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DIFFERENCES OF INTERDECADAL OSCILLATION BETWEEN MEAN TEMPERATURE OF NORTHERN AND SOUTHERN HEMISPHERE AND THEIR INFLUENCES ON WARMING SIGNAL

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ABSTRACT: On the basis of multi-taper spectral analysis, the work not only has examined and reformed monthly mean temperature time series of the Northern Hemisphere (NH) and Southern Hemisphere (SH) from 1856 to 1998, but also has systematically contrasted the differences of interdecadal oscillation (IDO) between the hemispheres, ocean-land surface in different seasons, with special analysis of IDO signals effects on global warming. The results show that the warming trend plays a dominant role in hemispheric mean temperature variability during the last 150 years. However, there are significant IDO with periods of about 40, 60 – 70 years superimposed on a linear warming trend for NH mean temperature which leads to the reduction of the linear warming rate in terms of its significance and stability, as opposed to that in the SH, especially in summer. Moreover, in comparison of land to sea surface temperature, IDO signals detected in the latter are found to be more remarkable than those in the former, as contrasted to the linear warming rate. It has been noticed that IDO shows its peak value in the middle 1990s and begins to descend recently, a fact that probably affects the coming warming rate of NH mean temperature. Meanwhile, In terms of the GCM results from the HadCM2 model, preliminary analysis implies that the IDO may be the inherent oscillation of the ocean and atmosphere system, but warming trends are not related to natural variability.

Key words: interdecadal oscillation; multi-taper spectral analysis; significance of warming

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1 INTRODUCTION

The interdecadal oscillation (IDO) has received much attention across the world climate community. As some studies show, the interdecadal time scale is an important bridge that connects with two other scales. Being background for the interannual scale, it plays an important role in interannual climate variability (such as ENSO)[1-3] on the one hand and may act as an essential perturbation for IDOs on the other. With the CLIVAR program, which started in mid-1990's, involving itself to the research of interdecadal variability, concerted efforts are being greatly pushed forward in the international arena.

As what two IPCC reports point out, the global mean temperature has risen by 0.3°C – 0.6°C since the end of the 19th century; the warming trend fluctuates, obviously rising from the 1920's to 1930's but obviously falling from the mid-1940's to mid-1970's; warming has been the main trend over the past 20 years, more significantly in the NH. It is well-known that the period from the 1940's to 1970's was one of reconstruction and development after World War II, during

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which atmospheric CO_2 increased in concentration, much more significantly in THE NH where major industries were blooming, though mean temperature was remarkably falling. It obviously goes against the theory that the enhancement of greenhouse effect would intensify the warming[3]. Recently, Ghi and Vautard[4] and and Elsner and Tsonis et al. [5] put forward that it is related to the IDO with periods of about 20 years and point out that they are the most pronounced interdecadal variabilities besides the persistent climatic trend. With the Singular Spectral Analysis (SSA), Schlesinger and Ramankntty[2] study four versions of global mean temperature and discover significant 65 – 70 yr periodic oscillation signals in residual series from which temperature trends brought about by radiative forcing changes. Lau et al. [6] isolate low-frequency variation signals with the scales of 40 – 60 yr and 180 yr in their wavelet analysis of global temperature series. With a 500-yr temperature series reconstructed with alternative data used for SVD analysis of frequency domain, Mann et al.[7] find that there are low-frequency variation signals at 15a –35a and 50a – 150a. Further study by Schlesinger et al.[2] shows that the 65 – 70 – yr oscillation of temperature may be associated with air-sea interactions. It is obvious that opinions are divided over dominant oscillatory scales from interdecadal to centennial lengths as far as mean global or hemispheric temperature is concerned. Specially, is there any imbalance between the NH and SH, seasons and land and ocean? And how would it affect the significance of global warming? More study is worth the try.

As the instrument-based series is only a little over 100 years long for surface temperature of the globally-averaged scale, we must establish and analyze all kinds of proxy data on the one hand and employ advanced signal detection techniques that help recognize weak signals in relatively short series and against high noise background. In this work, the Multi-taper Method (MTM) is used to detect and reconstruct various signals for monthly mean temperature series, which was compiled by Jones et al. [8] for the SH and NH from 1856 to 1998, with the focus on low-frequency signals varying from interdecadal to centennial scales; the IDO signals are comprehensively studied for differences between the hemispheres, land and sea surface and seasons, and their effect on global warming is probed. In the meantime, the HadCM2 numerical simulations by the Hadley Center[9] is directly used to cast preliminary investigation into possible causes for IDO, based on comparisons between simulations and observational, diagnostic study.

2 METHODS

2.1 *Detection and reconstruction of quasi-periodic signals using MTM*

The Multi-taper Method was designed by Thomson[10] and Park[11] for spectral estimation and signal reconstruction. It pens a new way for seeking balance between the resolution and stability of spectra by combining optimum window functions and multi-taper smoothing to estimate spectra that have low variance and high resolution. At the same time, time domain retrieval through multi-taper decomposition signals can help reconstruct all kinds of significant signals, together with their time-dependent phases and amplitudes. It is therefore suitable for diagnostic analysis of weak, time-dependent signals with short series and high noise in non-linear climatic systems. Basic principles and detailed algorithms have been given in [12] for the MTM and only brief account will be presented here in the work.

