THE UNIVERSITY OF BATH

Planetary Wave Dynamics of the Stratosphere, Mesosphere and Lower Thermosphere

by

Kerry Day

A thesis submitted for the degree of Doctor of Philosophy
University of Bath
Faculty of Engineering and Design
Department Electronic and Electrical Engineering

December 2011

COPYRIGHT
Attention is drawn to the fact that copyright of this thesis rests with its author. This copy of the thesis has been supplied on condition that anyone who consults it is understood to recognise that its copyright rests with its author and that no quotation from the thesis and no information derived from it may be published without the prior written consent of the author. This thesis may be made available for consultation within the University Library and may be photocopied or lent to other libraries for the purposes of consultation.

Kerry A Day
Abstract

The wave dynamics of the stratosphere, Mesosphere and Lower Thermosphere (MLT) have been globally investigated using a range of instruments. Theses studies presented here used meteor radars at Esrange, Sweden in the Arctic (68°N 21°E), Bear Lake Observatory (BLO), Utah in the USA (42°N 111°W) and Rothera, in Antarctica (68°S 68°W) to observe the winds and temperatures in the MLT. Further studies used the NASA EOS Aura satellite Microwave Limb Sounder (MLS) instrument to observe temperatures in the middle atmosphere.

The 5- and 16-day planetary waves dynamics have been investigated with ground-based radars, satellites and modelling observations and predictions of the winds and temperatures of the middle atmosphere. The instruments have been used for comparisons and to enhance the understanding of the winds and temperatures of the middle atmosphere.

Meteor radars have been used to observe the climatology of the 5-day planetary wave using wind amplitudes over Esrange and Rothera at heights of ∼80–100 km. A clear seasonal cycle was observed in both hemispheres, with summer and winter maxima. Variances were observed to reach 75 m² s⁻² in the summer and 65 m² s⁻² in the winter.

The 16-day planetary wave dynamics have been observed over Esrange and Rothera using meteor radar measured winds and temperatures at heights between 80–100 km. The 16-day wave seasonal cycle revealed the winter- and summer-time wave to reach amplitudes of 15 and 6 m s⁻¹. Further, radar temperature and wind observations of the 16-day wave were found to be linearly related.

Aura MLS temperature data have been used to investigate the 16-day planetary wave at heights of ∼10–100 km globally. The structure of the wave was revealed to peak in the polar regions at heights of about 30 and 70 km. The inter-annual variability of the wave was investigated to explain the unusual occurrence of the summer-time wave. The Quasi-Biennial Oscillation (QBO) and major Sudden Stratospheric Warming (SSW) were considered as possible influence, but with no clear persistence.

Finally, mean winds and temperatures and the 5- and 16-day planetary waves were studied over BLO using a meteor radar and Aura MLS, winds and temperatures, respectively. The variability of the mean winds and temperatures were compared with the URAP and HWM-07 models. The climatologies of the planetary waves were used to observed the wave dynamics of the middle atmosphere over BLO. A clear seasonal cycle was observed and temperatures and winds were found to be linearly related.
Acknowledgements

Thank you Nick Mitchell, my supervisor, for putting up with me and encouraging me to write papers. A special thanks to Charlie Beldon for all her help even after she left the group to work in industry. Finally, thank you to all my friends and family back in Colchester and my friends here in Bath, for all the support and encouragement through my PhD.
## Contents

Abstract i

Acknowledgements ii

List of Figures vi

List of Tables xiii

Abbreviations xiv

Physical Constants xv

Symbols xvi

1 Introduction to the atmosphere, waves and dynamics of the stratosphere, mesosphere and lower thermosphere 1

1.1 The Atmosphere – a general overview 2

1.2 Wind and temperature dynamics of the middle atmosphere 4

1.2.1 Pressure-gradient force 6

1.2.2 Coriolis force 7

1.2.3 Friction 10

1.3 Waves in the middle atmosphere 12

1.3.1 Tides in the MLT 15

1.3.2 Gravity Waves in the MLT 15

1.3.3 Planetary Waves in the MLT 15

1.4 Other large-scale dynamic phenomena of the middle atmosphere 24

1.4.1 Quasi-Biennial Oscillation 24

1.4.2 Sudden Stratospheric Warming 26

1.5 The importance of this study 27

1.6 The scope of this study 28

2 Meteor radar and the Aura Microwave Limb Sounder 30

2.1 Observing the stratosphere, mesosphere and lower thermosphere 30

2.2 Meteor Radars 32

2.2.1 A general overview 32

2.2.2 Meteor radar techniques used to measure the atmosphere 32

2.2.3 Meteor echoes observed in the atmosphere 34
## 5.1.6 Conclusions

### 6 Results - Mean winds, temperatures and the 16- & 5-day planetary waves over Bear Lake Observatory

6.1 Mean winds, temperatures and the 16- and 5-day planetary waves in the mesosphere and lower thermosphere over Bear Lake Observatory (42°N 111°W)

6.1.1 Abstract

6.1.2 Introduction

6.1.3 Data Analysis

6.1.4 Results

6.1.4.1 Seasonal mean winds and temperatures

6.1.4.2 Comparison with URAP and HWM-07

6.1.4.3 16- and 5-day planetary waves

6.1.5 Discussion

6.1.6 Conclusions

### 7 Conclusions and Suggestions for Future Work

7.1 Conclusions

7.1.1 Chapter 3 Summary – The Polar 5-day Planetary Wave in the MLT

7.1.2 Chapter 4 Summary – The Polar 16-day Planetary Wave in the MLT

7.1.3 Chapter 5 Summary – The 16-day wave in the middle atmosphere

7.1.4 Chapter 6 Summary – Mean winds, planetary wave, 16- & 5-day, over Bear Lake Observatory

7.2 Suggestions for Future Work

### A Further information

A.0.1 Aura MLS Analysis of Temperature Files

### References
List of Figures

1.1 The general structure of the atmosphere as defined by the temperature profile, also shown are the pressure and density profiles of the atmosphere. .................................................. 2
1.2 Short wave heating and long wave cooling rates (K/day) of the chemical species distribution and its dominance in the atmosphere [1]. .............................. 5
1.3 The zonally averaged temperature (K) at July solstice for all latitudes and at heights of \(\sim 10 - 100\) km, adapted from Geller [2]. .............................. 5
1.4 The Coriolis effect on an air parcel in the atmosphere with a constant pressure gradient, shown by the horizontal lines present. \(C = \) Coriolis force and \(P_n = \) Pressure gradient force. .................................................. 7
1.5 The forces acting on an air parcel in the hot northern hemisphere summer and cold southern hemisphere winter; where \(C = \) Coriolis force, \(P_n = \) pressure gradient force and \(v = \) velocity of the parcel. Note, the tilt of the Earth is not represented here as we are only considering the theory of forces acting on a rotating sphere. .................................................. 8
1.6 Zonal mean winds observed in January (top) and July (bottom) using UARS. .................................................. 9
1.7 The forces acting on an air parcel in the hot northern hemisphere summer and cold southern hemisphere winter; where, Coriolis force (C), pressure gradient force (\(P_n\)), velocity of the parcel (\(v\)) and the force associated with frictional drag (F) are represented. .................................................. 10
1.8 Brewer Dobson circulation. Streamlines of the mean meridional circulation of the middle atmosphere, in a quasi-Lagrangian representation. Adapted from Garcia and Solomon [3]. .................................................. 11
1.9 Hourly zonal winds over BLO for the month of April in 2009. .................. 12
1.10 Hourly zonal winds over BLO for April the 1\(^{st}\) to 9\(^{th}\) 2009. ............... 12
1.11 Lomb-Scargle periodogram of the meridional winds at a height of about 90 km over Esrange for July to September 2003 of the waves present between about 0.01 and 21 days, plotted in red are the 90 and 95% confidence levels. .................................................. 12
1.12 Lomb-Scargle periodogram of the zonal winds at a height of about 90 km over Esrange for December to February 2008/09 of the waves present between about 0.01 and 21 days, plotted in red are the 90 and 95% confidence levels. .................................................. 13
1.13 Phase fronts in the atmosphere showing how the wavelength is determined. 14
1.14 Planetary wave oscillations in the zonal winds and temperatures in the MLT over BLO Day et al. [4]. .................................................. 16
1.15 Wavelets of zonal winds for the year 2003 over a) Esrange, 2008 b) Bear Lake Observatory and c) Rothera at a height of about 90 km for periods of planetary waves of 1 – 20 days. .................................................. 17
1.16 Wavelets of meridional winds for the year 2003 over a) Esrange, 2008 b) Bear Lake Observatory and c) Rothera at a height of about 90 km for periods of planetary waves of 1–20 days. ................................. 17
1.17 An air parcel being displaced in the Northern hemisphere oscillating about the latitude band. ................................................................. 20
1.18 Aura MLS temperature amplitudes of composite-year data for the Northern hemisphere summer-time 16-day wave for August with overlaid UARS winds, Charney-Drazin, adapted from Day et al. [5] ... 22
1.19 Phase speed calculation geometry explained, where \( r \) = radius of the Earth, 6378 km, \( \phi \) = latitude of observation, \( x \) = distance from centre of the Earth to the latitude of observation. ................................................................. 22
1.20 The winds in the atmosphere to show how the QBO at the equator at 10 hPa (stratosphere) are reversed compared with those at 0.1 hPa (mesosphere) and block the flow from the Northern hemispheric winter to the Southern hemisphere summer. Where the orange arrows are the tropical waves, pink arrows are the planetary waves. From Baldwin et al. [6] ... 24
1.21 Composite-year UARS zonal winds for August, to show the effect of the negative background winds on the 16-day wave propagation in the summer-time. The circles show the 16-day wave, the blue arrows show the ability of the 16-day wave to propagate and the red arrows for the gravity-waves propagation and therefore in situ 16-day wave generation in the summer hemisphere. ................................................................. 25
1.22 Daily UKMO temperatures for the major SSW in the northern hemisphere winter of 2008/09. Also plotted are the UKMO daily zonal winds (m s\(^{-1}\)) as contour lines, Day et al. [5]. ................................................................. 26

2.1 Geometry of the backscatter of the meteor trail from the meteor radar transmitter radio wave pulse. ................................................................. 33
2.2 Geometry of the meteor to show, \( Z \) = zenith angle measured from the vertical, \( A \) = azimuth angle measured clockwise from North, \( h \) = elevation angle, measured up from the horizon. ................................................................. 33
2.3 Power plot of the decay of an underdense meteor echo. ................................................................. 34
2.4 Power plot of the decay of an overdense meteor echo. ................................................................. 35
2.5 Schematic of the phase shift of the meteor trail. ................................................................. 37
2.6 Global positions of radars presented in this thesis, Esrange, Bear Lake Observatory and Rothera. ................................................................. 38
2.7 Schematic of the five antenna and one transmitter interferometer array of the radar systems. ................................................................. 38
2.8 Height distribution of meteors. ................................................................. 40
2.9 Meteor distribution over Esrange, in one day, January 12\(^{th}\) 2009. ................................................................. 40
2.10 Meteor distribution over Bear Lake Observatory, in one day, January 12\(^{th}\) 2009. ................................................................. 41
2.11 Meteor distribution over Rothera, in one day, January 12\(^{th}\) 2009. ................................................................. 41
2.12 Histogram of the diurnal cycle in meteor counts, in Universal Time (UT). ................................................................. 43
2.13 The geometry to deriving the winds. ................................................................. 44
2.14 The schematic to show how the radar detects the bulk flow using arrow vectors for the winds for each meteor. ................................................................. 44
2.15 Sine-wave least-squares fit plot of each meteor using the observations from Fig. 2.14 where north is given the angle of zero, east, 90\(^{\circ}\), etc. ................................................................. 45
2.16 The NASA “A-train”. .......................................................... 46
2.17 Artist impression of the Aura satellite. ................................. 48
2.18 Orbit height and limb-scan geometry. The geometry shown is drawn to scale with the Aura satellite at a height of 705 km and the line of sight having a 50 km tangent height. The orbit plane is the plane of the page. Note that the instrument is not to scale. ........................................... 48
2.19 EOS MLS measurements for a 24 hour period. The crosses denote the location of the tangent points for individual limb scans. The continuous line is the suborbital track. This is displaced from the tangent points due to the Earth rotating as the satellite moves forward to the tangent point. The ascending orbits are those with the Southeast – Northwest tilt. There is the same daily coverage in the southern hemisphere as there is to the Northern Hemisphere shown here. ........................................... 50
2.20 Atmospheric spectral regions measured by Aura MLS. There is a separate panel for each radiometer. The red, green and blue curves are the calculated atmospheric limb spectra at 100, 30 and 10 hPa tangent pressure corresponding to heights of ~16, 24 and 32 km Livesey and Snyder. [7]. ........................................... 54
2.21 Aura MLS radiance profile of the R1A:118.B1F:PT band which is targeted on the O$_2$ line and used to measure temperature and tangent pressure. Only the radiances for the first 13 channels have been shown. The red lines correspond to the channels closest to the centres of the spectral lines, from Livesey et al. [8]. ........................................... 55
2.22 From Schwartz et al. [9] Aura MLS v2.2 temperature vertical two-dimensional averaging kernels. The variation of averaging kernels is small enough that this is representative of typical profiles, in this case for 35° N September climatology. The coloured lines show the contribution of atmospheric temperatures at each level, indicating the region of that atmosphere from which information is contributing to the measurements to a given retrieved temperature indicated by a plus sign of the same colour. The dashed black line indicates the vertical resolution in km and is determined by the full width at half maximum of the averaging kernels. The vertical solid black line shows the integrated area under the kernels. Values close to unity imply that the majority of the information comes from the atmosphere, whereas lower values imply contribution from a priori information. ........................................... 56
3.1 A wavelet analysis of a) hourly meridional winds over Esrange at a height of 90.4 km during the interval January to December 2003 and b) hourly meridional winds over Rothera at a height of 90.4 km during the interval January to December 2006. Amplitudes smaller than 3 m s$^{-1}$ are not plotted. ........................................... 63
3.2 Band-passed meridional winds over a) Esrange at a height of 90.4 km for 1999 to 2008 and b) Rothera at a height of 90.4 km for 2005 to 2008. Band-pass limits are wave periods of 4 to 7 days. ........................................... 64
3.3 Band-passed meridional winds as a function of height and time measured over Esrange during the year 2003, for heights from ~80 to 97 km. ........................................... 65
3.4 Time-height contours (filled colour contours) of the monthly variance of winds band-passed between 4 and 7 days over Esrange in the Arctic for both meridional and zonal components, for 1999 to 2008. Also plotted are the monthly-mean zonal winds. The zero-wind line is indicated by the heavy dashed line, red contour lines denote eastward mean winds and white contours denote westward mean winds. ......................... 67

3.5 Time-height contours (filled colour contours) of the monthly variance of winds band-passed between 4 and 7 days over Rothera in the Antarctic for both meridional and zonal components, for 2005 to 2008. Also plotted are the monthly-mean zonal winds. The zero-wind line is indicated by the heavy dashed line, red contour lines denote eastward mean winds and white contours denote westward mean winds. ......................... 68

3.6 A composite year analysis of 5-day wave activity over Esrange in the Arctic for the years 1999 to 2008 (filled colour contours) for a) meridional component and b) zonal component. Also shown are the composite year monthly-mean zonal winds (open contours). The zero-wind line is indicated by the heavy dashed contour, red contour lines denote eastward mean winds and white contours denote westward mean winds. ......................... 69

3.7 A composite year analysis of 5-day wave activity over Rothera in the Antarctic for the years 2005 to 2008 (filled colour contours) for a) meridional component and b) zonal component. Also shown are the composite year monthly-mean zonal winds (open contours). The zero-wind line is indicated by the heavy dashed contour, red contour lines denote eastward mean winds and white contours denote westward mean winds. The time axis has been shifted by six months to allow easy comparisons between the Arctic results of Fig. 3.6 and Antarctic. ......................... 70

4.1 A wavelet analysis of a) hourly zonal winds over Esrange at a height of 84.7 km during the interval January to December 2005 to 2009 and b) hourly zonal winds over Rothera at a height of 84.7 km during the interval January to December 2005 to 2009. Amplitudes smaller than 3 m s$^{-1}$ are not plotted. ......................... 82

4.2 Time-height contours of a) the hourly zonal winds band-passed between 12 and 20 days over Esrange and b) the hourly zonal winds band-passed between 12 and 20 days over Rothera. ......................... 85

4.3 Time-height contours (filled colour contours) of the monthly variance of winds band-passed between 12 and 20 days over Esrange in the Arctic for both meridional and zonal components, for 1999 to 2009. Also plotted are the monthly-mean zonal winds. The zero-wind line is indicated by the heavy dashed line. ......................... 87

4.4 Time-height contours (filled colour contours) of the monthly variance of winds band-passed between 12 and 20 days over Rothera in the Antarctic for both meridional and zonal components, for 2005 to 2009. Also plotted are the monthly-mean zonal winds. The zero-wind line is indicated by the heavy dashed line. ......................... 88

4.5 A composite-year analysis of 16-day wave activity over Esrange in the Arctic for the years 1999 to 2009 (filled colour contours) for the meridional component, top panel, and zonal component, bottom panel. Also shown are the composite-year monthly-mean zonal winds (contour lines). The zero-wind line is indicated by the heavy dashed contour line. ......................... 89
4.6 A composite-year analysis of 16-day wave activity over Rothera in the Arctic for the years 2005 to 2009 (filled contour) for the meridional component, top panel, and zonal component, bottom panel. Also shown are the composite-year monthly-mean zonal winds (contour lines). The zero-wind line is indicated by the heavy dashed contour line. 90

4.7 Band-passed mean daily zonal winds and daily temperatures over a) Esrange, at ∼85 km and b) Rothera, at ∼93 km, for the years 2002 to 2009. Band-pass limits are for the wave periods of 12 to 20 days. Coincident bursts of wave activity in temperature and winds are marked by a *. 91

4.8 A least-square fit of temperature versus wind amplitude for bursts of activity over Esrange and Rothera that are greater than 5 m s⁻¹, last for longer than 1 cycle and passing the Student T-test 90 % confidence level. 92

4.9 A composite year analysis of the 16-day wave activity using temperatures over Esrange in the Arctic and Rothera in the Antarctic for the years 2002 to 2009. 93

5.1 Zonal phase speed as a function of latitude for a 16-day wave of zonal wavenumber 1. 102

5.2 URAP winds for latitudes of 24°, 52° and 76° N for both winter (January) and summer (July). Also plotted are the zonal phase speeds of the 16-day wave for these latitudes. 103

5.3 Least-squares fit error in the wave amplitudes for January and July 2007 using a 95 % confidence level. 106

5.4 Time series of monthly-mean temperature amplitudes from 2004 to 2010 for the 16-day wave at a latitude 60° for both hemispheres. Also plotted is the stratopause height as a red contour line. 108

5.5 The monthly-mean temperature amplitude of the 16-day wave as a function of latitude at heights of ∼65 - 95 km for 2005. 109

5.6 Monthly-mean temperature amplitudes of the 16-day wave for 2005. Also plotted are the 2005 UKMO monthly-mean zonal winds (m s⁻¹) as contour lines and the stratopause height as a red contour line. 110

5.7 Composite-month temperature amplitudes for the 16-day wave in each month of the year, August 2004 – May 2010. Also plotted are the UKMO composite monthly-mean zonal winds (m s⁻¹) as contour lines and the stratopause height as a red contour line. 111

5.8 Northern summer-time wave amplitudes for the winter stratosphere and summer mesosphere. 114

5.9 Southern summer-time wave amplitudes for the winter stratosphere and summer mesosphere. 114

5.10 Mean summer-time temperature amplitudes of the 16-day wave in the MLT at heights from ∼80 – 96 km and latitudes of 50 – 75° N as a function of QBO zonal winds at 10 hPa. 115

5.11 Mean summer-time temperature amplitudes of the 16-day wave in the MLT at heights from ∼80 - 96 km and latitudes of 50 – 75° S as a function of QBO zonal winds at 10 hPa. 115

5.12 Daily UKMO temperatures for the major SSW’s in the northern hemisphere winters of 2004/05 to 2009/10. Also plotted are the UKMO daily zonal winds (m s⁻¹) as contour lines. 118
5.13 Monthly-mean Aura temperature amplitudes for post northern hemisphere major SSW’s, January 2005-2010. Also plotted are the UKMO composite monthly-mean zonal winds (m s$^{-1}$) as contour lines and the stratopause height as a red contour line. 

5.14 Monthly-mean Aura temperature amplitudes for post northern hemisphere major SSW's, February 2005–2010. Also plotted are the UKMO composite monthly-mean zonal winds (m s$^{-1}$) as contour lines and the stratopause height as a red contour line.

6.1 Monthly-mean meridional winds over BLO and 14 day Aura MLS temperatures. The zero wind contour is indicated in black and the white contours are in steps of 2 m s$^{-1}$. The temperatures are means for a latitude/longitude “box” of 40–45°N, 90–120°W for four height gates between on ∼81–97 km. The black vertical lines on the temperature plots indicate time of minimum meridional winds.

6.2 Monthly-mean zonal winds and the zonally averaged composite-year monthly-mean zonal URAP winds over BLO. The zero wind contour is indicated in black and the white contours are in steps of 5 m s$^{-1}$.

6.3 Monthly-mean meridional and zonal winds over BLO (41.9°N and 111.4°W), from the HWM-07 model. The zero wind line is indicated in black and the white lines indicate 5 m s$^{-1}$ steps.

6.4 The daily zonal winds and MLS temperatures at ∼90 km measured over BLO for the interval September 2009–January 2010. Wind maxima occurring at planetary wave periods (∼5 and 16 days) are indicated by the arrows, wind on the top axis and temperature on the bottom axis.

6.5 A Wavelet analysis of hourly zonal wind amplitudes at heights of ∼90 km, over BLO from March 2008 to July 2011.

6.6 Time-height contours (filled colour contours) of the monthly variance of winds band-passed between 12–20 and 4–7 days for the 16- and 5-day wave, respectively. Over BLO for both meridional and zonal components, 2008–2011. Also plotted are the monthly-mean zonal winds. The zero-wind line is indicated by the heavy dashed line.

6.7 On the right of the figure is the Hovmöller diagram of the Aura MLS data in 30° longitude bands for the month of December in 2009, at 40–45°N and ∼90 km. The black line shows the approximate location of BLO and the dashed line the wave fronts. On the left is the band-passed 16-day wave radar zonal winds for the same time and approximate height.

6.8 On the right of the figure is the Hovmöller diagram of the Aura MLS data in 30° longitude bands for the month of September in 2009, at 40–45°N and ∼90 km. The black line shows the approximate location of BLO and the dashed line the wave fronts. On the left is the band-passed 5-day wave radar zonal winds for the same time and approximate height.

6.9 Band-passed radar winds and Aura daily temperatures over BLO ∼90 km, for the years 2008–2011. Band-pass limits are for the wave periods of 12–20 days and 4–7 days for the 16- and 5-day wave, respectively. The Aura MLS data is from 40–45°N and 90–120°W. Note the temperatures have been multiplied by a factor of 3 for a by eye comparison with the winds.
6.10 A least-square fit of radar winds versus Aura temperature amplitudes at heights of $\sim 90$ km, for the 16- and 5-day waves for “bursts” of temperature amplitudes over BLO. Bursts are identified as, waves that are greater than $5 \, \text{m s}^{-1}$, that last for longer than 1 cycle and pass the Student T-test 90% confidence level. .................................................. 142

6.11 Time-series of monthly-mean temperature amplitudes from 2008–2011 for the 16- and 5-day wave at a latitude 35–45°N. Also plotted is the stratopause height as a red contour line. ................................. 142

A.1 Handwritten notes on how the radar measures and determines wind velocity and direction. .......................................................... 162

A.2 Wavelet mother Morlet wavenumber 6, as it approximates the signatures of the wave bursts. .................................................... 163

A.3 Planetary wave wavenumbers, k, 1 to 4, looking down on the globe and the wave on a circle of latitude. ......................................... 163

A.4 Rossby wave motion explaining why it is westward. ....................... 163

A.5 Meridional v zonal to compare the strength of the observed wave wrt the location of the observation. ................................. 163

A.6 Brewer Dobson with the wave breaking labelled. ......................... 163
List of Tables

1.1 Propagation limits ...................................................... 23
2.1 Meteor radar operating parameters ................................. 39
2.2 EOS MLS radiometers and measurements ....................... 52
2.3 Advantages and disadvantages of the meteor radar and Aura data ...... 57
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLO</td>
<td>Bear Lake Observatory</td>
</tr>
<tr>
<td>EOS</td>
<td>Earth Observing System</td>
</tr>
<tr>
<td>MF</td>
<td>Medium Frequency</td>
</tr>
<tr>
<td>MLS</td>
<td>Microwave Limb Sounder</td>
</tr>
<tr>
<td>MLT</td>
<td>Mesosphere Lower Thermosphere</td>
</tr>
<tr>
<td>MTS</td>
<td>Mesosphere Stratosphere Troposphere</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics Space Administration</td>
</tr>
<tr>
<td>QBO</td>
<td>Quasi-Biennial Oscillation</td>
</tr>
<tr>
<td>SSW</td>
<td>Sudden Stratospheric Warming</td>
</tr>
<tr>
<td>UARS</td>
<td>Upper Atmosphere Research Satellite</td>
</tr>
<tr>
<td>UKMO</td>
<td>UK MetOffice</td>
</tr>
<tr>
<td>URAP</td>
<td>Upper Reference Atmosphere Project</td>
</tr>
<tr>
<td>VHF</td>
<td>Very High Frequency</td>
</tr>
</tbody>
</table>
## Physical Constants

<table>
<thead>
<tr>
<th>Constant</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beta-effect ( \beta )</td>
<td>( 2.28 \times 10^{-11} \times \cos \phi )</td>
</tr>
<tr>
<td>Boltzmann constant ( k )</td>
<td>( 1.38 \times 10^{-23} \text{JK}^{-1} )</td>
</tr>
<tr>
<td>Brunt-Väisälä frequency ( N )</td>
<td>( \sim 5 \text{ minutes} )</td>
</tr>
<tr>
<td>( \pi )</td>
<td>( 3.14159265 )</td>
</tr>
<tr>
<td>Radius of the Earth ( r )</td>
<td>( 6378 \times 10^3 \text{m} )</td>
</tr>
<tr>
<td>Speed of sound ( c )</td>
<td>( 340 \text{ m s}^{-1} )</td>
</tr>
</tbody>
</table>
## Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_0$</td>
<td>initial amplitude</td>
<td>W</td>
</tr>
<tr>
<td>$A_t$</td>
<td>decay amplitude at time, $t$</td>
<td>W</td>
</tr>
<tr>
<td>$\dot{c}$</td>
<td>eastward wind speed</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>$c_X$</td>
<td>zonal phase speed</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>$C$</td>
<td>Coriolis force</td>
<td>N</td>
</tr>
<tr>
<td>$C_p$</td>
<td>specific heat capacity at constant pressure</td>
<td>N/A</td>
</tr>
<tr>
<td>$C_v$</td>
<td>specific heat capacity at constant volume</td>
<td>N/A</td>
</tr>
<tr>
<td>$d$</td>
<td>distance</td>
<td>m</td>
</tr>
<tr>
<td>$D_a$</td>
<td>radio wavelength</td>
<td>m</td>
</tr>
<tr>
<td>$E$</td>
<td>energy</td>
<td>J</td>
</tr>
<tr>
<td>$f$</td>
<td>Coriolis frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>$f_0$</td>
<td>Coriolis frequency at the surface</td>
<td>Hz</td>
</tr>
<tr>
<td>$F$</td>
<td>force (associated with friction)</td>
<td>N</td>
</tr>
<tr>
<td>$g$</td>
<td>gravity</td>
<td>m s$^{-2}$</td>
</tr>
<tr>
<td>$h$</td>
<td>true height of meteor</td>
<td>m</td>
</tr>
<tr>
<td>$h_f$</td>
<td>uncorrected height of meteor</td>
<td>m</td>
</tr>
<tr>
<td>$h_t$</td>
<td>layer thickness of fluid along the vertical</td>
<td>m</td>
</tr>
<tr>
<td>$H$</td>
<td>Scale height</td>
<td>km</td>
</tr>
<tr>
<td>$k$</td>
<td>zonal wavenumber</td>
<td>N/A</td>
</tr>
<tr>
<td>$K_{amb}$</td>
<td>plasma ambipolar diffusion</td>
<td>N/A</td>
</tr>
<tr>
<td>$\ell$</td>
<td>meridional wavenumber</td>
<td>N/A</td>
</tr>
<tr>
<td>$M_m$</td>
<td>mean molecular mass</td>
<td>kg mol$^{-1}$</td>
</tr>
<tr>
<td>$m$</td>
<td>vertical wavenumber</td>
<td>N/A</td>
</tr>
<tr>
<td>$N$</td>
<td>Brunt-Väisälä frequency</td>
<td>$\sim$ 5 minutes</td>
</tr>
<tr>
<td>$P$</td>
<td>pressure</td>
<td>N m$^{-2}$ (Pa)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
<td>Dimension</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
<td>-----------</td>
</tr>
<tr>
<td>$P_n$</td>
<td>Pressure gradient</td>
<td>Pa m$^{-1}$</td>
</tr>
<tr>
<td>$q$</td>
<td>potential vorticity</td>
<td>m$^2$s$^{-1}$K kg$^{-1}$</td>
</tr>
<tr>
<td>$r$</td>
<td>radius of the Earth</td>
<td>m</td>
</tr>
<tr>
<td>$r_m$</td>
<td>range to meteor</td>
<td>m</td>
</tr>
<tr>
<td>$t$</td>
<td>time</td>
<td>s</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
<td>K</td>
</tr>
<tr>
<td>$u$</td>
<td>zonal wind</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>$\bar{u}$</td>
<td>uniform flow</td>
<td>N</td>
</tr>
<tr>
<td>$U_c$</td>
<td>critical Rossby speed</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>$v$</td>
<td>meridional wind</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>$V$</td>
<td>amplitude of the wave</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>$V_0$</td>
<td>amplitude of the wave at the surface</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>$x$</td>
<td>distance from the center of the Earth to the latitude of observation</td>
<td>m</td>
</tr>
<tr>
<td>$z$</td>
<td>height</td>
<td>km</td>
</tr>
<tr>
<td>cir</td>
<td>circumference of the Earth at a given latitude</td>
<td>m</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Beta-effect</td>
<td>N/A</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>ratio of specific heat capacity $\frac{C_p}{C_v}$</td>
<td>N/A</td>
</tr>
<tr>
<td>$\zeta$</td>
<td>relative vorticity</td>
<td>s$^{-1}$</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>wavelength</td>
<td>m</td>
</tr>
<tr>
<td>$\lambda_x$</td>
<td>horizontal wavelength</td>
<td>m</td>
</tr>
<tr>
<td>$\lambda_z$</td>
<td>vertical wavelength</td>
<td>m</td>
</tr>
<tr>
<td>$\nu$</td>
<td>velocity</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>$\nu_g$</td>
<td>group velocity</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>$\nu_h$</td>
<td>horizontal velocity</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>$\nu_p$</td>
<td>phase velocity</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>$\nu_{rad}$</td>
<td>drift velocity</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>$\pi$</td>
<td>$\pi$</td>
<td>N/A</td>
</tr>
<tr>
<td>$\rho$</td>
<td>density of the atmosphere</td>
<td>kg m$^{-3}$</td>
</tr>
<tr>
<td>$\rho_0$</td>
<td>density at the surface</td>
<td>kg m$^{-3}$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>decay time</td>
<td>s</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>phase</td>
<td>rad</td>
</tr>
<tr>
<td>$\Phi_a$</td>
<td>phase at position a</td>
<td>rad</td>
</tr>
<tr>
<td>$\Phi_b$</td>
<td>phase at position b</td>
<td>rad</td>
</tr>
</tbody>
</table>
Symbols

\( \phi \) \hspace{1cm} \text{latitude} \hspace{1cm} ^\circ

\( \Omega \) \hspace{1cm} \text{Earth rotation rate} \hspace{1cm} \text{rad s}^{-1}

\( \omega \) \hspace{1cm} \text{wave frequency} \hspace{1cm} \text{Hz}

\( \Omega \) \hspace{1cm} \text{angular momentum} \hspace{1cm} \text{kg m}^2 \text{s}^{-1} \text{(N m s)}
Chapter 1

Introduction to the atmosphere, waves and dynamics of the stratosphere, mesosphere and lower thermosphere

This chapter introduces the following: The atmosphere of the Earth; dynamics of the stratosphere, mesosphere and lower thermosphere; waves present in the atmosphere; how we can observe this part of the atmosphere; and finally, the atmosphere’s dynamics and climatologies.

