

Mesospheric Dynamics Studies with an MF Radar at Jicamarca

2 Project Description

2.1 Introduction

In this proposal we outline a 5 year effort to design, build, and operate a medium frequency (MF) partial reflection radar at Jicamarca, Peru. The work proposed entails mainly engineering work during the first 3 years of the performance period and scientific studies during the last two years, after radar commissioning and a “shakeout” period. The outline of the proposal is as follows. In the Motivation section we discuss our scientific goals and educational benefits of the project. The following Engineering Design section describes the Jicamarca Radio Observatory (JRO) site and facilities, the main components of our proposed instrument, and our strategy for acquiring, storing, and processing data. Due to page limitations some technical details of the design are further described in an appendix. The Science Plan section pertains mainly to the last two years of the 5 year performance period and describes our approach for meeting the research goals outlined in the Motivation section. The concluding Personnel and Schedule section describes the team members, their assignments and qualifications. This section also contains a schedule for completion of key research tasks and milestones.

2.2 Motivation

In this section we discuss the scientific motivations for installing an MF radar at Jicamarca, as well as some wider impacts.

In summary, the main factors are:

1. Make joint observations with the Jicamarca incoherent scatter radar to better understand scattering processes at MF and VHF frequencies by making joint observations with the Jicamarca incoherent scatter radar and MF radar;
2. Study wave motions that contribute to the mesospheric semiannual oscillation (MSAO) and other important wind circulations at tropical latitudes;
3. Develop new and innovative techniques to retrieve winds and turbulence characteristics;
4. Wider impacts include enhanced capabilities for one of the major NSF Upper Atmosphere Facilities, and training opportunities for students.

2.2.1 Scattering Processes

Mesospheric echoes in the mesosphere observed by the Jicamarca VHF radar in Peru are localized into thin layers. These echoing layers can be observed during almost all days, although they disappear during the night. The layers observed by the Jicamarca VHF radar almost certainly represent enhanced turbulence at the Bragg scale (3 m for this radar). The nature of these layers is poorly understood, although certain observed characteristics, e.g., a descent of the layers in time, suggest an association with gravity waves. Evidence for a connection between Kelvin-Helmholtz instabilities and the layers seen in radar backscatter

has been reported [*Reid et al.*, 1987; *Yamamoto et al.*, 1988; *Parker and Bowhill*, 1991]. *Yamamoto et al.* interpreted the thin descending layers observed by the MU Radar as regions of minimum Richardson number due to local modification of the background wind shear by an upward propagating inertial gravity wave. Smaller (more unstable) Richardson numbers, or superpositions of gravity waves were found to cause thicker scattering layers.

Structuring of the electron density profile is continually produced by convective and shear driven instability processes, followed by adjustment back to stability. According to this conceptual picture, the competing processes lead to mixed layers or sheets of turbulent irregularities, bounded by quiescent regions. The persistence of the turbulent layers, often for many hours, seems surprising, but it has been observed that unstable conditions can exist in the mesosphere over these timespans across altitude extents of a few hundred meters to a few kilometers [*Larsen* 2002; *Gardner et al.*, 2002]. During the CADRE/MALTED and Guara/MALTED campaigns *Goldberg et al.*, 1997; *Lehmacher et al.*, 1997] rockets were launched from Peru to study the turbulent layers. The plasma probes on these rockets showed little in the way of plasma turbulence at the presumed height of the layers seen by the JRO incoherent scatter radar. The Layers in the Equatorial Mesosphere, Motions and Aerosol (LEMMA) rocket campaign is currently in the planning stages [*G. Lehmacher*, 2003, private communication]. This experiment will include measurements of neutral wind turbulence as well as plasma probes. Conceptually it seems probable that the necessary conditions for VHF radar backscatter are background plasma density gradients modified by neutral turbulence. However, this explanation has not been confirmed and the details are not currently known.

