Spatial / Temporal Features of Antarctic Climate Change①

Ge Ling (葛 玲), *Liang Jiaxing* (梁佳兴) and *Chen Yiliang* (陈毅良)
Department of Meteorology, Nanjing Institute of Meteorology, Nanjing 210044

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ABSTRACT

Based on January 1962–October 1993 mean value series of monthly mean temperature anomalies of 16 Antarctic stations on 10 standard isobaric surfaces from the surface to the 30 hPa, long term trends and periodic features of climate changes from the troposphere to the lower stratosphere over the Antarctic region are investigated by maximum entropy power spectrum analysis, and the relation between climate change of the stratosphere (troposphere) and total ozone (southern 500 hPa circulation) is discussed.

Key words: Antarctic; Climate change; Long term trend; Periodicity; Total ozone

Antarctic snow / ice cover is an important cold source for global atmospheric motion while the radiative heating of ozone in the polar atmosphere is an important heat source for the stratospheric motion. Climate change in this area must leave a distinct trace of the upper– and low–level heat forcing anomaly. So the study of the spatial / temporal features and the possible causes of the Antarctic climate change will be of help to deepening exploration of climate on a global basis.

I. DATA AND CALCULATION SCHEME

From January 1962–October 1993 monthly mean temperatures from 16 stations (the record length may differ) in the Antarctic region (see Fig. 1) at 10 standard levels ranging from ground to 30 hPa (Dept. of Commerce, U.S.A. 1962.1–1993.10), we get as basic datasets 10 mean value series $T''_j(p)$ of monthly temperature anomalies over the 16 stations for the 10 levels, where $j = 1,2,\cdots,382$ and $p =$ ground level, 850, 700, 500, 300, 200, 150, 100, 50 and 30 hPa.

The total ozone data (Environment of Canada, 1962–1993) come from Antarctic Amundsen–Scott (89.59°S, 24.48°W), Halley Bay (75.31°S, 26.44°W), Syowa (69.00°S, 39.35°W), and Faraday (65.15°S, 64.16°W) are similarly dealt with and considered in this work as well.

Calculation is based on maximum entropy power spectrum (MEPS) of Burg (1967) that satisfies the relation

$$S(T) = \sigma_m^2 \Delta t \Big/ \left| 1 - \sum_{j=1}^{m} b_{m,j} e^{-ij2\pi\Delta t / T} \right|^2 , \tag{1}$$

where Δt ($=1$ month) denotes the time interval of the discrete sequences, $i = \sqrt{-1}$, T is the

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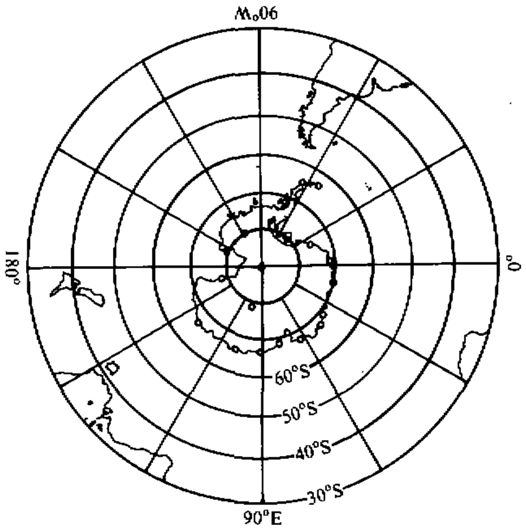

Fig. 1. Distribution of the Antarctic stations considered.

period of a spectral wave component, and $b_{m,j}$ the m–order autoregression coefficient with m denoting the ending order. We give

$$\sigma_m^2 = R(0) - \sum_{j=1}^{m} b_{m,j} R(j) \tag{2}$$

as the variance of forecast error, where $R(j)$ represents the autocorrelation function of time lag j.

To eliminate the linear trend of the series as time goes on, differencing is made of $T_j''(p)$

$$T_j' = T_j'' - a\left(j - \frac{N+1}{2}\right), \qquad N = 382, \tag{3}$$

where

$$a = \sum_{j=1}^{N} T_j'' \left(j - \frac{N+1}{2}\right) \Big/ \sum_{j=1}^{N} \left(j - \frac{N+1}{2}\right)^2 \tag{4}$$

denoting the temporal mean variation of the series per unit time.

