Investigations of Interactions in The Earth's Upper Atmosphere Using Optical and Radio Wave Techniques

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Ravindra Pratap Singh

Under the Supervision of

Prof. Duggirala Pallamraju
Space and Atmospheric Sciences Division
Physical Research Laboratory
Ahmedabad, India

Dr. N. K. Bhatt
Department of Physics
Sardar Patel University
Vallabh Vidyanagar, India

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CERTIFICATE

Certified that the work incorporated in this Thesis entitled **"Investigations of Interactions in The Earth's Upper Atmosphere Using Optical and Radio Wave Techniques"** submitted by **Mr. Ravindra Pratap Singh** comprises the result of independent and original investigations carried out. The materials obtained from other sources and used in the thesis have been acknowledged appropriately. The work contained in this thesis has not been submitted for the award of any other degree/diploma anywhere.

Place: Vallabh Vidyanagar
Date: 07/11/2017
Registration No.: 557, date: 16/10/2012

Ravindra Pratap Singh
(Research Student)

Certified that the work mentioned above was carried out under my/our guidance.

7 Nov 2017

Prof. Duggirala Pallamraju
(Research Guide)

Prof. N. K. Bhatt
(Research Co-Guide)

Forwarded Through:

7/11/17

Prof. P. Janardhan
Dean
PRL, Ahmedabad

प्रो. जनार्दन पद्मनाभन
Prof. Janardhan Padmanabhan
डीन, भौतिक अनुसंधान प्रयोगशाला
Dean, Physical Research Laboratory
(भारत सरकार, अंतरिक्ष विभाग की यूनिट)
(Unit of Department of Space, Govt. of India)
नवरंगपुरा, अहमदाबाद-380 009 भारत
Navrangpura, Ahmedabad-380 009 India

Prof. U. H. Patel
Head, Department of Physics
Sardar Patel University
Vallabh Vidyanagar - 388 120

HEAD
DEPARTMENT OF PHYSICS
SARDAR PATEL UNIVERSITY
VALLABH VIDYANAGAR

Dedicated to

Mummy-Papa

and

Garima-Aanya-Aashvi

Contents

List of Tables xiii

List of Figures xv

Acknowledgment xxi

Abstract xxvii

List of publications xxxi

1 Introduction 1

1.1 Background 1

1.2 The Mesosphere and Lower Thermosphere (MLT) Dynamics . . 3

1.3 Temperature and Wind Dynamics in MLT Region 6

1.4 Wave Dynamics 12

1.5 Short Time Scale Variations in MLT region 15

1.5.1 Gravity Waves (GWs) 15

1.5.2 Topographic Generation 18

1.5.3 Convective Activity Generation 19

1.5.4 Wind Shear Generation 20

1.5.5 Atmospheric Tides 21

1.5.6 Planetary Waves (PWs) 22

1.6 Long Time Scale Oscillations in the MLT region 25

1.7 Sudden Stratospheric Warming (SSW) 28

1.8 Mesospheric Inversion Layers (MILs) 31
1.9 Measurement Techniques for MLT investigation 33
1.9.1 Ground-based Techniques 33
1.9.2 Rocket-borne Techniques 35
1.9.3 Satellite-based Techniques 35
1.10 Airglow emissions in MLT region 36
1.10.1 OI 557.7 nm Green Line Emission 39
1.10.2 O_2 (0–1) Atmospheric Band Emission 39
1.10.3 NaD Line Emission 41
1.10.4 OH Meinel Band Emission 42
1.11 Scientific Questions Addressed 42
1.12 Scope and Layout of the Thesis 43

2 Instrumentation and Data Analysis 49
2.1 Introduction 49
2.2 Near InfraRed Imaging Spectrograph (NIRIS) 50
2.2.1 Primary mirror 52
2.2.2 Secondary Mirror and slit assembly 52
2.2.3 Off-axis Paraboloid 53
2.2.4 Diffraction Grating 53
2.2.5 Converging Optics 54
2.2.6 Detector and Data Acquisition System 54
2.3 Calibration of NIRIS 55
2.3.1 Wavelength Calibration 55
2.3.2 Angle Calibration 57
2.4 Mesospheric Nightglow Intensity Determination 58
2.5 Derivation of Mesospheric Temperatures 61
2.5.1 OH(6-2) Meinel Band Emission 62
2.5.2 O_2(0-1) Atmospheric Band Emission 64