Although these shear driven instabilities are likely to play a role in the layers observed over Jicamarca, simultaneous measurements of the layers (with VHF radar) and the background horizontal wind field (with MF radar) would allow them to be studied in detail. Instantaneous velocity measurements are difficult in the mesosphere at VHF frequencies because the backscatter is confined to thin and may not even be present in all beams at the same height and time [e.g., *Kamala et al.*, 2003]. With the MF radar providing winds, the frequency domain interferometry technique [*Kudeki*, 1988; *Kudeki and Stitt*, 1990; *Stitt and Kudeki*, 1991] can be applied to view the backscatter power vertical profiles at high vertical and temporal resolution.

2.2.2 Mesospheric Semiannual Oscillation

The zonal mean circulation in the tropical middle atmosphere is dominated by a semiannual oscillation (SAO) in the zonal mean zonal wind between 40 and 90 km [*Reid*, 1966; *Hirota*, 1978; *Hamilton*, 1982; *Hitchman and Leovy*, 1986; *Lieberman et al.*, 1993]. The SAO consists of two separate oscillations, with maxima near the stratopause (SSAO) and the mesopause (MSAO). The two oscillations are approximately 180° out of phase, with the first SAO cycle within each calendar year tending to be stronger than the second cycle [*Delisi and Dunkerton*, 1988]. Long-term observations of High Resolution Doppler Imager (HRDI) winds show an interannual modulation of the easterly phase of the MSAO, that may be related to the quasibiennial oscillation (QBO) [*Burrage et al.*, 1996].

The out-of-phase relationship between the MSAO and the SSAO is explained by selective transmission of eastward- and westward-propagating waves through the SSAO winds. This filtering results in the mesospheric wave spectrum (and driving) having opposite directionality to that of the SSAO winds [*Dunkerton*, 1982]. Yet, despite numerous diagnostic and theoretical advances, efforts to simulate the SAO numerically have been only partially successful. Many observed aspects of the phenomenon can be captured by mechanistic models with prescribed mean meridional circulations, and gravity and Kelvin wave parameters [e.g., *Dunkerton*, 1982; *Mengel et al.* 1995; *Sassi and Garcia*, 1997; *Mayr et al.* 1997; *Garcia and Sassi*, 1999]. However simulating the SAO—particularly in the mesosphere—remains a

challenge for General Circulation Models (GCM's) [*Sassi et al.*, 1993; *Hamilton et al.*, 1995].

Reviews of SAO observations and theory have been presented by *Garcia et al.* [1997] and *Garcia* [2000]. The conceptual outlines of SAO theory are by now fairly well-known. The westerly (eastward) phase of the SSAO has been shown to be driven in part by planetary-scale Kelvin waves [*Hitchman and Leovy*, 1988]. The easterly phase of the SSAO is driven by equatorward propagation of wintertime Rossby waves, and by advection of westward momentum by the mean meridional wind [*Holton and Wehrbein*, 1980; *Hamilton*, 1986; *Ray et al.*, 1998]. The MSAO is believed to be entirely wave-driven [*Dunkerton*, 1982]. The primary source of eastward momentum in the mesosphere is ultra-fast Kelvin waves. These waves have a zonal wavenumber of one and a period around 3 days. *Riggin et al.* 1997 noted that the Kelvin wave amplitudes and the associated momentum fluxes were much weaker at Christmas Island than Jakarta, and speculated that the longitudinal differences could be due to the close proximity of Jakarta to the “warm pool.” Convective heating is considered a leading excitation source for equatorial waves [e.g., *Holton et al.*, 1972; *Chang*, 1976; *Salby and Garcia*, 1987; *Wheeler and Kiladis*, 1999], and it is possible that the waves weaken as they propagate away from this source. Estimates of the momentum flux (force per unit mass) transported by the ultrafast Kelvin waves have been made using satellite measurements [*Lieberman and Riggin*, 1997; and by radar [*Riggin et al.*, 1997]. It is known that the zonal wavenumber of the ultrafast Kelvin waves is one [e.g., *Tsuda et al.*, 1999]. This allows the momentum flux to be estimated given a dispersion relation.

