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N85-32467

1. METEOROLOGICAL AND AERONOMICAL REQUIREMENTS FOR MST RADAR NETWORKS (Keynote Paper)

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INTRODUCTION

MST radar are phase coherent radars that measure the amplitude and Doppler shift of radio waves that are scattered back to the receiving antennas. For a monostatic system, the line-of-sight projection of the wind vector is obtained if one assumes that the atmospheric scatterers are being swept along with the wind velocity. The three-dimensional wind is then derived either by using multiple beams or by beam swinging. The turbulence intensity is derived either by measuring the backscattered power or by deriving the width of the autocorrelation function for the wind. Furthermore, some information on sharp changes in the atmospheric static stability (e.g. at the tropopause) can be obtained by looking for specular reflections. In the following, we will discuss how these MST measurement capabilities can contribute to various meteorological and aeronomical research areas.

TROPOSPHERE-STRATOSPHERE EXCHANGE

We can distinguish among various types of troposphere-stratosphere interactions. There are dynamical interactions. For instance, troposphere dynamics communicate with stratosphere and mesosphere dynamics through the vertical propagation of extratropical planetary waves, tropical waves, tides, and gravity waves. Extratropical planetary waves require global measurements and thus would require a global network of radars; however, since extratropical planetary wave motions are geostrophic, satellite measurements can be used for their study. On the other hand, since equatorial wave motions are ageostrophic their motions cannot be easily derived from satellite measurements, so MST radars can play a very important role in their study. Tides and gravity waves can also be studied by MST radars since they are capable of obtaining freqv ly space wind profiles with good altitude resolution.

On the subject of troposphere-stratosphere mass exchange, tropospheric air has long been thought to enter the stratosphere in the rising air of the Hadley circulation. More recently, however, evidence has been accumulating that this is not a symmetric process but takes place in conjunction with the intense convective activity that occurs in the Indonesian-Malaysian sector in the November-March period and over the Bay of Bengal and India during the Monsoon. Extensive aircraft programs are being mounted to study this process. MST radars could study these processes if they were located properly. For instance, a meridional chain of MST radars in the tropics could study the Hadley ciculation, and a zonal chain could study the Walker circulation. It should be noted that the first "equatorial" ST radar has recently been established at an island location at 158°E and 7°N.

Several groups in the world are making plans to establish prototype ST radar networks. One such network has already been operated for about one year in Colorado by NOAA's Wave Propagation Laboratory. The Australian Bureau of Meteorology and CSIRO are planning to establish a network to enhance the prediction of cold fronts during the summer season. The Pennsylvania State University is planning a network of three ST radars to study mesoscale dynamics, and finally NOAA is considering establishing an extensive ST network throughout the middle United States to provide data for their mesoscale forecasting models.

Given that more extensive ST networks are foreseen in the near future, various issues arise. Some of these are as follows:

(1) Since ST network data can be very valuable for both operational and research purposes, how can we best ensure that valuable information on gravity wave motions, for example, are not lost in the data reduction process and that the ST network data are available to be used for research purposes.

(2) It is very important that mesoscale modelers participate in the planning of future mesoscale ST networks.

Stratospheric air is thought to descend into the troposphere in extratropical latitudes in conjunction with tropopause folding events. Some work has been done on measuring the transverse circulation around the jet stream and more could be done on this.

ST radars can also obtain climatologies of clear air turbulence and vertical velocity. There is, however, the nagging problem of the apparent paradox between radar and aircraft measurements of lower stratosphere turbulence. Meteorological aircraft data indicate that turbulence plays a negligible role in vertical constituent transport in the lower stratosphere. Radar data indicates that turbulence plays a much larger role. This apparent discrepancy needs resolution. Balloon measurements of turbulence can play a very large role in this.

SEVERE WEATHER AND FRONTS

Conventional meteorological radar only gives returns when precipitation is present. ST radar networks potentially could be used to follow the organization of severe weather in clear air before precipitation begins. Given that millimeter radars can sense clouds in the precipitation phase, a properly conceived radar network could sense the entire life cycle of mesoscale events, occurring within such a network.

GRAVITY WAVES FROM STRATOSPHERE TO MESOSPHERE

MST radars can get wind profiles with very good height and time resolution. This makes them very well suited for gravity-wave studies. So far, there have been measurements of wave spectra, wave momentum fluxes, and some process studies from selected cases. MST networks are required to measure such important wave parameters as horizontal wavelength and wave phase velocity. In interpreting MST radar data on gravity waves it is very important to be aware that gravity waves can travel thousands of km from their tropospheric source and reacn mesospheric altitudes days after being launched. This, in addition to the fact that radiative damping processes will absorb many gravity waves in the stratosphere, should be kept in mind when analyzing mesospheric gravity wave data.

