Midweek intensification of rain in the U.S.: Does air pollution invigorate storms?

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The effect of pollution on rainfall has been observed to depend both on the type of pollution and the precipitating environment[1-4]. The climatological consequences of pollution for rainfall are uncertain. In some urban areas, pollution varies with the day of the week because of weekly variations in human activity[5-7], in effect providing a repeated experiment on the effects of pollution. Weekly variations in temperature, pressure, cloud characteristics, hail[8] and lightning[9] are observed in many areas[6,10-13]. Observing a weekly cycle in rainfall statistics has proven to be more difficult, although there is some evidence for it[5,11]. Here we examine rainfall statistics from the Tropical Rainfall Measuring Mission[14] (TRMM) satellite over the southern U.S. and adjacent waters, and find that there is a distinct, statistically significant weekly cycle in summertime rainfall over the southeast U.S., as well as weekly variations in rainfall over the nearby Atlantic and the Gulf of Mexico. Rainfall over land peaks in the

middle of the week, suggesting that summer rainfall on large scales may increase as pollution levels rise. Both rain statistics over land and what appear to be compensating effects over adjacent seas support the suggestion that air pollution invigorates convection and outflow aloft.

Pollution aerosols have been documented to suppress precipitation from shallow clouds (cloud heights below about the $-10°C$ isotherm)[1,2,15-17]. When polluted clouds develop to greater heights (lower temperatures), however, as often happens in the summertime over land, it has been suggested[18,19] that suppressed rainout enables unprecipitated water to reach greater heights where freezing can release latent heat and further invigorate the cloud updrafts. This might in turn delay the onset of precipitation and the development of downdrafts and so prolong the growth of the convective cloud, allowing more water vapor to be ingested and further invigoration of the storm[19]. Recent cloud simulations[20] support this suggestion: in a moist, unstable atmosphere such as prevails during the summer in the SE U.S., pollution aerosols can induce clouds to develop stronger updrafts and downdrafts, grow taller, trigger secondary storm development, and produce more rain. The analyses of weekly cycles in satellite precipitation estimates reported here might serve as the first observational evidence of this suggestion, and provide a first clue towards quantifying it on a climate scale.

It is well documented[6,7,13,21,22] that pollution levels change with the day of the week in many urban areas, generally attributed to changes in vehicular traffic, though variations in power consumption may also play a role. Searches for a weekly cycle in precipitation have yielded mixed

results[5,13,23,24]. Our results suggest in fact that the weekly cycle is weaker in coastal areas, and studies of data from coastal cities may therefore have failed to find a significant weekly cycle in precipitation for this reason. Cerveny & Balling[11] ("CB" hereafter), using rain estimates from the Microwave Sounding Unit (MSU) on TIROS-N satellites[25] for 1979–1995 found a weekly cycle in precipitation over the Atlantic near the east coast of the U.S., with peak rainfall occurring on Saturday and minimum rainfall on Monday.

The TRMM satellite has been orbiting the Earth since late 1997. It is unique in that it carries a meteorological radar which can be used to improve the rain estimates made with its passive microwave instrument, the TRMM Microwave Imager (TMI). Averages for each day of the week based on 6 years (1998–2003) of data for summertime (June–August) rain rates, estimated using version 5 of the TMI retrieval algorithm,[26] were obtained for each $2.5° \times 2.5°$ grid box viewed by TRMM in the vicinity of the continental U.S. (TRMM's orbital plane is inclined $35°$ with respect to the Equator, and the TMI cannot see poleward of $40°$.)

The daily averages $r(t)$ were fit to a sinusoidal form

$$r(t) = r_0 + r_7 \cos[\omega_7(t - \phi_7)] \tag{1}$$

with $\omega_7 = 2\pi/(7\,\mathrm{d})$, t the day of the week, r_0 the average rain rate, r_7 the amplitude of the weekly cycle, and ϕ_7 the day of the week when the sinusoidal fit peaks. The statistical significance of the amplitude r_7 relative to the hypothesis that there is no weekly cycle ($r_7 = 0$) was obtained using a technique based on the one described by Bell & Reid[27]. Figure 1a shows a map of the phase ϕ_7 for each grid box, with gray level adjusted according to the significance level of the weekly amplitude.