Accounting for the wave momentum flux to drive the westward phase of the MSAO is more difficult, because mixed Rossby gravity modes do not provide sufficient driving. This has led to a hypothesis that the missing driving is due to inertia-gravity wave modes with quasi-diurnal periods. *Bergman and Salby* [1994] determined the space-time spectrum of tropical convection, and modeled the associated “near field” geopotential response. The heating spectrum is isotropically “red” in zonal wavenumber and frequency, with additional peaks at harmonics of the diurnal cycle. However, the power spectrum of vertically propagating waves excited by the heating indicates a preference for waves at the diurnal and semidiurnal frequencies, and waves whose zonal phase speeds are near 15 and 40 m s⁻¹. The phase speed alignment corresponds to Rossby, Kelvin and inertia-gravity wave (IGW) modes whose vertical wavelengths are two-thirds and twice the depth of the convective heating scale *Salby and Garcia*, 1987]. Kelvin and IGW modes with the longer vertical wavelength have higher zonal phase speeds, and can propagate into the upper stratosphere where they are likely to play a role in forcing the SAO.

Sassi and Garcia [1987] incorporated ISCCP-based estimates of tropical Kelvin wave and IGW forcing into a three-dimensional, equatorial beta-plane SAO model with an imposed mean meridional circulation. Successful simulation of the SAO turned out to depend rather critically on forcing by IGW's with zonal wavenumbers between 4 and 15, referred to as “intermediate” scales. When diurnal IGW's were omitted from the forcing, the SSAO westerlies failed to descend below 50 km, while the MSAO disappeared altogether. *Garcia and Sassi* [1999] and *Garcia* [2000] went on to note that westward traveling intermediate-scale IGW's are preferentially dissipated during the easterly (i. e., stronger) phase of the QBO, which presumably diminishes the easterly forcing of the SAO. This premise was tested by *Garcia and Sassi* [1999] using a version of their SAO model with an imposed stratospheric QBO. The suppression of westward IGW's by the QBO easterlies was most pronounced for diurnal waves with zonal wavenumbers larger than 12. The simulated MSAO easterlies also exhibited a quasibiennial modulation similar to that documented by *Burrage et al.* [1996]. The results of *Garcia and Sassi* underscore the apparent significance of diurnal intermediate-scale IGW's for the SAO. However, no attempts have been made to confirm observationally the importance of diurnal IGW's for the SSAO/MSAO system. Global, twice daily synoptic coverage of the middle atmosphere is unavailable above the radiosonde altitudes.

Ground-based observing systems such as meteor wind and MF radars are too sparsely distributed to provide IGW wavenumber resolution. Therefore, we cannot estimate momentum flux using a dispersion relation as was done for Kelvin waves. Observations from middle atmosphere satellites such as TIMED are asymptotic, and normally resolve only zonal wavenumbers 0–6. Thus, there is no current direct experimental confirmation of quasi-diurnal inertia-gravity waves, although this is one of the most important unresolved issues in MLT dynamics. Confirmation of the existence of these waves and estimation of the momentum flux associated with these waves by radar requires direct measurement of the vertical motion. Although such a measurement is very difficult, the proposed Jicamarca radar will have a number of advantages that may help make such a measurement possible using a Doppler technique. The beam will be narrow compared to most existing MF radars, the multiple receivers will allow very accurate determination of echo location, allowing the Doppler signal to be corrected for angle of arrival. Because the measurements are continuous, we can composite vertical velocity estimates over several days (combining velocities obtained at the same time of day). Measurements from the Jicamarca incoherent scatter radar during the daytime will also provide a means to validate vertical velocity estimates obtained by radar. In summary, a leading scientific objective of the proposed radar in regard to large-scale MLT dynamics would be to obtain observational evidence for large-scale diurnal IGW's in the tropical middle atmosphere.

