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ATLAS OF LINEAR TRENDS IN
NORTHERN-HEMISPHERE
TROPOSPHERIC GEOPOTENTIAL
HEIGHT AND TEMPERATURE PATTERNS

by
Elmar R. Reiter and Daniel R. Westhoff

ATMOSPHERIC SCIENCE
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TABLE OF CONTENTS

	<u>Page</u>
TITLE PAGE	i
ACKNOWLEDGMENTS	iii
ABSTRACT	1
1. Introduction	1
2. Trend Analyses	2
3. Conclusions	15
References	16

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ABSTRACT

Gridded NMC data for 500-mb geopotential height, 300/500-mb and 500/700-mb thickness for the period 1951 to 1978 were subjected to linear trend analyses. These analyses were performed for each calendar month. Significant geographical and seasonal distributions of cooling and warming patterns emerged. An atmospheric cooling trend over the North Pacific during the winter months appears to be associated with oceanic cooling in that region, but also to planetary-wave adjustments, suggesting that ocean-atmosphere feedback mechanisms are effectively at work over climatic time scales. Consistently large temperature trends also appear over the Asian continent. Comparisons between thickness trends in the layer 300/500 mb with those in the layer 500/700 mb reveal well-pronounced patterns of stabilization and destabilization.

ABSTRACT

Gridded NMC data for 500-mb geopotential height, 300/500-mb and 500/700-mb thickness for the period 1951 to 1978 were subjected to linear trend analyses. These analyses were performed for each calendar month. Significant geographical and seasonal distributions of cooling and warming patterns emerged. An atmospheric cooling trend over the North Pacific during the winter months appears to be associated with oceanic cooling in that region, but also to planetary-wave adjustments, suggesting that ocean-atmosphere feedback mechanisms are effectively at work over climatic time scales. Consistently large temperature trends also appear over the Asian continent. Comparisons between thickness trends in the layer 300/500 mb with those in the layer 500/700 mb reveal well-pronounced patterns of stabilization and destabilization.

1. INTRODUCTION

Concern about possible effects of increased anthropogenic CO₂ concentrations in the atmosphere on climate have spawned a number of investigations of recent hemispheric temperature trends (e.g. Angell and Korshover, 1975;1977; Barnett, 1978; Lamb, 1977; van

Loon and Williams, 1976a,b, 1977; Williams and van Loon, 1976). Several of these authors have pointed out that warming or cooling trends do not have a uniform impact around the globe or the hemisphere by virtue of responses in the planetary wave patterns to changes in mean meridional temperature gradients, and in local forcing effects.

In a recent paper (Reiter and Westhoff, 1981) we described the mean annual cycle of planetary waves, derived from calendar-date averaged northern hemisphere 500-mb data (available from the National Meteorological Center) for the period January 1946 through February 1979. In addition we gained access to 700- and 300-mb geopotential height data for the period 1951-1978. These data were also subjected to calendar-date averaging. As in our previous investigation of 500-mb data, we applied a 21-day running mean filter twice to these date-averaged data in order to obtain a smooth seasonal behavior of pressure heights and thicknesses at each grid point. Daily and monthly departures from the mean annual cycles were computed for each grid point and for each pressure surface. These departures served as a basis for the present investigation.

2. TREND ANALYSES

The aforementioned daily departures of geopotential heights from their smoothed long-term daily mean values were subjected to simple linear trend analyses, by fitting "least-squares" regression lines. The slopes of these lines, expressed in units of gpm/year (isolines drawn for each 0.5 gpm/y) were analyzed on the polar stereographic base map shown in Fig. 1.

Trends were computed on a monthly basis, by constructing time series of departures from the long-term means at each grid point, and for each of the three pressure levels involved, as follows: Jan. 1, 1951; Jan. 2, 1951; . . . Jan. 31, 1951; Jan. 1, 1952; . . . ; . . . ; . . . ; Jan. 31, 1978. Height trends are shown here only for the 500-mb surface (Fig. 2). The trends of the 700- and 300-mb surfaces were combined with those of the 500-mb surface to yield thickness, hence temperature, trends with analysis intervals 0.25 gpm/year (Figs. 3 and 4). Differences between these two layers resulted in estimates of the long-term behavior of tropospheric stability (Fig. 5).

In interpreting the computational results we have to be aware of the fact that the upper-air observational systems in the northern hemisphere have undergone considerable changes during the last thirty years in both quality of measurements and density of data coverage. It would be surprising if those changes had not introduced certain biases in the NMC data upon which our study is based. It is difficult for us to estimate what effects the demise of weatherships, or the incorporation of aircraft and satellite data into the analyses, might have had on the quality of our

data base. In view of these unresolved shortcomings we have to exercise caution in assessing the significance of certain features of our analyses described in the following discussion:

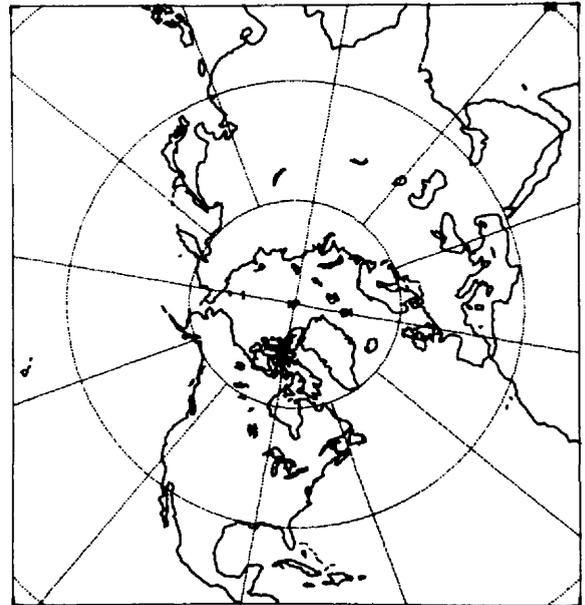


Fig. 1 Continental outline to be used in the interpretation of subsequent figures.