Setting $\{X_t\}, t = 0,1,2,\cdots\cdots, N-1$ is the sample series of the random process $\{X_t\}$, we can have a cluster of digital tiper function, $\left(w_t^{(k)}\right)\left(k = 0,1,\cdots\cdots, N-1; t = 0,1,\cdots\cdots, N-1\right)$, usually known as the eigen-function cluster, from the minimization issue of Rayleigh-Ritz, based on the principle that there is minimum spectral leakage out of the half-bandwidth pf_n (p is an integral and $f_n - 1/N\Delta t$ is the Rayleigh frequency). For every time series consisting of $\left(w_t^{(k)}\right)$, the discrete Fourier transformation (DFT) is run to determine that

$$y_k(f)=\sum_{t=0}^{N-1} w_t^{(k)} x_t e^{i2\pi ft} \tag{1}$$

where $|y_k(f)|^2$ is the kth estimated spectrum. With an integration equation for spectral estimation, a high-resolution, multi-taper spectral estimate $S(f)$ can then be determined by weighted averaging of the eigen-function so obtained

$$S(f)=\frac{\sum_{k=0}^{K-1} b_k^2(f)\,\lambda_k |y_k(f)|^2}{\sum_{k=0}^{K-1} b_k^2(f)\,\lambda_k} \tag{2}$$

in which $1>\lambda_0>\lambda_1>\lambda_2>\cdots>\lambda_{N-1}>0$ is the characteristic value for the cluster of characteristic tiper function and the weighted coefficient $b(f)$ can be obtained with the method of iteration via the minimizing of fitting between the real and estimated spectra.

As there are mid- and long- term tendencies in the temperature series, quasi-periodic signals are detected with the assumption of strong red-noise background put forward by Mann et al.[7], which is used to estimate the MTM spectra.

For every significant oscillatory signal picked up in the MTM estimate, reconstruction can be done by through the time domain retrieval of the multi-taper decomposed information, envelopes being significantly slowly varying. Park et al. have given a series of related study [11]. Refer to [12] for detailed derivation.

2.2 *Significance contrast of signals between domains of MTM*

For more study of the percentage of IDO and interannual variability (high-frequency signals) in temperature variability, we study the effect on the warming trend. Interdecadal components are from 7 to 19 years, interannual ones are from 2.0 to 6.9 years, IDO ones are from 20 years to centennial scale and those above centennial scale are background tendency. The percentages contributed by these components of MTM spectral power are then derived accordingly.

To separate the effect of long-term trends on the IDO, spectral contribution percentages by individual components are derived with the following schemes, in view of the fact that spectral curves from which background periodic trends less than 20 years are removed agree well with those of the original series (Fig.1).

Setting that $S(f)$ is the MTM spectra of the original series and $S'(f)$ is the MTM spectra from which background trends have been removed

$$D_y=\int_0^{\infty} S(f)\,\mathrm{d}f \tag{3}$$

$$D_{y'}=\int_0^{\infty} S'(f)\,\mathrm{d}f \tag{4}$$

then the spectral contribution percentages by background trends will be

$$\mathrm{Var}\,D_1=\frac{D_y-D_{y'}}{D_y} \tag{5}$$

For the IDO component, VarD_2 [$f\in(0,0.05)$], interannual component VarD_3[$f\in(0.05,0.143)$] and interannual variability VarD_3[$f\in(0.143,0.5)$], the spectral contribution percentages are respectively

$$\mathrm{Var}\,D_2=\frac{\int_0^{0.05} S'(f)\,\mathrm{d}f}{D_y} \tag{6}$$

$$\mathrm{Var}\,D_3 = \frac{\int_{0.05}^{0.143} S'(f)\,\mathrm{d}f}{D_y} \tag{7}$$

$$\mathrm{Var}\,D_4 = \frac{\int_{0.143}^{0.5} S'(f)\,\mathrm{d}f}{D_y} \tag{8}$$

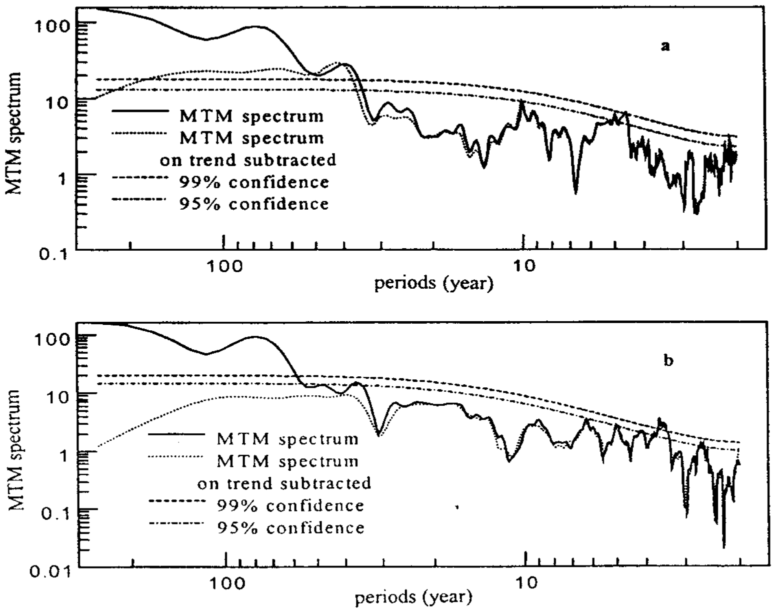

Fig.1 MTM spectral analysis of annual mean surface temperature series (1856 – 1998) for the NH (a) and SH (b). The solid line stands for the spectral estimates of the original series, the dotted line for those from which background trends are removed and the dotted / dashed line and dashed line for fitting spectra of strong red-noise with confidence level of 95% and 99%, respectively.

