Atmospheric Climatology and Its Effect on Sea Surface Temperature—Winter 1977 to Winter 1978

ROBERT R. DICKSON and JEROME NAMIAS

The previous report in this series (Dickson and Namias, In press) has described the progressive amplification of the Northern Hemisphere circulation in 1976 compared with the abnormally strong westerly flow of the preceding 5 years. In 1977 this amplified circulation type was maintained, characterized in addition by episodes of extreme circulation anomaly and by elements of great persistence.

All three of these characteristics—high amplitude flow, extreme abnormality, and tenacious persistence—were displayed during winter 1976-77. The mean distribution of 700 mb height anomaly for winter (Fig. 1A) leaves little doubt about the strong amplification of planetary waves in the upper westerlies in that season; the principal centers of height anomaly—an intense Pacific trough south of the Aleutians (-520 feet), the meridional ridge overlying the west coast of North America (+250 feet), the deep response trough downstream over eastern North America, and a major ridge (not shown) over northern Siberia—all represented departures of three standard deviations or more from the long term seasonal "normal."

Robert R. Dickson is with the Fisheries Laboratory, Ministry of Agriculture, Fisheries, and Food, Lowestoft, Suffolk, England NR33 OHT. Jerome Namias is with the Scripps Institution of Oceanography, La Jolla, CA 92093.

As Wagner (1978) pointed out, such intense abnormalities are unlikely to occur in a given location more than once per century. The dislocating effect on climate in this sector (including record breaking cold over eastern North America) was compounded by the extreme persistence of these cells. Since their establishment in fall 1976, the major troughs and ridges intensified but showed little change in position through most of the succeeding winter. Of the changes which did occur between fall and winter the principal feature was the establishment of an immense blocking high over the polar region in early January, encouraging a southward displacement of the zonal westerlies over much of the hemisphere which amounted to a record expansion of the circumpolar vortex (Angell and Korshover, 1978).

Figure 2 illustrates the resulting sympathetic shift in the principal storm track over the Atlantic sector by showing the total (3-month) change in winter storm activity from the previous winter (1975-76) to the winter under discussion. As shown, storm activity decreased markedly at high latitudes, principally along a zone connecting the east-central United States, south Greenland, and Iceland where the deficit exceeded 10 storms per season. The main zone of increased storm activity lay further south along the American Atlantic seaboard and eastward to western Europe.

The possible causes of such extreme and protracted climatic behavior have been discussed by Namias (1978). First, it is evident that the anomalous tendencies of the atmospheric circulation during fall and winter were almost completely in phase with the normal trends of seasonal forcing so that underlying seasonal changes did not oppose (and may have amplified) the factors responsible for generating the abnormal windfield. Thus a deep summer trough off the western seaboard and a downstream ridge over central North America, such as were observed in summer 1976, will normally retrogress to the east central Pacific and west coast respectively in fall, and from fall to winter there is normally a tendency for the Pacific trough and the west coast ridge to intensify further in these locations, accompanied by a southward shift of the main westerly wind axis and storm belt. The main point at issue here of course is the reason why these apparently normal tendencies of the circulation were exaggerated into features of extreme anomaly.

The factors at work appear to have included the following. First, retrogression of the high pressure anomaly cell to western North America in fall brought a strong southerly air flow to the eastern Pacific, inhibiting coastal upwelling, reducing the loss of sensible and latent heat to the atmosphere and boosting northward advection of warm water along the western seaboard. As a result, there occurred a progressive and dramatic anomalous warming (or more correctly a lack of normal seasonal cooling) of east Pacific waters from summer 1976 to winter 1976-77, by which time core anomalies off the west coast exceeded +3.5°F (Fig. 1B).

In sharp contrast, a vast zonal tongue of abnormally cold surface water (in places three standard deviations from normal) persisted in the west and central North Pacific, a remnant of the cold water belt of record extent which had prevailed in the summer of 1976 (Namias, 1978). The maintenance of these cold conditions into fall and winter under an intense and persistent Aleutian trough is readily explained by the enhanced cloud cover, increased sensible and