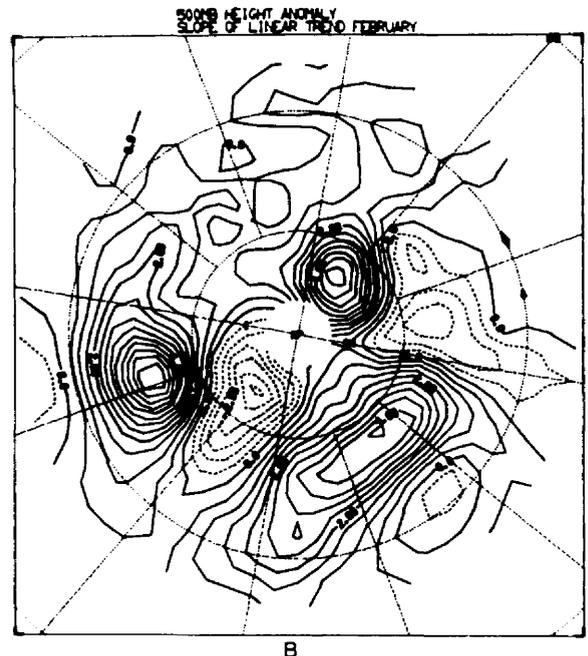
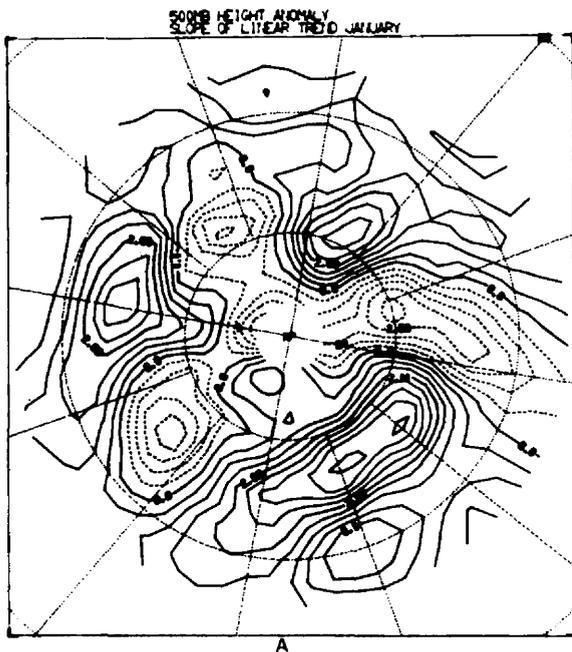
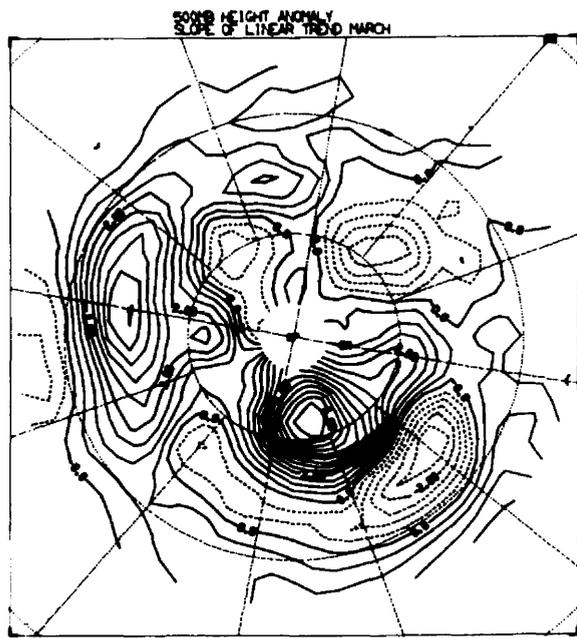
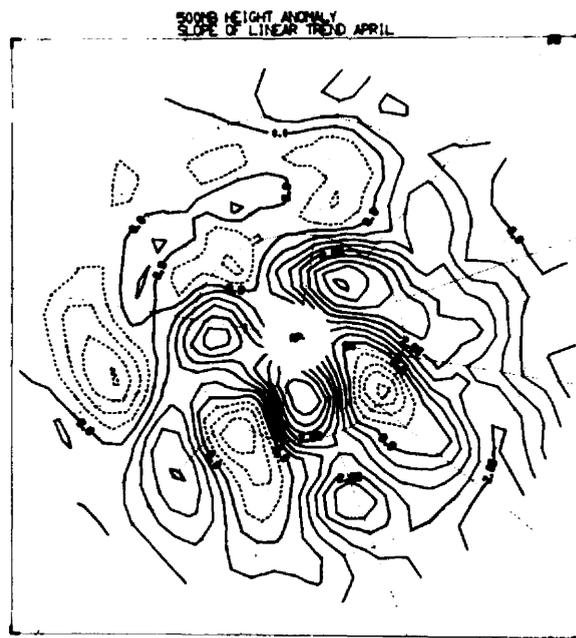


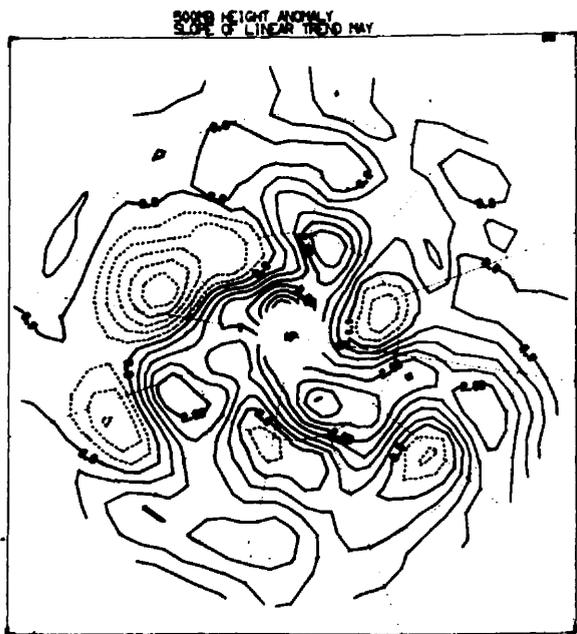
Fig. 2 Linear trends, by month, in gpm/year (analysis interval 0.5 gpm/year) of 500-mb heights. Solid lines: negative trend (i.e. height decreases with time); dotted lines: positive trend. Trends are based on data for the period 1951-1978.



C



D



E



F

Fig. 2 (Continued)

(1) An area of warming in the lower and upper troposphere (Figs. 3 and 4) and of a rising tendency in the 500-mb heights (Fig. 2) appears rather frequently over Tibet. We are tempted to dismiss this feature as being produced by inadequate data coverage in that region (especially during the earlier part of the data period), by the fact that the terrain elevation exceeds that of the 700-mb surface, and by the adoption of the International Barometric Conversion in that region between 1956 and 1957 (van Loon and Williams, 1976a). There is, however, circumstantial

evidence which suggests that the sign of the thickness tendencies shown in Figs. 3 and 4 over Tibet, if not their magnitudes, may be correct. Bryson* (1974) showed that precipitation yields during the summer monsoon in northwest India had improved between the 1950's and the 1970's. According to recent

*Bryson, R.A., 1974: The lessons of climatic history. Paper presented at Conference on Weather and Climate Change, Food Production and Interstate Conflict, Rockefeller Foundation, January, 1974.

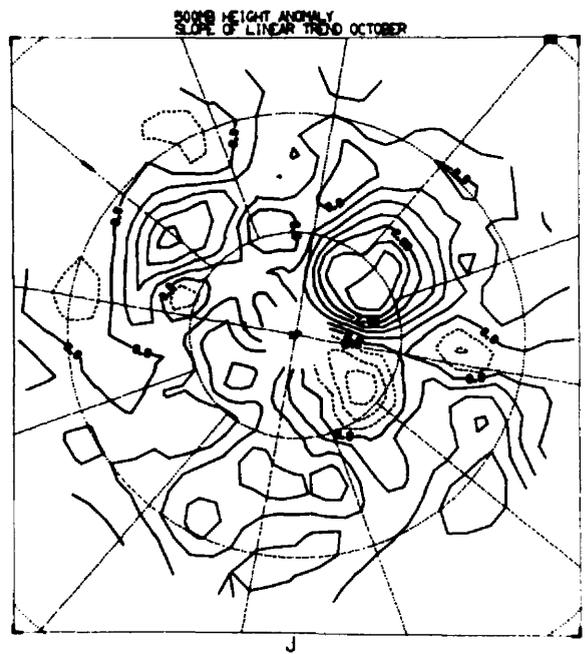
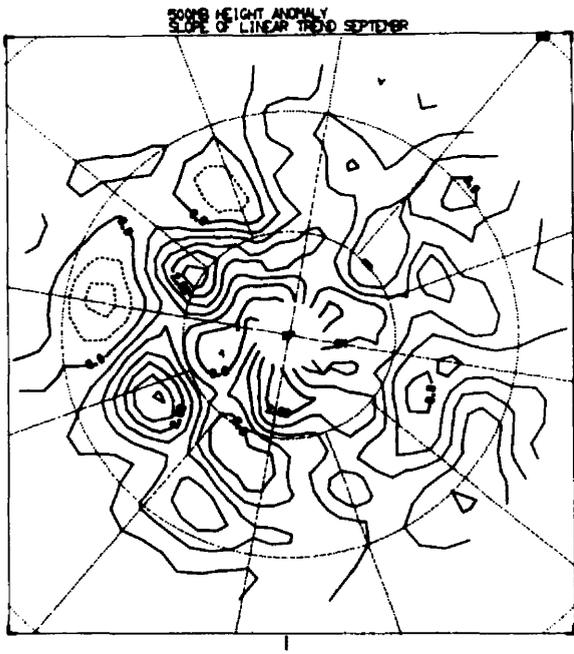
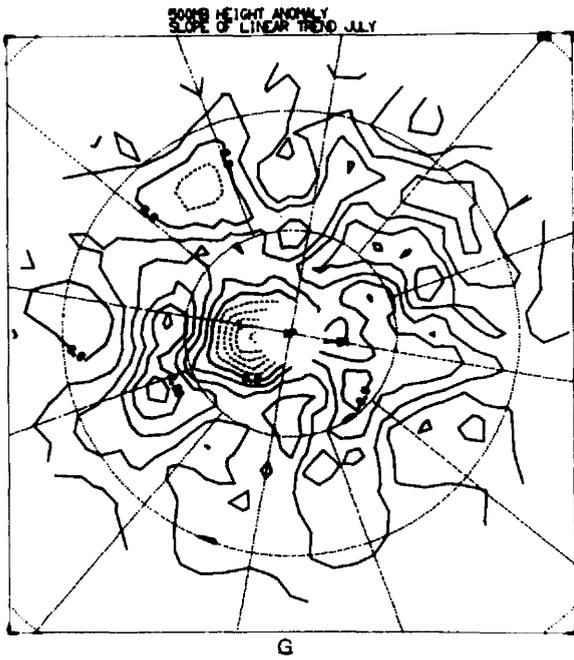


