1.2A JET STREAM RELATED OBSERVATIONS BY MST RADARS

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ABSTRACT

This paper presents an overview of the jet stream and its observation by MST radar. The climatology and synoptic and mesoscale structure of jet streams is briefly reviewed. MST radar observations of jet stream winds, and associated waves and turbulence are then considered. The possibility of using a network of ST radars to track jet stream winds in near real-time is explored.

INTRODUCTION

The jet stream is one of the most important and prominent features evident on upper level synoptic maps. Meteorological investigations of the jet stream have a long history dating back to early upper-level balloon observations. Actually, there are a multiplicity of jet stream phenomenon that have been observed in different regions of the atmosphere. For example, low-level jets are important in the dynamics of the planetary boundary layer (BONNER, 1968) and the Polar night jet plays a central role in the dynamics of the middle atmosphere (GELLER, 1979). The principal jet streams which have been studied by meteorologists are those which are evident at midlatitudes at tropopause heights: namely, the subtropical jet and the Polar front jet.

This survey is concerned primarily with MST/ST radar observations related to midlatitude jet streams. Before reviewing some of the jet stream-related observations the synoptic and mesoscale structure of jet streams will be briefly reviewed. The radar observations which follow are concerned with mean horizontal wind, vertical wind and concurrent measurements of turbulence and waves.

CLIMATOLOGICAL AND LARGE-SCALE FEATURES OF JET STREAMS

Synoptic scale analyses of jet stream structure can be found in REITER (1963), and PALMEN and NEWTON (1969) etc. Basically the jet streams are found in the baroclinic zones which are associated with the tropopause breaks as shown in Figure 1. DEFANT and TABA (1957) drew attention to this relationship by pointing out that there are three major latitude bands with different tropopause heights: The tropical tropopause (16-17 km) extending to about 40N, the midlatitude tropopause (10-12 km in the winter) ranging from about 30N to 60N and the polar tropopause (8-10 km, in the winter) north of 60N. Accordingly, the subtropical jet is found at about 12 km (200 mb) near latitude 30N and the polar front jet is found at about 9 km (300 mb) in the range 40-60 N.

The location of the jet stream varies greatly from day to day. The meandering of the jet stream follows the planetary waves and shows varying degrees of structure. At times the jet stream winds flow primarily, zonally, i.e., west to east. More often wave disturbances are evident and pronounced troughs and ridges are present. Such day-to-day variations are known to play an important role in the dynamics of tropospheric storms which give us our weather.

The jet streams are, of course, more pronounced during the winter season when meridional temperature gradients are most intense. The mean axis of the subtropical jet stream in the Northern Hemisphere is shown in Figure 2. Also shown in this figure is the principal range of the polar front jet stream. Both

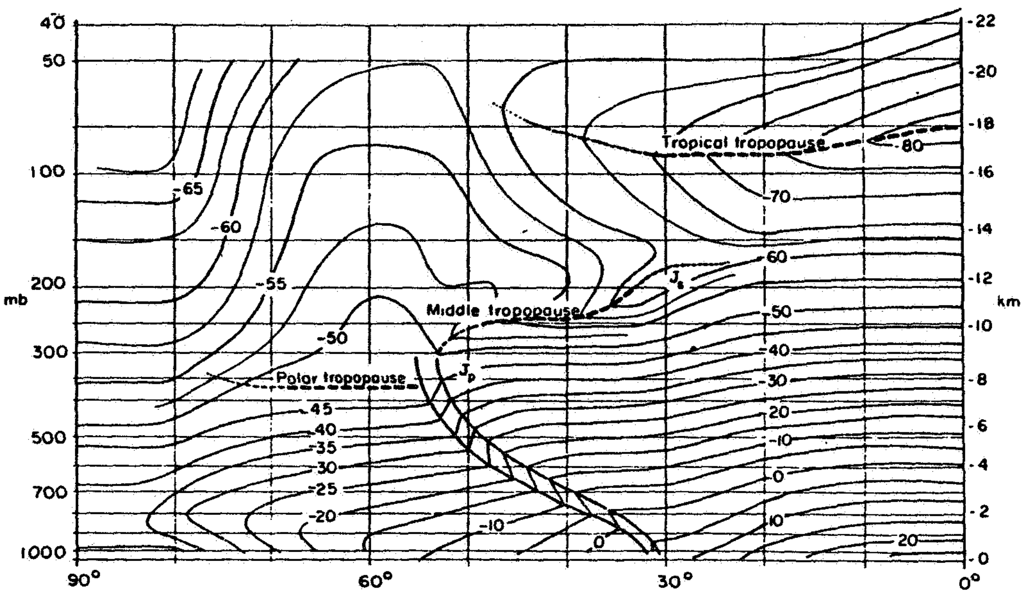

Figure 1. Meridional cross section showing mean conditions around the Northern Hemisphere on Jan. 1, 1956. J_p and J_s denote locations of the polar front and subtropical jet streams. Isotherms in degrees celsius (after DEFANT and TABA, 1957).