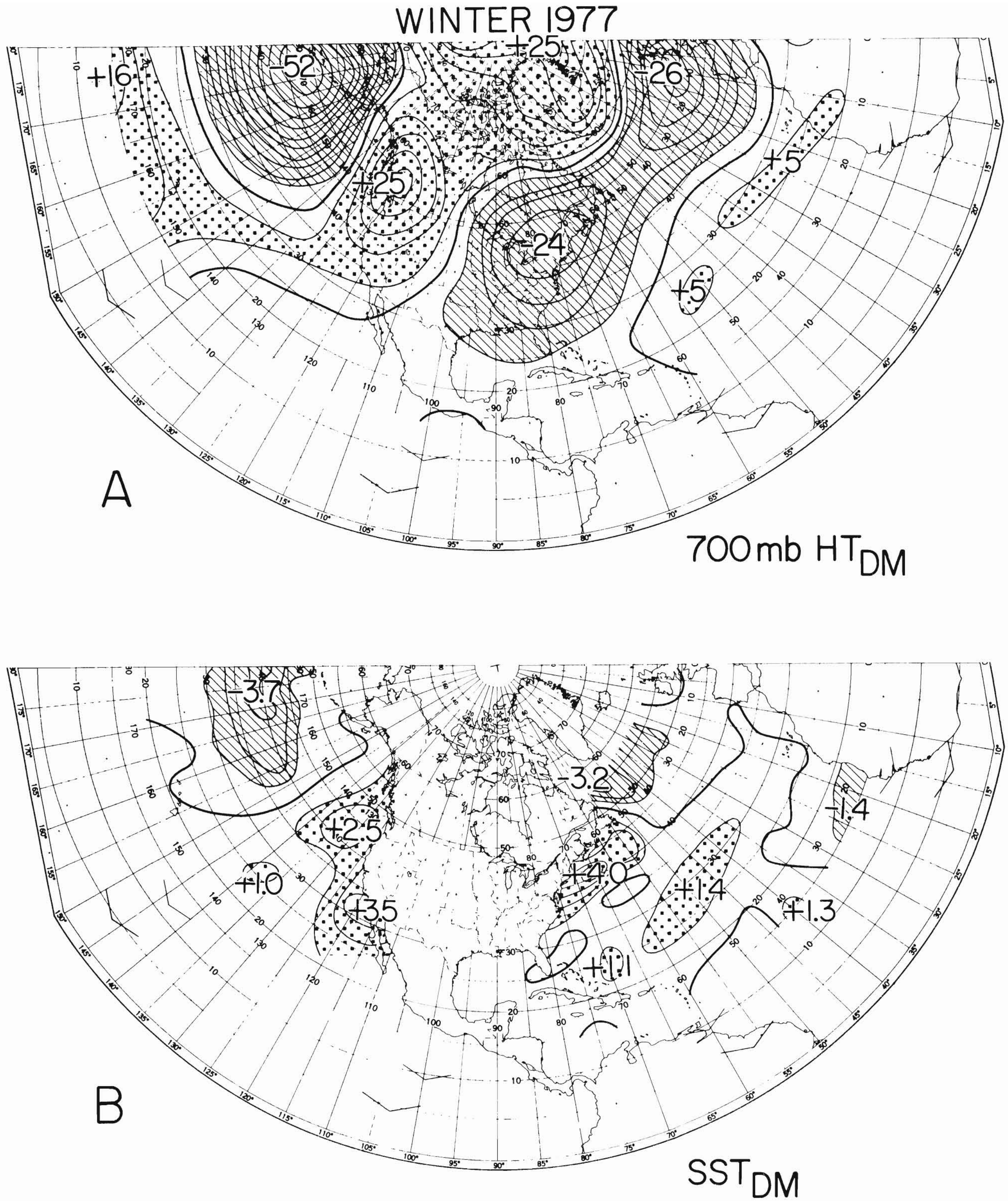


Figure 1.—Mean distribution of (A) 700 mb height anomaly (feet ÷ 10) and (B) sea surface temperature anomaly (°F) for winter 1976-77.

latent heat loss[1], cold frontal activity, and surface water divergence that such a cell implies.

Between these two extremes of Pacific surface temperature anomaly, a sharpening zone of east-west temperature contrast developed from fall to winter along long. 140°-150°W (Fig. 1B) and the baroclinic effect of this gradient (itself extreme) is suggested by Namias (1978) to have played a significant role in stabilizing the anomalous circulation pattern, sharpening frontal and cyclonic activity, augmenting the upper level southerly flow over the east Pacific and thus reinforcing the west coast ridge downstream.

The above discussion has concentrated on only two of the mechanisms which might have lent a degree of stability and persistence to the anomalous circulation of the fall and winter in question (i.e., compatibility with seasonal forcing and the feedback effect of extreme surface temperature gradients). Other possible contributory mechanisms have also been suggested; among these are the possible remote influence of El Niño conditions in the eastern tropical Pacific (present from summer 1976 to spring 1977) in maintaining the intensity of the deep Aleutian low via the mechanism described by Bjerknes (1966) and later simulated by Rowntree (1972, 1975).

Elsewhere, as Namias (1978) indicated, the recurrent outbreaks of Arctic air over eastern North America in the lee of the west coast ridge and the refrigerating effect of the greatly extended snow cover (the most extensive for at least 10 years; Matson, 1977) enhanced the baroclinic contrast at the eastern seaboard, leading to an intensification of east coast storm activity and thus to a reinforcement of the mean trough in this sector also. (In January, during its period of strongest development, upper westerly wind speeds were as much as 8 m/sec above normal off the southern Atlantic coast (Wagner, 1977).) The question as to which of these feedback loops exerted a significant control on the circulation is at present unknown; nevertheless, it is

