REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-05-

0337

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TY[illegible]
June 9, 2005	Final	December 2001-December 2004

4. TITLE AND SUBTITLE
Climatological studies of mesospheric and lower thermosphere thermal and neutral wind structure at Maui, Hawii

5. FUNDING NUMBERS
F49620-02-1-0155

6. AUTHOR(S)
John W. Meriwether

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Clemson University
Clemson, SC 29634-0978

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research
875 North Randolph Street
Suite 325, Room 3112
Arlington, VA 22203
Major Beyers

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The research supported by this award dealt in part with the application of the Rayleigh lidar located at the Air Force N4OS facility in Maui, Hawaii to observe the density and temperature profiles during the July campaign period of 2002. These results have been analyzed and submitted for publication in J. Geophysical Res. (Atmospheres) . The research funding also supported the analysis of all-sky images obtained at Clemson University during a period of active mesospheric gravity wave disturbances. This work was published in J. Geophysical Res. In December, 2004. The research funding also supported the writing of a detailed review on the phonemenon known as the mesospheric inversion layer; this review was published in Reviews of Geophysics, in November, 2004. Finally, the research supported by the AFOSR funding including the investigation of a simultaneous MIL event observed in the upper and lower mesosphere regions. This event was compared with a model prediction of the effects of the propagation of a long-period gravity wave through the upper mesosphere region.

14. SUBJECT TERMS			15. NUMBER OF PAGES
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT

John W. Meriwether

Department of Physics and Astronomy
Clemson University

Clemson, SC 29634-0978

Principal Investigator

F49620-02-1-0155

Climatological Studies of Mesospheric and Lower Thermosphere Thermal and Neutral Wind Structure at Maui, Hawaii

1. Scientific Objectives of ongoing work

The original intention of the proposed statement of work was to study the climatology of the thermal structure of the upper mesosphere and lower thermosphere over Hawaii with the use of the combined sodium and Rayleigh lidar instrumental facilities at the Maui facility of AMOS. However, this focus had to be changed. Instrumental problems regarding the optical interface between the Rayleigh Nd:YAG laser transmitter and the Air Force AMOS optics at the large 3.7 m telescope were encountered preventing the collection of the Rayleigh measurements that were originally planned. Tim Kane, Penn State, and I were going to collaborate in an effort that would have combined his receiver and detector system with the Clemson 24 watts laser.

Consequently, without the Rayleigh lidar system, it is not possible to determine the temperature profiles for the stratosphere and mesosphere regions as was originally intended. It now appears that the redesign effort of the interface optics will not happen at all because the AEOS facility is reluctant to modify the hardware as required. Indeed, the CEDAR community is planning to build an alternative lidar facility that would eliminate the reliance upon the AMOS system.

Fortunately, it has proved possible to utilize Aerospace Rayleigh measurements that has a range in excess of the altitude of 80 km. This provided sufficient overlap with the sodium wind and temperature observations carried out by the Univ. of Illinois at AMOS. The Aerospace lidar facility is located reasonably close (~250 km separation) to Maui for the results to be useful for comparison with the wind and temperature sodium data collected by the U. of Illinois group. Both the MauiMALT observations for the July 2002 period and the Aerospace Rayleigh lidar observations obtained simultaneously have been analyzed in detail and the analysis substantially developed with the additional use of SABER/TIMED satellite measurements of the global temperature structure. The results were summarized in a publication submitted in the current year to be a part of the special issue of the J. Geophys. Res. containing publications associated with the MauiMALT observations.

2. Status of Effort

The effort expended to date in the AFOSR award has been devoted to five areas:

1), The completion of an extensive mesosphere inversion layer (MIL) review paper that was submitted originally to the Journal of Geophysical Research (Atmospheres) and subsequently submitted to the Reviews of Geophysics,

2) The publication of a paper describing the modeling of a MIL event observed in Illinois utilizing the combined observations of Rayleigh and sodium temperature lidar measurements.

3), the completion of the analysis and development of an understanding of the July 2002 Hawaiian observations combined with submission of a publication to the J. of Geophys. Research,

4), the completion of the analysis of all-sky imaging observations at 557 and OH wavelengths obtained at Clemson on October 14-15, 2001 that is identified with a period of mesosphere bore activity that is believed to be initiated by planetary wave activity – a matter of considerable interest to the Air Force (Dr. Edmund Dewan, private communication), and

5) the preparation of a draft overview report on the status of CEDAR passive optics science for the National Science Foundation and for the CEDAR community. This report is also of great interest to the Air Force as it describes science goals and objectives relating to passive optics measurements that are of importance to the Air Force long-term needs.