2.5.3 Nocturnal Variation in OH(6-2) and O_2(0-1) Band Intensities and Temperatures 65
2.6 NIRIS and SABER Temperatures Comparison 67
2.7 CCD-based Multi-wavelength Airglow Photometer (CMAP) . . 69
2.7.1 Optical Configuration of CMAP 69
2.7.2 Filters and Filter Wheel Assembly 71
2.7.3 Detector and Data Acquisition System 74
2.7.4 Derivation of Nightglow Emission Intensities 75
2.8 Supplementary Datasets 75
2.8.1 Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) 75
2.8.2 Optical Spectrograph and Infrared Imaging System (OSIRIS) 77
2.8.3 Solar Occultation For Ice Experiment (SOFIE) 77
2.8.4 Kalpana-1 78
2.8.5 Modern Era Retrospective-analysis for Research and Application (MERRA) 78
2.8.6 F10.7 cm Radio Flux and SSN Numbers 79
2.9 Time Series Analysis (TSA) Methods 79
2.9.1 Lomb-Scargle Analysis 80
2.9.1.1 Fast Computation of Lomb-Scargle Periodogram 81
2.9.1.2 Phase and Amplitude Spectra 82
2.9.1.3 Uncertainty in the frequency 83
2.9.1.4 REDFIT 84
2.9.2 Wavelet Analysis 84
2.9.2.1 Continuous Wavelet Transform (CWT) 85
2.9.2.2 Wavelet Functions 86
2.9.2.3 Wavelet Power Spectrum 87
2.9.2.4 Cone of Influence (COI) 87
2.9.2.5 Significance Levels 88
2.10 Wave Characteristics using NIRIS data 88

2.10.1 Derivation of Wave Period (τ) 89
2.10.2 Derivation of vertical phase speed (c_z) and vertical wavelength (λ_z) 91
2.10.3 Derivation of Meridional Wavelength (λ_y) 93
2.10.4 Wavelet Spectrum 95
2.11 Schematic of the Wave Propagation 96
2.12 Summary 98

3 Large- and Small-Timescale Variations in the MLT region 101
3.1 Background 101
3.2 Data set 102
3.3 Large-time Scale Variations 103
3.3.1 Introduction 103
3.3.2 Results and Discussion 105
3.3.3 Conclusion of Large-Time Scale Variations 112
3.4 Short-Time Scale Variations 113
3.4.1 Introduction 113
3.4.2 Results and Discussion 115
3.4.3 Conclusion of Short-Time Scale Variations 123
3.5 Summary 125

4 Vertical Coupling of the Atmospheres 127
4.1 Background 127
4.2 Introduction 129
4.3 Data set 133
4.3.1 Spectroscopic Observations 134
4.3.2 Photometric Observations 134
4.3.3 Outgoing Longwave Radiation (OLR) Measurements . . 135
4.4 Observations 135
4.4.1 Tropospheric activity 135
4.4.2 Activity in MLT region 137

4.5 Data Analyses and Results 140
4.5.1 Wave Period (τ) 140
4.5.2 Vertical Phase Speed (c_z) and Vertical Wavelength (λ_z) . 146
4.6 Discussion 147
4.7 Conclusion of Vertical Coupling of Atmospheres During Cyclone Nilofar 155
4.8 Anomalous Increase in O_2 Temperatures 157
4.8.1 Introduction 157
4.8.2 Observations 159
4.8.3 Results 160
4.9 Summary 163

5 Mesospheric Temperature Variations During SSW Events 165
5.1 Background 165
5.2 Introduction 166
5.3 Measurement Techniques 168
5.4 Observations 169
5.4.1 NIRIS Temperatures for January 2013 169
5.4.2 MERRA Temperatures and Winds for 2004-2013 172
5.5 Results and Discussion 172
5.5.1 SABER, OSIRIS, and SOFIE Temperatures for 2009 and 2013 SSW Events 174
5.5.2 SABER Temperatures for 2006 and 2010 Major SSW Events 177
5.5.3 SABER Temperatures for 2011 and 2012 Minor SSW Events 178
5.5.4 SABER Temperatures for 2008 SSW Events 179
5.5.5 Difference in Stratospheric vs Mesospheric Temperatures for 2009 and 2013 SSW Events 181

5.5.6 ΔT_S vs ΔT_M for Major and Minor SSW Events from SABER Data 183
5.5.7 ΔT_S vs ΔT_M for Major SSW events from SOFIE and OSIRIS Data 186
5.5.8 Slope ($\Delta T_M/\Delta T_S$) vs Geographic Latitude for Major and Minor SSW Events 187
5.5.9 Relationship between SRL with T_{Smax} and D with T_{Smax} 190
5.5.10 SABER vs CIRA Temperatures Comparison During SSW Events 192
5.6 Summary and Conclusion 195

6 Summary and Scope for Future Work 197
6.1 Summary and Conclusions 197
6.1.1 Atmospheric Waves and Coupling in the Earths Upper Atmosphere 199
6.1.2 Solar Influences in the MLT Nightglow Emissions and Temperatures 200
6.1.3 Mesospheric Temperature Inversions and their Possible Sources 200
6.1.4 Global Mesospheric Temperatures During SSW Events . 201
6.1.5 Techniques to Measure MLT Nightglow Emission Intensities and Temperatures 202
6.2 Scope for Future Work 203