The aim of this chapter is to provide background information on the stratosphere, mesosphere and lower thermosphere (subsequently referred to as S and MLT) a region also known as the middle atmosphere, which is at heights of about 10–100 km. The middle atmosphere is important because the physical processes that occur there act to couple together the underlying troposphere and the overlying thermosphere. Further, the middle atmosphere is home to many interesting yet poorly-understood phenomena, including waves and tides of large amplitudes, airglow layers, meteors, polar mesospheric clouds, sprites and polar mesospheric summer echoes. Here the importance of describing coupling and dynamics of the S and MLT are explained.
The dynamics of the waves present in the S and MLT have been investigated in this thesis, which focuses on the 5- and 16-day planetary waves, mean winds and temperatures and other phenomena effecting their interactions, dynamics and coupling. The main focus has been on planetary waves which are global-scale waves. In particular, the 16- and 5-day planetary waves have been observed in these studies by using the winds and temperatures measured and observed directly by a variety of ground-based and satellite instruments and techniques. The dynamics of the waves and their influences with other phenomena in the atmosphere are investigated to develop and progress the understanding of the S and MLT regions. Ground-based and satellite observations were used to provide complementary analysis linking wave observations and a variety of analysis techniques were used to enhance the interpretation of the observational data. Observations and models were used for the comparisons studies of the real and predicted atmosphere.

1.1 The Atmosphere – a general overview

![Figure 1.1: The general structure of the atmosphere as defined by the temperature profile, also shown are the pressure and density profiles of the atmosphere.](image-url)
The Earth’s atmosphere can be divided according to its different properties, for example, ionisation, temperature gradient or composition. The temperature profile is frequently used, as shown here in Fig. 1.1.

The dynamics and coupling between layers of the atmosphere is important for scientists to improve the understanding of the atmosphere. A developed understanding of the coupled nature of the whole atmospheric system would lead to improvements in weather forecasting, modelling and identification of long-term trends. Further, this would lead to a better understanding of the effects of a changing climate on the atmosphere.

The troposphere is relatively easy to observe and many \textit{in situ} measurements are available. In contrast, as one progresses upwards in the atmosphere measurements become increasingly difficult to make, in particular in the stratosphere, mesosphere and lower thermosphere, at the heights of $\sim 10 - 100$ km. This region is bounded by the tropopause below, and by the mesopause above, and hence shall be referred to as the middle atmosphere. However, in the last few decades new technology has allowed for instruments to be developed that can observe the middle atmosphere.

In the last $\sim 20$ years measuring techniques have allowed for continuous, long-term (multiple years) and reliable measurements of the middle atmosphere. The difficulty in making \textit{in situ} measurements in the middle atmosphere stems from the air density. The density of air in the middle atmosphere is too high for satellites, but too low for other instruments, such as balloons and aircraft. Consequently it has been historically difficult to observe this region. While rockets can record \textit{in situ} data they are only able to take snap-shots on the way up and then again on the way back through the atmosphere. Newer instruments such as meteor radars can observe the MLT region, at heights of $\sim 80 - 100$ km by using meteor trails as tracers of atmospheric motion. Further, the development of satellite instruments means we can now observe the middle atmosphere, at heights of $\sim 10 - 100$ km.

In the atmosphere there are many different atmospheric waves that can propagate, for example, gravity-waves, tides and planetary-waves. Middle atmosphere dynamics is dominated by the ‘wave’ dynamics and the characteristics of such waves present. These
many different waves in the atmosphere propagate through the atmosphere and transport energy and momentum. Further, wave induced circulations are essential to understanding the observed transport of chemical species, where mixing by turbulence caused by dissipating waves plays a key role. As a consequence of the decreasing density with height, vertically propagating waves increase in amplitude as they ascend through the atmosphere, thus obey the law of conservation of energy. As waves propagate upwards the wave amplitudes increases until the wave becomes unstable. The wave eventually ‘breaks’ and transfers its energy and momentum to the mean flow of the atmosphere at the height at which it breaks, this often induces turbulence. The transferred momentum can drive global-scale circulation in the middle atmosphere, such as planetary waves. The waves in the atmosphere are known to interact strongly, for example, with each other, with background winds and the layers of the atmosphere, thus creating a greatly coupled system, transporting energy, chemical species and momentum. The planetary waves are also used as a tracer/proxy for the changes in the atmosphere in the short- and long-term, allowing studies of the climatological progression of the atmosphere and its changes with time.

1.2 Wind and temperature dynamics of the middle atmosphere

As previously described the atmosphere can be divided up into layers by its temperature profile. When trying to understand the atmosphere it is generally assumed to be in radiative equilibrium. This assumption leads to the situation where there is no heating or cooling and therefore the temperature is in a steady state throughout the atmosphere. However, the Earth’s radiative heating and cooling is dominated by the following chemical species, CO$_2$, H$_2$O$_{(g)}$ and O$_3$. Figure 1.2 shows how these chemical species effect the cooling and heating rates through the atmosphere. From Fig. 1.2 it can be seen that CO$_2$ is the dominant cooling species throughout the atmosphere. It has the greatest affect at heights of $\sim 50$ km. O$_3$ is the dominant heating species and it has the greatest affect at heights of $\sim 50$ km. Figure 1.2 allows the radiative equilibrium to be calculated using the heating and cooling rates of a more realistic atmosphere than of the assumed steady state atmosphere.
Figure 1.2: Short wave heating and long wave cooling rates (K/day) of the chemical species distribution and its dominance in the atmosphere [1].

Figure 1.3: The zonally averaged temperature (K) at July solstice for all latitudes and at heights of $\sim 10–100$ km, adapted from Geller [2].

Figure 1.3 shows the adapted figure from Geller [2] of the zonally averaged temperatures for the atmosphere using the heating and cooling rates from Fig. 1.2 for solstice conditions. The polar region which is experiencing summer is being heated because it is in continuous sunlight during summer-time, whereas the polar region which is experiencing winter, is in darkness during the winter-time. This leads to temperature gradients...
between the poles and the equator, as seen in Fig. 1.3. Maximum temperatures for
the summer and winter occur in the stratosphere where the temperatures can reach up
to $\sim 300\, \text{K}$ and $220\, \text{K}$, respectively. This heating can be explained by considering O$_3$, the
dominant traces gases in this region heating strongly at heights of $\sim 50\, \text{km}$. The
minimum temperatures are observed in the summer and winter mesosphere, at heights
of $\sim 85\, \text{km}$ or more. Here the temperatures can reach as low as $\sim 200\, \text{K}$ and $\sim 160\, \text{K}$,
respectively. This can be explained by considering Fig. 1.2, which shows that there is
no strong heating at this height by any species, and the cooling at this height domi-
nates. The winter pole is nevertheless cooler than the summer pole as a consequence of,
atmospheric adiabatic upwelling over the summer pole ducting crosses the equator and
adiabatic downwelling over the winter pole, like a large conveyer belt, this is explained
in more detail later in this chapter.

The general circulation of the atmosphere is influenced by the following four main forces
acting on it and producing a horizontal flow.


2. Coriolis force – rotation of the Earth spinning on its axis.

3. Friction – e.g., topography and orography.


1.2.1 Pressure-gradient force

Atmospheric heating can be local, for example land/sea boundary or global or equa-
tor/pole. Consider an air parcel. It attempts to flow away from a region of high press-
ure/temperature and towards a region of lower pressure/temperature. As it moves a
pressure-gradient is established and a circulatory cell is formed. For example, global
pressure-gradients create movement. Global movement is created by the summer-time
pole being in sunlight and therefore heated strongly, whereas the winter pole is in dark-
ness and therefore not heated strongly. The summer pole is thus much warmer than the
winter pole, so air parcels are displaced from the summer to the winter pole.
1.2.2 Coriolis force

We can assume the Earth surface to be on a rotating plane, the a moving air parcel experiences a "force": the Coriolis force. The force is proportional to the velocity $\times \sin(\text{latitude})$. The force acts at right angles to the direction of the motion of the air parcel, which is to the right in the northern hemisphere and to the left in the southern hemisphere. The Coriolis force deflects the air flow, thus the high to low pressure path flow of the air parcel is not direct, this is shown in Fig. 1.4.

\[
C = 2v \Omega \sin \phi
\]

Figure 1.4: The Coriolis effect on an air parcel in the atmosphere with a constant pressure gradient, shown by the horizontal lines present. $C =$ Coriolis force and $P_n =$ Pressure gradient force.

Coriolis force ($C$) and velocity ($v$) are approximately related by

\[
C = 2v \Omega \sin \phi
\]  

(1.1)

with angular momentum ($\Omega$) and latitude ($\phi$).

Considering Eqn. 1.1, a steady state is eventually reached when the pressure gradient force, $P_n$ equals $C$. In this situation only $P_n$ and $C$ are the acting forces and this steady state flow is known as the geostrophic flow.

The direction of the geostrophic flow in the stratosphere and mesosphere is dependent on the season. The summer pole is hotter than at the equator because it experiences 24-hour sunlight thus is continuously undergoing heating. In contrast, the winter pole is
colder as it is in continuous darkness. A pressure-gradient is set up in the same direction in both hemispheres, flowing from the summer to the winter pole, see Fig. 1.5. From the figure it can be seen that the summer polar atmosphere is hotter than the equator and the equator is hotter than the winter pole, thus the described temperature gradient is established.

As discussed earlier the Coriolis force acts in the opposite direction/sense in each hemisphere. As a result the geostrophic winds are easterly (westwards) in the summer hemisphere and westerly (eastwards) in the winter hemisphere, leading to a seasonal reversal of the mean wind flow. Note, pure geostrophic flow can only occur where there is no meridional (North-South) flow.

Using the heating and cooling rates, predictions of the zonal (East-West) can be made of ‘jets’ in each hemisphere. Geller [2] predicted the zonal mean geostrophic winds by radiative equilibrium to increase in speed with height and to reach $\sim 180 \text{ m s}^{-1}$ by a height of $\sim 100 \text{ km}$ in the winter hemisphere. In contrast to Geller [2], the real atmosphere as seen in Fig. 1.6 is different. Figure 1.6 shows the wind reversal from negative to positive at a height of about 90 km and the wind reaches $\sim 55 \text{ m s}^{-1}$ at a height of 110 km.

**Figure 1.5:** The forces acting on an air parcel in the hot northern hemisphere summer and cold southern hemisphere winter; where $C =$ Coriolis force, $P_n =$ pressure gradient force and $v =$ velocity of the parcel. Note, the tilt of the Earth is not represented here as we are only considering the theory of forces acting on a rotating sphere.
The atmosphere predicted by only radiative equilibrium differs from the observed winds and temperatures. The three main differences observed between the real atmosphere and the modelled atmosphere are listed below.

In the real atmosphere:

1. The zonal winds decrease at $\sim 60$ km and reverse above heights of about $85$ km, closing the zonal (E–W) jets.

2. Planetary-scale meridional (N–S) flow occurs and maximises at $\sim 90$ km, reaching speeds of $\sim 15$ m s$^{-1}$. 

**Figure 1.6:** Zonal mean winds observed in January (top) and July (bottom) using UARS.
3. At heights of $\sim 60\text{ km}$ the summer pole is no longer warmer than the winter pole and by $\sim 80\text{ km}$ it is colder than the winter pole in spite of the continuous heating. Thus, in the summer the coldest temperatures are in the mesospheric atmosphere.

To maintain equilibrium there must be a drag force acting on the air of the mesosphere, slowing and reversing the zonal jets. To explain these differences the forcing caused by the atmospheric waves must be considered. Critically it is important to consider the momentum deposited by dissipating waves.

### 1.2.3 Friction

In the lower atmosphere, at heights of $\sim 0\text{ – }10\text{ km}$, friction is dominated by the topography and orography. In contrast, in the middle atmosphere atmospheric waves cause a ‘drag’ force, $F$, opposing the air parcel motion.

At steady-state, flow occurs when:

$$ P_n = C + F \quad (1.2) $$

![Figure 1.7](image)

**Figure 1.7:** The forces acting on an air parcel in the hot northern hemisphere summer and cold southern hemisphere winter; where, Coriolis force ($C$), pressure gradient force ($P_n$), velocity of the parcel ($v$) and the force associated with frictional drag ($F$) are represented.

Figure 1.7 shows that steady-state occurs when the meridional ($N\text{–}S$) flow is away from the summer pole and towards the winter pole, creating a cross-equatorial meridional flow. This force, $F$, is the balancing force required to explain the unusually cold summer mesopause and the reduction of zonal winds. The source is thought to be the dissipation
or breaking of waves that have propagated upward through the atmosphere. They grow to amplitudes so large that they can no longer be sustained. Thus they break, causing turbulence in the atmosphere where they deposit the momentum of the dissipated waves.

Figure 1.7 illustrates that the resultant flow velocity, $\nu$, is not at right angles to the $P_n$ and the flow actually crosses isobars. The resultant meridional flow helps explain discrepancies between the radiative equilibrium model results and the observations.

The meridional wind flowing towards the winter pole in both hemispheres results in a convergence over the winter pole and a divergence over the summer pole. To sustain this system the flow must be continually replaced by upward moving air. In the summer pole, an upwelling of air which cools adiabatically creates a cold region in the summer-time mesopause and downwelling heating a warm region in the winter mesopause. A ‘conveyor belt’ circulation is set-up, the transport of air masses is known as the Brewer Dobson circulation, see Fig. 1.8. This circulation is known to be important in transporting meteor debris and NO$_x$ from the upper mesosphere into the winter polar stratosphere and troposphere creating coupling between the different layers.
1.3 Waves in the middle atmosphere

The dynamics of the Earth’s atmosphere, especially in the MLT, are dominated by large, global-scale waves and tides. Figures 1.9 and 1.10 show a representative month and part month of the unfiltered hourly zonal winds over BLO. The raw meteor radar data show the waves present in MLT.

**Figure 1.9:** Hourly zonal winds over BLO for the month of April in 2009.

**Figure 1.10:** Hourly zonal winds over BLO for April the 1st to 9th 2009.

**Figure 1.11:** Lomb-Scargle periodogram of the meridional winds at a height of about 90 km over Esrange for July to September 2003 of the waves present between about 0.01 and 21 days, plotted in red are the 90 and 95% confidence levels.
Chapter 1. Introduction

Figure 1.12: Lomb-Scargle periodogram of the zonal winds at a height of about 90 km over Esrange for December to February 2008/09 of the waves present between about 0.01 and 21 days, plotted in red are the 90 and 95% confidence levels.

Figures 1.11 and 1.12 shows a Lomb-Scargle periodogram. The seasons and component of the winds have been chosen to reveal the 5- and 16-day planetary waves signatures in the data. The figures show the prominent large amplitude waves in the atmosphere at heights of \( \sim 90 \) km at polar latitudes. They are:

1. Tides
2. Gravity waves
3. Planetary waves

Upward propagating atmospheric waves can reach large amplitudes by the time they reach MLT heights. Examples of sources are, topography (mountain ranges for gravity waves), storms, etc.

Consider a wave packet propagating away from its source and the group velocity, \( \nu_g \), of the wave and the energy flow has an upward component in the direction of the wave. The phase velocity, \( \nu_p \), is directed at approximately right angles and downwards to \( \nu_g \). The downward phase propagation denotes an upward energy propagation, as represented in Fig. 1.13.
Wavelength ($\lambda$), vertical wavelength ($\lambda_z$) and horizontal wavelength ($\lambda_x$) are related by:

$$\lambda^2 = \lambda_z^2 + \lambda_x^2$$  \hspace{1cm} (1.3)

As waves and tides propagate upwards through the atmosphere their amplitude increases with height because of the decreasing density.

Atmospheric density ($\rho$) and height ($z$) are approximately related by

$$\rho = \rho_0 \exp \left( \frac{-z}{H} \right)$$  \hspace{1cm} (1.4)

with $\rho_0$ is the density at the surface, and $H$ is a characteristic scale height.

$$H = \frac{kT}{M_m g}$$  \hspace{1cm} (1.5)

with Boltzmann constant ($k$), temperature ($T$), mean molecular mass ($M_m$), and gravity ($g$).

The energy, $E$, of the wave is constant in the absence of damping, giving:

$$E = \frac{1}{2} \rho V^2 = \frac{1}{2} \rho_0 V_0^2$$  \hspace{1cm} (1.6)
where $V$ is the amplitude of the wave and $V_0$ is the surface amplitude of the wave. $V$ can be calculated using:

$$V = V_0 \exp \left[ \frac{z}{2H} \right] = \sqrt{\frac{2E}{\rho}} = \sqrt{\frac{\rho V_0^2}{\rho}}$$

(1.7)

1.3.1 Tides in the MLT

Well-defined wave oscillations occur at sub-harmonics of a solar day at, 24, 12, 8 and 6 hours. The 24 and 12 are the strongest with higher frequencies, waves becoming smaller and are weaker in amplitude. Tides are the result of periodic solar heating of the atmosphere. Additionally, gravitational and lunar tides occur, but are of much smaller amplitudes. The amplitude of the wave generally increases with height, and tides in the MLT are known to reach approximately many tens of m s$^{-1}$.

1.3.2 Gravity Waves in the MLT

Gravity waves are mesoscale with a continuous spectrum of periods from $\sim$ 5 mins to $\sim$ 12 hrs (the Brunt-Väisälä frequency to the inertial period) and are restored by gravity and buoyancy forces. Gravity waves are very important in influencing the dynamics of the middle atmosphere. They are produced by many mechanisms in the troposphere and stratosphere. Sources include topography, convection, wind shear, unbalanced flows and frontal systems. The wavelengths are up to a few hundred kms. The importance of gravity waves is observed in their propagating over large distances and accounting for substantial fluxes of energy and momentum. They also filter and dissipate in the atmosphere, leading to the transfer of energy and momentum in situ. This results in forcing of large-scale circulation (e.g., planetary waves) and forcing thermal dynamics of the middle atmosphere.

1.3.3 Planetary Waves in the MLT

Planetary waves are observed to be giant meandering waves that are of a global-scale and oscillate with a integral number of cycles wrapped around a circle of latitude. In the MLT, the 5- and 16-day planetary waves have been observed to reach amplitudes of
Planetary waves produce purely horizontal air parcel displacements over large distances. They transport chemical species over long distances horizontally because of their long horizontal wavelengths. Further, they are also known to modulate temperatures in the atmosphere. Planetary waves are also known as Rossby waves when idealised on a plane [10]. Stationary planetary waves can propagate from topographic sources into the middle atmosphere. They can also be generated in situ, for example, by gravity wave breaking, these are known as travelling planetary waves. Planetary waves generally propagate westward from regions of forcing. Planetary waves are strongest in the northern winter, where the forces they exert act to decelerate strong winds of the polar vortex. The waves break when they become unstable, thus transporting their energy and momentum to the atmosphere. Conservation of potential vorticity requires the air parcel movement to be accompanied by the potential vorticity.

Planetary waves allow for the study of the dynamics and dynamical theory to aid weather forecasting and the understanding of the atmosphere. These studies focus on the ∼5- and 16-day travelling planetary waves in the middle atmosphere. Figures 1.11 and 1.12 show Lomb-Scargle periodograms identifying them at ∼90 km in the atmosphere.

Figure 1.14 presents the time-series of daily meteor radar zonal winds and MLS temperatures over Bear Lake Observatory (BLO) from the interval September 1, 2009 to January 31, 2010. It can be examined for oscillations that may be caused by planetary waves. It is evident from the figure that there are a number of intermittent oscillations.
in winds and temperatures with periods of several days or more. For example, an oscillation period of about 6 days with amplitudes of about 10 m s\(^{-1}\) and 5 K in September (lengthening to about 8 days in October). Also an oscillation period of about 16 days with amplitudes of about 15 m s\(^{-1}\) and 10 K in December and January. Successive wind (left axis, the solid black line) and temperature (right axis, the dashed green line) maxima are marked on the figure in the respective colours to highlight the oscillation.

**Figure 1.15:** Wavelets of zonal winds for the year 2003 over a) Esrange, 2008 b) Bear Lake Observatory and c) Rothera at a height of about 90 km for periods of planetary waves of 1 – 20 days.

**Figure 1.16:** Wavelets of meridional winds for the year 2003 over a) Esrange, 2008 b) Bear Lake Observatory and c) Rothera at a height of about 90 km for periods of planetary waves of 1 – 20 days.

Figures 1.15 and 1.16 shows the planetary waves with periods ranging from \(\sim 2 – 16\) days as observed over the three different meteor radar locations used in these studies, Esrange (68°N) 2003, BLO (42°N) 2009 and Rothera (68°S) 2009. Note that the data for Esrange is from 2003 and not 2009 as with the other radars as it was a problematic year for the Esrange system with long gaps in the data. The figures have been used as an examples
of the data, Chapters 3 to 6 present the 5- and 16-day waves in more detail over the three radar locations.

A 5-day wave signature can be seen in the summer months of all three radars, for example, over Esrange and BLO in the months of July-October also over Rothera in the months of November-February. A winter-time 5-day wave is observed, over Esrange and BLO and in the months of November to February and over Rothera in the months of July-October. The 5-day wave is not strictly restricted to precisely 5-days, but is observed to vary around 5-day generally within the period limits of 4 to 7 days.

The 16-day wave signature can be seen in the winter months over all three locations, December-February in the northern hemisphere and August in the southern hemisphere. A summer-time 16-day wave is intermittently observed, however, in this figure it is observed over BLO in August. Like the 5-day wave the 16-day wave varies around 16-days, it is generally within the period limits of 12 to 20 days.

The wavelet analysis used comprises of a Morlet wavelet of non-dimensional wavenumber 6 (chosen because it approximates to the planetary-wave bursts evident in the data). Similar wavelets have often been used to study activity in the MLT [e.g., 11, 12, 13, 14, 15]. A description of the wavelet technique can be found in e.g., Torrence and Compo [16].

Considering the origins of the planetary wave, the principle of conservation of potential vorticity, \( q \), simplifies and unifies the fluid dynamics. Potential vorticity combines the dynamics of the spinning Earth and the spinning of elements of fluids about the centers, which is smaller in scale. The Earth is surrounded by a fluid atmosphere which is concentrated into small spinning storms. Potential vorticity incorporates the effect of the sloping isentropic surface and shape of atmosphere lower boundary. Combining small scale fluid properties and large scale environmental properties gives:

\[
\frac{dq}{dt} = 0.
\]
With potential vorticity given by: \( q = f + \frac{\zeta}{h_t} \), \( \zeta \) = relative vorticity (vertical component only), \( h_t \) is the layer thickness of fluid (along the vertical) and \( f \) is the planetary vorticity.

Negating frictional heat sources and effects of small, unobserved, turbulence, planetary vorticity is given by:

\[
f = 2\Omega \sin \phi \tag{1.9}
\]

\( \Omega \) is the Earth rotation rate in radians per second \( (2\pi \text{ rad}/86400 \text{ s}, 7.27 \times 10^{-5} \text{ rad s}^{-1}) \).

The systematic gradient of the potential vorticity provided by the spherical shape of the planet is given by the beta-effect, \( \beta \), the rate of change of planetary spin with latitude:

\[
\beta = \frac{2\Omega \cos \phi}{r} \tag{1.10}
\]

Where \( r \) is the radius of the Earth \( \sim 6378 \text{ km} \).

Therefore, \( \beta = 2.28 \times 10^{-11} \times \cos \phi \). The beta-effect is of importance as it is the variation of Coriolis force with latitude that causes the mid-latitude large-scale tropospheric waves such as the westerlies to propagate vertically into the stratosphere.

From Fig. 1.17 it can be seen that for an air parcel rotating around the planet at a circle of latitude with no local rotation, \( \zeta \) is zero and planetary vorticity is the only influence. If the parcel is displaced towards the equator planetary vorticity decreases as its latitude decreases so to conserve absolute vorticity the relative vorticity must increase and therefore the spinning parcel moves anticlockwise. It overshoots and the scenario reverses and the planetary vorticity increases therefore the relativity vorticity decreases and it now spins clockwise. This results in a westward phase propagation of the disturbance, see Fig. 1.17. Therefore oscillations drift westward with respect to the mean flow of the atmosphere.

Planetary wave motion can be explained mathematically by considering the dispersion relation. Andrews et al. [17] details how the dispersion relation for planetary waves illuminates their motion but is not included here as it is beyond the scope of this study,
but Eqn 1.11 shows the result.

\[ \omega = \bar{u} \cdot k - \beta \frac{k}{k^2 + \ell^2} \]  

(1.11)

Equation 1.12 is the linear dispersion relation, here the zonal and meridional wavenumbers are k and \( \ell \), respectively, the uniform flow is \( \bar{u} \), the wave frequency is \( \omega \) and the westward phase velocity is denoted by \( \nu_p \).

\[ \nu_p = \frac{\omega}{k} = \bar{u} - \frac{\beta}{k^2 + \ell^2} \]  

(1.12)

To solve Eqn. 1.12 the velocity of the wave relative to the flow (\( \bar{u} > \nu_p \)) must be negative (as \( \beta / (k^2 + \ell^2) \) can only be positive). Thus the planetary wave propagation must be westward with respect to the mean flow of the atmosphere. The planetary wave can only propagate if the westward phase speed is greater than the eastward velocity of the mean flow, otherwise the, horizontal motion only - barotropic (quasi-geo), wave is transported eastward by the flow, Salby [18].

Considering the dispersion relationship in 3D, k becomes:

\[ \nu_p = \frac{\omega}{k} = \bar{u} - \frac{\beta}{k^2 + \ell^2 + \frac{m^2f^2}{N^2}} \]  

(1.13)
where $m =$ vertical wavenumber, $N =$ Brunt-Väisälä frequency ($\sim 5$ mins), given by:

$$N = \left(\frac{\gamma - 1}{\nu_p}\right)^{\frac{1}{2}} g.$$  \hfill (1.14)

The ratio the specific heat capacity at constant pressure / specific heat capacity at constant volume is of specific heat capacity ($\gamma$) is given by $\frac{C_p}{C_v}$. The vertical wavenumber, $m$, for a stationary planetary wave, $c_x = 0$, and no dependence on $\bar{u}$ can be written as:

$$m^2 = \frac{(k^2 + \ell^2)^{\frac{1}{2}}N^2}{\omega^2 - f^2}.$$  \hfill (1.15)

For a wave to propagate $m^2$ is positive, therefore:

$$0 < \pi < \frac{\beta}{(k^2 + \ell^2)} = U_c.$$  \hfill (1.16)

Thus a westward flow is given by $\pi < 0$ and an eastward flow by $\pi \gg 0$ so the wave would not propagate vertically. Therefore the waves can only vertically propagate in weak to moderate eastward winds speeds, $\hat{c}$.

$$c_x = \hat{c} + \bar{u}$$  \hfill (1.17)

Fig. 1.18 shows observations of the atmosphere in a state where planetary waves cannot propagate through the westward winds of the summer stratosphere up into the mesosphere and only low wavenumber waves propagate in the winter stratosphere to the mesosphere eastward winds. This is known as the Charney-Drazin criterion, in order for a planetary wave to propagate vertically it must obey Charney-Drazin criterion (theorem) 1961 which states:

$$0 < \pi - c_x < U_c$$  \hfill (1.18)

where $c_x$ is the zonal phase speed of planetary wave and $U_c$ the critical Rossby speed, given by Eqn. 1.16.
Figure 1.18: Aura MLS temperature amplitudes of composite-year data for the Northern hemisphere summer-time 16-day wave for August with overlaid UARS winds, Charney-Drazin, adapted from Day et al. [5]

Figure 1.19: Phase speed calculation geometry explained, where $r =$ radius of the Earth, 6378 km, $\phi =$ latitude of observation, $x =$ distance from centre of the Earth to the latitude of observation.

For example, $c_x$ over Esrange or Rothera (note they are both at latitudes of 68°) and BLO for the 5- and 16 day wave to propagate the phase speeds at these locations for the specific planetary waves can be calculated as follows with reference to Fig.1.20: $r =$ radius of the Earth, 6378 km, $x = \sin(90 - \phi) \times r$, circumference of the Earth at the latitude, $\text{cir.} = 2\pi x$, $c_x = \text{cir.} / \text{time to rotate once, time to rotate in seconds = planetary}$
wave number $\times$ hours $\times$ minutes $\times$ seconds.

<table>
<thead>
<tr>
<th>Location</th>
<th>5-day wave $c_x$</th>
<th>16-day wave $c_x$</th>
<th>$U_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Esrange/Rothera 68°</td>
<td>$\simeq -43 - 25$ m s$^{-1}$</td>
<td>$\simeq -14 - 9$ m s$^{-1}$</td>
<td>49 m s$^{-1}$</td>
</tr>
<tr>
<td>BLO 42°</td>
<td>$\simeq -85 - 49$ m s$^{-1}$</td>
<td>$\simeq -28 - 17$ m s$^{-1}$</td>
<td>369 m s$^{-1}$</td>
</tr>
</tbody>
</table>

Table 1.1 presents the limits for the waves to propagate upward from a latitude where the range of periods of the wave are considered. Thus, the mean zonal winds speed for the waves to propagate upwards in to the MLT at the specified location, $U$ must be greater than than $c_x$ and less than $U_c$, from Fig. 1.20 and Eqn. 1.16, respectively. This is discussed more in Chapter 3, 4, 5 and 7.

Some planetary waves are thought to be generated by flow over orography and by differential heating at the Earth’s surface (land/sea transition), these are known as stationary planetary waves as the have zero velocity with respect to the ground. They are known as forced modes [19]. In contrast, there are free modes, for example, the 5- and 16-day planetary waves discussed here which are global normal modes. These are natural resonances in the Earth’s atmosphere or may be forced by other generation mechanisms. The natural resonances can be modulated gravity-wave breaking, barotropic and baroclinic instabilities, these waves are known as travelling planetary waves.

Salby [20, 21] identified the wavenumber (low integer numbers), direction (westward or eastward) and period ranges (known as the limits). Identification of the “5-day” and “16-day” have been identified as the manifestation of the gravest symmetrical wavenumber 1 of the westward Rossby-Gravity mode (W1). The limits were identified by Salby as 4.4 to 5.7 day and 11.1 to 20 days, respectively. The limits were from modelling the waves [21]. Here the limits used are 4 - 7 days and 12 - 20 days for the 5- and 16-day wave, respectively, to make them comparable to other studies [e.g. 22, 23, 24, 25].
1.4 Other large-scale dynamic phenomena of the middle atmosphere

Two phenomena that affect the amplitude of the planetary waves are the Quasi-Biennial Oscillation (QBO) and major Sudden Stratospheric Warming (SSW). These are discussed in the following sections.