2.2.3 Innovative Techniques

Most of the existing MF radars were built by members of the Atmospheric Sciences Group at University of Adelaide. This development and manufacturing group was incorporated into a private company, Atmospheric Radar Systems (Atrad), in 1995. The uniformity of MF radar design and processing has some advantages for reliability, which is an important consideration since many MF radars run mostly unattended at fairly remote sites. However, this virtual monopoly on MF radars has also tended to suppress innovation. As an illustration, we suspect that the Atrad radars use a processing algorithm for spaced antenna receivers that is close to the original Briggs full correlation analysis (FCA) technique [Briggs, 1984]. We use the word “suspect” here, because the code used to retrieve the winds is proprietary. Because the code is proprietary, there is no opportunity to make improvements or compare the performance of different algorithms.

Very recently there have been some new developments in the processing of spaced receiver signals. Praskovsky and Praskovskaya (2003) presented a highly detailed explanation of the theoretical basis of a new technique based on structure functions instead of correlation functions. In addition to providing mean winds the structure function analysis (SFA) technique can provide turbulence estimates. The SFA technique was developed at the National Center for Atmospheric Research (NCAR) mainly for use in the boundary layer. Experiments were carried out using the NCAR Multiple Antenna Profiler (MAPR) radar that showed generally good agreement with a sonic anemometer mounted atop a 300 m tower at the NOAA Boulder Atmospheric Observatory (BAO) in Erie, Colorado [Praskovsky and Praskovskaya, 2004]. Subsequently, the technique was applied at the Chung-Li Radar in Taiwan and the MU Radar in Japan to measure horizontal winds in the troposphere and lower stratosphere. The structure function technique can be applied at essentially any spaced antenna radar system without hardware modification. However, since the technique is differential in space as well as time, it works best when the receivers are closer together than usual for full correlation analysis.

In 2003, Eleanor Praskovskaya and Dennis Riggan of Colorado Research Associates received a small funding supplement from NSF to test the feasibility of the structure function technique for MF radars. Tests were performed with the MF radar at Rarotonga and the Saura radar in Norway. The Rarotonga radar is a conventional MF radar except that an additional (fourth) receiver was added in the middle of the receiving

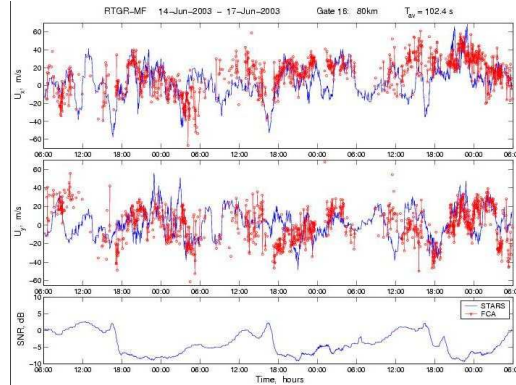


Figure 1: Example of winds obtained at Rarotonga using the structure function technique (blue), compared with winds derived using the online full correlation analysis program.

array, to better satisfy the requirements for structure function analysis. Figure 1 shows a sample result obtained at Rarotonga.

In the previous section we discussed how diurnal composites of vertical velocity could be used to estimate vertical velocities. Although difficult, vertical wind estimates have been demonstrated using time domain interferometry [Vandeppeer and Reid, 1995; Thorsen et al., 1997]. Time domain interferometry makes use of the radial Doppler velocity derived from the received signal's autocorrelation phase at first lag, and the angle of arrival (direction cosines) of the scattered signal, derived from the zero-lag cross-correlation phases. Corrected vertical velocity estimates are possible on a nearly pulse-to-pulse basis. Thorsen et al. carried out tests of the technique using the Urbana MF radar and estimated gravity wave momentum flux. Although these tests were promising, momentum flux estimation using this technique was not subsequently pursued and the Urbana radar is no longer operating. We are not prepared to promise that the technique can be used to measure gravity wave momentum fluxes at Jicamarca, but this project would allow further studies to be pursued. However, we are confident that the technique is practical for estimating tidal vertical wind amplitudes when data are composited over a sufficiently long time span.

