CAUSES AND EFFECTS OF ATMOSPHERIC INTERANNUAL VARIABILITY

PROGRESS REPORT
1 OCTOBER 1976 – 30 JUNE 1977
NATIONAL SCIENCE FOUNDATION
GRANT NO. ATM76-21017

DEPARTMENT OF ATMOSPHERIC SCIENCE
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

CAUSES AND EFFECTS OF ATMOSPHERIC INTERANNUAL VARIABILITY

Progress Report To

National Science Foundation

Grant No. ATM76-21017

By

Elmer R. Reiter, Principal Investigator

June 1977

Report on Research Activities Under

NSF Grant ATM76-21017

For the Time Period: 1 October 1976 through 30 June 1977

Principal Investigator: Dr. Elmar R. Reiter, Professor

Equipment Purchased: None

Personnel Associated with the Project:

W.L. Somervell, Jr.: Research Associate, Data Management

T. Henmi: Research Associate, Scientific Programming

J.P. McGuirk: Research Associate on temporary appointment until July 1977; received his Ph.D. March 1977 under the present NSF Grant. Dissertation: "Fluctuations in the Atmosphere's Energy Cycle".

Anne D. Seigel: Graduate Research Assistant. Received her M.S. degree February 1977 under the present NSF Grant. Thesis: "Oceanic Latent and Sensible Heat Flux Variability and Air-Interaction".

Publications:

McGuirk, James P., 1977a: Fluctuations in the Atmosphere's Energy Cycle. Environmental Research Paper No. 6, 59pp.

_____, 1977b: Planetary-Scale Forcing of the January 1977 Weather. Submitted to Science.

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_____, and _____, 1977: Non-Random Fluctuations in Atmospheric Energy Parameters. Submitted to Atmospheric Physics.

Reiter, Elmar R., 1976a: The General Circulation of the Atmosphere and Weather in the Mediterranean. Paper presented at the International School of Atmospheric Science, Erice, Trapani, Sicily.

_____, 1976b: Problems in General Circulation Research and Long-Range Weather Forecasting. Paper presented at the International School of Atmospheric Science, Erice, Trapani, Sicily.

_____, 1976c: Climatic Fluctuations on the African Continent. Paper Presented at the International School of Atmospheric Science, Erice, Trapani, Sicily.

Reiter, Elmar R., 1977: Interannual Variability of the Ocean-Atmosphere System. (In preparation).

Reiter, Elmar R., G.R. Johnson, W.L. Somervell, Jr., E.W. Sparling, E. Dreiseitl, B.C. Macdonald, J.P. McGuirk and A.M. Starr, 1976: The Effects of Atmospheric Variability on Energy Utilization and Conservation. Environmental Research Paper No. 5, 72pp.

Seigel, Anne D., 1977: Oceanic Latent and Sensible Heat Flux Variability and Air-Interaction. Environmental Research Paper No. 7. 31pp.

Abstract

During the present grant period we examined in some detail the 24-day vacillation in the atmospheric energy cycle. We arrived at the conclusion that this cycle is tied to baroclinic instabilities and to the amplification of cyclonic disturbances upon which feed the planetary wave modes. We also examined cases of sudden stratospheric warming. They are generally characterized by prolonged decreases in hemispheric zonal available potential energy, by the development of a blocking ridge over the Gulf of Alaska and by a tendency towards below-normal temperatures over the Eastern United States.

A feasibility study of hemispheric monthly precipitation anomalies revealed that large anomalies, indeed, exist simultaneously and with same sign over the continents of the northern hemisphere. From this conclusion the importance of the hydrological cycle in atmospheric variability studies has to be emphasized again.

Another source of atmospheric interannual variability has been identified in the sensible and latent heat transfers between ocean and atmosphere. The 24-day vacillation appears to be influenced by these heat transfers, especially in regions with large sea surface temperature (SST) anomalies.

The SST anomalies in the North Pacific between 40 and 50°N appear to be caused by fluctuations in the water transport around the Pacific gyro. This transport, in turn, seems to respond to long-term and large-scale fluctuations in the v-component of the trade winds in both hemispheres. Such fluctuations also appear to influence the global mean annual temperature, perhaps due to variations in the release of latent heat within the intertropical convergence zone.

3. Research Objectives:

Our original proposal, submitted in summer 1976, anticipated a three-year grant period at a funding level of approximately $150,000 per year. The following research program was proposed at that time:

Program

A. Atmospheric Variability Studies

Detailed studies of the 3-week (24-day) vacillation cycle of hemispheric energy parameters.

(i) Description of its interannual variability

(ii) Numerical model development, based upon the physical causes of the cycle.

(iii) Correlation with regional weather patterns; investigation of possible long-range forecasting applications. Detailed studies of the "mid-winter dip" in AZ and its interannual variability.

(iv) Its possible correlation with the phase and amplitude of the 24-day cycle.

(v) Its possible correlation with the stability of instability of the polar vortex.

(vi) Its association with stratospheric warming events.

(vii) Its possible correlation with prolonged surface anomalies in pressure and temperature.

(viii) Its effect on tropospheric weather patterns and possible applications to long-range forecasting.

B. Establishment of a Two-Year Hemispheric Data Bank of Daily Precipitation, Evaporation, Cloudiness and Albedo Data.

(i) Critical review of presently available hydrological models relating precipitation measured at the ground with hydrological run-off, ground storage and evaporation data.

(ii) Critical review of available models relating precipitation data with radar and satellite data.

(iii) Critical review of evaporation data and pertinent model calculations.

(iv) Acquisition of data (together with Roy Jenne, NCAR).

(v) Refinement of the most suitable models in order to allow application over data-sparse continental and oceanic regions; preliminary testing of models; error assessment.

(vi) Preparation of best-estimate, daily hemispheric precipitation, evaporation, cloudiness and albedo values.

(vii) Comparison of monthly and annual sums or mean values of the parameters listed in (vi) with standard monthly and/or annual summaries. Re-calibration of the models used in the computation of daily values.

(viii) Cost and effort estimate of an extension in time of the two-year data bank.

C. Application of Detailed Hydrological Data to General Circulation Problems.

(i) Identification of fluctuations in hemispheric precipitation, cloudiness and albedo, possibly also in evaporation, on time scales of several days to several weeks. Assessment of the possible interannual variability of these parameters. Error, significance, and confidence limit assessment of such fluctuations.

(ii) Estimate of the impact of such fluctuations on the energy cycle in the atmosphere. Qualitative and quantitative identification of possible feedback mechanisms. (Preliminary assessment.)

(iii) Investigation of a possible feedback on climatic time-scales between the CO_2 and H_2O effects in the atmosphere. (Preliminary assessment.)

Since actual funding was received for the first grant year (October 1, 1976 - September 30, 1977) only in the amount of $90.000, our research goals had to be reduced to a much less ambitious level. Especially the studies outlined under B and C above had to be curtailed. Nevertheless, significant progress was achieved. The highlights are given in the subsequent chapter. For further details the reader is referred to our published reports.

4. Highlights of Research Completed or in Progress

A. The 24-Day Vacillation

A 22- to 26-day vacillation in the atmospheric energy cycle which was described briefly by McGuirk, Reiter and Barbieri (1975), was studied in more detail (McGuirk and Reiter, 1976; 1977; McGuirk, 1977a, b). Figure 1 shows normalized power spectra of the eddy (subscripts "E") and zonal (subscripts "Z") modes of the available potential (A) and kinetic (K) energies. These energies were computed on a daily basis for a 9.5 year period between 1963 and 1972, for the northern hemisphere north of 20°N, and from 1000 to 100 mb, using NMC data as input. With the exception of K_Z, all energy parameters reveal a significant spectral peak at approximately 0.04 cycles per day, indicative of a vacillation centered at a period of 25 days. Another somewhat less significant cycle appears in A_E and K_E with a period of about 32 days (0.03 cycles per day). Since that periodicity does not show up in the zonal modes, we have not given it much attention so far.

Our main concern during the present grant period rested with the possible causes and effects of the 22- to 26-day vacillation depicted in Fig. 1. Webster and Keller (1974, 1975) described a similar, perhaps slightly shorter, vacillation in the kinetic energy of the southern hemisphere stratosphere. Their data base consisted of Eole balloon observations. They speculated that barotropic conversions took place between the zonal and eddy modes of kinetic energy. The lack of data which would allow the computation of potential energy modes precluded the calculation of baroclinic conversions in the southern hemisphere during the Eole experiment.

Volland and Hantel (1977) made some estimates of a possible forcing effect on atmospheric planetary wave modes from a variability in the solar constant associated with the rotation of sunspot groups. A rotation period of 27.5 days would correspond to 0.036 cycles per day. The spectra shown in Fig. 1 reveal a minimum at this frequency. We, therefore, are inclined to reject a solar-forcing hypothesis for the observed atmospheric vacillation. (This is not to say, however, that at times solar effects could not have a modulating influence on atmospheric vacillation. The primary cause of the vacillation has to be sought elsewhere, however.)

An example of the vacillation in the four energy modes is shown in Fig. 2. Here a narrow-band pass filter (centered at a period of 25 days) has been passed over the raw data consisting of daily estimates of A_E, K_Z. The out-of-phase relationship between A_Z and K_E can be easily seen from this diagram and has been confirmed by co-spectrum analyses.

From this and other evidence we concluded that the observed vacillation in the atmospheric energy cycle is predominantly baroclinic in nature. In simple words the nature of the vacillation can be expressed as follows:

Diabatic generation of A_Z, mainly by radiative processes, builds up the hemispheric reservoir of this energy mode until baroclinic instability causes cyclonic disturbances to grow, increasing A_E and K_E at the expense of A_Z. The eddy heat flux across latitude circles is directly correlated with the behavior of K_E, as we were able to demonstrate by co-spectrum analyses. As the reservoir of A_Z declines, the energy source upon which the baroclinic disturbances feed decreases in magnitude until these disturbances can no longer grow or even maintain their amplitude. As they collapse the vacillation cycle starts anew.

McGuirk (1977a) explored this hypothesis with a simple numerical model, using reasonable assumptions on the state of the hemispheric atmosphere as input. It might be considered fortuitous that his application of baroclinic instability theory also yielded a 25-day vacillation (Fig.3).

Having explained the nature of the observed vacillation to our own satisfaction as an internal atmospheric process involving baroclinic instability, we were searching for possible effects of this vacillation of atmospheric variability in general, and on regional weather patterns in particular.

Our analyses indicate that the 24-day vacillation undergoes a marked interannual variability in both, phase and amplitude. This can be seen qualitatively from Fig. 2 which shows the winter 1969/70, typical of a weak amplitude vacillation, succeeded by a winter with strong amplitudes. As can also be seen from this diagram, the vacillation is almost absent during summer. Different winter seasons also show a response of different planetary wave numbers to this vacillation; as can be seen from Fig. 4.

Figure 5 indicates that cyclone-scale waves also respond to the 24-day vacillation. At this time we are still at a loss to explain why certain wave numbers control the vacillation in one winter season but not in another. Also we do not know what predetermines the choice of wave number during fall, and what causes the general circulation to maintain its specific character during the whole winter season (see for instance the effect of wave number 2 during the winter of 1970-71. One might also call to mind the stationary wave situation which led to the devastating winter in the Eastern U.S. during the winter of 1976-77).

Since the long planetary waves tend to be more or less stationary it was hoped that their vacillatory behavior might reveal itself in local weather effects at least during certain years when the phase relationship between the lowest wave numbers is appropriate. A search for a 24-day periodicity in the 500-mb temperatures over the Great Plaines of the U.S., and the mean geostrophic winds at 200 mb along the North American west coast yielded negative results (McGuirk and Reiter, 1976). On the other hand, spectrum analyses of the pressure gradients at 1000 mb and 500 mb between two grid points straddling the Carcassone Gap (Fig. 6, Reiter, 1976a) revealed spectral peaks indicative of a 24-day vacillation during certain years. (Table 1, Fig. 7.) These pressure gradients are controlling the occurrence of the Mistral, and are sensitive to the planetary long-wave positions and amplitudes. We have not yet had a chance to explore any further the local response of weather phenomena to the 24-day vacillation. Our limited experience indicates that if such responses are present, they cannot be expected to work with the same degree of reliability every year.

Table 1.

Oct. to	May	22- to 26-Day Cycle	Other Periodicities
1963	1964	strongly evident	10 days
1964	1965	strongly evident	10 days
1965	1966	weak, shifted to higher frequencies	11 days
1966	1967	strongly evident	10-12 days
1967	1968	suppressed	12 and 32 days
1968	1969	extremely strong	12 days
1969	1970	suppressed	14 days
1970	1971	evident, but "broad" peak	----
1971	1972	evident	12 days

B. Stratospheric Sudden Warming and the Midwinter "Dip" in A_Z.

In her M.S. thesis Starr (1976) investigated a number of cases in which A_Z decreased markedly and remained at depressed values during prolonged time periods without equivalent increases in the other three energy modes. Since this phenomenon occurred only during the cold season it was termed the "midwinter dip of A_Z". Characteristic for this dip period appeared to be the development of blocking ridges in the Gulf of Alaska, but also in the Atlantic sector.

McGuirk (1977a, b) was able to tie some of the more spectacular midwinter dips of A_Z to episodes of sudden stratospheric warming. Table 2 summarizes some of his findings.

Table 2: Energy changes during midwinter dips of A_Z, and during periods of strong and sudden stratospheric warming.

	ENERGY				
	ΔAZ	ΔAE	ΔKZ	ΔKE	Duration of Decrease
All Midwinter Dips	-11.51	+.52	+.25	+2.57	15 days
Strong SSW Events	-12.71	+.33	-.95	+2.55	20 days
Annual Cycle Amplitude (units in $10^5 J/m^2$)	27	7	13	6	4-6 months

The following responses of the general circulation to "dip" episodes could be noted beyond those already reported by Starr (1976): The eddy available potential energy in the planetary long waves tends to be two to four times higher during dip periods than during "quiet" winter periods.

The northward eddy heat flux at latitudes between 50° and 60°N, averaged over the month in which the dip occurs, shows an increase over average values by approximately 15 percent (Fig. 8). Zonal winds in middle-to-high latitudes tend to decrease to the point where occasionally even easterly winds appear in mean meridional cross sections between 50° and 60°N throughout the troposphere (Fig. 9).