Bibliography 207

List of Tables

1.1 Different types of oscillations/waves in the low-latitude middle atmosphere. 14

1.2 Different types of airglow emissions 37

2.1 Characteristics of Near Infrared Imaging Spectrograph (NIRIS) 52

5.1 List of SSW events considered for this study 174

List of Figures

1.1 Schematic of lower and middle atmosphere showing thermal and dynamical structure [Adapted from Meriwether and Gerrard, 2004]. 5

1.2 Vertical distribution of heating rates due to absorption of solar short wave radiation [Adapted from *London* (1980)]. 7

1.3 Zonal mean temperature from SABER retrievals and from WACCM [Adapted from *Smith* (2012a)]. 9

1.4 Zonal mean zonal wind from the URAP climatology and simulated by WACCM [Adapted from *Smith* (2012a)]. 11

1.5 A Summary of atmospheric waves [Adapted from *Lin* (2007)]. . 13

1.6 A surrealistic representation of atmospheric gravity waves [Adapted from *Hines* (1974)]. 16

1.7 Vertical distribution of the amplitude of the MQBO, MSAO, SSAO, SQBO, and annual component at the equator [Adapted from *Baldwin et al.* (2001)]. 27

1.8 Temperature and zonal wind for 2013 SSW event 29

1.9 Schematic of upper and lower mesospheric inversion layers [Adapted from *Meriwether and Gerrard* (2004)]. 32

1.10 Red, green, and yellow airglow emission from the Earth's upper atmosphere photographed by the International Space Station. (http://auroranightglow.blogspot.in/2012/05/night-glow.html) 37

1.11 Schematic of the peak emission altitudes for the various nightglow emissions in the MLT region. 38

1.12 Schematic of the simplified energy level diagram along with various emissions of the atomic oxygen. 40

2.1 (a) Optical layout of Near InfraRed Imaging Spectrograph (NIRIS) [*Singh and Pallamraju* (2017a).]. 51

2.2 Schematic of a reflection grating. 53

2.3 NIRIS obtained spectral images 56

2.4 (a) View angles calibration of NIRIS. 58

2.5 A nocturnal spectral image and spectral lines obtained by NIRIS 60

2.6 Nocturnal variation of three different rotational lines of OH(6-2) Meinel band and O_2(0-1) atmospheric band emissions 61

2.7 Nocturnal variations in O_2 and OH intensities and rotational temperatures on the night of 16 April 2013 and 04 May 2013 . . 66

2.8 Vertical profile of SABER and NIRIS derived temperatures . . 68

2.9 Optical configuration and photograph of CMAP 70

2.10 The filter wheel assembly and bipolar temperature controller along with Peltier elements to control the temperature 73

2.11 Typical temperature stability achieved in our in-house developed temperature controlled chamber used in CMAP 74

2.12 Nocturnal variations in the OI(630.0), OI(557.7 nm), and sodium (589.0 and 589.6 nm) nightglow emission intensities as measured by CMAP at Gurushikhar, Mount Abu on the night of 24-25 October 2014 76

2.13 Real part (solid) and imaginary part (dashed) for the Morlet wavelet in the time domain. 87

2.14 Periods that are present in nocturnal variation in O_2 and OH emission intensities 90

2.15 Nocturnal variation in I(O_2) and I(OH) intensities and Lomb-Scargle periodograms of the residuals 91

2.16 Residuals of the nightglow emission intensities for both O_2 and OH emissions showing downwards phase propagation which indicate an upwards propagation of gravity wave 92

2.17 (Variations in the O_2 and OH intensities along N-S meridian and statistically significant meridional wavelengths for O_2 and OH intensity variation throughout the night of 4 May 2013 . . . 94

2.18 The wavelet transform of the residuals of I(O_2) and I(OH) showing occurrence of the same periodicities as seen from Lomb-Scargle method along with their temporal occurrences 96

2.19 A schematic of the propagation of gravity wave in which the phase is shown to be progressing downwards (upward propagating wave) 97

3.1 Details of the duration of observations obtained from the Near InfraRed Imaging Spectrograph (NIRIS) at Gurushikhar, Mount Abu (24.6^{o}N, 72.8^{o}E), in India. 103

3.2 Variations in nightly mean O_2 and OH intensities, daily mean sunspot numbers and F10.7 cm radio flux, and corresponding O_2 and OH temperatures 106

3.3 Lomb-Scargle periodograms of the O_2 and OH intensities and corresponding temperatures and solar parameters for different durations 108