Fig. 2 (Continued)

studies by Ye (1981) and Cheng (1981) the Indian monsoon system is coupled to the effectiveness of the Xizang (Tibet) plateau as a heat source. A low tropospheric warming trend, especially during spring, over Tibet, together with an increasing prevalence of anticyclonic conditions above the planetary boundary layer in the plateau region would agree with the observed monsoon trends. Stabilization trends indicated over Tibet during late spring and summer (Fig.

5) also point toward an intensification of the plateau effects.

(2) One of the most prominent features in the 500-mb height tendencies (Fig. 2) is the declining trend in midlatitudes over the Pacific during the cold season. This trend is matched by a low-tropospheric cooling trend during the same season and in the same region. Cooling also extends into the upper troposphere. Reiter (1978) and others observed a strong



Fig. 2 (Continued)

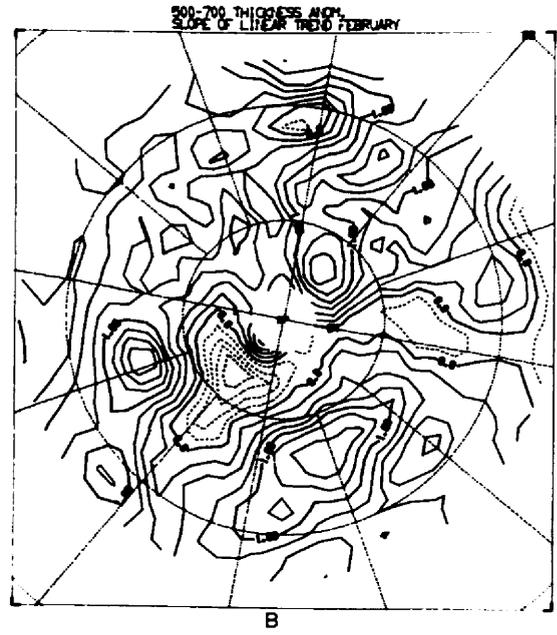
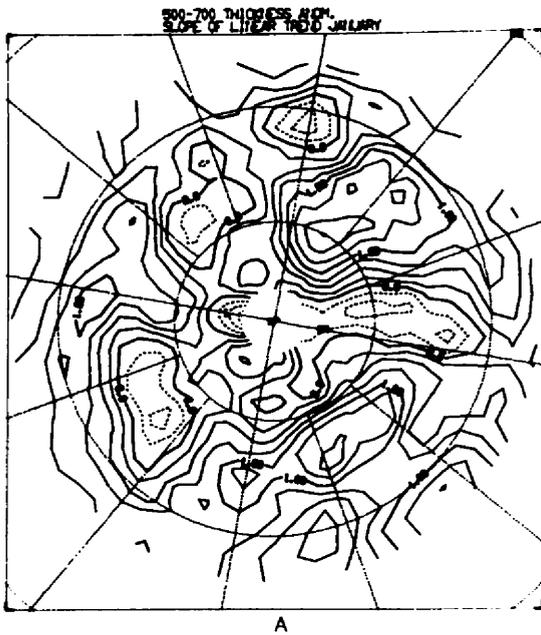


Fig. 3 Linear trends, by month, in gpm/year (analysis interval 0.25 gpm/year) of 500/700-mb thickness. Solid lines: cooling trend (i.e. shrinking thickness); dotted lines: warming trend. Trends are based on data for the period 1951-1978.



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Fig. 3 (Continued)

cooling of the sea surface after 1963 in the region 40-50°N over the Pacific. This cooling amounted to approximately 2°C in 15 years, averaged over the width of the Pacific in that latitude band, or to more than 0.1°C/year between maximum temperatures in 1963 and minimum temperatures in 1976. A decrease of 1 gpm/

year in the 500/700 mb thickness also corresponds to a cooling of that layer by approximately 0.1°C. According to Fig. 3 low-tropospheric temperature trends during winter exceed this value appreciably, but the annually averaged trends (Fig. 6) approach this magnitude. If the trends in 500-mb heights were entirely due to temperature changes between the earth's surface

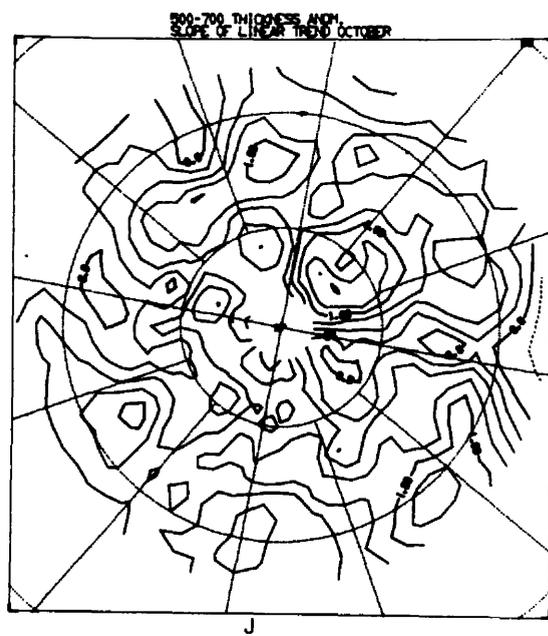
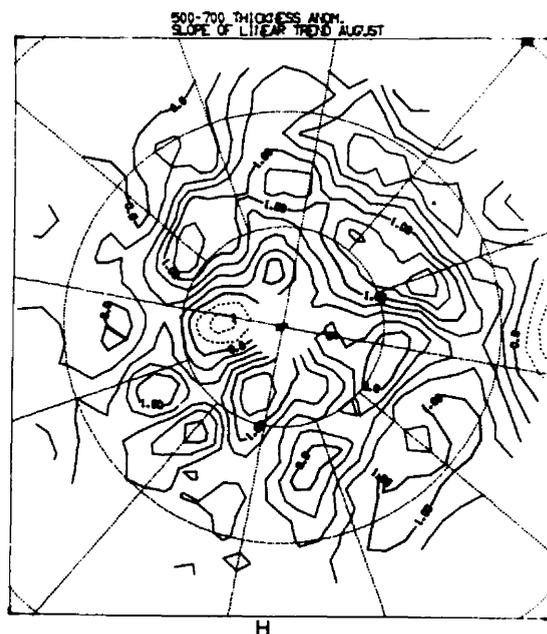
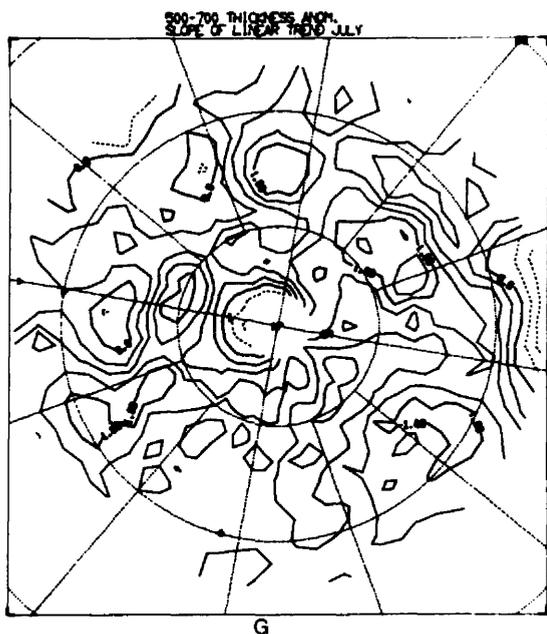