It has been mentioned before that blocking ridges in the Pacific and Atlantic tend to accompany the development of midwinter dips in A_Z and episodes of stratospheric warming. As a consequence, the United States east of the Rocky Mountains tends to experience below-normal temperatures during such periods. January 1977 is an example of such negative temperature anomalies.

C. Precipitation Variability

We encountered considerable difficulties in collecting daily precipitation data for the northern hemisphere with a station density sufficient for our purposes. Curtailment in funding prohibited purchase of the necessary data from Asheville and from abroad. We therefore decided to limit out thrust in this particular investigation to a feasibility study, using monthly precipitation values obtained from NCAR in Boulder, Colorado. We hoped to find out from a preliminary analysis whether the interannual variability of hemispheric precipitation is sufficiently large to emerge from the noise level of the data.

For our pilot study Tom Corona, M.S. candidate, used the monthly precipitation values of July 1966 and subtracted from these values those of July 1965. The two years were picked more or less at random without a conscious effort to search for extreme precipitation regimes. By analyzing precipitation differences rathen than absolute values we hoped to detect anomaly patterns which would be significant at least on a regional basis and would therefore help us to overcome some of the problems associated with station representativeness and of local effects that often dominate the patterns of absolute precipitation amounts. Figures 10 and 11 show the anomaly patterns between the two July months for the North American, North African and Eurasian continents. For our preliminary study we hand-gridded these analyzed patterns, using an equal-area grid bounded by one-degree latitude intervals and containing $10^4 km^2$ over North America, and 1.25^o latitude containing approximately $1.6x10^4 km^2$ over the North African and Eurasian continents. After assigning interpolated precipitation anomalies to each of these small grid boxes, the anomalies were summed and averaged, first for larger "boxes" and then for the whole continent. Results are shown in Figs. 12 and 13.

We were quite surprised that the precipitation discrepancy between the two July months averaged out to be 2.48 mm for the North American continent. The North African and Eurasian continents showed an average discrepancy of same sign of 1.30 mm. Thus, at least for these two months, the two continental sectors of the northern hemisphere do not compensate each other in their precipitation regimes. Large interannual variabilities in hemispheric precipitation, therefore, remain a real possibility and should be considered of importance in climate modelling and in the assessment of model sensitivities.

With partial support from NASA we intend to explore cloudiness trends over the two continental sectors, starting with the two July months investigated for their precipitation characteristics. If the cloudiness trends reflect the precipitation trends, we intend to use the cloudiness trends observed simultaneously over the oceanic areas as first indicators of the presence or absence of a large-scale compensation in precipitation anomalies between continents and oceans.

D. Variability of Air-Sea Interaction

From five years (October 1969 to September 1974) of gridded daily data of sea surface temperatures, air temperatures, vapor pressures, and wind speed at ship-deck level provided by the Fleet Numerical Weather Central of the U.S. Navy, Seigel (1977) computed daily values of latent and sensible heat transfer between the ocean and the atmosphere. Examples of the results are shown in Figs. 14 and 15. A considerable interannual variability in both parameters exists in the two large oceans of the northern hemisphere (Tables 3 and 4). This fact should heighten our suspicion that hemispheric precipitation regimes also reveal considerable variability.

Table 3. Mean Atlantic and Pacific Sensible Heat Flux Values For Six Winter Seasons.

OCT.-MAR.	MEAN ATLANTIC SENSIBLE HEAT FLUX cal cm^{-2} day^{-1}	MEAN PACIFIC SENSIBLE HEAT FLUX cal $cm^{-2}day^{-1}$	CORR COEF	σ_r	2.6 σ_r
1969-1970	34.92	39.8	.58	.07	.19
1970-1971	47.55	31.45	.26	.07	.19
1971-1972	48.10	35.13	.47	.07	.19
1972-1973	49.05	36.70	.47	.07	.19
1973-1974	42.56	33.71	.37	.08	.20
1974-1975	47.17	36.94	.46	.08	.20
6 Seasons Average	44.89	35.63	.43		

Table 4. Mean Atlantic and Pacific Latent Heat Flux Values for Five Winter Seasons.

OCT.-MAR.	MEAN ATLANTIC LATENT HEAT FLUX cal $cm^{-2}day^{-1}$	MEAN PACIFIC LATENT HEAT FLUX cal $cm^{-2}day^{-1}$	CORR COEF	σ_r	2.6 σ_r
1969-1970	162.11	245.24	.76	.07	.19
1970-1971	207.03	274.27	.41	.07	.19
1971-1972	194.74	270.55	.25	.07	.19
1972-1973	201.37	281.74	.31	.07	.19
1973-1974	195.26	269.51	.25	.07	.19
5 seasons Average	192.10	268.26	.40		

There are years in which the heat fluxes from both oceans are correlated well with each other, and other years in which the two oceans tend to interact with the atmosphere almost independent from each other. The degree of "cooperation" between the two oceans seems to be correlated with the meridionality of large-scale atmospheric flow patterns, as expressed by Mahlman's circulation index (Fig. 16).

Seigel also found a large interannual variability in the response of the ocean-atmosphere heat transfer to the 24-day atmospheric vacillation described earlier (Figs. 17 to 20). It is of interest to note that sensible heat flux from the Pacific (Fig. 17) reveals the strongest response to a 24-day cycle in the winter of 1969-70, when the atmosphere itself showed a very weak cycle (Fig. 2). On the other hand, the atmospheric cycle was very well expressed during the winter of 1970-71 (Fig. 2), when the sensible and latent heat transfers from the ocean showed hardly any response to that cycle (Figs. 17 to 20). We have not yet had a chance to explore this coincidence in detail. It might, in the end, offer an explanation of the interannual variability in this cycle. Sensible heat transfer from the ocean tends to destroy available potential energy in the atmosphere, especially by the warming of cold continental air masses which are advected over the warm oceans during winter. With strong meridional flow patterns (low Mahlman index numbers) the oceans thus tend to exercise a damping effect on the evloution of A_E and A_Z patterns with time. In the absence of such damping effects the atmospheric vacillation is allowed to maintain considerable amplitudes during the whole winter season, as appeared to be the case during the cold season of 1970-71.

We have concluded earlier that the 24-day vacillation appears to be an internal phenomenon of the atmosphere, controlled by the diabatic generation of A_Z and by baroclinic processes. It appears now, that these controlling mechanisms can be modulated to an appreciable extent by air-sea interaction processes. We will try to investigate this hypothesis further in our future NSF-sponsored research work.

Seigel (1977) pointed out that the response of the heat transfer from the ocean to the atmosphere to the 24-day atmospheric vacillation is not uniform over the whole ocean, but shows great variability with location. Areas with large sea-surface temperature (SST) anomalies in the North Pacific appear to be most responsive to the 24-day vacillation. Also the response is strongly governed by changes in surface wind speeds.

E. Ocean-Atmosphere Feedbacks

The results obtained by Seigel (1977) encouraged us to explore the possible effects of air-sea interaction on the longer time scales of interannual variability. Such exploration was warranted especially by the indication that North Pacific SST anomalies play a role in the interannual variability of the amplitude of the 24-day vacillation, and perhaps also in the selection of the planetary wave numbers which contribute most to this vacillation in a given year.

We started from the hypothesis that the appearance of SST anomalies in the North Pacific, most likely, is due to variations in the advective transport of large water masses rather than to local variations with time of the oceanic and atmospheric radiation and heat budgets. A detailed report of these investigations is in preparation (Reiter 1977). Specifically, we were hoping to tie the SST anomalies in the North Pacific to variations in the intensity of the tropical trade-wind circulation. The gist of our findings is illustrated by Fig. 21. Within the relatively short data sample on hand there appears to be a correlation between the northerly wind component in the North Pacific trade-wind belt and the SST anomalies of the Pacific between 40 and 50°N twenty months later. We intend to explore the time history of this correlation further by extending the data set of tropical surface winds and SST's to 1977.

Figure 21 also shows a strong positive correlation between the mean northerly wind component in the tropical North Pacific and the southerly wind component in the tropical South Pacific, suggesting a strong interannual variability in the mean divergence of the tropical wind field, hence in the intensity of the Intertropical Convergence Zone (ITCZ) and in the tropical cloudiness and precipitation regimes. Cloudiness data published by Sadler et al. (1976) support a correlation between cloudiness anomalies in the equatorial Pacific and the behavior of divergence in the trade-wind belt. It is of interest to note that the northern hemispheric and global temperature anomalies presented by Angell (1977) suggest a strong correlation between above-normal temperatures, and above normal convergence in the v-components of the northern and southern hemisphere trade-wind systems in the Pacific. The release of excessive amounts of latent heat in the ITCZ during such years might account for the observed global temperature trends (see chapter 3 in Reiter et al., 1976). Since rainfall in the tropical belt of Africa also undergoes marked interannual variability (Reiter, 1976b) we intend to investigate the behavior of the Atlantic trade-wind belts as well.

It should be pointed out, that the correlations supported by Fig. 21 emerged only after the wind fields were averaged over the whole Pacific trade-wind region (5°N to 19°N, 125°E to 95°W, and 1°S to 15°S, 125°E to 75°W) and after employing a 7-month running averaging process on the monthly wind anomalies from the long-term means. (Seasonal trends have been estimated.) The reason for this considerable amount of smoothing is that we should expect a response of oceanic wind-driven current systems to changes in atmospheric forcing only if atmospheric anomalies extend over large areas and are maintained over considerable time periods.

5. Conclusions

Our studies during the present grant period have indicated that some of the interannual variability of the atmosphere is brought about by feedback mechanisms with the ocean. We have identified two such feedbacks:

(1) The 24-day vacillation reveals considerable interannual variability in its amplitude and in its partitioning into contributions from individual planetary wave numbers. We have preliminary evidence that during cold seasons with large amplitudes of the atmospheric vacillation the interaction with the oceans in terms of sensible and latent heat transfer shows little response in the frequency range of this cycle. On the other hand, winters with only a weakly expressed 24-day vacillation in the atmosphere seem to have a relatively strong cycle with this frequency in the sensible heat transfer between ocean and atmosphere. Regions with relatively large sea surface temperature (SST) anomalies in the North Pacific seem to be most responsive to the 24-day vacillation, especially during time periods of meridional rather than zonal flow.

(2) The origin of SST anomalies in the North Pacific, which apparently can influence the atmospheric circulation as indicated above, can be sought in the advective water mass transport through the large current systems surrounding the Pacific gyro. Specifically, a 20-month lag correlation between anomalies in the v-components of the trade-wind circulation in both hemispheres over the tropical Pacific, and the SST anomalies in the North Pacific between 40 and 50°N, has been identified.

Small variations in the hemispheric and global mean temperatures also seem to be tied to these long-term anomalies in the trade-wind circulation, perhaps due to variations in the release of latent heat in the upwelling branches of the Pacific Hadley cells. Such a hypothetical conclusion would lend further weight to the importance of the hydrological cycle in modulating atmospheric variability.

We intend to further explore these aspects of air-sea interactions on time scales of a few weeks to several years during our next grant period. Especially the potential for improved long-range forecasting based upon these interactions will be examined.

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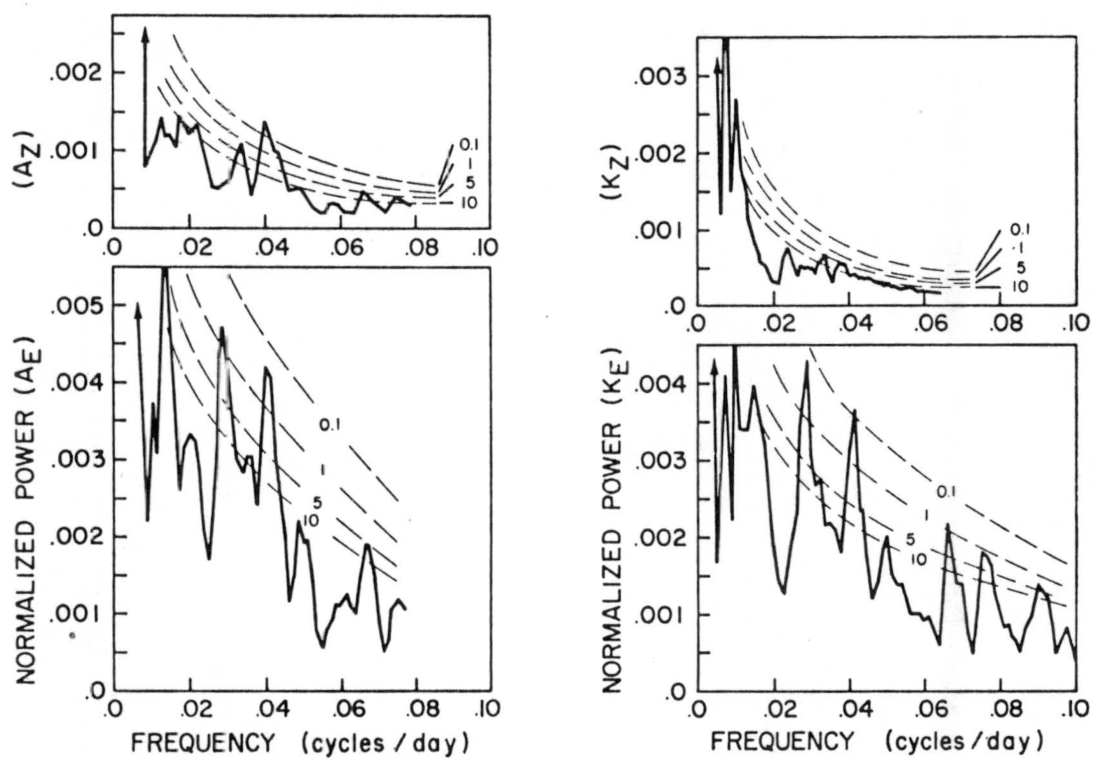


Figure 1. Periodograms of normalized variance per unit bandwidth for 9.5-year series of daily atmospheric energy by mode. High-frequency spectra not shown. Dashed lines show 90, 95, 99 and 99.9% chi-squared confidence limits for assumed background spectra.

