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Measuring the Global Distribution of Intense Convection over Land with Passive Microwave Radiometry

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ABSTRACT

The global distribution of intense convective activity over land is shown to be measurable with satellite passive-microwave methods through a comparison of an empirical rain rate algorithm with a climatology of thunderstorm days for the months of June–August. With the 18 and 37 GHz channels of the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR), the strong volume scattering effects of precipitation can be measured. Even though a single frequency (37 GHz) is responsive to the scattering signature, two frequencies are needed to remove most of the effect that variations in thermometric temperatures and soil moisture have on the brightness temperatures. Because snow cover is also a volume scatterer of microwave energy at these microwavelengths, a discrimination procedure involving four of the SMMR channels is employed to separate the rain and snow classes, based upon their differences in average thermometric temperature.

1. Introduction

The global distribution of thunderstorm activity over land has usually been estimated through surface observations of the number of thunderstorm days (days on which thunder is heard, WMO, 1953). Court and Griffiths (1983) reviewed the work of many investigators who have documented the incidence of thunder, hail and tornados on space scales, ranging from local to global, and time scales from a season to many decades. They point out that the observation of these events is greatly dependent upon several criteria: the density of reporting stations; the definition of the event being observed; the existence of diurnal maxima; and the noise level around the reporting station, to name a few.

Studies of satellite-sensed lightning discharges over the earth (e.g., Orville and Spencer, 1979; Orville, 1981) have revealed that the basic climatological patterns of convective activity are observable from a satellite.

Satellite passive microwave observations provide the opportunity to observe only the precipitating portions of storms, the nonprecipitating cloudy portions being relatively transparent to window frequency radiation below about 40 GHz. Here, data from the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) (Gloersen and Barath, 1977) will be used. The SMMR measures horizontally and vertically polarized brightness temperatures (T_B) of the earth at a 50° incidence angle at 37, 21, 18, 10.7, and 6.6 GHz, with spatial resolutions of 27, 46, 55, 91, and 148 km, respectively. The Nimbus-7 satellite is in a sun-synchronous polar orbit, with SMMR observations at local noon and midnight every other day. Spencer *et al.* (1983a) showed that the 37 GHz brightness temperatures observed by the SMMR are approximately linearly related to convective rain rates observed by operational WSR-57 radars over the United States (U.S.). When the SMMR observed convective activity, it was found that all T_B below 220 K (and as low as 163 K) corresponded to heavy convective rainfall as observed by radar. These storms had Digital Video Integrator and Processor (D-VIP) levels of at least three (rain rates of at least 28 mm h^{-1}). Such low temperatures were usually restricted to areas embedded within (and much smaller than) the thick cirrus canopy observed by infrared (IR) sensors. These low T_B can be explained by the scattering of upwelling radiation by precipitation-size ice particles in the upper portions of the storms.

Even though the 37 GHz channel is sensitive to this scattering effect, which is then related to the total attenuation and thus the rain rate, these rates can be measured more accurately if more than one SMMR channel is employed; this is because of the other effects that can lead to T_B changes that are not due to attenuation by rain. The rain rates (as determined by radar) are more closely related to the difference in T_B between the 37 GHz and the lower frequency SMMR channels (18 and 21 GHz: Spencer *et al.*,

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1983b; Spencer, 1984). The T_B ($=\epsilon T$) measured by a single channel is a function of thermometric temperature as well as different geophysical emissivity effects, of which rain is only one. Surface emissivity depressions due to water bodies or moist soil can be identified by either dual-polarization information (Weinman and Guetter, 1977), because of the highly polarized nature of moist surfaces compared to the low or moderately polarized signature of rain systems; or by dual-frequency information (Grody, 1984) because for emissive surfaces such as water or moist soil, the emissivity increases with frequency while for volume scatterers it decreases with frequency. The effects of thermometric temperature variations can also be greatly reduced by the utilization of two frequencies, since the difference between their brightness temperatures is much less affected by this signal than is a single frequency (Spencer, 1984). Therefore, two frequencies (here, 18 and 37 GHz) will be utilized to isolate the heavily precipitating storms, while polarization information will also be utilized to help remove the effects of water bodies and moist soil.