Fig. 3 (Continued)

and that pressure level, a decrease of 2 gpm/year would be roughly equivalent to a cooling of $0.1^{\circ}\text{C}/\text{year}$.

(3) Comparisons between Figs. 2 and 3 for the winter months December through March show that the height tendencies of the 500-mb surface are significantly more pronounced over the central North Pacific than the temperature trends indicated by the 500/700-mb thicknesses and applied to the layer 500/1000 mb would indicate. Also the center of cooling in the

500/700-mb layer during March lies to the west of the region of strongest 500-mb height decreases. These observations lead us to the conclusion that not only thermal, but also dynamic effects are involved in the observed long-term trends of the 500-mb heights. This conclusion is substantiated further by the presence of a zone of tropospheric destabilization (Fig. 5), meaning that the upper troposphere cooled more than the lower troposphere. An increase in the frequency and/or intensity of low-pressure disturbances in the central North Pacific during the course of the past 30

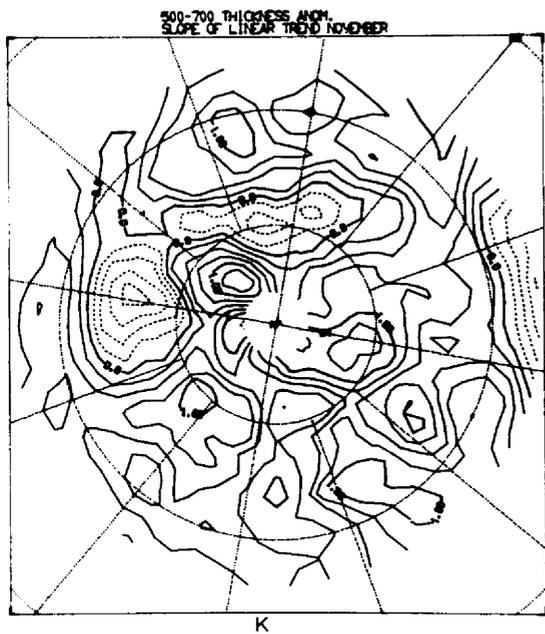


Fig. 3 (Continued)

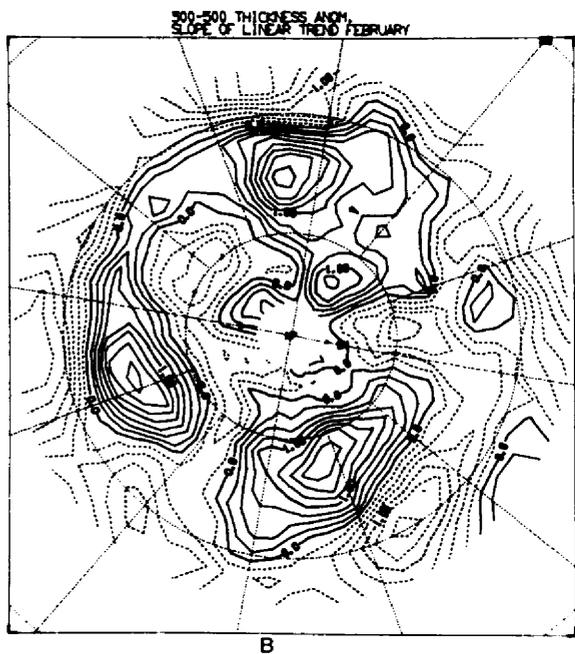
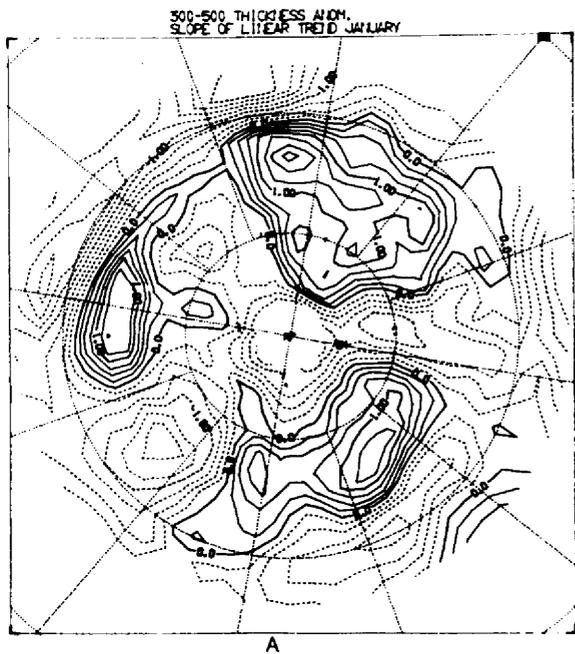


Fig. 4 Similar to Fig. 3, except 300/500-mb thickness trends are shown.