1.4.1 Quasi-Biennial Oscillation

There is a quasi-periodic oscillation of $\sim 2-3$ years for the equatorial zonal winds where it alternates between ascending phase of easterly (westward, negative) and westerly (eastward, positive) zonal winds. The Quasi-Biennial Oscillation (QBO) dominates the lower and middle stratosphere which affect the troposphere, upper stratosphere, mesosphere and extr-tropical middle atmosphere in the winter.

\[\text{Figure 1.20: The winds in the atmosphere to show how the QBO at the equator at 10\,hPa (stratosphere) are reversed compared with those at 0.1\,hPa (mesosphere) and block the flow from the Northern hemispheric winter to the Southern hemispheric summer. Where the orange arrows are the tropical waves, pink arrows are the planetary waves. From Baldwin et al. [6].}\]
Chapter 1. Introduction

The phase of the QBO has been suggested by e.g., Espy et al. [26], Hibbins et al. [27], Jacobi et al. [28], Jacobi [29] to have an important influence on planetary wave amplitudes in the summer-time. The phase of the equatorial zonal winds in the stratosphere at ∼10 hPa (∼32 km) is thought to influence large summer-time waves amplitude when the QBO phase of the winds are eastward. The QBO is thought to act as a switch for allowing waves to cross the equator from the opposite hemisphere. When the QBO is in its eastward (westerly) phase the duct is “open” and the waves can propagate from the winter to the summer hemisphere and thus increase the wave amplitude. However, when it is westward the duct is “closed” and the summer wave amplitude is thought to be reduced. This is investigated later in Chapter 5.

Figure 1.21: Composite-year UARS zonal winds for August, to show the effect of the negative background winds on the 16-day wave propagation in the summer-time. The circles show the 16-day wave, the blue arrows show the ability of the 16-day wave to propagate and the red arrows for the gravity-waves propagation and therefore in situ 16-day wave generation in the summer hemisphere.

Figure 1.21 shows the Charney-Drazin restricted region where the waves cannot propagate in the summer hemisphere of the 16-day wave. The QBO affects the location of the waves and whether it is able to be cross-equatorially ducted.
1.4.2 Sudden Stratospheric Warming

Sudden Stratospheric Warming can be categorised into major and minor events. Minor events are when the westerly (eastward) winds are slowed but, do not reverse. Subsequently, a breakdown of the polar vortex is never observed. Major SSW are defined as events where at 60°N latitude and a height of 10 hPa in the winter the winds have completely reversed and become negative (westward) therefore breaking down the polar vortex. It is also known that major SSW events can have a dampening effect on the planetary waves at high latitudes in the middle atmosphere [e.g. 30, 31, 32, 33].

In the Northern hemisphere there have been three events since 2004, in the years 2004, 2006 and 2009. In the Southern hemisphere there have been no events since 2004. The last observed southern hemisphere event was in 2002, as reported by Baldwin et al. [30]. Figure 1.22 shows the major SSW event in the winter of 08/09.

Another influence on the 16-day wave in the summer hemisphere is major Sudden Stratospheric Warmings (SSW). In the month proceeding a major SSW event the stratopause in the winter polar region is observed to be elevated. This results in dampening the planetary waves amplitude. It is proposed that this inhibits the ability of the planetary waves to cross-equatorial duct to the summer MLT. Chapter 5 discusses this in more detail.

Figure 1.22: Daily UKMO temperatures for the major SSW in the northern hemisphere winter of 2008/09. Also plotted are the UKMO daily zonal winds (m s$^{-1}$) as contour lines, Day et al. [5].
1.5 The importance of this study

This thesis focuses on the stratosphere, mesosphere and lower thermosphere at heights of $\sim 10 - 100$ km, and in a particular, the MLT region, at heights of $\sim 80 - 100$ km. Understanding the middle atmosphere is important for understanding the dynamics and coupling of the atmosphere as a whole. The coupling between layers can be observed in the transport of chemical species, energy and momentum. Waves are an important part of the dynamics of the middle atmosphere and play a key role in coupling it to the layers above and below. Understanding the role of waves in coupling different layers of the atmosphere is important because this coupling process may respond to solar variability and climate change.

The influence of planetary waves can be seen on many atmospheric phenomena. For example, in the polar region temperature perturbations caused by planetary waves modulate the occurrence of Polar Mesospheric Clouds [e.g. 34, 35, 36, 37] and the associated phenomena of Polar Mesospheric Summer Echoes [38].

Planetary waves modulate the gravity-wave field of the middle atmosphere and consequently modulate the fluxes of gravity-wave energy and momentum that drives the entire global circulation of the upper middle atmosphere [e.g. 39, 40, 41, 42, 43]. Modulated gravity-wave momentum fluxes can result in planetary-wave signatures penetrating to the thermosphere [44]. Studies of planetary waves are thus very important in the attempt to understand the coupling of the layers in the atmosphere.

Studies of the MLT have until recently, been comparatively limited because of the availability of suitable measurements. There are relatively few observations of the polar regions, in particular the Antarctic at MLT heights. Global observations by satellites have been used, but generally have a lower vertical spatial and temporal resolution than ground-based observations. Present observations are a compromise between spatial and temporal resolution.
1.6 The scope of this study

Chapter 1 briefly introduced the background of the atmosphere focusing on the middle atmosphere and the waves observed in this region. The waves are known to propagate from the surface of the Earth and transport energy and momentum. They can break and dissipate, thus transferring their properties to different layers of the atmosphere. They can also modulate other waves and phenomena in their turbulent/breaking transition. This thesis investigates the characteristics, behaviour, dynamics and propagation of the 5- and 16-day planetary waves in the MLT using meteor winds and temperatures data from radars at three locations, 68°N, 42°N and 68°S. Also measurements of atmospheric temperatures made by the Aura MLS instrument are used.

In Chapter 2 the instruments used in these studies are described and the techniques used discussed. Chapter 3 presents polar-region meteor radar wind data used to investigate the 5-day planetary wave in the MLT region. Chapter 4 presents polar-region meteor radar wind and temperature data used to investigate the 16-day planetary wave in the MLT region. Chapter 5 presents global temperatures from the NASA Aura satellite MLS instrument used to investigate the 16-day planetary wave dynamics and propagation in the global middle atmosphere. Chapter 6 presents mean winds, temperatures and the 5- and 16-day planetary wave dynamics over Bear Lake Observatory using radar winds and Aura MLS temperatures. Finally, Chapter 7 suggests areas for future work.

This thesis attempts to integrate and compare radar and satellite observations of the middle atmosphere to enhance the understanding of the winds and temperatures. The radar and satellite data sets observed, analysed and interpreted here are generally long in duration, spanning greater than five years. The satellite data from Aura MLS is computationally large in nature because of the volume of data it collects. This has lead to interesting comparisons and complementary data from the radars and satellites allowing developments in the understanding of the S and MLT. We have investigated the possible propagation of the 16-day planetary wave in the summer-time MLT and the roles of major SSW and QBO on propagation. Mean winds and temperatures over BLO have been observed investigating the link between them. The mean winds and temperatures have been compared to models to describe how the observed and modelled atmosphere differs.
Chapter 1. Introduction

Publications resulting from the work within this thesis:


Chapter 2

Meteor radar and the Aura Microwave Limb Sounder

2.1 Observing the stratosphere, mesosphere and lower thermosphere

The Earth’s atmosphere has been observed with many different instruments and techniques, ranging from early basic observations by eye, to recent technologically based satellite observations. Each has its merits, with a variety and combination allowing a developing understanding to progress and emerge. Basic observations have lead to the invention of new technologies and techniques.

Observations over the last ∼20 years, have given an insight into the dynamics of the stratosphere, mesosphere and lower thermosphere and the coupling between layers. The stratosphere, mesosphere and lower thermosphere has proven to be very difficult to observe. In situ measurements between 50 and 100 km are generally difficult to obtain. Only a limited number of instruments and techniques have been able to make measurements there. Satellites cannot orbit in the stratosphere, mesosphere and lower thermosphere, as the air is too dense. In contrast, balloons, radiosondes, aircraft etc. cannot fly at these heights as the air is not dense enough to support them. Rocket-borne
instruments have allowed for in situ measurements, but these are limited to one location and snap-shots on the ascent and descent. Remote sensing with ground-based radars and recent satellites allow for the middle atmosphere to be more readily observed. Radars can provide observations with a high temporal and vertical-spatial resolution, but a low horizontal-spatial resolution because the observations are limited to a single location. There are several research groups which have used ground-based instruments in multiple locations to try to resolve the issue, but land restrictions prohibit some locations from being observed. Recent satellites have been developed to make remote global observations of the stratosphere, mesosphere and lower thermosphere, for example, NASA Earth Observing System (EOS) Aura satellite Microwave Limb Sounder (MLS) instrument measures the temperatures at heights of \(~10 \text{–} 100\) km from \(75^\circ\text{N}\) to \(75^\circ\text{S}\), a more comprehensive description will be given later in this chapter. Data sets are now available from ground-based radars and satellites which are now making long-term studies of the stratosphere, mesosphere and lower thermosphere.
2.2 Meteor Radars

2.2.1 A general overview

Meteor radars are designed to observe the atmosphere at a height of $\sim 80 - 100$ km by using the ionised meteor trail as a tracer for the bulk flow of the atmosphere. When a meteor burns up it creates a trail of ionised particles which on formation drifts with the neutral winds at the height of its formation and can persist for up to several seconds. Meteors of size $0.5$ mm or greater and generally $1$ mm, ablate at heights of $\sim 90$ km, injecting extraterrestrial material into the atmosphere, i.e., metal ions. Meteors entering the atmosphere have speeds of $\sim 11.2 - 72.8$ km $s^{-1}$, because of gravity (slowing them down due to frictional forces) and head on speed (where they are in the same direction therefore the speeds add together), respectively. The average entry speed is $\sim 42$ km $s^{-1}$.

As the meteor particle penetrates the atmosphere its surface is heated rapidly by friction. The surface temperature can reach up to $\sim 2000$ K in the MLT. The surface of the particle ablates producing a wake in the form of a vapourised trail from the air molecule interactions. The free electrons in the trail act as scatters for the radio wave pulses emitted by the radars.

Meteor radar techniques observe the horizontal winds when considering the bulk flow of the atmosphere. The horizontal wind is resolved into its zonal, $u$, (East–West) and meridional, $v$, (North–South) components. The decay of the power signal observed from the radio wave pulse can also be used to determine the ambipolar diffusion coefficient of the atmosphere to infer the temperature of this region of the atmosphere.

2.2.2 Meteor radar techniques used to measure the atmosphere

Meteor radars are designed to detect the scatter from the radio wave pulse reflected from a meteor trail. The meteor radars in this study are a backscatter system, where the transmitted and receiver are located at the same site. A specular meteor trail, behaves as if it is a shiny surface, therefore the angle of incidence equals the angle of
reflection. The radar only detects pulses which are at right angles to the trail and so only detects a very small part of the total meteor trails, within the 1st Fresnel Zone, therefore only \( \sim 1 \text{ km} \) of the trail is detected. The radars only detect a few trails (\( \sim 1\% \)) compared with the actual influx because of the geometry required. For example, the specularly reflected overhead meteors are not detected. Most of the meteors that are observed are at 30° to the zenith.

**Figure 2.1:** Geometry of the backscatter of the meteor trail from the meteor radar transmitter radio wave pulse.

**Figure 2.2:** Geometry of the meteor to show, \( Z \) = zenith angle measured from the vertical, \( A \) = azimuth angle measured clockwise from North, \( h \) = elevation angle, measured up from the horizon.
2.2.3 Meteor echoes observed in the atmosphere

The expansion of the meteor trail is related to the decay rate as a function of atmosphere density. The meteor echo behaviour also depends on the electron line density within the meteor trail. If the electron line density is $< 10^{13} \text{ m}^{-1}$, the radio wave penetrates into the trail and is reflected back. As the radius increases with time, because of ambipolar diffusion, destructive interference of the echo power occurs. If the radio wave pulse signal can enter the meteor trail fully then the signal is scattered and individual interactions with the electrons in the trails can be detected. In seconds the radius of the trail increases, the typical radio wavelength of $\sim 5 - 10 \text{ m}$ undergoes destructive interference as the wave is scattered at different depths within the meteor trail and therefore extinguishes the echo amplitude.

The echo amplitude power increases very sharply, to the peak power amplitude in $\sim 0.5 \text{ s}$ and then decreases exponentially in $\sim 1 \text{ s}$ back to the background/noise level.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{power_plot.png}
\caption{Power plot of the decay of an underdense meteor echo.}
\end{figure}

Figure 2.3 shows the characteristic power amplitude “curve” of this echo, which is known as an underdense echo. Underdense echoes can be identified confidently as a meteor echo because of the distinctive shape. Comparing this power spectrum to the other common
type of echo, overdense echoes, reveals that there are significant differences in the characteristic power spectrum shape. The overdense echoes are from trails where the electron density is $>10^{15} \text{ m}^{-1}$ and the radio wave therefore reflects off the trail without any penetration. It has the same characteristic sudden power increase as the underdense echo, but it takes much longer to decay, see Fig. 2.4.

We cannot be certain that this observed echo is definitely a meteor, for example, it could be attributed to aurora, lightning, aircraft, satellites, rockets, etc. Therefore all overdense echoes are eliminated from all further analysis in determining the winds and temperatures in the meteor region of the atmosphere.

2.2.4 Temperatures calculated by the meteor radar

To calculate the temperature of the atmosphere in the meteor region the decay time of the underdense meteor echoes are used. This is the time it takes for the peak amplitude to decrease by $\frac{1}{2}$, $\tau_{0.5}$. This is related to the ambipolar diffusion coefficient, $D_a$ and the radio wavelength by:
\[
\frac{\tau}{2} = \frac{\lambda^2 \ln^2}{16\pi^2 D_a}
\]

(2.1)

where radar wavelength is denoted by \(\lambda\).

The exponential decay curve of the underdense echo and the modelled atmospheric density at the height it is formed can be used to determine the temperature of the meteor region, see Hocking [45], Hocking et al. [46, 47] for a full description. The initial sudden increase in amplitude, \(A_0\), is followed by the exponential decay, \(A(t)\). Note this method assumes that the ambipolar diffusion is constant and does not account for the seasonal variability or the effect of SSW’s etc., on the atmosphere.

\[
A(t) = A_0 e^{-\left(\frac{16\pi^2 D_a t}{\lambda^2}\right)} = A_0 e^{-\ln^2 \frac{1}{\tau_1/2}}
\]

(2.2)

With time given by \(t\) and the received field strength as a function of time given by \(A(t)\).

Note, \(t = 0\) is assigned to the time when the meteor signal first appears. \(\tau_1/2\) is generally 0.01 to 0.5 s.

\[
D_a = K_{amb} \frac{T^2}{P}
\]

(2.3)

Where \(K_{amb}\) is the plasma ambipolar diffusion, \(T\) the temperature and \(P\) the pressure. See Jones and Jones [48], Chilson et al. [49] for further details and a full derivation of Eqn. 2.3.

2.2.5 Winds calculated by the meteor radar

As a meteor passes through the atmosphere it burns up and produces an ionised trail. The ionised meteor trail is observed to move with the neutral winds of the atmosphere. The trail drifts with the wind at the height at which the trail is formed. The trail can thus be used to trace the bulk flow of the atmosphere’s neutral winds.

Figure 2.5 shows how the phase change can be measured to calculate the radial drift velocity of the ionised trail. In a time \(t\) that the pulse takes to go to \(t + \Delta t\), the trail
moves distance, d, and the phase changes from $\Phi_a$ to $\Phi_b$, therefore, $\Delta \Phi = \Phi_a - \Phi_b$, for a wavelength, $\lambda$, which is given by speed of light / frequency of the pulse. The phase change is given by $4 \pi d / \lambda$.

$$\nu_{rad} = \frac{d}{\Delta t} = \frac{(\lambda / 4 \pi)}{(\Delta t / \Delta \Phi)} \quad (2.4)$$

Where $\nu_{rad}$ is the drift velocity.

Assumptions used are; the flow of the neutral wind is purely horizontal; vertical motion is negligible and therefore horizontal velocity, $\nu_h$, can be determined. The meteor radars used in this study detect about 4000 useable meteors a day and have a 400 km collecting area. From the multiple measurements provided by so many meteors the motion of the atmosphere across the entire field of view winds can be determined. Further discussion can be found later in this chapter.

### 2.2.6 The University of Bath meteor radars

The meteor radars in this study are located at; Esrange, Sweden, in the Arctic, 68°N, 21°E, deployed in August 1999, BLO, Logan Utah, in the USA, 42°N, 111°W, deployed in March 2008 and Rothera in the Antarctic, 68°S, 68°W, deployed in February 2005. They are all commercially produced SKiYMET systems which operate an “all-sky”
configuration with height finding capabilities. They have all produced nearly continuous data since their initial deployments.

Figure 2.6: Global positions of radars presented in this thesis, Esrange, Bear Lake Observatory and Rothera.

Figure 2.7: Schematic of the five antenna and one transmitter interferometer array of the radar systems.

The operating parameters are shown in Table 2.1.

Note the high PRF compared with MF radars. This is to detect the entry speeds of the meteors. The “all-sky” operation of the radars means they radiate power generally independent of the azimuth. The arrangement of the radars, allows interferometry technique to determine the individual meteor echoes heights. The radar antenna configuration can
Table 2.1: Meteor radar operating parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio Frequency</td>
<td>32.5 MHz</td>
</tr>
<tr>
<td>Pulse Repetition Frequency (PRF)</td>
<td>2144 Hz</td>
</tr>
<tr>
<td>Peak Power</td>
<td>6 kW</td>
</tr>
<tr>
<td>Duty Cycle</td>
<td>15%</td>
</tr>
</tbody>
</table>

be seen in Fig. 2.7. The antenna are six crossed-element Yagi antennas, consisting of five Receiver Antennas (RA) and one Transmitter Antenna (TA). These radars do not use pulse coding, but a high PRF. To avoid mis-detection from multiple pulses, the possible range for a meteor being detected is limited to a height of \(\sim 70 - 110\) km, and any “meteors” measured to be outside of this are dismissed and rejected from further analysis. All of the possible meteors are detected by the radars are recorded and analysed in real time, but only those that meet the criteria to qualify as a definite meteor in the meteor region are kept for full analysis, Hocking et al. [46].

2.2.7 The distribution in height of detected meteors

The meteor distribution is approximately the same over all of the radar sites in this study. The height of each meteor echo is calculated to an accuracy of \(\sim 1\) km, which includes a curvature of the Earth correction, the elevation angle and the radar range. The meteor count distribution is observed to be approximately Gaussian, centered on a height of about 90 km, as seen in Fig. 2.8.

The Gaussian distribution is slightly skewed with more meteors being detected at heights below 90 km. Most of the meteors, \(\sim 96\%\) are detected at heights of 80 – 100 km, as above 100 km most of the meteors are overdense (this is the underdense echo ceiling). Below 80 km they generally burn up and therefore are not used as they are either unsuitable or not detected.
2.2.8 Azimuthal distribution of detected meteors

The radars in this study, as already stated, are an all-sky configuration. Meteor echoes are detected from all azimuths angles around the radars. The distribution is approximately even, as it can be seen in Figs. 2.9, 2.10 and 2.11.
Few meteors are detected at less than 100 km from the center of the plot as they are too near the zenith. The meteors are required to reflect the radio wave pulse as a specular reflection, which is not possible at angles close to the zenith. Further, few meteors are detected at distances of over about 400 km from the center. The inverse square law for
power, (note here the power is $1/r^4$ as it refers to the reflected signal), means a reduction
in the echo power with distance, therefore the reflected signal is too weak after about
400 km. Note, this system set up uses the peak power of 6 kW at an elevation of $\sim 30^\circ$.
Finally, distinct gaps in the Figs., 2.9, 2.10 and 2.11 occur at $\sim 140$, 210 and 280 km.
These are because the transmitters and receivers arrays are located on the same site
and the receiver is short circuited whenever a pulse is transmitted to prevent receiver
saturation. The gaps therefore correspond to times when the receiver is off during the
transmission of radar pulse.

2.2.9 Diurnal variation of meteors

Most of the interstellar matter enters the Earths atmosphere in a retrograde orbit and
the dust particles of the zodiacal cloud that have a circular orbital are accreted at 3 – 6
Local Time (LT). This is when the direction of the Earth’s motion (Apex) is high-
est in the sky. From Fig. 2.12 it can be seen that the highest count rates are in the
morning (LT) and fewest in the late afternoon/evening (LT). This variation is, in part,
because more meteors are ‘swept up’ by the leading hemisphere of the Earth in its orbit
around the Sun. The higher count in the morning corresponds to the radar being on the
leading hemisphere of the Earth in the morning and then on the trailing in the late af-
fternoon/evening as it rotates. The meteors are thus blocked from the view of the radar.
The diurnal cycle is radar site dependant, polar latitudes observe more meteors than
equatorial radar sites. Further, meteor rates tend to peak in the northern hemisphere.

2.2.10 Zonal and meridional winds as derived by the meteor radars

To measure the winds from the meteor radar we must firstly make two simplifying
assumptions:

1. Vertical velocities of the atmosphere in the MLT are negligible compared with the
   horizontal velocities [e.g., 50].
2. The MLT atmosphere moves as a bulk flow in each height gate across the collecting area of the radars.

From these assumptions hourly-mean winds can be calculated. In the usual method, two-hour window is incremented by one hour steps through the meteor time series to produce the hourly-mean zonal and meridional winds. Ambiguous position and overdense echoes are rejected from this analysis. These are meteors which the resolved height is either not within the meteor region or when multiple possible heights are resolved for the meteor and thus the true value is indistinguishable. The measured radial velocity, $v_{rad}$, for an individual echo is converted into horizontal velocities, $v_h$, using Eqn. 2.5.

$$v_h = \frac{v_{rad}}{\sin(\alpha)} \quad (2.5)$$

Where:

$$\alpha = \cos^{-1} \left( \frac{(r + h)^2 + r_m^2 - r^2}{2r_m(r + h)} \right) \quad (2.6)$$

Given the true height of the meteor (h), the radius of the Earth (r) and range to the meteor ($r_m$). The curvature of the Earth is incorporated in the equation. Figure 2.13 is
a schematic of the measurements used to derive the winds.

![Figure 2.13: The geometry to deriving the winds.](image1)

Note the difference between $h$ and $h_f$ which is the uncorrected height for the curvature of the Earth.

Echoes with high velocities ($>150\,\text{m}\,\text{s}^{-1}$) are rejected as meteors at such speeds have small $\alpha$, therefore the zenith angle is $<15^\circ$ and so these meteors are not used in this analysis as the reflection is not specular.

![Figure 2.14: The schematic to show how the radar detects the bulk flow using arrow vectors for the winds for each meteor.](image2)

By convention, positive horizontal velocities are directed towards the radar, and the negative velocities are directed away. Assuming bulk flow motion of the atmosphere,
Fig. 2.14 can be used to show the wind vectors in the collecting area. The vectors can be plotted, where the magnitude of the wind vector is the amplitude and the angle is measured from North, see Fig. 2.15. A sine-wave least-squares fit to two-hours of wind vector data from each “height-gate” in turn. The sine-wave fit, Fig. 2.15, can then be used to measure the wind speed (given the amplitude) and the direction of the wind (given by the phase) for each “height-gate” as a representation of the bulk flow motion of the atmosphere at that height.

The radars in these studies have height-finding capabilities, allowing for vertical profiles of the wind across the observed height range to be calculated. The meteor echoes are grouped in to six height gates which are separately analysed using the above method. The six independent height gates have depths of, 5, 3, 3, 3, 3 and 5 km. The depths were allocated to assure that there are enough meteors in the top and bottom height gates, considering height distribution of meteors from Fig 2.8. The average meteor echo height is calculated and this yields height of 80.8, 84.7, 87.5, 90.45, 93.3 and 97.1 km, as the weighted mean height for the six height gates. The distribution of the meteor echoes maximises at heights of ~90 km.
2.3 The Aura satellite for observing temperatures at heights of about 10 – 100 km

The NASA “A-train” includes the Aura satellite, see Fig. 2.16. It is part of the group of satellites that NASA has constructed and deployed as part of a group of missions to observe the Earth. Aura is part of the Earth Observing System (EOS). Aura was constructed to have a life-time of about five years with the intention that it would be operational for about six years. It has presently been observing and making measurements for about seven years, 2004 – 2011. During this operational running there has been only one main problem with the Aura data collection and analysis. This occurred on March the 26th till the 19th of April 2011 when Microwave Limb Sounder instrument was placed in standby mode. It was taken out of standby mode and has been operational again since the 19th. Aura is intended to gradually leave the A-train, its orbit is currently changing and is predicted to have completely left the A-train by the end of 2012.

![The A-Train](image)

**Figure 2.16:** The NASA “A-train”.

NASA’s EOS Aura satellite instruments include the HIgh Resolution Dynamics Limb Sounder (HIRDLS), the Ozone Monitoring Instrument (OMI), Tropospheric Emission Spectrometer (TES) and the Microwave Limb Sounder (MLS). This study focuses on
the MLS instruments temperature observations of the middle atmosphere.

Aura was initially designed to investigate three scientific areas of interest [51]:

1. To determine if stratospheric ozone chemistry is recovering from damage by such gases as CFC’s.
2. To quantify aspects of how the composition of the atmosphere affects climate change of the different layers and as a whole.
3. To study aspects of pollution in the upper troposphere.

Aura was developed to be an improvement on the previous mission of the Upper Atmosphere Research Satellite (UARS) which was launched in 1991. UARS recorded daily measurements from 1991 – 1994 and was intermittent up to 2001 when it stopped recording. UARS was also a MLS instrument, but had a 57° inclination and thus only recorded measurements at latitudes from 34° on one side of the equator to 80° on the other and had a 30 day yaw period. These factors restricted the ability for it to observe and investigate the atmosphere on a global-scale on a pole-to-pole and a resolution suitable for planetary wave investigations.

The Aura satellite MLS instrument is an improvement over the previous UARS MLS instrument because of advances made in microwave technology. It has additional stratospheric measurements for chemical composition, better global and temporal coverage and resolution and better precision for measurements of temperature. Aura also uses a polar orbit which allows nearly pole-to-pole coverage.

### 2.3.1 General information on Aura

Aura was launched on the 15th of July 2004 and started full-up science operations on the 13th of August of that year. It was launched into a near polar, sun-synchronous orbit at a height of ~705 km, at an inclination ~98° and with a period of ~100 minutes. The
spacecraft repeats its ground track every 16 days and does 233 revolutions per cycle. The ascending node is in daylight and crosses the equator at $\sim 1.45$ pm LT. This provides global atmospheric measurements in a repeating pattern. The Aura instruments are all limb instruments and observe roughly along the orbital plane. The MLS instrument looks forward, in the direction of motion, whereas the others all look backwards.

**Figure 2.17:** Artist impression of the Aura satellite.

**Figure 2.18:** Orbit height and limb-scan geometry. The geometry shown is drawn to scale with the Aura satellite at a height of 705 km and the line of sight having a 50 km tangent height. The orbit plane is the plane of the page. Note that the instrument is not to scale.
2.3.2 MLS instrument on Aura

The MLS instrument measures naturally-occurring microwave thermal emission from the limb of the Earth’s atmosphere to remotely sense vertical profiles. The vertical profiles include, atmospheric chemical species (OH, HO$_2$, H$_2$O, O$_3$, HCl, ClO, HOCl, BrO, HNO$_3$, CO, HCN, CH$_3$CN, volcanic SO$_2$), cloud ice, geopotential height and temperature. The thermal emission is from the atmospheric limb in broad spectral regions centered near 118, 190, 240 and 640 GHz and 2.5 THz. Vertical profiles are retrieved every 165 km along the suborbital track, covering 82$^\circ$N to 82$^\circ$S on each orbit, Waters et al. [51].

The MLS instrument uses the thermal emissions of the atmosphere. MLS is a forward looking limb scanning instrument that scans from the limb to $\sim$95 km every 24.7 s. Aura scans are synchronised to the orbit of the satellite, therefore scanning at the same latitude for each orbit. Temperatures used in this analysis are from the MLS version 2.2 (Temperature Analysis v2.2) where they are calibrated MLS limb radiances. v2.2 is the second public release of MLS data. It has been in use since March 2007, where data pre-March 2007 have been calculated retrospectively using the v2.2 algorithms. v2.2 data are used instead of the v1.5 as the v2.2 has twice the vertical resolution of the original v1.5 files.

There are three levels of products from the Aura MLS instrument available from NASA, they will be summarised briefly below. Level 1 A and B products have no geolocation, but B is daily data. Level 2 is daily data which consists of vertical profiling and retrievals of geophysical parameters along the instrument’s track, for example, temperature. Level 3 is monthly data. Level 2 has been used in these studies as it has daily data with geolocations of temperature, therefore it is suitable for planetary wave observations reported on in this thesis.
4.6. ADVANTAGES AND DISADVANTAGES OF SATELLITE REMOTE SENSING

Figure 4.14: EOS MLS measurements for a 24 hour period. The crosses denote the location of the tangent points for individual limb scans. The continuous line is the suborbital track. This is displaced from the tangent points due to the Earth rotating as the satellite moves forward to the tangent point. The ascending orbits are those with the Southeast–Northwest tilt. There is the same daily coverage in the Southern Hemisphere as there is to the Northern Hemisphere shown here.

Figure 2.19: EOS MLS measurements for a 24 hour period. The crosses denote the location of the tangent points for individual limb scans. The continuous line is the suborbital track. This is displaced from the tangent points due to the Earth rotating as the satellite moves forward to the tangent point. The ascending orbits are those with the Southeast–Northwest tilt. There is the same daily coverage in the southern hemisphere as there is to the Northern Hemisphere shown here.

2.3.3 The Aura MLS temperatures

One of the products available from the MLS instrument on Aura is temperatures. The measured temperatures are primarily derived from the thermal emission of oxygen, as oxygen is well mixed with a known atmospheric mixing ratio. It measures the vertical profile of temperature for the stratosphere, mesosphere and lower thermosphere. This is possible as the thermal emission is roughly linear with temperature, so small fractional errors in inferred absolute temperatures generally lead to correspondingly small errors.
inferred constituent abundance. Thus reliable vertical temperature profiles are measured with only small errors. The v2.2 data used are available from the 8th of August 2004 see Livesey et al. [52] for further details.

The data are recorded for 34 pressure levels ranging from 316 – 0.001 hPa (∼10 – 100 km). The vertical resolution is ∼7–8 km at 316–100 hPa, 4 km at 31–6.8 hPa, 6 km at 1 hPa and 9 km above 0.1 hPa. The pressure levels are converted to approximate heights, H, in km using Eqn. 2.7.

\[
H = -7 \log \frac{P}{1000}; \text{ or } H = (64.8/4) (3 - \log 10 P)
\]  

(2.7)

With pressure (P) in hPa.

Here results are presented as the approximation of the heights from the equation. This conversion has been chosen to facilitate comparisons with measurements made by ground-based instruments.

2.3.4 The Aura MLS temperature data

The MLS instrument on Aura uses seven microwave radiometer bands which cover five spectral regions. Spectrometers then analyse the radiometer signals. The spectral coverage is shown in Fig. 2.20, radiance is measured in Kelvin and has been calculated with respect to brightness temperature. The brightness temperature is equal to the exact temperature of the hypothetical black body which completely fills the field of view if given the same radiance. The brightness temperature from the radiance is then calculated for each channel in the spectrometer for the simulated ozone line spectrum.
2.3.5 The Aura MLS instrument

The MLS instrument on Aura consists of a group of radiometers (R), where 1–4 are in the GHz range, R5 is in the THz range. R1 provides temperatures at the different pressure heights using the \( \text{O}_2 \) spectra lines. Table 2.2 shows the Aura MLS radiometers measurements.

<table>
<thead>
<tr>
<th>Radiometer</th>
<th>Primary measurements for which the radiometer was included in EOS MLS</th>
<th>Additional measurements that are provided, or contributed to</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1 (118 GHz)</td>
<td>temperature, pressure</td>
<td>cloud ice, geopotential height</td>
</tr>
<tr>
<td>R2 (190 GHz)</td>
<td>( \text{H}_2\text{O}, \text{HNO}_3 )</td>
<td>cloud ice, ( \text{ClO}, \text{N}_2\text{O}, \text{O}_3, \text{HCN}, \text{CH}_3\text{CN} ), volcanic ( \text{SO}_2 )</td>
</tr>
<tr>
<td>R3 (240 GHz)</td>
<td>( \text{O}_3, \text{CO} )</td>
<td>cloud ice, temperature, pressure, ( \text{HNO}_3 ), volcanic ( \text{SO}_2 )</td>
</tr>
<tr>
<td>R4 (640 GHz)</td>
<td>( \text{HCl}, \text{ClO}, \text{BrO}, \text{N}_2\text{O}, \text{H}_2\text{O} )</td>
<td>cloud ice, ( \text{O}_3 ), ( \text{HOCl}, \text{CH}_3\text{CN}, \text{volcanic SO}_2 )</td>
</tr>
<tr>
<td>R5 (2.5 THz)</td>
<td>( \text{OH} )</td>
<td>( \text{O}_3 ), cloud ice, temperature, pressure</td>
</tr>
</tbody>
</table>

The instrument vertically scans from the surface to \( \sim 95 \) km and this takes about 20 s, it then takes a further 4.7 s to calibrate and then for the antenna to retrace. Therefore the total repeat period is 24.7 s as mentioned earlier for the scan, calibration and retracing process. During the scan there are 120 measurements and integrations performed.