The primary purpose of this paper is to show that the global mapping of intense convective activity over land is possible with passive microwave methods, through utilization of Nimbus-7 SMMR data from the period 1 June– 31 August 1980. This satellite-derived distribution will be compared to a global climatology of surface-observed thunderstorm days. The SMMR-observed storms, however, will not be referred to as "thunderstorms" due to the lack of corroborative information on the existence of thunder within storms that are not in the vicinity of a meteorological observing station.

2. Scanning the SMMR data

To develop a method for identifying storms in the 1980 data set, a dependent set of original resolution SMMR data from 25 February to 22 May 1979 over the United States and Southern Canada, and from 3 July to 31 July over the global land areas covered by the SMMR, were screened and analyzed on the University of Wisconsin's Man-computer Interactive Data Access System (McIDAS; Suomi *et al.*, 1983). The first screening procedure involved accepting only those footprints where the 37 GHz polarization (difference between the vertically and horizontally polarized T_B) was relatively small, i.e.

$$T_B^{V37} - T_B^{H37} \leqslant 19°C. \qquad (1)$$

This is based upon observations from the SMMR that have revealed that polarizations associated with intense convective clouds seldom rise above 19°C (Spencer, 1984), while snow cover often has polarizations from 20–50°C (Foster, *et al.*, 1984), and wet ground or water surfaces also have values in this range (Weinman and Guetter, 1977).

We then utilized the horizontally polarized 18 and 37 GHz channels to isolate those regions having strong volume scattering signatures, requiring

$$(T_B^{H18} - T_B^{H37}) \geqslant 20°C. \qquad (2)$$

This will include data from rain systems having rain rates of 21 mm h^{-1} or greater, based upon a comparison between data from nine passes of the SMMR over the central United States to data from eighty-five WSR-57 radars during the summer of 1979 (Spencer, 1984). However, this will also include snow fields having depths > 31 cm, that were not first ruled out by the screening procedure represented by (1), as established by Kunzi *et al.* (1982) in their analysis of Asian and European snow fields with the SMMR data. Because snow fields typically have 37 GHz polarizations of 20–50°C (depending upon the depth), any snow field data accepted by (1) and (2) would represent relatively rough surfaces on the scale of the 37 GHz wavelength (0.81 cm). Like precipitation, snow cover is a volume scatterer of microwave radiation due to ice particles and other snow inhomogeneities contained within the snow layer (Foster *et al.*, 1984); thus if we only look for volume scatterers, snow can be mistaken for rain, and *vice versa.* These screening criteria were then applied to the 1979 data, which led to a mixture of storm and snow observations (Fig. 1) that were manually checked to separate the

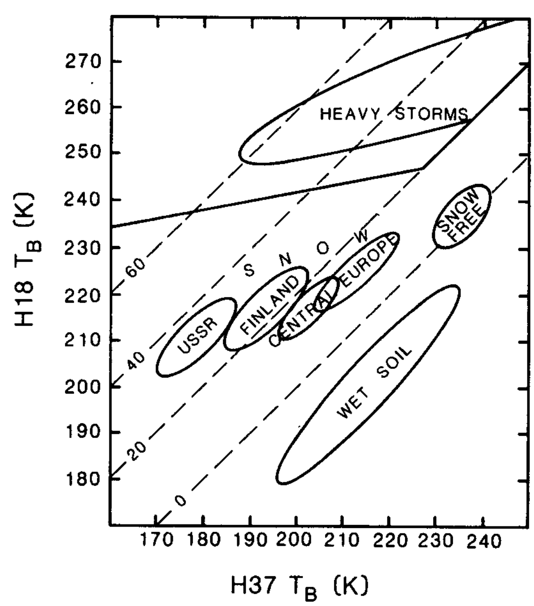

FIG. 1. Nimbus-7 SMMR 18 and 37 GHz signatures of snow cover and wet soil (from Kunzi *et al.*, 1982), and SMMR-observed convective storms from around the world during July of 1979. The ellipses enclose 90% of the data in each class. Sloping dashed lines are constant values of $T_B^{H18} - T_B^{H37}$, the larger values of which represent stronger volume scattering. The sloping solid lines represent part of the screening procedure for isolating the relatively intense convective events.