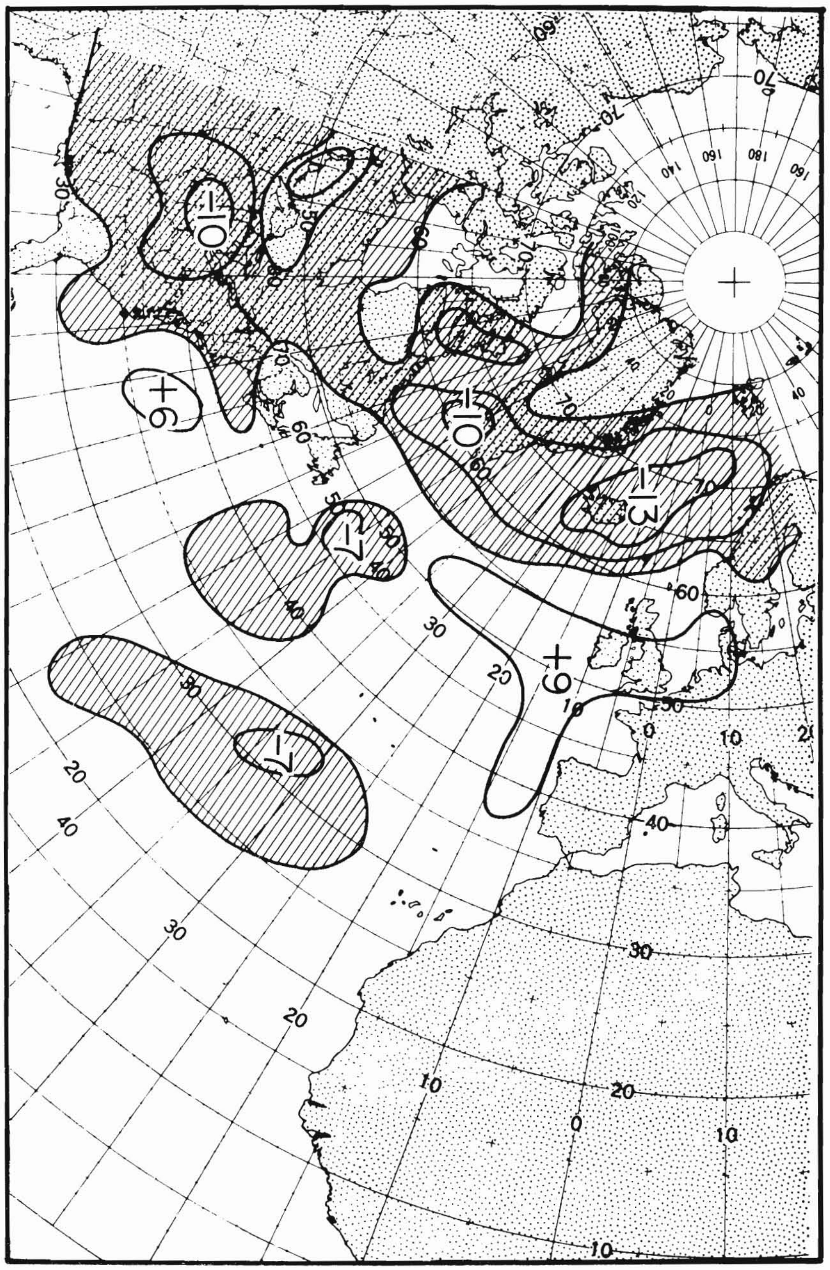


Figure 2.—Change in the total number of storms from winter 1975-76 to winter 1976-77. Contours represent an overall change of 5 or 10 storms per season with areas of decrease shaded. Based on monthly storm track charts published in the *Mariners Weather Log*.

[1]In January, Wagner (1977) reported that the westerlies at 700 mb level were as much as 11 m/sec stronger than normal in the vicinity of the Pacific trough.

hard to avoid the suggestion that acting (as they did) in unison, their combined effect was at least partly responsible for the tenacious persistence of the anomalous circulation through two consecutive seasons.

The effects of this intense and protracted atmospheric forcing on sea surface temperature (SST) over the North Pacific has already been described. In the Atlantic sector (Fig. 1B) the major centers of SST anomaly lay off the Atlantic seaboard where a tongue of abnormally warm water (+4.0°F) followed the axis of the Gulf Stream, and off south Greenland where a broad zone of cold surface water (-3.2°F) extended southward and eastward towards Europe. The former center may not simply be due to the strong southerly circulation around the American coastal trough; Worthington (1977) has presented evidence that intense cold air outbreaks from the American continent in winter may bring about a radical deepening of the thermocline south of the Gulf Stream and hence an intensification of warm water transport by the Gulf Stream system. The cooling in the northern North Atlantic is the expected result of strong anticyclonic circulation over Greenland which tends to occur (as in this case) when a well-developed baroclinic zone at the American Atlantic seaboard encourages a south-eastward shift in the mean position of the Iceland Low (Dickson and Namias, 1976).

The last week of winter finally saw the breakdown of the hemispheric circulation pattern which had dominated the fall and winter seasons but the spring circulation which replaced it displayed features of almost equivalent abnormality. As Figure 3A shows, the circulation anomaly pattern which emerged was almost exactly out of phase with the pattern of the preceding fall and winter over much of the Northern Hemisphere. Centers of positive height anomaly abruptly replaced the preexisting intense troughs over the North Pacific, eastern North America, and western Europe, while a narrow salient of negative height anomaly extended over western North America from a deep trough centered on the Bering Sea. Once established, however, this new planetary wave pattern persisted with almost as much regularity as had the winter pattern. As Wagner (1978) pointed out, such persistence is even more unusual in spring than winter since the "transition season" of spring is characterized by rapid changes in solar angle, in the length of day, and in thermal contrast between continent and ocean.

Although the principal anomaly cells of the spring circulation were considerably less extreme than those of winter (only the Great Lakes ridge approached three standard deviations from normal), the reversed sense of the circulation brought a rapid modification of surface temperature anomalies over both oceans. The elimination of the mean trough from the central North Pacific (coincident with the cessation of El Niño conditions in the tropics), brought a relative change toward less cloudy skies, settling air, surface water convergence, and a slackening of midlatitude westerly flow; as a result the long established cold water tongue in the west Central Pacific was considerably eroded, with core anomalies warming by 1°F compared with winter (Fig. 3B). Off the American west coast where the anomalous temperature field was less well entrenched, the change from anomalous southerly to northerly air flow (Fig. 3A) led to a reversal of the warming processes there (including a resumption of coastal upwelling) and hence to the almost total destruction of the preexisting warmth in the eastern Pacific. Together, these new tendencies towards warming in the west and cooling in the eastern Pacific also brought the virtual elimination of the strong east-west surface temperature gradient which had been an important feature of the winter season. In the Atlantic sector the only center of SST anomaly to persist unaltered into spring was the tongue of anomalous warmth overlying the Gulf Stream axis off the Atlantic seaboard. If real, this center most probably reflects the continued influence of strong Gulf Stream transports initiated by the extreme cold air outbreaks of the winter season. In April the volume transport of 95 sverdrups was the largest value ever computed for the Gulf Stream (Worthington, 1977).

In summer 1977 (Fig. 4A) the hemispheric circulation became progressively less amplified than hitherto with weak tongues and ridges progressing rather rapidly from month to month. In the seasonal mean, however, a zonal belt of below-normal heights extended from south of the Aleutians to eastern Canada and this, coupled with moderate subtropical ridges farther south, gave rise to a flat and fairly fast flow across the North Pacific and along the U.S.-Canadian border (where an active frontal zone with enhanced storm activity developed between the cool Canadian air and the stagnant heat of the South).

In the Pacific sector this enhanced westerly flow maintained (or rather amplified) the cool surface temperatures in the west central region and completed the demolition of the preexisting warmth at the American seaboard so that an unbroken belt of cool surface water now followed the main west-wind axis from coast to coast (Fig. 4B). In the Atlantic sector the eastward spread of warm surface temperatures from the eastern seaboard continued, and a less dramatic but more extensive surface warming took place farther south beneath the expanded subtropical ridge. Tropical storm activity was exceptionally weak in both Pacific and Atlantic sectors.