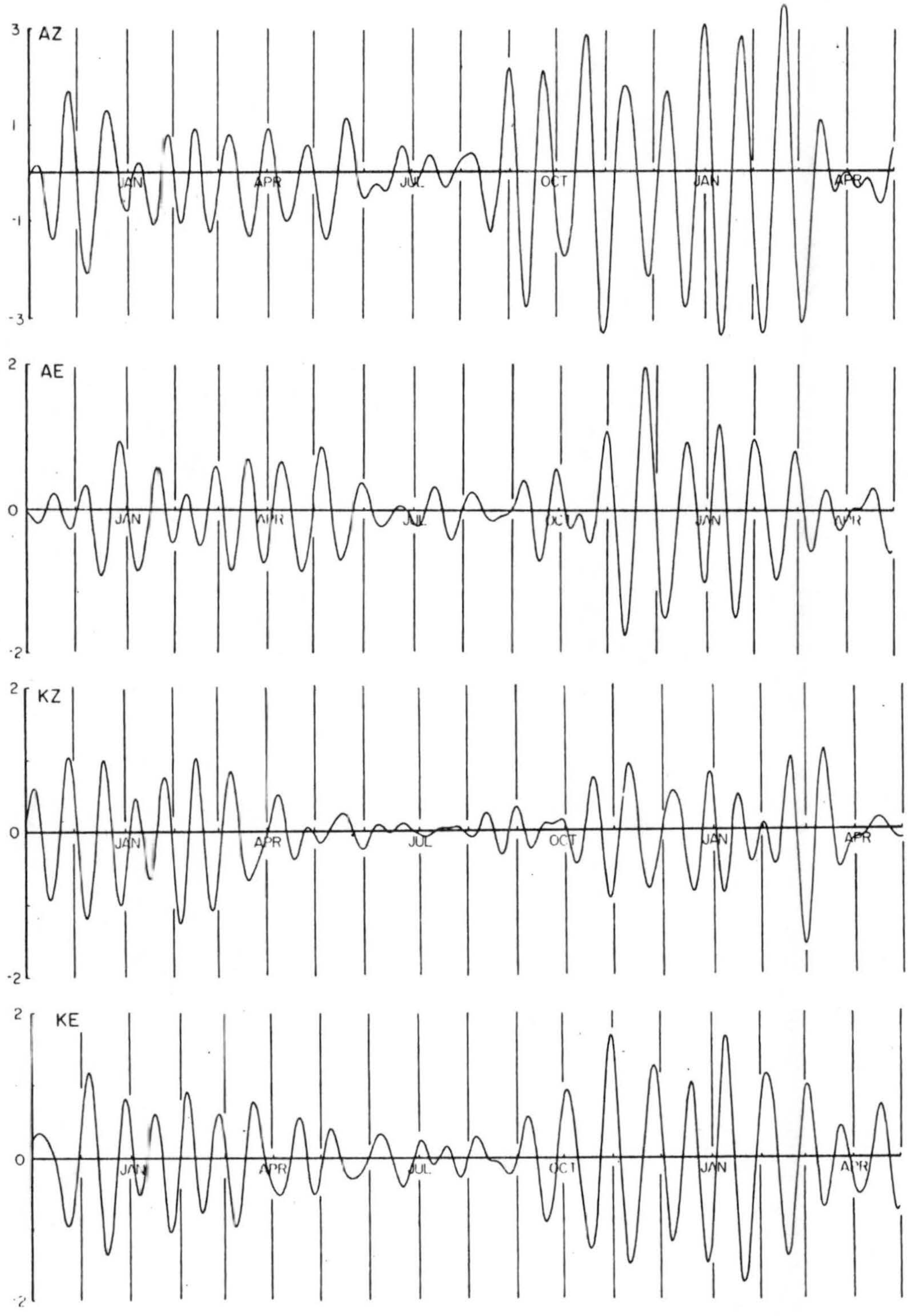


Figure 2. Bandpass-filtered daily energy by mode for 1 November 1969 - 15 April 1971. Units in $10^5 J\ m^{-2}$.

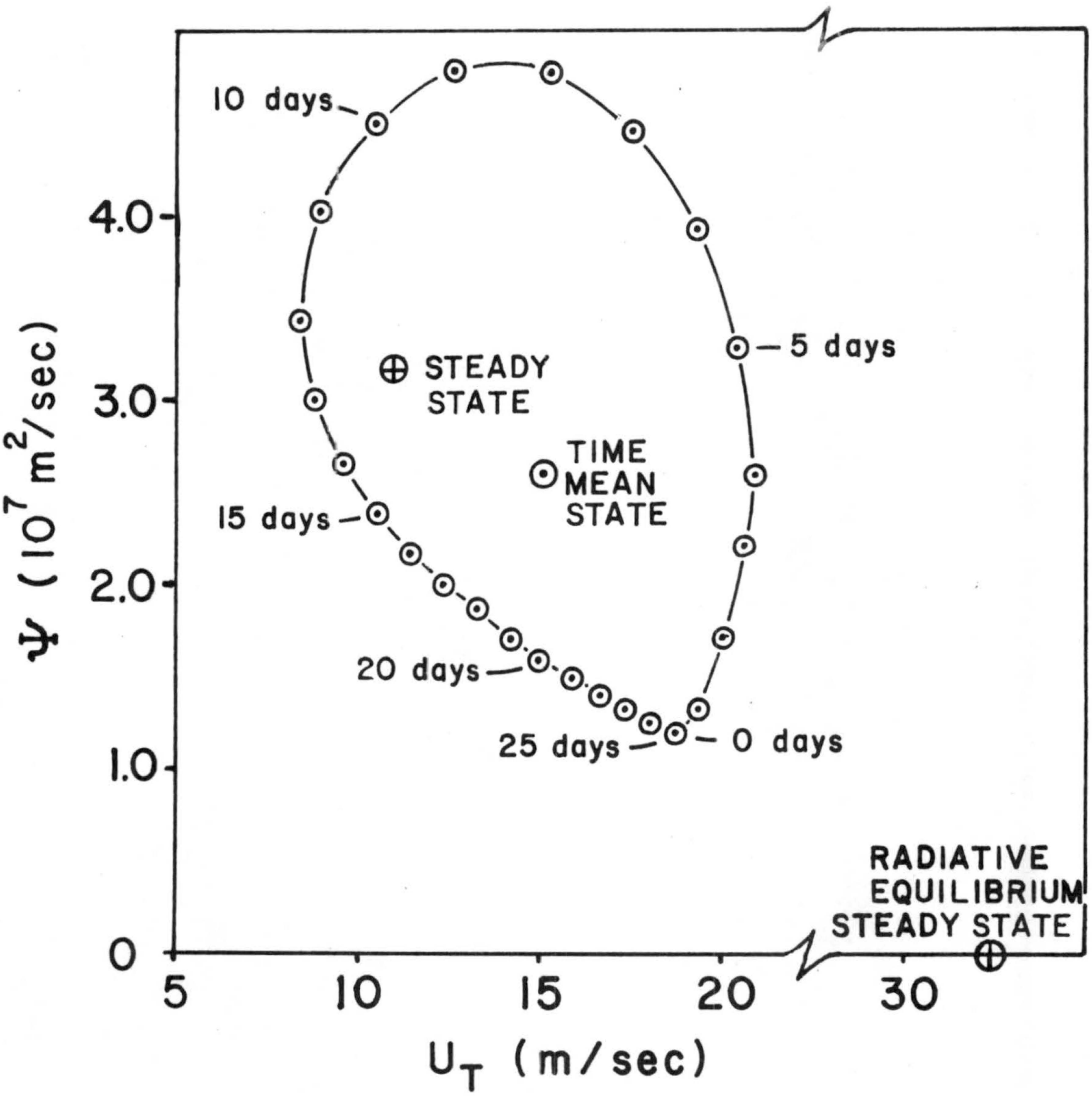


Figure 3. Solution trajectory in stream function-thermal wind phase space with a 25-day periodicity. The symbols ⊕ show steady states with the "radiative equilibrium" state obtained by $\psi \equiv 0$. The symbol ⊙ is the time average state of the periodic orbit.

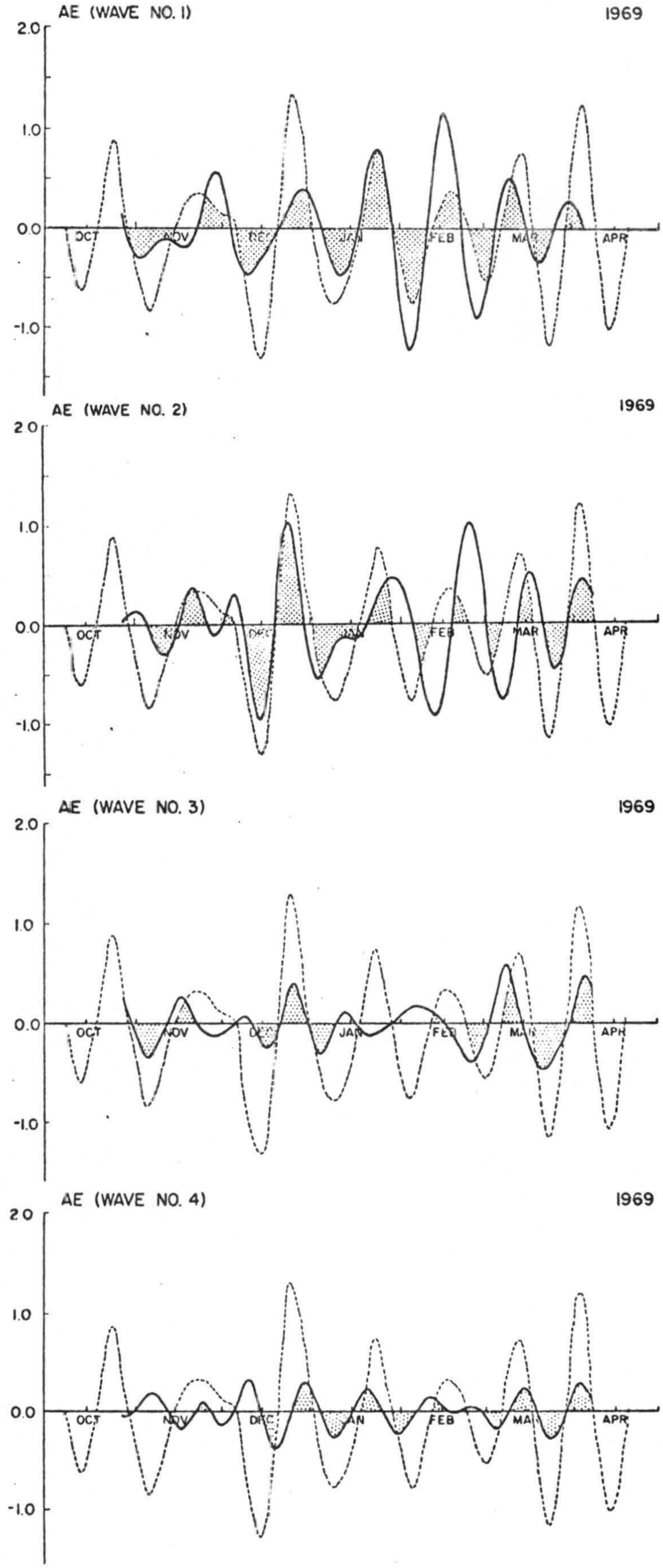


Figure 4, Bandpass-filtered contributions to total A_E by planetary wavenumbers 1-4 (solid lines) for the 1968-71 cold season. Bandpass-filtered total A_E is given by the dasked line for reference and the shaded area gives the positive in-phase contribution of each wavenumber to the total A_E. Units in $10^5 Jm^{-2}$.

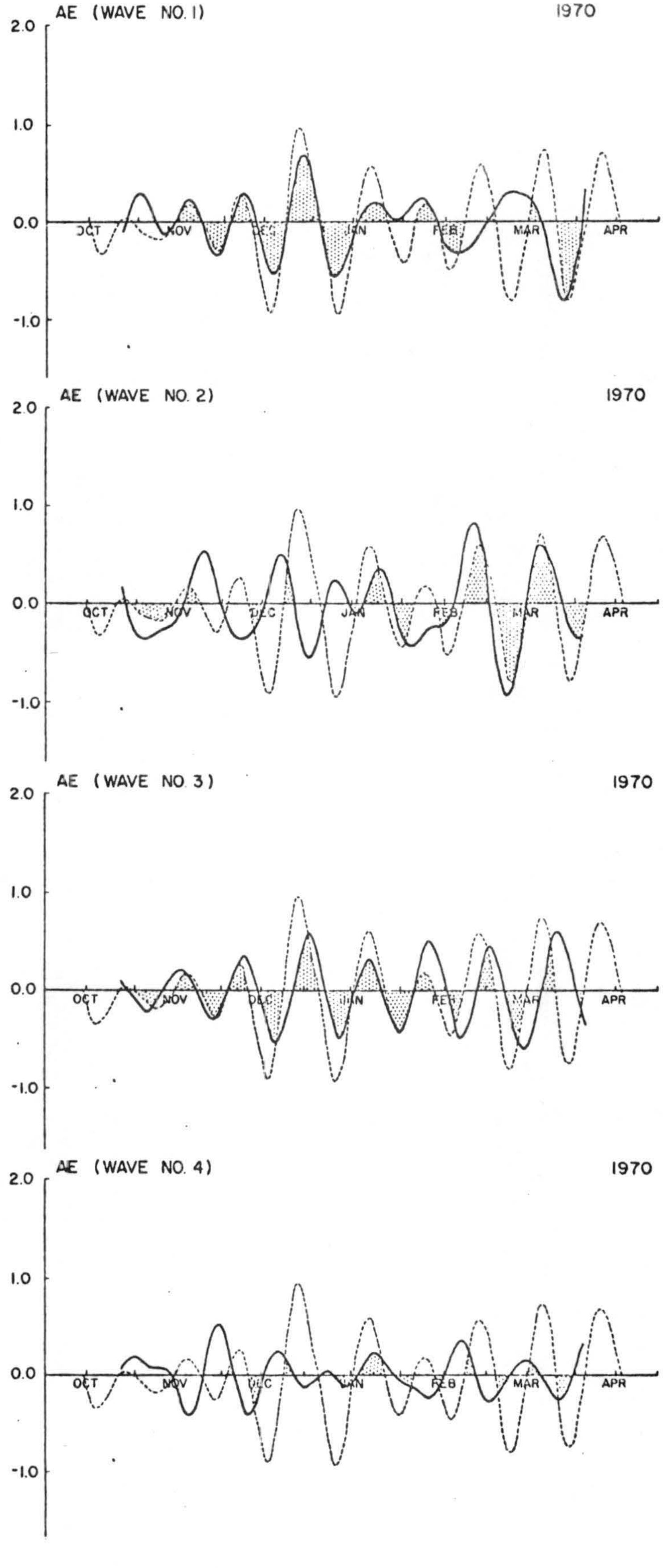


Figure 4
(continued)