3.4 Four-day running averages of O_2 and OH intensities and SSN and correlation coefficients in between these parameters 111

3.5 The procedure used to derive gravity wave periodicities from the nocturnal variations of the nightglow intensity data is shown for a sample night of 10 June 2015 116

3.6 Gravity wave periodicities obtained from the O_2 and OH emission intensities for all the 437 nights of observations are shown which are folded into a one year interval 118

3.7 Same as in Figure 3.6 but for the temperatures obtained from the O_2(0-1) atmospheric and OH(6-2) band emissions intensities. 120

3.8 Statistical results of the GW occurrence frequency observed by all sky camera [Adapted from *Wu and Killeen* (1996)]. 123

3.9 Same as in Figures 3.6 and 3.7 (a, b, d, e) but for the periods that have been derived from only those nights of observation for which the total duration of observation was greater than 6 h . . 124

4.1 Time sequence of difference OH images in geographic coordinates from 0340 to 0500 UT on 11 May 2004 [Adapted from *Yue et al.* (2009)] 132

4.2 Outgoing longwave radiation (OLR) on 26 October 2014 as derived from VHRR on-board Indian meteorological satellite (Kalpana-1) 136

4.3 Nocturnal variations in the OI (557.7 nm), O_2(0-1) atmospheric band, Na (589.3 nm), and OH(6-2) Meinel band nightglow emission intensities as measured by CMAP and NIRIS at Gurushikhar, Mount Abu 138

4.4 Nocturnal variation in OI, O_2, Na, and OH nightglow emission intensities on the night of 26 October 2014. Variation of OLR values at the location 'P' for 24-hour duration 141

4.5 Lomb-Scargle periodograms of the zero mean unit variance for the parameters shown in Figures 4.4 for the night of 26 October 2014. 143

4.6 Periods obtained using Lomb-Scargle analyses for OI, O_2, Na, and OH nightglow emission intensities and in OLR(P) data obtained for each night during 16–27 October 2014. 145

4.7 Normalized wavelet spectra of the corresponding zero mean unit variances of the O_2, Na, and OH nightglow emission intensities as shown in Figure 4.4 and OLR(CR1) showing temporal evolution of the periods seen in Figure 4.5 148

4.8 Schematic showing the wave propagation direction and distance from the source region to the observational location. 150

4.9 Nocturnal variation in meridional and zonal wind at 94 km altitude as obtained from HWM14 and in vertical wavelength calculated using GW linear dispersion relation with the HWM14 winds 152

4.10 TIDI (TIMED Doppler Interferometer) winds showing the presence of shear in the zonal/ meridional winds. 154

4.11 The difference in T(O_2) and T(OH) on the night of (a) 16 April 2013, and (b) 6 May 2013 159

4.12 The five rows in the different subplots represent the difference in T(O_2) and T(OH), I(O_2) and I(OH), residuals of O_2 and OH emission intensities, and the periodicities present in the O_2 and OH emission intensities, respectively. 162

5.1 NIRIS derived O_2 and OH rotational temperatures over Gurushikhar, Mount Abu for a few selected nights during 2013 SSW period. 170

5.2 Temperatures in the polar cap poleward of 60^oN and longitudinally averaged zonal wind at 60^oN at 10 hPa pressure level obtained from MERRA dataset for eleven SSW events which occurred during 2004–2013 173

5.3 Longitudinally averaged mesospheric temperatures derived from the SABER, SOFIE, and OSIRIS dataset at 10° latitude interval for 2009 and 2013 SSW events 176

5.4 Similar to Figure 5.3 but for 2006 major SSW event. 177

5.5 Similar to Figure 5.3 but for 2010 major SSW event. 178
5.6 Similar to Figure 5.3 but for 2011 minor SSW event. 179
5.7 Similar to Figure 5.3 but for 2012 minor SSW event. 180
5.8 Similar to Figure 5.3 but for 2008 SSW event. 181
5.9 Differences in SSW temperatures (ΔT_S) over 60°–90^oN at 10 hPa pressure level vs difference in mesospheric temperatures (ΔT_M) for six selected latitude ranges for 2013 and 2009 SSW event as derived from SABER datasets 183
5.10 Difference in SSW temperatures (ΔT_S) over 60°–90^oN at 10 hPa pressure level vs difference in mesospheric temperatures (ΔT_M) at 10° latitude intervals as derived from SABER dataset from both the hemispheres for three major and five minor SSW events as shown in Figure 5.2 184
5.11 Same as in Figure 5.9 but for SOFIE data at two latitudinal ranges in NH and SH for three major SSW events of 2009, 2010, and 2013 combined together and for OSIRIS data for two major SSW events of 2009 and 2010 187
5.12 Slopes ($\Delta T_M/\Delta T_S$) derived from analyses for each individual major SSW event using SABER data with respect to the geographic latitude for all major and minor SSW events 189
5.13 Peak stratospheric temperature for all the eleven selected SSW events with slope reversal latitudes in the poleward direction in both hemispheres. Latitudinal difference in peak slopes of the "double-humped" structure with respect to the peak stratospheric temperatures are also shown 191
5.14 Daily mean mesospheric temperatures derived from SABER data for all the eleven SSW events with respect to geographic equator and CIRA-86 derived temperatures. The differences in the SABER measured and CIRA-86 estimated mesospheric temperature are also shown 193