The effort in these five areas is directed to the improvement of our understanding of the dynamical processes that govern the behavior of the winds and temperature structure of the mesosphere and lower thermosphere region (MLT). The dynamics of this region are of great interest to the Air Force as this is the region of reentry for missiles and spacecraft. Consequently, achieving accurate trajectory analysis requires that the dynamical influences that might perturb the flight of any projectile passing through this region be understood for modeling purposes.

3. Accomplishments / new Findings

3.1 Modification of MIL paper for submission to the Reviews of Geophysics

In the spring of 2002 the PI submitted a paper to the J. Atmos. Solar Terr. Physics that summarized the new results of MIL lidar studies that have emerged in the literature since the review paper published by Meriwether and Gardner (2000). This paper was based upon the invited talk that the PI presented at the Clemson workshop on the mesosphere and lower thermosphere region in September, 2001, and the submitted paper was intended to be part of a special issue of this journal. After quite of bit of time elapsed, it eventually worked out that the paper was withdrawn from JASTP (there was no special issue), submitted to AGU Atmospheres but rejected because this journal discovered it has a policy against the publication of review papers (in spite of the fact that the JGR editor encouraged submission of the paper initially). The JGR draft was then rewritten to include material describing the thermal structure of the polar stratosphere region (to make the paper more general). This new version was submitted to the Reviews of Geophysics and accepted after review. It was published in November, 2004.

The MIL paper was intended to be a review of the topic regarding the mesospheric inversion layer, which is a strange feature of the upper mesosphere that have been observed by both Rayleigh and sodium temperature lidar facilities on numerous occasions (Meriwether and Gardner, 2000). The new MIL paper was intended to summarize the recent findings in the lidar literature and makes the point that rather than there being one mechanism responsible for the production of the double MIL (70 km, 95 km), it is more likely that there are two separate mechanisms that are engaged in the development of MIL activity simultaneously in two separate regions of the MLT region. The higher MIL is likely to be generated by the coupling of gravity waves with the tidal structure. The lower MIL is likely generated by the breaking of planetary waves, which would naturally be a winter phenomenon. Until the advent of the sodium wind and temperature lidar technique, it had not been appreciated that two MIL events may occur simultaneously separated by the vertical wavelength of the diurnal tidal structure but each driven by a separate mechanism.

3.2 Modeling of an MIL event observed over Urbana, Illinois

Also related to the review work on the MIL was a paper featuring the presentation of the modeling analysis of lidar measurements of the upper and lower MIL events observed at Urbana, Illinois, on November 17, 1997. This paper was published as part of the TOMEX special issue of JGR-Atmospheres, which appeared in the Spring of 2004. These results were obtained through the simultaneous operations of the U. of Illinois sodium temperature lidar and the Clemson University Rayleigh lidar achived by utilizing two separate transmitters and one receiver telescope common to both lidar systems. The modeling was carried out by Dr. Hanli Liu, National Center of Atmospheric Research. In this paper we compared the results for this night which featured the observations of a sudden appearance of a large MIL event with the results of a model that studied the coupling of a long period gravity wave with the diurnal tidal structure. It was demonstrated that there was enough energy released in this interaction to produce the large temperature rise observed.

The subject addressed in both of these papers is the question of the origin of the mesosphere inversion layer. The conclusion that there might be two separate mechanisms rather than one is an important result. It had been known for years that the MIL events observed during the summer displayed different characteristics than the one observed during the winter. It had been thought that this was a result of the change in gravity wave characteristics that occur between the two seasons of winter and summer. The gravity wave field in the winter feature waves with higher initial amplitudes which consequently will break at a lower altitude while conversely, during the summer the waves observed are traveling in the opposite direction and have weaker initial amplitudes. Now it appears that planetary wave breaking is the major cause of the lower MIL and that this phenomenon is not directly related to the breaking of gravity waves. Gravity waves still remain important because the gravity waves produce the reduction of the zonal component of the mesospheric winds which in turn is essential to the breaking of the planetary wave.

