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EARTH AND ENVIRONMENTAL SCIENCE
NOVEL-RESULT

On the correction of temperatures derived from meteor wind radars due to geomagnetic activity

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Abstract
Radars used to observe meteor trails in the mesosphere deliver information on winds and temperature. Use of these radars is becoming a standard method for determining mesospheric dynamics and temperatures worldwide due to relatively low costs and ease of deployment. However, recent studies have revealed that temperatures may be overestimated in conditions such as high geomagnetic activity. The effect is thought to be most prevalent at high latitude, although this is not yet proven. Here, we demonstrate how temperatures might be corrected for geomagnetic effects; the demonstration is for a particular geographic location (Svalbard, 78°N, 16°E) because it is local geomagnetic disturbances that affects local temperature measurements, therefore requiring co-located instruments. We see that summer temperatures require a correction (reduction) of a few Kelvin, but winter estimates are more accurate.

Keywords: correction due to geomagnetic disturbance; mesosphere; meteor radar; neutral temperatures

1. Introduction

Observations of ionization trails from meteors using so-called meteor-wind radars (MWRs) have, of late, become the *de facto* method of determining winds and temperatures in the upper mesosphere. Currently, research is being performed and publications are produced using such observations: for example, Shepherd et al. (2020), Pancheva et al. (2020), and Pedatella et al. (2020) to name but a few, not to mention studies in progress. While these studies have most focus on mesospheric dynamics, radar echoes also reveal diffusion coefficients for the ions in the meteor trails, and these are used to estimate temperatures (e.g., Hocking, 1999; Hocking et al., 2004; Holdsworth et al., 2006; McKinley, 1961). Results are thereafter used to investigate *inter alia* middle atmosphere temperature trends (e.g., Hall et al., 2012; Holmen et al., 2015), and thus, the reliability of the temperature determinations is becoming increasingly important.

Ambipolar diffusion determined by MWRs has been critically examined by Chilson et al. (1996), Dyrud et al. (2001), Hall (2002), Hocking et al. (2004), Hall et al. (2005), Dyrland et al. (2010), and so on. Recently, however, it was noticed that increases in diffusivity are associated with strong geomagnetic activity (Hall & Johnsen, 2020). The implications of this include overestimation of temperatures particularly in the auroral zones regions (i.e., high latitudes). Secular changes in geomagnetic activity and even migration of the geomagnetic poles could easily induce misleading identification of temperature trends, but any research based on high latitude temperature observations from MWRs could be affected. Furthermore, the findings of Hall and Johnsen (2020) were based on the results from two high-latitude radars, and lower latitude effects were not dismissed. The derivation of temperatures from MWR echo fading times via estimation of ambipolar diffusivity is well described in the literature (and the references herein) and will not be explained in detail here. Instead, we focus on the effects of geomagnetic activity on temperature estimates (note use of the term "estimates") and how we may correct for them, both for long-term time-series and conceivably in quasi-real-time.

It must be stressed that this study is intended to highlight potential problems using MWR data and thereafter drawing scientific conclusions from derived temperatures without taking geomagnetic activity into account. We give an account of how temperatures may be corrected to alleviate the geomagnetic effects, but do not attempt to present a comprehensive set of tools that result in reliable temperatures under all circumstances.

2. Method and results

The Nippon/Norway Svalbard Meteor Radar (NSMR at 78°N, 16°E, since 2002) is used for provision of temperature estimates, in particular, employing the pressure method of Holdsworth et al. (2006). A comprehensive list of references is given above and thus the exact method of derivation is not described here. It should be mentioned, however, that models for air pressure and composition of the meteor trail are implicit. Because of these, the initial derivations of temperatures are normalized to satellite data (AURA specifically, as explained in the references). Data between 2002 and 2019 are employed here and analyzed to yield daily temperature estimates at 90 km altitude

In order to parameterize geomagnetic activity, we employ the auroral zone activity index as introduced by Hall and Johnsen (2020), this being a local metric and, in this study, determined from magnetometer observations in the vicinity of NSMR. Figure 1 shows both the geomagnetic and temperature data on the same plot. These values are those used in the subsequent analyses.