In processing the series by the MEPS term, a remarkable linear trend should be removed, or otherwise the linear trend will not be considered. Then,

$$R(j) = \frac{1}{N-j} \sum_{p=1}^{N-j} T_p' T_{p+j}' \qquad (j = 1,2,\cdots,m) \ . \tag{5}$$

The calculation of $b_{m,j}$ follows a recursive algorithm for filtering coefficient of prediction error, $b_{m,j}$ (Burg, 1968) of the form

$$\left\{\begin{aligned}
&b_{1,1}=2\sum_{p=1}^{N-1}T'_pT'_{p+1}\Big/\sum_{p=1}^{N-1}(T'^2_p+T'^2_{p+1}),\\
&b_{K+1,K+1}=\frac{2\sum\limits_{p=1}^{N-K-1}\left[(T'_p-\sum\limits_{j=1}^{K}b_{K,j}T'_{p+j})(T'_{p+K+1}-\sum\limits_{j=1}^{K}b_{K,j}T'_{p+K+1-j})\right]}{\sum\limits_{p=1}^{N-K-1}\left[(T'_p-\sum\limits_{j=1}^{K}b_{K,j}T'_{p+j})^2+(T'_{p+K+1}-\sum\limits_{j=1}^{K}b_{K,j}T'_{p+K+1-j})^2\right]},\\
&b_{K+1,j}=b_{K,j}-b_{K+1,K+1}b_{K,K+1-j},\quad (j=1,2,\cdots,K),\quad 1\leqslant K<N-1.
\end{aligned}\right. \tag{6}$$

From the MEPS scheme composed of (1), (2), (5) and (6), we derived a generally–accepted power spectrum estimate, high in resolution and excellent in adaptation to the series.

The authors employed the final prediction error (FPE) criterion proposed by Akaike (1968) to specify the ending order of autoregression, viz.,

$$(FPE)_K=\left[\left(1+\frac{K}{N}\right)\Big/\left(1-\frac{K}{N}\right)\right]\sigma_K^2\ , \tag{7}$$

the ending order is given by the K corresponding to the minimum of FPE when K is about N / 5.

Finally, significance test is performed of the MEPS analysis by means of red or white noise power spectrum, when the autoregression correlation function $R(1)>0.20$, the red noise spectrum estimate is employed for the test, in which mean $\bar{S}$ of the series power spectrum is found first and then calculation is made for the upper limit of confidence for red noise estimate, i.e.,

$$S^*_{\sigma T}=\bar{S}\left[\frac{1-R(1)^2}{1+R(1)^2-2R(1)\cos\left(\frac{2\pi}{T}\right)}\right]^2\lambda\ , \tag{8}$$

where λ is a pertinent positive number, and generally $\lambda=1.88$ and the confidence limit is set to be 95%.

For a series with $R(1)<0.20$, the test is based on white noise spectrum estimate, which is evaluated to be 1, thus leading to the upper limit of confidence in the form

$$S^*_{\sigma T}=\bar{S}\lambda\ , \tag{9}$$

For a MEPS's peak value $S(T)>S^*_{\sigma T}$, an oscillation of period T is available in the sequence.

II. SPATIAL / TEMPORAL FEATURES OF ANTARCTIC CLIMATE CHANGE

1. *Long–term Trend*

Analysis of the linear trend term in Table 1 shows that the significant long–term change versus time exists in temperature up to 30 hPa and that the altitude–dependent variability follows a pattern for tropospheric warming and stratospheric cooling, with the warming of 0.21°C / decade at 700–hPa level, below and above which the rate is decreased, compared to the surface warming of 0.10°C / decade only. It follows that the maximum Antarctic warming occurs at 700 hPa rather than at ground level; the cooling rate attains –0.68°C / dec. at 100 hPa, below and above which the rate is reduced in the stratosphere; 300–hPa is around the tropopause where temperature has not experienced a marked long–term–trend changing.