3.3 Analysis of Hawaiian measurements

For the July campaign of 2002 it has proved possible to utilize simultaneous Aerospace Rayleigh lidar measurements (Dr. Bob Farley, PI) obtained from the Barking Sands Rocket Range on the island of Kuai. The range of these measurements proved to be sufficient to reach the altitude of 80 km overlapping with the sodium wind and temperature observations carried out by the Univ. of Illinois at the AMOS facility on Mt. Haleakala. The Rayleigh lidar facility is located reasonably close to Maui (~250 km) for the data to be useful for comparison with the wind and temperature sodium data collected by the U. of Illinois group.

These results proved to be quite interesting. The beginning and end of the series of observations indicated that the semi-diurnal tidal variation of temperatures in the MLT region was regular and repeatable for the two nights as might be expected. There was no strong indication of any MIL activity, which is also expected for summer periods. However, for the other three nights of 11 July, 13 July, and 15 July, 2002, vigorous MIL activity was observed with amplitudes of 20 to 35 K. Unfortunately, for the night with the

largest MIL amplitude seen with the Aerospace Rayleigh lidar, 11 July, there were no Illinois sodium temperature observations available due to strong winds and high humidity.

As a further extension of the Rayleigh lidar measurements, Bob Farley (Aerospace) and the PI discussed the idea of determining profiles of root mean square temperature variances (averaged over a short interval of a few minutes) for the Rayleigh lidar measurements. The idea was to determine whether the MIL event might be correlated with periods of high gravity wave activity that would be signified by localized height bands of high variances. This showed the appearance of a wave disturbance that propagated to higher altitudes over the period of time from the initial onset of the MIL event.

Analysis of these results suggests that there is a close relationship between the development of the MIL activity during the "active" period and the observations of enhanced winds by the meteor radar system at Maui. There is a phenomenon known as the "two day" planetary wave in which the speed of the low latitude mesosphere winds are found to be enhanced by significant fraction, perhaps 20 to 30% in speed. The mechanism for the development of this planetary wave is not clearly understood but it is thought to be a non-linear outgrowth of the normal mode forcing of the atmosphere by tidal activity.

Recent work by Salby et al. (2003, JGR, Atmospheres) and by Sassi et al.(2003, JGR Atmospheres) has demonstrated by detailed modeling that the MIL activity may be caused by the breaking of planetary waves to transfer by dissipation the energy of this large scale global wave into an increase in the mean thermal structure in the region of breaking planetary waves. Crucial to the development of the dissipation of planetary wave is a zero wind line within the upper mesosphere that is generated by the breaking of gravity waves that imposes a strong drag upon the winds of the upper mesosphere. Without the contribution of these breaking gravity waves, the mesosphere zonal jet would not be closed and reduced to a zero wind. Without this zero wind to form a critical layer, the planetary wave mode would continue to propagate into the upper region of the atmosphere and there would be no dissipation or wave breaking taking place. In this case it appears that the development of the MIL activity for the three "active" nights is a result of the dissipation of the two-day wave as this is the only source of planetary wave activity that might exist within the summer hemisphere.

Clearly, these results illustrate the value of having simultaneous observations from multiple instruments capable of measuring different parameters that pertain to different aspects of the MLT dynamics whether winds or temperatures for the MLT region and temperatures and density fluctuations for the stratosphere region.

At the close of the presentation of these results at the MauiMALT workshop at the CEDAR 2003 meeting, Dr. Maura Hagan suggested that the PI broadens the scope of the interpretation of these results. Her suggestion was that we should seek to include the results of the global analysis of large-scale wave activity that is available from the network of MF and meteor radar systems that Dr. Scott Palo has organized to analyze for global scale variations of the mesosphere winds. Such results would give better insight into the global scale dynamics of the circulation which the-two day wave is part. This did indeed turned out to be true and the extension of the analysis was carried out with a paper organized to present these results submitted to JGR Atmospheres. Out of the three reviews, one was very favorable about publication, one was neutral suggesting that our paper be made more concise, and the third reviewer asking that we provide modeling results. We are not in the position of carrying out any such modeling and so, if the editor continues to insist upon this, then we will submit the paper to JASTP, most likely.

3.4 Mesosphere bore analysis for October 14-15, 2001

An area of interest to the Air Force is the mesosphere region where reentry vehicles may encounter significant atmospheric density changes that occur because layers of turbulence are sandwiched between stable regions. Of particular interest in this regard is the phenomenon known as the "mesosphere bore" that has been the subject of considerable interest ever since Dewan and Picard (AFRL) published their work in regard to their novel interpretation of the ALOHA 90 imaging observations of a "spectacular gravity wave" event that was observed by Dr. Mike Taylor imager. The two papers (Dewan and Picard, 1998; Dewan and Picard, 2001) laid out an explanation how the mesosphere inversion layer combined with the MIL represents a possible channel for the development of a non-linear process in which airglow waves are observed in the wake of a moving airglow front observed in the 557 nm airglow emission emission. These waves have been found to be phase locked and moving with the same speed as observed in the motion of the front.