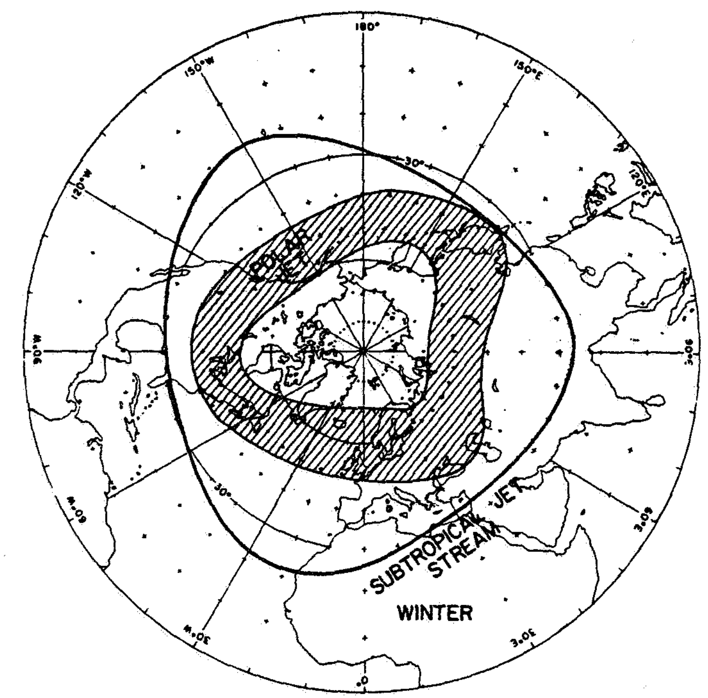

Figure 2. Mean axis of subtropical jet stream during winter, and area (shaded) of principal activity of polar-front jet stream (after RIEHL, 1962).

jet streams show a pattern distorted by standing planetary waves. There is an out-of-phase relation between the troughs and ridges in the two jet streams. For example, Japan and the eastern United States are located at longitudes where the two jet streams come together. As a consequence jet streams in these locations are particularly strong.

MESOSCALE STRUCTURE OF JET STREAMS

While jet streams can be resolved on upper level synoptic maps, they possess considerable mesoscale structure which cannot be resolved. Continuous MST/ST radar observations from a single station have been used to infer some of this structure (GREEN et al., 1978; LARSEN and ROTTGER, 1982; and SHAPIRO et al., 1983). Nevertheless, most of our knowledge of the mesoscale structure of jet streams has been derived from careful analysis of data collected by research aircraft (SHAPIRO, 1974, 1978).

A typical cross section across a polar-front jet stream is reproduced in Figure 3a. This schematic cross section shows the relationship of the jet stream winds to the locations of the tropopause and the upper level frontal zone. If the jet stream is zonal (west-east), the maximum winds are found just below the tropopause and just south of the upper level front. Strong wind shear is concentrated in the polar front beneath the jet stream.

The MST radar (at lower VHF) observes enhanced reflectivity at vertical incidence from stable regions of the atmosphere (GAGE and GREEN, 1978, 1979; and ROTTGER and LIU, 1978). As a consequence, it is possible to resolve the tropopause and frontal structure associated with jet streams from continuous MST radar observations. This capability is shown most clearly in Figure 3b reproduced from LARSEN and ROTTGER (1982). Wind measurements, of course, can be made simultaneously.

One of the important features associated with the polar-front jet stream is the occurrence of stratospheric intrusions. These have been studied extensively (see, e.g., DANIELSEN, 1968; and REITER, 1975) as an important mechanism for the exchange for chemical constituents between the stratosphere and troposphere. Basically, the upper level fronts which protrude into the troposphere contain stratospheric ozone, etc. and provide a locus for turbulent mixing of tropospheric and stratospheric constituents (SHAPIRO, 1980). These stratospheric intrusions are visible to the MST radar as evidenced by Figure 3.