storms (typically a few low T_B embedded within a higher T_B land background) from the snow "false alarms" (typically one or two footprints embedded within a large snow field having widespread low 37 GHz T_B, usually in mountainous regions). From Fig. 1 we can see that the average brightness temperatures of the rain events are considerably higher than those of the snow fields observed by Kunzi *et al.* (1982). Based upon our storm and snow signatures in the 18 and 37 GHz data, a threshold was chosen above which heavy storms make up most of the population and below which snow is the primary constituent, represented by the sloping solid line intersecting the ordinate in Fig. 1, and defined by

$$T_B^{H18} > 234 + 0.2(T_B^{H37} - 160). \quad (3)$$

This line can be interpreted as separating the warm scattering media (storms) from the cold scattering media (snow fields). When this additional screening procedure was then applied to the North American data (25 February–22 May 1979) a few footprints (total 45 versus 136 storm-related) were still misinterpreted as storms, within the vast snow fields of the Rocky Mountains. In an effort to more completely separate these two classes, we analyzed the remaining storm and snow cases at 37, 21, 18, and 10.7 GHz statistically with stepwise discriminate analysis (Dixon, 1983). It was found that even these "borderline" cases were separable with 93% accuracy by requiring that

$$216.65 - 0.65(T_B^{H21}) + 0.276(T_B^{V37}) - 0.283(T_B^{V18}) - 0.190(T_B^{V21}) < 0 \quad (4)$$

be satisfied for the data to be classified as storm related. Because the 21 GHz channels are near the 22.235 GHz water vapor absorption line (and so are more affected by the temperature of the atmosphere than the other SMMR channels), the appearance of the 21 GHz terms in Eq. (4) is interpreted as an indication that the snow cases are attended by colder environmental conditions than the storms are. Thus, the four conditions described by Eqs. (1)–(4) establish the screening procedure for intense convective storms over land, and are summarized in Table 1.

TABLE 1. Four-step screening procedure for the isolation of intense convective systems over land from Nimbus-7 SMMR full resolution data. See text for details.

Screening procedure	Reason
$T_B^{V37} - T_B^{H37} \leq 19°C$.	To rule out highly polarized surfaces (oceans, lakes, wet soil, most snow fields).
$T_B^{H18} - T_B^{H37} \geq 20°C$.	Accept strong volume scatterers of microwave energy (heavy rain cells and deep snow fields).
$T_B^{H18} > 234 + 0.2(T_B^{H37} - 160)$.	Rough separation between weakly polarized snow fields and rain cells, partly based upon thermometric temperature differences.
$216.65 - 0.65(T_B^{H21}) + 0.276(T_B^{V37}) - 0.283(T_B^{V18}) - 0.190(T_B^{V21}) < 0$.	Fine separation between weakly polarized snow fields and rain cells, partly based upon thermometric temperature differences.

Because of the relatively poor sampling characteristics of the SMMR for this type of study (instantaneous views twice per day, every other day, and noncontiguous orbital coverage), many orbits over the same area are required to adequately sample a subset of all the thunderstorms that occur in that area. If a significant diurnal variation in thunderstorm activity exists, this will skew the density of the SMMR observed storms to the high side if that maximum is near noon or midnight, or to the low side if the maximum is in the early morning or late afternoon. The noncontiguous coverage provided by the SMMR swaths of ~800 km width results in 25% coverage at the equator to 50% coverage at 55°N, resulting in a factor of 2 difference in the probability that a storm will be observed between these two regions. Because of these time and space sampling constraints, only qualitative assessments of the resulting satellite-observed storm distributions will be attempted here. Also, due to the infrequent occurrence of convective storms at extreme latitudes, data were not evaluated north of 60°N or south of 45°S.