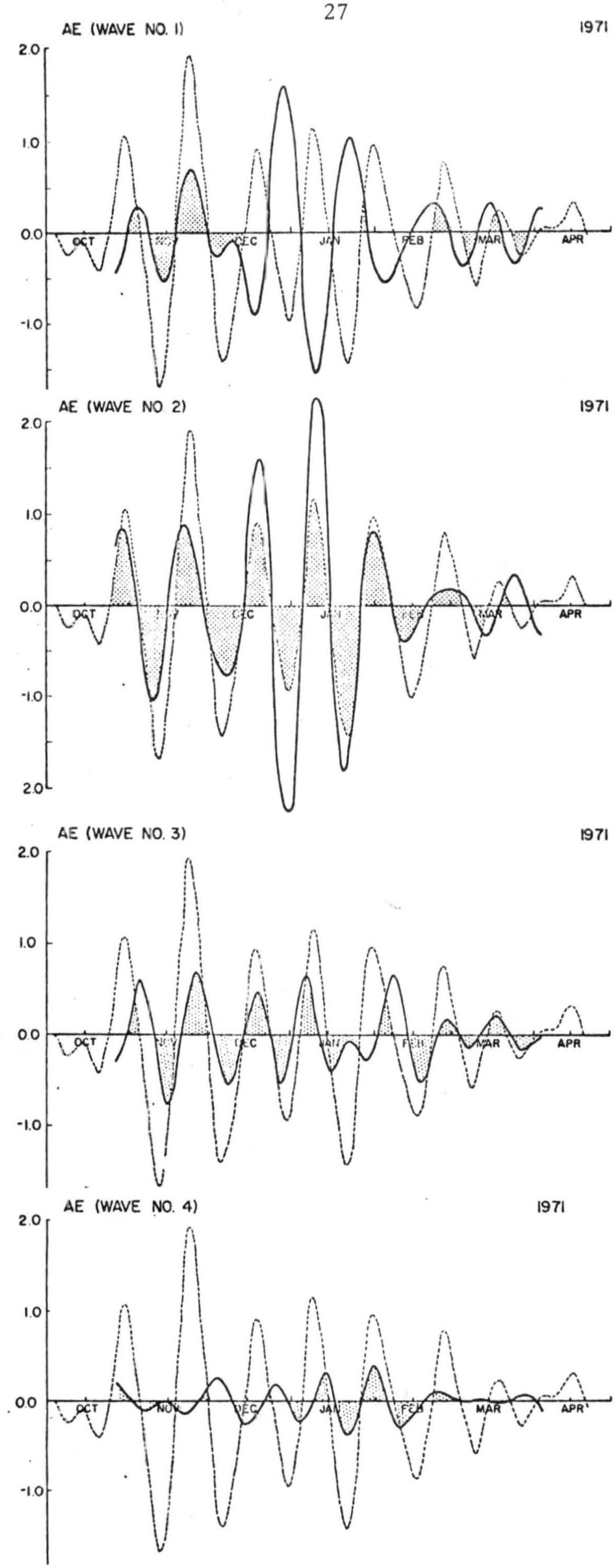


Figure 4
(continued)

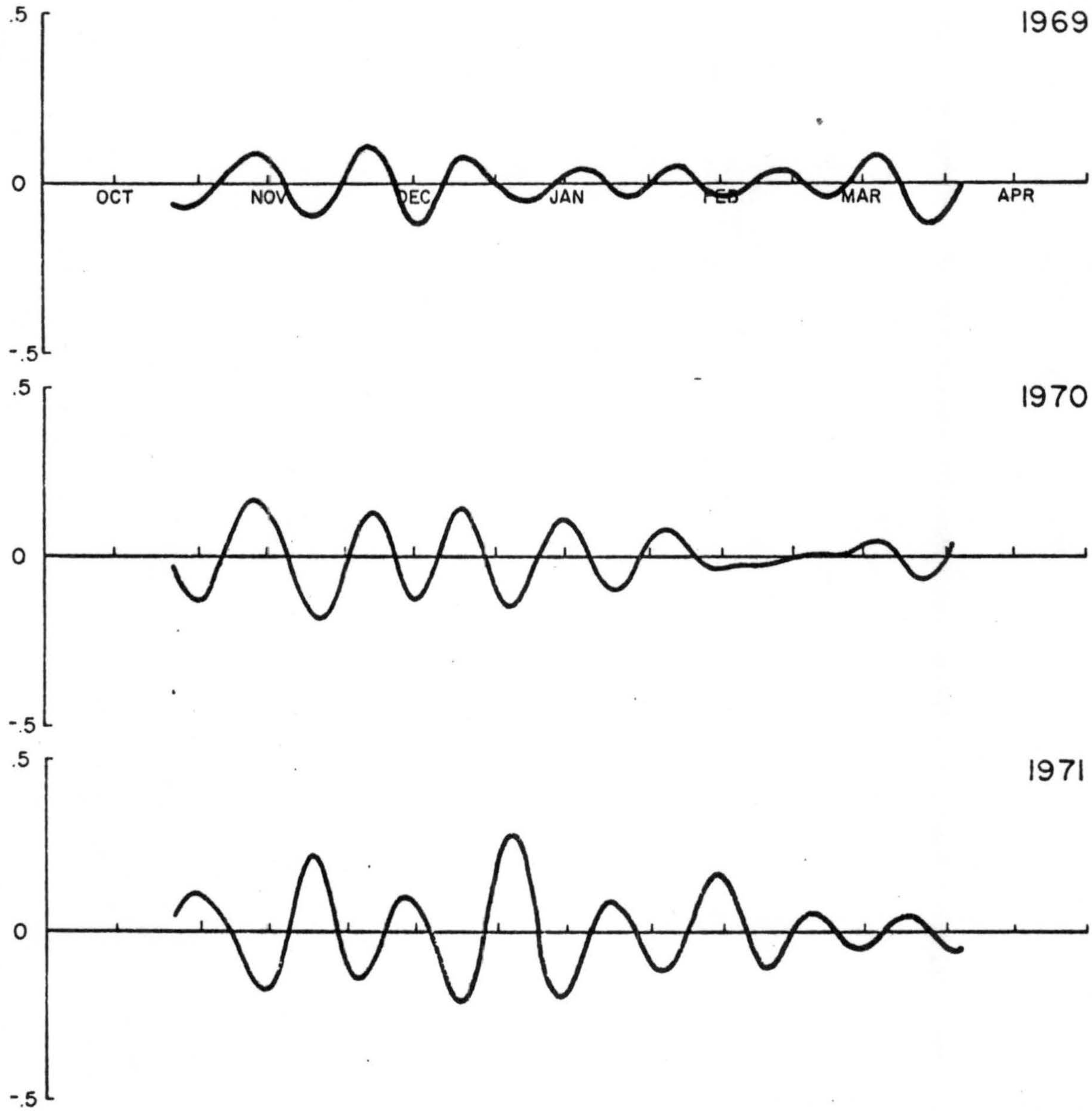


Figure 5. Bandpass-filtered A_E associated with wavenumber 6 (cyclone scale) for the cold seasons of 1968-71 showing the steadiness of the vacillation cycle for cyclone scale events. Units in 10^5 J m^{-2}.

Figure 6. Two NMC grid points used for the calculation of geodynamic height differences.

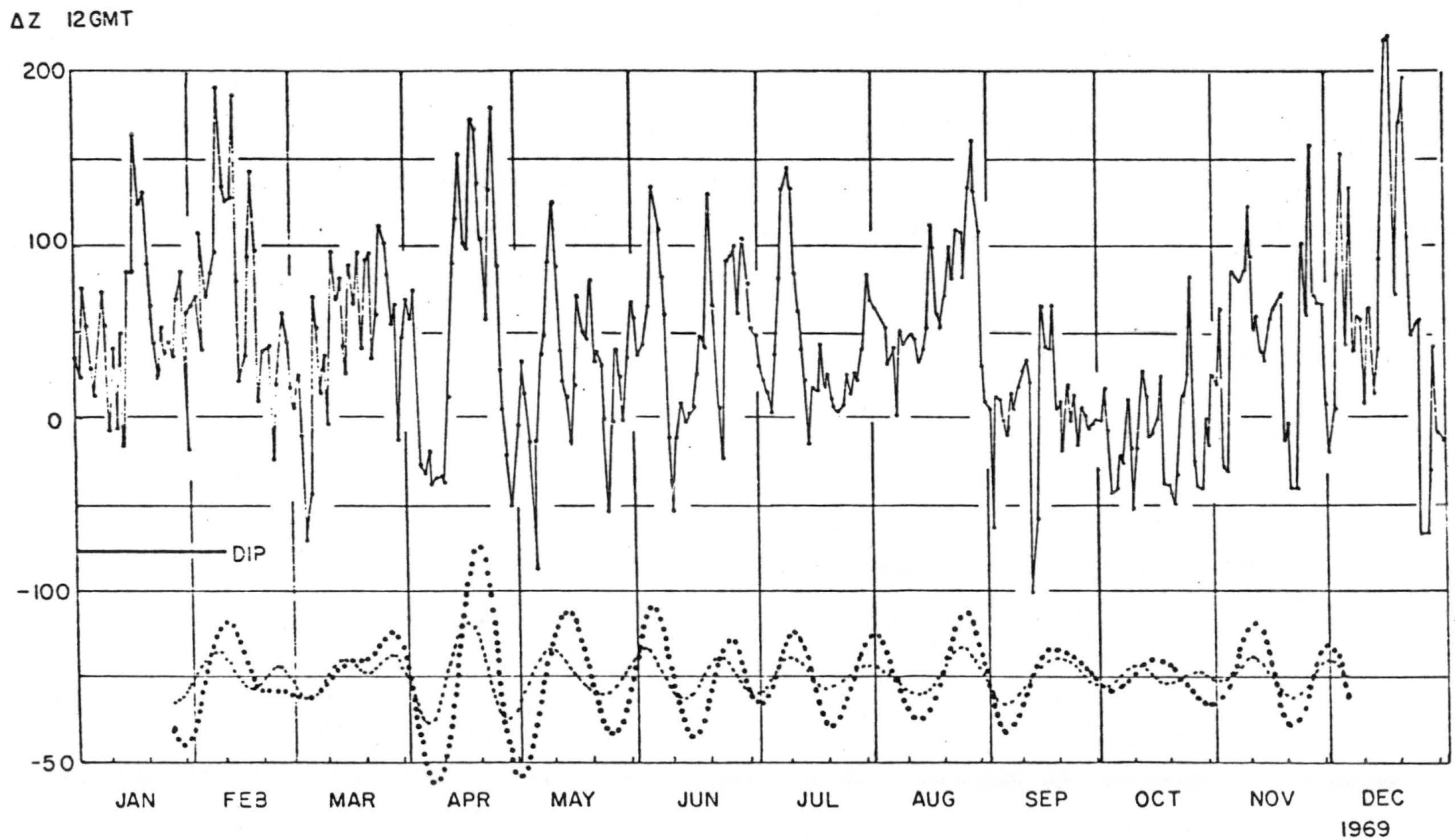


Figure 7. Daily values at 12 GMT, 1969, of height differences at 500 mb between grid points shown in Fig. 4 (upper curve), and 22-day filtered series for 500 mb data (heavy-dotted curve) and 1000 mb data (light-dotted curve). The period of the "mid-winter dip" in ΔZ is indicated by a heavy line.

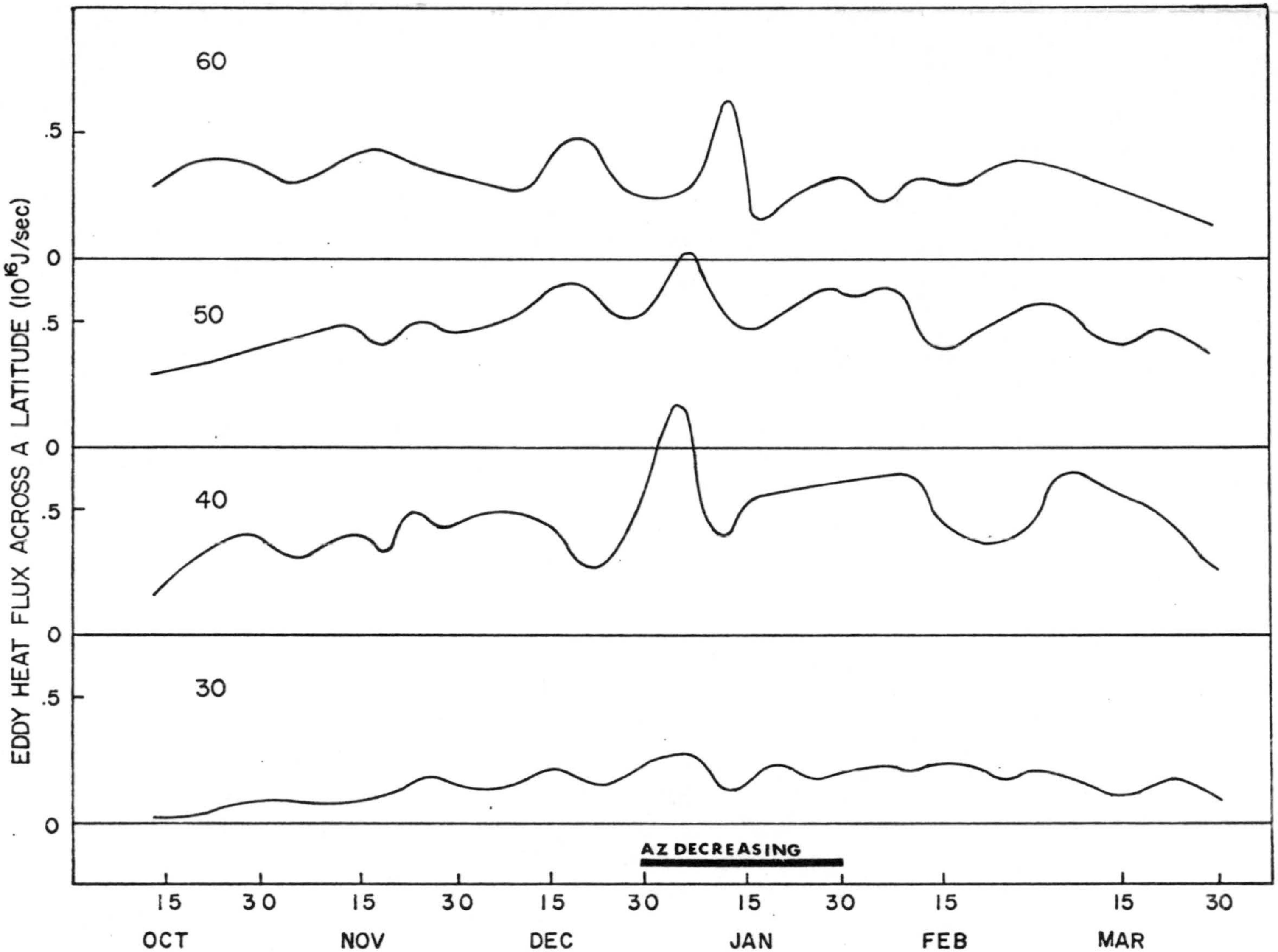


Figure 8. Total eddy heat flux across four latitude circles from 1000-100 mb for 1971. The spikes in early January correspond to the stratospheric warming period.