The fast zonal westerly circulation generally continued into fall, disrupted somewhat by a recurrent blocking tendency over eastern Canada and the western Atlantic (Fig. 5A). As a result, the patterns of air temperature anomaly over the American continent and sea temperature anomaly over both oceans changed relatively little from summer to fall (Fig. 4B, 5B). The summer warming of the Bering Sea under the polar anticyclone was, however, extended southward in fall to the northernmost North Pacific as an isolated remnant of this ridge settled over the Aleutians. This, in turn, brought a narrowing of the cold water belt at midlatitudes and together with

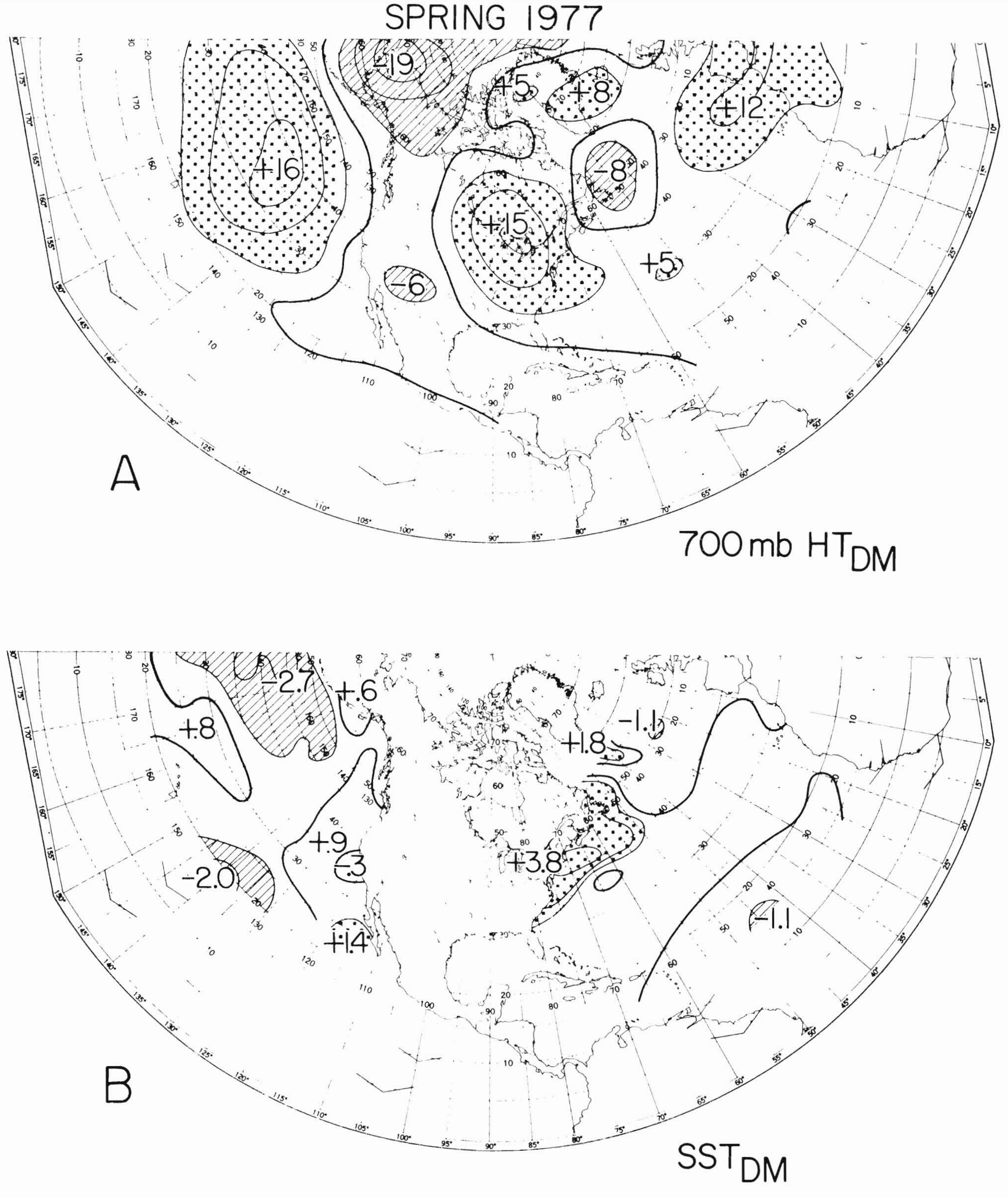


Figure 3. Mean distributions of (A) 700 mb height anomaly (feet ÷ 10) and (B) sea surface temperature anomaly (°F) for spring 1977.