A student, Mr. Bailes Brown, was supported during the summers of 2002, 2003, and 2004 by the AFOSR funding to work on the analysis of a similar event observed in the OH and 557.7 nm imaging observations obtained by the Clemson all-sky imaging system located at the Clemson Airglow Research Laboratory. Excellent data were obtained for these observations but the results for the night of October 14-15, 2001 proved to be especially interesting.

The scenario that we have developed to explain these results is that a mesosphere inversion layer was formed as a consequence of the wave breaking and dissipation of the

planetary wave observed. It is expected that such MIL events would occur during the autumn as lidar work has demonstrated that the frequency of such events exceeds 60-70% in this season. Once the MIL has been formed, the chances for the development of a bore depends upon vigorous gravity waves occurring that drive the non-linear development of the bore. We found that we could identify a region of convective activity off the coast of South Carolina. Dr. Andrew Gerrard's ray tracing model was successful in identifying how the gravity waves from this region of convective activity would be able to generate the atmospheric bore observed in the all sky imaging results.

With AFOSR funding support these results were prepared for publication and the paper was reviewed, accepted, and published in the December 2004 issue of JGR Atmospheres.

3.5 Other work

NSF requested the CEDAR lidar scientists prepare an overview of the program pertaining to CEDAR studies of lidar measurements over the past 20 years, since the beginning of CEDAR. The PI was requested to prepare an overview section of the science highlights that has emerged as a result of this 20 years of activity. The PI interacted with the several scientists to solicit contributions and to have the facts assembled by the PI reviewed and checked. The outcome of this activity has resulted in a draft of this report on Passive Optics self-assessment submitted to the National Science Foundation. Part of the PI time supported by AFOSR during the summer of 2004 was utilized in the conduct of this study.

4. Personnel Supported

A student, Mr. Bailes Brown, was supported for the summers for 2002 -2004. He is now a sophomore at Harvard University. He learned to write IDL code very quickly and has done an excellent job of helping to put together our mesosphere bore paper by analyzing the all-sky images.

The AFOSR award provided for one summer month of salary support for the PI.

5. Publications

Four papers have been prepared with the support of this AFOSR award. Three of these have been published, and one is undergoing a major revision for the J. of Geophysical Research. The titles are:

Mesosphere inversion layers and stratosphere temperature enhancements. J. W. Meriwether and A. J. Gerrard, *Reviews of Geophysics*, 42, doi2003RG000133, 2004

Analysis of a temperature inversion event in the lower mesosphere, Han-Li Liu and **Error! Contact not defined.**, *J. Geophys. Res.*,109, doi2002JD003026, 2004

All-sky imaging observations of a mesospheric bore in OI and OH airglow emissions and a possible production mechanism. L.B. Brown, J. W. Meriwether, A. J. Gerrard, J. Makela, J. Geophys. Res. (Atmospheres), 109, doi,2003JD0042232004.

Observed development of a summer mesosphere inversion layer in Hawaii: Possible relationship to the two day wave, R. W. Farley, J. L. Wellel, J. W. Meriwether, X. Chu, s. J. Franke, C. S. Gardner, A. Z. Liu, G. R. Swenson, S. E. Palo, J. Geophysical Research Atmospheres, in review, 2004

6. Interactions

I have been interacting with Dr. Edward Dewan, AFRL, Hanscom, in regard to the interpretation of the interesting event observed in October of 2001 in which it appeared that a dark streak seen in successive airglow images was a result of possible bore production. Further details are provided on the web site http://people.clemson.edu/~meriwej.

I presented a talk at the Air Force Research Laboratory, Hanscom Field, on December 8, 2004 on the subject of new techniques for observing thermosphere winds in the daytime.

7. New discoveries

The possibility of a planetary wave source for the creation of a bore may be an important result. Only time will tell when more comprehensive data sets are available for analysis. The observations at MauiMALT illustrate how important and useful it is to obtain extensive coverage of the many geophysical parameters.

8. Honors/Awards

None