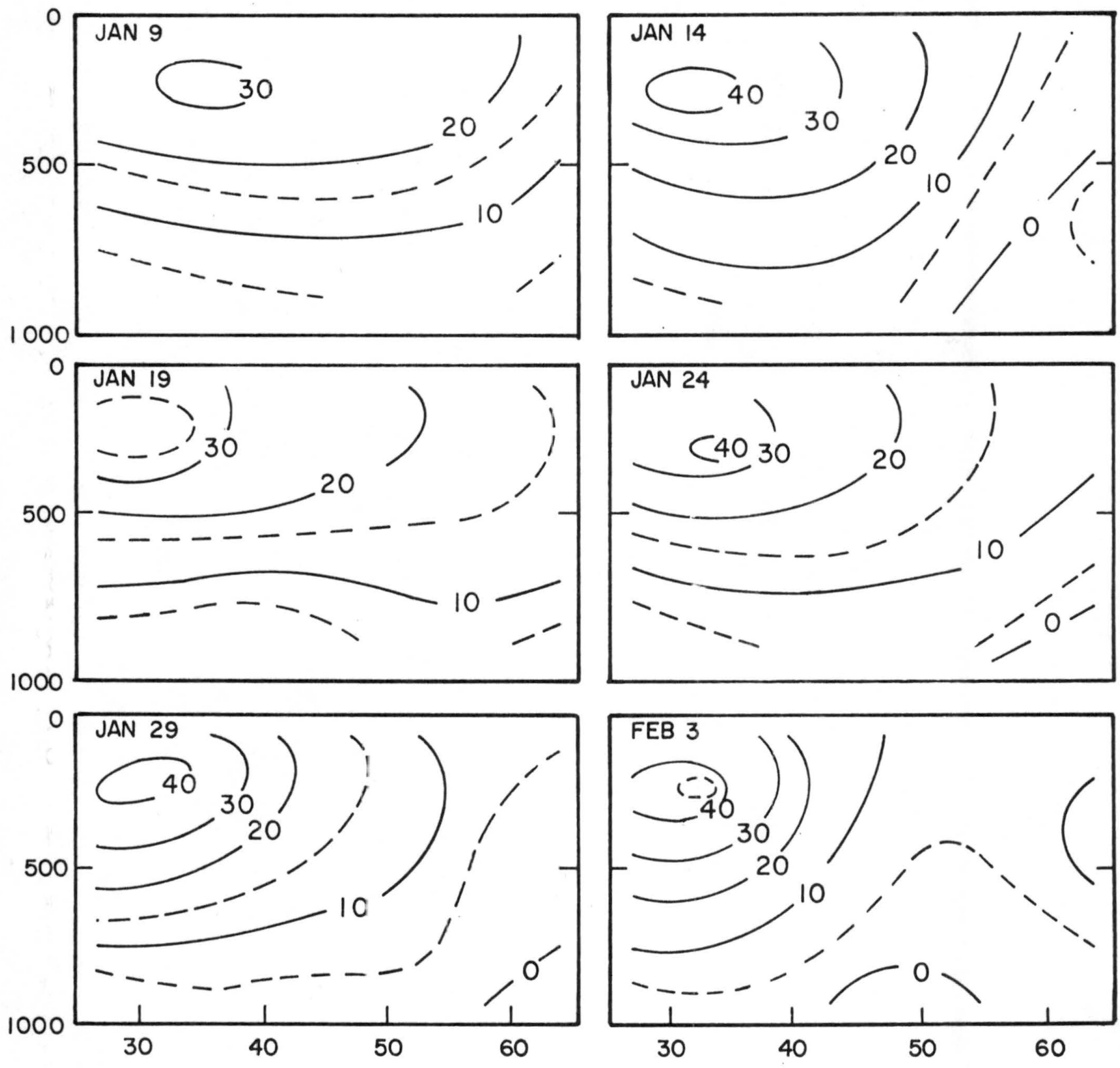


Figure 9. Meridional cross-section of the mean geostrophic zonal wind at 5-day intervals for the northern hemispheric midlatitude for 1971. Winds in m/sec.

Figure 10. North America - contours of the differences in the monthly mean precipitation between July 1966 and July 1965. Areas of positive values indicate that July 1966 received more precipitation than July 1965. All values are in tenths of mm. (Courtesy of Tom J. Corona.)

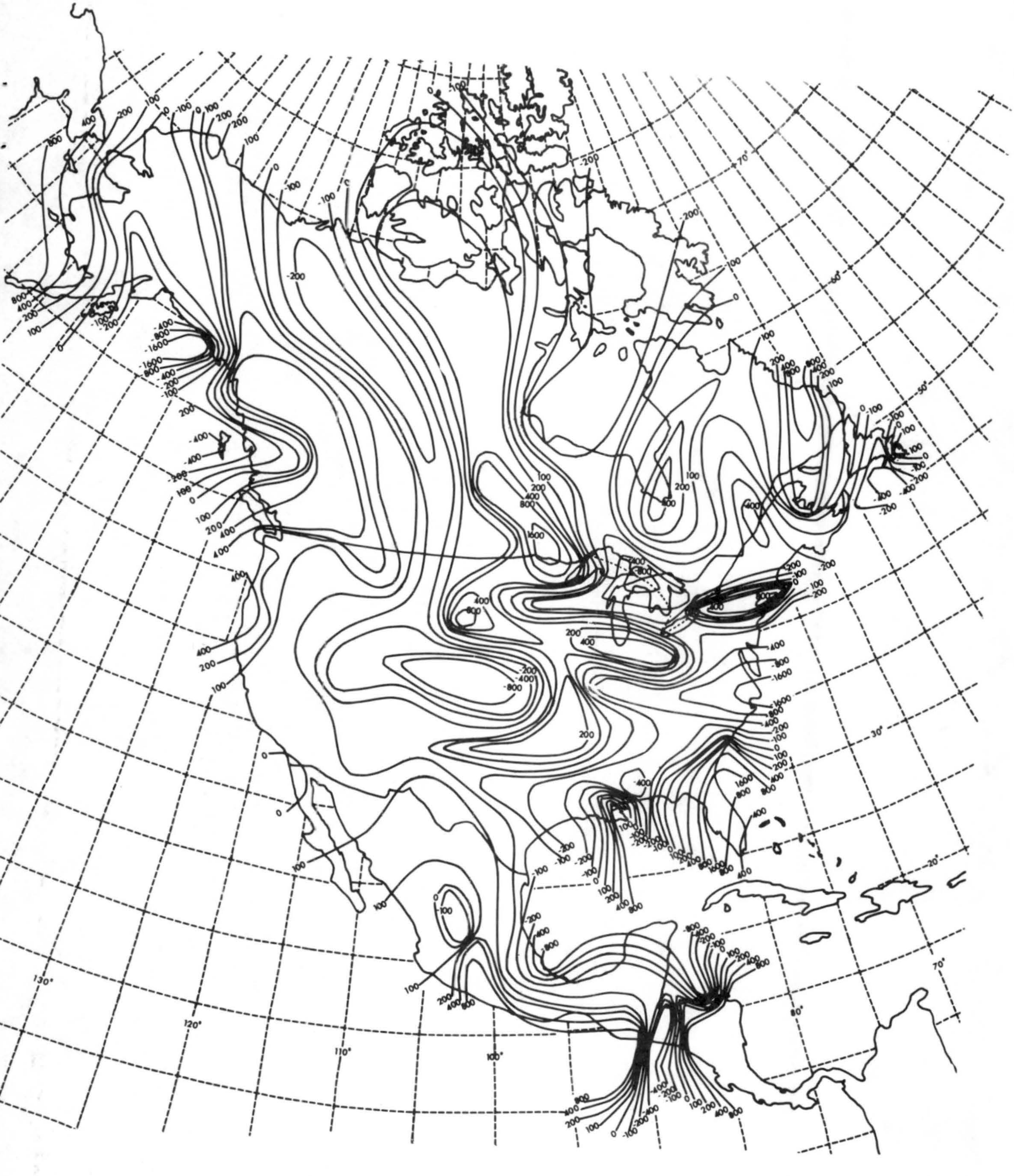

70°
60°
50°
30°
20°
70°
80°
130°
120°
110°
100°

Figure 11. Eurasia - same as Fig. 10, except different geographic area. (Courtesy of Tom J. Corona.)

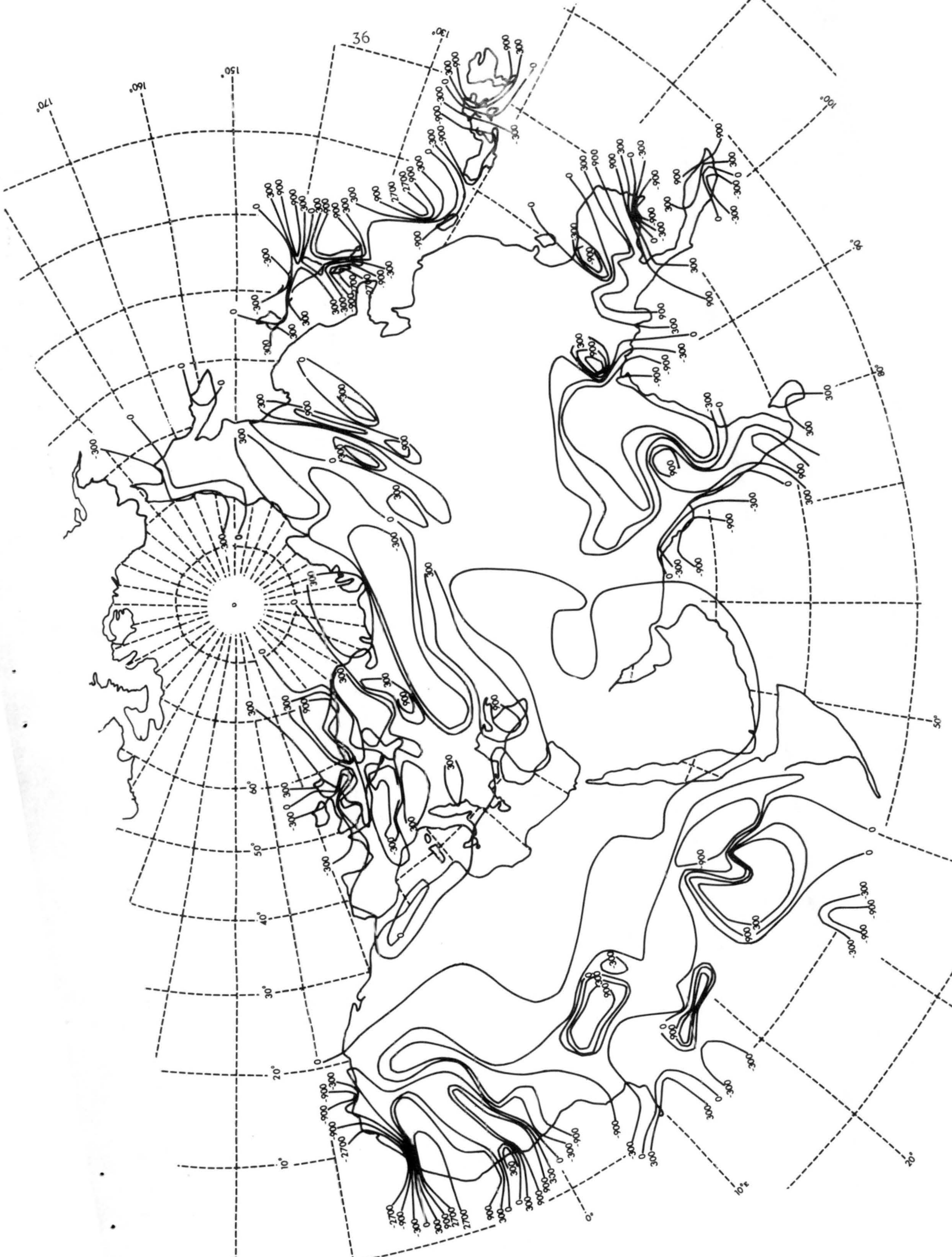


Figure 12. An equal area grid for North America. All numbers are in tenths of mm. Each box was subdivided into 25 smaller boxes with one interpolated value per small box. These were summed and divided by 25 to obtain the area average for the large box. The values along the right edge are latitudinal averages obtained by summing the values in the large boxes and dividing by the number of large boxes in that latitude band. (Courtesy of Tom J. Corona.)

