

Global Precipitation and Thunderstorm Frequencies. Part I: Seasonal and Interannual Variations

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ABSTRACT

Present and past weather reports from ~15 000 stations around the globe and from the Comprehensive Ocean–Atmosphere Data Set from 1975 to 1997 were analyzed for the frequency of occurrence for and the percentage of the days with various types of precipitation (drizzle, nondrizzle, showery, nonshowery, and snow) and thunderstorms. In this paper, the mean geographical, seasonal, and interannual variations in the frequencies are documented. Drizzles occur most frequently (~5%–15% of the time) over mid- and high-latitude oceans. Nonshowery precipitation is the preferred form of precipitation over the storm-track regions at northern mid- and high latitudes in boreal winter and over the Antarctic Circumpolar Current in all seasons. Showery precipitation occurs ~5%–20% of the time over the oceans, as compared with < 10% over land areas except in boreal summer over Northern Hemisphere land areas, where showery precipitation and thunderstorms occur in over 20% of the days. Inferred mean precipitation intensity is generally < 1.0 mm h⁻¹ at mid- and high latitudes and ~1.5–3.0 mm h⁻¹ in the Tropics. The intertropical convergence zone and the South Pacific convergence zone are clearly defined in the frequency maps but not in the intensity maps. Nonshowery precipitation at low latitudes is associated with showery precipitation, consistent with observations of stratiform precipitation accompanying mesoscale convective systems in the Tropics. The seasonal cycles of the showery precipitation and thunderstorm frequencies exhibit a coherent land–ocean pattern in that land areas peak in summer and the oceans peak in winter. The leading EOFs in the nondrizzle and nonshowery precipitation frequencies are an ENSO-related mode that confirms the ENSO-induced precipitation anomalies over the open oceans previously derived from satellite estimates.

1. Introduction

Precipitation has many characteristics, such as amount, frequency of occurrence,¹ intensity, phase, and type or form (e.g., drizzle, showery, nonshowery, rain, snow, etc.). Documentation of precipitation has traditionally focused on precipitation amounts (e.g., Jaeger 1983; Legates and Willmott 1990; New et al. 1999). This is partly because most observations (e.g., rain gauge records) only measure the total amount of precipitation accumulated within a certain period of time. Global climatologies of monthly precipitation amounts have been improved considerably during the last decade because of improvements in satellite-based estimates of precipitation over the oceans (e.g., Xie and Arkin 1997). Our knowledge of the other characteristics of precipi-

tation is, however, still very poor on a global scale. For example, there are no global climatologies of frequency of occurrence for all-form precipitation or precipitation types. Such climatologies are needed for evaluating model-simulated precipitation, which tends to have higher-than-observed precipitation frequency (Chen et al. 1996; Dai et al. 1999). Information of precipitation types (e.g., showery precipitation) can be applied to study precipitation processes such as moist convection.

Observational data of precipitation frequency, intensity and type are sparse on a global scale. Global climatologies of thunderstorm days based on station and shipboard data before 1975 were summarized by Court and Griffins (1983) and Sanders and Freeman (1983). Over the United States, spatial (Court and Griffins 1983; Easterling 1991) and diurnal (Wallace 1975; Easterling and Robinson 1985) variations of thunderstorm activity have been investigated. Climatologies of precipitation frequency (Higgins et al. 1996), its diurnal variation (Wallace 1975; Dai et al. 1999), and recent changes in the diurnal cycle of precipitation (Dai 1999) over the United States have also been documented. Outside the United States, Petty (1995) analyzed shipboard present-weather reports and showed seasonal maps of precipitation frequencies at various intensities over the oceans.

¹ The frequency of occurrence is defined here as the number of reports of a precipitation type or thunderstorms divided by the number of total weather reports expressed in a fraction or percentage. It is also referred to as precipitation frequency in this paper.

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Present and (recent) past weather reports from land stations and ships provide valuable information about precipitation frequency, intensity, phase, and type. Although these reports potentially contain various biases (discussed below; also see Petty 1995), they represent one of the best available observations of precipitation characteristics on a global scale.

In this study, we derive global climatologies of the frequency of occurrence for various types of precipitation by analyzing present and past weather reports from about 15 000 weather stations around the globe and from the Comprehensive Ocean–Atmosphere Data Set (COADS) from 1975 to 1997. Mean precipitation intensity is also inferred from the frequency and precipitation amounts (from Xie and Arkin 1997). The types of precipitation analyzed include drizzle, non-drizzle precipitation (including all types of precipitation except drizzle), showery precipitation, nonshowery precipitation, thunderstorms, and snow. Here we focus on the geographical, seasonal, and interannual variations in the frequencies for these types of precipitation and thunderstorms. In Part II of this study (Dai 2001a), we shall investigate their diurnal variations. To the best of our knowledge, this study represents the first attempt to document the frequency of occurrence for various types of precipitation and thunderstorms on a truly global scale.

2. Data and analysis method

a. Datasets

The present² (WMO code “ww”) and past³ (WMO code “W₁”) weather code data were extracted from the Global Telecommunication System (GTS) synoptic weather reports archived at the National Center for Atmospheric Research (NCAR) (DS464.0, <http://www.scd.ucar.edu/dss/datasets/ds464.0.html>). This surface dataset, which covers the time period from February 1975 to present and has a volume of about 2.5 GB per year, contains 3-hourly [0000, 0300, 0600 Coordinated Universal Time (UTC), etc.] observations of all the major meteorological variables, including present and past weather information in coded formats. The total number of fixed land and island stations exceeds 15 000 in the dataset, but there are only about 4000–7000 stations having weather reports at any given time. The weather codes are defined specifically by the World Meteorological Organization (WMO; WMO 1988). Tables 1 and 2 list the possible values of ww and W₁ and their corresponding weather phenomena for manned stations or ship observations. Since 1 January 1982, weather reports from certain automatic stations use slightly different code tables (WMO 1988).

Although there are shipboard weather reports in the above data set, the coverage is poor over the oceans. We therefore extracted the 3-hourly shipboard present and past weather reports from the COADS (Woodruff et al. 1993; the 1999 release was used) for the 1975–97 period (COADS data after 1997 had not been released).

Because of their near-global coverage and relatively high temporal resolution, the surface synoptic data have been used to study diurnal and semidiurnal variations in global surface pressure (Dai and Wang 1999) and surface winds and divergence (Dai and Deser 1999), and variations in cloudiness (Warren et al. 1988; Norris 1998).

The weather codes, like cloud reports, are made by a trained human observer (except for a still relatively small number of automatic stations where sophisticated sensors and other schemes are used to derive weather condition reports). Although the guidelines on ww and W₁ are fairly specific (WMO 1988), these observations contain only qualitative information about precipitation characteristics (intensity, phase, and type). Quantitative measurements of precipitation are not available in these datasets. The quality of the weather code data is affected by changes in the WMO guidelines and coding practices, observer biases (such as preference to certain weather codes), ships’ tendency to avoid bad weather, poor sampling over the oceans, and other problems (Petty 1995). The major inhomogeneities in these data are discussed below. Despite these problems, the weather codes contain valuable information about precipitation frequency, intensity, phase, and type. Here we used them to document the geographical, seasonal, and interannual variations in the frequency of occurrence for various types of precipitation and thunderstorms.

Figure 1 shows the temporal evolution of annual count of ww reports from all stations and ships (solid curves), together with the count of ww reports made by human observers (short-broken curves, overlays the solid curve for COADS reports). The COADS data after 1997 were not available (marine reports after 1997 in Fig. 1 are from DS464.0). In 1997, a change in the archiving format of DS464.0 was also introduced. We therefore did not use the data after 1997. During the 1975–97 period (except for 1975 and 1997), the number of reports from land stations is relatively stable, while the count of marine reports decreases gradually. A moderate drop in the number of reports occurs around 1981/82, when a new coding practice⁴ was introduced.

Figure 1 also shows the annual count of Ix (long-

² At the time of observation or during the preceding hour.

³ The past 6 h for observations at 0000, 0600, 1200, and 1800 UTC, and the past 3 h for observations at 0300, 0900, 1500, and 2100 UTC; see WMO (1988).

⁴ The major changes in coding practice around 1 January 1982 include: a) nonsignificant phenomena (e.g., ww = 01–03) can be omitted; b) Ix, an indicator for type of station operation (manned or automatic) and for present and past weather codes, is added [code table 1860, WMO (1988)]; and c) new code tables for certain automatic stations [code Table 4680 for ww and 4531 for W₁, WMO (1988)] were introduced.

TABLE 1. WMO present weather codes.

	Code figure ww	Weather description				
ww = 00–49 No precipitation at the station at the time of observation						
ww = 00–19 No precipitation, fog, ice fog (except for 11 and 12), duststorm, sandstorm, drifting or blowing snow at the station at the time of observation or, except for 09 and 17, during the preceding hour						
No meteors except photometeors	{	00	Cloud development not observed or not observable	{	Characteristic change of the state of sky during the past hour	
		01	Clouds generally dissolving or becoming less developed			
		02	State of sky on the whole unchanged			
		03	Clouds generally forming or developing			
Haze, dust, sand or smoke	{	04	Visibility reduced by smoke, e.g., veldt or forest fires, industrial smoke, or volcanic ashes			
		05	Haze			
		06	Widespread dust in suspension in the air, not raised by wind at or near the station at the time of observation			
		07	Dust or sand raised by wind at or near the station at the time of observation, but no well-developed dust whirl(s) or sand whirl(s), and no duststorm or sandstorm seen; or, in the case of ships, blowing spray at the station			
		08	Well-developed dust whirl(s) or sand whirl(s) seen at or near the station during the preceding hour or at the time of observation, but no duststorm or sandstorm			
		09	Duststorm or sandstorm within sight at the time of observation, or at the station during the preceding hour			
		10	Mist			
		11	Patches		{	shallow fog or ice fog at the station, whether on land or sea, not deeper than about 2 meters on land or 10 meters at sea
		12	More or less continuous			
		13	Lightning visible, no thunder heard			
		14	Precipitation within sight, not reaching the ground or the surface of the sea			
		15	Precipitation within sight, reaching the ground or the surface of the sea, but distant, i.e., estimated to be more than 5 km from the station			
		16	Precipitation within sight, reaching the ground or the surface of the sea, near to, but not at the station			
		17	Thunderstorm, but no precipitation at the time of observation		{	at or within sight of the station during the preceding hour or at the time of observation
		18	Squalls			
		19	Funnel cloud(s)			
ww = 20–29 Precipitation, fog, ice fog, or thunderstorm at the station during the preceding hour but not at the time of observation						
	{	20	Drizzle (not freezing) or snow grains	{	not falling as shower(s)	
		21	Rain (not freezing)			
		22	Snow			
		23	Rain and snow or ice pellets			
		24	Freezing drizzle or freezing rain			
		25	Shower(s) of rain			
		26	Shower(s) of snow, or of rain and snow			
		27	Shower(s) of hail**, or of rain and hail			
		28	Fog or ice fog			
		29	Thunderstorm (with or without precipitation)			
ww = 30–39 Duststorm, sandstorm, drifting or blow snow						
{	{	30	Slight or moderate duststorm or sandstorm	{	—has decreased during the preceding hour —no appreciable change during the preceding hour —has begun or has increased during the preceding hour	
		31				
		32				
{	{	33	Severe duststorm or sandstorm	{	—has decreased during the preceding hour —no appreciable change during the preceding hour —has begun or has increased during the preceding hour	
		34				
		35				