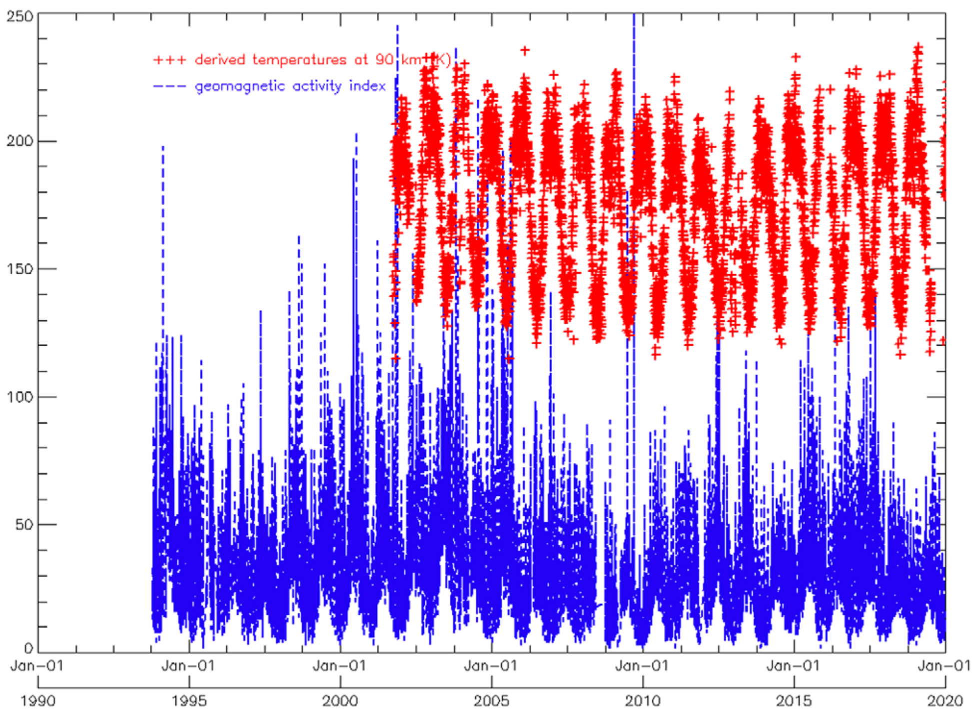

Figure 1. Geomagnetic Activity Indices (blue) in nT and, from start of operations, derived neutral air temperatures at 90 km (red) in Kelvin, both from Svalbard (78°N, 16°E).

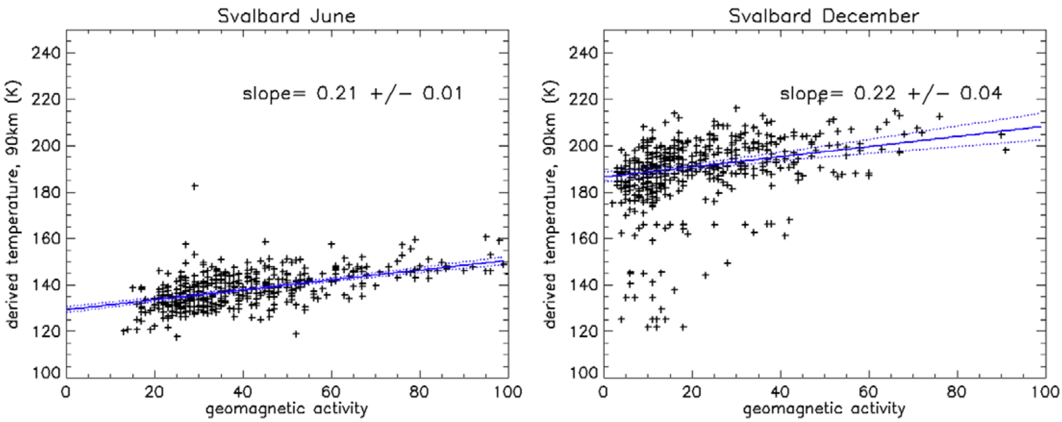

Figure 2. Scatter plots of derived 90 km temperatures versus geomagnetic activity index employing data from the preceding figure. Left panel: June; right panel: December. The plots show the same results as those of Hall & Johnsen, 2020. Lines show least-squares fit regressions, taking geomagnetic activity indices as the independent variable. Dotted hyperbolae indicate the 95% confidence limits according to Working and Hotelling (1929).