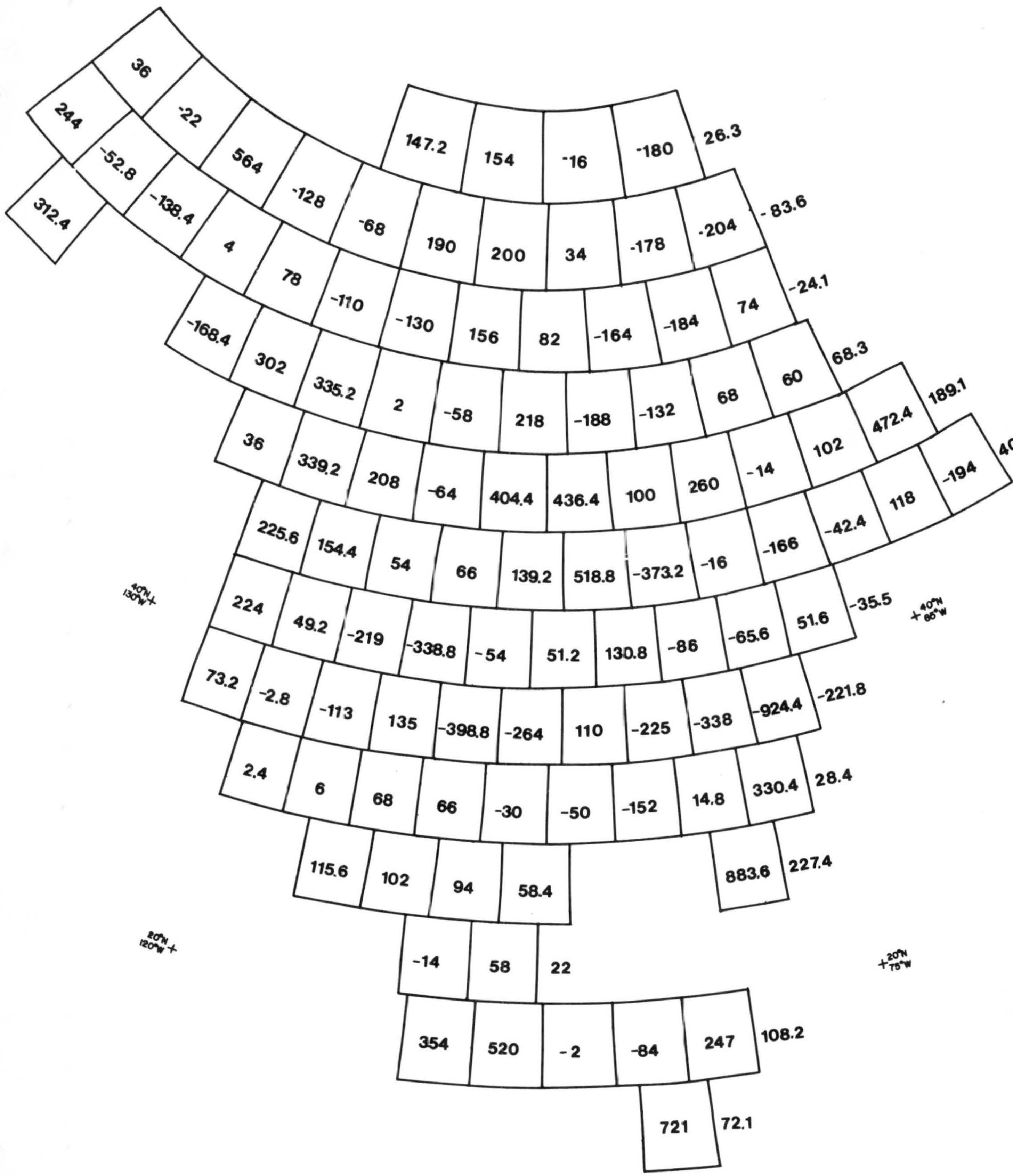
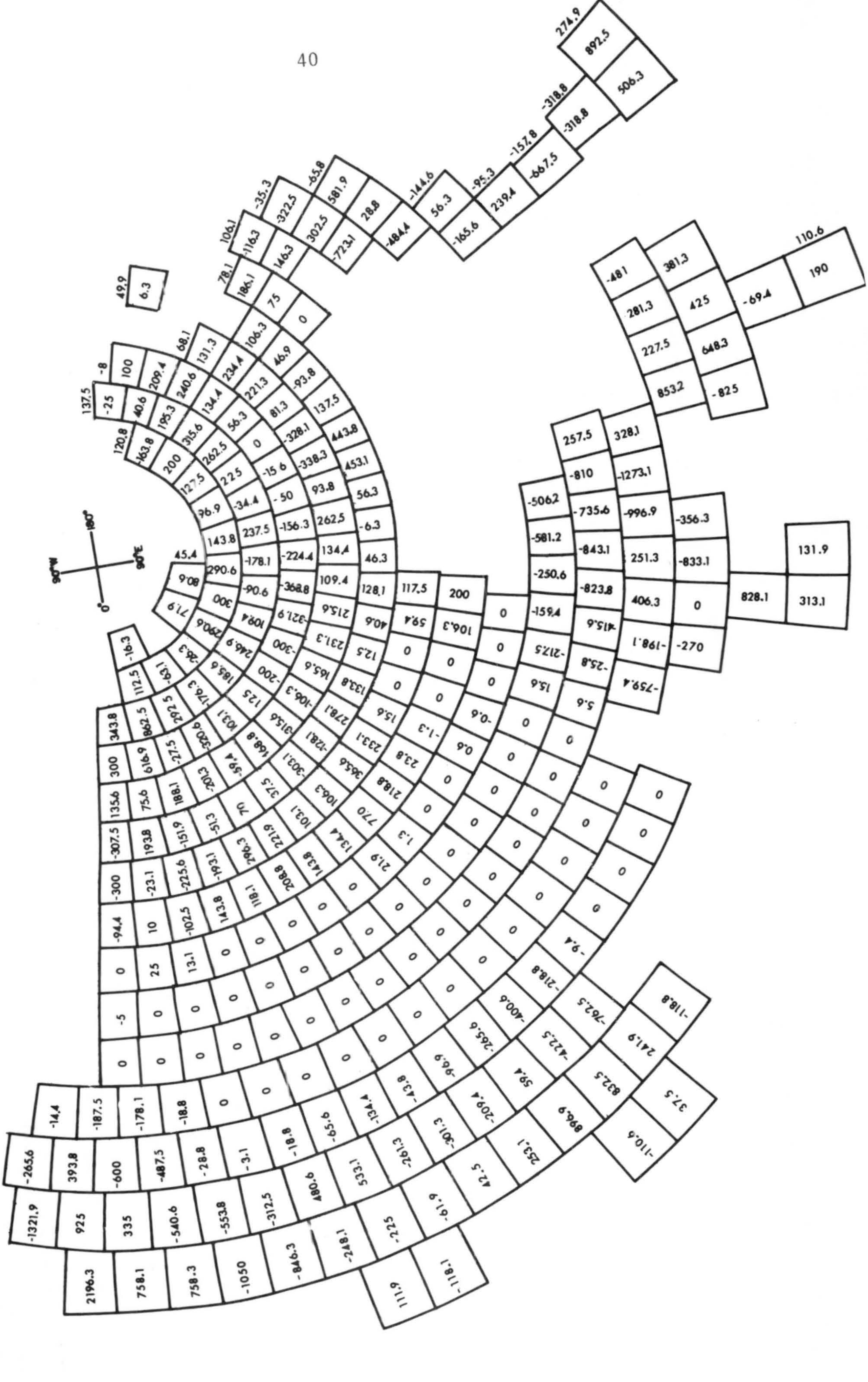

36
244
-22
312.4
-52.8
564
147.2
154
-16
-180
26.3
-138.4
-128
-68
190
200
34
-178
-204
-83.6
4
78
-110
-130
156
82
-164
-184
74
-24.1
-168.4
302
335.2
2
-58
218
-188
-132
68
60
68.3
472.4
189.1
36
339.2
208
-64
404.4
436.4
100
260
-14
102
-194
40.4
225.6
154.4
54
66
139.2
518.8
-373.2
-16
-166
-42.4
118
40°N 130°W
224
49.2
-219
-338.8
-54
51.2
130.8
-86
-65.6
51.6
-35.5
40°N 85°W
73.2
-2.8
-113
135
-398.8
-264
110
-225
-338
-924.4
-221.8
2.4
6
68
66
-30
-50
-152
14.8
330.4
28.4
115.6
102
94
58.4
883.6
227.4
20°N 120°W
-14
58
22
20°N 75°W
354
520
-2
-84
247
108.2
721
72.1

Figure 13. Same as Fig. 12, except for Eurasia and Africa and subdivision of each box into 16 smaller boxes. (Courtesy of Tom J. Corona.)


180°
90°E
0°
90°W

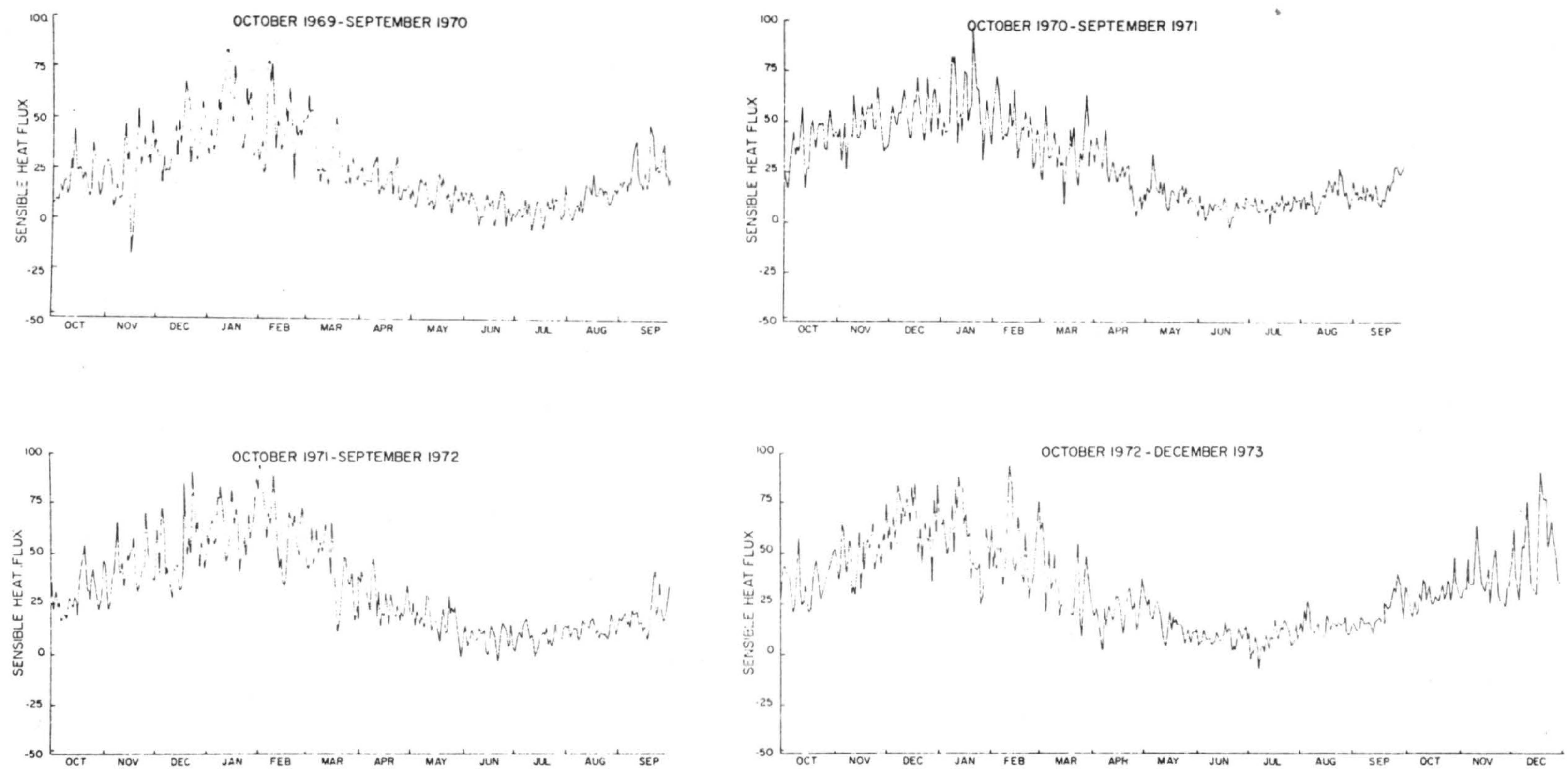


Figure 14a. Daily averaged sensible heat transfer from the Atlantic ocean, October 1969 - December 1973 (cal cm^{-2} day^{-1}).

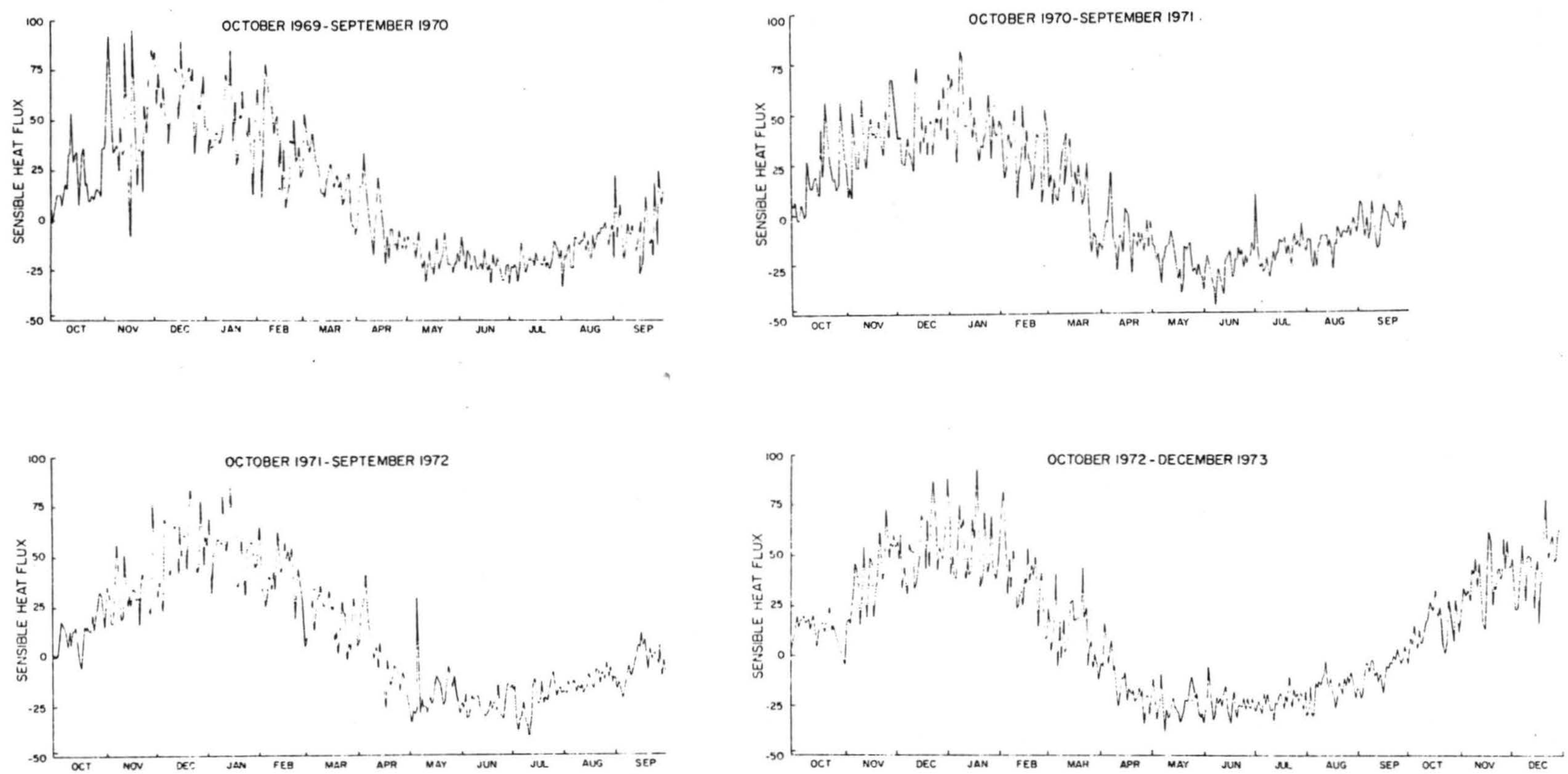


Figure 14b. Daily averaged sensible heat transfer from the Pacific ocean, October 1969 - December 1973 (cal cm^{-2} day^{-1}).