TABLE 1. (Continued)

	Code figure ww	Weather description		
ww = 30–39	Duststorm, sandstorm, drifting or blow snow			
	36	Slight or moderate drifting snow	} generally low (below eye level)	
	37	Heavy drifting snow		
	38	Slight or moderate blowing snow	} generally high (above eye level)	
	39	Heavy blowing snow		
ww = 40–49	Fog or ice fog at the time of observation			
	40	Fog or ice fog at a distance at the time of observation, but not at the station during the preceding hour, the fog or ice fog extending to a level above that of the observer		
	41	Fog or ice fog in patches		
	42	Fog or ice fog, sky visible	} has become thinner during the preceding hour	
	43	Fog or ice fog, sky invisible		
	44	Fog or ice fog, sky visible	} no appreciable change during the preced- ing hour	
	45	Fog or ice fog, sky invisible		
	46	Fog or ice fog, sky visible	} has begun or has become thicker during the preceding hour	
	47	Fog or ice fog, sky invisible		
	48	Fog, depositing rime, sky visible		
	49	Fog, depositing rime, sky invisible		
ww = 50–99	Precipitation at the station at the time of observation			
ww = 50–59	Drizzle			
	50	Drizzle, not freezing, intermittent	} slight at time of observation	
	51	Drizzle, not freezing, continuous		
	52	Drizzle, not freezing, intermittent	} moderate at time of observation	
	53	Drizzle, not freezing, continuous		
	54	Drizzle, not freezing, intermittent	} heavy (dense) at time of observation	
	55	Drizzle, not freezing, continuous		
	56	Drizzle, freezing, slight		
	57	Drizzle, freezing, moderate or heavy (dense)		
	58	Drizzle and rain, slight		
	59	Drizzle and rain, moderate or heavy		
ww = 60–69	Rain			
	60	Rain, not freezing, intermittent	} slight at time of observation	
	61	Rain, not freezing, continuous		
	62	Rain, not freezing, intermittent	} moderate at time of observation	
	63	Rain, not freezing, continuous		
	64	Rain, not freezing, intermittent	} heavy at time of observation	
	65	Rain, not freezing, continuous		
	66	Rain, freezing, slight		
	67	Rain, freezing, moderate or heavy		
	68	Rain or drizzle and snow, slight		
	69	Rain or drizzle and snow, moderate or heavy		
ww = 70–79	Solid precipitation not in showers			
	70	Intermittent fall of snowflakes	} slight at time of observation	
	71	Continuous fall of snowflakes		
	72	Intermittent fall of snowflakes	} moderate at time of observation	
	73	Continuous fall of snowflakes		
	74	Intermittent fall of snowflakes	} heavy at time of observation	
	75	Continuous fall of snowflakes		
	76	Diamond dust (with or without fog)		
	77	Snow grains (with or without fog)		
	78	Isolated star-like snow crystals (with or without fog)		
	79	Ice pellets		
ww = 80–99	Showery precipitation, or precipitation with current or recent thunderstorm			
	80	Rain shower(s), slight		
	81	Rain shower(s), moderate or heavy		
	82	Rain shower(s), violent		
	83	Shower(s) of rain and snow mixed, slight		
	84	Shower(s) of rain and snow mixed, moderate or heavy		
	85	Snow shower(s), slight		

TABLE 1. (Continued)

	Code figure ww	Weather description		
ww = 80–99	Showery precipitation, or precipitation with current or recent thunderstorm			
	86	Snow shower(s), moderate or heavy		
	87	Shower(s) of snow pellets or small hail, with or without rain or rain and snow mixed	{	—slight
	88			—moderate or heavy
	89	Shower(s) of hail*, with or without rain or rain and snow mixed, not associated with thunder	{	—slight
	90			—moderate or heavy
	91	Slight rain at time of observation	{	thunderstorm during the preceding hour but not at time of observation
	92	Moderate or heavy rain at time of observation		
	93	Slight snow, or rain and snow mixed, or hail** at time of observation		
	94	Moderate or heavy snow, or rain and snow mixed, or hail** at time of observation		
	95	Thunderstorm, slight or moderate, without hail**, but with rain and/or snow at time of observation	{	thunderstorm at time of observation
	96	Thunderstorm, slight or moderate, with hail** at time of observation		
	97	Thunderstorm, heavy, without hail**, but with rain and/or snow at time of observation		
	98	Thunderstorm combined with duststorm or sandstorm at time of observation		
	99	Thunderstorm, heavy, with hail** at time of observation		

* French: grêle.

** Hail, small hail, snow pellets. French: grêle, grésil ou neige roulée.

broken curves), an indicator for type of station operation and for present and past weather codes. The I_x is needed for determining whether ww and W_1 are omitted because of no significant phenomenon to report ($I_x = 2$ or 5), or because of no observations ($I_x = 3$ or 6). Figure 1

TABLE 2. WMO past weather codes.

W—Weather during past hour	
W_1	} Past weather
W_2	
Code figure	Weather description
0	Cloud covering $\frac{1}{2}$ or less of the sky throughout the appropriate period
1	Cloud covering more than $\frac{1}{2}$ of the sky during part of the appropriate period and covering $\frac{1}{2}$ or less during part of the period
2	Cloud covering more than $\frac{1}{2}$ of the sky throughout the appropriate period
3	Sandstorm, duststorm, or blowing snow
4	Fog or ice fog or thick haze
5	Drizzle
6	Rain
7	Snow, or rain and snow mixed
8	Shower(s)
9	Thunderstorm(s) with or without precipitation

shows that the count of I_x in marine reports increases from January 1982 to December 1984, indicating that the new coding practice took a few years to become fully implemented for ship observations. To minimize the effect of missing I_x , we set $ww = 03$ when ww and I_x are both missing and total cloud cover is ≤ 7 octas. This was found to have only a minor effect on the results.

Figure 2 shows the geographical distribution of the count of ww reports within each 2° lat $\times$ 2° long grid box during 1975–97 for December–February (DJF; similar for the other seasons). It can be seen that the number of ww reports is very large (up to 2×10^5) over most land boxes at northern middle and low latitudes (except the Saharan desert and the Himalaya mountains). The count is also large (10^3 – 10^4) over the North Atlantic, the North Pacific, and the ship routes at low latitudes. The number of ww reports is <100 over the southern oceans (south of $\sim 45^\circ\text{S}$), the polar regions, and the sparsely populated land areas (such as central Australia, central Africa, and northern Canada), where our results are less reliable and should be interpreted with caution.

b. Analysis method

Petty (1995) classified the precipitating weather codes listed in Table 1 into 31 groups based on the intensity,

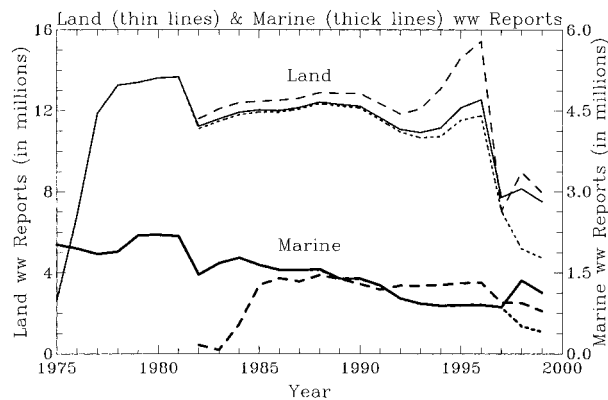


FIG. 1. Time series of annual counts of present weather (ww) reports from fixed stations (thin curves) and ships (thick curves). The solid curves are counts from both manned and automatic station operations, and the short-broken curves (overlying the solid curve for the marine reports before 1998) are counts from manned station operation only. The long-broken curves are counts of all 1x (an indicator for station operation and weather codes) reports, which are available only after 1 Jan 1982.

phase, and character of precipitation. In this study, we shall focus on those precipitation types that have different underlying physics, such as drizzle, nonshowery, and showery precipitation. Precipitation events including all forms but drizzle (referred to as nondrizzle precipitation hereinafter) are a class that closely resembles precipitation events recorded by rain gauges and thus can be compared with rain gauge data. Thunderstorms and snow are also of interest to many applications and will be analyzed as well. The present weather codes were used to compute the frequency of occurrence for drizzle, nondrizzle precipitation (*AllPrc*), nonshowery precipitation (*NonShw*), showery precipitation (*Shw*-

Prc), thunderstorms (including nonprecipitating ones), and snow. The corresponding code values of ww for these types of precipitation/thunderstorm events are listed in Table 3. In most cases, the ww code table for manned station operation (Table 1) is specific enough for categorizing the precipitation types using ww.⁵ In a few cases, the code description is ambiguous regarding the occurrence of precipitation (ww = 29) or precipitation types (ww = 24). We had to make a choice in these cases (e.g., we counted ww = 24 and 29 as *AllPrc* events). For ww = 93–94, snow is assumed if the station air temperature is less than 0.5°C. Tests showed that the results are insensitive to these choices.

For the very small number of automatic stations (Fig. 1), the code table [WMO (1988) code table 4680] is less specific than Table 1. For the present weather code from these stations ($w_a w_a$), we counted the observation as missing or not available if the code is too generic for determining a specific precipitation type. For example, for $w_a w_a = 21$ (precipitation) there is no information regarding precipitation type and thus no observation is available for all the precipitation types except for *AllPrc*. The automatic weather codes have only minor effects on the results due to the relatively small number of automatic stations (see Fig. 1).

To derive the frequency of occurrence for the six types of precipitation/thunderstorm events, we counted all the present weather reports by season for each $2^\circ \text{ lat} \times 2^\circ$

⁵ According to the WMO manual on codes (WMO 1988), the highest possible code value should be assigned to a weather phenomenon. Therefore, showery precipitation is assigned code values 80–99 whereas rain (60–69) is nonshowery precipitation.

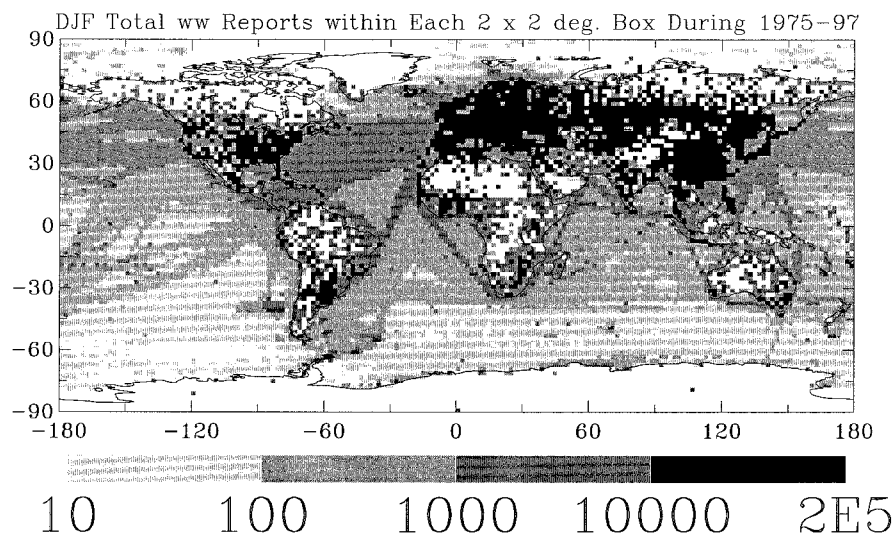


FIG. 2. Geographical distribution of the number of present weather reports within each $2^\circ \text{ lat} \times 2^\circ \text{ long}$ grid box for DJF during 1975–97. Blank areas have no or fewer than 10 reports. Plots for the other seasons are similar.