3. The global distribution of storms

The distribution of SMMR footprints classified as "storms" that result from the screening procedure applied to Nimbus-7 SMMR data from 1 June–31 August 1980, is shown in Fig. 2. Because of the relatively large size of the 37 GHz footprint (~800 km^2), these storms are probably quite large, and likely the result of significant mesoscale organization capable of lifting great quantities of water to high altitudes. The gross features of the global distribution of June–August thunderstorm days (Fig. 3) are fairly well reproduced by the satellite-derived distribution, with the maxima over North America and Africa as the most obvious examples. These areas also had the most intense storms, with a few having $T_B^{H18} - T_B^{H37}$ reaching 80°C. Many of the African storms were traced to topographic features, where the storms form preferentially by upslope forcing. Similarly, many of the South American storms are associated with the foothills of mountain ranges, whereas relatively few Amazon basin storms were picked up, possibly because of their small size, lower intensity, or the timing of their diurnal maximum. The maximum over southern Brazil and Uruguay is also reflected in both Figs. 2 and 3. In Asia, most of the SMMR-observed storms occurred in southeast China, southern Russia, the Himalayan foothills, and southeast Asia. The

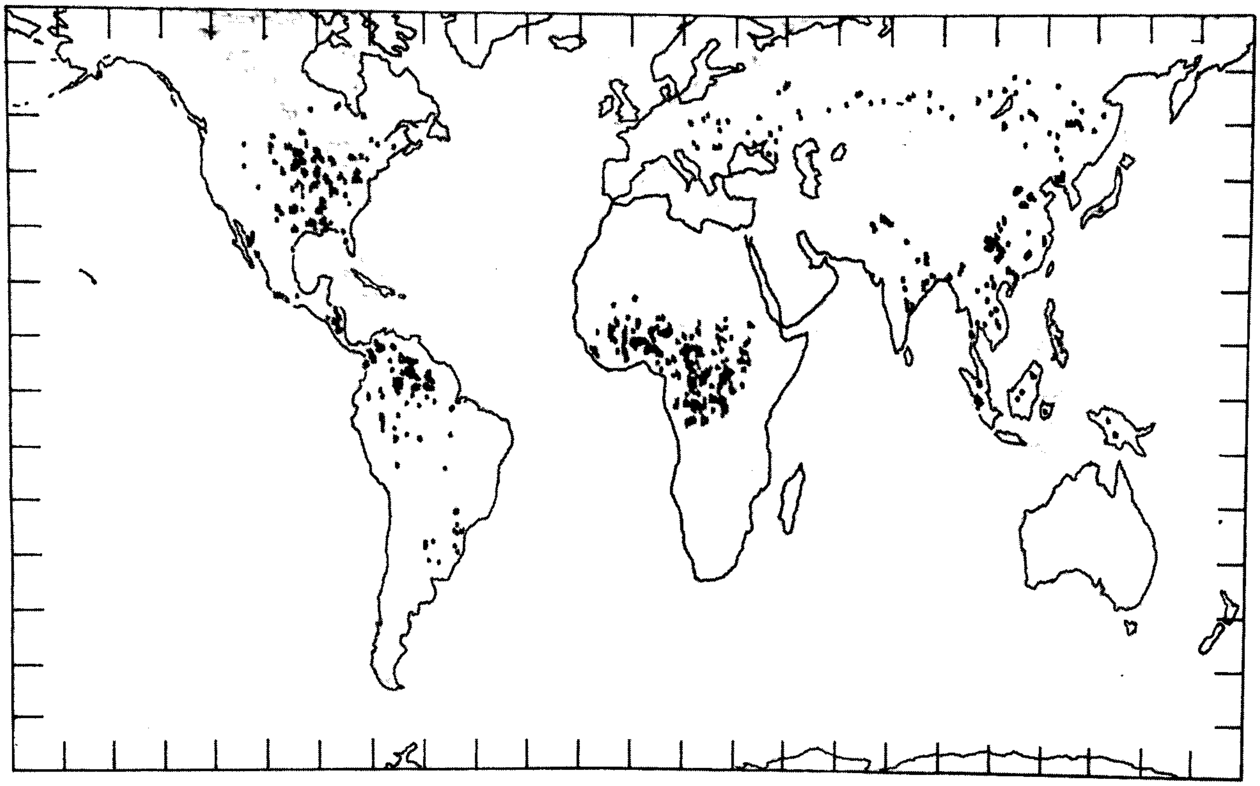

FIG. 2. The global distribution of SMMR-observed intense convective signatures over land during 1 June–31 August 1980, based upon the screening procedure presented in Table 1.