Recently, considerable attention has been focused on ageostrophic circulations associated with jet streaks (SECHRIST and WHITTAKER, 1979; UCCELLINI and JOHNSON, 1979; SHAPIRO 1981; and SHAPIRO and KENNEDY, 1981). Jet streaks are regions of local wind maxima which can often be seen to propagate along jet streams. Entrance and exit regions of jet streaks have been shown to possess significant ageostrophic motions resulting from adjustment of the wind to the mass field.

In the entrance region a thermally direct transverse circulation is set up so that warm air rises and cold air sinks. By contrast a thermally indirect transverse circulation is set up in the exit region. SECHRIST and WHITTAKER (1979) consider the implications of propagating jet streaks on the development of cyclonic disturbances in the atmosphere.

While the magnitude of the transverse circulations referred to above may be too small to detect in routine MST radar observations, other ageostrophic motions exist which should easily be observed. UCCELLINI and JOHNSON (1979) describe the ageostrophic winds to be expected in the entrance and exit regions of jet streaks. In the entrance region confluent streamlines and downstreams acceleration of geostrophic wind leads to an ageostrophic component directed

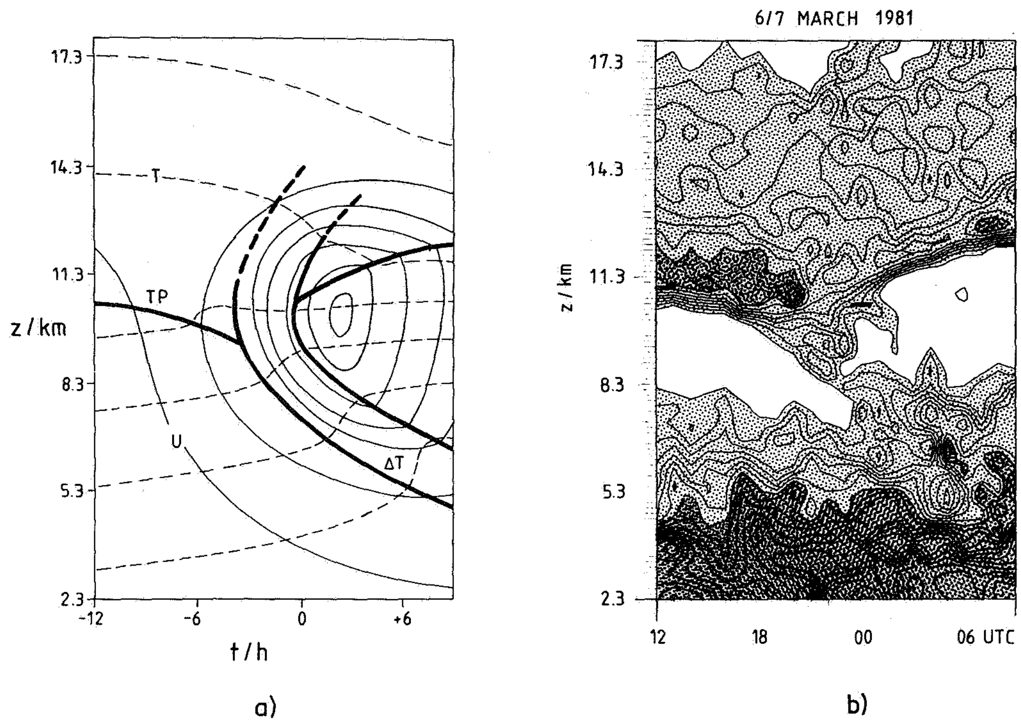

Figure 3. a. Thermal structure and winds near fronts adapted from PALMEN and NEWTON (1969) by LARSEN and ROTTGER (1982). The heavy line labeled TP corresponds to the height of the tropopause. The dashed lines are isotherms, and the solid lines are the isotachs. The jet is located on the warm side of the front just below the tropopause. b. Reflectivity contour plot obtained using the SOUSY radar. Difference between contour lines is 2 dB. Intensity of shading corresponds to intensity of echoes (after LARSEN and ROTTGER, 1982).

toward the cylonic side of the jet streak. In the exit region diffluent streamlines and downstream deceleration of the geostrophic wind leads to an ageostrophic component directed to the anticyclonic side of the jet streak. The magnitude of these ageostrophic winds are expected to be about 10 ms^{-1}. SHAPIRO and KENNEDY (1981) report cross-height contour ageostrophic winds as exceeding 20 ms^{-1}.