2.3.6 Radiance at observed heights

It is well known that the density of the atmosphere changes as height increases and therefore the tangents observed must change as a consequence. The emission decreases as the height increases because of the decrease in density with height. The ray path decreases as the density increases and the emissions increase until the atmosphere becomes opaque and therefore observations are not possible as the radiances are saturated or blacked out by the air above absorbing the emission. From Fig. 2.21 the measured radiances from the \( \text{O}_2 \) spectral band are presented. The saturated radiances can be seen
where the curves “kink” downwards. This is described as the “knee” of the radiance curve.

### 2.3.7 The Aura MLS data screening

The standard product for temperature from the satellite is taken for the Core retrieval (118 GHz only) from 316 to 1.41 hPa and from the Core+R2A (118 and 190 GHz) retrieval from 1 hPa from 1 – 0.001 hPa. Temperature precision is $\sim \pm 1$ K from 316 – 0.01 hPa and degrades down to $\sim \pm 3$ K at 0.001 hPa, Schwartz et al. [9]. The data is assigned a “flag” to comment on the data quality. A $\chi^2$ statistic is computed for all of the radiances considered to have a significant effect on the retrieved species, then normalised by dividing by the number of radiances. Quality is simply given by the reciprocal of this statistic. If the data has a quality flag of “0” then it is regarded as poor quality and not used in the analysis in this study.
Figure 2.20: Atmospheric spectral regions measured by Aura MLS. There is a separate panel for each radiometer. The red, green and blue curves are the calculated atmospheric limb spectra at 100, 30 and 10 hPa tangent pressure corresponding to heights of ~16, 24 and 32 km Livesey and Snyder. [7].
Figure 2.21: Aura MLS radiance profile of the R1A:118.B1F:PT band which is targeted on the $O_2$ line and used to measure temperature and tangent pressure. Only the radiances for the first 13 channels have been shown. The red lines correspond to the channels closest to the centres of the spectral lines, from Livesey et al. [8].
4.4. DATA PROCESSING AND PRODUCTS

Figure 4.11: From Schwartz et al. (2008) MLS v2.2 temperature vertical two-dimensional averaging kernels. The variation of averaging kernels is small enough that this is representative of typical profiles, in this case for 35° N September climatology. The coloured lines show the contribution of atmospheric temperatures at each level, indicating the region of that atmosphere from which information is contributing to the measurements to a given retrieved temperature indicated by a plus sign of the same colour. The dashed black line indicates the vertical resolution in km and is determined by the full width at half maximum of the averaging kernels. The vertical solid black line shows the integrated area under the kernels. Values close to unity imply that the majority of the information comes from the atmosphere, whereas lower values imply contribution from a priori information.

Figure 2.22: From Schwartz et al. [9] Aura MLS v2.2 temperature vertical two-dimensional averaging kernels. The variation of averaging kernels is small enough that this is representative of typical profiles, in this case for 35° N September climatology. The coloured lines show the contribution of atmospheric temperatures at each level, indicating the region of that atmosphere from which information is contributing to the measurements to a given retrieved temperature indicated by a plus sign of the same colour. The dashed black line indicates the vertical resolution in km and is determined by the full width at half maximum of the averaging kernels. The vertical solid black line shows the integrated area under the kernels. Values close to unity imply that the majority of the information comes from the atmosphere, whereas lower values imply contribution from a priori information.
2.3.8 Advantages and disadvantages of the instruments

Table 2.3: Advantages and disadvantages of the meteor radar and Aura data

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Meteor radar</th>
<th>Aura</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal resolution</td>
<td>local (400 km radius)</td>
<td>global</td>
</tr>
<tr>
<td>Vertical resolution</td>
<td>3 – 5 km</td>
<td>varying with height,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>from 4 – 9 km</td>
</tr>
<tr>
<td>Temporal resolution</td>
<td>1 hour</td>
<td>16 day repeat track</td>
</tr>
<tr>
<td></td>
<td></td>
<td>27 sec sampling</td>
</tr>
<tr>
<td>Heights observed</td>
<td>80 – 100 km</td>
<td>10 – 100 km</td>
</tr>
<tr>
<td>Cost</td>
<td>comparatively cheap</td>
<td>expensive to set-up and</td>
</tr>
<tr>
<td></td>
<td>cf. satellites</td>
<td>sustain</td>
</tr>
<tr>
<td>Longevity</td>
<td>12+ years</td>
<td>typically 6 years</td>
</tr>
<tr>
<td>Maintenance</td>
<td>low maintenance and</td>
<td>difficult to fix</td>
</tr>
<tr>
<td></td>
<td>easy to access</td>
<td>in orbit</td>
</tr>
<tr>
<td>Operating</td>
<td>remotely operated by</td>
<td>remotely operated by</td>
</tr>
<tr>
<td></td>
<td>a small organisation</td>
<td>a large organisation</td>
</tr>
<tr>
<td>Other</td>
<td>can’t resolve vertical winds</td>
<td>can’t observe a solar cycle</td>
</tr>
<tr>
<td></td>
<td>can’t resolve gravity waves</td>
<td>multiple instruments to</td>
</tr>
<tr>
<td></td>
<td>because of collecting area size</td>
<td>answer many scientific questions</td>
</tr>
</tbody>
</table>
Chapter 3

Results - The Polar 5-day Planetary Wave in the MLT

3.1 The Five-Day Wave in the Arctic and Antarctic Meso-
sphere and Lower Thermosphere

3.1.1 Abstract

The 5-day planetary wave in the polar mesosphere and lower thermosphere has been investigated using meteor radars at Esrange (68ºN, 21ºE) in the Arctic and Rothera (68ºS, 68ºW) in the Antarctic. The measurements span the 9-year interval from October 1999 to December 2008 and the 4-year interval February 2005 to December 2008, respectively. The height range covered is approximately 80–100 km. Horizontal wind variance within a wave period range of 4–7 days is used as a proxy for the activity of the 5-day wave. Strong wave activity is seen in winter and late summer. However, there is a high degree of inter-annual variability and in some individual years wave activity is almost absent. The data are used to construct a representative climatology for the Arctic and Antarctic. The seasonal cycle of the 5-day wave is found to be very similar in both polar regions. Wave activity in winter is present across the entire height range observed. Winter-time wave variance can reach about 65 m²s⁻². The wave is
largely absent around the equinoxes. Wave activity is also very strong in late summer, reaching about 75 m$^2$ s$^{-2}$, but occurs only for 1 to 2 months and is confined to heights above about 90 km and excluded from the stronger westward winds at lower heights. Summer-time wave activity peaks at a height of about 95 km and decays rapidly above and below that height. During this summer maximum, the wave cannot have ascended to the mesosphere and lower thermosphere from below and so must have either been generated *in situ* and/or been ducted across the equator from the winter hemisphere. The seasonal cycle of the 5-day wave is remarkably similar to that observed for the 2-day wave at these latitudes.

3.1.2 Introduction

Planetary waves can reach large amplitudes in the mesosphere and lower thermosphere (MLT). The waves are known to interact with and modulate the amplitudes of atmospheric tides and gravity waves [e.g., 39, 40, 41, 43, 53]. Planetary waves with periods between about 5 days and 6.5 days have been reported in many observations of the stratosphere and MLT [e.g., 21, 22, 54, 55, 56, 57, 58]. These waves have been identified as manifestations of the gravest symmetrical wavenumber 1 westward travelling Rossby mode [e.g., 21]. There have, however, been comparatively few studies of these waves at high latitudes. At high latitudes it is now known that planetary waves, including the 5-day wave, can modulate the occurrence of Polar Mesospheric Clouds (PMC) [e.g., 34, 37] and Polar Mesospheric Summer Echoes [e.g., 59].

It has been suggested on the basis of modelling studies that there are actually two separate waves in the MLT, of approximately 5-day period; a 5-day and a 6.5-day wave [57]. However, other studies have revealed that the longer-period oscillations have the structure predicted for the 5-day wave and so imply that the observed longer periods arise from a Doppler shifting of a 5-day wave by the background winds [e.g., 60]. In the MLT there are a number of reports of waves with periods between 5 and 6.5 days and, in fact, the longer period appears to be the more common [e.g., 22, 23, 55, 56, 58, 61, 62]. In the present study we will consider all oscillations with periods between 4 and 7 days as being the “5-day wave”.
The vertical propagation of the summer-time 5-day wave into the MLT from below should be “blocked” by the strong westward zonal winds of the summer-time middle atmosphere [63] and planetary-wave activity in the summer-time MLT appears significantly reduced in the summer because of this mechanism [e.g., 11]. However, a number of observations of the 5-day wave in the summer-time MLT have led to suggestions that the summer-time wave is either generated \textit{in situ} in the MLT by baroclinic instability of the summer-time mesospheric jet, or is ducted across the equator from the winter MLT, or arises from a combination of the two [e.g., 22]. Similar mechanisms have also been proposed to amplify the 4-day wave in the MLT [64].

At polar latitudes there have been only a limited number of studies of 5-day waves in the MLT. Prata [61] reported reoccurring observations of the 5-day wave in the stratosphere and mesosphere using temperature data from the Nimbus-6 Pressure Modulated Radiometer. Williams and Avery [56] analysed one year of radar wind data from Poker Flat, Alaska (65°N). They observed a significant summer-time wave in the mesosphere that reached largest amplitude at a height near 90 km. Merkel et al. [34] considered nitric oxide (NO) measurements from the Student Nitric Oxide Explorer Satellite (SNOE) and showed that the 5-day wave is a possible cause of PMC brightness modulation. Lawrence and Jarvis [65] observed radar zonal wind data in the middle and upper atmosphere at 76°S during austral winters. They concluded that a 5-day winter-time wave reaches maximum amplitudes at heights near 75–80 km. Riggin et al. [22] observed the 5-day wave using temperature perturbations from TIMED/SABER and mesospheric radar wind data. They suggested that the summer-time 5-day wave originates in cross-equatorial ducting of the wave from the winter to the summer hemisphere, where it is then amplified by baroclinic instability. The excitation mechanisms of polar 5-day waves was further investigated by Belova et al. [58], who used temperatures and ozone mixing ratios data from the Odin satellite and wind data from ground-based radars. They suggested that upward propagation and amplification by baroclinic instability may independently account for polar 5-day waves at different times. Merkel et al. [37] observed the 5-day wave using temperatures and NO measurements from TIMED/SABER and SNOE, respectively, in both hemispheres at latitudes of up to 80°. They reported the presence of a strong 5-day signature in the summer-time polar MLT.
Here we present observations of the Arctic and Antarctic MLT made using two meteor radars located at conjugate geographical latitudes. Several years of data are available from each site and these are used to construct simple representative climatologies of the 5-day wave in the polar MLT. A particular focus of the work is comparing and contrasting the behaviour of the wave in the two hemispheres.

### 3.1.3 Data Analysis

Two meteor radars were used in this study. Both radars are commercially-produced SKiYMET VHF systems that operate in an “All-Sky” configuration. Both radars operate at a radio frequency of 32.5 MHz and have peak powers of 6 kW. One is located at Esrange in Arctic Sweden (68°N, 21°E). This radar was deployed in August 1999 and has produced largely-uninterrupted measurements since. The other is located at Rothera in the Antarctic (68°S, 68°W). This radar was installed in February 2005 and has also produced largely-uninterrupted measurements since. This gives a near-continuous data set of approximately nine years for Esrange and four years for Rothera.

Both of the radars are used to measure horizontal winds at heights of \(~80–100\text{ km}\). The data are analysed in six independent non-overlapping height gates with representative height and time resolutions of either 3 or 5 km and 1 hour, respectively. The vertical distribution of meteor echoes is strongly peaked at a height of \(~90\text{ km}\). The height gates used therefore have depths of 5, 3, 3, 3, 3, 5 km to ensure there are enough meteors in the uppermost and lowermost height gates. The uneven distribution of meteor echoes then yields weighted height-gate centers of 80.8, 84.7, 87.5, 90.4, 93.3 and 97.1 km. The horizontal winds are calculated for each height gate in time steps of 1 hour and resolved into zonal and meridional components. A full description of the radars and data analysis can be found in Hocking et al. [46] and Mitchell et al. [66]. These time series of the hourly winds form the bases of our data analysis.
3.1.4 Results

A spectral analysis of the horizontal winds described above reveals the regular occurrence of a wave with a period near 5-days. As an example, Fig. 3.1 a) presents a wavelet analysis for meridional winds recorded at a height of $\sim$90 km over Esrange in the time interval of January to December 2003. Figure 3.1 b) presents a wavelet analysis for meridional winds recorded at a height of $\sim$90 km over Rothera in the time interval of January to December 2006. The wavelet analysis used comprises of a Morlet wavelet of non-dimensional wavenumber 6 (chosen because it approximates to the planetary-wave bursts evident in the data - see later in Fig. 3.2 a and b). Similar wavelets have often been used to study activity in the MLT [e.g., 11, 12, 13, 14, 15]. From the figures it can be seen that the wave activity is intermittent and occurs in short bursts lasting approximately 5 – 30 days. Further, the wave period varies from burst to burst and therefore is only approximately 5 days. A significant number of wave bursts are observed in the period range of 4 to 7 days. The wave amplitudes regularly reach $12 \, \text{m} \, \text{s}^{-1}$ during the bursts of activity. Other planetary-waves are also evident in the figures, including the quasi-2-day wave in summer and winter and waves with periods of longer than 10 days that occur mostly in winter.

To investigate these waves further, a band-pass analysis of the horizontal winds in each height gate was carried out. An elliptical band-pass filter (part of the MatLab toolkit) was used with period limits of 4.0 to 7.0 days. This filter was chosen because it has a comparatively sharp cut-off at the high and low frequencies. This bandwidth was chosen because the wavelet analysis in Fig. 3.1 a) and b) suggests that there is significant wave activity within this period range. Hereafter we will refer to waves within this period range as the “5-day wave”, since it is dominated by burst of wave activity of the sort shown in Fig. 3.1.

As an example of these results, Fig. 3.2 a) presents the band-passed winds for 1999 to 2008 for the meridional wind component at a height of 90.4 km over Esrange in the Arctic. Bursts of wave activity are evident in most of the years. The bursts last from as little as 10 to 15 days, to as long as a few months. An inspection of Fig. 3.2 a) suggests that the wave tends to maximise in winter (January/February) and late
Figure 3.1: A wavelet analysis of a) hourly meridional winds over Esrange at a height of 90.4 km during the interval January to December 2003 and b) hourly meridional winds over Rothera at a height of 90.4 km during the interval January to December 2006. Amplitudes smaller than 3 m s$^{-1}$ are not plotted.

summer (August/September). For example, in 2003 the wave amplitudes are greater than 10 m s$^{-1}$ throughout January and February. Similarly, in 2004 wave amplitudes are greater than 10 m s$^{-1}$ throughout August, September and early October. However, note that there is also a high degree of inter-annual variability.

Figure 3.2 b) presents a similar analysis of band-passed winds for the years 2005 to 2008.
for the meridional winds over Rothera in the Antarctic at a height of 90.4 km. A similar seasonal behaviour can be seen.

![Band-passed meridional winds over a) Esrange at a height of 90.4 km for 1999 to 2008 and b) Rothera at a height of 90.4 km for 2005 to 2008. Band-pass limits are wave periods of 4 to 7 days.](image)

**Figure 3.2:** Band-passed meridional winds over a) Esrange at a height of 90.4 km for 1999 to 2008 and b) Rothera at a height of 90.4 km for 2005 to 2008. Band-pass limits are wave periods of 4 to 7 days.

The vertical structure of the wave can be investigated using the six independent height
gates available from each radar. As an example, time-height contours of band-passed meridional winds recorded over Esrange are presented in Fig. 3.3. The data are for the year-long interval of 2003. Bursts of wave activity are evident at all heights throughout winter. In contrast, the bursts of wave activity observed in the summer are only evident in the upper heights observed at $\sim 90$ to $95$ km. Maximum amplitudes for the 5-day wave in all seasons generally reach $\sim 20$ m s$^{-1}$. The phase fronts of the wave are often close to vertical, indicating a very long vertical wavelength.

![Band-passed meridional winds over Esrange 2003](image)

**Figure 3.3:** Band-passed meridional winds as a function of height and time measured over Esrange during the year 2003, for heights from $\sim 80$ to $97$ km.

The seasonal variability suggested above can be further investigated using an analysis in which horizontal wind variance is used as a proxy for wave activity. In this analysis the band-passed winds in each height gate for each month are used to calculate a variance value for the zonal and meridional components of the winds. These variances can be examined as a function of height and time to investigate the seasonal behaviour of the 5-day wave. Note that for a constant amplitude oscillation, amplitude is equal to the square root of two times the variance. So, for example, a variance of 10 m$^2$ s$^{-2}$ corresponds to a wave amplitude of 4.5 m s$^{-1}$, a variance of 50 m$^2$ s$^{-2}$ corresponds to a wave amplitude of 10 m s$^{-1}$, a variance of 100 m$^2$ s$^{-2}$ corresponds to a wave amplitude of 14.1 m s$^{-1}$, etc.

Time-height contours of zonal and meridional monthly variances for all years of data recorded over Esrange are presented in Fig. 3.4. The monthly-mean zonal winds for each year have been plotted over the top for that year to allow a comparison of the background winds and the level of 5-day wave activity for that particular year. The
figure shows significant inter-annual variability in the observed activity of the Arctic 5-day wave. For example, meridional variances in August and September 2004 show a strong 5-day wave above \( \sim 85 \) km where variances reach values in excess of \( \sim 100 \text{ m}^2\text{s}^{-2} \). In contrast, during August and September 2008, wave variances at the same height reach only \( \sim 25 \text{ m}^2\text{s}^{-2} \).

If we consider the strong wave activity observed in the upper height ranges during late summer, it can be seen that in most of the summers observed the meridional variances are greater than the zonal variances (the average difference is approximately a factor of 1.5). This shows that the summer-time wave has larger amplitudes in the meridional component than in the zonal component. Consideration of the figure shows that in late summer wave activity occurs almost always in the region of eastward flow and weak westward flow in the monthly-mean zonal winds and is largely absent in the stronger westward flows. However, note that there are also occasional bursts of wave activity in early summer, e.g. in the meridional component in May of 2003, 2005 and 2007. Because the eastward and weak westward flow is higher in early summer, these bursts of wave activity also seem to occur at a greater height than is the case later in the summer. However, it should be kept in mind that the use of monthly winds and variances may conceal short-term variability in both wave activity and the winds.

Strong wave activity is also evident in winter, again with significant inter-annual variability. For example, zonal variances in December, January and February 2002/3 show a strong 5-day wave at all heights observed and where variances reach values in excess of \( \sim 100 \text{ m}^2\text{s}^{-2} \). In contrast, during December, January and February 2005/6, wave variances at the same height reach only \( \sim 50 \text{ m}^2\text{s}^{-2} \).

If we consider the winter-time activity, it can be seen that in contrast to the summer-time activity, in most of the winters observed the zonal variances are greater than the meridional variances (the average difference is approximately a factor of 1.3). Further, in winter the activity can be observed across the entire height range, whereas in summer it is largely confined to regions of eastward/weak westward flow.

Figure 3.5 shows the results of a similar analysis for winds recorded over Rothera during 2005 to 2008. As with the Arctic in Fig. 3.4, wave activity maximises in summer and
winter. A high level of inter-annual variability is also apparent. For example, meridional variances in January and February 2008 (Antarctic summer) show a strong 5-day wave in the eastward flow. Above this, wave variance rises and eventually reaches $\sim 100 \text{ m}^2 \text{s}^{-2}$ at heights above 95 km. In contrast, during January and February 2007, wave variances
at the same height reach only $\sim 50 \text{ m}^2 \text{s}^{-2}$. In August and September 2005 (Antarctic winter) there is a strong 5-day wave evident in meridional variances across the height range observed, where variances reach values in excess of $\sim 100 \text{ m}^2 \text{s}^{-2}$. In contrast, during August and September 2008, wave variances at the same height range reach only $\sim 25 \text{ m}^2 \text{s}^{-2}$.

**Figure 3.5:** Time-height contours (filled colour contours) of the monthly variance of winds band-passed between 4 and 7 days over Rothera in the Antarctic for both meridional and zonal components, for 2005 to 2008. Also plotted are the monthly-mean zonal winds. The zero-wind line is indicated by the heavy dashed line, red contour lines denote eastward mean winds and white contours denote westward mean winds.

In order to investigate the seasonal variability of the 5-day wave in more detail, a composite-year ("superposed epoch") analysis was applied in which data from all years was used. A simple arithmetic mean for the monthly variances was used. The results of this analysis are shown in Figs. 3.6 and 3.7.

Figure 3.6 a) and b) presents a composite-year analysis of the meridional and zonal wave activity calculated using all available data recorded over Esrange in the years 1999 to 2008. The monthly-mean zonal winds from the same period of time are also plotted on as contour lines. It can be seen from Fig. 3.6 there are two significant episodes
of wave activity evident in the composite year. The first of these is when the 5-day wave is strong in a relatively short-lived burst in late summer (August and September). This late summer burst occurs generally at heights above $\sim 90$ km. The strongest wave activity occurs at $\sim 95$ km in the meridional component, where wave variance reaches $\sim 75$ m$^2$ s$^{-2}$. The second of these episodes of strong wave activity is observed in winter (December, January and February) where in contrast to summer it is present across the entire height range observed and where wave variance reaches $\sim 65$ m$^2$ s$^{-2}$. The wave is almost entirely excluded from the region of westward winds in spring and summer.

Figure 3.7 a) and b) shows a similar composite-year analysis for all available data recorded over Rothera in the years 2005 to 2008. Again, the monthly-mean zonal winds
Figure 3.7: A composite year analysis of 5-day wave activity over Rothera in the Antarctic for the years 2005 to 2008 (filled colour contours) for a) meridional component and b) zonal component. Also shown are the composite year monthly-mean zonal winds (open contours). The zero-wind line is indicated by the heavy dashed contour, red contour lines denote eastward mean winds and white contours denote westward mean winds. The time axis has been shifted by six months to allow easy comparisons between the Arctic results of Fig. 3.6 and Antarctic.

are plotted. From Fig. 3.7 it can be seen that wave activity is strongest in winter and summer, but wave activity is also present above \( \sim 95 \) km in early summer-time (November). The 5-day wave is strong in January and February (Antarctic summer), but only above \( \sim 85 \) km. In August and September (Antarctic winter) the wave is present across the height range observed. For example, meridional wind variances in February (late summer) reach a maximum of \( \sim 60 \) m\(^2\) s\(^{-2}\) at heights above \( \sim 85 \) km. In contrast, the zonal wind variance maximises in August and September (winter-time) at all heights observed, with a variance maximum of \( \sim 65 \) m\(^2\) s\(^{-2}\). The seasonal pattern of wave activity over Rothera is thus very similar to that observed over Esrange. However, it should be considered that the composite-year analysis over Rothera is based on only three full
years of observations compared with nine full years for Esrange. Detailed comparison should therefore be treated with caution.

3.1.5 Discussion

The results presented in this chapter reveal a clear seasonal behaviour in the occurrence of the 5-day wave in the MLT region. The wave is present across the $\sim 80 - 100 \text{ km}$ height range observed in winter and at heights above $\sim 85 \text{ km}$ in summer.

Observations of the seasonal cycle of the “5-day wave” at high latitudes have been reported by Williams and Avery [56] who used an MST radar at Poker Flat ($65^\circ \text{N}$) to record mesospheric winds in the first 340 days of 1984. They reported significant wave activity throughout the year, but with a strong maximum during July centered at a height of $\sim 92 \text{ km}$. The peak amplitudes reported were $\sim 9 \text{ m s}^{-1}$, which is in good general agreement with the results of this chapter. In contrast to the results presented here, there was no winter maximum observed, but this may be a consequence of there only being one year of data considered, combined with the strong inter-annual variability evident in the results of Figs. 3.4 and 3.5.

Lawerence and Jarvis [65] reported observations of 5-day waves over Halley ($76^\circ \text{S}$) made in the winters of 1997 to 1999. They reported weak signatures of a 5-day wave in the $80 - 105 \text{ km}$ height range in one of these years.

Belova et al. [58] used satellite observations of the stratosphere up to heights of 54 km and local ground-based meteor-radar observations from Esrange ($68^\circ \text{N}$), Andenes ($69^\circ \text{N}$), Resolute Bay ($74^\circ \text{N}$) and Yellowknife ($62^\circ \text{N}$) at heights of $85 - 90 \text{ km}$, to observe the 5-day wave in the temperature of the northern hemisphere summer MLT. Typical wave amplitudes were found to be $\sim 2.5 - 5 \text{ K}$, but with maximum amplitudes reaching about $15 \text{ K}$.

Riggin et al. [22] used SABER data from the TIMED satellite and ground-based meteor and MF radar to investigate the global structure of the 5-day wave. They concluded that, in at least some cases, the 5-day wave originated in the winter hemisphere and was ducted across the equator into the summer hemisphere where it was amplified by
baroclinic instability. This amplification has been investigated in a number of other studies [e.g., 54, 67]. Riggin et al. [22] presented a climatology using wind data for the 5-day wave at heights near 80 km based on three years (2002-2004) of SABER temperature data. Largest amplitudes were observed in April and May, particularly 2003 and 2004, but significant wave activity was also evident in August and September in the northern hemisphere. Our results suggest that in a multiple-year climatology, wave activity in April to May is not, in fact, particularly strong at heights of 80–100 km. Further, our results suggest that the northern hemisphere wave activity in August to September observed over Esrange increases rapidly with height until a height of \(\sim 95\) km where it peaks in amplitude. Summer is the season at which the strongest wave activity occurs, at least at heights of \(\sim 80–100\) km.

We thus see that there are a number of significant differences between the observations reported here and those of earlier studies. However, some of these differences appear to arise because of the high degree of inter-annual variability of the 5-day wave, e.g. the small winter amplitudes reported by Williams and Avery [56] from one year of data disappear when considering multiple analysis presented here. Similarly, the great variation of wave activity with height observed at heights of \(\sim 80–100\) km accounts for the largest activity observed by Riggin et al. [22] being in April to May at heights near 80 km, compared to the August-September maximum observed at heights of \(\sim 95\) km reported here.

The zonal phase speed of the 5-day wave determines how it is controlled by the background wind. The phase speed was calculated for the 5-day wave assuming a westward wavenumber 1. This means it takes 5 days to travel once round a circle of latitude. For the latitude of the radars, 68°, this means the wave travels \(\sim 14,997\) km in 5 days, corresponding to a phase speed of \(\sim 35\) m s\(^{-1}\). Recent observations have revealed 2-day waves in the polar MLT [e.g., 68, 69, 70]. By a similar argument to the above, a summer-time 2-day wave of westward wavenumber 3 will have a phase speed of \(\sim 28\) m s\(^{-1}\). These very similar phase speeds mean that the interaction of background winds with these two waves may be rather similar and should therefore result in a similar seasonal behaviour.
In fact, a study of the 2-day wave has been carried out using the same data set and analysis techniques as presented here Tunbridge and Mitchell [70]. This latter study found that, on average, over the duration of the data set the summer-time 2-day wave has a remarkably similar behaviour to that presented here for the 5-day wave. In particular, 2-day wave activity maximises in July and August and is strongest at a height near $\sim 95$ km. As with the 5-day wave, little wave activity is present below $\sim 85$ km. This strongly suggests that interactions with the background winds control the occurrence of both the 5-day and the 2-day waves in the summer mesosphere.

The observation that the 5-day wave is largely absent below $\sim 90$ km in the summer-time MLT strongly suggests that the wave activity seen to maximise at heights near 95 km cannot have propagated there from below. Further, the strong westward winds observed should also, on theoretical grounds, inhibit propagation of the wave from below. From Charney and Drazin theorem (1961), in order to propagate a planetary wave must obey $0 < \bar{u} - c_x < U_c$, where $\bar{u}$ is the zonal wind speed, $c_x$ is the zonal phase speed of the planetary wave and $U_c$ is the critical Rossby speed. Hence, if the zonal winds are greater than -35 m s$^{-1}$ the wave can propagate vertically. However, the zonal winds of the summer polar middle atmosphere reach values more westward than -35 m s$^{-1}$ which will prevent vertical propagation of the wave. In fact, the zonal winds observed in summer over both Esrange and Rothera reach westward speeds approaching -30 m s$^{-1}$ and this may account for the small wave activity at the lower heights observed. In summary, this means that the wave activity observed in the summer-time mesosphere must either have been generated in situ or been ducted across from the winter hemisphere - or even have arisen from a combination of the two as suggested by Riggin et al. [22].

If there is indeed ducting from the winter to the summer hemisphere, then one might expect to see wave activity occurring simultaneously in the Arctic and Antarctic. By considering the nearly complete four years (2005 to 2008) of data available from both sites (Arctic and Antarctic) the occurrence of ducting can be investigated. Such investigations depend, in part, upon the level of wave activity which is considered to be significant. In the following we will consider only monthly-mean variances of 60 m$^2$ s$^{-2}$ or above, because these correspond to strong wave activity.
Arctic winter-time wave activity accompanied by simultaneous Antarctic summer-time wave activity can be seen in February 2007 and February 2008. Similarly, Antarctic winter-time wave activity accompanied simultaneously by Arctic summer-time wave activity can be seen in August 2005, September 2006 and August 2007 (however, the Esrange data has a gap in summer 2006 and so only the end of the burst of wave activity can be seen). All these episodes are consistent with the possibility of inter-hemispheric ducting of the 5-day wave (but, of course, this does not prove that such ducting is taking place).

In contrast, there are also episodes of wave activity in the winter-time which it are not accompanied by simultaneous summer-time wave activity in the other hemisphere. Arctic winter-time wave activity not accompanied by simultaneous Antarctic summer-time wave activity can be seen in December 2005, 2006, 2007 and 2008. This means that there are at least some episodes where ducting is definitely not occurring, at least to the latitudes of Esrange or Rothera. These results suggest that if ducting does occur, it does not occur to high latitudes in every year.

3.1.6 Conclusion

The 5-day wave has been observed in both the Arctic and Antarctic MLT. The observations span several years and reveal a high level of inter-annual variability. Observations nevertheless demonstrate that the wave has a clear and well-defined seasonal cycle which is very similar in each polar region. Throughout the winter the wave can be present at all the heights observed (∼80 – 100 km). In the summer, the wave maximises late in the season and only at heights of ∼85 km (approximately August/September over Esrange and February over Rothera).