TABLE 3. Precipitation types and their associated present weather codes from manned (ww) and automatic ($w_a w_a$) stations.

Precipitation type	ww	$w_a w_a$
Drizzle precipitation	20, 50–58	22, 50–57
Nondrizzle precipitation ^a	21–27, 29, 59–99	21, 23–26, 40–48, 60–68, 70–76, 80–87, 90, 92–93, 95–96, 99
Nonshowery precipitation ^b	21–24, 59–79	25, 60–68, 70–76
Showery precipitation	25–27, 29, 80–99	26, 80–87
Thunderstorms ^c	17, 19, 29, 91–99	26, 90–96, 99
Snow	22, 26, 70–79, 85–86, 93–94 ^d	21 ^d , 24, 40 ^d , 45–46, 70–76, 85–87

^a Including all types of precipitation except drizzles.

^b Including all types of precipitation except drizzles and showery precipitation.

^c Including nonprecipitating thunderstorms.

^d When the air temperature is less than 0.5°C.

long grid box⁶ (i.e., all reports within a box were treated equally and no reports outside the box were used). The count was done for each year (marine reports were counted for each 4° lat × 5° long box in this case) and for all the years. The mean frequency maps presented in this paper are derived from the count of all the years, which yielded frequency maps similar to those by averaging the frequencies of each year. The interannual variations were derived based on the frequencies of individual years.

Besides the frequency of occurrence, we also computed a wet-day probability statistic (i.e., the number of days, expressed as a percentage of the number of all days with observations, on which at least one event of the precipitation types or thunderstorms occurred). Since past weather codes (W_1 for manned and W_{1a} for automatic stations) were also used in this count, the wet-day probability (p_w ; also referred to as thunderstorm-day probability in the thunderstorm case) is derived based on 24-h complete sampling over most land areas. This differs from the frequency of occurrence which was based on eight samples (each sample covers 1 h) per day. The wet-day probability is a better measure than the frequency of occurrence for episodic events such as showers and thunderstorms. However, because temporal sampling only covers a fraction of the day over the oceans, the wet-day probability is underestimated by the marine reports. One simple way to account for this insufficient sampling is to multiply the wet-day probability by a sampling factor, f , defined as $24/(N \cdot \Delta t)$, where N is the average number of (past) weather reports per day (≤ 4), and Δt is the sampling interval of W_1 (6 h). The f is 1.0 at most land stations and larger than 1.0 over most oceanic regions. There are more discussions on this sampling issue in Dai (2001b, manuscript submitted to *J. Climate*).

c. Inhomogeneities in the data

The frequency of occurrence and wet-day probability derived from the present and past weather codes potentially contain inhomogeneities resulting from 1) WMO-introduced changes in code tables and recording practices, 2) temporal changes in the number of reports, station operation types (Fig. 1), and spatial coverage, 3) biases associated with individual observers or ships, and 4) a bias due to missing reporting times (e.g., more missing data at night).⁷ For example, if the change in coding practice introduced on 1 January 1982 (i.e., ww can be omitted if there are no significant phenomenon to report) is not accounted for, an upward jump in the frequency and wet-day probability would occur around this time.

To quantitatively assess the inhomogeneities in the frequency and wet-day probability, we decomposed the seasonal frequency and probability maps (for each year from 1976 to 1997) using the EOF method (North et al. 1982). Figure 3 shows the first and second EOF modes in the wet-day probability of *AllPrc* (similar modes also seen for precipitation types) that appear to be spurious changes. The first mode has a linear trend since 1985 and comes mostly from the oceans, where the number of reports decreased steadily during the period (Fig. 1). The second mode is associated primarily with the WMO-introduced changes in code tables and recording practices on 1 January 1982. Apparently, these changes still induce spurious jumps even though we used the *Ix* data to account for the changes in recording practices of ww and $w_a w_a$ (the jump around January 1982 would have been much larger if the *Ix* data were not used). These spurious modes can significantly increase the year-to-year variability of the frequency and wet-day probability. We therefore removed them before computing the interannual variations. However, we did not adjust these changes in computing the

⁶ Results are similar if the counting is done at each station, except for the wet-day probability of showery precipitation and thunderstorms whose counting was done at individual stations.

⁷ This bias was minimized in this study by computing the frequency of occurrence for each reporting hour and averaging the frequency over the reporting hours to obtain the mean frequency.

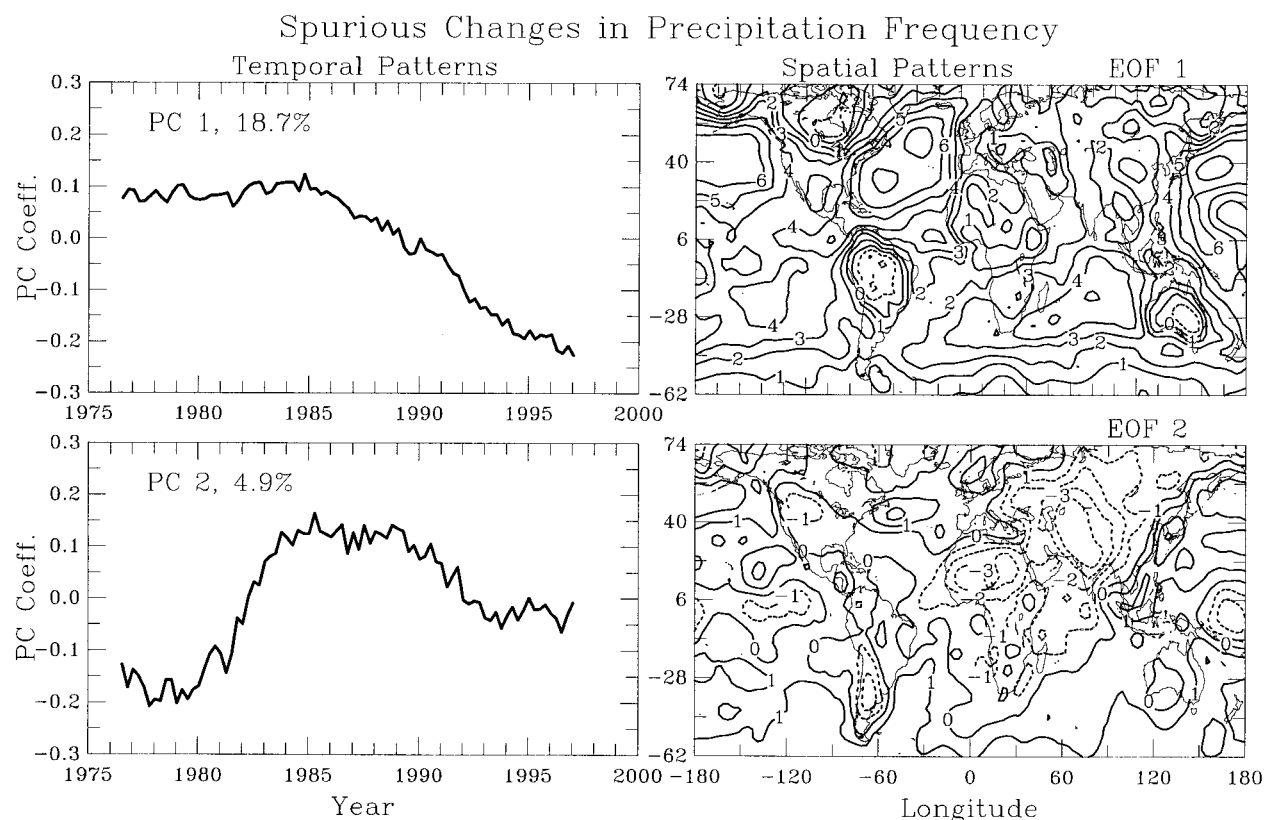


FIG. 3. The first and second EOF modes of the seasonal mean wet-day probability for nondrizzle precipitation derived from present and past weather codes. The seasonal cycle was removed before the EOF analysis.

mean frequencies because we do not know which period has the smallest bias. Instead, we shall present the mean frequency and wet-day probability maps derived using the count of all reports from 1975 to 1997. These mean maps may contain some systematic biases that are likely to be within about $\pm 10\%$ based on the magnitudes of the spurious modes.

3. Results

a. Geographical and seasonal variations

Figure 4 shows the geographical distribution of DJF and June–August (JJA) mean frequency of occurrence for drizzle, *AllPrc*, *NonShw*, *ShwPrc*, and snow. The corresponding wet-day probability (after being multiplied by the sampling factor f) is shown in Fig. 5 (note that the bottom row is for thunderstorms). The frequencies for March–May (MAM) and September–November (SON) do not differ greatly from the DJF frequency and will be shown only for the zonal means. Differences in the spatial patterns of the frequency of occurrence and wet-day probability result primarily from spatial variations in the diurnal cycle of precipitation events (Dai et al. 1999; Dai 2001a). If there were no diurnal variations in the frequency of occurrence, the

frequency and wet-day probability would differ only by a constant.

1) DRIZZLE

Drizzles occur more frequently (up to 15% of the time) over mid- and high-latitude oceans than over land areas and the low-latitude oceans in both DJF and JJA (Fig. 4, and in MAM and SON, not shown). Drizzles are observed less than 1% of the time over most land areas, except for some coastal areas (e.g., coastal western Europe in DJF, southeastern North America in DJF, and Indian subcontinent in JJA) where the frequency can reach 5%. Over the marine stratus-cloud regions west off South America and Africa, the frequency is not particularly high when compared with the surrounding areas. This may be due to poor sampling over these regions (Fig. 2). Petty (1995) found generally much higher frequencies (up to 50% of all ww reports) for light-intensity precipitation (including drizzle). This may be partly due to the fact that Petty (1995) included ww reports outside a 2.5° grid box in computing the frequency for the grid box and did not have the I_x data to account for the changes in coding practices introduced on 1 January 1982 (which could result in a large upward jump in the frequency of occurrence).