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ABSTRACT

The Earth's upper atmosphere is influenced by the incoming solar radiation from above and upward propagating atmospheric waves from lower atmosphere. The present thesis deals with the understanding of these two influences on the Earth's upper atmosphere. While Earth's upper atmosphere have been studied in the past using all sort of available techniques, there still exist large gap in our understanding of mesosphere lower thermosphere (MLT) region. MLT region is the part of the upper atmosphere where most of the atmospheric waves deposit their energy and momentum affecting overall structure and composition of the middle atmosphere. Therefore, quantitative understanding of the various processes that influence MLT region becomes essential. In this work, the main atmospheric parameters that have been used to understand the various coupling processes in the MLT region are nightglow emission intensities and mesospheric temperatures. Nightglow is a very weak emission occurring in the Earth's upper atmosphere in the infrared, visible, and ultraviolet wavelength regions. These nightglow emissions comes mainly from the recombination processes e.g., when two oxygen atoms recombine to form molecular oxygen. Therefore, intensity of these nightglow emissions depends upon the number densities of the reactants. Hence, by measuring the variations in nightglow emission intensities provides information on the densities of the reactants that is mainly affected by the atmospheric waves and/or solar influences. Measurements of these parameters are carried out mostly by ground- and space-based remote sensing techniques and less frequently using in-situ rocket-based measurements.

In this work, the main focus was to characterize various coupling processes in the MLT region, wave dynamical couplings under varying geophysical conditions, effect of the solar influences in the MLT region, lower- and upper-atmosphere coupling during cyclones, and latitudinal couplings during sudden stratospheric warming (SSW) events. These investigations were carried out

mainly by using ground-based long-term data obtained from couple of in house built instruments namely, Near InfraRed Imaging Spectrograph (NIRIS) and CCD-based Multi-Wavelength Airglow Photometer (CMAP). NIRIS provides nightglow emission intensities and temperatures corresponding to 87 and 94 km altitudes using OH(6-2) Meinel and O_2(0-1) atmospheric band emissions, CMAP provides nightglow emission intensities using sodium doublet line (589.0 and 589.6 nm), OI green line (557.7 nm), and OI red line (630.0 nm) which emanate from 92, 100, and 250 km altitudes, respectively. In addition to these nightglow emission intensities and temperatures, mesospheric temperatures obtained from multiple satellite-based observations, data of F10.7 cm radio flux and SSN number, stratospheric zonal winds and temperatures from reanalysis dataset, OLR data from Kalpna-1 satellite etc. have been used. In the present doctoral thesis entitled "**Investigations of Interactions in The Earth's Upper Atmosphere Using Optical and Radio Wave Techniques**" an attempt has been made for a detailed investigations on the basis of the above stated broad topics. The work carried out in this thesis is presented in six chapters.

In this thesis work, development of a new spectrograph, NIRIS, which is capable of simultaneous measurements of OH(6-2) Meinel and O_2(0-1) atmospheric band nightglow emission intensities have been described. In this spectrographic technique, rotational line ratios are obtained to derive temperatures corresponding to the emission altitudes of 87 and 94 km. In addition to NIRIS, development of a new nightglow photometer, CMAP, to measure the nightglow emission intensities at multiple wavelength is also described. These two instruments have been commissioned for continuous operation from optical aeronomy observatory, Gurushikhar, Mount Abu (24.6^{o}N, 72.8^{o}E).

Large- and small-timescale variations in the mesosphere have been investigated using three (2013-2015) years of O_2(0-1) and OH(6-2) bands nightglow emission intensities and corresponding rotational temperatures as tracers of mesospheric dynamics. The solar activity show different small- and large-time

periods along with well known 27 days and 11 years periods. Both O_2 and OH intensities show variations similar to those of number of sunspots and F10.7 cm radio flux indicating a strong solar influence on mesospheric dynamics. In addition, both mesospheric airglow intensities also showed periodicities which are of atmospheric origin. Statistical study were performed using the periodicities derived from the nocturnal variations in all the four parameters (O_2 and OH intensities and their respective temperatures) in order to understand mesospheric gravity wave behaviour over long term.