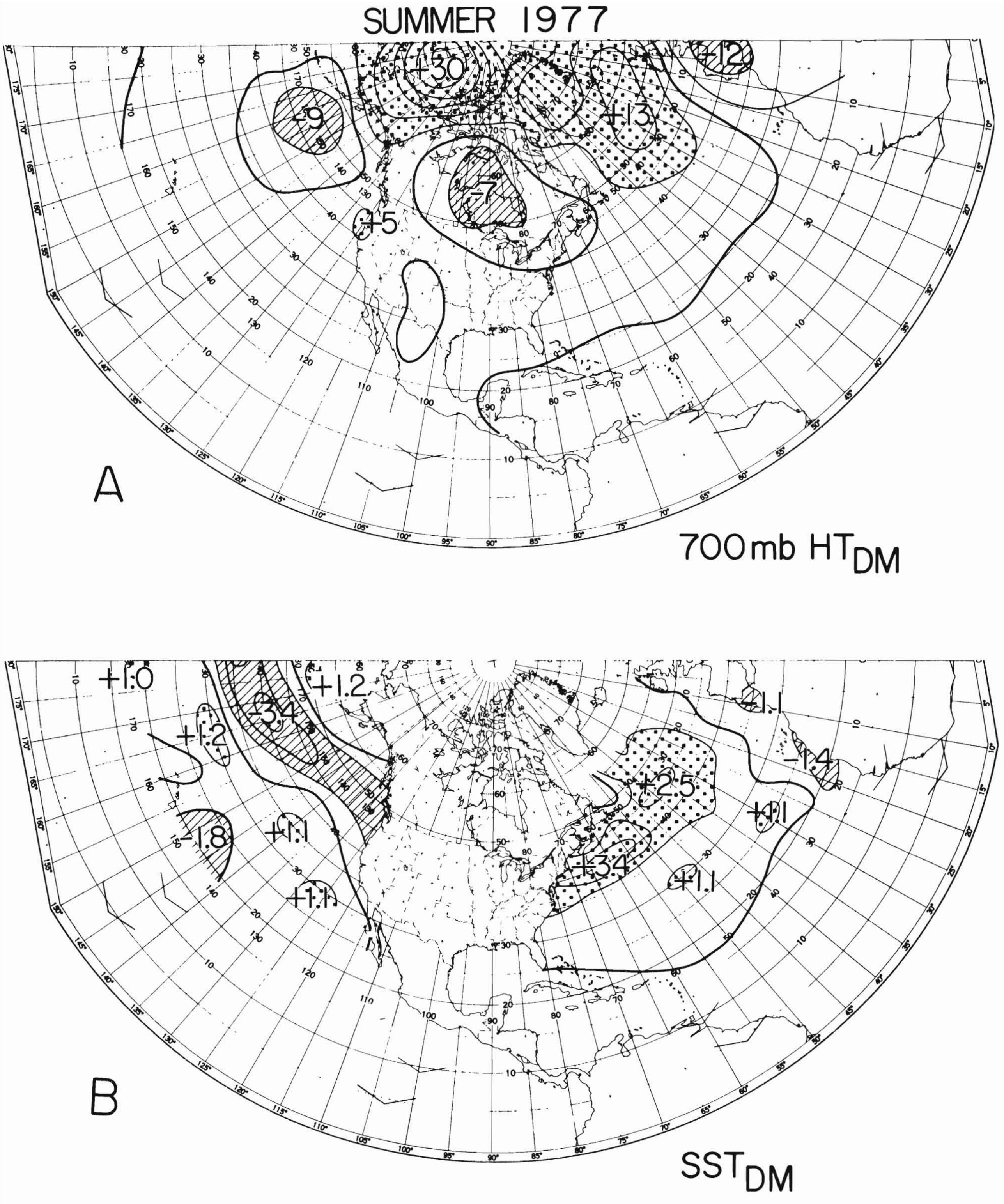


Figure 4.—Mean distributions of (A) 700 mb height anomaly (feet ÷ 10) and (B) sea surface temperature anomaly (°F) for summer 1977.

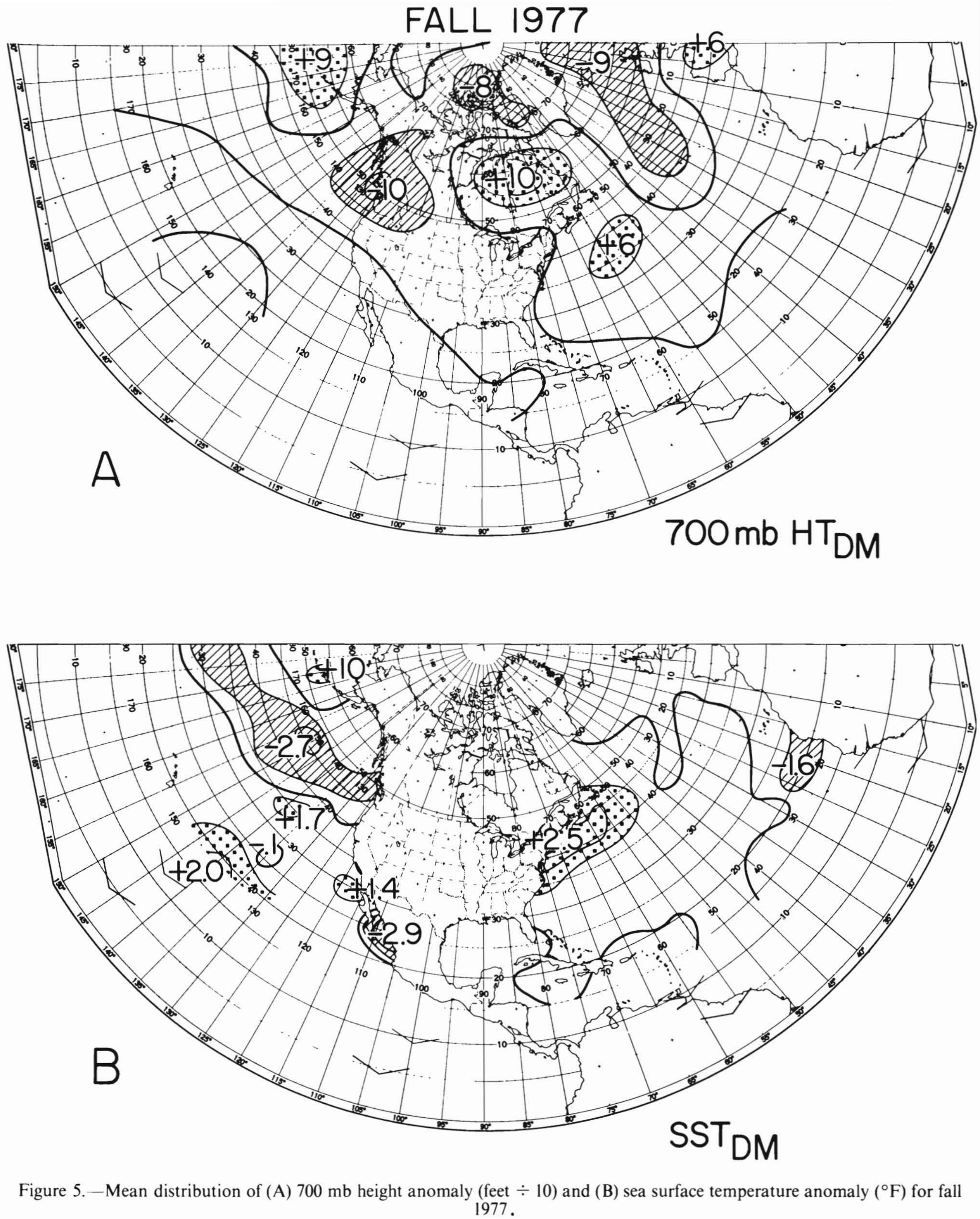


Figure 5.—Mean distribution of (A) 700 mb height anomaly (feet ÷ 10) and (B) sea surface temperature anomaly (°F) for fall 1977.