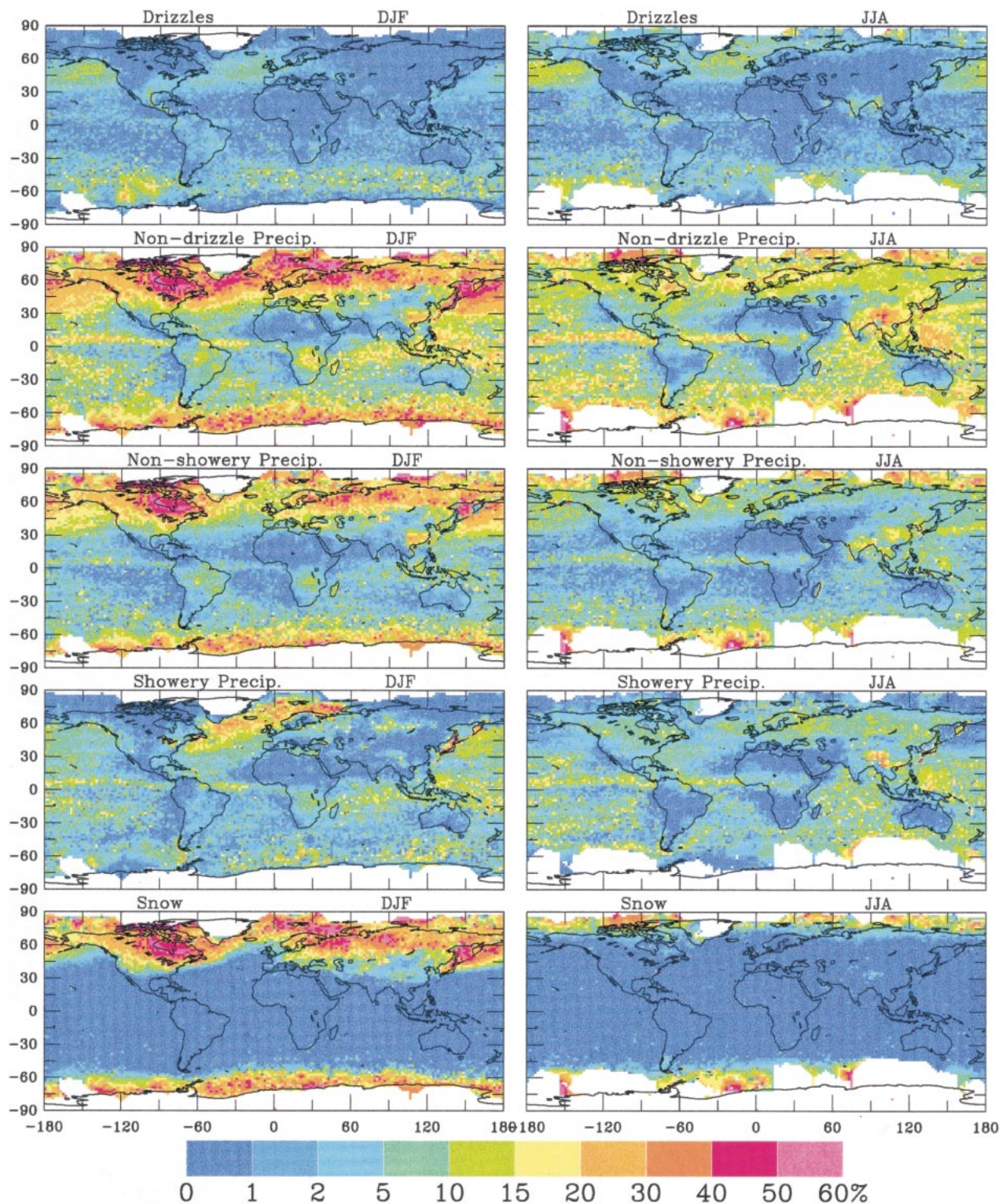


FIG. 4. Geographical distributions of frequency of occurrence (in %) for (top row) drizzle precipitation, (2d row) nondrizzle precipitation, (3d row) nonshowery precipitation (excluding drizzle), (4th row) showery precipitation, and (bottom row) snow for (left) DJF and (right) JJA.

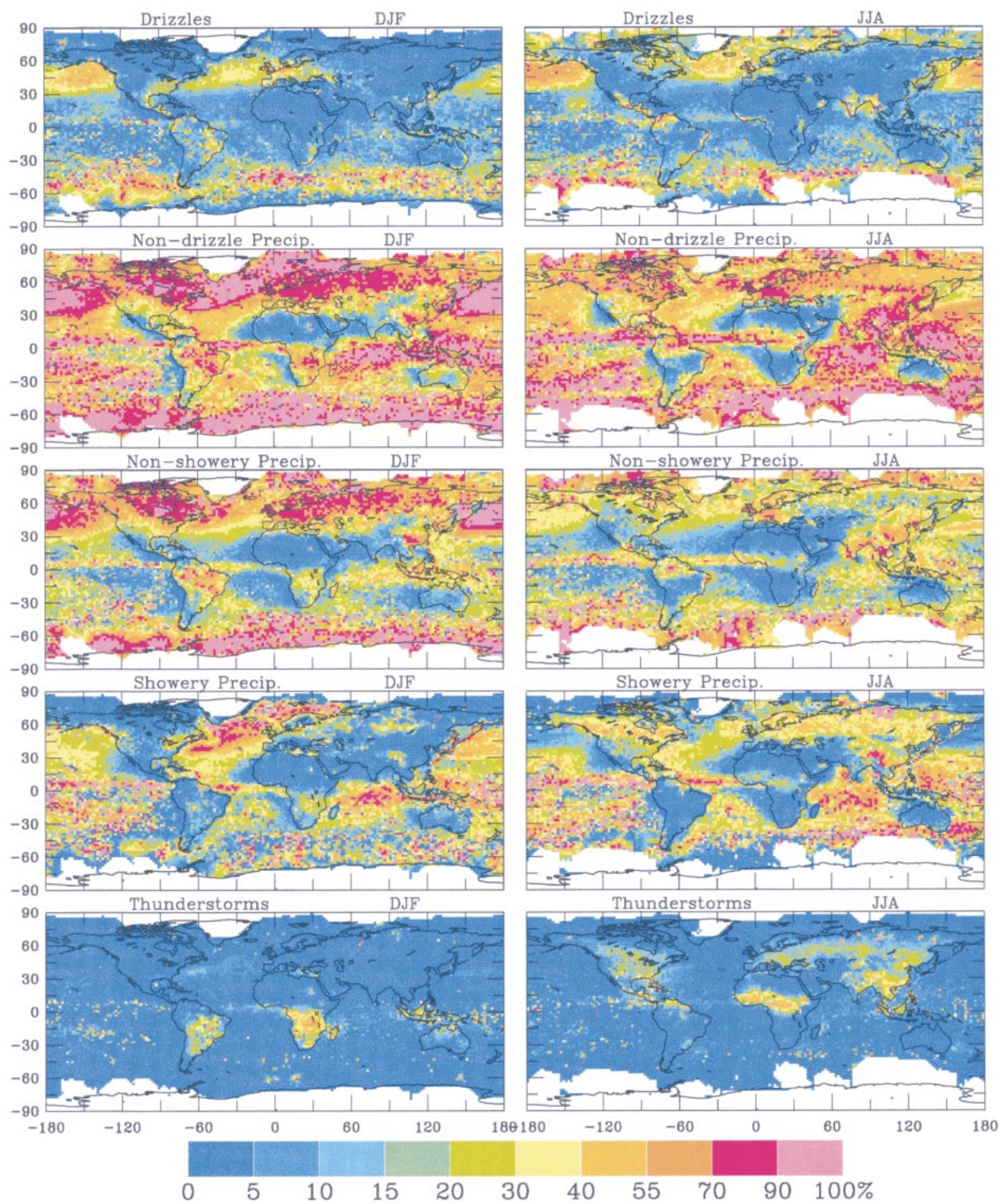


FIG. 5. Same as Fig. 4 but for the wet-day probability and (bottom row) thunderstorm-day probability.

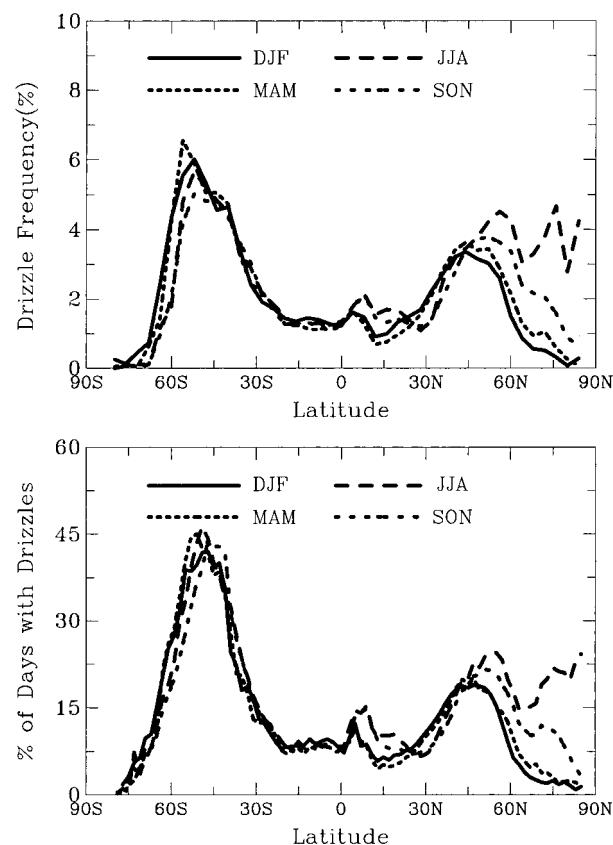


FIG. 6. (top) Latitudinal distributions of seasonal zonal mean frequency of occurrence (%) and (bottom) wet-day probability (%) for drizzle precipitation.

The wet-day probability for drizzle is much higher (around 40%–70%) over the midlatitude oceans than most other areas ($\leq 15\%$) (Fig. 5). Over most inner-land areas, drizzles occur in less than 5% of the days. Figure 6 shows that drizzles occur most frequently at mid-latitudes in both hemispheres, whereas they happen only about 1.5% of the time at low latitudes (30°S–30°N). Drizzles are also infrequent at high ($> \sim 70^\circ$) latitudes except for JJA at northern high latitudes where they occur as often as at northern midlatitudes ($\sim 3\%$ – 4% of the time). The largest percentage of the days with drizzles ($\sim 40\%$) occurs at southern middle latitudes (mostly over the oceans, cf. Fig. 5).

2) NONDRIZZLE PRECIPITATION

Nondrizzle precipitation, which includes precipitation of all forms other than drizzle, occurs more than 20% of the time over the storm-track regions (Dai et al. 2001) at middle and high latitudes (in DJF only at the northern latitudes) (Fig. 4). In particular, nondrizzle precipitation is most frequent (40%–60% of the time) from eastern Canada to northern Europe and in the western North Pacific in DJF. This high-frequency band at northern latitudes disappears in JJA and is weaker in MAM and

SON (not shown) as the synoptic activity weakens. The relatively high frequency band (evident in all the seasons) over the Antarctic Circumpolar Current is consistent with the strong activity of synoptic storms over the region 50°–70°S (Trenberth 1991; Dai et al. 2000). In the Tropics, a narrow ($\sim 6^\circ$ – 10° lat) band of relatively high frequency (15%–30%) over the equatorial central and eastern Pacific and the Atlantic sharply depicts the intertropical convergence zone (ITCZ). This band spreads to much wider areas and becomes less well defined from the western tropical Pacific to the Indian Ocean, especially in JJA. A southeast-oriented band of relatively high frequency ($\sim 15\%$) is evident over the western and central South Pacific in DJF (less clear in the other seasons), which is a depiction of the South Pacific Convergence Zone (SPCZ). Outside the tropical convergence zones, precipitation occurs less frequently ($\leq 10\%$) at low latitudes than at mid- and high latitudes. It rains less than a few percent of the time over the subtropical divergence regions such as northern Africa, the Middle East, southern Africa in JJA, central South America in JJA, and northern Australia in JJA. During the summer monsoon season over southeastern Asia, it rains about 20%–40% of the time, which is much higher than $\sim 10\%$ – 15% over northern midlatitudes.