2.2.4 Wider impacts

The Jicamarca Radio Observatory is one of NSF's major upper air facilities. In addition to the large transmitters used for incoherent scatter experiments on a campaign basis, the observatory has several instruments used for climatological studies. These include an ionosonde, magnetometer, and the low-power JULIA radar facility. The JULIA radar can make measurements in the troposphere and/or ionosphere, but there is no instrument at Jicamarca for longterm monitoring of the mesosphere. Such an instrument would make an important contribution to future studies outside the scope of this proposal, for example, studies of gravity wave seeding of spread-F. As explained in the following section the radar development will provide training and research opportunities for graduate students at the University of Arkansas at Little Rock. We will also encourage the involvement of Peruvian students to the extent possible.

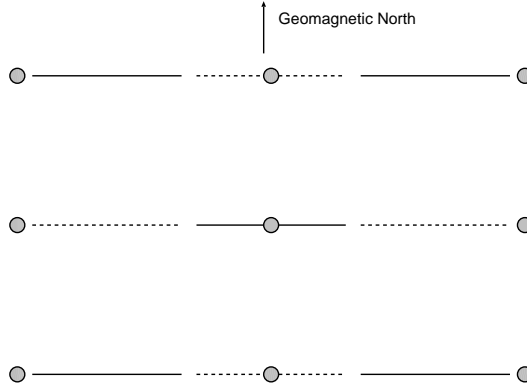


Figure 2: Plan view of the nine dipole element antenna array. All nine dipoles are used for transmission. The dipoles shown as solid lines would be used for both transmission and reception, while the dipoles shown as dashed lines would be used only for transmission. The circular symbols show positions of antenna towers.

2.3 Engineering Design

The two techniques for long-term, continuous (round-the-clock) monitoring of winds in the mesosphere are MF partial reflection radar and meteor scatter radar. Meteor scatter radars compute horizontal winds by collecting echoes over a wide region (~ 600 km) in diameter. The extremely broad spatial averaging makes this radar less suitable than MF radar for the mesospheric scattering layer studies described in the previous section. More seriously, *Chang et al.* [1999] analyzed meteor echoes from a radar at Christmas Island and found an apparent vertical motion with a diurnal period and amplitude of $10\text{--}15\text{ m s}^{-1}$. Chang et al. argued that this motion was not representative of the neutral wind, and that it was probably associated with plasma instabilities under the influence of large polarization electric fields near the geomagnetic equator. Simulations by *Oppenheim et al.* [2000] provided further evidence that meteor trail motion near the equator is controlled by the $\mathbf{E} \times \mathbf{B}$ plasma drift velocity. All meteor radar observations near the geomagnetic equator of waves with periods of 24 hours or less are likely to be contaminated by this effect. In contrast, an MF radar has been operated for a decade at Christmas and the only effect of the magnetic field is a slight elongation of the irregularity pattern along the magnetic field at the upper ranges [R. Vincent, private communication, 2003].

MF radars have some well known disadvantages compared to other techniques, for example, a fairly coarse spatial resolution and a lack of error estimates on the wind retrievals. We propose an innovative design that will address some of these limitations. Most MF radars have a height resolution of ~ 4 km and a beamwidth of $\sim 40^\circ$. Operationally, the effective beam width is probably considerably less than this due to specularity of the echoes. Our antenna configuration (shown in Figure 1) is designed to provide a relatively narrow beam and takes advantage of the position of Jicamarca directly on the geomagnetic equator. As seen in Figure 1 the array consists of 9 linear halfwave dipole elements aligned perpendicular to the magnetic meridian. The dipoles within a string are spaced 0.6λ apart and the strings are also spaced 0.6λ apart. This provides compatibility with the usual FCA configuration with baseline separations of 1.2λ . Normally MF radars transmit and receive a circularly polarized waves on crossed-dipole antennas. However, a wave propagating at exact perpendicularity to the magnetic field will not feel the influence of the magnetic field (i.e., will not rotate or change polarization). We can greatly reduce the cost and complexity of the antenna