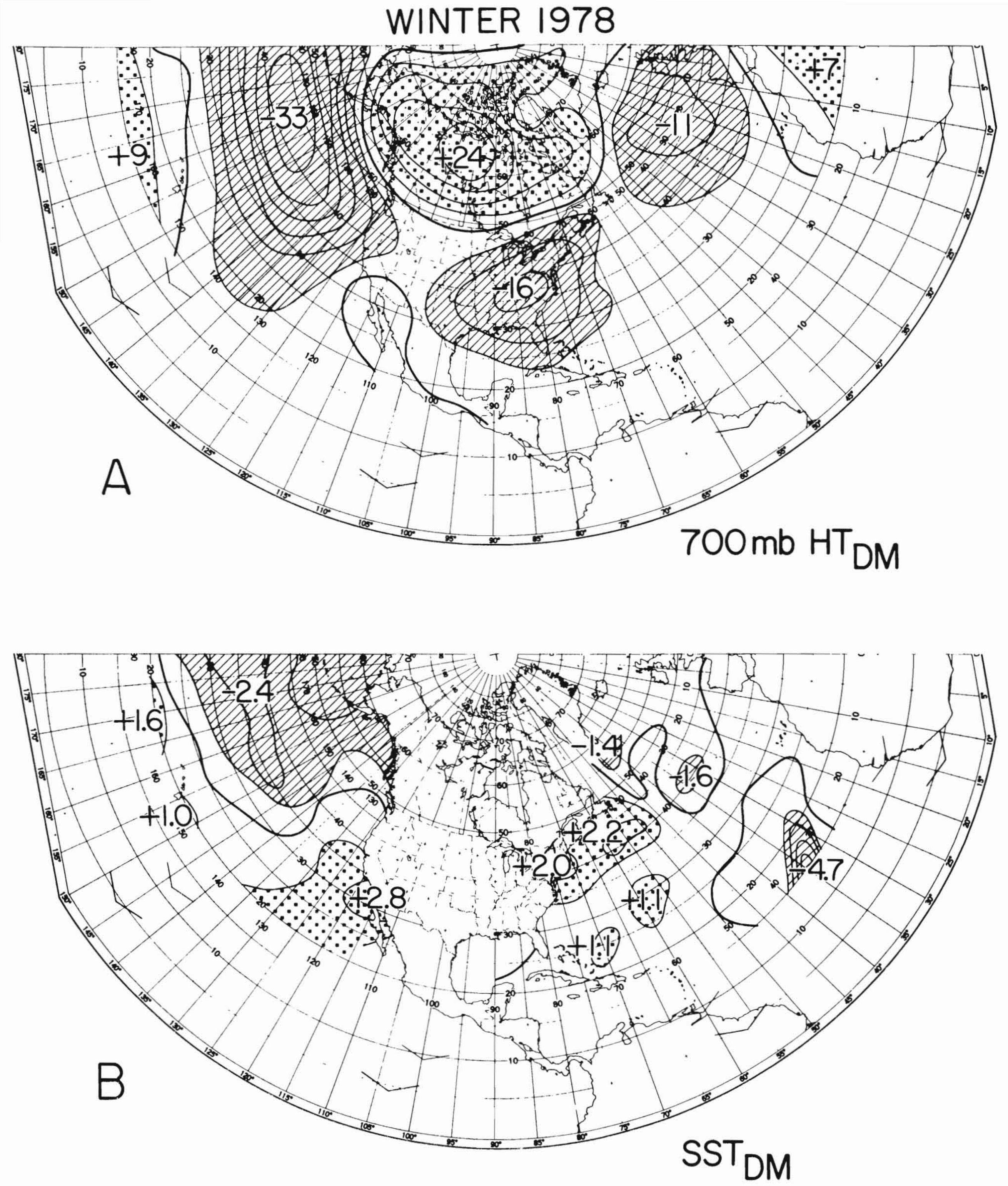


Figure. 6—Mean distributions of (A) 700 mb height anomaly (feet ÷ 10) and (B) sea surface temperature anomaly (°F) for winter 1977-78.

enhanced storminess off British Columbia, drew the center of cooling closer to the American coast.

These changes, however, were largely a feature of the early fall. As fall progressed the normal retrogression of troughs and ridges initiated the establishment of a different but rather familiar circulation anomaly pattern with the west coast trough moving offshore to intensify south of the Aleutians, with a distinct ridging tendency over the western seaboard and with a lee trough developing downstream in a variable location between the Appalachians and the Mississippi Valley. As yet these features were relatively weak or intermittent and, occurring late in the season, were not even evident in the seasonal mean, but they were significant precursors of the forthcoming winter circulation.

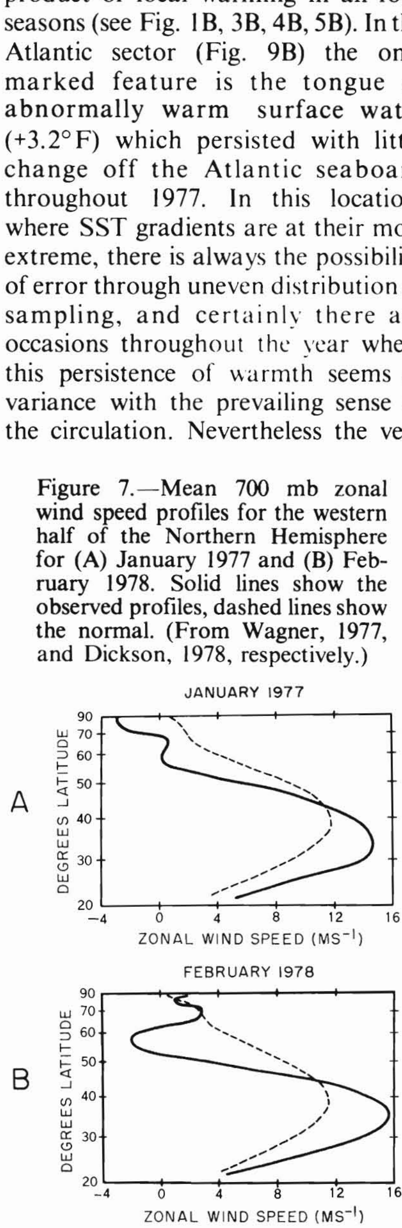
As Figure 6A demonstrates, the winter circulation of 1977-78 was once again characterized by a well amplified wave train at mid- and high latitudes, and its component pressure anomaly cells—while less extreme—did display certain marked similarities to those of the previous winter. Once again, a deep full-ocean trough (-330 feet) centered south of the Aleutians brought widespread cooling to the surface waters of the northern North Pacific (Fig. 6B). Once again (Fig. 1A, 6A), a zonal belt of negative height anomaly extended between deep troughs over eastern North America and the eastern Atlantic; and, once again, an intense polar ridge over west and central Canada helped displace these midlatitude troughs and the main west wind axis far to the south of normal, aided by the SST anomaly pattern in the central and eastern Pacific which was compatible with major storminess. However, the two winter circulation patterns did display important differences also which were particularly significant over west and southwest America. Although a full-latitude west coast ridge was able to form on limited occasions throughout the winter, the near record cold in the midwest and eastern states was not due to this cause but to severe Arctic outbreaks from the high pressure center over Canada. The displaced Pacific westerlies were stronger this winter and were able to break through the southern half of the west coast ridge. The eastward extension of the Pacific trough over California (as in the seasonal mean, Fig. 6A) brought frequent storm activity and twice-normal precipitation to break the 2-year drought in the southwest, aided by a moisture-laden southerly flow around the southern remnant of the west coast ridge (centered over Baja California). Locally, this southerly flow and the anticyclonic conditions over Baja California were also able to bring about some renewal of ocean warming off southern California and Mexico (Fig. 6B).