Because drizzle contributes little to precipitation amounts over most areas, the frequency for nondrizzle precipitation events is probably the most relevant frequency for rain gauge recorded precipitation events. Current climatologies of monthly precipitation amounts have large discrepancies over the oceans because of the lack of direct measurements (Xie and Arkin 1997). The frequency of occurrence for nondrizzle precipitation (Fig. 4) provides one of the two constraints (the other one is intensity, i.e., the precipitation rate over the precipitating time period) on precipitation amounts over the oceans. The location and width of the ITCZ in the frequency for nondrizzle precipitation (Fig. 4) and in the Xie–Arkin precipitation climatology (Xie and Arkin 1997) are fairly similar over the central and eastern Pacific and the Atlantic. For example, a weak ITCZ in DJF and a strong ITCZ extending northward in JJA over the eastern Pacific and eastern Atlantic are evident in both the frequency maps and the Xie–Arkin climatology, which is derived from satellite observations of high-level cloudiness over the oceans. In contrast, the ITCZ in earlier precipitation climatologies (e.g., Jaeger 1983; Legates and Willmott 1990), whose oceanic precipitation was derived from a limited number of ship-board rain gauge records, differs substantially from that in the frequency maps.

The wet-day probability for nondrizzle precipitation (Fig. 5) is $> 50\%$ over most oceans and mid- and high-latitude land areas. Figure 7 shows the frequency of occurrence for nondrizzle precipitation is about 2–3 times higher at high latitudes than at low latitudes (except for JJA in the Northern Hemisphere). As shown below, this is largely a feature of the nonshowery pre-

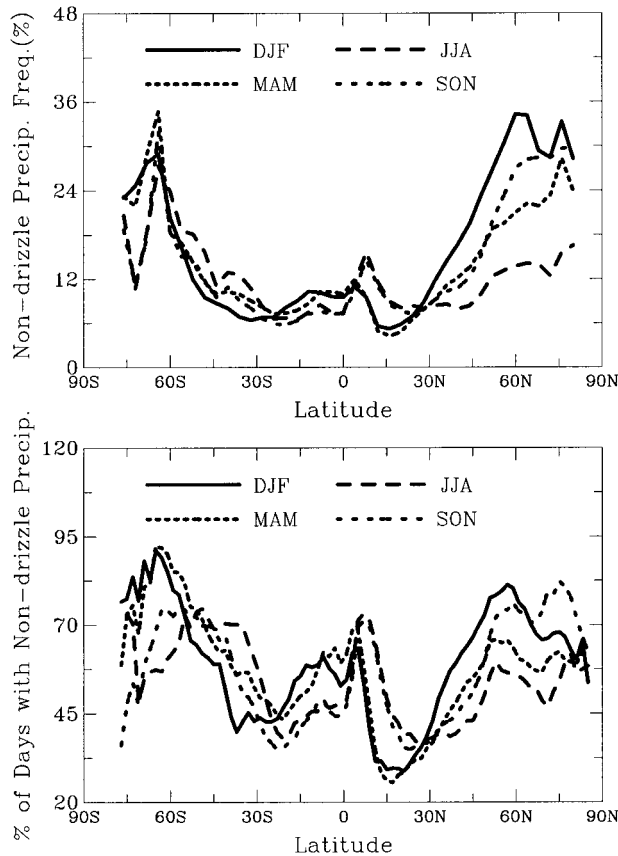


FIG. 7. Same as Fig. 6 but for nondrizzle precipitation.

cipitation. The zonal mean position of the ITCZ (centered at $\sim 8^\circ\text{N}$ in JJA and SON and $\sim 4^\circ\text{N}$ in DJF and MAM) is well defined in both the frequency of occurrence and the wet-day probability and is in good agreement with that defined by surface wind convergence (Dai and Deser 1999).

Over the oceans, the spatial patterns of the frequency of occurrence for nondrizzle precipitation are comparable to those for “moderate to heavy” intensity precipitation from Petty (1995), although Petty’s frequency is slightly higher (which could result from the differences in the analyzing methods mentioned above). There are few frequency maps derived using high-resolution rain gauge records. Higgins et al. (1996) computed the percentage of the days with various precipitation amounts over the United States using gridded hourly rain gauge records. Our wet-day probability for nondrizzle precipitation is comparable to Higgins’ frequency maps (with $>1 \text{ mm day}^{-1}$ cut-off) over the United States. In addition, the diurnal cycle of the frequency of occurrence for nondrizzle precipitation (Dai 2001a) is in good agreement with that based on hourly rain gauge records over the United States and other regions where data are available (Dai et al. 1999).

3) PRECIPITATION INTENSITY

The frequency of occurrence and the Xie–Arkin climatology of precipitation amounts (based on rain gauge records, satellite observations, and numerical model estimates) are derived from independent records. A climatology of precipitation intensity can therefore be inferred from the frequency and amount (recall that amount = frequency $\times$ intensity). Figure 8 shows the seasonal mean precipitation intensity⁸ (mm h^{-1}). It can be seen that the mean precipitation intensity is generally less than 1.0 mm h^{-1} at mid- and high latitudes, where stratiform nonshowery precipitation predominates (except for JJA in the Northern Hemisphere, cf. Fig. 4); whereas the intensity is about $1.5\text{--}3.0 \text{ mm h}^{-1}$ in the Tropics, where convective showery rainfall is frequent (cf. Fig. 4). The seasonal cycle of the intensity is largest over land areas, especially at low latitudes such as southeastern Asia, the Sahel, southern North America, and northern Australia. This seasonal cycle is induced by strong moist convection that follows the zone of seasonal maximum solar heating. The most intense rainfall is located in northern South America where the mean intensity can be as high as 10 mm h^{-1} . The intensity over the tropical oceans is about 2.0 mm h^{-1} , which is substantially lower than the largest intensity over tropical land areas. This suggests that moist convection can be more vigorous over certain land areas where moisture is abundant (such as the Amazon) than over the oceans (due to large warming of the land surface by solar heating). Another feature is that the mean intensity is not particularly high inside the ITCZ and the SPCZ when compared with other parts of the Tropics, in contrast to the frequency and amount patterns. From this we conclude that the large amount of precipitation inside the ITCZ (and the Indonesia region) results primarily from relatively high frequencies of precipitation events rather than from enhanced strength of moist convection.

4) NONSHOWERY PRECIPITATION

Figure 4 shows that nonshowery precipitation is the preferred form of precipitation at northern mid- and high latitudes in DJF (and in MAM and SON also, not shown) and over southern high latitudes (south of $\sim 60^\circ\text{S}$) in all seasons. Over northern mid- and high latitudes, nonshowery precipitation occurs in 50%–90% of the days in DJF (Fig. 5, and in MAM and SON also, not shown).

⁸ Precipitation intensity is defined here as total precipitation amount from Xie–Arkin seasonal climatology divided by the seasonal mean frequency of occurrence for nondrizzle precipitation. The contribution of drizzle to Xie–Arkin’s climatology is small and thus the intensity is essentially for nondrizzle precipitation. Also note that the intensity is likely at the lower limit of the range since the frequency overestimates the precipitating time for showery precipitation. This is because present weather reports of showery precipitation include those showers lasting less than 1 h.

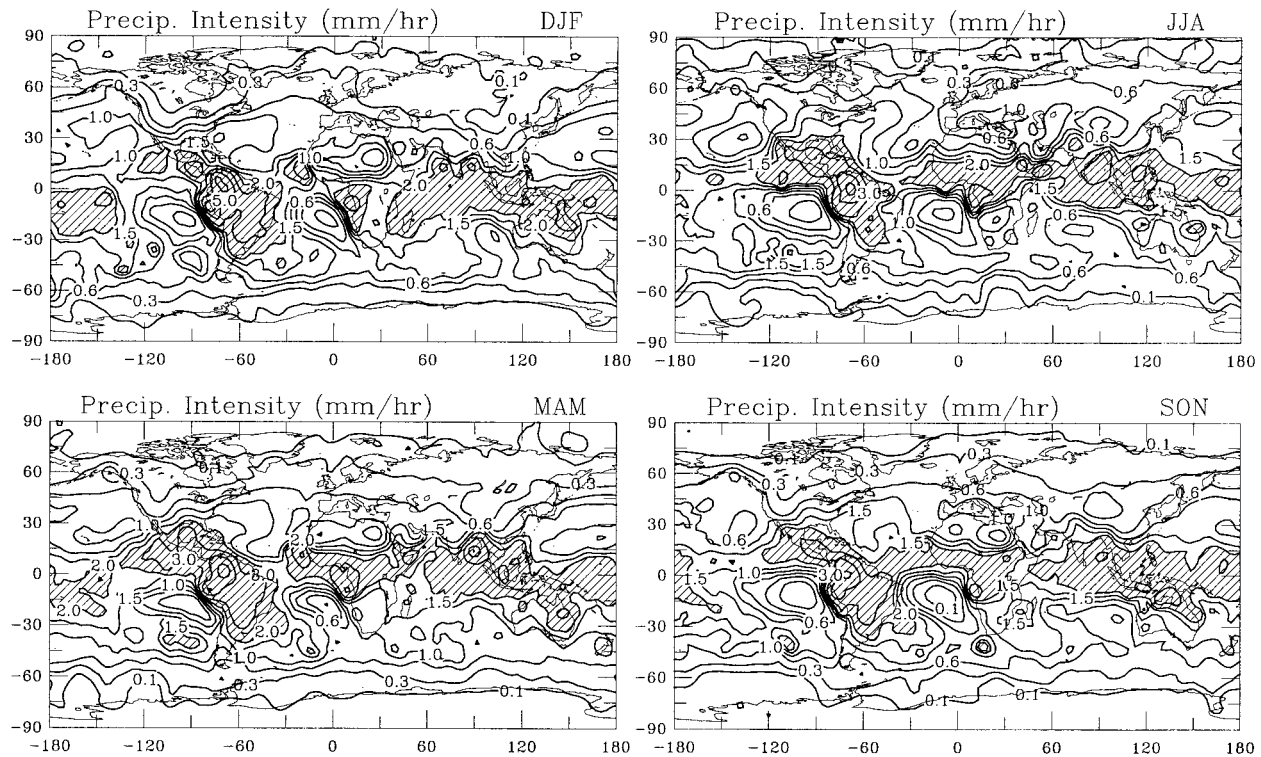


FIG. 8. Seasonal mean precipitation intensity (mm h^{-1}) derived by dividing the seasonal precipitation amount from Xie and Arkin (1997) by the frequency of occurrence for nondrizzle precipitation. Values over 2.0 mm h^{-1} are hatched.