This seasonal cycle has a number of differences compared to those reported elsewhere. However, the long data sets considered here reveal that these differences are probably the result of the high level of inter-annual variability displayed by the wave and the great variation of wave activity with height.
As a result of the strong westward winds below the zero-wind line during the summer, the 5-day wave cannot propagate upwards into the mesosphere from below. The summertime wave therefore has to be either created \textit{in situ}, or to have propagated across the equator from the other hemisphere by ducting; or to be a result of a combination of the two. Our observations of simultaneous wave activity in the summer and winter polar mesosphere suggest that such ducting may occur, but this cannot be confirmed using the data considered here. To investigate this further will require either ground-based observations at lower latitudes or global observations made by satellites.
Chapter 4

Results - The Polar 16-day Planetary Wave in the MLT

4.1 The 16-Day Wave in the Arctic and Antarctic Meso-
sphere and Lower Thermosphere

4.1.1 Abstract

The 16-day planetary wave in the polar mesosphere and lower thermosphere has been investigated using meteor radars at Esrange (68°N, 21°E) in the Arctic and Rothera (68°S, 68°W) in the Antarctic. The measurements span the 10-year interval from October 1999 to July 2009 and the 5-year interval February 2005 to July 2009, respectively. The height range covered is about 80–100 km. In both polar regions the wave is seen to occur in intermittent bursts, where wave amplitudes typically reach a maximum of about 15 m s\(^{-1}\), and never more than about 20 m s\(^{-1}\). Horizontal wind variance within a wave-period range of 12 to 20 days is used as a proxy for the activity of the 16-day wave. Wave activity is strong for 3 to 4 months in winter, where it is present across the entire height range observed and monthly wave variance reaches about 65 m\(^2\) s\(^{-2}\). Some weak and intermittent activity is observed throughout the other seasons including summer. However, there is a high degree of inter-annual variability and in some individual years
wave activity is almost absent. The data are used to construct a representative climatology for the Arctic and Antarctic. The seasonal cycle of the 16-day wave is found to be very similar in both polar regions. The 16-day wave has slightly greater amplitudes in the zonal component of the winds than in the meridional. Mesospheric temperatures measured by the radars were used to further investigate the 16-day wave. The temperatures reveal a clear signature of the 16-day wave. Temperature amplitudes are generally only a few Kelvin but occasional bursts of up to 10 K have been observed. Observations of the wave in summer are sometimes consistent with the suggestion of ducting from the winter hemisphere.

4.1.2 Introduction

Planetary waves are important agents in the coupling between the layers of the atmosphere. They act to move energy, momentum and chemical species both horizontally and vertically in the atmosphere. Planetary waves are known to propagate from sources in the troposphere and stratosphere into the mesosphere and lower thermosphere (MLT) and also to be generated \textit{in situ} in the MLT [e.g., 20, 21, 63, 71, 72]. Planetary waves can reach amplitudes of several tens of ms$^{-1}$ in the MLT. The waves are known to interact with and modulate the amplitudes of atmospheric tides [e.g., 73, 74]. They also modulate the gravity-wave field of the middle atmosphere [e.g., 39, 40, 41, 42, 43, 53]. Planetary waves with a period of 16 days have been reported in observations of wind, temperature and geopotential height in the MLT region [e.g., 24, 25, 26, 35, 43, 72, 75, 76, 77, 78]. The temperature perturbations associated with planetary waves are believed to modulate the occurrence of Polar Mesospheric Clouds [e.g., 34, 35, 37]. Modelling studies have also investigated the 16-day wave [e.g., 24, 72, 79].

The wave has been reported to have amplitudes of up to $\sim 20 \text{ ms}^{-1}$ in the winter-time MLT and up to $\sim 7 \text{ ms}^{-1}$ in the summer-time MLT. The vertical wavelength has generally been reported to have values between $\sim 30$ to 60 km [e.g., 24, 76, 77]. The 16-day wave has been identified as the manifestation of the gravest symmetrical wavenumber 1 westward travelling, $s = 1$, Rossby mode and suggested on theoretical grounds to occur with periods between 11.1 – 20.0 days [e.g., 21].
A number of studies have investigated the 16-day wave at mid- and low-latitudes in the MLT region. These studies have revealed that the wave has a clear seasonal behaviour in the MLT and displays wave periods of between about 12 to 20 days, as predicted by Salby [21]. Forbes et al. [72] analysed 2 months of wind data, from a meteor-radar over Obninsk, (54°N) and from a medium-frequency (MF) radar over Saskatoon (52°N) to observe the 16-day wave in the MLT at a time when there was a large oscillation in the troposphere and stratosphere. Mitchell et al. [75] used 5 years of meteor-radar wind data and reported that the 16-day wave maximised in winter and was also present in late summer over the UK at 53°N. The comprehensive studies of Luo et al. [24, 76, 77] used MF-radar, HRDI/UARS and The Global Scale Wave Model. They used wind data to observe the 16-day wave and reported largest wave amplitudes in winter and smaller amplitudes in summer. Jiang et al. [78] used meteor-radar wind data from over Wuhan (31°N) and MF-radar data from over Adelaide (35°S) to study the 16-day wave in 2002 and 2003. The wave was observed in all seasons over at least one of the sites. In general, the mid-latitude studies suggest that wave activity is strongest in winter with a secondary maximum occurring around the summer mesopause.

At lower latitudes Lima et al. [25] observed the MLT region for five years with a meteor-radar at Cachoeira Paulista (23°S). They concluded that there was no clear seasonal behaviour and that the strongest wave activity was observed in autumn-winter for some years and spring-summer for others.

In contrast to the situation at mid-latitudes, there have been only a limited number of studies of the 16-day wave in the polar MLT. Williams and Avery [56] used a mesosphere-stratosphere-troposphere (MST) radar to observe winds over Poker Flat (65°N) and reported significant wave activity in summer and winter. Espy et al. [26] used optical measurements of OH-layer temperatures over Stockholm (60°N) in the summers of 1992 to 1995 to investigate the 16-day wave. They reported a temperature oscillation corresponding to the 16-day wave. Luo et al. [24] used an MF-radar and reported observations of winds over Tromsø (70°N) during 1993 to 1994. They also reported stronger wave activity in the winter, but some summer-time wave activity was also evident.
Miyoshi [79] reported numerical simulations in which the 16-day wave maximised in winter and summer, with the winter amplitudes being greater. It was suggested that the 16-day wave may be mainly excited by heating due to the moist convection in the troposphere.

One of the most interesting things about the 16-day wave is that a number of explanations have been proposed for the wave activity observed in summer. The key point here is that the summer-time wave activity in the MLT cannot have propagated to those heights from the summer troposphere/stratosphere. This is because the 16-day wave has a low zonal phase speed and so wave propagation is prohibited through the strong westward winds of the summer-time middle atmosphere [63].

A mechanism that could account for in situ excitation of the wave has been proposed by Williams and Avery [56]. In this mechanism, gravity waves rising from the lower atmosphere are filtered by a 16-day wave in the troposphere/stratosphere. This imposes a 16-day modulation on the gravity-wave field in the MLT. As these gravity waves dissipate and transfer their momentum into the mean flow of the MLT this then excites a 16-day wave in situ. Smith [80] demonstrated in a modelling study that this mechanism can produce significant planetary-wave amplitudes in the MLT, at least for stationary planetary waves.

An alternative explanation proposed by Miyahara et al. [81] is that the 16-day wave of the winter hemisphere propagates across the equator into the summer-time MLT at heights above the strong westward flow of the summer-time middle atmosphere. This suggestion received further support from the modelling study of Forbes et al. [72]. However, these authors also noted that this ducting may be impeded by gravity-wave stresses in the mesosphere. Experimental results which suggest such ducting takes place have been reported by Espy et al. [26] and Hibbins et al. [27]. These authors report a correlation between long-period planetary wave activity in the summer polar mesosphere and the phase of the equatorial Quasi-Biennial Oscillation (QBO), such that largest amplitudes occur during eastward phases of the QBO at highest levels (MLT). These suggest that the waves observed in the polar regions have travelled there across the equator from the winter hemisphere, i.e., have been ducted.
Here we present observations of winds and temperatures in the MLT made using two meteor radars, one at Esrange in the Arctic and one at Rothera in the Antarctic. These radars are located at conjugate geographical latitudes. Comparatively long data sets are available from the sites (10 and 5 years, for Esrange and Rothera, respectively). The data from these radars are used to characterize the inter-annual variability of the 16-day wave in the polar MLT and to construct simple representative climatologies of the 16-day wave in the Arctic and Antarctic MLT.

4.1.3 Data Analysis

Two all-sky meteor radars were used in this study. The radars are SKiYMET VHF systems that operate with radiated power being largely independent of azimuth. The radio frequency that the radars operate at is 32.5 MHz, the pulse repetition frequency is 2144 Hz, the duty cycle is 15% and the peak power is 6 kW. One radar is located at Esrange in Arctic Sweden (68°N, 21°E). It was deployed in August 1999 and has produced largely-uninterrupted measurements since October of that year. The other is located at Rothera in the Antarctic (68°S, 68°W). It was deployed in February 2005 and again has produced largely-uninterrupted measurements since deployed. This gives a near-continuous data set of approximately ten years for Esrange and five years for Rothera.

Horizontal winds are measured by both radars at heights of ~80–100 km. Six independent non-overlapping height gates are used with representative height and time resolutions of either 3 or 5 km and 1 hour, respectively. The vertical distribution of meteor echoes is strongly peaked at a height of ~90 km. The height gates used from 80 to 100 km have depths of 5, 3, 3, 3, 3, 5 km to ensure there are sufficient meteors in the uppermost and lowermost height gates. The meteor-count-weighted centres of the height-gates are at 80.8, 84.7, 87.5, 90.4, 93.3 and 97.1 km. The horizontal winds are calculated for each height gate in time steps of 1 hour and resolved into zonal and meridional wind components. A more full description of the radars and data analysis can be found in Hocking et al. [46] and Mitchell et al. [66]. These time series of the hourly winds form the basis of the wind data analysis presented here.
To complement the wind data, temperatures can also be measured by both of the radars. The temperature data is a daily value, representative of the whole height range available, thus supplying one daily temperature for the meteor region. The temperature data used here for Esrange covers the interval from August 2002 to July 2009 and for Rothera from February 2005 to July 2009. A full description of the temperature data analysis can be found in Hocking [45], Hocking et al. [46, 47].

As described in Chapter 4 (Introduction section), the 16-day planetary wave has been observed to occur with a wide range of periods between $\sim 12$ to 20 days. Here, we will consider all planetary wave activity within the period range 12 to 20 days to be attributable to the “16-day wave”. This range of periods has also been used in the studies of Lima et al. [e.g., 25], Forbes et al. [e.g., 72], Luo et al. [e.g., 77], Jiang et al. [e.g., 78], and is used here so that our results will be directly comparable with these other studies.

### 4.1.4 Results

To investigate the planetary-wave field over Esrange and Rothera, the time series of winds recorded over each site were analysed using a wavelet technique. The wavelet analysis uses a Morlet wavelet of non-dimensional wavenumber 6. This wavelet and wavenumber were chosen because they have approximately similar form to the bursts of planetary wave activity often reported in the MLT [e.g., 12, 13, 15].

An example of this analysis is shown in Fig. 4.1. The figure presents the results of the wavelet analysis for zonal winds recorded at a height of $\sim 85$ km over Esrange and Rothera in the time interval 2005 to 2009. These years are presented because they are the ones in which simultaneous data exists for Esrange and Rothera. Results are only plotted for amplitudes greater than $3 \text{ m s}^{-1}$ to highlight episodes of strong wave activity.

From the figures it can be seen that the planetary-wave activity is intermittent and occurs in bursts lasting approximately 1–2 months. Further, the wave period varies from burst to burst and is only approximately 16 days. A significant number of wave bursts are observed across the whole period range 12 to 20 days. For example, a burst
of strong wave activity is evident in March 2005 over Esrange with a period of near 16 days. However, over Rothera in July 2005 the period of the burst of wave activity is nearer 13 days. Considering only the 16-day wave, it can be seen that wave amplitudes reached as large as $\sim 15 \text{ m s}^{-1}$ over Esrange and $\sim 10 \text{ m s}^{-1}$ over Rothera. Other bursts of wave activity are evident that occur at wave periods outside of the 12 to 20 day range. For example, strong wave activity with a period near 9 days is evident over Esrange in January 2005 and over Rothera August 2007.

![Wavelet analysis of zonal winds](image)

**Figure 4.1:** A wavelet analysis of a) hourly zonal winds over Esrange at a height of 84.7 km during the interval January to December 2005 to 2009 and b) hourly zonal winds over Rothera at a height of 84.7 km during the interval January to December 2005 to 2009. Amplitudes smaller than $3 \text{ m s}^{-1}$ are not plotted.

To investigate these 16-day waves further, a band-pass analysis of the horizontal winds
in each height gate was performed. A second-order Butterworth band-pass filter was used that had period limits of 12 to 20 days (the filter used is the standard Butterworth found within MatLab). These period limits were chosen to make the analysis as similar as possible to that of some previous studies e.g., Luo et al. [24], Espy et al. [26], Mitchell et al. [75], Jiang et al. [78]. From the wavelet analysis in Fig. 4.1 it can be seen that wave activity is significant within this period range and the theoretical work mentioned above suggests that this is due to a global-scale wave number 1 planetary wave. Hereafter we will refer to oscillations within this period range as the “16-day wave”.

The vertical structure of the wave was then investigated using the six independent height gates available from each of the radars. The time-height contours of the band-passed zonal winds recorded over Esrange and Rothera are presented in Fig. 4.2 a) and b) respectively (the meridional winds, not shown, reveal a generally similar behaviour). The data is for all years of data available, i.e. for Esrange, 1999 to 2009 and for Rothera, 2005 to 2009. Wave activity is evident in all years observed. Wave activity is generally stronger in winter than summer and is present in all winters observed. The wave is present in most summers observed, but is generally weaker than in winter. Only in one year, 2005, wave activity appear to fall below amplitudes of $\sim 3 \text{ m s}^{-1}$ in summer. The bandpassed winds reveal a strongly phase coherent wave structure across the height range observed. Clear phase fronts are evident in all seasons, although the pattern begins to break up when the wave reaches small amplitudes in some summer months. This phase coherency across the six independent height gates provides strong evidence that the data are revealing the presence of a 16-day planetary wave.

Considering the figure in more detail, it can been seen that the winter-time wave is present through all the heights observed. The winter-time enhancement in amplitude lasts for several months and extends into the equinoxes, for instance the months of October to March over Esrange and May to October over Rothera. Wave amplitudes regularly reach $\sim 15 \text{ m s}^{-1}$ for intervals of several months. For example, over Esrange this amplitude is reached in most years from October to March. A similar behaviour is observed over Rothera with strong wave activity evident from May to October. However, there is also significant inter-annual variability. For example, over Esrange in December
2001 the amplitude is mostly below \(\sim 5\, \text{m s}^{-1}\), whereas in December 2003 it is mostly above \(15\, \text{m s}^{-1}\). Similarly, over Rothera in July 2006 the amplitudes are generally less than \(5\, \text{m s}^{-1}\) compared with July 2007 where they reach \(15\, \text{m s}^{-1}\).

In contrast to the winter, wave amplitudes are generally smaller in summer. However, there are still some episodes of strong, but short-lived activity in the summer where wave amplitudes reach between \(5\) and \(10\, \text{m s}^{-1}\) on several occasions. For example, over Esrange in June and July at heights at below \(90\, \text{km}\) in 2000 and for the same months at heights above \(90\, \text{km}\) in 2004. Summer-time wave activity is even stronger over Rothera. For example, wave amplitude exceed \(10\, \text{m s}^{-1}\) in January and February in 2007.

Over Esrange there are six years where we have a continuous three months of data for observing the 16-day summer-time wave. In this there are five bursts where amplitudes reach greater than \(5\, \text{m s}^{-1}\). Over Rothera there are four bursts reaching amplitudes greater than \(5\, \text{m s}^{-1}\).

Examination of the phase fronts of the wave reveals that there is phase slope with height. Good examples of this include November and December over Esrange in 2003 and August to October over Rothera in 2007. This suggests that the vertical wavelength, even though still long, is not as long as other planetary waves. A least-squares fit to the data for winter conditions suggests a vertical wavelength of \(\sim 70\, \text{km}\).

The seasonal and long-term variability suggested above can be investigated further using horizontal wind variance as a proxy for wave activity. In this analysis the band-passed winds in each height gate for each month are used to calculate a variance value for the meridional and zonal components of the winds. By examining these variances as a function of height and time the seasonal and inter-annual behaviour of the 16-day wave can be investigated. A similar analysis has been used in the study of the 2-day and 5-day planetary waves [70, 82]. Note that for a constant-amplitude oscillation, amplitude is equal to the square root of twice the variance. For example, a variance of \(10\, \text{m}^2\, \text{s}^{-2}\) corresponds to a wave amplitude of \(4.5\, \text{m s}^{-1}\), a variance of \(50\, \text{m}^2\, \text{s}^{-2}\) corresponds to a wave amplitude of \(10\, \text{m s}^{-1}\) and a variance of \(100\, \text{m}^2\, \text{s}^{-2}\) corresponds to a wave amplitude of \(14.1\, \text{m s}^{-1}\), etc.
Figure 4.2: Time-height contours of a) the hourly zonal winds band-passed between 12 and 20 days over Esrange and b) the hourly zonal winds band-passed between 12 and 20 days over Rothera.
Time-height contours of meridional and zonal monthly variances for all the years available over Esrange are presented in Fig. 4.3. The monthly-mean zonal winds for each year have been plotted over the top of the figure for that specific year to enable a comparison of the background winds and the level of 16-day wave activity.

Figure 4.3 shows a clear seasonal cycle in Arctic wave activity on top of which is superposed significant inter-annual variability. Wave activity is strongest in winter. For example, zonal variances in February and March of 2005 show a strong 16-day wave at $\sim 85\text{ km}$ where variances reach values in excess of $\sim 100\text{ m}^2\text{s}^{-2}$. In contrast, during February and March of 2007, wave variances at the same height reached only $\sim 30\text{ m}^2\text{s}^{-2}$.

When considering the strong winter-time wave it can be seen that the zonal component is greater than the meridional for most winters (the average difference is approximately a factor of 1.2). Consideration of the figure shows that the wave has generally largest variances in the winter and equinoxes.

In the summer the wave is present but has significantly smaller variances and is sometimes completely absent. For example, in the summer of 2003, zonal wave variance reaches values of $\sim 35\text{ m}^2\text{s}^{-2}$ at the upper heights in June and July. Similarly, the summers of 2000, 2003, 2005 and 2007 all show wave activity with variances in the range of 15 to 40 $\text{m}^2\text{s}^{-2}$. Careful inspection of the bandpass data (Fig. 4.2) reveals short-lived episodes of wave activity corresponding to these maxima in variance.

Figure 4.4 shows the results of a similar analysis for winds recorded over Rothera in the Antarctic during February 2005 to July 2009. As with the Arctic results of Fig. 4.3, these show a seasonal cycle and significant inter-annual variability. The activity maximises strongly in winter, compared with summer where it is weaker. For example, zonal variances during August 2007 (Antarctic winter) show a strong 16-day wave in all the height gates observed, maximising at $\sim 92\text{ km}$ and reaching variances of $\sim 100\text{ m}^2\text{s}^{-2}$. In contrast, during August 2005, wave variances at the same height reached only $\sim 25\text{ m}^2\text{s}^{-2}$.

The figure also shows a clear secondary maximum in summer. For example, in January and February of all of the years the variance reaches a maximum of about $60\text{ m}^2\text{s}^{-2}$.
Figure 4.3: Time-height contours (filled colour contours) of the monthly variance of winds band-passed between 12 and 20 days over Esrange in the Arctic for both meridional and zonal components, for 1999 to 2009. Also plotted are the monthly-mean zonal winds. The zero-wind line is indicated by the heavy dashed line.

From Charney and Drazin theorem (1961), in order to propagate, a planetary wave must obey $0 < \bar{u} - c_x < U_c$, where $\bar{u}$ is the zonal wind speed, $c_x$ is the zonal phase speed of the planetary wave and $U_c$ is the critical Rossby speed. For the 16-day wave at a latitude of $68^\circ$ the phase speed, $c_x$, is $-10.9 \text{ ms}^{-1}$. The mean zonal wind speed, $\bar{u}$, should
Figure 4.4: Time-height contours (filled colour contours) of the monthly variance of winds band-passed between 12 and 20 days over Rothera in the Antarctic for both meridional and zonal components, for 2005 to 2009. Also plotted are the monthly-mean zonal winds. The zero-wind line is indicated by the heavy dashed line.

Thus be greater than -10.9 ms\(^{-1}\) for the wave to propagate. The observations of Fig. 4.3 and Fig. 4.4, however, reveal significant wave activity in winds more westerly than this value. Similar behaviour has been reported by, e.g., Luo et al. [24] and probably reflects the fact that the Charney-Drazin theorem is an approximation.

In order to investigate the seasonal variability of the 16-day wave in more detail, a composite-year (“superposed epoch”) analysis was applied in which data from all years was used. A simple arithmetic mean of the monthly variances was used. The results of this analysis are shown in Fig. 4.5 and Fig. 4.6.

Figure 4.5 presents a composite-year analysis of the monthly meridional and zonal wave activity calculated using all the years of data available over Esrange, October that is 1999 to July 2009. The monthly-mean zonal winds from the same period of time are plotted on the figure as contour lines. It can be seen that the strongest wave activity is in winter and maximises in January where variances reach \(\sim 70 \text{ m}^2\text{s}^{-2}\). Wave activity
is present at all heights observed. Wave activity is evident into the equinoxes and is generally very weak in summer.

Figure 4.5: A composite-year analysis of 16-day wave activity over Esrange in the Arctic for the years 1999 to 2009 (filled colour contours) for the meridional component, top panel, and zonal component, bottom panel. Also shown are the composite-year monthly-mean zonal winds (contour lines). The zero-wind line is indicated by the heavy dashed contour line.

Figure 4.6 presents a similar analysis for Rothera. It can be seen that the strongest wave activity is again in winter and maximises in August where variances reach $\sim 65 \text{ m}^2\text{ s}^{-2}$. Note that this is approximately one month later than in the Arctic, but this is based on only five complete winters of observations and so may not be significant. Again, wave activity extends into the equinoxes and is weakest in summer.

However, note that this analysis will tend to mask the short-lived occasional bursts of activity present in summer as seen in Fig. 4.2 a) and b). This is because the bursts are sometimes of less than one-month duration and do not occur every year and so are smoothed out in the multiple-year composite analysis of Fig. 4.5 and Fig. 4.6. In some years the high level of inter-annual variability evident in Fig. 4.3 and Fig. 4.4 means the strongest wave activity occurs one or two months either side of the maxima evident in Fig. 4.5 and Fig. 4.6.
Figure 4.6: A composite-year analysis of 16-day wave activity over Rothera in the Arctic for the years 2005 to 2009 (filled colour contours) for the meridional component, top panel, and zonal component, bottom panel. Also shown are the composite-year monthly-mean zonal winds (contour lines). The zero-wind line is indicated by the heavy dashed contour line.

The radars also produce a daily estimate of meteor-region temperature. This was used in a further investigation of the 16-day wave. The temperature time series from each radar was subject to a band-pass analysis with the same bandpass filter and limits as those used for the winds of Fig. 4.2 to Fig. 4.6. Temperature data are available from August 2002 over Esrange and February 2005 over Rothera.

Figure 4.7 presents the bandpassed daily temperatures and zonal winds over Esrange and Rothera, respectively. The heights chosen for the wind time-series are \( \sim 85 \text{ km} \) and \( \sim 93 \text{ km} \), respectively. These height gates were chosen because they are the corresponding heights at which the largest wind variances occur in Fig. 4.5 and Fig. 4.6. The figure allows comparison of each year’s temperature and wind perturbations. From the figure it can be seen that there are bursts of wave activity in the temperatures. Generally these bursts coincide with bursts of wave activity in the winds. A number of the strongest bursts of coincident temperature and wind fluctuations are indicated by a * on the figures. These bursts are selected as those events where the wind amplitude exceeds \( 5 \text{ m s}^{-1} \) for more than one cycle of the wave.

The coincidence of the bursts in both wind and temperature provide strong support for
the suggestion that the fluctuations in the temperature time series are caused by the 16-day planetary wave.

From the figure it can be seen that there were 25 such bursts observed over Esrange and 17 observed over Rothera. Generally, larger bursts of activity in zonal winds correspond to larger bursts of activity in temperature perturbations. For example, in June 2003 over Esrange the $\sim 15 \text{ m s}^{-1}$ amplitude winds are accompanied by $\sim 5 \text{ K}$ amplitude temperature perturbations. A similar event can be seen over Rothera in September-October 2007. The wind perturbation and temperature perturbations are $\sim 10 \text{ m s}^{-1}$ and $\sim 8 \text{ K}$ respectively. It can be seen that when the wind and temperature perturbations are at their largest values they appear to be generally in phase. This is evident in most events marked by a * in Fig. 4.7.

Figure 4.7: Band-passed mean daily zonal winds and daily temperatures over a) Esrange, at $\sim 85 \text{ km}$ and b) Rothera, at $\sim 93 \text{ km}$, for the years 2002 to 2009. Band-pass limits are for the wave periods of 12 to 20 days. Coincident bursts of wave activity in temperature and winds are marked by a *.
The bursts of wave activity show that there is a relationship between wind and temperature perturbations. Generally, greater wind perturbations correspond to greater temperature perturbations. The temperature perturbations range from 1 K to more than 6 K. To quantify the relationship between them, a least-squares fit of the wind and temperature amplitudes for the above bursts of activity was carried out. The burst are also subjected to the criteria of the Student T-test for them to be statistically related at a 90% confidence level. Figure 4.8, presents the wind and temperature amplitudes determined for the 35 burst of wave activity that satisfied this criterion over Esrange and Rothera. A least-squares straight-line fit to these data suggests that temperature and wind perturbations, $T'$ and $u'$, are related by $T' = 0.27 u'$. Note that the fit was forced through zero.

The seasonal behaviour of the 16-day wave can also be investigated using the temperature data. A temperature variance can be used as a proxy for wave activity in much the same way as the analysis of the wind data, although there is no height resolution for the temperature data and thus it represents an average across the meteor region.

Further investigation into the seasonal variability of the 16-day wave can be made by a composite-year variance analysis of the temperatures, as per the results of Fig. 4.5 and
Fig. 4.6. The results of this analysis are shown in Fig. 4.9, which presents a composite-year analysis of the temperature variances calculated using all the years data available. From the figure it can be seen that the winter-time wave over Esrange is large from November through to February, reaching variances as large as $\sim 13 \text{K}^2$. The summertime wave is significantly weaker and the variances only reach $\sim 4 \text{K}^2$. In contrast, the winter-time maximum is not evident over Rothera and, in fact, the largest variances occur in November. From inspection of Fig. 4.7 b) it can be seen that this spring-time peak largely results from the single large-amplitude event of November 2006.

\begin{figure}[ht]
\centering
\includegraphics[width=\textwidth]{composite_year_monthly_temperature_variances.png}
\caption{A composite year analysis of the 16-day wave activity using temperatures over Esrange in the Arctic and Rothera in the Antarctic for the years 2002 to 2009.}
\end{figure}

\subsection*{4.1.5 Discussion}

There are a comparatively small number of published studies of the 16-day wave in the polar MLT. Radar and satellite observations have revealed wave amplitudes of up to about $15 \text{m s}^{-1}$ and $5 \text{K}$. The wave has been observed to have a wide range of periods ranging from about 12 to 20 days. These observations have been interpreted as a manifestation of the Rossby (1,3) normal mode, proposed on theoretical grounds to have wave periods in the range of 11.1 to 20.0 days by Salby [21].
The results presented in this chapter display a clear seasonal behaviour in the occurrence of the 16-day wave in the polar MLT. The wave is evident mainly in the winter over the whole height range observed, but is also present more weakly in the summer-time. The zonal wind component is generally slightly greater than the meridional.

Williams and Avery [56] reported observations of the 16-day wave in one year of MST radar data from Poker Flat (65°N). They reported wave amplitudes maximising in summer with monthly-mean values of $\sim 6 \text{ m s}^{-1}$, roughly comparable to the summer-time amplitudes observed over Esrange and Rothera. Wave activity had equinoctial minima and a weaker secondary maximum in winter. This is different from the multiple-mean year seasonal behaviour reported here. However, the difference may well arise from the fact that they observed only one year and the degree of inter-annual variability is high. Williams and Avery reported wave periods ranging from 13 to 19 days, which again is very similar to our observations.

Espy et al. [26] reported observations of the nightly temperatures at heights of about 87 km made using a ground-based OH compact Michelson interferometer at Stockholm (60°N) in June to August of the summers of 1992–1995. They concluded that the 16-day wave was present in 1992 and 1994, but not in 1993 and 1995. They observed temperature perturbations during wave bursts of $\sim 5 \text{ K}$, which is similar to the observations here. They also suggested that the amplitude was much greater in the polar summer mesosphere during eastward (westerly) phases of the QBO. Similar conclusions were drawn by Hibbins et al. [27] based on observations of the Antarctic summer-time mesosphere. However, our results do not support the conclusion that there is a simple correspondence between the occurrence of the wave in polar summer and the phase of the QBO.

Mitchell et al. [75] reported observations of the 16-day wave in the MLT using a meteor radar at Sheffield (53°N) from January 1990 to August 1994. Largest amplitudes were observed in winter-time, where they reached $\sim 14 \text{ m s}^{-1}$, comparable to the results presented here. Significant wave activity was observed in mid-summer where it reached $\sim 7$ to $10 \text{ m s}^{-1}$ in June and July.
Chapter 4. Results - The Polar 16-day Planetary Wave in the MLT

Luo et al. [24, 76, 77] carried out a comprehensive study of the 16-day wave using data from multiple MF radars sited from 70°N to 2°N, High Resolution Doppler Imager (HRDI) data, and the Global Scale Wave Model (GSWM) model. The winter-time wave was present at heights of 60–100 km and reached amplitudes of up to 20 m s\(^{-1}\). The summer-time wave was only present at heights above 85 km and reached amplitudes of \(\sim 5\) to 10 m s\(^{-1}\). They observed the zonal wave amplitudes to be slightly larger than the meridional. They observed that the summer-time wave was excluded from the regions of strongest westward zonal wind. They found the 16-day wave to be strongest at latitudes of 40° to 60° in both hemispheres. Seasonal and inter-annual variability was investigated with the GSWM and, in part, attributed to the Biennial Oscillation (BO) and the Quasi-Biennial Oscillation (QBO). They measured the vertical wavelength to be \(\sim 50\) km at a height of 85 km and 30–60 km across the whole MLT. They attributed the observation of the 16-day wave in the summer-time MLT to cross-equator propagation.

Jiang et al. [78] observed the MLT with a meteor radar at Wuhan (31°N) and MF radar at Adelaide (35°S) during the intervals February 2002 to November 2003 and January 2002 to October 2003, respectively. They reported the seasonal cycle of the 16-day wave. Maximum amplitudes occurred from September to October over Wuhan and July to October over Adelaide. Zonal wave amplitudes were found to be slightly greater than the meridional, as reported here.

Lima et al. [25] used a meteor radar at Cachoeira Paulista (23°S) to measure the 16-day wave from April 1999 to April 2004. No clear seasonal behaviour was apparent, although wave activity was observed in summer. They measured peak amplitudes to be \(\sim 14\) m s\(^{-1}\) at a height of 90 km and measured the vertical wavelength to be \(\sim 51 \pm 11\) km.

Forbes et al. [72] reported on both observations and modelling of the 16-day wave in the northern hemisphere winter-time MLT. The observations were from a meteor radar at Obninsk (54°N) and MF radar at Saskatoon (52°N). They observed wave amplitudes of \(\sim 10\) m s\(^{-1}\) (slightly smaller than the means reported here). Their observations agreed with their modelling study, which predicted wave amplitudes of 5 to 10 m s\(^{-1}\). They also modelled temperature amplitudes. At high latitudes they predicted temperature amplitudes of 5 to 10 K, which agrees well with our observations.
The high-latitude results we have presented in Chapter 4 Results section generally agree with those discussed above for middle- and high-latitude studies. We observe similar seasonal cycles in wind and temperature amplitudes to those described. The general pattern of wave activity appears to quite similar in our Arctic and Antarctic observations. There is little evidence of significant differences in the wave between the hemispheres in strong contrast to the inter-hemispheric differences known to be the case for the 2-day wave [e.g., 83, 84], although the high level of inter-annual variability prevents us from making definite conclusions.