array by only using elements which are orthogonal to the magnetic field. Of course some backscatter power is lost because transmitted signal that is propagating to the north or south of the antenna array will not maintain exact perpendicularity to the magnetic field and hence the plane of polarization will have rotated slightly upon reception. Figure 2 shows the effective beam pattern including the loss due to this rotational effect. We estimate that a total of $\sim xx\%$ of the transmitted signal will be lost. However, besides reducing the cost, using only one polarization in the the antenna array has the additional benefit of achieving a narrower effective beamwidth. The antennas would be strung three to a row, although the individual dipoles would not be electrically connected. All of the dipole elements would be used for transmission and 5 dipoles (in the center and four corners) would be used for reception as well and transmission. We have received a frequency allocation from the Peruvian government to transmit at a frequency of 3.1x MHz. This is somewhat higher than the usual transmission frequency of MF radars (~ 2 MHz), but it is similar to the SAURA radar in Norway, and the now decommissioned Urbana MF radar. One advantage of the higher frequency is to reduce the array size. A second advantage of the higher frequency is that we can easily improve the height resolution by a factor of two, from ~ 4 km for a typical MF radar to ~ 2 km. Wind measurements using rocket chemical releases [Larsen, 2002] and lidar sometimes show considerably larger wind magnitudes and shears than have ever been observed with MF radar. This discrepancy is partly explained by the coarse height resolution of typical MF radars, although there also appears to be bias problems that we intend to address using innovative processing. A disadvantage of the higher frequency is to somewhat lower signal-to-noise ratio (mainly an issue at low altitudes during nighttime). The structure function technique discussed earlier in this proposal appears to function better at low signal-to-noise ratio than correlation analysis and can be used to recover some of the lower altitude nighttime winds.

Another principle of our radar design to trade off transmitter power in favor of increased processing power. We intend to improve the velocity estimates by increasing the number of receivers to 5 (most existing MF radars use 3 receivers). The increased number of receivers allows multiple baselines to be formed. The multiple baselines allow independent velocity estimates to be formed and also provides a means of estimating meaningful error bars. Future upgrades (not under this proposal) could conceivably increase the number of receivers up to 9, although there would be a concomitant increase in the requirements for computational power and data storage. The multiple receivers are a significant cost driver, so we intend to adopt a design based on the Gnu Radio Project that has been made available to the community through the Free Software Foundation. GNU Radio is a collection of software that when combined with minimal hardware, allows the construction of receivers where the actual waveforms are detected by software. Developing these receivers is an ideal project for students. Some preliminary work has already been carried by one of our co-I's, Julio Urbino, together with his students at University of Arkansas at Little Rock. Students labor will also be used to design and build a data acquisition system. The T/R switches and transmitter will be purchased from a commercial vendor.

The proposed site for the Jicamarca MF is adjacent to the JRO incoherent scatter radar. This site is on the outskirts of Lima Peru (11.95° S, 76.87° W). The facility is operated by the Geophysical Institute of Peru and personnel are normally on-site during business hours. During the 5 years of this proposal we plan to take advantage of the manpower at the JRO site and collect raw data. New tape drives from the Exabyte Corporation use a new packet technology and can write tapes with very high storage capacity (currently 160 GB). As mentioned in the previous Innovative Techniques Eleanor Praskoskaya of Colorado Research Associates has a proposal to NSF to develop efficient structure function analysis for MF radars. The algorithms developed (if funded) can be directly applied to the Jicamarca MF radar.