2.3 *Linear trends and its significance and stability*

Assuming that the annual series of meteorological variables is $\{y_t\}$, t=1, 2, ……, n, then the estimated value of its linear tendency b subjecting to least square estimator will be

$$\hat{b} = \frac{\sum_{t=1}^{n}(t-\bar{t})(y_t-\bar{y})}{\sum_{t=1}^{n}(t-\bar{t})^2} \tag{9}$$

in which $\bar{t}=(n+1)/2$. To study the significance of the estimated linear tendency, we need to verify that of climate tendency coefficient. It is defined to be about the correlation between meteorological variables series and time-dependent variable t = 1, 2, ……, n.

Following the regression theory, the stability of linear variability estimates are found to be mainly associated with residual variance; the smaller the residual variance, the larger the regression and the more steady the estimated linear variability will be.

3 LOW-FREQUENCY MEAN HEMISPHERIC TEMP. & EFFECT ON WARMING SIGNIFICANCE

3.1 *Comparison of hemispheric annual mean temp. variation for quasi-periodic characteristics*

With MTM method introduced in 2.1, a MTM spectral analysis is conducted of the 1856 – 1998 annual mean temperature anomaly for the SH and NH with a red-noise background the 1856 – 1998 annual mean temperature anomaly for the Southern and NHs. Fig.1 (a & b) are estimated MTM spectra of annual mean surface temperature anomalies and corresponding critical values of the strong red-noise for both hemispheres. For the figure, we know that the series vary significantly on scales above the IDO (f < 0.02, period > 20 years). As there are long-term tendencies in the original series, the background is eliminated, i.e. MTM reconstruction is performed for the f = 0 signal, which is basically warming (Fig.2 & 3) and called background tendency; the residual series with background series removed is then applied with MTM spectral analysis, from which a corresponding spectral curve is shown as the dotted and dashed line in Fig.1. It is seen that IDOs with periods of 40 years and 60 – 70 years with a confidence level of 99% are found in the temperature series for the NH while they are not significant in the SH. In addition, with a spectral section where f > 0.02 and a confidence level of 95%, there are significant periodic signals on the 10-yr, 4.6 – 5 – yr, and 2.1 – 2.2 – yr scales for the boreal temperature and on the 6.2-yr, 4.2 – 4.9 – yr, 3.4 – 3.6 – yr and 2.0 yr scales for the austral temperature. It is then clear that with background warming in both hemispheres, low-frequency oscillations are significant at the periods of 40 – 70 yrs and 9 – 11 yrs in the NH while they are significant at periods shorter than five years.

Tab.1 gives the significant signals detected by the MTM spectrum and accumulative power contribution (%) over all sections of frequency. It shows that the background tendency usually takes up about 50% of the total power in either of the hemispheres; the IDO contributes more in power than the interannual variability does; the NH is higher in the IDO power contribution but lower in background tendency power contribution than the SH; the IDO is the biggest perturbation in which low-frequency variation is superimposed on the boreal warming trend while the interannual variability has the relatively large effect in the SH.

Tab.1 Significant signals of annual mean temperature determined by MTM spectral analysis and accumulated power contributions over sections of frequency (%)

		Low-frequency variation				
		Background trends	IDO	Decadal variability	Accum. power	Interannual variability
NH	Significant period* / year	/ (rising)	68.3 42.7	10.0		4.6～5.0 2.1～2.2
NH	MTM spectral power/ %	45.8	21.2	11.0	78.0	22.0
SH	Significant period* / year	/ (rising)	/	/		6.2 4.2～4.9 3.4～3.6 2.0
SH	MTM spectral power / %	63.1	11.5	9.6	84.3	15.7

* The significant IDO periods are for their spectral peaks.

3.2 *Interdecadal oscillation and its warming significance*

Using the MTM-based signal reconstruction technique developed by Park et al. [11], we have reconstructed the low-frequency significant signals in the annual mean temperature series in the two hemispheres. Fig.2 and 3 give their time-dependent characteristics.

From the figures, we know that warming is the basic trend of the background in both

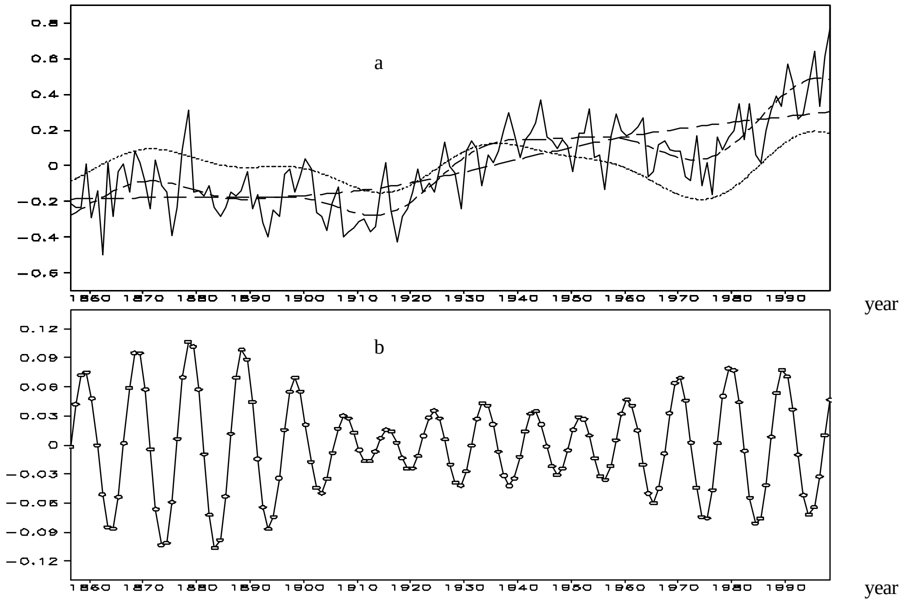

Fig.2 Reconstructed series of low-frequency significant signals of annual mean temperature in the NH. a. The solid line stands for the observed series, the dashed line for the background, the dotted line for the IDO in the 1940's – 1970's and the dotted and dashed line a series superimposed with the two; b. Decadal oscillation signals.