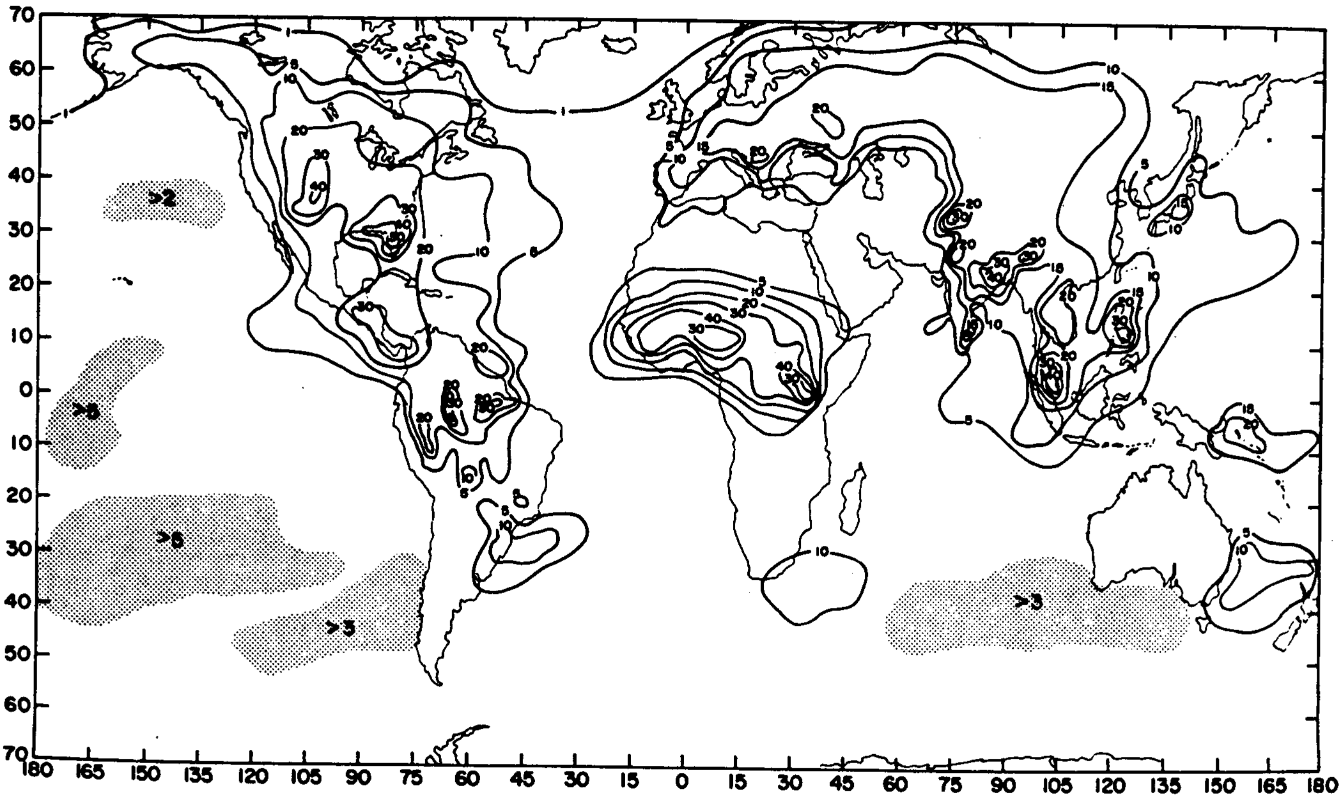

FIG. 3. The global distribution of thunderstorm days for June through August based upon surface observations (reproduced from Court and Griffiths, 1982).

agreement in areas where few storms are reported is also quite good.

4. Conclusions

If a more extensive satellite network were developed with passive microwave observation capabilities (e.g., one or more full-time, sun-synchronous sensors, or a geostationary instrument), it would be possible to monitor global storm activity in a more quantitative way than that presented here. Given enough satellite coverage, quantitative rain estimates over most areas of the earth might be possible, including the oceans (Wilheit *et al.,* 1977; Spencer *et al.,* 1983c). While it is still not clear what microwave frequencies provide the best mix of rain measurement ability and non-ambiguity of the type of geophysical signal being measured, there seems to be sufficient promise to more thoroughly evaluate the frequencies in the 10–200 GHz range for their skill in these areas. Accurate rain measurements would be an important component of our understanding of the global hydrologic cycle, and would allow the monitoring and study of rain systems over those vast areas where conventional data are scarce.

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