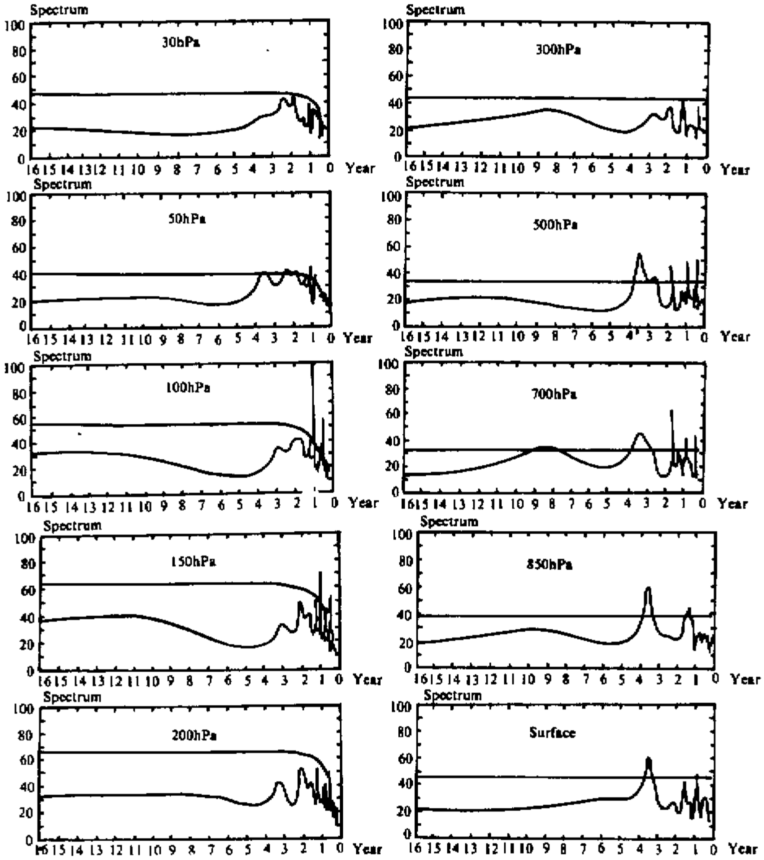

Fig. 2. Diagram of MEPS for Antarctic temperarture variation.

It should be noted that in this study period, the 100–hPa cooling is a lot greater than the 700–hPa warming in the Antarctic; the temperature lapse rate tends to be increasing; atmospheric stability is becoming smaller and smaller there.

Table 1. Long–Term Change in Antarctic Temperature

hPa	30	50	100	150	200	300	500	700	850	surface
linear trend term (°C / decade)	−0.17	−0.42	−0.68	−0.46	−0.25	0.01	0.19	0.21	0.19	0.10

2. *Period of the Change*

In the light of $R(1)$ values for all the levels of Table 2, power spectrum significance test is done using red (white) noise spectrum estimate for the stratospheric levels (tropopause and the levels below). MEPS for Antarctic temperature change is presented in Fig. 2. Illustrated in Table 3 are the intensities of significant–period entropy spectra for all the levels, with the related monthly significant period lengths shown in order.

Table 2. Antarctic Temperature Autocorrelation Function $R(1)$

hPa	30	50	100	150	200	300	500	700	850	surface
$R(1)$	0.26	0.27	0.45	0.41	0.34	0.15	0.11	0.17	0.16	0.16

Table 3. Significant–Period Lengths of Antarctic Temperature Variation Units: Month and $\alpha = 0.05$

hPa	serial number 1	2	3	4	5	6	7
	period length						
30	22	29					
50	13	27	21	9	16	5	3
100	12	6	8	4			
150	12	6	8	4			
200	8	6	4				
300							
500	42	5	11	21	32		
700	20	41	5	11	100	15	
850	42	16	19				
surface	41	11					

Connection of Fig. 2 and Table 3 indicates that

1) the 30–and 50–hPa temperature change is marked by pronounced quasi–biennial period; the 50–hPa and levels below it dominate a range of periods shorter than an annual scale; the 50–, 100– and 150–hPa levels characterized by remarkable annual period and the 100–hPa peak is the strongest of all the peaks shown in all the levels and periodic changes of all the time scales; 6–, 8– and 4–month periods are found for the 100, 150 and 200 hPa, respectively.