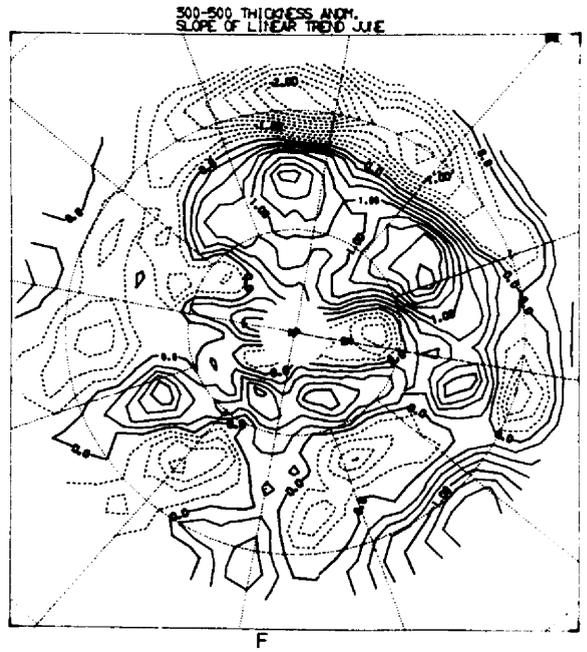
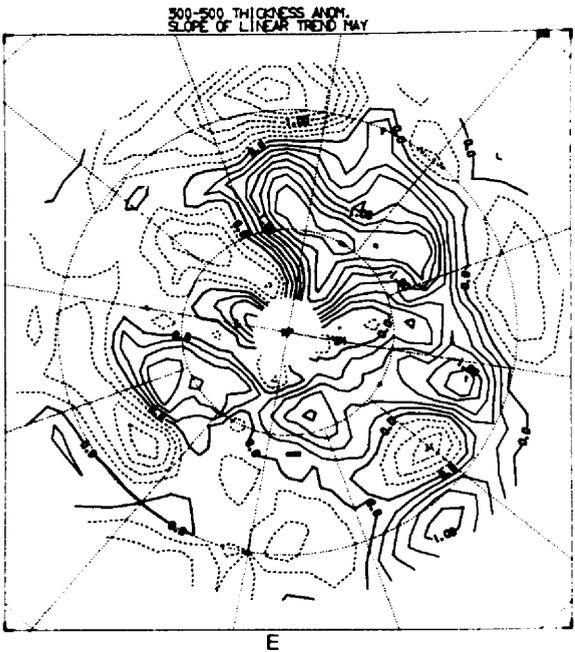
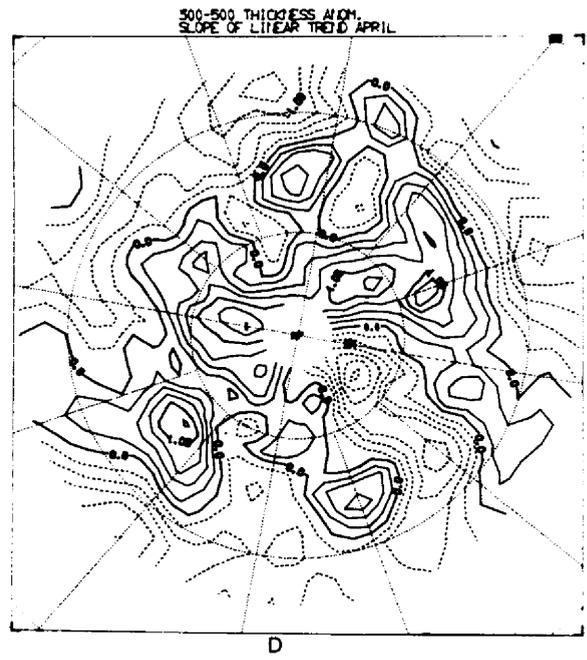
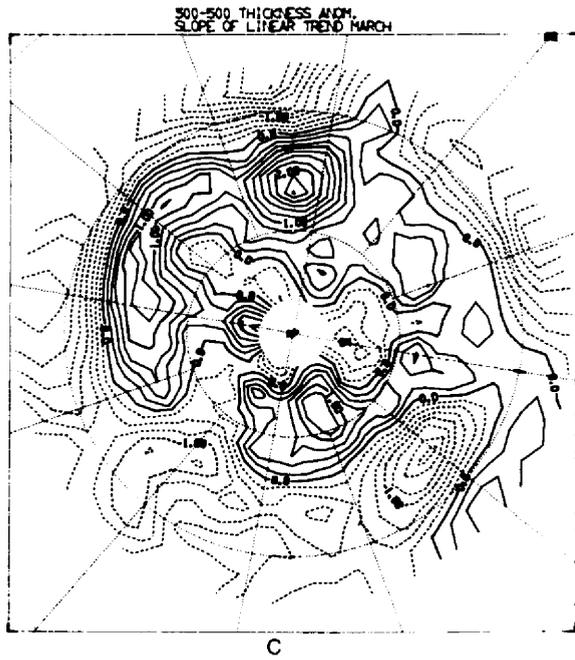


Fig. 4 (Continued)

years could explain these cooling trends and 500-mb height trend patterns. Figure 11 in the paper by van Loon and Williams (1976a), indeed, depicts a decreasing surface pressure trend between 1950 and 1964 in the central North Pacific. The superposition of the region of enhanced cyclogenesis over a region with decreasing sea-surface temperatures, even on a long-term trend basis, agrees with the results obtained by

Namias (1978) involving seasonal ocean-atmosphere coupling, but not with the "negative" feedback of high pressure overlying cold water, described in a more recent paper (Namias, 1980).

Perhaps we can attribute the oceanic cooling and the observed atmospheric trends in the central North Pacific to air-sea interaction feedback processes,

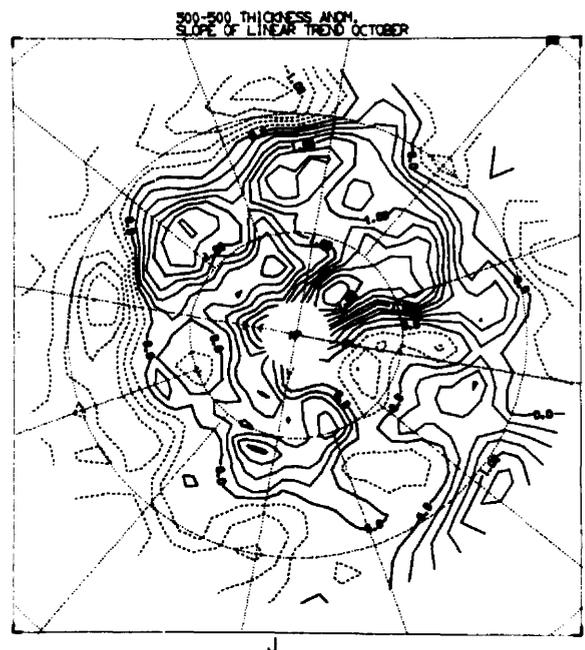
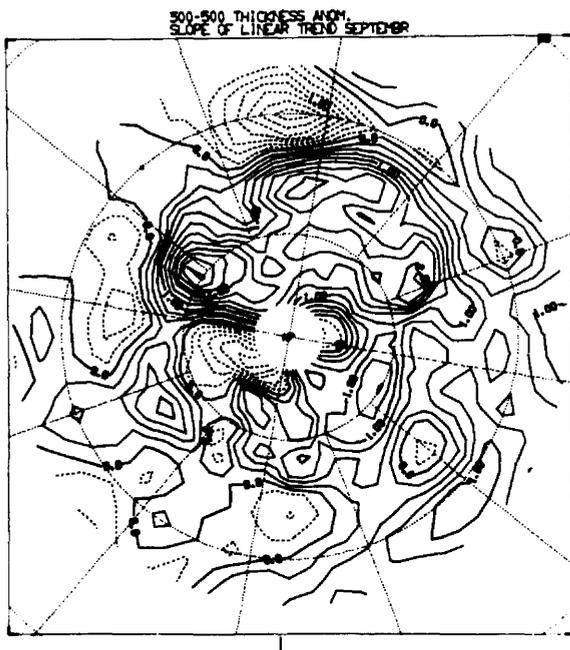
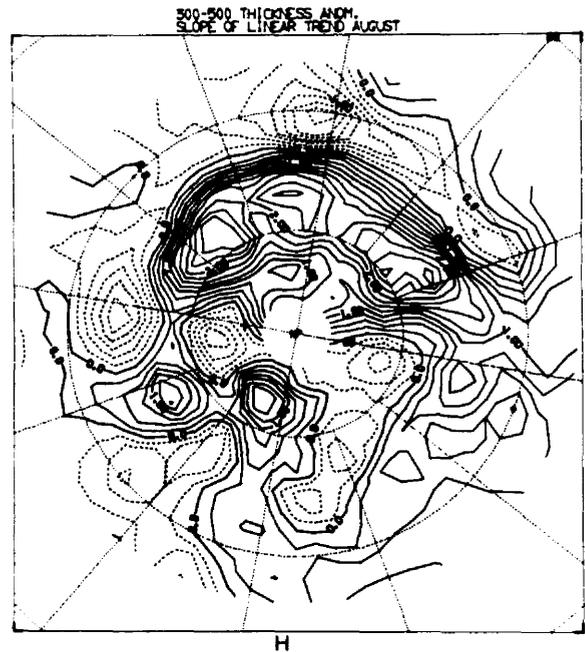


Fig. 4 (Continued)

such as increased oceanic heat loss to the atmosphere and increased cooling by turbulent mixing in the ocean due to increased storminess, and enhanced cyclonic activity due to negative SST anomalies. Such processes have been investigated recently by many authors, using synoptic data as well as numerical models. The crucial questions however, still loom unanswered: What would induce such feedback mechanisms to "take off" and produce the large-amplitude

trend patterns shown in Figs. 2 to 5, and how much farther could these trends proceed? There can be no doubt about the effects of such trend patterns on planetary-wave configurations and regional climate anomalies. The severe winters of 1976/77 and 1977/78 over the eastern United States bear witness to such possible effects.