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The strongest colors indicate significance levels at $p = 0.05$ ("2-sigma") or better. Although there is considerable variability in the phase (much of which can be explained by sampling error due to the length of the dataset), it appears that there is a tendency for average rain rates to peak during the middle of the week (Tue–Thu) over the continental U.S., and to peak Sat–Mon over the nearby Atlantic and perhaps the Gulf of Mexico. There also appears to be a tendency for the weekly cycle to weaken near the coasts. (We note that weekly variations in hail intensity have been observed to weaken as one approaches the Atlantic coast of France from inland[8].)

Even with 6 years of data, the statistical uncertainty in the weekly cycle in many of the grid boxes is large. We therefore try to increase the signal-to-noise ratio by averaging over larger areas, guided by our physical understanding of where and how the weekly cycle in pollution is likely to affect precipitation. Summer precipitation over the U.S. differs markedly in the eastern and western halves, due in part to the effects of the moisture brought to the eastern half from the Gulf of Mexico by prevailing winds and in part to the differences in topography. We have therefore derived average rain rates from the five averaging areas A–E shown in Fig. 1b. Grid boxes containing substantial amounts of coastline are excluded. Area C is identical to the region examined by CB except for two 2.5° grid boxes in their area too far north for TRMM.

Figure 2a shows the average rain rate for each day of the week for areas A-C. The SE U.S. (area B) average daily rain rate for Tue–Fri is higher than for Sat–Mon, with a maximum on Tue. The SW U.S. (area A) seems to show a weak cycle with slightly higher rates during weekdays compared with weekends. In contrast, the coastal Atlantic (area C) shows strongest rain rates

Sat–Mon and lower rain rates Tue–Fri, similar to what CB found, but it should be noted that they averaged data over entire years whereas our average includes only summers. Figure 3a shows the average rain rate for areas C–E. The Atlantic region D east of region C seems to show a weaker but similar cycle. The Gulf of Mexico area E has a mild cycle with largest values Fri–Sun and smallest values Mon–Thu.

Figures 2b and 3b show the daily average fraction of TMI footprints (nominally of order 10 km in diameter) with detectable rain in them. It appears that the weekly cycle over the SE U.S. is due as much to intensification of rain rates as to an increase in the area or frequency with which it rains, whereas over the other areas the weekly response is more due to changes in area or frequency than to intensification. This is brought out further in Figs. 2c and 3c, where the ratio of the mean rain rate (panel a) to mean fraction-with-rain (panel b) is plotted. Note the increase in intensity over the SE U.S. in Fig. 2c during midweek (although the minimum on Friday is not readily explained).

The question immediately arises concerning whether these cycles are artifacts of the observational characteristics of TRMM, or accidents due to natural variability of precipitation unrelated to the day of the week. In Methods we discuss why the sampling pattern of TRMM is unlikely to have generated spurious weekly cycles of the magnitude seen here. Bootstrap techniques used to estimate the statistical signficance of the cycles are also described there.

Figure 4 shows the phases and significance levels p for the averages over each of the 5 areas in Fig. 1b derived from fitting the 6 summers of TRMM data to the sinusoid (1), with p estimated

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using the bootstrap approach described in Methods. Distance from the origin is proportional to $\sqrt{-\ln p}$. The weekly cycle of the average over the SE U.S. (area B) is significant at the $p = 0.03$ level [$r_0 = 0.180\,\mathrm{mm\,h^{-1}}$, $r_7 = 0.042\,\mathrm{mm\,h^{-1}}$, $\phi_7 = 4.7\,\mathrm{d}$ ($\phi_7 = 0 \rightarrow 0000$ Saturday)]. The coastal Atlantic (area C) cycle is significant at the $p = 0.08$ level [$r_0 = 0.266\,\mathrm{mm\,h^{-1}}$, $r_7 = 0.054\,\mathrm{mm\,h^{-1}}$, $\phi_7 = 0.9\,\mathrm{d}$]. The other 3 area averages have weekly amplitudes that are approximately "1-sigma" in size, and so are not very well determined by the amount of data analyzed; by themselves they would not constitute much "proof" of a weekly cycle, but if one accepts that there is a weekly cycle in these last three area averages, there is some information to be gleaned.