2) temperature variation of the 500 hPa and levels below it dominates very low frequency periods of different time scales; a significant 3.5–year oscillation is observed in all the levels; the ground level and 850 hPa appear relatively stronger; a pronounced period of 19–21 months is seen at 500, 700 and 850 hPa; the 700–hPa level shows a noteworthy period of 8–9 years. In addition, the 500 and 700 hPa also shows distinct periods of 11 and 5 months.

3) the 300 hPa around the tropopause displays no significant period for the temperature change.

III. RELATION OF STRATOSPHERIC CLIMATE CHANGE TO OZONE LAYER OVER ANTARCTIC ZONE

The computation of long term trend of Antarctic ozone variation at Amundsen–Scott, Halley Bay, Soywa and Faraday station indicates that the Antarctic total ozone is decreasing at a rate of 5% per decade in the last 30 years, with a remarkable reduction in the past 15

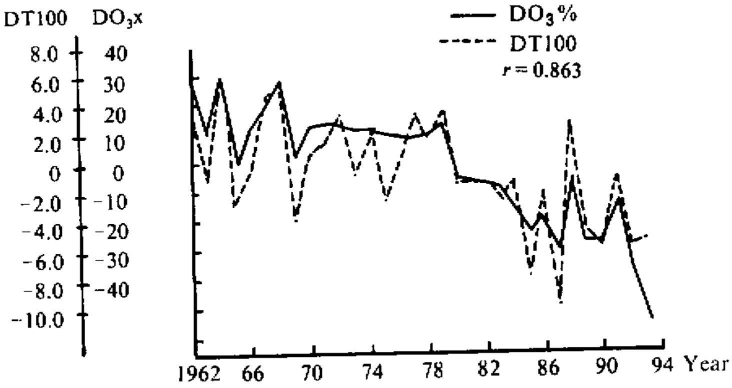

Fig. 3. Antarctic October–November ozone percentage departure ($DO_3\%$) and 100–hPa temperature departure curve (DT 100).

springs (September, October, and November). Fig. 3 depicts the total ozone percentage departures and 100 hPa temperature anomaly curve based on October and November data from the above four stations, which display surprising agreement with each other, with a correlation coefficient of 0.863. The 100 hPa is the layer among 10 standard isobaric surfaces where temperature is most significantly correlated with total ozone in that season.

The MEPS analysis of Antarctic total ozone shows that significant period lengths with a confidence of 0.05 are successively 6, 12, 4, 20, 28, 9 and 15 months (Table 4), where in each of the first three has a stronger spectrum peak. It is known from contrast with Table 3 that the significant periods of total ozone variation are basically consistent with those of temperature variation at the 50, 100, and 150 hPa.

Table 4. Significant–Period Lengths of Antarctic Total Ozone Variation Units: Month and $\alpha = 0.05$

serial number	1	2	3	4	5	6	7
period length	6	12	4	20	28	9	15

Because the maximum partial pressure of ozone is near 70 hPa, it is inferred that the substantial cooling trend around the 100 hPa and the remarkable spectrum peak of annual period are associated with the considerable decrease in ozone total for the last 15 years and the steadiest annual course of ozone radiation heating in the neighborhood of the polar maximum ozone layer, which are the results of interaction among radiation, dynamic and photochemical processes in the Antarctic atmosphere. As to which one dominates in interaction between temperature and ozone is seemingly related with the season and time scale of processes. Taking the relation between June, July, August and September Antarctic total ozone (100 hPa temperature) and October to November Antarctic 100 hPa temperature (total ozone) as example, it is found from statistical analysis that the correlation coefficient between September total ozone and October to November 100 hPa temperature is as 0.588($\alpha = 0.001$), however the correlation coefficient between September 100 hPa temperature and October to November total ozone is only 0.369 ($\alpha = 0.05$) (see Table 5), indicating that the influence of