As shown by the bottom row of Fig. 4, snow consists of a large portion of the nonshowery precipitation events at high latitudes for DJF (and MAM and SON). During the boreal summer, nonshowery precipitation at northern mid- and high latitudes occurs only about 5%–15% of the time, much less frequently than the other seasons.

At low latitudes and southern midlatitudes, the frequency of nonshowery precipitation events seems to be correlated spatially with that for showery precipitation (Figs. 4 and 5). For example, nonshowery precipitation events inside the ITCZ, which has been thought to be a zone of convergence and moist convection, are more frequent than in other parts of the Tropics. Dai (2001a) also found similar diurnal phase patterns for showery and nonshowery precipitation over the oceans at these latitudes. These results suggest that nonshowery precipitation at these latitudes may be physically related to moist convection (e.g., stratiform rainfall may occur from anvil clouds that result from strong moist convection) (Houze 1997). This differs from high and northern midlatitudes where nonshowery precipitation usually results from the passing of synoptic systems.

5) SHOWERY PRECIPITATION AND THUNDERSTORMS

In general, the frequency for showery precipitation over the oceans ($\sim 5\%$ – 20%) is higher than over land areas ($\sim 0\%$ – 10%), except for JJA over Northern Hemisphere land areas where showery precipitation becomes

as frequent as over oceanic areas (Fig. 4). Showery precipitation is more frequent than nonshowery precipitation over the low-latitude oceans, whereas it is generally the opposite over the land areas (except for JJA).

Figure 5 shows that showery precipitation occurs over 40% of the days over most low-latitude oceans. During JJA showery precipitation occurs very frequently ($\geq 50\%$ of the days) in southern China and frequently (30%–50% of the days) over Europe, central Asia, and Canada. Showery precipitation (including snow) is also very frequent over the northern North Atlantic Ocean in all but JJA season. JJA is also the season with minimum showery precipitation events over the North Pacific Ocean, where there is a strong high pressure center in JJA. The land–ocean difference in the phase of the seasonal cycle will be discussed in more detail below.

Thunderstorms (including nonprecipitating ones) are observed in less than 10% of the days over most oceans (Fig. 5). They occur primarily over the land areas in the summer hemisphere. For example, during the boreal summer, thunderstorms occur in 30%–50% of the days over southeastern Asia, the southeastern United States, Central America, and the western part of Africa from 0° to 15°N . Summer thunderstorms are also frequent (10%–30% of the days) over other parts of the United States except California and the Northwest. During the austral summer, there are thunderstorms in about 30%–50% of the days in Africa south of the equator, and 20%–40% of the days in central South America.

During MAM and SON (not shown), the percentage of the days with thunderstorms is about 20%–50% over equatorial Africa, 20%–30% in southeastern Asia and central South America, 10%–20% over the southeastern United States and Central America.

The global patterns of thunderstorm days⁹ inferred from the thunderstorm-day probability are comparable to those based on the data before the mid-1950s (WMO 1956), although Fig. 5 reveals much more detail.

6) SNOW

Over the Northern Hemisphere, snow occurs mostly at high latitudes (in all but JJA season) and over land areas at midlatitudes (in DJF only; Fig. 4). It snows 40%–60% of the time in DJF over eastern Canada, northern Europe and the adjacent Barents Sea, and the northwestern North Pacific. Snowing is observed 5%–20% of the time in DJF over much of the United States except for the very southern part of the country (e.g., Florida) where it seldom occurs. Snow is also not common ($\leq 5\%$ of the time) in southern Asia (south of 45°N). Figure 9 shows that the starting latitude with substantial snow in the Northern Hemisphere varies seasonally ($\sim 35^\circ\text{N}$ in DJF, 40°N in MAM, 43°N in SON, and 67°N in JJA), in phase with the seasonal cycle of zonal mean temperature ($\sim 10^\circ\text{C}$ at these latitudes).

Over the Southern Hemisphere, significant snow occurs only south of about 50°S in all the seasons (Figs. 4 and 9). From the equator to $\sim 50^\circ\text{S}$, zonal mean temperatures have relatively small seasonal variations and do not fall below $\sim 10^\circ\text{C}$ (Fig. 9). It should be pointed out that snow over mountains such as the Andes and the Himalaya is not well sampled (cf. Fig. 2).

7) SPATIAL PATTERNS OF THE SEASONAL CYCLE

As mentioned above, the seasonal cycle of the showery precipitation frequency may be out of phase between the land and oceanic areas. To investigate this in more detail, we analyzed the seasonal frequencies of each year using the EOF method (with the seasonal cycle included in the data). Figure 10 shows the time series and spatial patterns of the seasonal EOF mode of the wet-day probability (similar EOFs for the frequency of occurrence) for drizzle, nonshowery, and showery precipitation. The positive (negative) contours correspond to a DJF (JJA) maximum of the seasonal cycle. The seasonal cycle explains about 20%–30% of the total variance of the seasonal probability (frequency) for nondrizzle, nonshowery, and showery precipitation. This percentage is lower for thunderstorms and snow ($\sim 16\%$ for both) and drizzle ($\sim 12\%$). The EOF for nondrizzle precipitation is

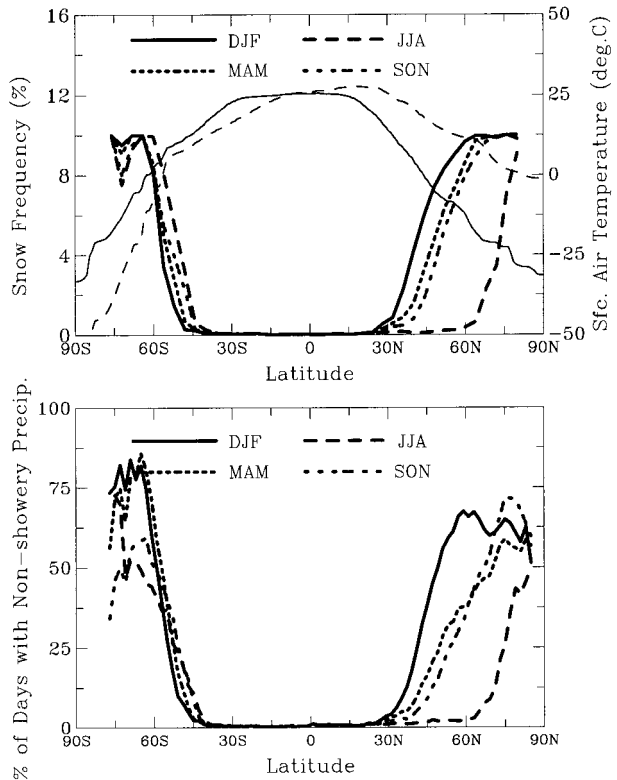


FIG. 9. Same as Fig. 6 but for snow. Also shown are DJF (thin-solid curve) and JJA (thin-broken curve) zonal mean surface air temperatures from surface observations.

similar to that for nonshowery precipitation, whereas the EOF for thunderstorms is comparable to that for showery precipitation.

Figure 10b shows that for drizzle the seasonal cycle occurs primarily in the Northern Hemisphere, where the frequency peaks in JJA over the subtropical North Atlantic, Europe, northern Africa, and the subtropical North Pacific, while it reaches a maximum in DJF over other regions. For nonshowery (and nondrizzle) precipitation, the seasonal cycle is generally larger over land areas (especially at northern mid- and high latitudes) than over the oceans (Fig. 10c). Nonshowery precipitation is most frequent in DJF north of about 25°N and over the land areas between 0° and 30°S , while the maximum is in JJA between about 5° and 20°N and over many of the oceanic areas between 10° and 50°S . The DJF maximum at the northern latitudes is consistent with increased winter synoptic activities at northern mid- and high latitudes. The JJA maximum over the 5° – 20°N zone is related to the increased moist convection around the ITCZ. Over the low and midlatitudes in the Southern Hemisphere, the pattern resembles that for showery precipitation (Fig. 10d). This is consistent with the hypothesis stated above that nonshowery precipitation results from physical processes that are associated with moist convection at low latitudes and southern midlatitudes.

⁹ A thunderstorm day is a local calendar day on which thunder is heard (WMO 1956).

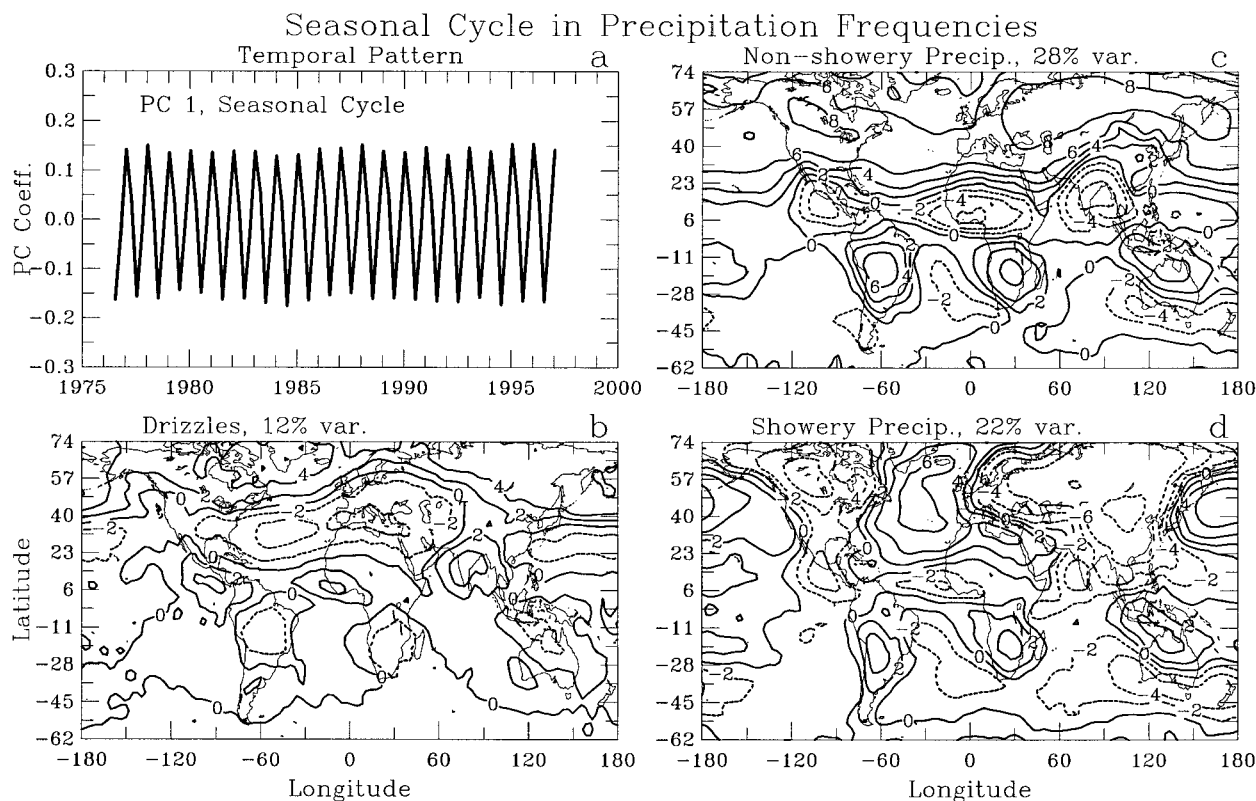


FIG. 10. EOF (a) temporal coefficient and (b) spatial patterns for drizzle, (c) nonshowery and (d) showery precipitation for the seasonal cycle. For (b)–(d) the percentage variance explained by the EOF is indicated at the top.