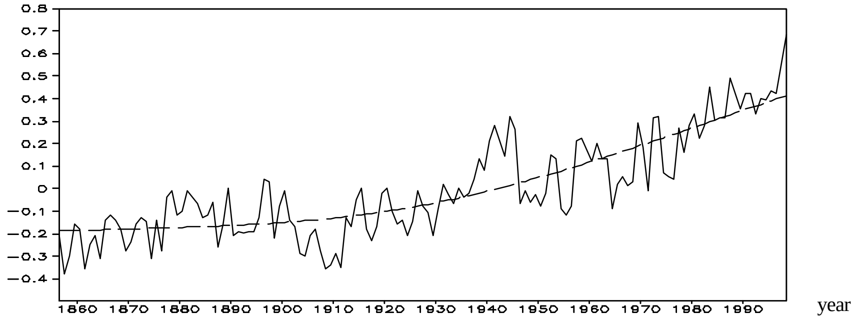

Fig.3 Reconstructed series of low-frequency significant signals of annual mean temperature in the SH. The solid line stands for the observed series and the dashed line for the background trend.

hemispheres, amplitude being larger over the SH and the boreal warming trend being superimposed with significant 40-yr and 60 – 70 – yr IDOs. From the temporal evolution of the reconstructed signals, we know that peaks of warm IDO phases are respectively in the 1870's, mid-1930's and mid-1990's while cold IDO phases are respectively in the middle periods of the 1910's and 1970's, and both phases appear where undulation is prominent during the warming processes. In view of the discussion of power contribution by background trends and signals from different frequency sections, it is not hard to find that the 40-year and 60 – 70 – yr IDOs are playing an essential role in the undulation of the warming processes in NH.

Tab.2 gives the statistic characteristics of linear warming rate and linear regression for the annual mean temperature in both hemispheres. The table shows that over the past 150 years, the linear warming is slightly higher in Southern than in NH, and correlation coefficient between the variance contributed by the linear regression (higher than 65%), correlation coefficient between mean temperature and the time-dependent variables are much higher in Southern than in NH. It shows that linear warming is more significant and stable in SH than in NH. When the previously-presented MTM analysis results of annual mean hemispheric temperature are considered, one conclusion can be drawn: the IDO of the boreal 40 - yr and 60 – 70 – yr periods are the main causes for smaller linear warming and lower significance and stability. It reflects from one aspect that the diagnostic study of low-frequency oscillations at the scales of a few decades and their mechanism study are a subject to which much attached must be drawn in the field of global changes research.

There is one point worth noticing. The above IDO signals peaked in the mid-1990's and began declining in recent years, which may affect the rate with which the NH climate warms up in the future.

Tab.2 Linear warming rates and statistic characteristics of SH, NH and global annual mean temperatures

	Linear warming rate / ℃/100 year	Contribution from linear regression equation / %	Correlation coefficient
NH	0.395	47.6	0.690
SH	0.440	66.4	0.815

4 SEASONAL DIFFERENCES OF LOW-FREQUENCY CHANGES OF MEAN TEMP. BETWEEN NH AND SH

From the MTM spectral analysis of annual mean temperature changes between the two hemispheres, we can see that the difference is large and thus causes the SH and NH stand apart in terms of the warming significance and stability. It is necessary to study more on whether IDO has seasonal tendency.

4.1 *Seasonal difference of low-frequency changes in mean temperature between NH and SH*

Applying the MTM spectral analysis, with strong infrared noise, to the mean temperature series and residual series without background tendency, for periods over December – February and June – August, from 1856 to 1998, in the SH and NH. Tab.3 gives significant signals and accumulated power contributions for sections of frequency (%), as determined by MTM spectral detection for all seasons.

As shown in Tab.3, significant 40 – 45 – year and 60 – 70 – year IDOs in the lower section of the spectra are superimposed on mean temperature in the boreal winter / summer, though power contribution is much more obvious from the summer IDO, even exceeding that from background trends. It indicates that it mainly displays as low-frequency on the scale of a few decades. In Fig.4, owing to the technique of MTM signal reconstruction, the IDO evolutions are further compared with the amplitude of background warming to discover that the IDO has exceeded the background warming, implying possible trends to alter it. In mid- 1990's, IDO signals peaked in both winter and summer. It arouses much attention in the study of global changes and prediction of future climate.

Compared with NH, the SH warming trend is quite significant, with power contribution percentage being 60% in winter and over 45% even in summer. The quasi-40-year IDO existed only in winter and tended to disappear after the 1950' s (figure omitted).

Tab.3 Significant annual signals and accumulated power contributions for sections of frequency (%), as determined by MTM spectral analysis for summer mean temperature

			Low-frequency variation				Annual variability
			Background trend	IDO	Interannual variability	Accu. power	
Northern Hemisphere	Dec.—Feb.	Significance period* / year	/ (rising)	64.0 41.0	10.5	/	5.9〜6.0, 3.7〜4.1 2.5〜2.6, 2.3, 2.0
		MTM spectra power / %	27.9	13.4	13.5	54.8	45.2
	Jun.—Aug.	Significance period* / year	/ (rising)	68.0 43.0	9.2	/	6.2, 4.2〜4.9 3.4〜3.6, 2.0
		MTM spectra power / %	29.2	32.4	9.9	72.2	27.8
Southern Hemisphere	Dec.—Feb.	Significance period* / year	/ (rising)	/	9.0	/	3.4〜3.8, 2.6〜2.7 2.3〜2.4
		MTM spectra power / %	47.1	10.7	9.9	67.8	32.2
	Jun.—Aug.	Significance period* / year	/ (rising)	39.4	/	/	5.9〜6.2, 3.5〜3.7 2.7〜2.8
		MTM spectra power / %	59.5	13.9	9.2	82.6	17.5

*The significant IDO periods are for their spectral peaks.