Vertical coupling of atmospheres during cyclone Nilofar have been studied, wherein, we have observed a common periodicity of around 4-hours in mesospheric nightglow intensities at three emissions (O_2(0-1), OH(6-2) bands, and Na(589.3 nm)) from Gurushikhar, Mount Abu on the night of 26 October 2014. A convective activity due to the cyclone Nilofar, which had developed in the Arabian Sea during 25–31 October 2014, was found to be the source as this too showed a gravity wave period coherent with that of the mesospheric emissions on the 26th. The periodicities at the source region were obtained using Outgoing Longwave Radiation (OLR) fluxes (derived from Kalpana-1 satellite) which were used as a tracer of tropospheric activity. We have derived all the GW parameters (wave period, τ, horizontal phase speed, c_h, horizontal wavelength, λ_h, vertical phase speed, c_z, vertical wavelength, λ_z, and vertical propagation angle, θ_v) which were obtained experimentally from ground-based optical data that exist during cyclone Nilofar. These results thus provide not only unambiguous evidence on the vertical coupling of atmospheres engendered by the tropical cyclone Nilofar, but also the characteristics of waves that exist during such cyclonic events.

Significant enhancements observed in the NIRIS derived mesospheric rotational temperatures at 87 and 94 km altitudes during the major sudden stratospheric warming (SSW) event of January 2013 provided motivation for the further investigation on the global scale. To investigate the relationship of these enhancements in the context of SSW occurrences, a detailed study

was carried out for eleven SSW events that occurred during 2004–2013 using SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) data. In addition to SABER, Optical Spectrograph and InfraRed Imaging System (OSIRIS) and Solar Occultation For Ice Experiment (SOFIE) mesospheric temperatures were also used which showed similar latitudinal behaviour as obtained by SABER. The longitudinal mean mesospheric temperatures at different latitudes of northern and southern hemispheres have been derived. It is found that, during SSW events the well-known mesospheric cooling over the northern hemispheric high-latitudes turns to heating over mid-latitudes and then reverts to cooling closer to equatorial regions. This trend continues into the southern hemisphere as well. These variations in the mesospheric temperatures at different latitudes have been characterized based on northern hemispheric stratospheric temperature enhancements at high-latitudes during SSW periods. In comparison with the CIRA-86 derived temperatures the SABER temperatures show an increase/decrease in southern/northern hemisphere. Such a characterization in mesospheric temperatures with respect to latitudes reveals an hitherto unknown intriguing nature of the latitudinal coupling in the mesosphere that gets set up during the SSW events.

Keywords: Nightglow emissions, Mesospheric temperatures, OH(6-2) and O_2(0-1) rotational temperatures, Mesosphere Lower Thermospheric (MLT) dynamics, Gravity wave characteristics, Tropical cyclone generated gravity waves, Atmospheric coupling, Low-latitude MLT dynamics, Stratospheric mesospheric coupling, Inter-hemispheric mesospheric couplings, Sudden Stratospheric Warming (SSW), Mesospheric inversion layers, Mesospheric temperature inversions, Optical techniques, Near Infrared Imaging spectrograph (NIRIS), CCD-based Multi-Wavelength Airglow Photometer (CMAP).

LIST OF PUBLICATIONS

A. Publications in Peer Reviewed Journals

1. **Singh, R. P.,** and D. Pallamraju (2017), Near Infrared Imaging Spectrograph (NIRIS) for ground-based mesospheric OH(6–2) and O_2(0–1) intensity and temperature measurements, **J. Earth Sys. Sci.**, 126:88, doi:10.1007/s12040-017-0865-4.

2. **Singh, R. P.**, and D. Pallamraju (2017), Large- and small-scale periodicities in the mesosphere as obtained from variations in O_2 and OH nightglow emissions, **Ann. Geophys.**, 35, 227–237, doi:10.5194/angeo-35-227-2017.

3. **Singh, R. P.,** and D. Pallamraju (2016), Effect of cyclone Nilofar on mesospheric wave dynamics as inferred from optical nightglow observations from Mt. Abu, India, **J. Geophys. Res. Space Phys.**, 121, 5856-5867, doi:10.1002/2016JA022412.

4. **Singh, R. P.,** and D. Pallamraju (2015), On the latitudinal distribution of mesospheric temperatures during sudden stratospheric warming events, **J. Geophys. Res. Space Phys.**, 120, 2926-2939, doi:10.1002/2014JA020355.

5. Pallamraju, D., J. Baumgardner, **R. P. Singh**, F. I. Laskar, C. Mendillo, T. Cook, S. Lockwood, R. Narayanan, T. K. Pant, and S. Chakrabarti (2014), Daytime wave characteristics in the mesosphere lower thermosphere region: Results from the Balloon-borne Investigations of Regional-atmospheric Dynamics experiment, **J. Geophys. Res. Space Phys.**, 119, 2229-2242, doi:10.1002/2013JA019368.