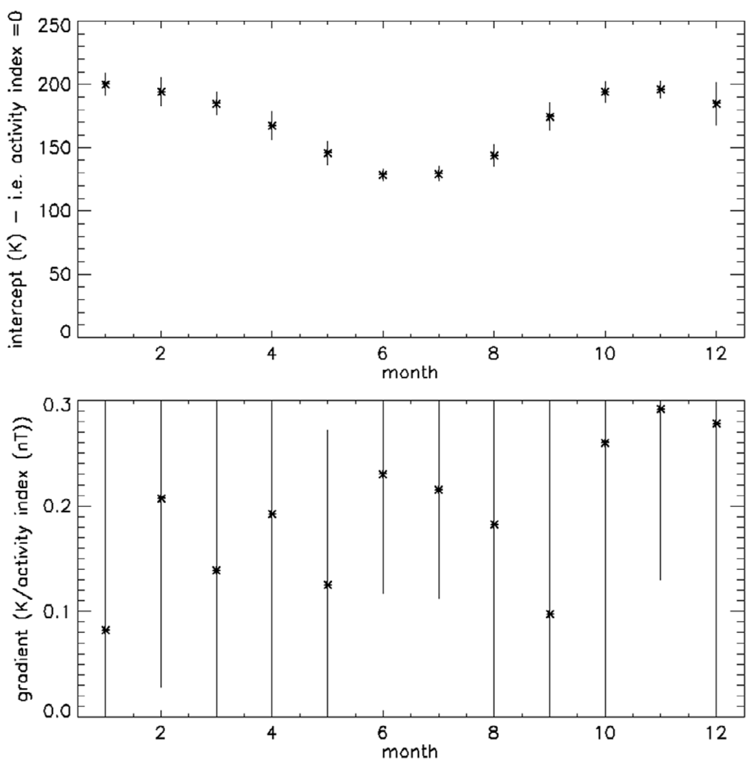

Figure 3. Results of linear fits exemplified by the previous figure, here all available years and sorted by month. Upper panel intercepts (zero activity index); lower panel: slopes. Error bars (1-sigma) are indicated by the vertical lines.

In Figure 2, the results of Hall and Johnsen (2020) are, in part, reproduced. Temperature estimates are plotted as a function of auroral zone activity index as are linear least-squares fits with geomagnetic activity as the independent variable; all years are utilized and June and December months are selected as representative for winter and summer, respectively. It can be seen that the summer and winter slopes are very similar, indeed, but that the intercepts (corresponding to no geomagnetic disturbance at all) reflect