There are, however, a number of differences between the observations reported here and those of the earlier studies. These differences can probably be attributed to the high degree of inter-annual variability of the 16-day wave. For example, the small winter amplitudes reported by Forbes et al. [72] and Williams and Avery [56] may result from inter-annual variability since similar amplitudes are observed in some of the years of data reported here. The lack of clear seasonal cycle in the study of Lima et al. [25] almost certainly is because of the low latitude of that study.

The propagation of the 16-day wave into the MLT is controlled by the mean zonal winds, as discussed in this chapter. Charney and Drazin’s theorem (1961) explains the free propagation of the 16-day wave from the lower atmosphere to the MLT in winter, as observed. In fact, the observed phase slope in the winter MLT corresponds to an upwardly-propagating wave. However, the zonal wind must have a speed greater than $-10.9\, \text{m s}^{-1}$ at 68°N/68°S for the wave to propagate upwards. Therefore, the wave cannot have propagated from below in summer-time because of the strong westward winds of the middle atmosphere.

Our observations show that the 16-day wave is largely absent from the regions of strong westward flow observed in summer (e.g., Fig. 4.5 and Fig. 4.6) this therefore leads to the conclusion that the wave has not propagated from below to the heights where it is observed. As discussed in this chapter introduction section, it has been proposed that the summer-time wave activity must then result from either ducting across the equator from the winter hemisphere or from \textit{in situ} excitation by modulated gravity-wave fluxes.
If ducting is indeed occurring from the winter to the summer hemisphere, then simultaneous wave activity should be observed in the Arctic and Antarctic. Considering the years of simultaneous data, occurrences of simultaneous wave activity can be searched for. The level of wave activity that we will consider to be significant is taken to be monthly variances of above an arbitrary threshold of $50 \text{ m}^2 \text{s}^{-2}$.

Using this criterion, Arctic winter-time wave activity accompanied by simultaneous Antarctic summer-time wave activity can be seen in the Januaries of 2007, 2008, and 2009. Similarly, Antarctic winter-time wave activity accompanied simultaneously by Arctic summer-time wave activity can be seen in September 2005 and October 2006. These episodes are consistent with the possibility of inter-hemispheric ducting, but are not in themselves conclusive proof.

In contrast, there are also episodes of wave activity in the winter-time which are not accompanied by simultaneous summer-time wave activity in the other hemisphere. In particular, Arctic winter-time wave activity is not accompanied by simultaneous Antarctic summer-time wave activity in January 2006. Similarly, Antarctic winter-time wave activity not accompanied by simultaneous Arctic summer-time wave activity in the Septembers of 2007 and 2008. These results suggest that ducting is not occurring in the high latitudes over Esrange and Rothera for at least some years and that therefore if ducting does occur, it does not occur every year. One possible explanation for variability in inter-hemispheric ducting has been proposed by Espy et al. [26] and Hibbins et al. [27], who suggests that the QBO strongly modulates such ducting, resulting in a QBO modulation of polar planetary-wave activity in summer.

A deeper investigation of the role of inter-hemispheric ducting would ideally require observations of the 16-day wave at low latitudes where the wave could be observed in any cross-equator duct. Such observations could be made by low-latitude ground-based radars and/or by satellite observations. Observations of a summer-time polar 16-day wave where no such wave was detected crossing the equator would strongly support the proposal that the wave was excited \textit{in situ} by modulated gravity-wave momentum fluxes [e.g., 56], whereas the presence of such a wave at the equator would support
the suggestion of inter-hemispheric ducting [e.g., 72, 81]. We intend to investigate this possibility in a follow-on study.

4.1.6 Conclusions

The 16-day wave has been observed in both the Arctic and Antarctic MLT using wind and temperature data. The observations span several years and reveal a high level of inter-annual variability. Observations nevertheless demonstrate that the wave has a clear and well-defined seasonal cycle, which is very similar in each polar region. Throughout the winter the wave is present in all the heights observed (∼ 80–100 km). Wave activity, measured by the winds, during the winter-time was found to be strongest at a height of ∼ 85 km where it reached amplitudes in excess of ∼ 15 m s\(^{-1}\). A summer-time wave was also observed, but with weaker amplitudes seldom in excess of ∼ 6 m s\(^{-1}\). Weak wave activity is also evident throughout some of the equinoxes. In all seasons the wave amplitudes vary over time scales of a few tens of days. In the long-term average the wave amplitudes are slightly larger in the zonal component.

The temperature data also reveal a clear 16-day wave signature. Temperature amplitudes typically range from 1 to 6 K. Examination of wind and temperature amplitudes suggests a relationship of form \(T' = 0.27 u'\).

Comparisons with other studies reveal generally similar seasonal behaviour, but some differences are apparent. However the high level of inter-annual variability evident in our extended data set suggests that such differences can be explained by the shorter duration of other studies.

In some cases simultaneous wave activity is evident in the winter and summer hemispheres. This observation is not inconsistent with the suggestion that the 16-day wave observed in the summer MLT has propagated there from the winter hemisphere.
Chapter 5

Results - The 16-day wave in the middle atmosphere

5.1 Aura MLS observations of the westward-propagating $s = 1$, 16-day planetary wave in the stratosphere, mesosphere and lower thermosphere

5.1.1 Abstract

The Microwave Limb Sounder (MLS) on the Aura satellite has been used to measure temperatures in the stratosphere, mesosphere and lower thermosphere. The data used here are from August 2004 to December 2010 and latitudes 75°N to 75°S. The temperature data reveal the regular presence of a westward-propagating 16-day planetary wave with zonal wavenumber 1. The wave amplitudes maximise in winter at middle to high latitudes, where monthly-mean amplitudes can be as large as $\sim 8$ K. Significant wave amplitudes are also observed in the summer-time mesosphere and lower thermosphere (MLT) and at lower stratospheric heights of up to $\sim 20$ km at middle to high latitudes. Wave amplitudes in the northern hemisphere approach values twice as large as those in the southern hemisphere. Wave amplitudes are also closely related to mean zonal winds and are largest in regions of strongest eastward flow. There is a reduction in wave
amplitudes at the stratopause. No significant wave amplitudes are observed near the equator or in the strongly westward background winds of the atmosphere in summer. This behaviour is interpreted as a consequence of wave/mean-flow interactions. Perturbations in wave amplitude summer MLT are compared to those simultaneously observed in the winter stratosphere of the opposite hemisphere and found to have a correlation coefficient of +0.22, suggesting a small degrees of inter-hemispheric coupling. We interpret this to mean that some of the summer-time MLT wave may originate in the winter stratosphere of the opposite hemisphere and have been ducted across the equator. We do not observe a significant QBO modulation of the 16-day wave amplitude in the polar summer-time MLT. Wave amplitudes were also observed to be suppressed during the major sudden stratospheric warming events of the northern hemisphere winters of 2006 and 2009.

5.1.2 Introduction

Planetary waves with periods of $\sim 2–16$ days are an important component in the coupling between the lower and middle atmosphere. Planetary waves play a key role in the transport of energy, momentum and chemical species, both vertically and horizontally. The waves interact very strongly with the background winds of the atmosphere because their horizontal phase speeds tend to be similar to the wind speeds, thus promoting wave/mean-flow interactions. Planetary waves are also known to modulate the gravity-wave field of the middle atmosphere and consequently modulate the fluxes of gravity-wave energy and momentum that drives the entire global circulation of the upper middle atmosphere [e.g. 39, 40, 41, 42, 43]. These modulated gravity-wave momentum fluxes can result in planetary-wave signatures penetrating to the thermosphere [44].

Temperature perturbations caused by planetary waves also modulate the occurrence of Polar Mesospheric Clouds [e.g. 34, 35, 36, 37] and the associated phenomena of Polar Mesospheric Summer Echoes [38]. Studies of planetary waves are thus very important in the attempt to understand the coupling of the lower, middle and upper atmosphere.

A major class of planetary waves are the so-called normal modes, which have periods near 2, 5, 10 and 16 days [20, 21]. These waves can be generated in the lower atmosphere
and propagate from the troposphere into the stratosphere and the mesosphere and lower thermosphere (MLT).

In this paper we will consider the 16-day planetary wave. Salby [20] suggested on theoretical grounds that the 16-day planetary wave is a manifestation of the gravest symmetrical wavenumber 1, westward-travelling Rossby wave. The period of the 16-day wave has, in fact, been observed to lie between about 12–20 days. The wave has been reported to have wind amplitudes of up to about $\sim 15\text{ m s}^{-1}$ and temperature amplitudes reaching $\sim 10\text{ K}$ in the MLT [e.g. 56, 72, 85].

Previous studies of the 16-day wave have concentrated in particular on its manifestation in the MLT region. This seems to be partly because meteor and medium-frequency radars and airglow spectrometers are able to make extended measurements at these heights [e.g. 25, 72, 75, 77]. However, a number of modelling studies have suggested that the wave can also reach large amplitude in the stratosphere [e.g. 24, 72, 79].

These and other studies of the 16-day wave have reported a clear seasonal cycle in wave amplitudes in the MLT at middle and low latitudes. Largest wave amplitudes generally occur in the winter-time. However, a secondary maximum in the summer-time MLT is also sometimes observed [e.g., 26, 75, 76]. Lower polar-stratosphere studies of planetary-wave activity also report the 16-day wave in the winter-time with larger amplitudes in the northern hemisphere than the southern hemisphere [e.g. 31].

There have been only a limited number of studies of the 16-day planetary wave in the polar atmosphere [e.g. 24, 27, 56, 85]. These studies have also revealed a winter-time maximum in wave amplitudes and a weaker secondary maximum in summer.

The presence of the wave in winter is fully consistent with its having propagated upwards from sources in the lower atmosphere to the MLT. The propagation of a planetary wave in the atmosphere is controlled by the wave’s interaction with the background winds [63]. From Charney and Drazin theorem, in order to propagate vertically a planetary wave must obey $0 < \bar{u} - c_x < U_c$, where $\bar{u}$ is the zonal wind speed, $c_x$ is the zonal phase speed of the planetary wave at the latitude in question and $U_c$ is the critical Rossby speed. For example, the westward-propagating $s = 1$ 16-day wave at latitudes of 25, 50
and 75°, has phase speeds $c_x$ of -26, -19 and -8 m s$^{-1}$ respectively. The mean zonal wind speed, $\bar{u}$, must therefore be greater than -26, -19 and -8 m s$^{-1}$, respectively, for these three latitudes for the wave to propagate.

However, the summer-time 16-day wave reported in the MLT cannot have propagated upwards through the stratosphere to the MLT from source regions in the troposphere and lower stratosphere. This is because the zonal phase speed of the 16-day wave is less than the zonal winds of the middle atmosphere. To illustrate this, Fig. 5.1 presents the zonal phase speed of a 16-day wave as a function of latitude. Figure 5.2 presents for comparison climatological zonal winds from the UARS Reference Atmosphere Project (URAP) for the tabulated latitudes of 24°, 52° and 76° N. Also indicated on the figures are lines corresponding to the zonal phase speed of the 16-day wave at these latitudes. From Fig. 5.2 it can be seen that the wave cannot propagate above heights of about 32, 38 and 38 km, respectively in summer. However, the wave can propagate at MLT heights in summer where the zonal winds have increased to values that again allow propagation. In winter the zonal winds are strongly eastward at all latitudes and so the wave can propagate vertically through the entire depth of the atmosphere. There must therefore be a mechanism to explain the presence of the 16-day wave observed in the summer-time MLT. Two principal mechanisms have been proposed for the excitation of the summer-time 16-day wave in the MLT. These are:

![Figure 5.1: Zonal phase speed as a function of latitude for a 16-day wave of zonal wavenumber 1.](image-url)
1. *In situ* excitation has been suggested by Williams and Avery [56]. In this mechanism, gravity waves from the lower atmosphere propagate upwards, but are filtered by the 16-day wave in the upper troposphere and lower stratosphere, thus imposing a 16-day modulation on the field of ascending gravity waves. The gravity waves then dissipate and transfer their momentum and energy into the mean flow of the MLT, which in turn excites a 16-day wave *in situ*. Smith [86] observed this *in situ* forcing of planetary-scale disturbances due to variations in gravity-wave drag caused by stratospheric filtering. The modelling study by Smith [80] further showed that such a mechanism can produce significant planetary-wave amplitudes in the MLT, at least in the case of stationary planetary waves.

2. Cross-equatorial propagation has been suggested, where the winter-time wave crosses the equator to the summer hemisphere MLT at heights above the strong westward zonal mean flow of the summer-time middle atmosphere through which wave propagation is prohibited. This mechanism has been investigated in the modelling studies of Forbes et al. [72], Miyahara et al. [81].

Observational studies by Espy et al. [26], Hibbins et al. [27], Jacobi et al. [28], Jacobi [29] considered the cross-equatorial propagation mechanism and attributed year-to-year
fluctuations in the amplitude of the 16-day wave in the summer-time MLT to a modulation of the ducting process by the equatorial QBO. These authors proposed that the amplitude of the 16-day wave was greater in the middle- to high-latitude summer MLT during the eastward (westerly) phase of the QBO. This is because when the QBO is in the negative (easterly) phase the QBO winds in the middle atmosphere reduce the winds of the background circulation yielding a more westward total wind which, through Charney-Drazin theorem, prevents the cross-equator propagation of the wave. Note that here we are defining the QBO by the equatorial stratospheric zonal mean wind.

Finally, we should note that the amplitude of the 16-day wave and other planetary waves has been observed to be suppressed in the winter hemisphere after major SSW [e.g. 30, 31, 32, 33].

Here, we present observations of wave temperature amplitudes of the 16-day wave in the global atmosphere at heights of \(\sim 20-100\) km made using Aura Microwave Limb Sounder (MLS). The data set is about 7 years long, spanning the interval from August 2004 to December 2010. In the first part of this study we present a representative climatology of the 16-day wave. In the second part of the study we investigate the occurrence of the summer-time 16-day wave in the polar MLT and its connection to the winter stratosphere of the opposite hemisphere and the possible role of the QBO in modulating the amplitude of the wave in the summer-time MLT.

5.1.3 Data Analysis

Data from the MLS instrument on the NASA EOS Aura satellite are used in this study. Data have been recorded almost continuously since 15\textsuperscript{th} July 2004. Aura MLS is a limb-scanning emission microwave radiometer which measures radiation in the GHz and THz frequency range (millimetre and sub-millimetre wavelengths). The instrument measures the vertical profile of temperature in the middle atmosphere. Aura MLS provides daily global coverage. The satellite is in a high inclination, sun-synchronous orbit. It repeats the ground track every 16 days, providing atmospheric measurements over virtually the whole globe in a repeated pattern. The Limb instruments are designed to observe roughly
Chapter 5. *Results - The 16-day wave in the middle atmosphere*

along the orbit plane. MLS is on the front of Aura and so observes in a forward-velocity direction.

MLS temperatures from the Version 2.2 Temperature Analysis are used in this study. This version has data available from 8th August 2004 [52]. The data are recorded on 34 pressure levels ranging from \(316 - 0.001\) hPa \((\sim 10 - 96\) km\). The vertical resolution is \(7 - 8\) km from \(316 - 100\) hPa, \(4\) km at \(31 - 6.8\) hPa, \(6\) km at \(1\) hPa and \(9\) km above \(0.1\) hPa. We converted the pressure levels to approximate heights and will present the results as a function of this approximate height. This is done to facilitate comparisons with measurements made by ground-based radars.

The standard product for temperature is taken for the Core retrieval \((118\) GHz only\) from \(316\) to \(1.41\) hPa and from the Core+R2A \((118\) GHz and \(190\) GHz\) retrieval from \(1\) hPa to \(0.001\) hPa. The temperature precision is \(\sim \pm 1\) K from \(316\) - \(0.1\) hPa and degrades to \(\sim 3\) K at \(0.01\) hPa Schwartz et al. [9]. The data are assigned a “flag” to comment on the quality of the data. Quality is computed from a \(\chi^2\) statistic for all the radiances considered to have significantly affected the retrieved species, normalised by dividing by the number of radiances. Quality is simply the reciprocal of this statistic. Here, if the data have a quality flag of “0” then they are regarded as poor quality and not used in the analysis.

The 16-day planetary wave has been observed to occur with a wide range of periods between \(\sim 12\) to \(20\) days, as described in this chapter introduction section. Here, we will consider all planetary-scale wave fluctuations within the period range \(12\) to \(20\) day and of westward travelling wavenumber 1 to be attributable to the “16-day wave”. This range of periods has also been used in the majority of studies of the 16-day wave, [e.g. 25, 72, 77, 78, 79, 85]. Our results should thus be directly comparable with these other studies.

The least-square fitting method of Wu et al. [87] was used to calculate wave amplitudes. Wu et al. [87] discuss the advantages and disadvantages of the method in depth. This method has been used previously for Aura MLS temperature and geopotential data analysis [e.g. 88, 89, 90, 91]. The advantage of this method is that it can utilise a
non-uniform or irregular sampling pattern, but is less computationally intensive than alternative methods such as FFT or asynoptic transforms.

Here, the temperature data are sorted into 10° latitude bands and the least-squares fitting of a westward-propagating zonal wavenumber 1 wave is applied to the monthly data within each latitude band. The data are then gridded into 31 latitude bins, in steps of 5° from 75°N to 75°S. Wave periods of 12 – 20 days are fitted in hourly steps. The largest amplitude signal within this period range is then identified as the 16-day wave for a particular latitude band and month. For each height and latitude bin we have thus produced a time series of the temperature amplitude of the 16-day wave.

The error in the least-squares fit amplitude was calculated using the standard deviations on the least-squares periodic fitting of the data with a 95% confidence level. Figure 5.3 presents height-latitude contours of this error for the example months of January and July 2007 (not all years and months are shown for reasons of space). As can be seen the errors are generally 0.6 K or smaller and this was true for all months examined.

To investigate the role of the QBO in modulating the summer-time MLT 16-day wave, we considered monthly-mean equatorial zonal winds at 10 hPa. The QBO data product was obtained from Freie Univeristät Berlin (FUB)
This data set has been produced from the Singapore radiosonde data, January 1987 to December 2010.

5.1.4 Results

5.1.4.1 Climatology

In this section we will present a representative climatology of the 16-day wave. Firstly, we will consider the variation of wave amplitudes from year-to-year. Figure 5.4 presents the monthly-mean amplitude of the wave at a latitude of 60° for the northern and southern hemisphere. The height of the stratopause is indicated by a line on each figure. The approximate position of the stratopause, has been derived using a 4th order polynomial fit to the Aura temperature profile as per McDonald et al. [91].

From the figure it can be seen that there is a clear seasonal cycle in wave amplitude that approximately repeats from year to year. In particular, the wave amplitude maximises in winter and has a minimum in summer, but with small amplitudes present in the MLT for most years observed. There is considerable inter-annual variability evident. For example, in most of the winters the peak northern-hemisphere wave amplitudes were ∼6 K, but is still weakly present in the summer at the greater heights. The wave is generally present throughout the year at heights greater than about 80 km where it can reach up to ∼3 K in the northern summer-time.

Wave amplitudes in the southern hemisphere are generally smaller than in the northern hemisphere, but occasionally reach up to ∼6 K in the winter-time, i.e., August 2008. This wave, as in the northern hemisphere, is also present throughout most of the year at greater heights. Finally, it can be seen that there is often a local minimum in winter-time wave amplitude around the stratopause.

To investigate the seasonal structure of the wave further, Figure 5.5 presents the monthly-mean wave amplitude in the MLT (65 – 95 km) as a function of latitude for 2005. The figure reveals that wave amplitudes have an equatorial minimum in all months. Around
Chapter 5. Results - The 16-day wave in the middle atmosphere

Figure 5.4: Time series of monthly-mean temperature amplitudes from 2004 to 2010 for the 16-day wave at a latitude 60° for both hemispheres. Also plotted is the stratopause height as a red contour line.

The equinoxes the wave is simultaneously present in both hemispheres and maximises at latitudes of ~60°. Near the solstices, the wave is largely confined to the winter hemisphere and appears much reduced in the summer hemisphere. It is notable that, despite the largest amplitudes occurring in the winter hemisphere, there is still small but some small wave amplitudes in summer, e.g., in the southern hemisphere in December and February and in the northern hemisphere in August. Similar behaviour is observed for other years of data (not shown for reasons of space).

The seasonal and long-term variability suggested above can be investigated further by considering latitude-height contour plots of monthly-mean wave amplitude. An example representative year of this analysis is presented here in Fig. 5.6. Figure 5.6 shows the monthly-mean Aura temperature amplitudes for 2005, with monthly-mean UKMO zonal wind contours and the stratopause height over plotted.

The summer-time wave can be seen to maximise in August and December for the northern and souther hemisphere respectively at MLT heights of ~80–100 km. The winter-time wave in both hemispheres maximises in both the stratosphere and the MLT, polewards of ~25° latitude. The stratopause height, plotted in red on Fig. 5.6 generally shows the separation between the stratosphere and MLT maxima. Amplitudes are generally greater in the northern hemisphere reaching ~6 K c.f. ~4 K in the southern
Figure 5.5: The monthly-mean temperature amplitude of the 16-day wave as a function of latitude at heights of $\sim 65 - 95$ km for 2005.

The tendency for wave amplitudes to decrease at heights above $\sim 80$ km was also reported in the radar studies of the polar MLT 16-day wave by Day and Mitchell [85].

Larger temperature wave amplitudes correspond to stronger zonal winds, as can be seen in Fig. 5.6. For example, in January and December northern hemisphere the amplitudes reach $\sim 6$ K where the winds exceed $50 \text{m s}^{-1}$.

In the summer hemisphere the wave is largely absent. However, some wave activity is
Figure 5.6: Monthly-mean temperature amplitudes of the 16-day wave for 2005. Also plotted are the 2005 UKMO monthly-mean zonal winds (m s$^{-1}$) as contour lines and the stratopause height as a red contour line.

present at heights above $\sim 80$ km at middle and high latitudes and also at heights below the stratopause at high latitudes. With regard to these observations of the 16-day wave below the stratopause, we note that Williams and Avery [56] also reported significant wave amplitudes at heights below 30 km throughout most of the year measured at Poker Flat (65°N).
Chapter 5. *Results - The 16-day wave in the middle atmosphere*

Figure 5.7: Composite-month temperature amplitudes for the 16-day wave in each month of the year, August 2004 – May 2010. Also plotted are the UKMO composite monthly-mean zonal winds (m s\(^{-1}\)) as contour lines and the stratopause height as a red contour line.

The regular seasonal cycle present in Figs. 5.4, 5.5 and 5.6 means that a composite-month analysis can be used to reveal a representative seasonal behaviour. Figure 5.7 presents the 12 composite months of the entire seasonal cycle. In each month the data from all years of observation have been averaged. Also plotted on the figure are the monthly-mean zonal winds from the UKMO climatology and the approximate stratopause height derived from the Aura MLS temperatures (as above). Note that the Aura and UKMO data are coincident in time, making comparisons of climatological average behaviour possible.

From the figure it can be seen that:

1. Wave amplitudes are largest in the winter hemisphere and are larger in the northern hemisphere than the southern hemisphere.

2. Stratospheric wave amplitudes in winter tend to maximise at the heights and latitudes where the zonal winds are the most strongly eastward. For example, in December the strongest zonal winds of \(\sim 50\) m s\(^{-1}\) occur at a latitude of \(\sim 55^\circ\)N and a height of \(\sim 45\) km which coincides with the largest-amplitude occurrence of the wave. Similar behaviour in the stratosphere can be seen in all months.
3. The wave is usually less than 1 K in amplitude in regions of westward zonal wind, which accounts for the wave’s absence in the summer stratosphere and lower mesosphere.

4. Throughout the year the largest wave amplitudes tend to occur at latitudes near 60°.

5. In all months the wave amplitudes are usually very small at the equatorial latitudes.

6. In most months of winter, spring and autumn there is a minimum in wave amplitude around the stratopause.

7. In most summer months in both hemispheres small but significant wave amplitudes are evident in the upper mesosphere and lower stratosphere (above and below the region of strong westward winds).

8. Near the equinoxes, the wave is present in both hemispheres simultaneously. At these times the zonal winds are either eastward or weakly westward in both hemispheres.

5.1.4.2 Inter-annual variability

The above results show that there is considerable inter-annual variability in the observed amplitude of the wave. We will now consider three particular aspects of this variability. The first is to investigate the suggestion that the wave observed in the summer-time MLT has been ducted across the equator from the stratosphere of the winter hemisphere and so might display a correlation in wave amplitude between the two regions. The second is to investigate the observationally-based suggestion that the amplitude of the wave in the summer-time MLT varies from year to year in response to a filtering effect caused by the winds of the equatorial QBO (a mechanism that, of course, requires that the summer-time wave is actually being ducted from the winter hemisphere). The third aspect investigated is the suggestion that major sudden stratospheric warmings (SSWs) have a suppressing effect on the wave amplitudes (See this chapter introduction section).
Firstly, we will consider the relationship between the wave amplitudes observed simultaneously in the summer-time MLT and the winter stratosphere. If the summer-time wave is indeed ducted across from the winter hemisphere, then we might expect a correlation between wave amplitudes in the two regions. Examination of the amplitudes can thus provide a simple test of this ducting hypothesis. To carry out the test, we calculated wave amplitudes for each month as an average amplitude measured within a representative height-latitude “box” covering, i) heights of 80–96 km and latitudes of 50–75° to represent the summer MLT at the heights where radar and satellite observations show the wave to reach maximum amplitude, and ii) heights of 35–45 km and latitudes of 50–75° for the winter stratosphere. This process allows a simple measure of wave amplitude to be estimated for each region for each month.

For each summer month we calculated the mean amplitude in the MLT and stratospheric boxes. For each, we then subtracted the average amplitude observed for that month over the entire data set yielding amplitude perturbations for each month in each year. We then correlated these perturbations for each summer season to see if, for example, larger than average amplitudes in the winter stratosphere were accompanied by larger than average amplitudes in the mesosphere of the opposite hemisphere.

Figure 5.8 presents the monthly-mean summer-time MLT wave amplitude perturbations for the northern hemisphere plotted against the simultaneously-observed winter stratospheric amplitude perturbations for the months of June, July and August. The correlation between the two regions is +0.17, suggesting that there is a small connection between the amplitude of the wave in the two regions.

Figure 5.9 presents an identical analysis for the summer months of December - February in the southern hemisphere. Here the correlation is +0.29, suggesting that there is a small connection between wave amplitudes in the two regions.

Further, the correlation between the perturbations in monthly-mean amplitudes in the two regions for all of the summer months (irrespective of hemisphere, i.e. all summer MLT c.f. all winter stratosphere) is calculated to be +0.22, suggesting that there is a small correlation between the amplitude of the wave in the two regions.
The second aspect of inter-annual variability that we investigated is the suggestion that the summer-time wave amplitudes are influenced by the phase of the QBO such that larger summer-time wave amplitudes occur when the QBO winds are eastward. A simplistic but clear method to test for a possible QBO modulation is to sort the MLT summer-time wave amplitudes by the phase of the QBO. Here we used QBO winds at a height of 10 hPa calculated from the FUB database. This measure of QBO winds is used because it enables direct comparison with the results of Espy et al. [26], Hibbins et al. [27], although we also examined how the results varied using winds for pressure levels
between 70 and 10 hPa. The wave amplitudes were calculated in “boxes”, as described above for the summertime MLT.

Figure 5.10: Mean summer-time temperature amplitudes of the 16-day wave in the MLT at heights from $\sim 80 - 96$ km and latitudes of $50 - 75^\circ$ N as a function of QBO zonal winds at 10 hPa.

Figure 5.11: Mean summer-time temperature amplitudes of the 16-day wave in the MLT at heights from $\sim 80 - 96$ km and latitudes of $50 - 75^\circ$ S as a function of QBO zonal winds at 10 hPa.

Figure 5.10 presents the monthly-mean wave amplitudes plotted against the corresponding QBO winds at 10 hPa for the northern hemisphere. Considering each month in turn, and averaging the wave amplitudes measured in the same month in different years
for which the phase of the QBO is the same, the mean wave amplitudes for the eastward and westward phases of the QBO, respectively, are 0.86 K and 0.71 K for June, 0.61 K and 0.68 K for July, 1.67 K and 1.19 K for August. The seasonal means for the amplitudes sorted by QBO phase are $1.17 \pm 0.19$ K for the eastward phase of the QBO and $0.86 \pm 0.09$ K for the westward phase (the uncertainty being the standard error on the mean). From these results we conclude that in the northern hemisphere there was no significant difference in the amplitude of the summertime mesospheric 16-day wave between eastward and westward phases of the QBO in the years 2004–2010.

Figure 5.11 presents an identical analysis applied to data from the southern hemisphere. This analysis yields mean amplitudes for eastward phase and westward phases of the QBO, respectively, of 0.95 K and 0.93 K for December, 0.73 K and 0.93 K for January and 1.13 K and 1.46 K for February. The seasonal means sorted by QBO phase are $0.94 \pm 0.14$ K for the eastward phase of the QBO and $1.11 \pm 0.10$ K for the westward phase. This might suggest a small but significant tendency for larger summer-time MLT amplitudes to occur during westward phases of the 10 hPa QBO (i.e, opposite to the results of Espy et al. [26]). However, for reasons we will explore below, we believe that in February 2006 and February 2009 the amplitude of the 16-day wave in the northern hemisphere throughout the stratosphere and MLT was suppressed by the influence of a major SSW that occurred there in the previous month. On the assumption that reduced wave amplitudes in the winter hemisphere would in turn lead to reduced amplitudes in any wave observed in the summer MLT after being ducted across the equator, we therefore recalculated the seasonal mean amplitudes with February 2006 and 2009 removed. In this case, the seasonal-mean MLT wave amplitudes become $0.98 \pm 0.16$ K for the eastward phase of the QBO and $1.05 \pm 0.08$ K for the westward phase - not significantly different.

Considering the above analysis, we therefore conclude that the observations we have presented do not demonstrate a significant modulation of the amplitude of the summertime MLT 16-day wave by the equatorial QBO winds (note that we also explored the impact on the analysis of sorting the amplitudes by the phase of the QBO winds at different pressure levels, but found this did not significantly change this conclusion).
Finally, as mentioned, we note that two major SSW occurred in the northern hemisphere in January 2006 and January 2009 (a major warming being defined as a reversal of the winds at 10 hPa at a latitude of 60°). It is known that major SSW can have dampering effect on planetary waves at high latitudes. In particular, it has been observed that planetary-wave amplitudes can be suppressed after major SSW events [e.g. 31]. If the ducting hypothesis is correct, then the MLT summer-time wave originates in the winter hemisphere and so any changes in wave amplitude due to major SSW may be reflected in reduced wave amplitudes in the summer MLT of the opposite hemisphere.

To see if such effects are present in our analysis, we examined the UKMO stratospheric winds and temperatures at 10 hPa to characterise the two major SSW. Figure 5.12 presents contours of these zonal-mean winds and temperatures for the six northern-hemisphere winters observed (the southern hemisphere is not considered because no major SSW occurred there during the observations). From the figure it can be seen that in January 2006 and 2009, the zonal winds reversed and temperatures increased considerably.

Figure 5.13 presents the sequence of wave amplitudes, UKMO background winds and stratopause heights for January in the successive years observed. From the figure it can be seen that, although wave amplitudes are not particularly high in the winter hemisphere in January of 2006 and 2009, they are at least comparable to those in January of 2007 and 2008.