6. Pallamraju, D., F. I. Laskar, **R. P. Singh**, J. Baumgardner, and S. Chakrabarti (2013), MISE: A Multiwavelength Imaging Spectrograph

using Echelle grating for daytime optical aeronomy investigations, **J. Atmos. Sol-Terr. Phys.**, 103, 176-183, doi: 10.1016/j.jastp.2012.12.003.

B. Peer-Reviewed Technical Publications

1. Phadke, K. A., R. Narayanan, **R. P. Singh**, and D. Pallamraju (2014), An Automated CCD-based Multi-wavelength Airglow Photometer (CMAP) for Optical Aeronomy Studies, PRL Technical Note, PRL-TN-2014-107.

2. **Singh, R. P.**, D. Pallamraju, and R. Narayanan (2012), Development of Automated Digital Optical Imagers for Photography of Vapour Cloud Releases by Rocket, PRL Technical Note, PRL-TN-2012-102.

C. Papers in International Conferences/ Symposia/ Workshops/ Meetings

Sr. No.	Paper title	Name of the Conference/ Symposia/ workshops	Mode of presentation
1.	Low-latitude mesospheric wave dynamical variability over large- and short-timescales **Singh, R. P.** and D. Pallamraju	IAPSO-IAMAS-IAGA Joint Assembly 2017, 27 August–1 September 2017, Cape Town, South Africa	Oral presentation
2.	Mesospheric temperature inversions over a low latitude location and their possible causes **Singh, R. P.** and D. Pallamraju	IAPSO-IAMAS-IAGA Joint Assembly 2017, 27 August–1 September 2017, Cape Town, South Africa	Oral presentation
3.	Results from first three dimensional waves in the daytime obtained from dayglow emissions and their comparison with those derived from ionospheric measurements Pallamraju, D., D. K. Karan, S. Mandal, and **R. P. Singh**	14th Asia Oceania Geo Sciences (AOGS) meeting 6–11 August, 2017, Singapore	Oral presentation
4.	On the nature of latitudinal distribution of mesospheric temperatures during sudden stratospheric warming events **Singh, R. P.** and D. Pallamraju	9th workshop on Long-Term Changes and Trends in the Atmosphere, 19-23 September 2016, IAP, Kühlungsborn, Germany	Oral Presentation
5.	Effect of cyclone Nilofar on mesospheric wave dynamics as inferred from optical nightglow observations from Mt. Abu, India **Singh, R. P.** and D. Pallamraju	9th workshop on Long-Term Changes and Trends in the Atmosphere, 19-23 September 2016, IAP, Kühlungsborn, Germany	Poster Presentation

Sr. No.	Paper title	Name of the Conference/ Symposia/ workshops	Mode of presentation
6.	"Double-humped" structure in latitudinal distribution of mesospheric temperatures revealed during sudden stratospheric warming events **Singh, R. P.** and D. Pallamraju	14th International Symposium on Equatorial Aeronomy (ISEA-14), 19–23 October 2015, Bahir Dar, Ethiopia	Oral Presentation
7.	Effect of Sudden Stratospheric Warming (SSW) events on the latitudinal distribution of mesospheric temperatures **Singh, R. P.** and D. Pallamraju	40th COSPAR Scientific Assembly, 2–10 August 2014, Moscow, Russia	Poster Presentation
8.	Results on the Wave Dynamics in the Lower Thermosphere Obtained From Balloon-borne Investigations of Regional-atmospheric Dynamics (BIRD) Experiment Pallamraju, D., J. Baumgardner, **R. P. Singh**, et al.	International CAWSES-II Symposium, 18–22 November 2013, Nagoya, Japan	Oral Presentation
9.	A search for seeds of equatorial plasma irregularities: Results from ground- and balloon-borne optical measurements Chakrabarti, S., D. Pallam-Raju, J. Baumgardner, **R. P. Singh**, et al.	American Geophysical Union, Fall Meeting, 9–13 December 2013, San Francisco	Oral Presentation