The SE U.S. area B appears to have a significant weekly cycle; its amplitude is almost 25% of the mean. The plot in Fig. 2a indicates that average rain rate over the SE U.S. is largest during the middle of the week and drops to its lowest value on Sunday—behavior very similar to anthropogenic pollution. This suggests that summertime (mostly convective) rain amounts are increased, at least on large scales, by the increase in the kinds of pollution that vary weekly because of human activity. Figs. 2b,c suggest that the increase is due in about equal parts to intensification and increase in area/frequency. It is important at this point, however, to recall how the TMI is used to obtain rain-rate estimates. Over land the estimates are based mostly on microwave radiance measured by the 85 GHz channel, which responds chiefly to the amount and size of ice particles at the tops of clouds. Since production of ice aloft is common during the intense convection in summer storms, this method of estimating rainfall at the surface generally works quite well[26]. However, clouds with smaller drops such as caused by air pollution have been documented to produce larger raindrops for the same rain intensities, mainly due to the larger ice hydrometeors aloft[28]. The

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pollution-induced invigoration of the clouds also produces larger ice hydrometeors aloft[20]. Therefore it is possible that the weekly cycle in the TRMM rain estimates may be due to changes in the ice aloft that are not in fact accompanied by much change in rainfall at the surface. The dynamical implications of such changes in cloud structure would be important, however, even if surface rainfall were to be unaffected.

The weaker response over the SW U.S. (area A) is consistent with simulations showing that invigoration of convection by pollution is diminished in drier conditions, and may even reverse[20].

The weekly cycle in the Atlantic off the east coast of the U.S. (area C) is remarkable in that it is almost exactly opposite in phase to the cycle over the nearby land. Several explanations are possible:

1) the effect of pollution on rain formation over the ocean may be quite different from its effect on the more vigorous convection over land;

2) the phase difference may be due to the lag in time when pollution is carried to this region from the land;

3) precipitation over the ocean may be dynamically suppressed when it is most vigorous over the nearby continent.

Explanation 1 is plausible, given that convection is less vigorous and less ice is formed over the ocean, and sea salt aerosols mitigate some of the suppression effects of the pollution aerosols[17]. Explanation 2 was offered by CB, who mention that they saw a steadily increasing delay in peak rainfall in the oceanic areas further and further east of area C. The almost simultaneous peak in

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the rainfall over area D (Fig. 3) does not seem to be consistent with this hypothesis, however. (We examined the rainfall over an area east of D and adjacent to it, which has a slight weekly cycle, but its phase is not statistically distinguishable from that of the two oceanic areas C and D.) Explanation 3 is consistent with invigoration of the convection over land, which must be compensated somewhere with downward motion of the air. It involves quantitative dynamical understanding of how changes in convection over the continent might affect offshore convection, and will probably require modeling studies to evaluate it.

Methods

Because TRMM visits a grid box several days in a row at the same hour (local time) of the day, then visits the box for several days one hour earlier (local time), etc.[29], there is some danger that the satellite might, for example, consistently overfly an area on weekends at noontime while visiting the area during the middle of the week only at night. In other words, the diurnal variation of rainfall might produce an artificial weekly cycle in the TRMM observations. This possibility has been ruled out by examining the number of observations as a function of both the day of the week and the hour of the day: all hours of the day are about equally observed each day of the week. We have also replaced the actual time series of area averages with an artificial diurnal cycle and found that the spurious weekly cycle it generates is two orders of magnitude smaller than the observed cycle.

The likelihood that the weekly cycle is an accident of natural variation in rainfall, which, of course, has no preferred day of the week, has been estimated in two ways, both of which proved

to give similar values for the statistical significance level of the cycles: The first method is based on a method described in [27], and involves estimating the sampling error in a sinusoidal fit to the weekly cycle as in Eq. (1). The time series is broken into 2-week long chunks, each of which is fit to the linear version of Eq. (1) with 3 unknown amplitudes, $r(t) = r_0 + c_7 \cos(\omega_7 t) + s_7 \sin(\omega_7 t)$. The amplitude and phase r_7, ϕ_7 in (1) are derived from c_7 and s_7. The variance in the coefficients c_7 and s_7 can then be used to estimate the error in the least squares estimates of r_7, ϕ_7 from the entire series. The second method uses a bootstrap (resampling) approach that generates artificial (resampled) time series from randomly chosen chunks of data while attempting to preserve the time correlation in the data[30]. (Most bootstrap studies use randomly chosen data points.) Resampling was carried out by using the original time sequence of observations, dividing it into chunks of lengths 4, 5, or 6 days (randomly chosen) and replacing each chunk with another segment of the same length randomly selected from those segments of the data whose local times of observation are within 2 hours of the chunk being replaced. This preserves the effects of the diurnal cycle of rainfall in the statistics, but scrambles any associations with the day of the week. A set of 10,000 fake time series and the associated fits $r_7^{(\alpha)}$ and $\phi_7^{(\alpha)}$, $\alpha = 1, \ldots, 10,000$, were obtained. The fraction of fits $r_7^{(\alpha)}$ larger than the observed amplitude r_7 for the actual data was used to estimate the probability p that the observed amplitude was an accident, under the null hypothesis that there is no real weekly cycle.