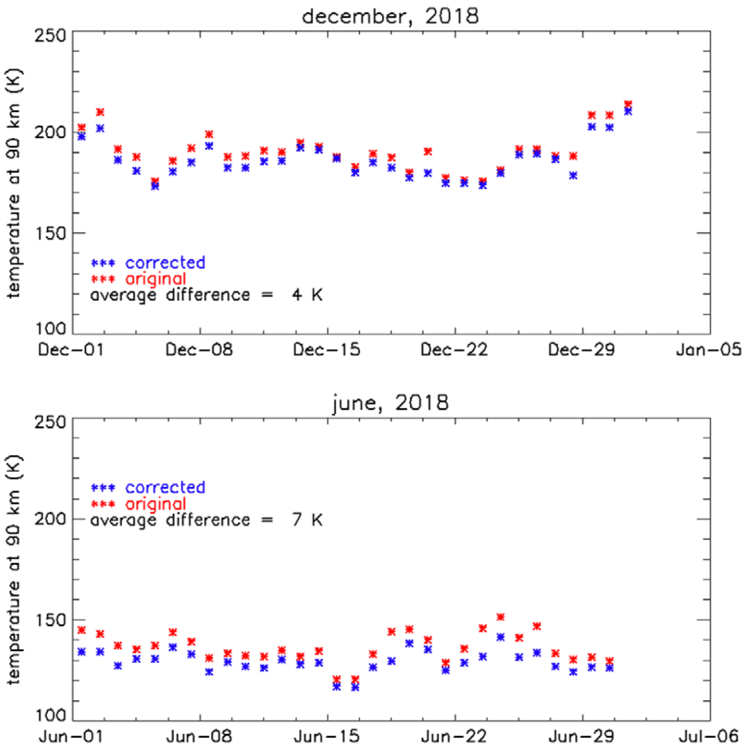

Figure 4. Typical examples of temperatures corrected for geomagnetic effects. Upper panel: December 2018 and lower panel: June 2018. Original temperature estimates are shown in red, and corrected values in blue. The mean corrections over all days are indicated in the plot: 4 K in winter and ~7 K in summer.

the typical summer and winter upper mesosphere temperatures. The most striking difference is in the spread—points being much more concentrated near the regression line in summer. The 95% confidence limits are indicated (Working & Hotelling, 1929). Intercepts and slopes for Individual months are shown in Figure 3. Again, the intercepts illustrate the seasonal variation of the upper mesosphere temperature and with little uncertainty. In contrast, the slopes vary considerably with month and uncertainties are considerable.

Here, we shall illustrate corrections to the original temperatures estimates based on the dependence on auroral zone activity index. The presentation is merely a demonstration; different scientific requirements may dictate choice of length of time series for performing preceding regression analyses. In this instance, we employ the monthly mean coefficients (i.e., Figure 3) and correct the temperature time-series at one-day resolution. Examining the entire time-series, we find the correction is small, but it is possible to discern an overall reduction in temperatures. Rather than presenting these, and in order to better illustrate the effect, Figure 4 shows December and July time-series from 2018 where differences between individual days are evident. Both original and corrected values, the latter consistently slightly lower, are shown together with the average difference over the respective month. In summer, the difference is somewhat larger than in winter. If we place these results in the framework of observation of phenomena related to low temperatures in the summer mesopause (e.g., noctilucent clouds, etc.), the difference discerned in the latter part of July has significance, indicating the importance of making this correction.

3. Conclusion

It has been demonstrated that temperature estimates derived from meteor-radar data, wherein the method involves estimating the diffusion coefficient of ions in the meteor trail can be falsely enhanced during conditions of high geomagnetic activity. The enhancement is however quite well-defined, and by obtaining coefficients of linear fits of temperature estimated to the geomagnetic activity (which we parameterize by the activity index presented by Hall & Johnsen, 2020) it is possible to apply a correction. For the data presented here from Svalbard (78°N, 16°E) a typical summer overestimate can be around 7 K whereas in winter only 4 K. The timescales used to obtain the dependence depend somewhat on the scientific circumstances, and in principle corrected temperatures could be delivered daily assuming magnetometer and radar installations are similarly located.

Acknowledgments. The meteor-wind-radar (NSMR) providing results for this study is partly owned by National Institute of Polar Research, Japan and the authors therefore thank co-investigator Masaki Tsutsumi for his involvement.

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

Authorship contributions. The NSMR system is operated by C.M.H., and the magnetometer systems by M.G.J. Both the authors contributed equally to data analysis and interpretation.

Data availability statement. Data from the radar are available from the Svalbard Integrated Arctic Earth Observing System portal (https://sios-svalbard.org/): via https://sios-svalbard.org/metsis/display/metadata/?core=l1&datasetID=308345a1-51ea-5751-b67b-f31afc6c5c71&calling_results_page=https://sios-svalbard.org/results?page=1. The Arctic University of Norway has a repository at: http://radars.uit.no/MWR/NSMR/METADATA.txt.

The geomagnetic data used in this research are available via TGO's data repository (http://www.tgo.uit.no), IMAGE (https://space.fmi.fi/image/www/index.php?page=home), SuperMAG (http://supermag.jhuapl.edu/) and, for Tromsø, World Data Centre for Geomagnetism (Edinburgh), (http://www.wdc.bgs.ac.uk/, IAGA code TRO). The first of these is the primary repository for Norwegian geomagnetic data. The last also provides a URL to the Norwegian national repository.

All sites were accessed on 20th January 2021.