MST RADAR OBSERVATIONS OF WAVES AND TURBULENCE ASSOCIATED WITH JET STREAMS

MST radars have been used successfully in the past few years to observe waves and turbulence associated with jet streams. These observations include: Kelvin-Helmholtz instabilities, clear air turbulence and gravity waves.

Shear flow instabilities in stratified fluids are commonly referred to as Kelvin-Helmholtz instabilities. For many years fluid dynamicists investigated this class of instabilities using linear stability theory applied to highly idealized models with specified profiles of mean flow and stability (DRAZIN and HOWARD, 1967; and DRAZIN and REID, 1981). With the use of power UHF radars in the 1960s the connection between the occurrence of clear air turbulence and Kelvin-Helmholtz instability was clarified (ATLAS et al., 1970; and DUTTON and PANOFSKY, 1971). With the advent of more powerful VHF and UHF Doppler radars capable of detailed wind measurements over a broad range of altitudes, it became possible to quantitatively investigate Kelvin-Helmholtz instabilities. For the first time the stability of realistic models simulating observed atmospheric flows were investigated and the results compared to detailed radar observations (VANZANDT et al., 1979; and KLOSTERMEYER and RUSTER, 1980).

An example of the high-frequency velocity fluctuations which can be resolved by an MST radar is contained in Figure 4. This figure shows the filtered radial velocity fluctuations observed by the SOUSY radar during a jet stream passage. The decrease in amplitude and the phase shift evident at the height of generation in the observations has been modelled successfully. In addition to the instability a clear modulation of background turbulence with the phase of the resulting "wave" disturbance has been shown by VANZANDT et al. (1979) and by KLOSTERMEYER and RUSTER (1981).

The occurrence of clear air turbulence in the free atmosphere is thought to be controlled by the magnitude of the Richardson number. If the wind shear is large enough to overcome the stabilizing effect of buoyancy, instabilities arise and turbulence is generated. Under such circumstances the Richardson number should be close to .25. However, the Richardson number depends very much on the vertical scale over which it is calculated. The scale dependence of the Richardson number appears to be a result of the perturbing influence of waves and is consistent with the idea that the occurrence of clear air turbulence is related to <u>both</u> the background wind and temperature fields and the intensity of the background wave field (BRETHERTON, 1969).

The fact that the wave activity varies greatly from day-to-day can be seen in the variability of the vertical wind (ECKLUND et al., 1981, 1982). Figure 5 shows the strong correlation that exists between zonal wind and the intensity of wave activity observed at Platteville, CO in the lee of the Colorado Rockies.

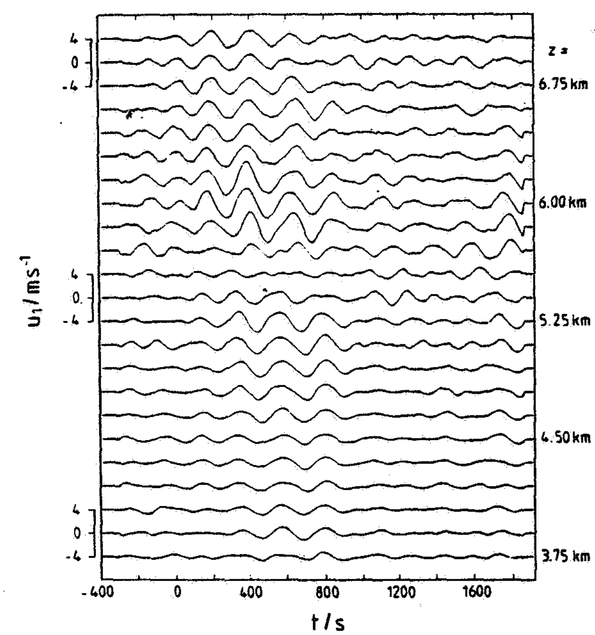

Figure 4. Band-pass-filtered time series of radial velocity observed by the SOUSY radar illustrating Kelvin-Helmholtz instability during a jet stream passage (after KLOSTERMEYER and RUSTER, 1981).