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Competing Interests The authors declare that they have no competing financial interests.
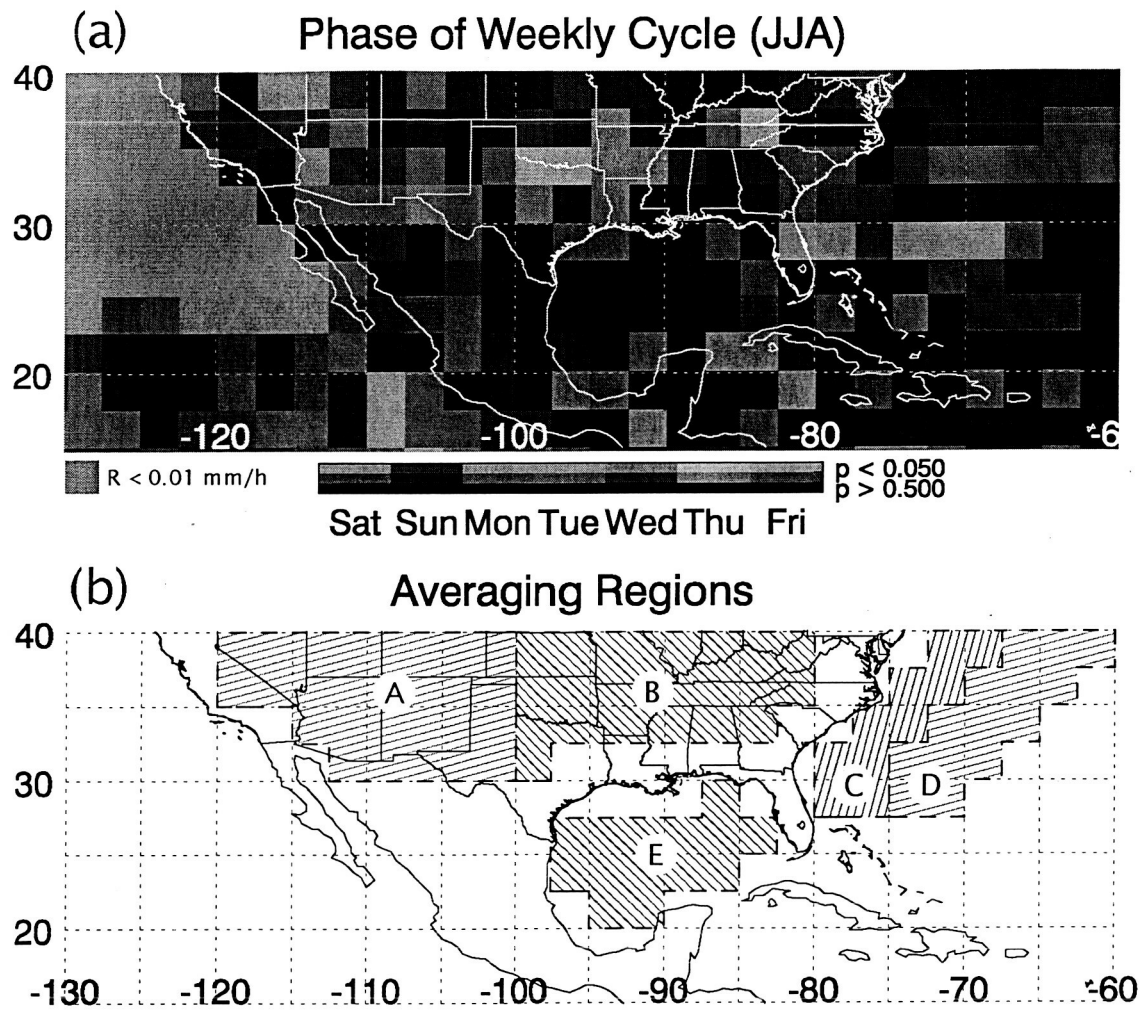
Correspondence and requests for materials should be addressed to T.L.B. (Thomas.L.Bell@nasa.gov).