References

Chilson, P. B., CzechowskyP., & Schmidt, G. (1996). A comparison of ambipolar diffusion coefficients in meteor trains using VHF radar and UV lidar. *Geophysical Research Letters*, **23**, 2745–2748. https://doi.org/10.1029/96GL02577.

Dyrland, M. E., Hall, C. M., Mulligan, F. J., & Tsutsumi, M. (2010). Improved estimates for neutral air temperatures at 90 km and 78°N using satellite and meteor radar data. *Radio Science*, **45**, RS4006. https://doi.org/10.1029/2009RS004344.

Dyrud, L. P., Oppenheim, M. M., & vom Endt, A. F. (2001). The anomalous diffusion of meteor trails. *Geophysical Research Letters*, **28**, 2775–2778. https://doi.org/10.1029/2000GL012749.

Hall, C., & Johnsen, M. G. (2020). Influence of geomagnetic activity on derivation of temperatures from meteor wind radars. *Radio Science*, **55**, e2020RS007123. https://doi.org/10.1029/2020RS007123.

Hall, C. M. (2002). On the influence of neutral turbulence ambipolar diffusivities deduced from meteor trail expansion. *Annales Geophysicae*, **20**, 1857–1862. https://doi.org/10.5194/angeo-20-1857-2002.

Hall, C. M., AsoT., Tsutsumi, M., Nozawa, S., Manson, A. H., & Meek, C. E. (2005). Testing the hypothesis of the influence of neutral turbulence on deduction of ambipolar diffusivities from meteor trail expansion. *Annales Geophysicae*, **23**, 1071–1073. https://doi.org/10.5194/angeo-23-1071-2005.

Hall, C. M., Dyrland, M. E., Tsutsumi, M., & Mulligan, F. (2012). Temperature trends at 90km over Svalbard seen in one decade of meteor radar observations. *Journal of Geophysical Research*, **117**, D08104. https://doi.org/10.1029JD017028.

Hocking, W. K. (1999). Temperatures using radar-meteor decay times. *Geophysical Research Letters*, **26**, 3297–3300. https://doi.org/10.1029/1999GL003618.

Hocking, W. K., Singer, W., Bremer, J., Mitchell, N. J., Batista, P., Clemesha, B., & Donner, M. (2004). Meteor radar temperatures at multiple sites derived with SKiYMET radars and compared to OH, rocket and lidar measurements. *Journal of Atmospheric and Solar-Terrestrial Physics*, **66**, 585–593. https://doi.org/10.1016/j.jastp.2004.01.011.

Holdsworth, D. A., Morris, R. J., Murphy, D. J., Reid, I. M., Burns, G. B., & French, W. J. R. (2006). Antarctic mesospheric temperature estimation using the Davis MST radar. *Journal of Geophysical Research*, **111**, D05108. https://doi.org/10.1029/2005JD006589.

Holmen, S. E., Hall, C. M., & Tsutsumi, M. (2015). Neutral atmosphere temperature change at 90 km, 70_ N, 19_ E, 2003–2014. *Chemistry and Physics Discussion*, **15**, 15289–15317. https://doi.org/10.5194/acpd-15-15289-2015.

McKinley, D. W. R. (1961). *Meteor science and engineering* (309pp.) McGraw-Hill.

Pancheva, D., Mukhtarov, P., Hall, C., Smith, A. K., & Tsutsumi, M. (2020). Climatology of the Short-Period (8-h and 6-h) Tides Observed by Meteor Radars at Tromsø and Svalbard. *Journal of Atmospheric and Solar-Terrestrial Physics*, **212**, 105513. https://doi.org/10.1016/j.jastp.2020.105513.

Pedatella, N., Liu, H.-L., Chau, J., Hall, C., Jacobi, C., Mitchell, N., & Tsutsumi, M. (2020). Migrating semidiurnal tide during the September equinox transition in the northern hemisphere. *Journal of Geophysical Research: Atmospheres*, **126**, e2020JD033822. https://doi.org/10.1029/2020JD033822.