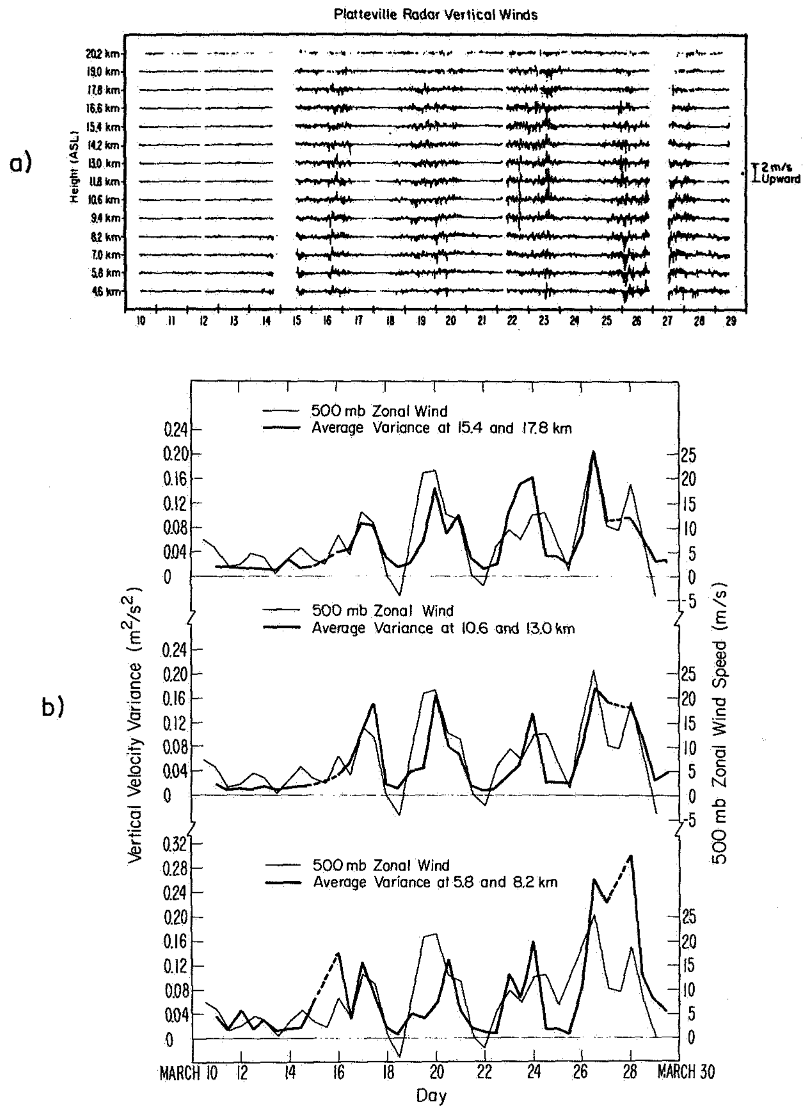

Figure 5. a. Vertical velocities observed by the Platteville radar during March 1981. b. A comparison of the vertical velocity variance shown in a. with the 500 mb zonal wind (after ECKLUND et al., 1982).

While further observations in other locations will be required to determine how much of this variability is due to topography, all indications to date suggest a significant dependence of wave activity on wind speed (NASTROM and GAGE, 1983).

If the occurrence of clear air turbulence depends on both the background wind and stability and the background wave activity, it follows that the magnitude of clear air turbulence should be significantly enhanced under jet stream conditions. This is in accord with common experience that MST radars can see to higher altitudes during jet stream conditions. Indeed, the analyses of VANZANDT et al. (1978), NASTROM et al. (1981), and SMITH et al. (1983) show a clear relation between the magnitude of C_n^2 and jet stream level winds. Following GAGE et al. (1980) it is possible to estimate eddy dissipation rates observations of C_n^2. Figure 6 shows the variation of eddy dissipation rates determined in this fashion during a jet stream passage over the Sunset radar in Colorado. These observations reveal a variation of eddy dissipation rates in excess of 3 orders of magnitude. The most intense regions of turbulence are located as expected in the shear zones above and below the jet stream core.

