line 850: Sentence beginning with “Summing up..” Suggest changing this to something less informal. A possible suggestion is something like “In summary, although there has been significant progress made in studies published between 2018-2022, it is clear that there is still much work to be done in reaching scientific closure on these outstanding issues.”

*Your suggested sentence is much better and it is now used in the paper. Thank you.*

Response to comments of reviewer #1 (in italics – marked yellow in article with tracked changes):

This paper presents a review of trends in the mesosphere, thermosphere and ionosphere based on results published during the period 2018-2022. It is important to understand how the upper atmosphere is modified by global climate change and such a study can be an interesting contribution to the topic. However, a major revision of the paper is needed before it can be published in ACP.

A long list of publications has been reviewed, but the paper appears to be a long list of results obtained by the authors. It is difficult for the reader to extract the main results and understand how recent publications have improved our understanding of trends in the mesosphere, thermosphere and ionosphere. At the end of each section, a summary of the main results should be provided. This is particularly true for the very long section on the mesosphere and for the section on the ionosphere.

*Each section (except for Introduction and Conclusions) has now separated Summary.*

Further remarks are listed below.

Section 2, problems in calculating long-term trends.

This section focuses mainly on the impact of solar activity in the calculation of long-term trends. This is an important contribution to consider because of the strong response of the upper atmosphere to the 11-year solar cycle. However, other problems may arise when calculating long-term trends, in particular the impact of atmospheric tides where the local time of measurement is not fixed or where there are trends in the tides that make the trend dependent on the local time.

*The following paragraph has been added to section 2: “It should be mentioned here that an important problem of some trend calculations may be atmospheric tides. The impact of atmospheric tides via data sampling might be important when the local time of measurement is not fixed or where there are trends in the tides that make the trend dependent on the local time. One more problem is that particularly ionospheric trends might be strongly seasonally and diurnally (local time) dependent up to the change of trend sign as it is demonstrated in section 5; this is not the effect of tides.”*

Section 3: Trends are generally given in K/decade or %/decade but in some cases in K/year (lines 262 and 263) or %/year (lines 377 and 416). Please homogenise.

*All was homogenized to “per decade”.*

Line 289: Observations at the Observatoire de Haute Provence are made by Raileigh lidar, not by Rayleigh radar.

*I replaced “radar” by “lidar”. I keep “Rayleigh” as this name is used by authors of the paper related to original line 289, Ardalan et al. (2022), and also in other papers cited by Ardalan et al. (2022).*

Lines 424-428 and 452-462 concern trends in wind measurements. Please group the two sections together.

*Original lines 452-462 describe trends in dynamics, in wind and atmospheric waves. On the other hand, original lines 424-428 describe trends in the length of summer, not in winds; wind is only used as a tool for definition of summer length. Therefore if you do not mind, I keep these two paragraphs separately where they were originally.*