GENERAL CIRCULATION OF THE MIDDLE ATMOSPHERE INCLUDING EQUATORIAL WAVES

Since the general circulation is, by definition, a global scale phenomenon, a global network of MST radars would be required to study the general circulation of the middle atmosphere in a straightforward manner. Radar data and temperature data would still be required. On the other hand, MST data from even a few stations are valuable as is evidenced by the significance of the radar measurements of meridional motions in the mesosphere. One difficulty, however, is to demonstrate the representativeness of single station measurements. This can be done by using satellite data, for example.

Single station statistics of wind profile fluctuations can be quite useful to test general circulation model simulations. Also, radar data together with satellite data can be used to look at the transition from a predominantly geostrophic to an ageostrophic regime.

One issue to which MST radars can contribute significantly is in the study of stratopsheric gravity waves. It is now appreciated that gravity waves play a very important role in the general circulation of the mesosphere, but it is not known how important a role they play in the stratosphere.

Finally, an equatorial MST radar could be used to look at the interactions between tropical waves and the mean flow.

WIND AND CAT PROFILING

As was mentioned in the introduction, MST radars provide profiles of wind velocity and turbulence. These profiles could be used operationally (e.g. near airports), could substitute for rawinsonde wind measurements in providing initial conditions for meteorological forecasts, as well as be used for research purposes.

Experience with the Colorado Wind-Profiling Network has illustrated some of the practical difficulties that are encountered with an MST radar network. These include frequency allocation problems, altitude limitations on data acquisition, radio interference problems, site selection; and slow data processing procedures.

TROPOPAUSE HEIGHT DETERMINATION

It has been demonstrated that there is enhanced backscattered power from the tropopause for a vertically pointing beam relative to that for one pointing off-vertical due to specular reflection. These measurements can be used to obtain ground-based measurements of tropopause heights. These measurements can be quite useful. For example, such knowledge can be helpful in satellite temperature retrievals.

SYNOPTIC-SCALE DYNAMICS WITH VERTICAL VELOCITY

MST radars are unique in their ability to directly measure vertical velocities instead of deriving it indirectly as is usually done in meteorology. Experience has shown that one can statistically obtain large-scale vertical velocities at a single radar site to ± 2 cm s^{-1} with about nine hours of data during quiet times. These "quiet" times have been found to occur about 10-40% of the time depending on the terrain of the radar site. Studies have shown that radar measured vertical velocities are usually quite similar to those derived from meteorological models but have a tendency to be a bit larger than the derived vertical velocities. The reasons for this are not understood at the present time.

OPTIMIZATION OF ST RADAR NETWORKS FOR STUDIES OF ATMOSPHERIC STRUCTURE AND PROCESSES

ST networks can contribute valuable data for many studies of the atmosphere. Among these are studies of mesoscale dynamics and studies of tropospheric sources for gravity waves. It is not clear that we can define a single optimal network of all these purposes or indeed whether it is best to use a variety of network configurations with transportable ST radars to investigate phenomena with various radar spacings. We believe that studies should be carried out with portable ST systems to investigate optimal spacings. We also believe that studies with mesoscale model simulations can help in establishing desired network configurations.

SUMMARY

Since equatorial wave motions are ageostrophic their motions cannot be derived easily from satellite measurements, so MST radars can play a very important role in their study. Tides and gravity waves can also be studied by MST radars since they are capable of obtaining frequently spaced wind profiles with good altitude resolution.

A meridional chain of MST radars in the tropics could study the Hadley circulation, and a zonal chain could study the Walker circulation.

ST radars can also obtain climatologies of clear air turbulence and vertical velocity. Balloon measurements of turbulence can play a very large role in this.

A properly conceived radar network could sense the entire life cycle of mesoscale events occurring within such a network.

In interpreting MST radar data on gravity waves it is very important to be aware that gravity waves can travel thousands of km from their tropospheric source and reach mesospheric altitudes days after being launched. This, in addition to the fact that radiometric damping processes will absorb many gravity waves in the stratosphere, should be kept in mind when analyzing mesospheric gravity-wave data.

One difficulty, however, is to demonstrate the representativeness of single station measurements. Single station statistics of wind profile fluctuations can be quite useful to test general circulation model simulations.

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Experience with the Colorado Wind-Profiling Network has illustrated some of the practical difficulties that are encountered with an MST radar network. These include frequency allocation problems, altitude limitations on data acquisition, radio interference problems, site selection, and also data processing procedures.

These measurements can be used to obtain ground-based measurements of tropopause heights. These measurements can be quite useful. For example, such knowledge can be helpful in satellite temperature retrievals.

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It is not clear that we can define a single optimal network of all these purposes or indeed whether it is best to use a variety of network configurations with transportable ST radars to investigate phenomena with various radar spacings.

We believe that studies should be carried out with portable ST systems to investigate optimal network spacings. We also believe that studies with mesoscale model simulations can help in establishing desired network configurations.