In addition, there are on the decadal scale significant quasi-10-year oscillations of mean temperature in NH, with winter slightly stronger than summer; the evolutions of reconstructed signals are quite consistent and time-dependent amplitude and period also agree with the annual mean series, showing that there is little difference seasonably.

4.2 *Effect of IDO on seasonal difference of warming*

Tab.4 gives the statistics of linear warming rate and linear regression for winter / summer mean temperature in SH and NH. It shows that the linear warming rate is the highest in the NH winter but lowest in summer. Regardless of the season, the SH linear warming rate is more stable and significant, with the variance contribution surpassing 60% for the linear regression of winter temperature in the SH winter but only 21% in the NH summer. As the power contribution is the highest from the NH summer IDO, winter interannual variability has the largest effect on the warming trend. It is therefore thought that strong NH summer IDO is the main cause for low linear warming, significance and stability, and high-frequency perturbations like ENSO are the main triggers for the reduction of linear warming and stability in winter.

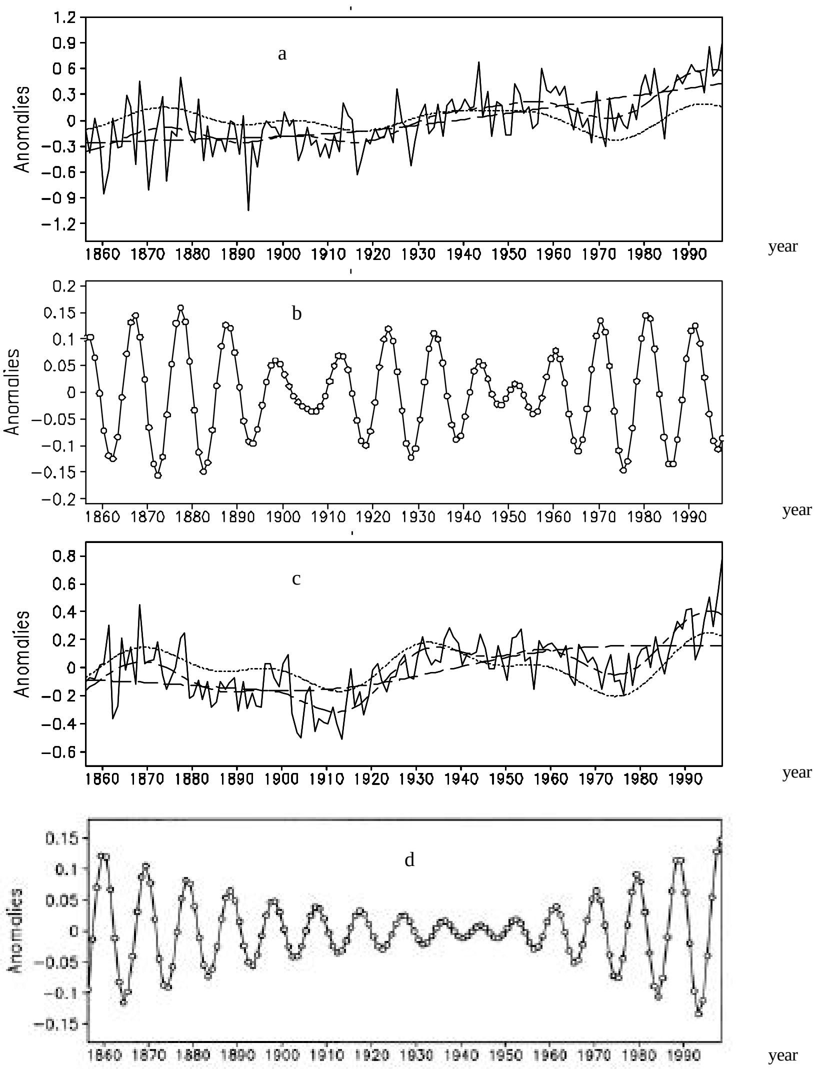

Fig.4 Reconstructed series of low-frequency significant signals of mean temperature in winter (a, b) and summer (c, d) in the NH. The solid lines in a and c stand for the observed series, the dashed lines for the background trends, the dotted lines for IDO signals, dotted / dashed lines for the superimposed series of the two; b, d stand for decadal signals.

Tab.4 The statistics of linear warming rate and linear regression for winter / summer mean temperature in the SH and NH

		Linear warming rate / ℃/100 year	Contribution from linear regression equation / %	Correlation coefficients
NH	DJF	0.491	34.3	0.586
	JJA	0.241	21.3	0.462
SH	DJF	0.418	54.4	0.738
	JJA	0.465	63.9	0.799

5 LAND-SEA DIFFERENCE IN LOW-FREQUENCY MEAN TEMPERATURE

As shown in the discussion above, the IDO is marked with sharp difference between the SH and NH and significant seasonal trends, leading to differences in warming significance and stability during winter and summer between the SH and NH. But is the oscillation not equivalent between land and sea? It apparently deserves more study. According to some of the recent diagnoses and numerical simulations, the IDO variability is thought to be related with air-sea interactions. It is therefore important to have more thorough study of the land-sea difference in low-frequency if we want to know more about the mechanism for generating IDOs. In view of the fact that IDO is active mainly in the NH, the land-sea difference in low-frequency changes of mean NH temperature will be discussed in detail.