Figure 5.14 presents an identical treatment of the successive Februarys observed. In this case, however, it can be seen that wave amplitudes in the winter hemisphere in 2006 and 2009 were reduced to about half compared to the other years. Using the same analysis as above, the wave amplitudes in the winter hemisphere stratospheric “box” were 1.5 K and 2.3 K in 2006 and 2009, compared with 4.7, 6.1, 9.9 and 3.4 K in 2005, 2007, 2008 and 2010. We therefore conclude that, at least for the two major SSW observed, the stratospheric wave amplitudes in the winter hemisphere were significantly reduced in the month following a major SSW.
5.1.5 Discussion

The seasonal variability of wave amplitudes described above can be compared with those reported by ground based observations made at particular latitudes. The majority of these studies report the wave in the MLT. Ground-based studies include e.g. Luo et al. [24], Hibbins et al. [27], Jacobi [29], Espy and Witt [35], Williams and Avery [56], Mitchell et al. [75], Luo et al. [76, 77], Day and Mitchell [85]. Only some of
these studies measured temperatures, including Espy and Witt [35] and Espy et al. [26] who used a Michelson interferometer to measure OH rotational temperatures near the mesopause over Stockholm (60°N). They observed the 16-day wave and reported MLT temperature amplitudes of up to 5 K. Day and Mitchell [85] used a meteor radar to measure temperatures in the polar mesosphere over Esrange (68°N) and Rothera (68°S).
They reported instantaneous temperature amplitudes of up to 10 K in winter and 5 K in summer. These reported summer-time temperature amplitudes are larger than those presented here measured by Aura MLS. However, this difference is very likely because these studies reported temperature amplitude related to short-lived maxima, whereas our results are based on monthly means.
A number of modelling studies have examined the 16-day wave in the middle atmosphere. Luo et al. [24], Forbes et al. [72], Miyoshi [79] used a variety of different models and reported significant wave amplitudes present in both the stratosphere and MLT of the winter hemisphere. All show an approximately similar latitudinal structure with maximum amplitudes occurring at middle to high latitudes. However, wave amplitude is either absent or significantly reduced in the summer in all three models, (see below for further discussion).

As noted earlier, the 16-day wave is largely absent (less than 1 K in amplitude) from the summer-time middle atmosphere. However, there are two relatively restricted regions of the summer-time atmosphere where wave activity is nevertheless present in our observations.

The first of these is in the lower stratosphere at middle and high latitudes. We suggest that the presence of the wave here is because the zonal background winds are less than the zonal phase speed for a particular latitude and the wave is thus trapped below this height, but free to propagate below. Similar behaviour is observed in the northern hemisphere in June-August. The ground-based observations of Williams and Avery [56] made by a Mesosphere-Stratosphere-Troposphere (MST) radar at Poker Flat (65°N) reported significant wave activity around the summer tropopause, reinforcing the suggestion that the wave is present in the lower stratosphere in summer. The models of Forbes et al. [72], Miyoshi [79] also indicate small but significant wave activity in the high-latitude summer-time lower stratosphere. This wave activity most likely arises because the zonal winds of this region of the atmosphere are not sufficiently strong to prevent the wave from propagating.

The second region where the wave is observed in summer is in the MLT at heights above those where the zonal wind speed is likely to be greater than the zonal phase speed.

As discussed earlier, the 16-day summer-time wave cannot have propagated upward through the atmosphere to the MLT where we observe it because its propagation would be prevented by the blocking effect of the zonal background wind. To explain the observations of a summer-time MLT 16-day wave it has been hypothesised that the wave must have been cross-equatorially ducted [e.g. 26, 27, 29, 76].
Our results for the correlation of perturbations around the mean wave amplitude between the summer-time MLT wave and that of the winter stratospheric wave in the opposite hemisphere reveal a small correlation, suggesting that larger wave amplitude in the winter stratosphere are accompanied by larger wave amplitudes in the summer hemisphere. This may suggest that there is some degree of ducting from the winter stratosphere to the summer MLT, since if there were no ducting we might expect no correlation. However, the fact that the correlation is small suggest that there may be other sources of excitation of the wave in the summer-time MLT.

Our results suggest that there is no significant QBO modulation of 16-day wave amplitudes in the summer-time MLT. However, such a modulation has been reported in some studies [e.g. 26, 27]. One possible explanation for this discrepancy is that any such modulation is intermittent and not a persistent feature of the MLT. Support of this suggestion comes from the long-term studies of Luo et al. [76] who reported 16 years of MF radar data recorded at Saskatoon (52°N). Luo et al. [76] observed the presence of the 16-day wave in the summer-time MLT. They showed that the wave activity appeared to be modulated by the QBO, but only in some years and only in some months. This suggests that any QBO modulation may be intermittent in nature and this may be why the QBO modulation is not observed in our data set.

Finally, our observation of reduced wave amplitudes immediately after the major SSW events of 2006 and 2009 is in good agreement with the similar observation reported by Alexander and Shepherd [31] for 2006.

5.1.6 Conclusions

The 16-day wave is a persistent, large-amplitude feature of the winter stratosphere and MLT – at least in the seven years of observations reported here. Monthly-mean wave amplitudes exceed 6 K in most northern winters and 4 K in most southern winters. Large wave amplitudes are confined to latitudes poleward of $\sim 25^\circ$. Smaller wave amplitudes are nevertheless observed in both hemispheres in the summer months, where they reach $\sim 3$ K. Summer-time wave amplitudes are observed at heights up to $\sim 30$ km in the lower stratosphere and again at heights above $\sim 70$ km in the MLT. This behaviour is
interpreted as a consequence of wave/mean-flow interactions. The wave in the summertime MLT can therefore not have propagated from below.

There is a small correlation between the perturbations in wave amplitude of the summertime MLT and the winter stratosphere of the opposite hemisphere. This suggest some degree of inter hemispheric coupling and perhaps ducting of the wave from winter to summer hemisphere.

Our observations do not suggest that the QBO modulates the amplitude of the wave in the polar summer-time MLT. The absence of such a QBO modulation maybe a consequence of our comparatively short data set or an intermittency in the modulation.

The major SSW events of the northern hemisphere winter of 2006 and 2009 have an influence on the winter-time wave amplitudes following the warming, in which they decrease wave amplitudes to values of about half of those observed in undisturbed years.
Chapter 6

Results - Mean winds, temperatures and the 16- & 5-day planetary waves over Bear Lake Observatory

6.1 Mean winds, temperatures and the 16- and 5-day planetary waves in the mesosphere and lower thermosphere over Bear Lake Observatory (42°N 111°W)

6.1.1 Abstract

Atmospheric temperatures and winds in the mesosphere and lower thermosphere have been measured simultaneously using the Aura satellite and a meteor radar at Bear Lake Observatory (42°N, 111°W). The data presented in this study is from the interval March 2008 to July 2011.

The mean winds observed in the summer-time over Bear Lake Observatory show the meridional winds to be equatorward at all heights during April-August and to reach
monthly-mean speeds of -12 m s\(^{-1}\). The mean winds are closely related to temperatures in this region of the atmosphere and in the summer the coldest mesospheric temperatures occur about two weeks after the strongest equatorward meridional winds. The zonal winds are eastward through most of the year and in the summer strong eastward zonal wind shears of up to \(\sim 4.5 \text{ m s}^{-1} \text{ km}^{-1}\) are present. However, westward winds are observed at the upper heights in winter and sometimes during the equinoxes. Considerable inter-annual variability is observed in the mean winds and temperatures.

Comparisons of the observed winds with URAP and HWM-07 reveal some significant differences. Our radar zonal wind observations are generally more weakly eastward than these predicted by the URAP model zonal winds. Considering the radar meridional winds, in comparison to the HWM-07 our observations reveals equatorward flow at all heights in the summer whereas HWM-07 suggests that only weakly equatorward, or even poleward, flows occur at the lower heights. However, the zonal winds observed by the radar and modelled by HWM-07 are generally similar in structure and strength.

Signatures of the 16- and 5-day planetary waves are clearly evident in both the radar-wind data and Aura-temperature. Short-lived wave events can reach large amplitudes of up to \(\sim 15 \text{ m s}^{-1}\) and 8 K and 20 m s\(^{-1}\) and 10 K for the 16- and 5-day wave, respectively. A clear seasonal and short-term variability are observed in the 16- and 5-day planetary wave amplitudes. The 16-day wave reaches largest amplitude in winter and is also present in summer, but with smaller amplitudes. The 5-day wave reaches largest amplitude in winter and in late summer. An inter-annual variability of the amplitude of the planetary waves are evident in the four years of observations. Some 32 episodes of large-amplitude wave occurrence are investigated and the temperature and wind amplitudes, \(A_T\) and \(A_W\), are found to be related by, \(A_T = 0.49 A_W\) and \(A_T = 0.58 A_W\) for the 16- and 5-day wave, respectively.

### 6.1.2 Introduction

Ground-based meteor and MF radars are able to make continuous observations of winds in the Mesosphere and Lower Thermosphere (MLT) and have thus been extensively used to study the background winds and planetary waves of the MLT.
Previous ground-based observations have been made at Bear Lake Observatory (BLO) using an Imaging Doppler Instrument (IDI) to observe MLT mean winds and planetary waves. Berkey et al. [92] presented results from February 1999 to April 2000. The mean meridional mean winds were found to be strongest at heights of $\sim 90$ km in mid-winter reaching $\sim 15$ m s$^{-1}$. The zonal mean winds were found to be westward in late spring to early summer, reaching speeds of $\sim 25$ m s$^{-1}$. They additionally observed planetary waves, in particular a 16- and 5–6-day wave were evident.

Jones et al. [93] compared four months of IDI measurements with those made by a meteor wind radar at the same site. It was concluded that there was overall very good agreement between the two techniques. In addition, they noted the presence of long-period planetary waves in mid-late February. Note this meteor radar was operated at BLO for a relatively short deployment and is not the same instrument now permanently sited there.

Roper and Berkey [94] reported observations of mean winds, gravity waves and turbulence for the year 2000 made at BLO by the IDI. It was observed that the zonal winds maximised in summer at speeds of $\sim 35$ m s$^{-1}$ and reduced in the spring to speeds of $\sim 10$ m s$^{-1}$. The meridional winds were observed to be nearly continuously equatorward, expect for a very short-lived region at the upper heights in April and May.

Further studies at similar latitudes in the USA and Canada include those of Manson et al. [14], Luo et al. [77], who used MF radars to investigate the planetary-wave field in the MLT and reported a strong seasonal variability.

The Brewer Dobson large-scale circulation of winds drives the upwelling of cold air over the northern polar region in northern summer. This circulation thus implies an intimate connection between the mean temperatures and the mean meridional winds of the MLT region. A limited number of observational studies have investigated the connection between these winds and temperatures. Further, it has been suggested that short-term perturbations in the meridional winds result in related short-term perturbations in temperature. For example, polar observations by Espy et al. [95] revealed a clear correlation between meridional winds and temperatures over Rothera ($68^\circ$S, $68^\circ$W) and Halley ($76^\circ$S, $27^\circ$W) in a study made using an MF radar and OH rotational temperatures.
in Austral winters. Cho et al. [96] reported meteor-radar and OH airglow observations of meridional winds and temperatures in the Arctic MLT over Resolute Bay (74°N, 95°W) and Esrange (68°N, 21°E). They observed a positive correlation between the mean meridional winds and temperatures that is consistent with the large-scale circulation.

In contrast, Jacobi et al. [97] measured meridional winds and temperatures in the MLT over Collm (51°N, 13°E) using a meteor radar. They considered time-scales of up to one month and reported that they did not observe a correlation between the meridional winds and temperatures in the summer, but did observe a positive correlation in the winter.

Significant meridional winds have been reported in the summer-time MLT at polar latitudes [e.g., 98, 99], midlatitudes [e.g., 94, 100, 101] and equatorial latitudes [e.g., 102, 103, 104].

At middle latitudes the characteristics of the meridional and zonal mean winds and temperatures of the MLT have been investigated using ground-based and satellite data. The meridional winds of the MLT are particularly important because they play a key role in transporting air from the summer polar MLT into the winter polar stratosphere, [e.g., 105, 106]. Ultimately, diabatic subsidence transports some of the meteor smoke particles carried by this circulation down into the lower stratosphere, where they may influence ozone and, potentially, climate, [e.g., 107, 108].

Planetary waves are a major feature in the dynamics of the middle atmosphere. In the MLT they can reach large amplitudes and are important because they can modulate the amplitude of atmospheric tides [e.g., 73, 109, 110, 111], influence the transport and photochemistry of minor species [e.g., 112], modulate the fluxes of gravity-wave momentum that drives the planetary-scale circulation of the upper middle atmosphere [e.g., 39, 40, 41, 42, 43] and cause perturbations in temperatures that can modulate the occurrence of Polar Mesospheric Clouds [e.g., 34, 35, 37, 113] and Polar Mesospheric Summer Echoes [e.g., 38]. A major component of the planetary-wave field in the MLT is the so-called normal modes that manifest as the 2-, 5-, 10- and 16-day planetary waves [e.g., 20, 21].
Salby [20] suggested on theoretical grounds that the 16- and 5-day planetary waves are manifestations of the gravest symmetrical wavenumber 1, westward-travelling Rossby wave. The period of the 16- and 5-day wave has, in fact, been observed to lie between about 12 – 20 days and 4 – 7 day, respectively. The 16-day wave has been reported to have wind amplitudes of up to about $\sim 15 \, \text{m s}^{-1}$ and temperature amplitudes reaching $\sim 10 \, \text{K}$ in the MLT [e.g. 56, 72, 85]. The 5-day wave has been reported to have wind amplitudes of up to about $\sim 20 \, \text{m s}^{-1}$ and temperature amplitudes reaching $\sim 15 \, \text{K}$ in the MLT [e.g. 56, 58, 82].

This study considers near-continuous observations of MLT winds and temperatures made over a 41-month interval using a meteor radar at BLO and the Aura Microwave Limb Sounder (MLS), respectively. The first focus of the study is to establish a climatology of mean winds over BLO at heights of about 80 – 100 km and to relate this to the seasonal variation in temperature. This is compared to the URAP and the HWM-07 models. Secondly, a representative climatology of the 16- and 5-day waves over BLO measured by simultaneous meteor radar winds and Aura MLS temperatures is presented. These data are used to investigate the relative magnitude of the wind and temperature perturbations caused by each wave. The two day wave will be the subject of a separate study. Note that here we will not consider the atmospheric tides or long-term variability of the mean winds and planetary waves. These subjects will be considered in subsequent publications.

### 6.1.3 Data Analysis

The winds used in this study were measured by a meteor radar located at BLO, near Logan, Utah, in the USA (42°N, 111°W) installed in March 2008. The radar is a standard all-sky, SKiYMET VHF system operating at a radio frequency of 32.5 MHz, with a pulse repetition of 2144 Hz and a peak power of 6 kW. The interferometer arrangement of radars consists of six crossed-element Yagi antenna, five receiving and one transmitting. More than 95% of meteor echoes are detected at heights between 80 – 100 km. The radar typically records $\sim 4000$ meteors a day. Only underdense echoes are recorded. A more complete description of a very similar radar design can be found in Hocking et al. [46].
Chapter 6. Results - Mean winds, temperatures and the 16- and 5-day planetary waves over Bear Lake Observatory

The radar data were used to estimate zonal and meridional winds with a time step of 1 hour at heights between \( \sim 80-100 \) km. This height range was divided into six independent height-gates of depth 5, 3, 3, 3, 3, 5 km. However, the vertical distribution of meteor echoes maximises at a height near 90 km and the meteor counts decrease strongly above and below this height. To allow for this, in each height gate the average meteor echo height was calculated yielding heights of 80.8, 84.7, 87.5, 90.4, 93.3 and 97.1 km as the weighted mean height of the six height gates. The radar data set thus consists of hourly-spaced zonal and meridional winds in six height gates.

These local measurements of wind were complemented by estimates of temperature measured by Aura MLS. Aura MLS Version 2.2 Temperature Analysis was used in this study. MLS observations commenced from early August 2004 [52]. The data are recorded on 34 pressure levels, 316–0.001 hPa (\( \sim 10-96 \) km). The vertical resolution is 7–8 km at 316–100 hPa, 4 km at 31–6.8 hPa, 6 km at 1 hPa and 9 km above 0.1 hPa. For this study the pressure levels were converted to approximate heights for comparisons with the meteor radar measurements.

The standard product for temperature was taken for the Core retrieval (118 GHz only) from 316–1.41 hPa and from the Core+R2A (118 and 190 GHz) retrieval from 1–0.001 hPa. The temperature precision is \( \sim \pm 1 \) K from 316–0.1 hPa and degrades to \( \sim 3 \) K at 0.01 hPa Schwartz et al. [9]. The data are assigned a “flag” commenting on the quality of the data. The quality comment is computed from a \( \chi^2 \) statistic for all the radiances that are considered to have significantly affected the retrieved species and then normalised by dividing by the number of radiances. The quality flag is simply the reciprocal of this statistic. Data that have a quality flag of “0” they are regarded as poor quality and therefore discarded.

6.1.4 Results

6.1.4.1 Seasonal mean winds and temperatures

This section presents the climatology of the mean winds and temperatures in the MLT over BLO. The climatological winds are then compared with the predicted winds from
the UARS (URAP) and the HWM-07 models. To investigate the behaviour and characteristics of the background winds over BLO monthly-mean mean zonal and meridional winds were calculated for each month and height gate.

Firstly, we will consider the mean meridional winds and temperatures and examine how they are related. Figure 6.1 shows the monthly-mean meridional winds for each individual year and also a composite-year. Note that the monthly-mean values may mask any short-term perturbations. Plotted below each meridional wind plot is the corresponding temperature plot. MLS temperatures were calculated as 14-day means.

**Figure 6.1:** Monthly-mean meridional winds over BLO and 14 day Aura MLS temperatures. The zero wind contour is indicated in black and the white contours are in steps of 2 m s$^{-1}$. The temperatures are means for a latitude/longitude “box” of 40–45°N, 90–120°W for four height gates between ∼81–97 km. The black vertical lines on the temperature plots indicate time of minimum meridional winds.
Chapter 6. Results - Mean winds, temperatures and the 16- and 5-day planetary waves over Bear Lake Observatory

Figure 6.2: Monthly-mean zonal winds and the zonally averaged composite-year monthly-mean zonal URAP winds over BLO. The zero wind contour is indicated in black and the white contours are in steps of 5 m s$^{-1}$.

for the height gates centred on 81, 86, 91 and 97 km to allow a comparison with the meridional winds. The temperatures are means for a latitude/longitude “box” of 40–45°N, 90–120°W for four the height gates between on ∼81–97 km.

The figure reveals a clear seasonal cycle in which the meridional winds are equatorward (negative) in the summer and poleward (positive) in the winter. The meridional winds are generally equatorward from April–September at all heights observed by the radar. The flow is generally strongest at heights of ∼85 km, regularly reaching speeds of ∼12 m s$^{-1}$. In contrast, the winter-time flow is poleward and strongest in the upper heights. The strongest poleward flows are generally observed in early–mid winter reaching speeds of ∼12 m s$^{-1}$ in most years. In the late winter the winds maximise again, but at slightly lower heights of ∼83 km, reaching speeds of ∼6 m s$^{-1}$. However, we should note monthly-means can hide short-term fluctuations in the mean winds.

The figure also reveals a high degree of inter-annual variability. For instance, if we consider the winds in summer we find that the strongest equatorward flows occurred in May in 2008 but in June in 2009, 2010 and 2011. We also note that the strongest equatorward flows peak at heights near 85 km in all years, except in 2010 when a region of strong flow existed at heights of above 85 km in May. Further, the winter flow is not
consistently poleward throughout the season, for example, in January 2011 the winds reverse and are equatorward reaching speeds of \(-4\,\text{m}\,\text{s}^{-1}\).

To compare the meridional winds with the temperatures, the temperature plots are marked with a vertical line where the strongest equatorward winds occurred (two lines are shown for 2010 because the winds had two distinct episodes of maximum flow). It can be seen that the temperature minima in most cases lag the corresponding meridional wind minima (i.e., time of strongest equatorward flow) by about two weeks. For example, in 2008 the strongest equatorward winds occur in May whereas the coldest temperatures occur in early June. This behaviour is also apparent in the composite-year plots of the mean winds and temperatures. However, we did not observe a link between the strength of the mean meridional winds and temperatures.

A similar mean-wind analysis was used to produce Fig. 6.2, which shows the monthly-mean zonal winds for each individual year, a composite year and also the composite-year URAP zonally-averaged monthly-mean zonal winds.

The figure shows a well-defined seasonal cycle in monthly-mean zonal winds. Eastward flow occurs throughout the summer and through most of the winter except at the uppermost heights observed in winter and during late spring/early summer. The summer-time zonal winds maximise at heights of \(\sim 93\,\text{km}\) with wind speeds reaching up to \(\sim 40\,\text{m}\,\text{s}^{-1}\). Above and below these heights the wind speeds decrease. In the winter the zonal winds generally maximise at the lowest heights observed, at \(\sim 83\,\text{km}\) with winds reaching up to \(\sim 30\,\text{m}\,\text{s}^{-1}\). There is a minimum observed at the equinoxes. In two of the four years (2009 and 2010) the winds actually reverse at all heights near the spring equinox.

Some inter-annual variability is evident from the figure. Considering the winds in summer, we find that the strongest eastward flows occurred every June and peak at heights of \(\sim 93\,\text{km}\). However, the duration of these strongly eastward winds varies from year-to-year. For example, in 2008, 2009 and 2011 the winds are strongly eastward from May–August and reach speeds of \(\sim 35\,\text{m}\,\text{s}^{-1}\), whereas in 2010 the winds are strongly eastward from May–July and reach rather stronger speeds of \(\sim 45\,\text{m}\,\text{s}^{-1}\). The spring equinoctial flow in 2009 and 2010 is strongly westward at all heights observed, reaching speeds of \(\sim -20\,\text{m}\,\text{s}^{-1}\). In contrast, in 2008 and 2011 the westward flow is significantly
weaker or even absent around the spring equinox. In these two years the strongest winds reach only speeds of \( -5 \, \text{m} \, \text{s}^{-1} \) and are restricted to the lower heights, below \( \sim 85 \, \text{km} \).

### 6.1.4.2 Comparison with URAP and HWM-07

The URAP model uses measurements from the Upper Atmosphere Research Satellite (UARS), the High Resolution Doppler Instrument (HRDI) and the UK Met Office Stratospheric data assimilation system. See Swinbank and Ortland [114] for more details. The data have been used to produce a composite-year analysis of the monthly-mean zonally-averaged zonal winds. The monthly data are available from November 1991 to November 1999 at heights of \( \sim 0 – 118 \, \text{km} \) and at latitudes of \(-80 – 80^\circ\). Note that although this data set does not overlap in time with that of the radar and uses zonal rather than local averages, it nevertheless can be used to provide a useful comparison. The URAP model is used as it is an empirical model of global coverage.

Comparing the zonal wind composite-year from our radar with the URAP model reveals some significant differences. The zonal winds are generally stronger in the URAP model. A striking difference is that the deep region of westward flow following the spring equinox is not well represented in the URAP model. Further, the winds in winter are significantly stronger in URAP than those observed and do not reverse at any height, whereas our observations suggest the winter zonal winds often reverse at heights between 90 – 95 km. We will consider possible explanations for this in Section 4. Considering the difference years observed by the radar and the composite-year URAP monthly-mean zonal winds we see that they are most similar in the years 2008 and 2011, where for example, there is no spring equinox reversal observed across the entire height range.

The HWM-07 model predicts both meridional and zonal winds using assimilated ground-based and satellite data. Full details of the model can be found in Drob et al. [115]. The model predicts results for specified longitude, latitude and height. Here, the HWM-07 model has been used to estimate the meridional and zonal winds at 41.9\(^\circ\)N and 111.4\(^\circ\)W, i.e., over BLO, for heights of 80 – 100 km.
Figure 6.3: Monthly-mean meridional and zonal winds over BLO (41.9°N and 111.4°W), from the HWM-07 model. The zero wind line is indicated in black and the white lines indicate 5 m s$^{-1}$ steps.

Figure 6.3 presents the meridional and zonal monthly-mean winds from the HWM-07 model. Considering the meridional winds, a comparison with the composite-year radar results of Fig. 6.1 reveals a general similarity in that the strongest equatorward winds occur in summer. However, there are a number of notable differences. In particular, the model shows equatorward winds present, at least at some heights, throughout the year (although some poleward flow does occur) whereas our observations show a clear seasonal reversal in meridional winds such that equatorward flow occurs at all heights from about April–August. Further, the model predicts poleward flows in winter of generally less than 2 m s$^{-1}$, whereas our observations suggest rather faster flows of up to $\sim$ 8 m s$^{-1}$. Finally, the model suggests the summer-time equatorward flow actually reverses heights below $\sim$ 80 km, whereas our observation show that the flow is strongly equatorward even at the lowest heights observed.

Considering the zonal winds from the HWM-07 model, it can be seen that they are
generally in good agreement with our composite-year zonal winds. However, a number of differences are again apparent. In particular, the winter-time zonal winds at the lower heights are much stronger in HWM-07 model than we observe. For instance, at the lowest heights considered the strongest winter-time winds reach almost 50 m s\(^{-1}\), whereas our observations indicate winds only about half that speed. In the summer-time, the eastward winds in the model reach up to \(\sim 50 \text{ m s}^{-1}\) compared to our observations in which they reach up to \(\sim 40 \text{ m s}^{-1}\).

In summary we see that both the URAP and HWM-07 models predict stronger zonal winds in the winter than we observe at the lower heights. Further, although HWM-07 model predicts summer-time equatorward flows of similar speed to those observed, it does not show the deep region of poleward flow evident over BLO.

### 6.1.4.3 16- and 5-day planetary waves

This section presents observations of the 16- and 5-day planetary waves over BLO. A particular focus will be observations of the waves made simultaneously in winds and temperatures.

The time-series of daily radar winds and MLS temperatures were first examined for oscillations that might be caused by planetary waves. Figure 6.4 presents an example of the winds and temperatures from the interval September 1, 2009 to January 31, 2010. It is evident from the figure that there are a number of intermittent oscillations in wind and temperature with periods of several days or more. Successive wind (left axis) and temperature (right axis) maxima are marked on the figure to highlight the oscillations. For example, there is an oscillation with the period of \(\sim 6\) days and amplitude of order \(\sim 10 \text{ m s}^{-1}\) and 5 K in September (the period lengthening to \(\sim 8\) days in October). There is also an oscillation of period \(\sim 16\) days and amplitudes of order \(\sim 15 \text{ m s}^{-1}\) and 10 K in December and January, similarly marked on the figure. These periods are consistent with those reported for the “5-day wave” and the “16-day wave”, respectively [e.g., 5, 22, 23, 24, 26, 35, 82, 85].
Chapter 6. Results - Mean winds, temperatures and the 16- and 5-day planetary waves over Bear Lake Observatory

Figure 6.4: The daily zonal winds and MLS temperatures at \(\sim 90\) km measured over BLO for the interval September 2009–January 2010. Wind maxima occurring at planetary wave periods (\(\sim 5\) and 16 days) are indicated by the arrows, wind on the top axis and temperature on the bottom axis.

To examine the evolution of these oscillations throughout the wind data, a wavelet analysis of the zonal-wind time-series at a height of \(\sim 90\) km was performed and the results of this analysis are presented in Fig. 6.5. The analysis used a Morlet wavelet of non-dimensional wavenumber 6. The figure shows “bursts” of wave activity occurring at different wave periods throughout the data set in a similar manner to those reported in observations of MLT winds [e.g., 69].

Wave amplitudes in the wavelet analysis can reach peak values of more than 20 m s\(^{-1}\). Particularly large-amplitude bursts include the 5- and 16-day wave bursts described above, i.e., in September–October 2009 (wave period \(\sim 6–8\) days) and December 2009 (wave period \(\sim 16\) days) which have amplitudes of \(\sim 13\) m s\(^{-1}\) and 10 m s\(^{-1}\), respectively. Note that the 5-day wave appears to be occur in bursts throughout the year in every year, whereas the 16-day wave is mainly present during the solstice.

Figure 6.5: A Wavelet analysis of hourly zonal wind amplitudes at heights of \(\sim 90\) km, over BLO from March 2008 to July 2011.
To investigate the seasonal variability of the 16- and 5-day waves, the horizontal wind variance has been used as a proxy for wave activity. In this analysis, the band-passed winds in each height gate for each month are used to calculate a variance value for the meridional and zonal components of the winds. The time-series where band-passed between period limits of 12 – 20 days and 4 – 7 days, corresponding to the period ranges of the 16- and 5-day waves, respectively. These limits were chosen on the basis of the results presented above and because they are commonly used in studies of these two particular planetary waves.

By examining these variances as a function of height and time the seasonal and inter-annual variability of the 16- and 5-day waves can be investigated. A similar analysis has been used in the the studies of the 16-day and 5-day planetary waves at polar latitudes [e.g., 82, 85]. Note that for a constant amplitude oscillation, amplitude is equal to the square root of twice the variance. For example, a variance of $10 \text{ m}^2 \text{s}^{-2}$ corresponds to a wave amplitude of $4.5 \text{ m s}^{-1}$, a variance of $50 \text{ m}^2 \text{s}^{-2}$ corresponds to a wave amplitude
of 10 m s\(^{-1}\) and a variance of 100 m\(^2\) s\(^{-2}\) corresponds to a wave amplitude of 14.1 m s\(^{-1}\) etc.

Time-height contours of meridional and zonal monthly variances for all of the years of data available over BLO are presented in Fig. 6.6. The monthly-mean zonal winds for each year have been plotted over the top of the figure for that specific year to enable a comparison of the background winds and the level of 16- and 5-day wave variances.

Figure 6.6 shows the 16-day wave generally maximises in winter-time throughout the height region observed, where it reaches variances of up to \(\sim 100\) m\(^2\) s\(^{-2}\). In contrast, in summer-time the variances are much smaller, reaching only up to \(\sim 30\) m\(^2\) s\(^{-2}\) in 2009 and 2010 and 70 m\(^2\) s\(^{-2}\) in 2008. The summer-time 5-day wave is observed to be short-lived and localised in height, whereas the winter-time wave is generally longer-lived and occurs through the whole height region observed. The 5-day wave reaches maximum variances of up to \(\sim 100\) m\(^2\) s\(^{-2}\) in both summer-time and winter-time. Both waves usually display smaller variances around the equinoxes. The figure reveals a significant inter-annual variability of the waves in both the zonal and the meridional components.

**Figure 6.7:** On the right of the figure is the Hovmöller diagram of the Aura MLS data in 30° longitude bands for the month of December in 2009, at 40 – 45°N and \(\sim 90\) km. The black line shows the approximate location of BLO and the dashed line the wave fronts. On the left is the band-passed 16-day wave radar zonal winds for the same time and approximate height.
We will now compare these radar observations of the waves with observations of the waves in MLS temperature data. Figures 6.7 and 6.8 present data from December and September 2009 as examples of the wave signatures in Hovmoller diagrams. Other months showed similar wave signatures and are not shown here for reasons of space. Figures 6.7 and 6.8 also present the bandpassed zonal winds, using the same bandpass limits as used for Fig. 6.6. On each Hovmoller diagram a line indicating the longitude of BLO is shown.

Considering Fig. 6.7, the 16-day wave can be clearly seen in both the wind and temperature data. The wind amplitudes appear to be \( \sim 10 \text{ m s}^{-1} \) and temperature amplitudes at the longitude of BLO appear to be \( \sim 5 \text{ K} \). Considering Fig. 6.8, the 5-day can similarly be clearly seen wave in wind and temperature data. The wind amplitudes appear to be \( \sim 15 \text{ m s}^{-1} \) and temperature amplitudes at the longitude of BLO appear to be \( \sim 6 \text{ K} \).

To examine the planetary waves in more detail temperature and zonal wind time series were band-passed as previously described. The zonal winds were used because of the larger variances evident in Fig. 6.6. The results of this analysis are presented in Fig. 6.9.
Chapter 6. Results - Mean winds, temperatures and the 16- and 5-day planetary waves over Bear Lake Observatory

Figure 6.9: Band-passed radar winds and Aura daily temperatures over BLO ~ 90 km, for the years 2008 – 2011. Band-pass limits are for the wave periods of 12 – 20 days and 4 – 7 days for the 16- and 5-day wave, respectively. The Aura MLS data is from 40–45° N and 90–120° W. Note the temperatures have been multiplied by a factor of 3 for a by eye comparison with the winds.