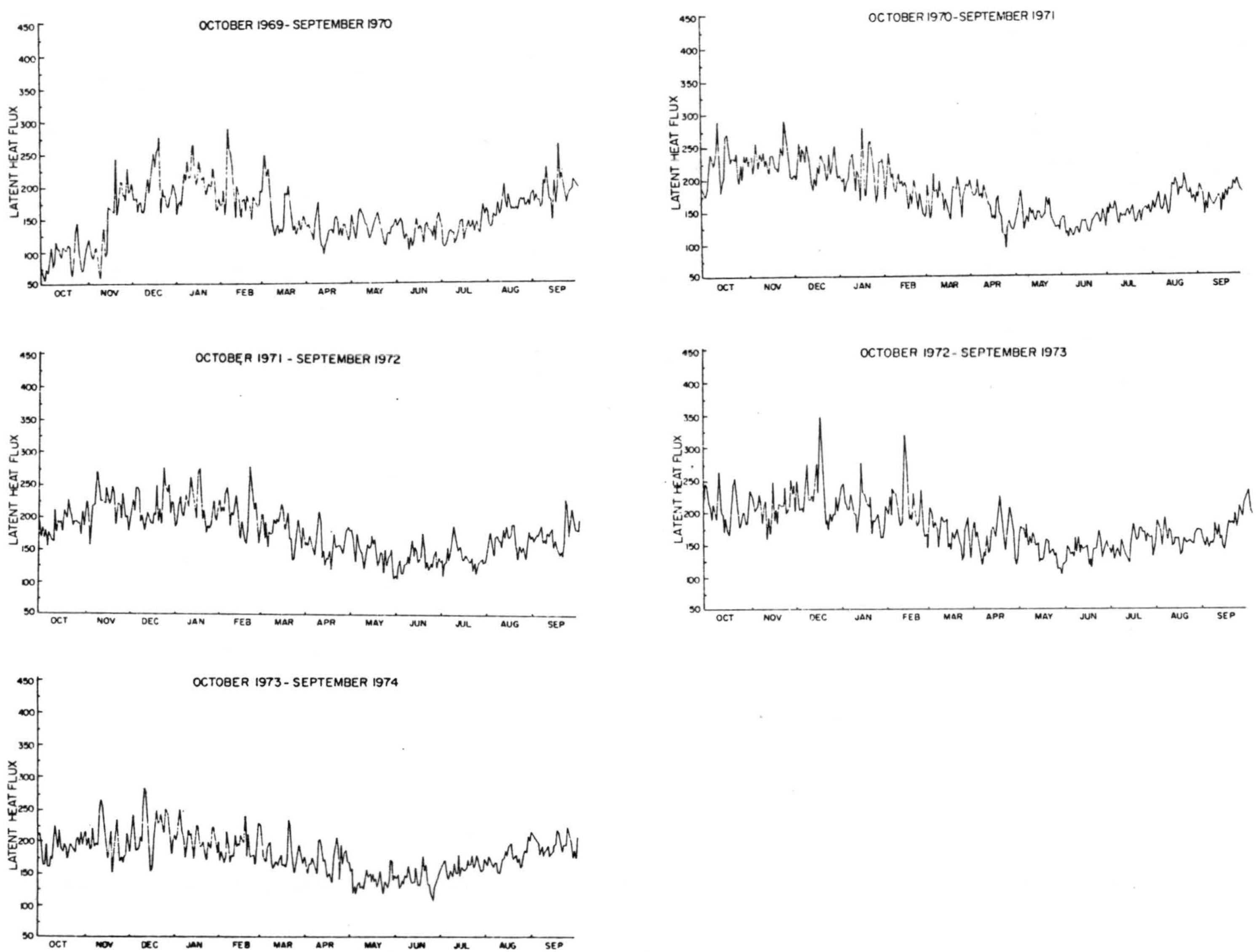


Figure 15a. Daily averaged latent heat transfer from the Atlantic Ocean, October 1969 - September 1974 (cal cm^{-2} day^{-1}).

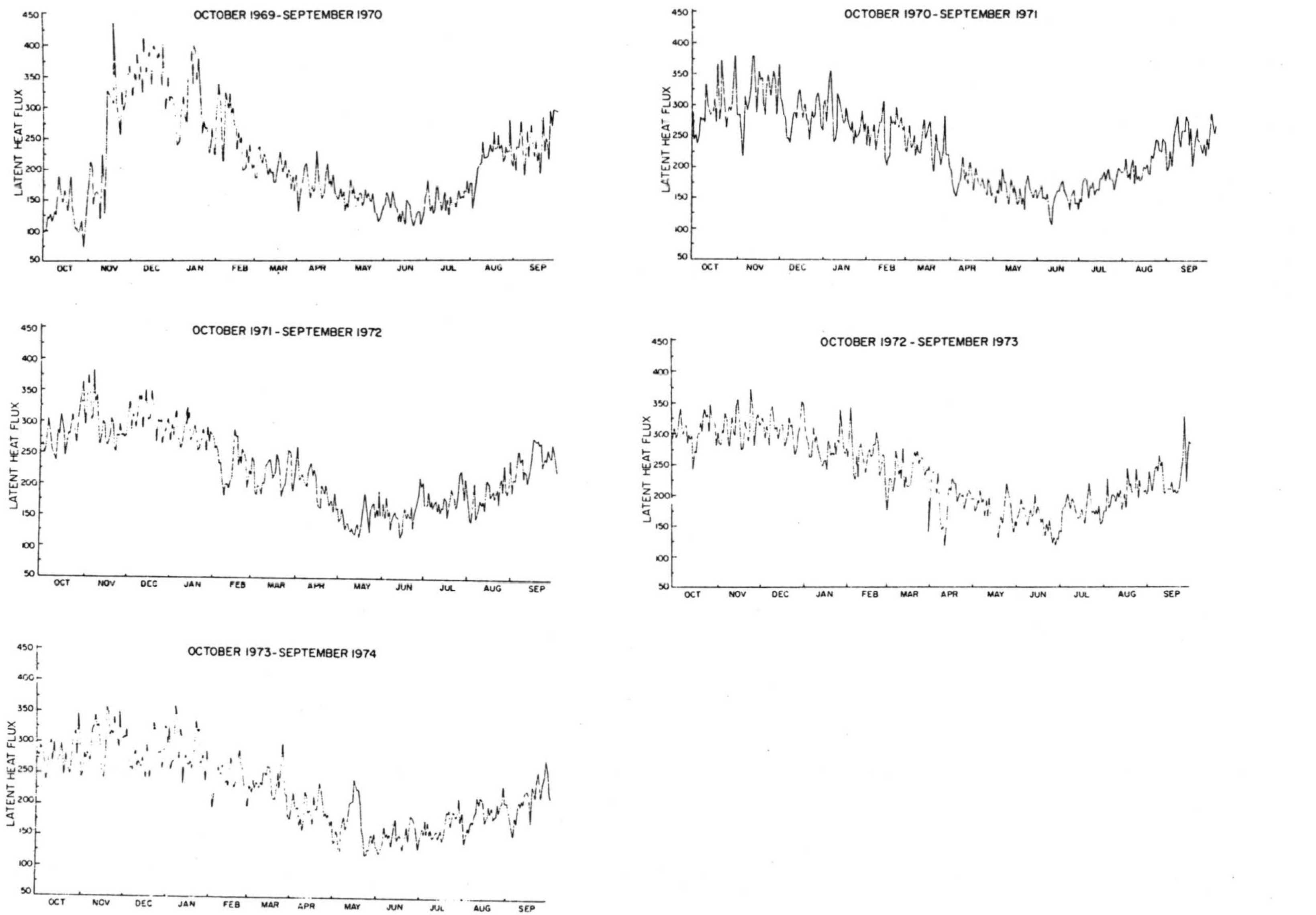


Figure 15b. Daily averaged latent heat transfer from the Pacific Ocean, October 1969 - September 1974 (cal cm^{-2} day^{-1}).

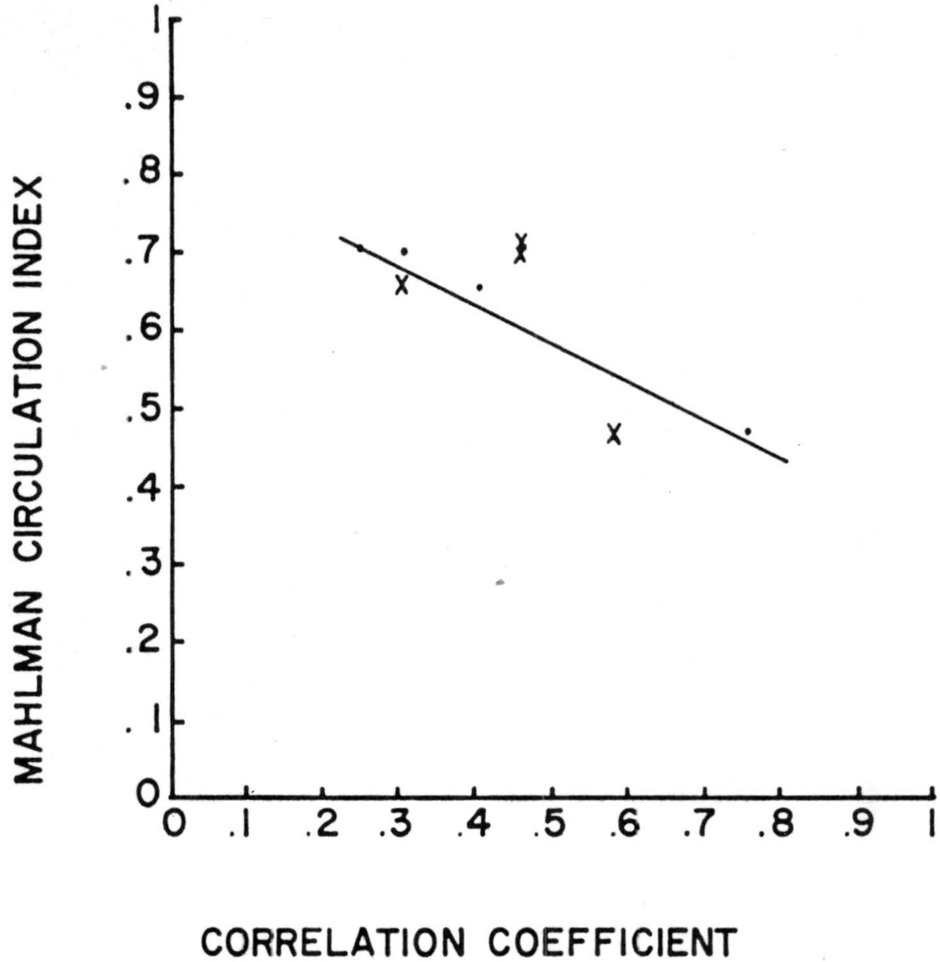


Figure 16. Mahlman Circulation Index (0 ≡ meridional, 1 ≡ zonal) vs. correlation coefficients. The dots represent the latent heat flux correlations; the x's sensible heat flux correlations.

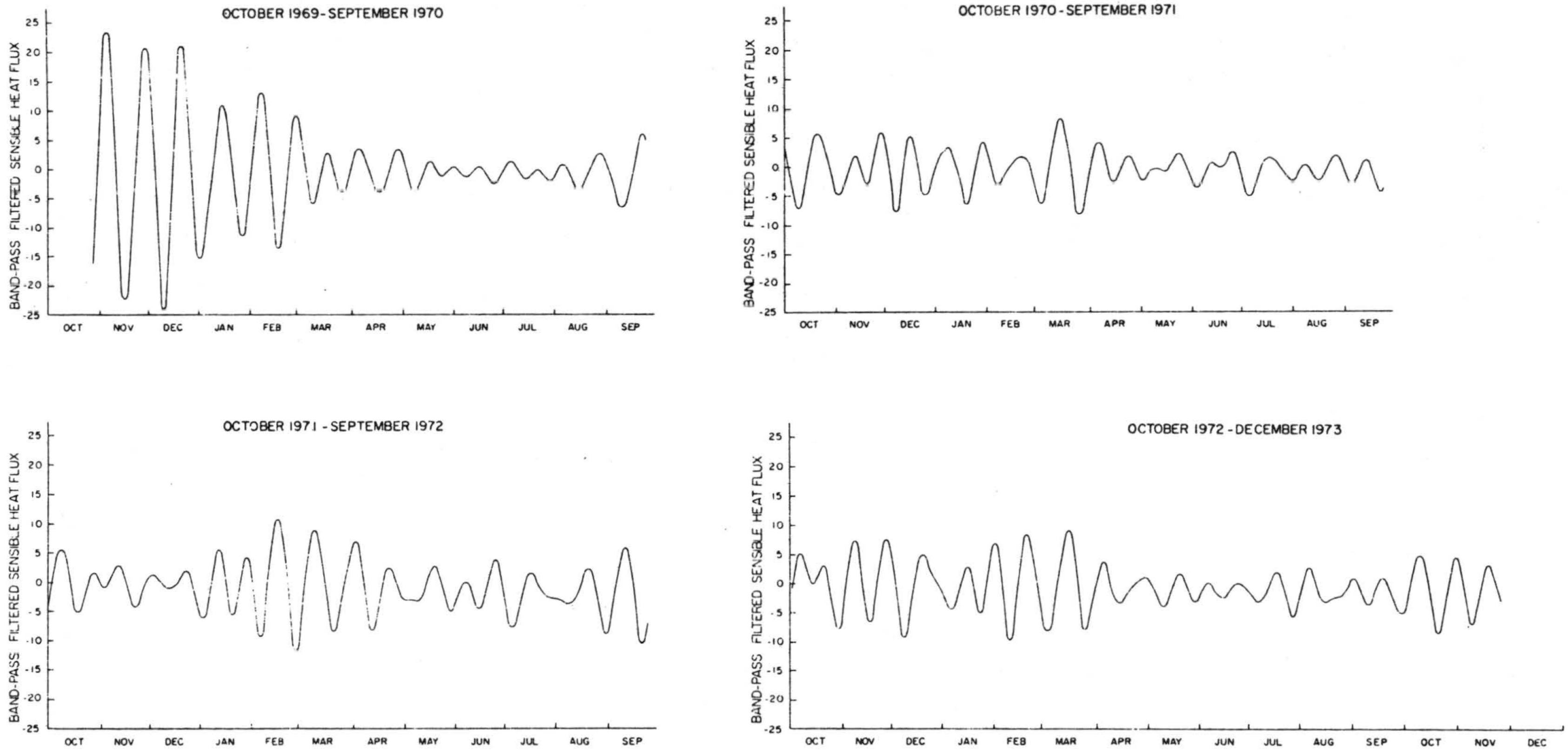


Figure 17. Band-pass filtered sensible heat flux from the Pacific ocean, October 1969 - December 1973.