5.1 *Land-sea differences of low-frequency variation of mean temperature in NH*

Tab.5 gives the significant signals on the decadal and above scales as determined by MTM spectral detection for annual mean land and sea surface temperature in the NH. Tab.6 is the accumulated power contributions for sections of frequency in corresponding MTM spectra.

Tab.5 Significant signals on the decadal and above scales as determined by MTM spectral analysis for annual mean land and sea surface temperatures in the NH

		Background trends	IDO／Year	Decadal variability／Year
land	Annual mean	Rising	64.0, 42.7	/
	DJF	Rising	/	/
	JJA	Spiral rising	68.3, 42.7	/
ocean	Annual mean	Spiral rising	64.0, 41.0	9.9 —10.2
	DJF	Spiral rising	60.2, 41.0	10.2 —10.3
	JJA	Spiral rising	68.3, 42.7	9.1 —9.5

* The IDO significance periods are for their spectral peaks.

Tab.6 Accumulated power contributions for sections of frequency in corresponding MTM spectrum of mean land and sea surface temperatures (%) in the NH

MTM spectral power / %		Low-frequency changes				Interannual variability
		Background trends	IDO	Decadal variability	Accumulated power	
land	Year	31.3	15.1	10.8	57.1	42.9
	DJF	12.4	9.0	13.0	34.4	65.7
	JJA	11.5	40.3	13.9	65.7	34.4
ocean	Year	43.2	25.6	13.7	81.9	18.1
	DJF	38.1	18.0	12.2	68.3	31.7
	JJA	28.7	26.7	14.8	70.3	29.7

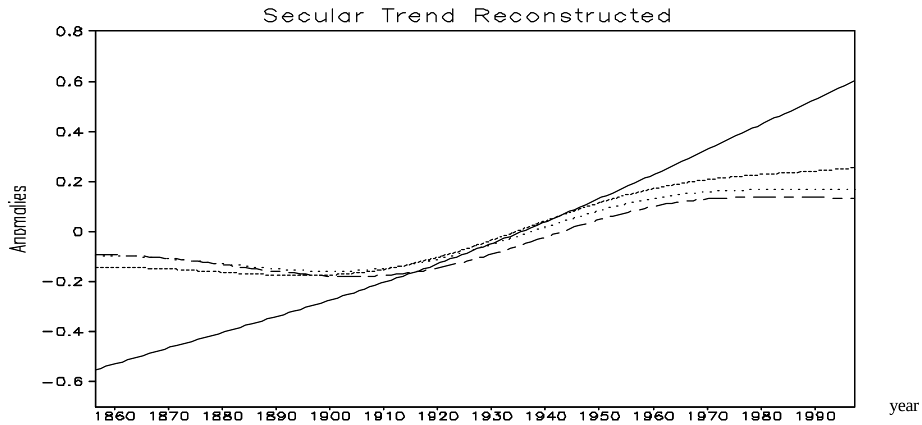

Fig.5 Background trends for wintertime land (solid line) and summertime air temperature (dotted / dashed line) and wintertime sea surface temperature (dashed line) in the NH.

It is seen in Fig.5 that the warming trend is found in the surface of both land and sea in NH but the background trends are basically warming in linearity and with large amplitude (up to 1.12°C, as shown in Fig.5). It becomes more clear from comparisons of land-sea background tendency that power contribution from sea surface temperature is relatively high in both winter and summer, especially in SH, in which it could around 50%, indicating the relative higher importance of oceanic background warming in temperature variability than the terrestrial one. On the interdecadal scale, significant quasi-40 yr and 60-70 yr IDOs are superimposed on the warming trends of annual mean land and sea surface temperature in NH, though they are insignificant over land in winter. Fig.6 tells how the reconstructed IDO signals evolve for land surface temperature for summer and sea surface temperature for summer and winter. It is seen that oscillation has generally consistent phases over land and sea surface, with the ocean slightly lagging behind land but being consistent with the undulation of the global warming process. The IDO signals are stronger in summer, for both ocean and land, especially over the latter, with the amplitude up to 0.5°C – 0.6°C, well surpassing that for the background warming (0.3°C). In recent times, the summer IDO also varies by as much as 0.45°C over the ocean. Further examination of IDO shows that its power contribution is over 40% for land surface in summer, much higher than that of background warming; the IDO is also near the background warming for the ocean in summer. It shows that the quasi – 40 yr and 60 – 70 yr IDO signals are very significant over the surface of land and sea in NH. In mid-1990's, the IDO signals reached their peaks over land in summer while remaining on top presently for sea surface temperature. It should have attracted more attention from meteorologists working on global changes and predicting future climate.

On the decadal scale, however, the 9 – 10 yr oscillation of sea surface is the only scale found in NH, suggesting large land-sea difference in the quasi-10-year oscillation. See Fig.7 for the evolution of reconstructed signals of sea surface temperature. It shows that they are quite consistent in amplitude, phase and time-dependence of the amplitude for both winter and summer, without much difference from season to season; the amplitude is small for 1900's – 1950's but large for 1860's – early 20th century and 1970's to present.