Figure 1 Study region and gridded phases of weekly cycle. **a**, Colors for each grid box indicate day of the week with maximum rainfall, based on fits to a 7-d sinusoid of averages of TRMM rain estimates for 6 summers. Grayness of colors is based on the significance level p for the amplitude. Areas with rain rates less than 0.01 mmh^{-1} are masked. **b**, Five averaging areas chosen to improve the signal-to-noise ratio for cycle detection.
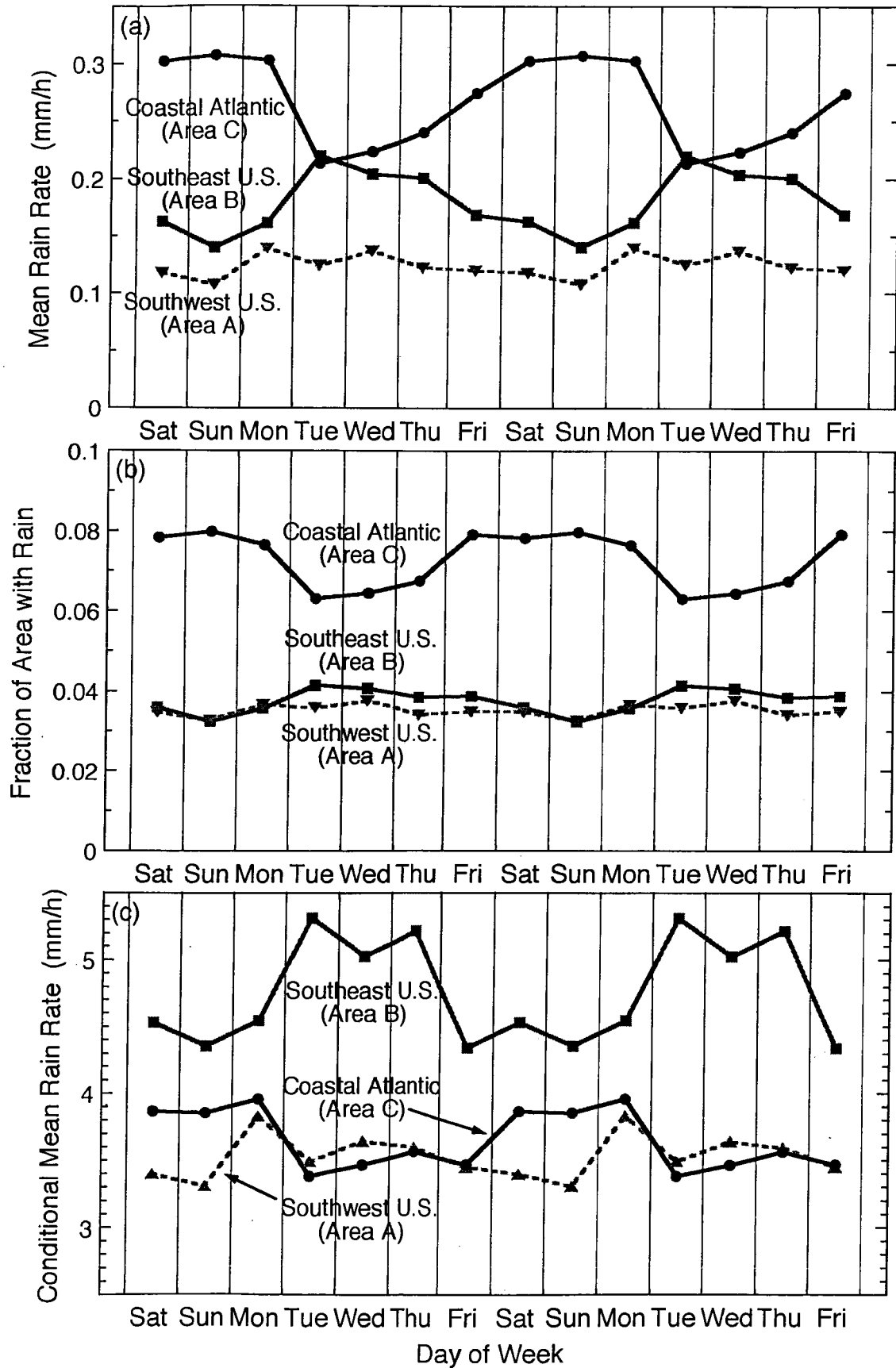
Figure 2 Rain statistics from TRMM for each day of the week for areas A–C in Fig. 1b. **a**, Average rain rate. **b**, Fraction of TMI footprints with rain. **c**, Ratio of results in panels a and b, indicating intensity of rain where it rains (i.e., conditional on $R > 0$).