Note on the figure the temperatures have been multiplied by a factor of 3 to facilitate a simple by-eye comparison with the winds.
Chapter 6. *Results - Mean winds, temperatures and the 16- and 5-day planetary waves over Bear Lake Observatory*

Considering both Fig. 6.6 and 6.9, the inter-annual variability of the waves are clearly evident. The winter-time 16-day wave maximises in January/February of the years 2008 and 2010. In 2009 there was a major Sudden Stratospheric Warming (SSW) event. SSWs are known to dampen planetary-wave amplitudes and this is clearly observed in this particular case.

Further, the 5-day wave is known to have large amplitudes in the summer-time, but to be highly influenced by the background winds [e.g., 22, 58, 82]. This may, in part, account for the inter-annual variability evident in our results. For example, in the summers of 2008 and 2009 the wave maximises at the middle and upper heights observed. In contrast, in the summer of 2010 the wave appears to extend to lower heights observed and maximises approximately one month earlier in the season.

Considering the band-passed winds and temperatures of Fig. 6.9 in more detail, generally, larger wind perturbations correspond to larger temperature perturbations in the case of both the 16- and 5-day waves. For each wave the correlation between the wind and temperature time series was calculated as a function of lag. In the case of the 16-day wave the correlation coefficient reached a maximum of 0.40 at a lag of 5 days with the winds leading the temperatures. This means for the 16-day wave that the coldest temperatures occur when the winds are zero and reversing from eastward to westward. In the case of the 5-day wave the correlation coefficient reached a maximum of 0.22 at a lag of 2 days with the winds leading the temperatures.

To quantify the relationship between the wind and the temperature perturbation of the two waves we considered episodes where the waves displayed large amplitude bursts. The bursts have been arbitrarily defined as a continuous event in which the wind amplitude exceeded 5 m s$^{-1}$ for a duration of more than one cycle. Bursts were only used if a Student T-test showed them to be statistically related above a 90% confidence level. Figure 6.10 presents the results of this analysis for both waves. A least-squares straight-line fit forced through zero to these data suggests that the temperature and wind amplitudes, $A_T$ and $A_W$, respectively are related by $A_T = 0.49 A_W$ for the 16-day wave and $A_T = 0.58 A_W$ for the 5-day wave (i.e., for the 16-day wave a 1 m s$^{-1}$ wind amplitude corresponds to a temperature perturbation amplitude of 0.49 K).
Chapter 6. Results - Mean winds, temperatures and the 16- and 5-day planetary waves over Bear Lake Observatory

Figure 6.10: A least-square fit of radar winds versus Aura temperature amplitudes at heights of \( \sim 90 \text{ km} \), for the 16- and 5-day waves for “bursts” of temperature amplitudes over BLO. Bursts are identified as, waves that are greater than 5 \( \text{m s}^{-1} \), that last for longer than 1 cycle and pass the Student T-test 90\% confidence level.

Finally, we analysed the Aura MLS temperatures using the method of Wu et al. [87], which yields the zonal-mean amplitude and phase of particular zonal wavenumbers.

Figure 6.11: Time-series of monthly-mean temperature amplitudes from 2008 – 2011 for the 16- and 5-day wave at a latitude 35 – 45°N. Also plotted is the stratopause height as a red contour line.
within a height-latitude band. Here, we have used this analysis to determine the temperature amplitudes of the 16- and 5-day waves within a latitude band of 35–45°N, assuming both waves to be westward-propagating zonal-wavenumber 1 features. In each case, the zonally-averaged amplitudes were calculated as monthly means.

Figure 6.11 presents the zonal-mean monthly wave temperature amplitudes calculated by this analysis. The monthly analysis was used to reduce the uncertainty in the results. Figure 6.11 reveals the same general seasonal cycle for the 16- and 5-day waves observed in winds over BLO in the upper mesosphere (Fig. 6.6).

Figure 6.11 reveals that the 16-day wave reaches largest amplitudes of ∼4 K in winter at heights near ∼80 km but also has a second maximum at ∼45 km. This was also observed by e.g., Day et al. [5] when considering the 16-day wave. Figure 6.11 also shows the 5-day wave to maximise in winter and late summer with amplitudes of up to ∼4 K at heights of ∼90 km. A winter-time maximum is also observed near the stratopause with amplitudes of up to ∼3 K at heights of ∼45 km.

Comparing these satellite observations with our radar observations, the winter-time and summer-time signatures for the 16- and 5-day waves, respectively, can be seen to be clearly represented in both the satellite and radar observations. However, the satellite observations of Fig. 6.11 reveal that the summer-time 5-day wave only reaches significant amplitudes at heights above ∼70 km and so does not extend to heights much lower than those observed by the radar. Figure 6.11 also shows that the 16-day wave does not reach amplitudes of greater than 1 K in summer.

6.1.5 Discussion

The seasonal pattern of zonal and meridional winds we report here is in good general agreement with earlier observations made at BLO [e.g., 92, 93, 94] and other mid-latitude northern hemisphere observations [e.g., 14]. However, some differences are apparent. The meridional mean winds reported here are stronger than those reported for the year 2000 in the IDI study of Roper and Berkey [94] and they did not observe the equinoctial reversals evident in Fig. 6.1. These differences observed may be a consequence of the
different years of observation or may result from instrument biases between meteor radar and IDI.

The seasonal variability of the mean winds and temperatures presented in this study agree very well with the simple concepts of the Brewer Dobson circulation. In particular, the seasonal reversal of the meridional winds in summer to an equatorward flow is accompanied by a decline towards the lowest temperatures and the lowest temperatures of all occur a few weeks after the strongest equatorward winds have been established in the MLT. The strongest shears in the zonal winds occur at the same time as the strongest equatorward winds. This general pattern agrees well with other ground-based observations made by radar and/or lidar at middle latitudes in the northern hemisphere, [e.g., 94, 97, 100, 101, 116].

A particularly interesting comparison can be made between our results and the composite-year results reported by Yuan et al. [117]. Yuan et al. [117] used a Na lidar at the nearby site of Fort Collins, Colorado (41°N, 105°W) to measure winds and temperatures in the MLT from 2002–2006. They observed slightly stronger equatorward meridional winds in summer peaking, at a speed of \( \sim 17 \text{ m s}^{-1} \) compared to the \( \sim 12 \text{ m s}^{-1} \) that we observed. However, the height at which the strongest equatorward flow occurs is in remarkable agreement being \( \sim 84 \text{ km} \) in our study and \( \sim 86 \text{ km} \) in theirs. Yuan et al. [117] observed the late summer reversal to poleward winds occurred later in the season at greater heights in their lidar data, whereas our observations show the reversal to occurs almost simultaneously at all heights.

The seasonal pattern of temperatures reported by Yuan et al. [117] are very similar to that reported here. For example, in the summer-time they observed temperatures to be \( \sim 167 \text{ K} \) at heights of \( \sim 84 \text{ km} \), our observations are similar, 173 K at \( \sim 81 \text{ km} \) and 167 K at \( \sim 86 \text{ km} \). The seasonal pattern they report for the zonal winds is in remarkably good argument with ours, with regards with the timing of the wind and the speeds, generally agreeing to within 10 m s\(^{-1}\). The observed lag of about two weeks between the strongest mean meridional winds and the lowest mean temperatures is also evident in the lidar radar observations of Yuan et al. [117]. The relatively small differences in the composite
winds observed in the two studies may result from either measurement biases between the Na lidar and the meteor radar techniques or inter-annual variability.

Comparing the radar winds with the URAP and the HWM-07 models reveals a number of notable differences. Specifically, URAP presents zonal winds as being much more eastwards than in our observations for all months at all heights except for heights of 82–85 km in June–August, where URAP presents them as being weaker.

An explanation for these differences may be that the URAP winds were modelled using data from 1991–1999 and therefore there may be some differences that can be explained by changes in the general circulation in the MLT occurring over decadal time scales. Further, URAP presents zonally-averaged zonal winds and so any longitudinal structure in the winds may cause differences when comparisons are made with localised ground-based measurements. Such structure may be caused by stationary planetary waves. Finally, differences may also arise from measurement biases existing between the meteor radar and the satellite instrument used in the model, (the High Resolution Doppler Imager, HRDI).

HWM-07 models the equatorward (negative) meridional winds in the summer-time to be weaker than we observed and to occupy a smaller height range. In contrast, the zonal winds predicted by the model are in quite good agreement with our observations. These differences may arise for similar reasons to those suggested in the case of URAP.

The observations of the 16- and 5-day waves reveal that both waves have a winter maxima and equinoctial minima. In winter, both waves can be present throughout the height range observed by the radar. This observation is consistent with the simple interpretation that the waves have ascended from sources in the lower atmosphere of the winter hemisphere, through the eastward winds of the winter stratosphere, to the MLT. In the case of both waves, the observed amplitudes are broadly consistent with those reported in other studies made at middle latitudes [e.g., 5, 23, 75, 76].

Further, in the radar observations, both the 16- and 5-day planetary waves display secondary maxima in the summer at heights above the regions of strong westward wind in the mesosphere, which would prevent the waves from having propagated there directly.
through the underlying lower atmosphere [63]. Note that the summer maximum of the 16-day wave is not evident in the satellite observations, probably because its amplitude is too small.

In the case of the 16-day wave, the presence of the wave in the summer-time MLT has been reported in a number of studies made at middle and high latitudes [e.g., 5, 26, 56, 75, 76, 85]. Two mechanisms have been advanced to explain these observations.

In the first mechanism, the 16-day wave in the summer-time lower stratosphere is proposed to modulate the field of ascending gravity waves such that when they dissipate at MLT heights the resulting modulated momentum flux and zonal wind acceleration excites the wave in situ [56]. Modelling support for this hypothesis is provided by the study of Smith [80], who reported that significant planetary-wave amplitudes were excited in the MLT by this process, at least in the case of stationary planetary waves.

The second mechanism proposes that the 16-day wave is ducted across the equator from the winter hemisphere, above the heights where the strong westerly winds of the summer hemisphere prohibit propagation. The plausibility of this mechanism has been demonstrated in modelling studies [e.g., 40, 72] and experimental studies have sought to determine if any such equator-crossing wave is modulated in amplitude by the Quasi-Biennial Oscillation - although with sometimes contradictory conclusions [e.g., 5, 26, 27, 28, 29].

We should note that the 16-day wave in the summer MLT is observed to be generally confined to high latitudes and so the small amplitudes observed over BLO in summer may also be a consequence of this site's location towards the equatorward edge of the region of significant wave amplitude [e.g., 5].

In the case of the 5-day wave, the wave amplitudes in summer are slightly larger than those of the 16-day wave. Riggin et al. [22] observed a particularly strong 5-day wave event using TIMED/SABER data and suggested that this wave was ducted from the winter hemisphere to the summer hemisphere, where it is then amplified by baroclinic
instability. Belova et al. [58] considered satellite and ground-based observations to suggest that upward propagation from the stratosphere in the summer-hemisphere, cross-equator propagation from the winter hemisphere or \textit{in-situ} excitation as a result of the baroclinic instability may all be capable of exciting the 5-day wave in the summertime MLT. It thus seems that cross-equatorial ducting may well explain the 5-day planetary wave observed over BLO in summer, but that other mechanisms may also contribute.

Throughout the period of observation, both in summer and winter, the two planetary waves display a high degree of intermittency, with significant fluctuations in both amplitude and period occurring on time scales of a few days (e.g., Fig. 6.5). These fluctuations appear to be a universal feature of planetary waves in the MLT, regardless of year or season [e.g., 24, 69, 77, 85]. The origin of such intermittency has been suggested to lie in the sensitivity of planetary-wave propagation to the relative magnitudes of the zonal jets in the summer and winter hemispheres, which can vary on relatively short timescales [e.g., 118]. This intermittency leads to a high degree inter-annual variability observed in the waves.

### 6.1.6 Conclusions

The monthly-mean mean zonal and meridional winds over BLO in the MLT reveals a clear seasonal cycle. The mean meridional wind is usually poleward throughout the year except for a region of strong equatorward flow occurring in the summer. The coldest temperatures generally occur about two weeks after the time at which the equatorward winds of the summer-time are at their strongest. The mean zonal winds are eastward throughout much of the year but do display some westward flow in winter and around the equinoxes. The observed eastward winds in winter are significantly weaker than those suggest by the URAP and the HWM-07 models. This maybe a result of measurement biases or, more likely, stationary planetary waves in the winter MLT.

The 16- and 5-day planetary waves reach large amplitudes in winter and are present in summer. The planetary wave amplitudes are evident in both wind and temperature and the largest amplitudes in wind and temperature generally occur simultaneously. The amplitudes display a high degree of intermittence and therefore inter-annual variability
which is probably dependant on fluctuations of the background winds. The presence of the waves in summer requires that they have either an *in situ* source or have been ducted across the equator from the winter hemisphere.
Chapter 7

Conclusions and Suggestions for Future Work

7.1 Conclusions

This thesis presents a collection of investigations into the dynamics and coupling of the 16- and 5-day planetary wave in the middle atmosphere. The mean winds and temperature dynamics of the MLT region are observed and where possible further investigations at stratospheric heights have been made.

These studies present observations from meteor radars at three locations, Esrange, Sweden in the Arctic (68°N 21°E), Bear Lake Observatory, Logan Utah in the USA (42°N 111°W) and Rothera, in Antarctica (68°N 68°W). Other observational data include temperatures observations from the MLS instrument onboard the NASA EOS Aura satellite, winds observations of the Quasi-Biennial Oscillation (QBO) from the Freie Universität Berlin (FUB) Singapore radiosonde data set. Modelled outputs in the form of zonal winds and temperatures were used from the UK Met Office (UKMO) Stratospheric Assimilated Data model, predicted zonally averaged zonal winds from the NASA URAS and URAP model and predicted mean zonal and meridional winds from the HWM-07 model.
7.1.1 Chapter 3 Summary – The Polar 5-day Planetary Wave in the MLT

A study of the 5-day planetary wave signatures in the winds from meteor radars over Esrange and Rothera revealed the climatology of the waves in the atmosphere at conjugate polar locations to be similar where a well defined seasonal cycle was observed. The 5-day wave was observed across the heights, \(\sim 80–100\) km during the winter-time, where variances were observed to reach up to about \(65\) m\(^2\) s\(^{-2}\). In contrast, the late summer-time wave was restricted to regions of westward flow of background winds at heights of \(\sim 95\) km, where variances were observed to reach up to about \(75\) m\(^2\) s\(^{-2}\). The long data sets, of about 9 and 4 years, respectively, allowed for the investigation of inter-annual variability. A high level of variability was displayed by the wave and may account for some of the differences noted between observations in published studies.

In the results section it was observed that in the summer the meridional variances are greater than the zonal with an average difference of approximately a factor of 1.5. The explanation considers the structure of the wave in latitude and longitude. A wavenumber, \(k = 1\), would have a region of high and region of low temperature where the winds would be anti- and cyclonic, respectively, around the regions. If the hot and cold regions are centered on the latitude observed by the radar then the meridional component would be greatest and the zonal minimum. Whereas, if the hot and cold regions are centered either above or below the observed latitude then the meridional component would be less and the zonal greater. This means that the maximum of the hot and cold regions compared to the latitude of the radar observations can be inferred. In the paper Day and Mitchell [82] the signature of the summer-time 5-day wave was observed to be greater in the meridional variances, by a factor of \(\sim 1.5\) and therefore the wave must be approximately centered over the latitude of the radar. In contrast, the signatures of the winter-time 5-day wave was observed to be greater in the zonal variances, by a factor of \(\sim 1.3\) and therefore the wave must not be approximately centered over the latitude of the radar. This observation was the same over both radars, as would be expected, as they are at conjugate latitudes of \(68^\circ\). In the discussion of the paper Day and Mitchell [82]
the background wind filtering was discussed. The background winds are known to filter the planetary wave vertical propagation, therefore the planetary wave must have a minimum phase speed to propagate upward. In the paper this was calculated for the exact 5-day wave, but the periods limits of 4 – 7 days was used in the data analysis therefore a range should be considered. The lower limit, $c_x$ would be between $\sim -43 - 25 \text{ m s}^{-1}$ and the upper limit, $U_c$ would be $49 \text{ m s}^{-1}$. Therefore the exact period of the wave being observed determines if the wave can propagate through the summer-time background winds.

7.1.2 Chapter 4 Summary – The Polar 16-day Planetary Wave in the MLT

The 16-day planetary wave field was investigated over Esrange and Rothera using winds and temperatures recorded by meteor radars. The wave was found to have a clear seasonal cycle in the meteor region over both of the sites. In the winter-time the wave signature was observed to be at all heights, ($\sim 80 - 100 \text{ km}$) but was found to be strongest at heights of about $\sim 85 \text{ km}$, where it reached about $15 \text{ m s}^{-1}$. However, the summer-time wave, which was observed to be weaker, reaching about $6 \text{ m s}^{-1}$ was restricted to regions where the background winds were westward. Weak wave signatures were also evident during the equinoxes of some of the years. There was a high degree of inter-annual variability observed. Further investigation of the temperature data revealed a clear 16-day wave signature in the MLT. Temperature amplitudes typically ranged from 1 to 6 K. An examination of simultaneous zonal winds and temperatures amplitudes suggests a relationship of form $T' = 0.27 u'$.

Considering Fig.4.2 in the results of Day and Mitchell [85] it should be noted that the winter-time downward phase slope is related to an upward propagating wave. As explained in the summary for chapter 3 above the dominance of the wind component helps explain the location of the hot and cold regions of the wave. The 16-day wave zonal component was greater than the meridional for most winters (the average difference was approximately a factor of 1.2). Therefore the wave must not be approximately centered
over the latitude of the radar. In the results section of the paper by Day and Mitchell [85] the background wind filtering was discussed. The background winds are known to filter the planetary wave vertical propagation, therefore the planetary wave must have a minimum phase speed. In the paper this was calculated for the exact 16-day wave, but the periods limits of 12–20 days was used in the data analysis therefore a range should be considered. The lower limit, $c_x$ would be between $\sim 14-9 \text{ m s}^{-1}$ and the upper limit, $U_c$ would be $49 \text{ m s}^{-1}$. Therefore the exact period of the wave being observed determines if the wave can propagate through the summer-time background winds.

### 7.1.3 Chapter 5 Summary – The 16-day wave in the middle atmosphere

Temperatures observed by Aura MLS have been used to observe the middle atmosphere globally. Here the temperatures were used to observe the 16-day $s=1$ planetary wave. The wave was observed to maximise at middle and high latitudes in the winter-time, at heights of about 30 and 70 km, respectively. The wave in addition appears to be restricted to latitudes polewards of $25^\circ$ and largest amplitudes were observed at about $60^\circ$. The seasonal cycle of the 16-day wave is clearly observed to maximise in winter at all heights, where temperature amplitudes reach excesses of 6 K. However, there is a stratopause amplitude minima as would be expected when considering the change in temperature profile of the atmosphere. In contrast, the summer-time wave is generally restricted to heights of about 80 km where it reaches smaller amplitudes compared to the winter-time wave, reaching about 2–3 K. The seasonal cycle can be linked to the wind speeds and direction. Larger westward background wind flows are generally linked to larger temperatures.

Further, the tendency for the wave’s interaction with the background wind to restrict the propagation of waves when the background winds are westward in the summer-time, as explained in the Charney-Drazin theorem, has been investigated in this study. Here we observed the westward summer-time winds were observed to be restricting the upward propagation of planetary waves and thus there must be some other mechanism for generating the observed summer-time wave in the MLT. The inter-annual variability
was investigated and the QBO and major SSW events were considered as effects on the summer-time wave presence in the MLT. The paper by Day et al. [5] stated that our observations do not suggest that the QBO modulates the amplitude of the wave in the polar summer-time MLT. This may be a consequence of our comparatively short data set or an intermittency in the modulation. In contrast, major SSW events could affect the ducting of the 16-day wave from the winter to the summer polar region.

However, on reconsideration of the results from the inter-annual variability results section, specifically, Fig. 5.11: If the QBO switch was to be considered a gate where once it is opened, it opens quickly but in contrast it closes slowly, then this interpretation could account for the approximately linear fit for the QBO in the negative wind phase, but the apparent random spread of observations for the QBO in the positive wind phase. The switch should may be considered to be less of an on/off switch and more linked to the strength of the QBO winds. In the same results section of the paper the significance of the phase of the QBO and wave amplitudes was considered. A detailed re-analysis of the values quoted and interpretation of there meaning has lead to the following conclusions: There was in the northern hemisphere a small but significant eastward greater than westward QBO phase observed, whereas in the southern hemisphere there was a small but insignificant westward greater than eastward QBO phase observed, which may be due to the SWW events damping the planetary wave amplitude. This observation then, in fact, agrees with the findings of Espy et al. [26] and Hibbins et al. [27]. The explanation for the reconsideration is as follows: For the northern hemisphere QBO the values in the paper are, for the eastward QBO $1.17 \pm 0.19$ K which would give a minimum value of $0.98$ K, for the westward QBO $0.86 \pm 0.09$ K which would give a maximum value of $0.95$ K. The is a significant difference and we cannot exclude this as an influence on the wave; for the southern hemisphere QBO the values in the paper are, for the eastward QBO $0.94 \pm 0.14$ K which would give a maximum value of $1.08$ K, for the westward QBO $1.11 \pm 0.10$ K which would give a minimum value of $1.01$ K. There is no significant difference, the values overlap, therefore we can exclude this as an influence on the wave.

In the paper we observed the major SSW events of the northern hemisphere winter of 2006 and 2009 to have an influence on the winter-time wave amplitudes following the
warming, where they can be seen to decrease wave amplitudes to values of about half of those observed in undisturbed years, however no clear persistent link was concluded because of the relatively short data set available.

7.1.4 Chapter 6 Summary – Mean winds, planetary wave, 16- & 5-day, over Bear Lake Observatory

Investigations of the relationship between the mean wind and temperature field were carried out using data from the meteor radar, satellite instruments and model outputs over BLO. Meteor radar winds, Aura MLS temperatures data were used to investigate the effect of the mean winds on temperatures. It was observed that the mean meridional winds over BLO lag the temperatures observed by about two weeks, this suggests that there is a link between them. The link may be local and a local phenomenon a consequence of the location of the radar, a mountainous region, or it could be symptomatic of the global circulation. Unfortunately with only one site this cannot be determined.

Secondly, the URAP and the HWM-07 model predictions were compared to our wind observations. Both URAP and HWM-07 models predict stronger zonal winds in the winter-time than observed in the meteor radar data in the MLT. The HWM-07 model predicted the summer-time equatorward flows of similar speed to those we observed, but it did not show the deep region of poleward flow evident over BLO in the equinox.

Thirdly, the 16- and 5-day planetary waves are observed in multiple analysis techniques. Both waves display a clear seasonal cycle in the meteor region, $\sim 80–100$ km. The 16-day wave maximise in the winter-time, in contrast to the 5-day wave which is present throughout the year, but largest in the late summer-time and again enhanced in the winter-time. Large short-lived events can reach amplitudes of up to about $15\text{ m s}^{-1}$ and $8\text{ K}$ for the 16-day wave and $20\text{ m s}^{-1}$ and $10\text{ K}$ for the 5-day wave. Further, larger winds generally correspond to larger temperatures. The relationship is, $A_T = 0.49A_W$.
and $A_T = 0.58 A_W$ for the 16- and 5-day wave, respectively.

In the discussion of the paper by Day et al. [4] the background wind filtering was discussed. The background winds are known to filter the planetary wave vertical propagation, therefore the planetary wave must have a minimum phase speed. In the paper this was calculated for the exact 16- and 5-day wave, but the periods limits of 12–20 and 4–7 days, respectively, was used in the data analysis therefore a range should be considered. The lower limit, $c_x$ would be between $\sim -28 - 17 \text{ m s}^{-1}$ and $\sim -85 - 49 \text{ m s}^{-1}$, respectively, and the upper limit, $U_c$ would be $369 \text{ m s}^{-1}$. Therefore the exact period of the wave being observed determines if the wave can propagate through the summer-time background winds.

7.2 Suggestions for Future Work

The planetary wave studies of the 5- and 16-day waves using both winds and temperatures in the stratosphere, mesosphere and lower thermosphere presented here answer only a few scientific questions.

- What is the climatology of the 5-day winds in the polar regions over the radar sites?
- What are the difference between 5-day winds in the two polar regions over the radar sites?
- How does the inter-annual variability of the 5-day wave in the polar regions compare over the radar sites?
- Is there any annual variability of the 5-day wave over the two radar sites?
- How does the 5-day wave interact with the background winds over the radar sites?
- What is the climatology of the 16-day winds in the polar regions over the radar sites?
• What are the difference between 16-day winds in the two polar regions over the radar sites?

• How does the inter-annual variability of the 16-day wave in the polar regions compare over the radar sites?

• How does the 16-day wave interact with the background winds over the radar sites?

• Is there a relationship between winds and temperatures of the 16-day wave over the radar?

• What are the global temperatures of the 16-day wave like in the atmosphere at 10 – 100 km?

• Is the phase of the QBO a simple switch for the cross-equatorial ducting of the polar summer-time 16-day wave?

• How do major SSW events effect the 16-day wave in the atmosphere and does it effect the ability of the wave to cross-equatorially duct?

• How are the mean meridional, zonal winds and temperatures related over BLO?

• How do the observations of the mean winds and temperatures compare with the modelled atmosphere?

• What is the climatology of the 16- and 5-day waves in radar winds and Aura MLS temperatures over BLO?

• Is there a link between the radar wind amplitudes and Aura temperature amplitudes of the 16- and 5-day waves over BLO?

The meteor radars, Aura satellites MLS instrument and other data measurement can be used to answer further questions on the dynamics and coupling in these regions of the atmosphere. The following proposed areas of studies are logical progression and developments of the work already presented in this thesis.

1. The understanding of the climatology and variability of the 5-day wave in Chapter 3 would be enhanced by studying the excitation mechanism for the summer-time 5-day wave. The 5-day summer-time wave cannot have propagated from
lower in the atmosphere through the background winds to the observed height in the MLT because of the Charney-Drazin theorem. A study which focuses on the barotropic and baroclinic instabilities during the summer-time would allow quantified verification of the role of these two mechanisms for exciting the 5-day wave at this time in the MLT. Aura MLS global temperatures and calculated winds from Aura data along with ground-based wind shears could be used to investigate these instabilities.

2. In Chapter 6 the observed meridional mean winds and their effect on temperatures in the MLT was observed locally over BLO. As the link is known to be greater in the polar regions a study of the three available meteor radar sites, Esrange, BLO and Rothera would aid the understanding of the Brewer Dobson circulation of the atmosphere and explain how the meridional mean winds effect on the modulation of the temperatures.

3. Bear Lake Observatory now hosts a suite of instruments, including a meteor radar, an OH airglow imager and a newly operational (2011) Na lidar. Combining these ground-based instruments with the Aura MLS measurements would allow for studies of the atmosphere to observe times of known large wave fluctuations. For example, the winter-time waves, 16- and 5-day and the late summer-time 2- and 5-day waves. Considering temperatures and winds with the suite of instruments to compare observations and observe the short- and long-term variability of the waves would develop and extend the research in Chapter 6.

4. Meteor radars are commonly used to measure winds and can be used to deduce temperatures. However, it has been identified that the deduced temperatures need some development and may be improved by the incorporation of model data. Younger et al. [119] questioned the assumptions of the ambipolar diffusion and a further question surrounding the effect of the steep change in temperature gradient present at the mesopause has arisen. A full detailed analysis of the radar deduced temperatures method addressing the issues raised by Younger et al. [119] which was fully documented would allow for concise and confident use of radar temperature analysis technique and measurements. The development, refinement
and documentation of the method of determining temperatures from meteor radar would allow for future use. The temperature data would be particularly useful for short-term comparisons and application and adaptation to other meteor radar instruments. A possible area of future research and collaboration is the adaptation of the technique to the wind profiler radars owned by the UK MetOffice.

5. The temperature data from the Aura MLS have been analysed by multiple methods. Commonly used are: the method devised by Wu, [87], where zonally averaged temperatures are analysed for individual wavenumbers; the Hovmöller method, which retains both latitudinal and longitudinal structure but the wavenumbers cannot be identified and extracted; and the Salby method [20], which retains both latitudinal and longitudinal structure and extracts all of the wavenumbers for all waves simultaneously, this last method is therefore very powerful as it eliminates aliasing. This method is very computationally expensive and intensive. A study documenting, describing and explaining the method in full would help satellite data users to extract all the data from the satellites and use them to their full capabilities.

6. The 5-day wave has been suggested to modulate the temperatures in the MLT and thus modulate the occurrence of NLC’s, PMSE’s, MSE’s etc. in the Northern Hemisphere. The meteor radars at Esrange and BLO along with the suite of instruments at BLO, Aura MLS temperatures data and the AIM satellite could be used to investigate the suggestions by e.g., Nielsen et al. [113]. Further, the NLC occurrence increase has been suggested to be linked to climate change and could be used as an indicator, specifically a change in the temperature in the MLT region.

7. McDonald et al. [91] observed the 16-day wave using the Aura satellite and the Wu et al. [87] method. They investigated not only the W1 Rossby-gravity wave, but also suggested that there was a W2, E1 and E2 component. This was not predicted in the models by Salby [20]. Data from the Aura satellite analysed with the Salby method (see above) could help investigate the suggestion further.
8. The Esrange radar has been running since 1999 and thus has accumulated over 11 years of data, over one solar cycle. Tides in the upper atmosphere are known to be influenced by perturbations in their forcing because of changes in UV flux entering the atmosphere. Tidal and planetary wave variability over a solar cycle could be investigated using this extended data set from Esrange.
Appendix A

Further information

A.0.1 Aura MLS Analysis of Temperature Files

There follows is an explanation of how the data was analysed. Two programs were written. The first used the downloaded temperature data files from the Aura website (v2.2), referred to here as raw data, and analysed them. It produced new matrices of outputs of wave amplitudes, wave error amplitudes, wave phases, wave error phases for each height. This was analysed for each wavenumber and all the periods of the desired wave (5- or 16-day in this case). The second program used the output of the wave amplitude for each height and constructed a new matrix of height, time, latitude of temperatures.

The methodology is from the Wu et al. [87] satellite analysis technique.

Program 1

Observing each height gate in turn the data was binned into latitude bins from -80 to 80° in steps of 5° using a 10° window. The raw data was selected for each month of each year and the UT, latitude, longitude and temperature for the height gate then analysed. The program then analyses each wavenumber in turn. This analysis randomises the data for the time and longitudes and minuses the mean temperature from the observed temperature to produce a time series of temperature amplitudes in the atmosphere at each height for each wavenumber and in 5° latitude bins. A least-squares fit to this
time-series fits the data for all the period limits of the desired wave in hour steps. This produces the matrices of outputs of wave amplitudes, wave error amplitudes, wave phases, wave error phases for each height. Note this program does not simultaneously extract all wavenumbers for all waves.

Program 2
Observing each height gate in turn the data from the output of the amplitude of the wave from program 1 is analysed to chose a wavenumber and a latitude. The data is gridded to produce a matrix of time and latitude and then the height gates stacked to create a 3D matrix of temperature amplitudes of the desired planetary wave in period and wavenumber that have been specified.

This data was then used in further programs to observe the specified planetary waves.
Figure A.1: Handwritten notes on how the radar measures and determines wind velocity and direction.
Appendix A. Further information

**Figure A.2:** Wavelet mother Morlet wavenumber 6, as it approximates the signatures of the wave bursts.

**Figure A.3:** Planetary wave wavenumbers, k, 1 to 4, looking down on the globe and the wave on a circle of latitude.

**Figure A.4:** Rossby wave motion explaining why it is westward.

**Figure A.5:** Meridional v zonal to compare the strength of the observed wave wrt the location of the observation.

**Figure A.6:** Brewer Dobson with the wave breaking labelled.
References


References


[34] A. W. Merkel, G. E. Thomas, S. E. Palo, and S. M. Bailey. Observations of the 5-day planetary wave in pmc measurements from the student nitric oxide explorer
References


[42] T. Nakamura, D. C. Fritts, J. R. Isler, T. Tsuda, R. A. Vincent, and M. Reid. Short–period fluctuations of the diurnal tide observed with low–latitude MF and