3 References

- Bergman, J. W. and M. L. Salby, 1994: Equatorial gravity wave activity generated by fluctuations in observed convection. *J. Atmos. Sci.*, 51, 3791–3806.
- Briggs, B. H., 1984: The analysis of spaced sensor records by correlation techniques, MAP Handbook, 13, 166–186.
- Burrage, M. D., R. A. Vincent, H. G. Mayr, W. R. Skinner, N. F. Arnold, and P. B. Hays, 1996: Long term variability in the equatorial middle atmosphere zonal wind. *J. Geophys. Res.*, 101, 12, 847–12,854.
- Chang, C. P., 1976: Forcing of stratospheric Kelvin waves by tropospheric heat sources. *J. Atmos. Sci.*, 27, 133–138.
- Chang, J. L., S. K. Avery, and R. A. Vincent, 1999: New narrow -beam meteor radar results at Christmas Island: Implications for diurnal wind estimation. *Radio Sci.*, 34, 1, 179–197, 1999.
- Delisi, D. P. and T. J. Dunkerton, 1988: Seasonal variations of the semiannual oscillation. *J. Atmos. Sci.*, 45, 2772–2787.
- Dunkerton, T. J., 1982: Theory of the mesopause semiannual oscillation. *J. Atmos. Sci.*, 39, 2681–2690.
- Garcia, R. R., T. J. Dunkerton, R. S. Lieberman, and R. A. Vincent, 1997: Climatology of the semiannual oscillation of the tropical middle atmosphere. *J. Geophys. Res.*, 102, 26,019–26,032.
- Garcia, R. R. and F. Sassi, 1999: Modulation of the mesospheric semiannual oscillation by the quasibiennial oscillation. *Earth, Planets and Space*, 51, 563–569.
- Garcia, R. R., 2000: The role of equatorial waves in the semiannual oscillation of the middle atmosphere. In *Atmospheric Science across the stratopause*, volume 123 of Geophysical Monograph series. American Geophysical Union, Washington, D. C., 161–176. Edited by D. E. Siskind, M. E. Summers and S. D. Eckermann.
- Gardner, C. S., Y. Zhao, and A. Z. Liu, 2002: Atmospheric stability and gravity wave dissipation in the mesopause region, *J. Atmos. Sol. Terr. Phys.*, 64, 923–929.
- Hamilton, K., 1982: Rocketsonde observations of the mesospheric semiannual oscillation at Kwajalein. *Atmos.-Ocean*, 20, 281–286.
- Hamilton, K., 1986: Dynamics of the stratopause semiannual oscillation. *J. Meteor. Soc. Japan*, 64, 227–244.
- Hamilton, K., R. J. Wilson, J. D. Mahlman, and L. J. Umscheid, 1995: Climatology of the SKYHI troposphere-stratosphere-mesosphere general circulation model. *J. Atmos. Sci.*, 52, 5–43.
- Hirota, I., 1978: Equatorial waves in the upper stratosphere and mesosphere in relation to the semiannual oscillation of the zonal mean wind. *J. Atmos. Sci.*, 35, 714–722.
- Hitchman, M. H. and C. B. Leovy, 1986: Evolution of the zonal mean state in the equatorial middle atmosphere during October 1978–May 1979. *J. Atmos. Sci.*, 43, 3159–3176.
- Hitchman, M. H. and C. B. Leovy, 1988: Estimation of Kelvin wave contribution to the semiannual oscillation. *J. Atmos. Sci.*, 45, 1462–1475.
- Holton, J. R., 1972: Waves in the equatorial stratosphere generated by tropospheric heat sources. *J. Atmos. Sci.*, 29, 368–375.