APPLICATION OF ST RADARS TO JET STREAM NOWCASTING

Considerable interest and attention has been focused recently (CARLSON and SUNDARARAM, 1982) on the potential savings to the aviation industry of having accurate and timely wind information at flight altitudes. The network of rawinsonde sites which currently provide upper level wind data is shown in Figure 7. This network is too sparse and the 12-hour sounding schedule currently in use is inadequate to resolve mesoscale jet stream structure. A network of ST radars constructed on a 100 km grid is illustrated in Figure 8. Such a network could be constructed for less than $100 million. The estimated annual fuel savings to the domestic commercial aviation industry range from 1-3%. Current annual fuel consumption is in the neighborhood of 45 billion liters. At a cost of 25 cents a liter a 1% fuel savings would be sufficient to pay for the construction cost in the first year of operation.

CONCLUDING REMARKS

Jet stream related observations of MST radars have been summarized. To date these observations have been limited to single stations and mostly to case studies. The uniqueness of the data sets obtained by MST radars lies in their temporal continuity. Temporal continuity enables the inference of spatial structure provided temporal evolution is not too fast. It is clear, however, that the ultimate utility of MST radars for jet stream analysis will be realized only after mesoscale networks of ST radars are in operation.

Mesoscale networks of ST radars may be in operation in the very near future. A small network is nearing completion in Colorado to be used in conjunction with the Prototype Regional Observation and Forecast System (PROFS). As

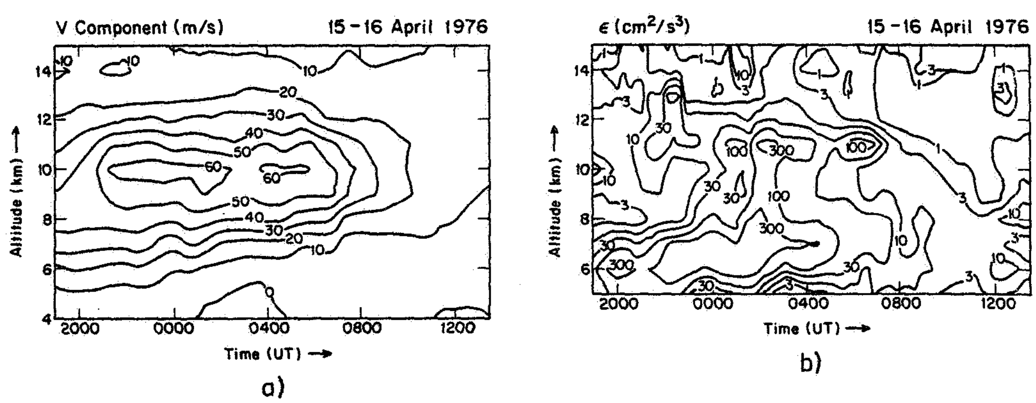

Figure 6. Observations of the Sunset radar during a jet stream passage April 15-16, 1976: a. Time-height contours of south wind v; b. Time-height contours of ε estimated from C_n^2 (after GAGE et al., 1980).

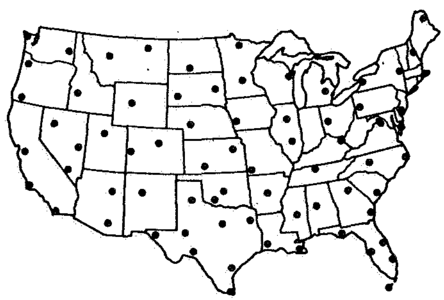

Figure 7. Existing upper-air observational network.

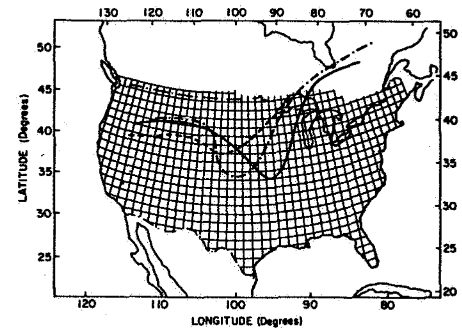

Figure 8. Illustrative network of ST radars for tracking jet stream in real time at a spacing of every 100 km. Also shown are representative locations of the jet stream core at three consecutive 24 hr intervals (after REITER, 1963; CARLSON and SUNDARARAMAN, 1982).

noted earlier, the potential savings to the airline industry of an operational mesoscale network of ST radars may provide the incentive for the realization of much larger networks in the very near future. Finally, the National Weather Service is considering how to implement the wind sensing capabilities of ST radars into their observing system. Clearly, the wind information obtained from dense networks of ST radars should lead to a greatly improved understanding of mesoscale structure of jet streams.

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