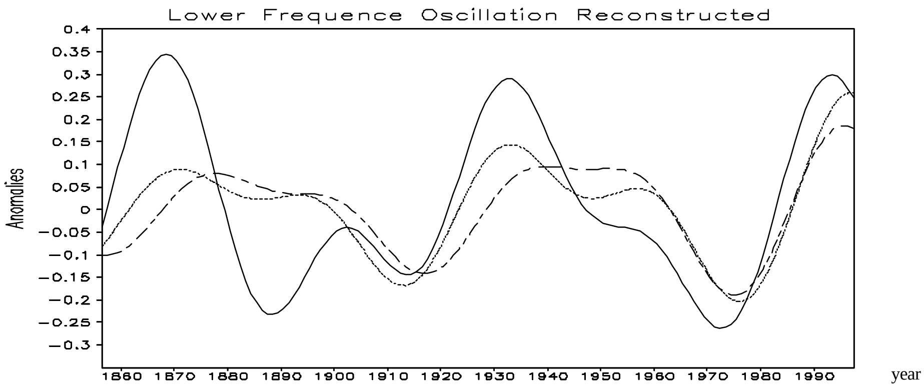

Fig.6 Summertime land air temperature (solid line) and IDO of sea surface temperature for the winter (dotted / dashed line) and summer (dotted line) in the NH.

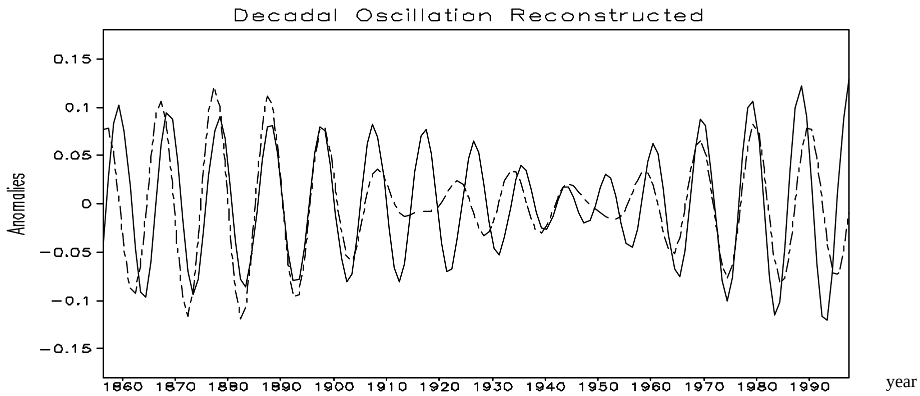

Fig.7 Quasi decadal oscillations of sea surface temperature for winter (dotted & dashed line) and summer (solid line) in the NH.

5.2 *Land-sea differences of linear warming of winter, summer and annual mean temperature*

Tab.7 gives the land-sea differences of linear warming of mean temperature in NH and SH. It shows that the linear warming is significant ($g_{0.01} = 0.254$) in all seasonal and annual mean temperature over the surface of land and sea but for the land surface temperature in the summer of both hemispheres. The warming rate, 0.893°C / 100a, is the largest over land in NH winter while being the lowest over land in summer (0.184°C / 100a) and insignificant. For the variance contribution by linear regression, it is also the lowest (5%) over land in the NH and SH summer. It is always higher over sea than over land whether it is winter or summer, SH or NH; it is more than 55% in summer and more than 65% in winter, over the austral ocean. It indicates that the linear warming rate is usually higher for land surface than sea surface in either hemispheres with the exception of summer, though it is more stable for sea surface temperature. In addition, the linear warming is more stable in SH, winter, than in NH, summer.

Factors causing such difference may be multiple. From the low-frequency variation and comparisons of relative contribution between different signals, we know that the linear warming rate is the maximum but with lower stability over land, due to relatively large contribution from high-frequency variability. For the ocean, the relatively small contribution from high-frequency variability makes the warming more stable. It now appears that the quasi-40-yr and 60 – 70 yr IDOs over the NH land in summer and ocean may be the main factors responsible for low significance and stability of linear warming. In their recent studies, Zeng and Yan[13] also note that the most stable warming is recorded in the Indian Ocean and southern Atlantic and the least stable warming is found in high latitudes of NH, varying significantly in season and periods of time.

Tab.7 The linear warming rates of land and ocean surface mean temperatures in the NH and SH and their statistics

			Linear warming rate / ℃/100a	Variance contribution by linear regression /%	Correlation coefficients
Northern Hemisphere	land	annual	0.647	39.3	0.628
		DJF	0.893	19.5	0.441
		JJA	0.184	5.6	0.237
	ocean	annual	0.332	44.5	0.667
		DJF	0.375	41.1	0.643
		JJA	0.263	25.2	0.502
Southern Hemisphere	land	annual	0.418	23.0	0.479
		DJF	0.289	5.7	0.239
		JJA	0.653	28.6	0.535
	ocean	annual	0.446	67.1	0.819
		DJF	0.426	55.6	0.746
		JJA	0.471	65.7	0.811

6 COMPARISONS OF VARIATIONS OF SIGNALS SIMULATED FOR MEAN TEMPERATURE IN NH AND SH

In the study above, we have found the IDO signals of temperature are specially obvious in NH, mostly so in summer and over the ocean. In our work, a 240-yr control experiment' s results from the second generation of air-sea coupling model (HadCM2) developed at the Hadley Center, with the current level of greenhouse gas and aerosol unchanged, are directly used to isolate IDO signals of mean temperature in the coupling model in the hope that possible causes are discussed of the oscillations.

Fig.8 gives the linear warming rates of annual mean temperature in both hemispheres for different sizes of sample in the control experiment. It shows that the linear warming rate is generally lower than 0.05°C / 100 yr for either the hemispheric or global mean, and the conclusion applies to all samples. It proves that the warming trend is not significant as far as the annual mean temperature of the control experiment is concerned, in contrast to the significant warming trend for the past 100 over years in the observational series. It reflects in some way that the warming trend has nothing to do with the natural variability within the climate system.