Shepherd, M., Meek, C. E., Hocking, W. K., Hall, C. M., Partamies, N., Sigernes, F., Manson, A. H., & Ward, W. E. (2020). Multi-instrument study of the mesosphere-lower thermosphere dynamics at 1 80°N during the major SSW in January 2019. *Journal of Atmospheric and Solar-Terrestrial Physics*, **210**, 105427, https://doi.org/10.1016/j.jastp.2020.105427.

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.

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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.

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Review 1: On the correction of temperatures derived from meteor wind radars due to geomagnetic activity

Reviewer: Dr. Cory Martin

RedLine at NOAA NWS NCEP EMC, MDAB-DA, 5830 University Research Court, Room 2767, College Park, Maryland, United States, 20740;709 Quincy St NW, Apt A, Washington, District of Columbia, United States, 20011

Date of review: 22 April 2021

Conflict of interest statement. Reviewer declares none

Comments to the Author: The authors present a solution for correction of upper atmosphere temperature derived from meteor radars as a function of geomagnetic activity. The results presented show a consistent overestimation of temperature that must be corrected, and this correction factor is generally larger in polar summer. While the manuscript does not go into detail (but this is covered in references) proving that this is indeed an overestimation of temperature, the authors do sufficiently show that there is a relation between temperature estimation and geomagnetic activity and how one might correct for it.

Score Card

Presentation

5.0 /5

Is the article written in clear and proper English? (30%)	5/5
Is the data presented in the most useful manner? (40%)	5/5
Does the paper cite relevant and related articles appropriately? (30%)	5/5

Context

5.0 /5

Does the title suitably represent the article? (25%)	5/5
Does the abstract correctly embody the content of the article? (25%)	5/5
Does the introduction give appropriate context? (25%)	5/5
Is the objective of the experiment clearly defined? (25%)	5/5

Analysis

4.4 /5

Does the discussion adequately interpret the results presented? (40%)	4/5
Is the conclusion consistent with the results and discussion? (40%)	5/5
Are the limitations of the experiment as well as the contributions of the experiment clearly outlined? (20%)	4/5

doi:10.1017/exp.2021.11.pr2

Review 2: On the correction of temperatures derived from meteor wind radars due to geomagnetic activity

Reviewer: Dr. Alexander Kozlovsky

University of Oulu, Sodankylä Geophysical Observatory, Finland

Date of review: 26 May 2021

Conflict of interest statement. No conflict of interest

Comments to the Author: This paper is clearly written and may be interesting to the meteor radars' community. I have only minor comments below.

1. It may be useful to mention that decay of meteor trails is primarily determined by the ambipolar diffusion and, hence, depends on the temperature of ions and electrons (i.e., the plasma temperature). Thus, using the meteor trails decay time for deriving the temperature of neutral atmosphere assumes thermal equilibrium between plasma and neutral particles. This assumption may be violated during ionospheric disturbances associated with strong electric field, such that a correction for the disturbed condition is needed. Another assumption is that collisional or Joule heating may be neglected at the meteor heights, which may be checked, e.g., in a way similar to (Jarvis, 2010).
2. Lines 53-55: Holdsworth et al. (2006) considered two methods, the pressure model and the temperature gradient model, for the temperature estimate. Please specify which of these two is used in the present study.
3. Line 40 (typo): "Hall and Johnsen (2010)" correct to "Hall and Johnsen (2020)"

Reference

Jarvis, M. J. (2010). The ineffectiveness of Joule heating in the stratosphere, Journal of Atmospheric and Solar-Terrestrial Physics, 72, 1110–1113.

Score Card

Presentation

4.0 /5

Is the article written in clear and proper English? (30%)	4/5
Is the data presented in the most useful manner? (40%)	4/5
Does the paper cite relevant and related articles appropriately? (30%)	4/5

Context

4.2 /5

Does the title suitably represent the article? (25%)	5/5
Does the abstract correctly embody the content of the article? (25%)	5/5
Does the introduction give appropriate context? (25%)	3/5
Is the objective of the experiment clearly defined? (25%)	4/5

Analysis

3.4 /5

Does the discussion adequately interpret the results presented? (40%)	3/5
Is the conclusion consistent with the results and discussion? (40%)	4/5
Are the limitations of the experiment as well as the contributions of the experiment clearly outlined? (20%)	3/5