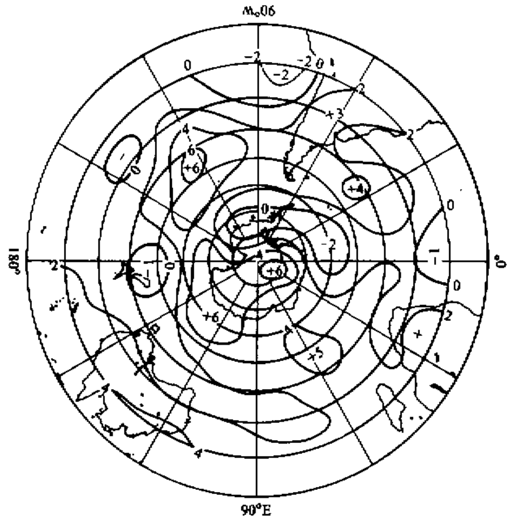

Fig. 4. Differences of Southern Hemispheric 500 hPa mean height fields [H(1986.5–1993.4)–H(1972.5–1979.4)]

the early spring September total ozone on the warm (cool) of October to November 100 hPa temperature is more important.

Table 5. Correlation Coefficients between Antarctic Winter–Early Spring Monthly Total Ozone (100 hPa Temperature) and October to November 100 hPa Temperature (Total Ozone)

Month		June	July	Aug.	Sept.
Oct. to Now	$\bar{T}$100 hPa	−0.069	0.181	0.291	0.588
	O_3	−0.116	0.003	0.171	0.369

IV. CONNECTION BETWEEN THE WARMING ANTARCTIC TROPOSPHERIC CLIMATE AND THE SOUTHERN HEMISPHERIC 500 HPA CIRCULATION CHANGE

It has been pointed out in the second section that the Antarctic tropospheric climate shows a warming trend. Fig. 4 presents the difference field between 7–year means of 500 hPa geopotential height from may 1986 to April 1993 and those from May 1972 to April 1979, in order to investigate the statistical features of circulation evolution in the warming process of Antarctic tropospheric climate. It is seen from Fig. 4 that there is a positive allohypsic center of +6 dagpms over the Antarctic area, and there are four positive allohypsic areas of +4 to +6 dagpms over the three oceans along the latitude belt of 40°–60°S. The polar vortex centered at 80°S, 180°–170°W and circumpolar flow show a weakening trend. The weakness of the Southern Hemispheric tropospheric polar circulation can be considered as the direct cause for the warming of the Antarctic tropospheric climate.

V. DISCUSSION AND CONCLUSIONS

1. The Antarctic climate has a substantial long–range trend and periodic variations, i.e.,

there are significant lower stratospheric cooling (the maximum cooling at 100 hPa) and tropospheric warming (the maximum warming at 700 hPa), with lower atmospheric vertical stability tends to be weakened; strong quasi–biennial (very low frequency) period is observed at 30–50 hPa; the lower stratosphere (around 100 hPa) climate change shows the most noticeable annual period in the polar region and other periods of shorter time scales; a dramatic 3.5–year period and other very low frequency periods are found in all the levels in the troposphere; 11 and 5 month periods remarkably appear at the 700 and 500 hPa; climate is steady in the vicinity of the Antarctic tropopause with no appreciable trend nor periodic variation observed.

2. The 100–hPa substantial cooling and the sharp peak on the annual–period curve are related to the dramatic reduction of total ozone in the past 15 years and also to the steady yearly course of the radiative heating in the vicinity of the maximum ozone layer. The remarkable warming around 700 hPa is associated with the weakening of middle tropospheric polar lows and circumpolar flows.

REFERENCES

Burg J. P. (1967), Maximum entropy spectral analysis, Paper presented at 37–th Annual International Meeting, Soc. of Explor, Geophys., Oklahama City.

Burg J. P. (1968), A new analysis technique for time series data, Paper presented at Advanced Study Institute on Signal Processing, NATO, Euschede, Netherlands.

Department of Commerce, United States of America, Monthly Climatic Data for the World, 15(1)–46(10): 1962.1–1993.10, Published by NCDC, NESDIS, NOAA.

Environment of Canada, AES Ozone Data for the World, 1962– 1993, Published by the AES, Department of the Environment, in Co–operation with the WMO.