The seasonal cycle for showery precipitation (Fig. 10d) (and thunderstorms) exhibits a coherent land–ocean pattern, in which the land areas peak in summer and the oceans peak in winter. Similar land–ocean patterns are seen in the seasonal and diurnal cycles of surface wind convergence and have been attributed to the differential surface temperature responses (larger warming over the land than the ocean during summer and the day) to seasonal and diurnal solar heating over the land and oceanic areas (Dai and Deser 1999). The seasonal cycle pattern for showery precipitation, which results from moist convection and is therefore closely related to surface convergence, is in good agreement with the convergence data of Dai and Deser (1999). It is also in broad agreement with the land–ocean pattern of the diurnal cycle of showery precipitation (Dai 2001a).

b. Interannual variations

In this subsection, we first describe the year-to-year standard deviation (s.d.) of the precipitation frequency and wet-day probability and then their leading EOF modes. Although distributions of short-time (e.g., hourly) precipitation rates are heavily skewed (with a long tail of large precipitation rates), seasonal and annual precipitation are fairly close to normal distributions and therefore the s.d. is a reasonable measure of the year-

to-year variability. Although the records are relatively short, the leading EOFs of the seasonal wet-day probability (similar EOFs for the frequency of occurrence) still provide some insights into the physical processes underlying the year-to-year variability.

Figures 11 and 12 show the s.d. of DJF and JJA mean wet-day probability (similar patterns with smaller magnitudes for the frequency of occurrence) for the six types of precipitation and thunderstorms. It can be seen that spatial patterns of the s.d. generally follow those of the mean probability (cf. Figs. 4 and 5; note that many of the small-scale features seen in Figs. 4 and 5 were smoothed out in Figs. 11 and 12). The magnitude of the s.d., which ranges from a few percent to ~20% of the days, is about 10%–20% of the mean over most areas except for the regions with small mean probability (e.g., northern Africa and the Middle East) where the s.d. is as large as the mean. The southern oceans (south of ~50°S) have relatively large s.d. This partly reflects the large sampling errors over these regions. The seasonal cycle in the s.d. also follows that of the mean probability (e.g., larger over the land areas of the summer hemisphere for convective precipitation and thunderstorms).

Figure 13 shows the first and second EOFs of the wet-day probability for nondrizzle precipitation, and the first EOFs for nonshowery and showery precipitation. It can be seen that the first EOFs for nondrizzle and

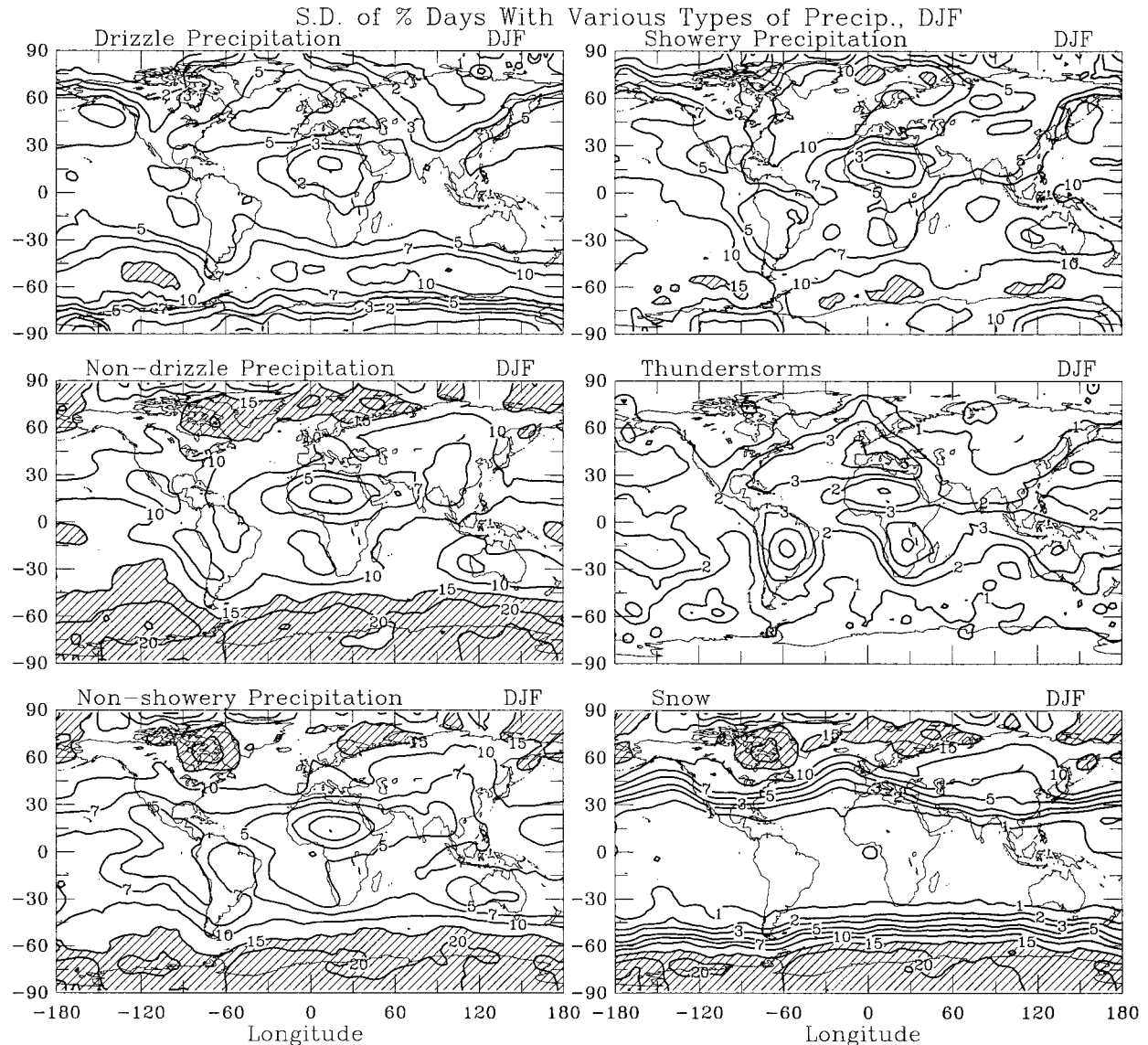


FIG. 11. Standard deviation of the wet-day probability for various types of precipitation and of the thunderstorm-day probability. Contour levels are 1%, 2%, 3%, 5%, 7%, 10%, 15%, 20%, and 25%. Values over 15% are hatched.

nonshowery precipitation, which explain about 4.3% of the total variance, are significantly correlated with ENSO in both time and space. The spatial patterns match the ENSO EOFs of seasonal precipitation amounts (Dai et al. 1997; Dai and Wigley 2000). For example, during El Niño years, the wet-day probability for nondrizzle precipitation is substantially (~ 1 s.d. or more) below normal over the Indonesia region, Australia, and the eastern India Ocean. The probability is also below normal over northern South America, and the equatorial Atlantic during El Niño years. On the other hand, during El Niño years nondrizzle precipitation is more frequent over the central and eastern equatorial Pacific, the southern United States, and the adjacent oceans. The patterns of the 1st EOFs over the open oceans (Fig. 13; top right)

are in situ observations of the ENSO-induced precipitation anomalies that confirm those derived previously from satellite estimates of rainfall (Dai and Wigley 2000). In the frequency and wet-day probability for the other types (including showery, Fig. 13) of precipitation and thunderstorms, the ENSO mode was not well separated from other variations, presumably because of the relatively short length of the record.

The second EOF of the wet-day probability for non-drizzle precipitation and the first EOF of the wet-day probability for showery precipitation exhibit decadal oscillations with periods of ~ 10 – 12 yr and large weighting over North America. Although there is some correlation between the time series of the second EOF for nondrizzle precipitation and the seasonal mean sunspot

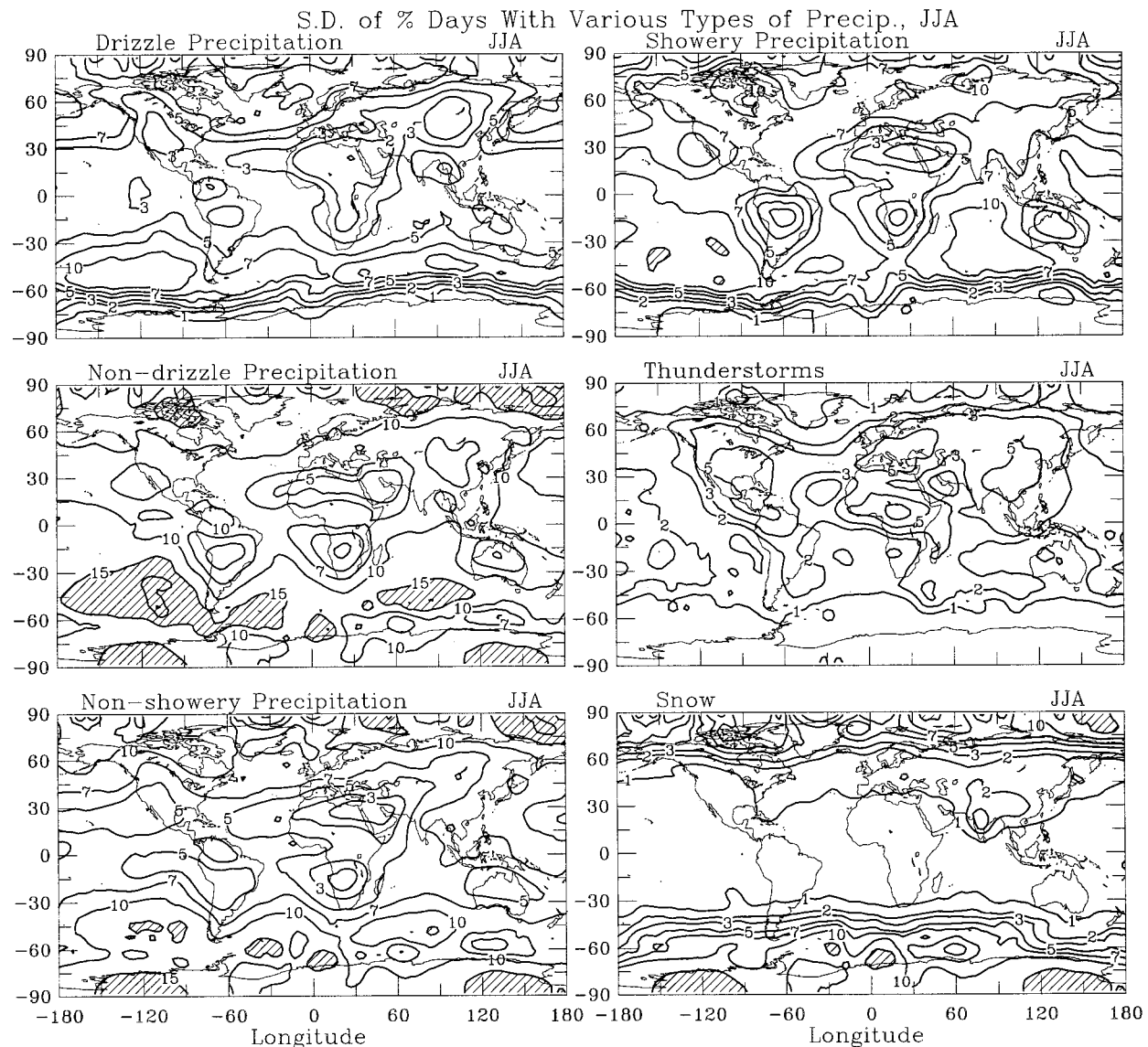


FIG. 12. Same as Fig. 11 but for JJA.

number, this correlation is statistically insignificant because of the short length of the record.