- Holton, J. R. and W. M. Wehrbein, 1980: The role of planetary waves in the annual cycle of the zonal-mean circulation of the middle atmosphere. *J. Atmos. Sci.*, 37, 1968–1983.
- Kamala, S., D. Narayana Rao, S. C. Chakravarty, J. Datta, B. S. N. Prasad, 2003: Vertical structure of mesospheric echoes from the Indian MST radar, *J. Atmos. Sol. Terr. Phys.*, 65, 71–83.
- Kudeki E., 1988: Radar interferometer observations of mesospheric echoing layers at Jicamarca, *J. Geophys. Res.*, 93, 5413–5421.
- Kudeki, E. and G. R. Stitt, Frequency domain interferometry studies of mesospheric layers at Jicamarca, *Radio Sci.*, 25, 575–590, 1990.
- Larsen, M. F., 2002: Winds and shears in the mesosphere and lower thermosphere: Results from four decades of chemical release wind measurements, *J. Geophys. Res.*, 107(A8), 1215, 10.1029/2001JA000218.
- Lieberman, R. S., M. D. Burrage, D. A. Gell, P. B. Hays, A. R. Marshall, D. A. Ortland, W. R. Skinner, D. L. Wu, R. A. Vincent, and S. J. Franke, 1993: Zonal mean winds in the equatorial mesosphere and lower thermosphere observed by the High Resolution Doppler Imager. *Geophys. Res. Letts.*, 20, 2849–2852.
- Lieberman, R. S., and D. Riggin, 1997: High resolution Doppler imager observations of Kelvin waves in the equatorial mesosphere and lower thermosphere, *J. Geophys. Res.*, 102, 26,117–16,130.
- Mayr, H. G., J. G. Mengel, C. O. Hines, K. L. Chan, N. F. Arnold, and C. A. Reddy, 1997: The gravity wave Doppler spread theory applied in a numerical spectral model of the middle atmosphere. 2. Equatorial oscillations. *J. Geophys. Res.*, 102, 26,093–26,105.
- Mengel, J. G., H. G. Mayr, K. L. Chan, C. O. Hines, C. A. Reddy, N. F. Arnold, and H. S. Potter, 1995: Equatorial oscillations in the middle atmosphere generated by small-scale gravity waves. *Geophys. Res. Letts.*, 22, 3027–3033.
- Oppenheim, M. M., A. F. Endt, and L. P. Dyrud, 2000: Electrodynamics of meteor trail evolution in the equatorial E-region ionosphere, *Geophys. Res. Letts.*, 27, 3173–3176.
- Ray, E. A., M. J. Alexander, and J. R. Holton, 1998: An analysis of the structure and forcing of the equatorial semiannual oscillation in zonal winds. *J. Geophys. Res.*, 103, 1759–1774.
- Reid, R. J., 1966: Zonal wind behavior in the equatorial stratosphere and lower mesosphere. *J. Geophys. Res.*, 71, 4223–4233.
- Reid, I. M., R. Ruester and G. Schmidt, VHF radar observations of cat's-eye like structures at mesospheric heights, *Nature*, 327, 43-45, 1987.
- Riggin, D. M., D. C. Fritts, T. Tsuda, T. Nakamura, and R. A. Vincent, 1997: Radar observations of a 3-day Kelvin wave in the equatorial mesosphere, *J. Geophys. Res.*, 102, 26,141–26,157.
- Salby, M. L. and R. R. Garcia, 1987: Transient response to localized episodic heating in the tropics. Part I: Excitation and short-time, near-field behavior. *J. Atmos. Sci.*, 44, 458–498.
- Sassi, F., R. R. Garcia, and B. A. Boville, 1993: The stratopause semiannual oscillation in the NCAR Community Climate Model. *J. Atmos. Sci.*, 50, 3608–3624.
- Sassi, F. and R. R. Garcia, 1997: The role of equatorial waves forced by convection in the tropical semiannual oscillation. *J. Atmos. Sci.*, 54, 1925–1942.
- Stitt G. R. and E. Kudeki, 1991: Interferometric cross-spectral studies of mesospheric scattering layers, *Radio Sci.*, 26, 783-799.

- Thorsen, D., S. J. Franke, and E. Kudeki, 1997: A new approach to MF radar interferometry for estimating mean winds and momentum flux, *Radio Sci.*, 32, 707-726.
- Tsuda, T., K. Ohnishi, S. Yoshida, A. Shimizu, et al., 1999: Observations of atmospheric waves in the tropical Pacific with radars and radiosondes. *Adv. Space Res.*, 24(11), 1591–1600.
- Vandeppeer, B. G. W., and I. M. Reid, Some preliminary results obtained with the new Adelaide MF Doppler radar, *Radio Sci.*, 30, 1191–1203.
- Wheeler, M. and G. N. Kiladis, 1999: Convectively coupled equatorial waves: Analysis of clouds and temperature in the wavenumber-frequency domain. *J. Atmos. Sci.*, 56, 374–399.
- Yamamoto, M., T. Tsuda, S. Kato, T. Sato, and S. Fukao, Interpretation of the structure of mesospheric turbulence layers in terms of inertia gravity waves, *Physica Scripta*, 37, 645–650, 1988.