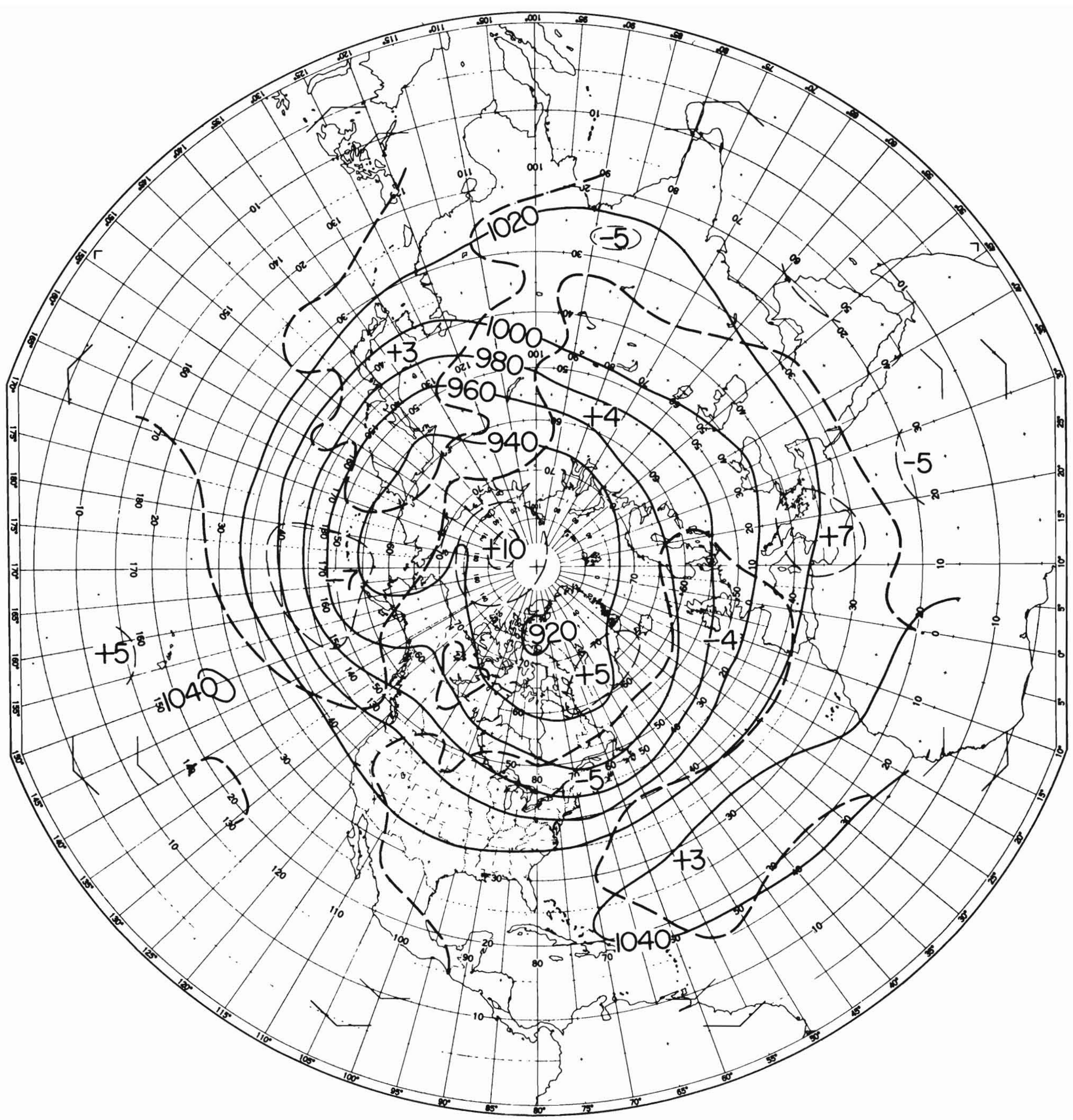
Continuing on their low-latitude track, the disturbances in the subtropical westerlies picked up additional moisture crossing the Gulf of Mexico and, invigorated by the sharp baroclinic contrast at the Atlantic coast, continued eastwards along a southerly path towards southwest Europe. This excess of kinetic energy above normal at low latitudes, the deficit at higher latitudes between lat. 45° and 60°N, and the similarity (in this regard) between the two winters under discussion is well illustrated by Figures 7A and 7B (from Wagner, 1977, and Dickson, 1978, respectively) which compare the extreme conditions of January 1977 with those of February 1978. There is little evidence of this vigorous southerly storm track in the SST anomaly distribution for the North Atlantic (Fig. 6B); it is perhaps reflected in the new cooling center west of Spain, but in the western Atlantic the warmth along the Atlantic seaboard showed little change from the fall.