4. Summary

Global climatologies of the frequency of occurrence for various types of precipitation are an important aspect of the climate and are needed for climate-model evaluations. Here we analyzed 3-hourly present and past weather reports from $\sim 15\,000$ stations and from the COADS ship observations from 1975 to 1997 for the frequency of occurrence and wet-day probability for drizzle, nondrizzle, showery, and nonshowery precipitation, thunderstorms, and snow. The 3-hourly sampling appears to be sufficient for computing the mean frequency of occurrence based on comparisons with hourly

rain gauge data over the United States. However, the weather report data were found to contain inhomogeneities resulting from changes in recording practices, the number of reports, the spatial coverage, and other biases. The uncertainty of the mean frequencies associated with the inhomogeneities is likely to be within about $\pm 10\%$. Sampling errors are large (especially for the wet-day probability) over the southern oceans (south of $\sim 45^\circ\text{S}$), the polar regions, and the sparsely populated land areas (such as central Australia, central Africa, and northern Canada). Nevertheless, the weather reports still provide valuable information about the mean geographical, seasonal and interannual variations in the precipitation frequency and wet-day probability.

Drizzles occur 5%–15% of the time over mid- and high-latitude oceans. Over land areas and the low-lati-

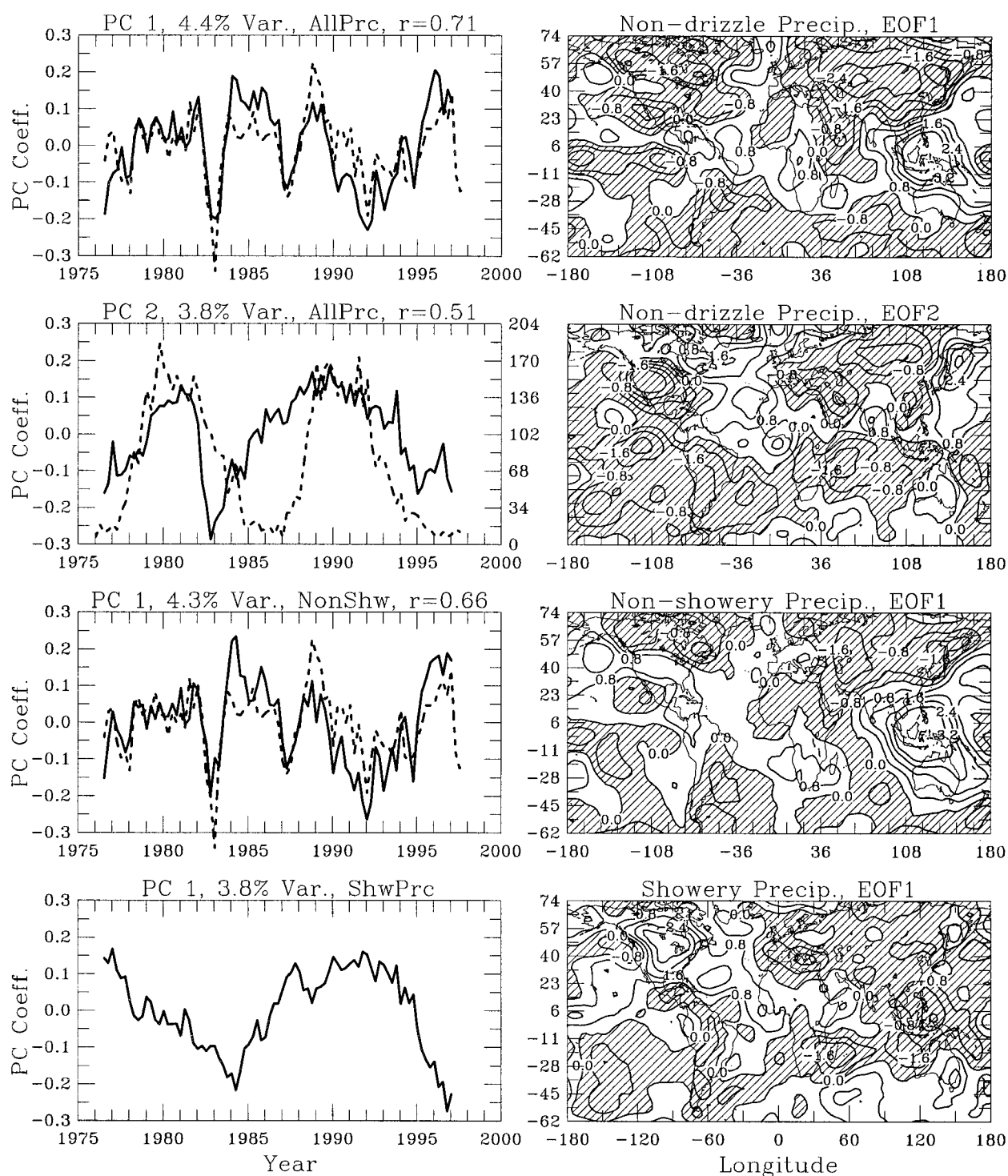


FIG. 13. (left) Time series and (right) spatial patterns (negative values are hatched) of the leading EOFs of the wet-day probability for (top 2 rows) nondrizzle, (3d row) nonshowery, and (bottom row) showery precipitation. The seasonal cycle was removed before the EOF analysis. The percentage variance explained by the EOF is indicated at the top of the left panels. The r is the correlation coefficient between the solid and dashed curves, which are seasonal mean Southern Oscillation index (divided by 10) in the 1st and 3d panels of the left-hand side and sunspot numbers in the 2d panel (read on right-side ordinate).

tude oceans, drizzles occur less than a few percent of the time. Drizzles are observed in ~40%–70% of the days over midlatitude oceans. The seasonal cycle in the drizzle frequency is relatively weak and occurs mostly in the Northern Hemisphere, where the frequency peaks in JJA over the subtropical North Atlantic, Europe, northern Africa, and subtropical North Pacific, whereas it reaches a maximum in DJF over other regions.

Nondrizzle precipitation occurs 20%–60% of the time over the storm-track regions at northern mid- and high latitudes (mostly in DJF) and over the Antarctic Circumpolar Current (in all seasons). In the Tropics, a narrow (~6°–10° lat wide) band of relatively high frequency (15%–30%) of precipitation over the equatorial central and eastern Pacific and the Atlantic outlines the location of the ITCZ. The southeast-oriented SPCZ is also evident in the frequency maps with ~15% of the time having rainfall. Outside the convergence zones, nondrizzle precipitation occurs less than 10% of the time at low latitudes, as compared with 10%–40% at mid- and high latitudes. Nondrizzle precipitation occurs less than 2% of the time over the subtropical divergence regions such as northern Africa and the Middle East.

The locations and their seasonal variations of the ITCZ and SPCZ shown in the frequency maps for nondrizzle precipitation are in good agreement with those seen in satellite-based estimates of precipitation amounts and in surface wind convergence fields. The seasonal mean precipitation intensity inferred from the frequency for nondrizzle precipitation and the Xie–Arkin climatology of precipitation amounts is generally less than 1.0 mm h⁻¹ at mid- and high latitudes and ~1.5–3.0 mm h⁻¹ in the Tropics. The mean intensity inside the ITCZ and the SPCZ is comparable to many other parts of the Tropics, suggesting that it is mainly the high frequency (rather than intensity) that contributes to the large precipitation amounts inside the ITCZ and the SPCZ (and the Indonesia region).

Nonshowery precipitation is the preferred form of precipitation at northern mid- and high latitudes in all but JJA season (occurring in 50%–90% of the days) and over southern high latitudes in all seasons. At low latitudes and southern midlatitudes, where showery precipitation is more frequent than nonshowery precipitation, the occurrence of nonshowery precipitation tends to be correlated spatially with showery precipitation. The seasonal cycle at these latitudes is also similar for showery and nonshowery precipitation. These results suggest that nonshowery precipitation at low latitudes and southern midlatitudes may result from physical processes that are associated with moist convection (e.g., anvil clouds resulting from deep convection often produce stratiform rainfall), in contrast to high latitudes and northern midlatitudes where nonshowery precipitation usually results from the passing of synoptic systems.

Nondrizzle and nonshowery precipitation are most frequent in DJF north of ~25°N and over the land areas

between 0° and 30°S, while the seasonal maximum is in JJA between 5°N and 20°N and over many oceanic areas between 10°S and 50°S.

The frequency for showery precipitation is generally higher over the oceans (~5%–20%) than over land areas (~0%–10%), except for JJA over Northern Hemisphere land areas where showery precipitation becomes as frequent as over the oceans. In particular, summer showery precipitation occurs very frequently (≥50% of the days) in southern China and frequently (30%–50% of the days) over Europe, central Asia, and Canada.

Thunderstorms (including nonprecipitating ones) occur in less than 10% of the days over the open oceans but much more frequently over the land areas of the summer hemisphere. During the boreal summer, thunderstorms occur in 30%–50% of the days over southeastern Asia, the southeastern United States, Central America, and the western part of Africa from 0° to 15°N. During the austral summer, there are thunderstorms in ~30%–50% of the days in Africa south of the equator, and 20%–40% of the days in central South America. During MAM and SON, the thunderstorm-day probability is ~20%–50% over equatorial Africa, 20%–30% in southeastern Asia and central South America, 10%–20% over the southeastern United States and Central America.

The seasonal cycles of showery precipitation and thunderstorm frequency and wet-day probability exhibit a coherent land–ocean pattern, in which the land areas peak in summer and the oceans peak in winter. This pattern is consistent with the land–ocean patterns seen in the diurnal cycle of showery precipitation and the seasonal and diurnal cycles of surface wind convergence, and results from the differential surface temperature responses to solar heating.

Substantial snow occurs poleward of the latitude where zonal mean surface air temperature is near 10°C such as 50°S, 35°N in DJF, 40°N in MAM, and 43°N in SON.

The spatial patterns of the standard deviation of year-to-year variations for the precipitation frequency and wet-day probability generally follow those of the mean, with a magnitude of ~10%–20% of the mean (except for regions with small mean values). The first EOFs of nondrizzle and nonshowery precipitation frequency and probability are an ENSO-induced mode that confirms the ENSO-induced precipitation anomalies over the oceans derived previously from satellite estimates. There are also decadal modes in nondrizzle and showery precipitation frequency and probability with periods of ~10–12 yr, but these modes may contain large sampling errors resulting from the short length of the record.

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