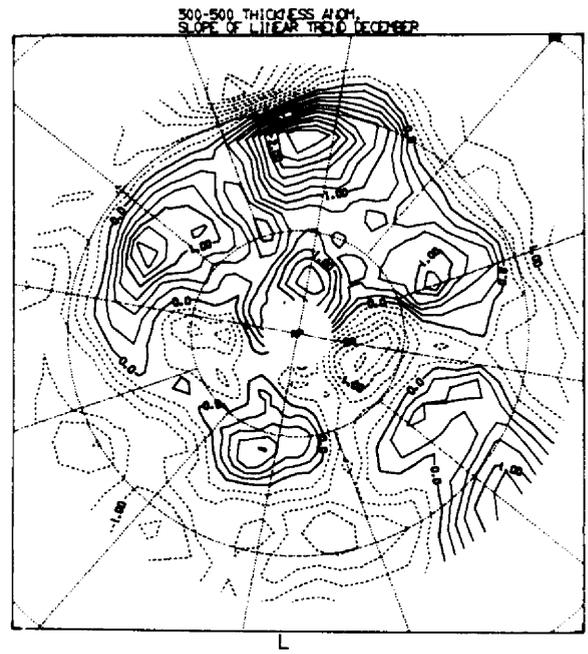
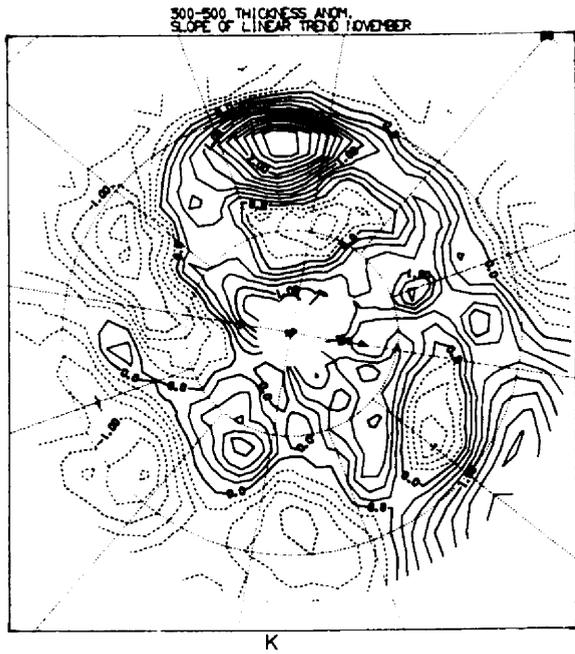


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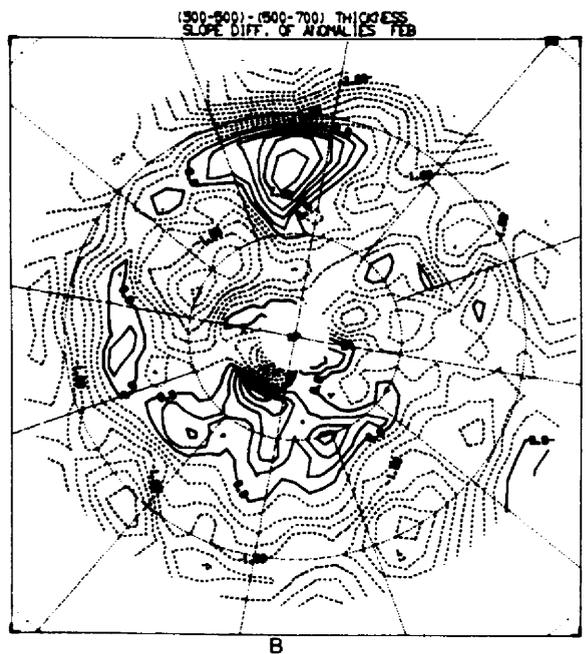


Fig. 5 Differences, by month, between the trends of the 300/500-mb layer and those of the 500/700-mb layer, in gpm/year (analysis interval 0.25 gpm/year). Solid lines: destabilization (i.e. upper layer cooled relative to lower layer); dotted lines: stabilization. Trends are based on data for the period 1951-1978.

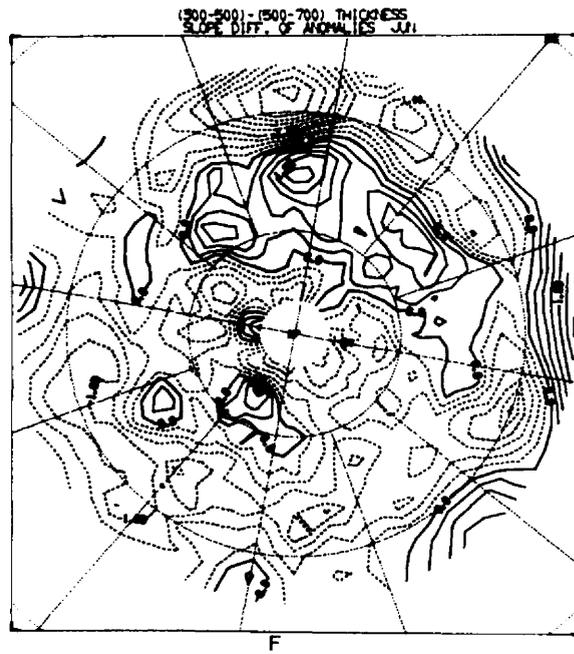
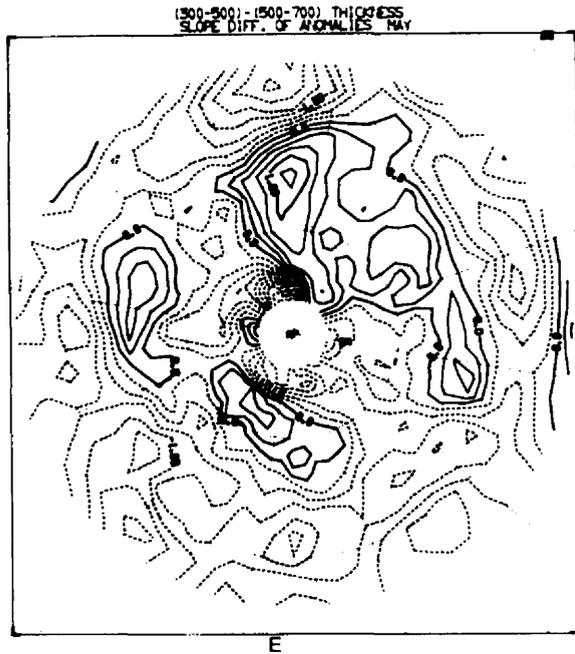
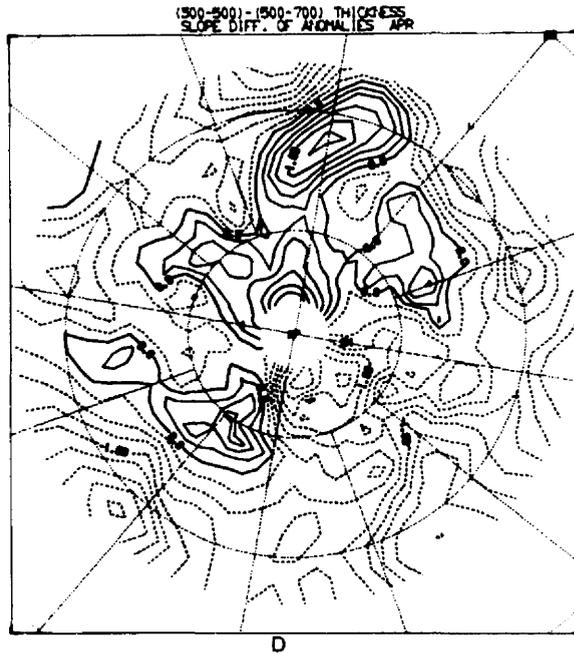
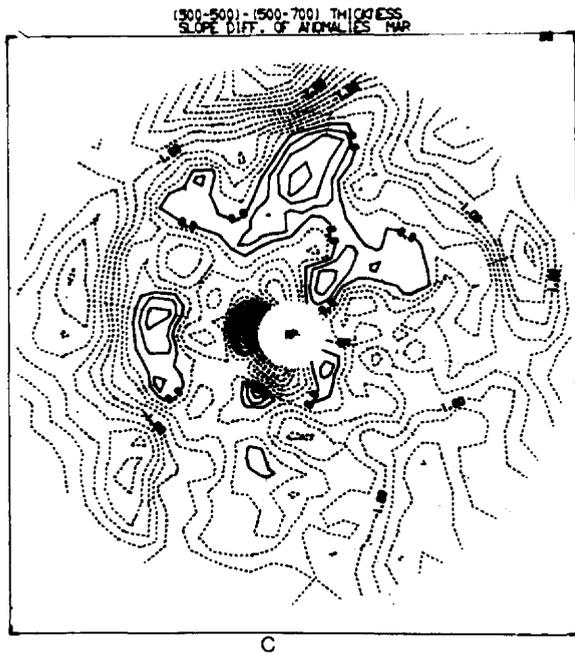