D. Papers in National Conferences/Symposia/ Meetings

Sr. No.	Paper title	Name of the Conference/Symposia/Meetings	Mode of presentation
1.	Gravity waves in the ionosphere as derived from digisonde measurements at Ahmedabad, India Pallamraju, D., S. Mandal, K. A. Phadke, D. K. Karan, and **R. P. Singh**	3rd URSI-Regional Conference on Radio Science, 1–4 March 2017, Tirupati, India	Oral Presentation
2.	Anomalous distribution in mesospheric temperatures: Causes and Implications **Singh, R. P.,** D. Pallamraju, and N. K. Bhatt	Interdisciplinary Research Scholars Meet, 3–4 march 2016, Sardar Patel University, Vallabh Vidyanagar	Oral Presentation
3.	Latitudinal distribution of mesospheric temperatures during stratospheric warming events **Singh, R. P.,** D. Pallamraju, and N. K. Bhatt	National Space Science Symposium, 9–12 February 2016, Space Physics Laboratory, VSSC, Thiruvananthapuram	Oral Presentation
4.	Investigation of upper atmospheric wave dynamics as inferred from optical nightglow observations **Singh, R. P.,** D. Pallamraju, and N. K. Bhatt	National Space Science Symposium, 9–12 February 2016, Space Physics Laboratory, VSSC, Thiruvananthapuram	Poster Presentation
5.	Influence of gravity waves and tidal variability on mesospheric temperatures over Mount Abu (24.6^{o}N, 72.7^{o}E) obtained using a high-resolution spectrograph **Singh, R. P.,** D. Pallamraju, R. Narayanan and K. A. Phadke	18th National Space Science Symposium, 29 January–1 February, 2014, Dibrugarh University, Dibrugarh	Oral Presentation

Sr. No.	Paper title	Name of the Conference/Symposia/Meetings	Mode of presentation
6.	Recent advancements in the understanding of coupling of atmospheres Pallamraju, D., F. I. Laskar, **R. P. Singh,** et al.	51st annual convention of Indian Geophysical Union, 19–21 November 2014, Kurukshetra University, Kurukshetra	Oral Presentation
7.	A CCD-based multiwavelength airglow photometer Narayanan, R., K. A. Phadke, **R. P. Singh,** S. Panchal, and D. Pallamraju	18th National Space Science Symposium, 29 January–1 February, 2014, Dibrugarh University, Dibrugarh	Poster Presentation
8.	Daytime wave characteristics in the lower thermosphere as obtained from the Balloon-borne investigation of Regional Atmospheric Dynamics (BIRD) experiment Pallamraju, D., S. Chakrabarti, J. Baumgardner, **R. P. Singh,** et al.	18th National Space Science Symposium, 29 January–1 February, 2014, Dibrugarh University, Dibrugarh	Oral Presentation (INVITED)
9.	Remote sensing of mesospheric temperatures using a grating spectrograph **Singh, R. P** and D. Pallamraju	Interdisciplinary perspectives: Defence studies, Earth system science & Bio-medical science (IPDEB-2013), November 15–17, 2013, Sardar Patel University, Vallabh Vidyanagar	Poster Presentation
10.	Development of automated digital optical imagers for photography of rocket released vapour clouds **Singh, R. P.,** D. Pallamraju, and R. Narayanan	National Space Science Symposium, 14–17 February 2012, Sri Venkateshwara University, Tirupati	Poster Presentation
11.	Multi-wavelength High-resolution optical technique for the investigations of daytime upper atmospheric processes Laskar,F. I., D. Pallamraju, **R. P. Singh,** R. Narayanan, and S. Chakrabarti	National Space Science Symposium, 14-17 February 2012, Sri Venkateshwara University, Tirupati	Oral Presentation

E. Participation in Advanced Course:

1. 2012 International School on Atmosphere-Ionosphere Radar at National Central University, Taiwan (ISAR-NCU-2012), 12–17 November 2012, National Central University, Chung-Li, Taiwan.

F. Participation in National/ International Conferences/ Symposia/ Workshop:

1. IAPSO-IAMAS-IAGA Joint Assembly 2017, 27 August–1 September 2017, Cape Town, South Africa.

2. 9th workshop on Long-Term Changes and Trends in the Atmosphere, 19–23 September 2016, Kühlungsborn, Germany.

3. Seminar on Space Qualified Processes, Space Application Centre, Ahmedabad, 8 April 2016.

4. UGC Sponsored National Level Interdisciplinary Research Scholars Meet, Sardar Patel University, Vallabh Vidyanagar, 3–4 March 2016.

5. National Space Science Symposium (NSSS–2016), Space Physics Laboratory, VSSC, Thiruvananthapuram, 9–12 February 2016.

6. 14th International Symposium on Equatorial Aeronomy (ISEA-14), Bahir Dar, Ethiopia, 19-23 October 2015.

7. National Space Science Symposium (NSSS–2014), Dibrugarh University, Dibrugarh, 29 January–1 February, 2014.

8. DST-PURSE Sponsored national conference on Interdisciplinary perspectives: Defence studies, Earth system science & Bio-medical science (IPDEB-2013), Sardar Patel University, Vallabh Vidyanagar, 15–17 November, 2013.

9. National Space Science Symposium (NSSS–2012), Sri Venkateshwara University, Tirupati, 14-17 February, 2012.

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