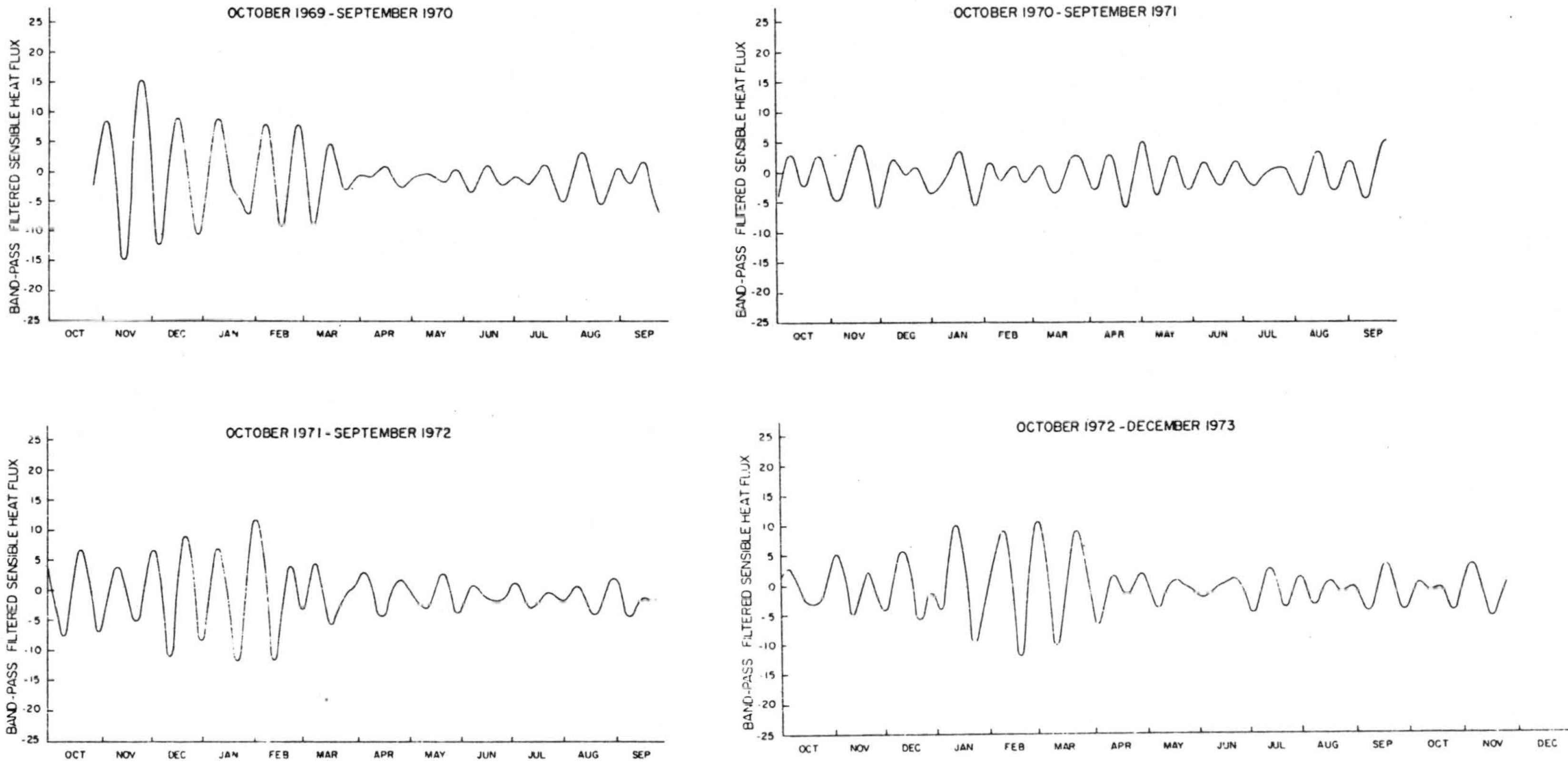


Figure 18. Band-pass filtered sensible heat flux from the Atlantic ocean, October 1969 - December 1973.

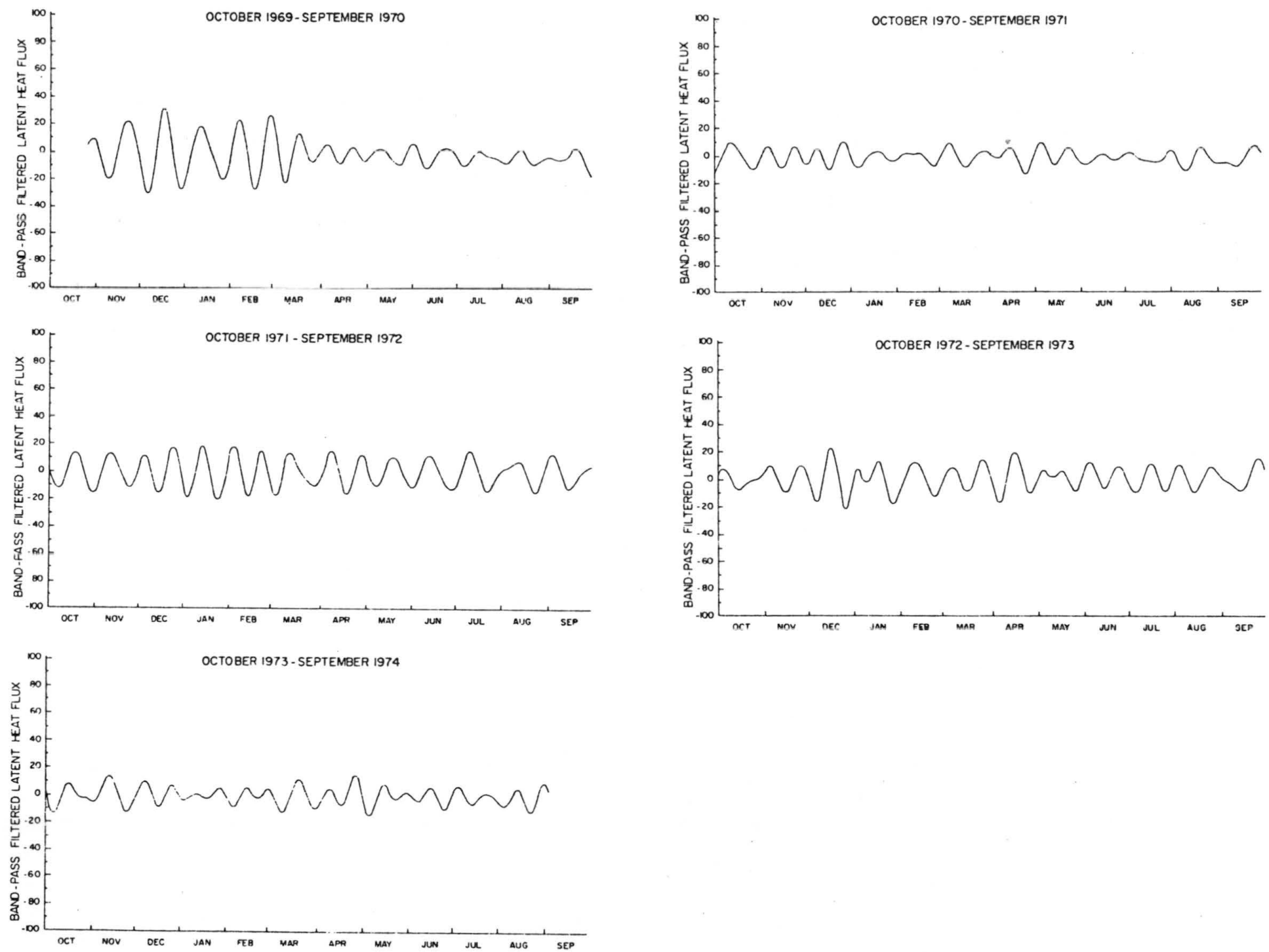


Figure 19. Band-pass filtered latent heat flux from the Atlantic ocean, October 1969 - September 1974.

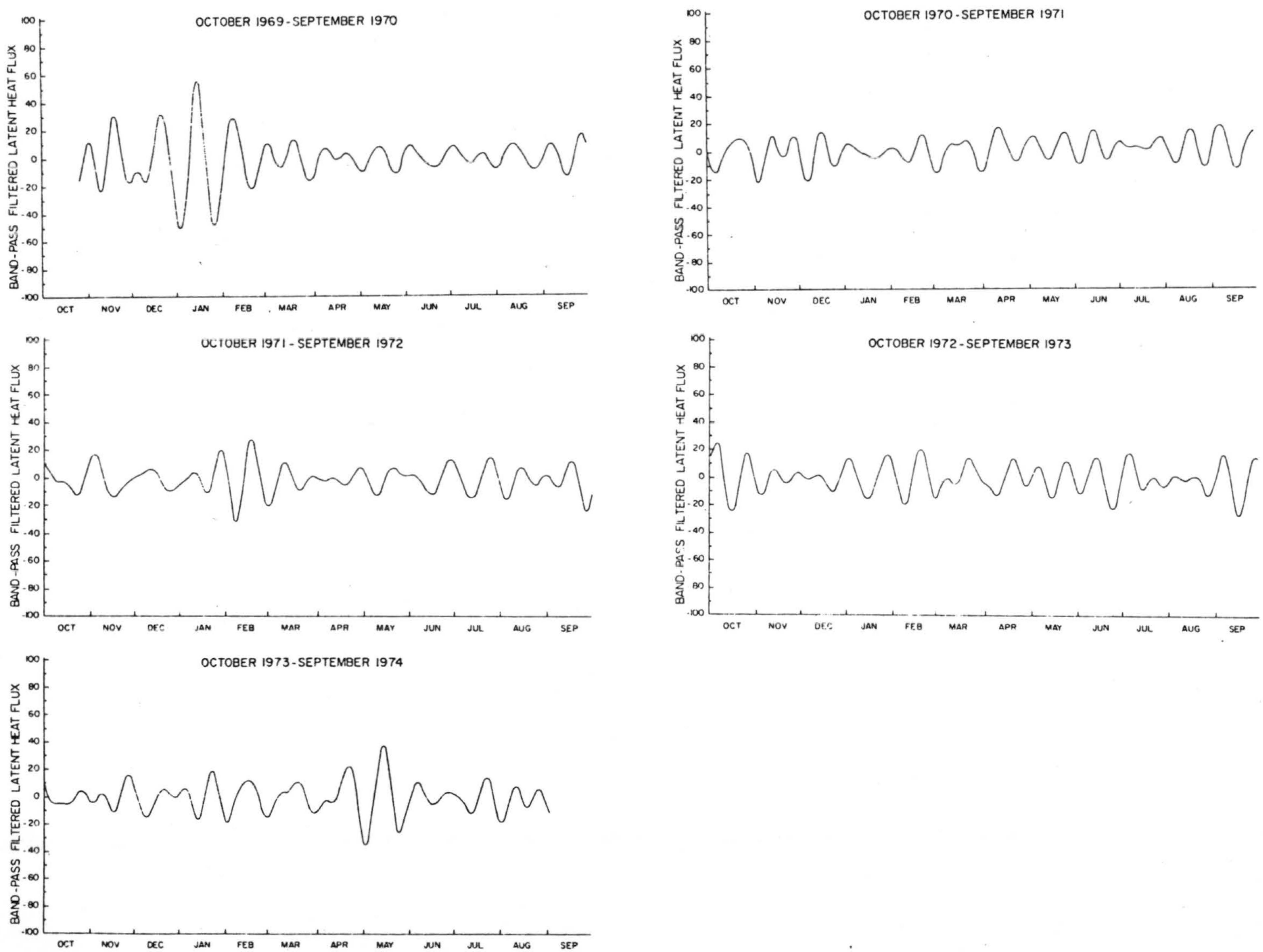


Figure 20. Band-pass filtered latent heat flux from the Pacific ocean, October 1969 - September 1974.

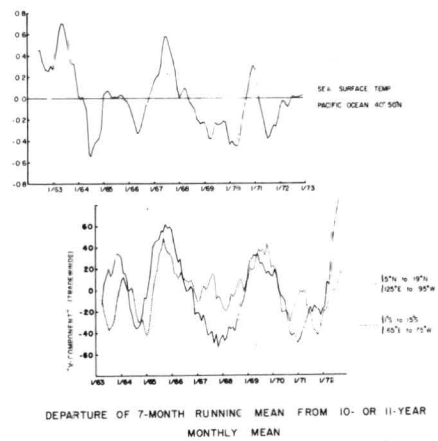


Figure 21. Sea-surface temperature anomalies 40-50°N time-lagged against northern and southern hemisphere trade-wind v-components in areas indicated. All curves are departures of 7-month running means from long-term monthly averages.