Fig. 5 (Continued)

(4) The cooling and height tendencies described above, by virtue of their overwhelming magnitude, especially during winter, may constitute the key to the trend patterns over the remainder of the hemisphere. The tendency of the formation of a ridge over the Canadian Rocky Mountains and a mid-tropospheric winter warming trend over Alaska may well be a downstream consequence of the North Pacific anomaly development. The trough development at 500 mb over

North America seems to have undergone an enhancement trend that extends into the North Atlantic, especially during January and February. A mid-tropospheric cooling trend is well established for January and February in this region. The continuity between successive monthly trend patterns in Figs. 2, 3 and 4 is severely disrupted in March/April, when slight warming is found over North America in the low troposphere and a cooling region extends from Greenland to

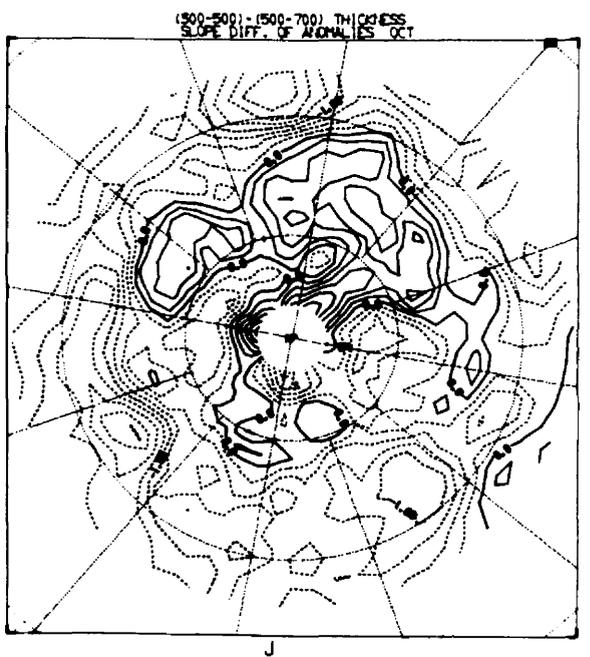
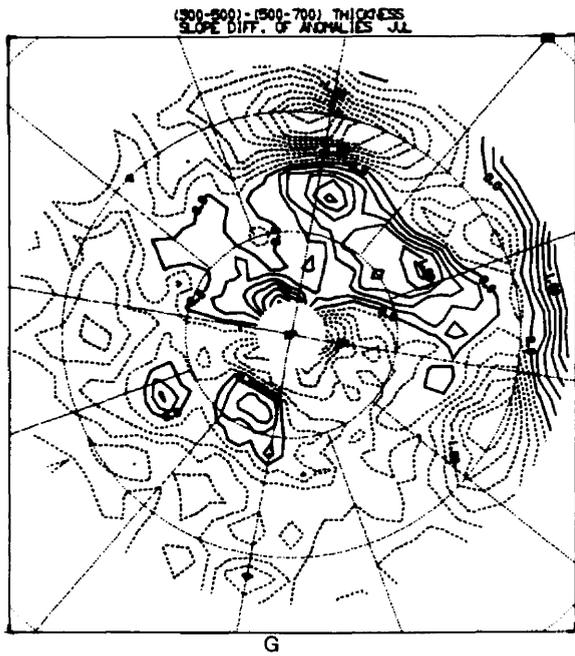


Fig. 5 (Continued)

England. The upper-tropospheric shift in trend patterns also takes place between March and April, and is even more accentuated than in the lower troposphere.

(5) The winter months are characterized by another area of consistent 500-mb height decreases, accompanied by a low-tropospheric cooling trend, over western Siberia and in the region of the Ural Mountains. These cooling trends are even more pronounced in the 300/ 500-mb layer (Fig. 4). A more or

less consistent warming trend area is formed to the west of there. This pattern of warming and cooling tendencies and 500-mb height increases and decreases shifts somewhat to the east in March and maintains a certain degree of consistency throughout summer.

(6) The spring and summer patterns over the Pacific are changed drastically from those of winter. In April the major cooling and 500-mb height decrease zone is displaced northward into the region of

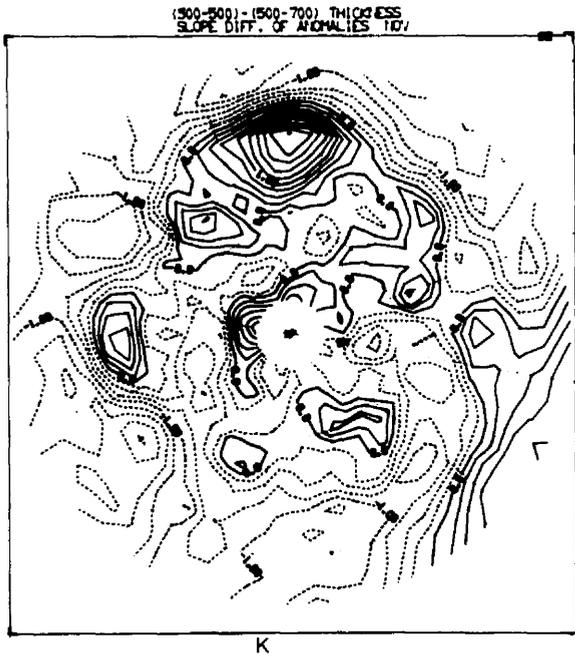


Fig. 5 (Continued)