Figure 3 Rain statistics as in Fig. 2 for areas C–E in Fig. 1b. Statistics for area C in Fig. 2 repeated here to aid comparisons.
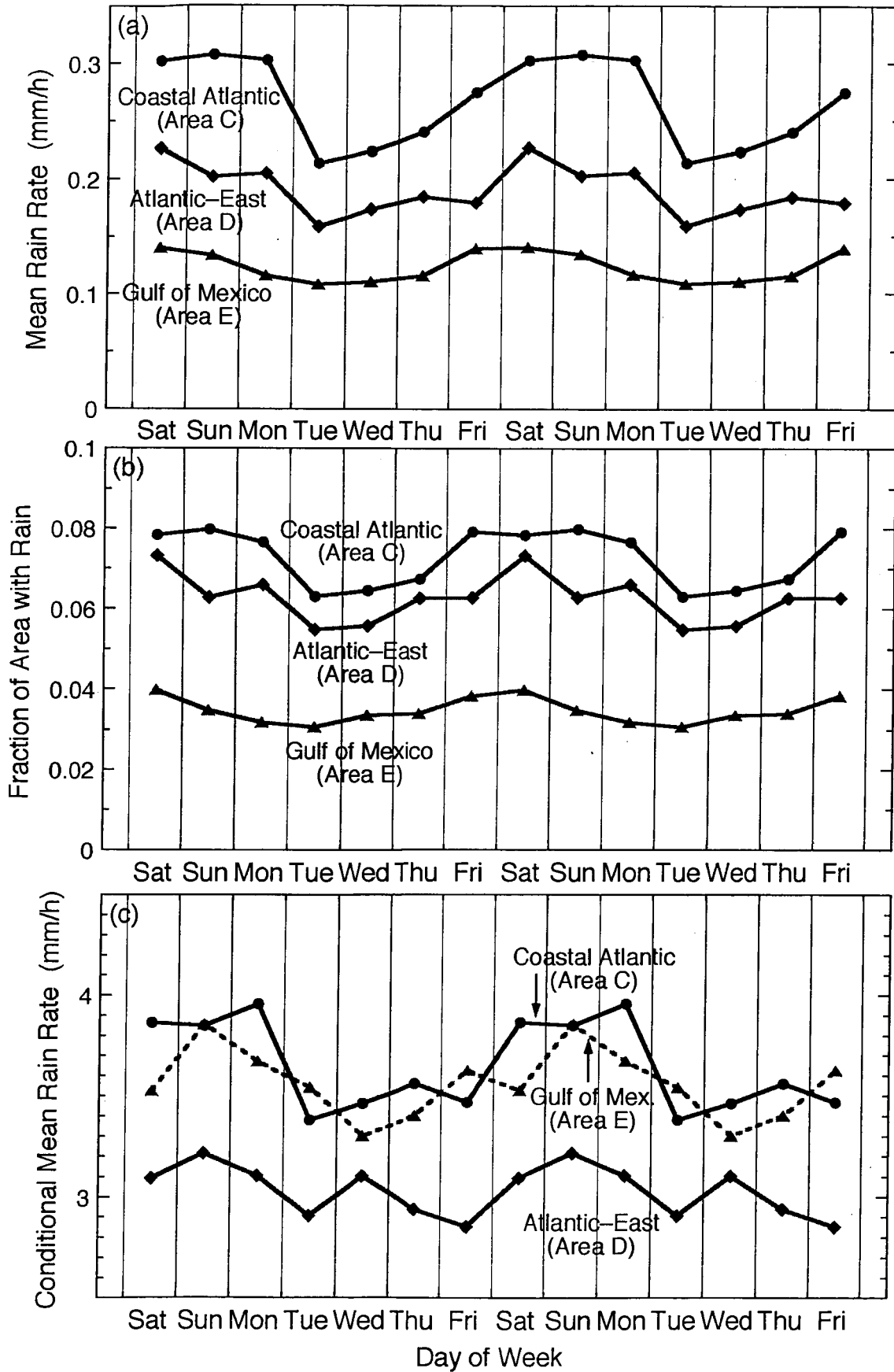
Figure 4 Phase and significance level of weekly cycles for 5 areas. Angular position is determined by day of week with maximum rain rate in sinusoidal fits to plots in Figs. 2a and 3a, and radial position is determined by significance level of weekly cycle.

(a) Phase of Weekly Cycle (JJA)

(b) Averaging Regions

Weekly Cycle Phase and Significance Level p

A - SW US
B - SE US
C - Atl, Coastal
D - Atl, East of C
E - Gulf of Mexico