Finally, Figures 8 and 9 summarize the anomalous tendencies of atmosphere and ocean for the year 1977 as a whole. As expected (Fig. 8) the mean annual distribution of 700 mb height anomaly is mainly a reflection of the extreme developments of the winter season, with its polar ridge, Pacific trough, pan-Atlantic trough, and subtropical ridge anomalies all clearly displayed. The influence of the winter season is also evident in the mean annual distribution of Pacific SST anomaly (Fig. 9A). Colder water than normal occupies all but the Bering Sea and the southeastern Pacific, with the principal cold water belt (core anomalies -2.4°F) extending zonally beneath the displayed axis of westerly winds and storms.

The general cooling at the American seaboard in spring, summer, and fall has left little trace of the preexisting winter warmth beyond a slight northward inflexion of the 0° isopleth, but further south off Baja California an isopleth center remains which is the product of local warming in all four seasons (see Fig. 1B, 3B, 4B, 5B). In the Atlantic sector (Fig. 9B) the only marked feature is the tongue of abnormally warm surface water (+3.2°F) which persisted with little change off the Atlantic seaboard throughout 1977. In this location, where SST gradients are at their most extreme, there is always the possibility of error through uneven distribution of sampling, and certainly there are occasions throughout the year where this persistence of warmth seems at variance with the prevailing sense of the circulation. Nevertheless the very

Figure 7.—Mean 700 mb zonal wind speed profiles for the western half of the Northern Hemisphere for (A) January 1977 and (B) February 1978. Solid lines show the observed profiles, dashed lines show the normal. (From Wagner, 1977, and Dickson, 1978, respectively.)





1977 MEAN ANNUAL 700mb HEIGHT & ITS ANOMALY (feet÷10)

Figure 8.—Mean annual distribution of 700 mb height and its anomaly (feet ÷ 10) for 1977.

extent and persistence of the warming does suggest that the data are meaningful, and if so a possible explanation might concern the record Gulf Stream transport following the frigid Arctic outbreaks of the winter season.

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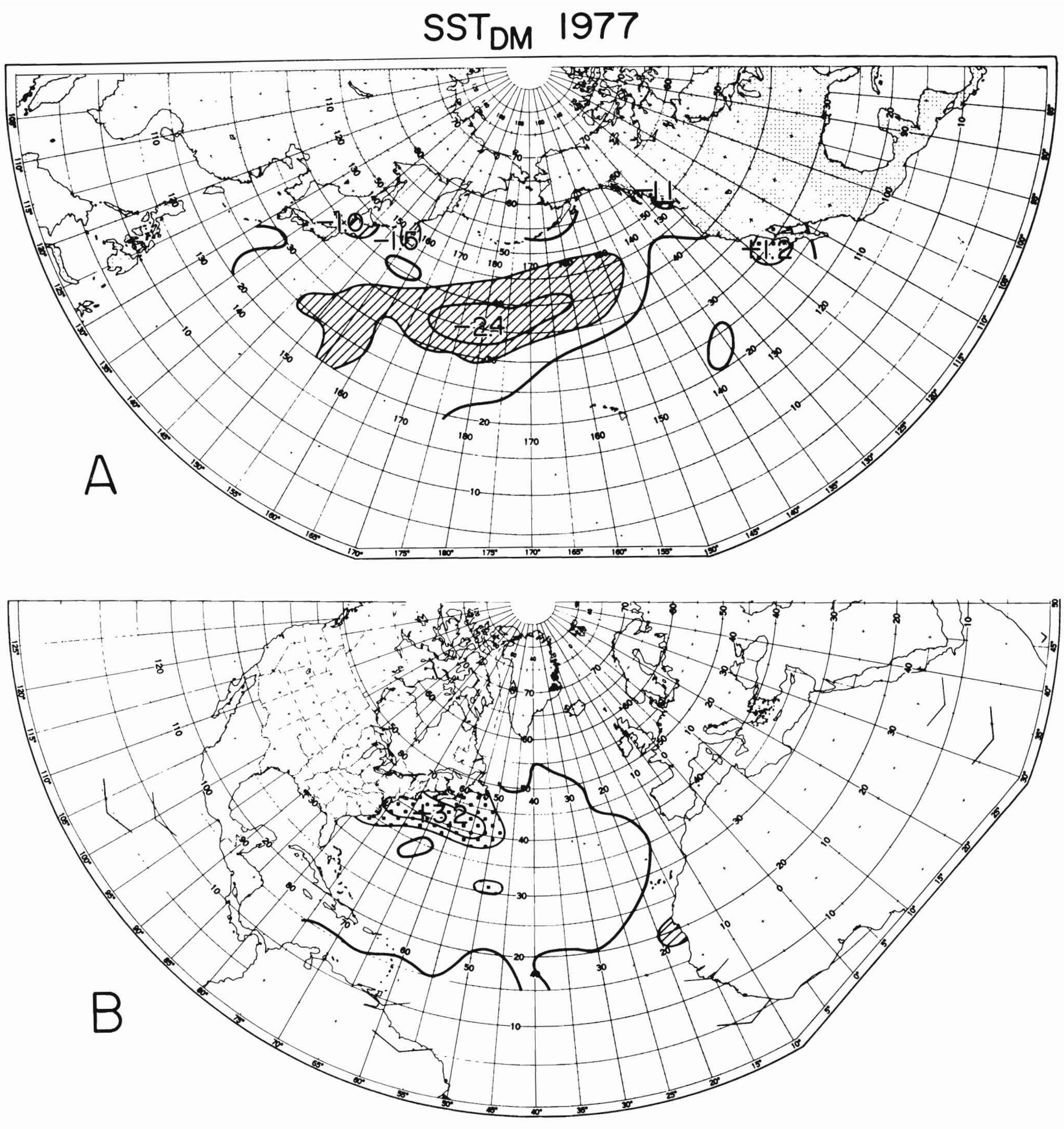

Figure 9.—Mean annual distribution of sea surface temperature anomaly (°F) in 1977 over the Pacific and Atlantic sectors.

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