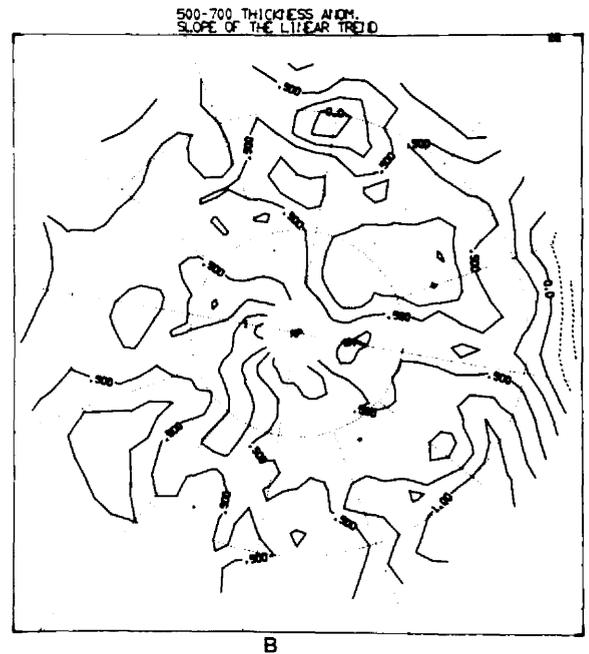
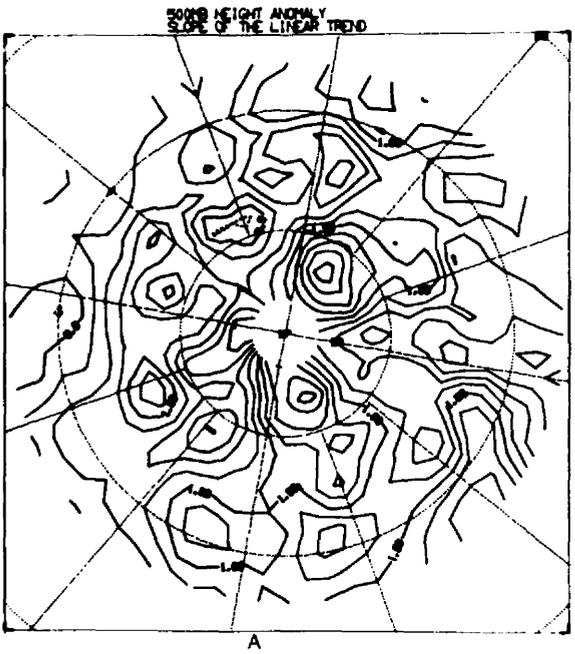


Fig. 6 Average annual trends for the period 1951-1978, in gpm/year (analysis interval 0.25 gpm/year), presented with the same convention for solid and dotted lines as in the previous diagrams. (a) 500-mb height trends; (b) 700/500-mb thickness trends; (c) 300/500-mb thickness trends; (d) 300/500-mb thickness trends minus 500/700-mb thickness trends (i.e. stabilization trends).

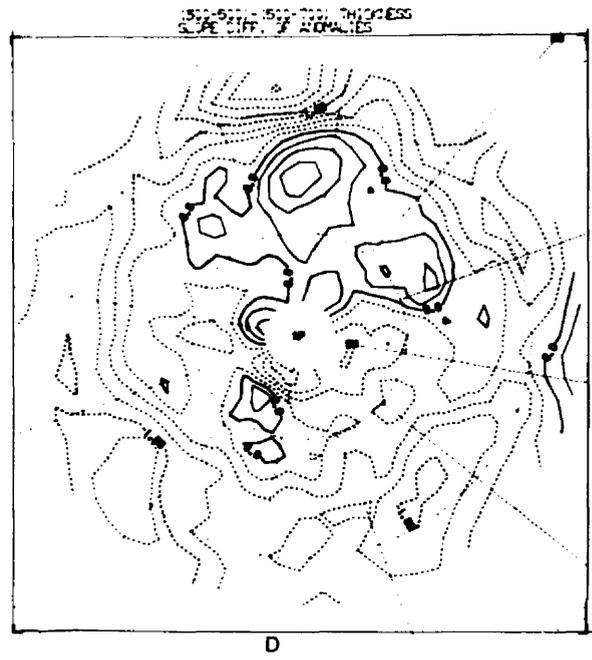


Fig. 6 (Continued)

Kamchatka. An area of height rises with warming trends in the lower and upper troposphere appears over the central North Pacific and remains through June. In July 500-mb height decreases and cooling begin to dominate again the Pacific longitude sector in the lower troposphere but not so much in the 300/500-mb layer where warming trends are significant until November. Especially during autumn, the center of gravity of the 500-mb height trends is shifted towards western Siberia, before the winter pattern, described under (2), is established. In November the Siberian cooling and height decrease areas extend along the East Asian seaboard, forming an arc around the Plateau of Tibet.

The trend patterns described in the foregoing discussion are significant from various points of view. Even a cursory examination of Figs. 2, 3 and 4 reveals the fact that the recent "hemispheric cooling trend" which has been commented on by several authors, impacts significantly on ultralong and long planetary wave configurations. Quite obviously, waves 1, 2 and 3 sustained major effects from the recent climatic trend. The differences in tropospheric temperature and 500-mb height trends between winter and summer also should not come as a surprise, in view of the mean annual cycles which planetary waves undergo (Reiter and Westhoff, 1981). The mean annual trends shown in Fig. 6 will have to be considered as the (rather noisy) residual between seasonal trends which oppose each other over wide regions. The fact that the trend patterns shown in Figs. 2 to 4 are reaching rather high amplitudes in midlatitudes also agrees well with the fact that amplitudes and phase angle stabilities for ultralong planetary waves are highest in midlatitudes (Reiter and Westhoff, 1981): Climatic trends obviously have the greatest impact in regions in which the quasi-stationary planetary waves are best developed.

This apparent agreement between maxima in climatic trends and planetary-wave configurations not

only holds over relatively long time periods, as described in the present report, but also for shorter anomalies with time scales commensurate to a season. Barnett and Preisendorfer (1978) computed eigenvectors of a climate state vector which describe the covariability between different regions of the fields of 700-mb height, 1000/700-mb thickness, sea-surface temperature and rainfall. For winter as well as summer the patterns of the first eigenvector computed by them match excellently the configurations of extremes in the trend patterns shown in Figs. 2 and 3. So do the components of eigenvector 1 of surface temperatures reported by Barnett (1978).

3. CONCLUSIONS

Trend analyses of 500-mb height fields and 500/700-mb and 300/500-mb thickness fields reveal significant climatic changes that have taken place during the past thirty years. These changes had profound effects on the pattern of ultralong and long planetary waves, especially in midlatitudes. A significant seasonal variability of these trends has been described in detail.

In view of the fact that similar patterns are obtained from eigenvector fields describing atmospheric teleconnections that prevail during individual seasons (Barnett and Preisendorfer, 1978) we are led to interpret the regions of extreme trends revealed in this study as those regions which react most sensitively to short- and long-term climate changes. We deem it significant that the most prominent and consistent 500-mb height decreases and tropospheric cooling trends were observed over the North Pacific, where sea-surface temperatures also revealed a marked decline during the past years. We are still at a loss to explain the cause-effect relationship between the atmospheric and oceanic trends in this region, nor can we state unequivocally that these trends were entirely caused by feedbacks within the ocean-atmosphere system without any external forcing.

If we accept the notion that the trend patterns revealed in Figs. 2 to 5 are indicators of sensitivity to climate change, we have to view with alarm the large pattern amplitudes extending from the Ukraine to Kazakhstan, affecting the grain belt of the USSR. Over the United States and Canada the recent climate changes mainly manifest themselves in the cooling trends of January and February, of which some outstanding examples still are fresh in our memories.

Because of the strong impact of the recent climate trend on planetary wave patterns it will be

difficult to ascertain the impact of anthropogenic effects, such as the increase of CO₂ and of aerosol loading of the atmosphere. The notion that hemispheric warming or cooling trends should first reveal themselves in the polar region certainly is too simplistic in view of the planetary-wave interactions with climate changes.

The significance of climate fluctuations superimposed upon the linear trends reported in this paper will be the subject of further investigation.

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