Tab.8 Linear warming rates of hemispheric and global annual mean temperature in the control experiment (°C / 100 yr)

Sample size / year	global	NH	SH
140	0.044	-0.002	0.088
240	0.014	-0.017	0.044

Applying MTM spectral analysis to the series of annual mean temperature in NH and SH for the 240 years derived from the control experiment, we have determined MTM spectral estimates of the series and corresponding critical spectra of red-noise as presented in Fig.8 (a & b). For the sake of illustrative comparison, the figure also gives the MTM spectral curves of corresponding observed series (1856 – 1998). Tab.9 is the significant signals detected by MTM spectral analysis and the accumulated power contributions over sections of frequency (%).

From Fig.8 and Tab.9, we know three things. One, in the simulated series, significant quasi –

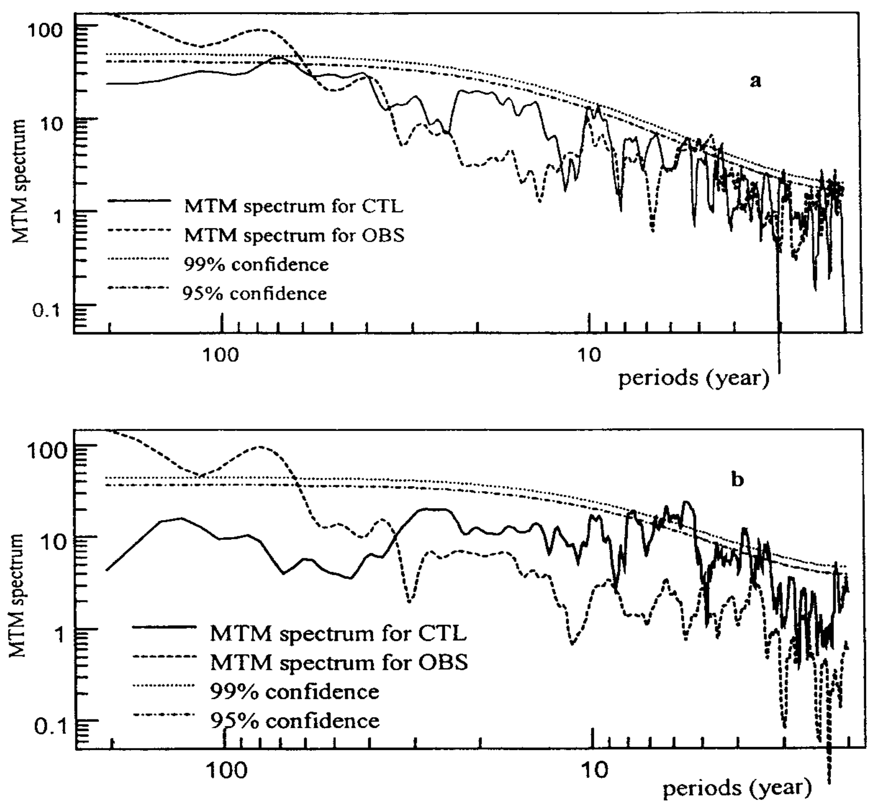

Fig.8 MTM spectral analysis of annual mean temperature series (240 years) simulated for NH (a) and SH (b) in the control experiment. The solid line stands for the spectral estimates of the simulated series, the dotted line for those of the observed series and the dotted line and dotted & dashed line for fitting spectra of strong infrared noise with confidence level of 95% and 99%, respectively.

60 – 70 – yr oscillations are present in the NH annual mean temperature series only, though without significant signals of background tendency. Two, in contrast to the spectral

characteristics of the observed series, those of the simulated series of mean hemispheric temperature less than the decadal scale generally agree with the observed series; the decadal-scale signals are stronger than those in the observed series, especially in NH; the above-IDO-scale signals are weaker, particularly so in the mean series for SH. Three, signals are stronger in NH than in SH when the scale is over decadal for the simulated series while the 2 – 7 – yr interannual high-frequency signal is stronger in SH. It agrees with the difference reflected by the observed series of temperature variability in both hemispheres. As there is no external forcing in the above coupling model, it reflects to some extent that the IDO may come from the interactions between physical processes of various spatial and temporal scales in the air-sea system; the difference in land-sea distribution in the SH and NH may be the primary cause for the fact that the IDO signal is prominently active in NH.

Tab.9 Significant signals tested up by MTM spectral analysis and comparison of accumulated power contributions (%) over sections of frequency for annual mean temperature in the control experiment

		Low-frequency variation (>20 year)			Interannual variability
		Background trend	IDO oscillation	Annual variability	
NH	Significant period / year	/	64～73	9.3～9.4	5.3～5.5，4.3～4.4 2.9，2.1～2.3
	MTM spectral power / %	/	42.8	30.4	26.7
SH	Significant period / year	/	/	7.5～7.9	5.2～6.5, 4.5 3.7～3.9, 2.1～2.2
	MTM spectral power / %	/	15.6	29.2	54.9

7 CONCLUDING REMARKS

With the MTM technique, the monthly mean temperature series in the SH and NH as compiled by Jones et al. for 1856 – 1998 is detected and reconstructed in terms of multiple signals, with the focus on IDO signals; its effect on global warming is discussed and signal difference between NH and SH, land and sea, and between seasons are compared comprehensively. The possible causes for IDO is preliminarily probed using the numerical simulation of an air-sea coupling model.

a. The MTM technique offers the best balance between resolution and variance for limited-length series spectrum and paves a new way for coping with contradiction between spectral resolution and stability. It is specially good for diagnostic analysis of weak and time- and space- dependent signals against high levels of noise background in short series of non-linear climatic system. It can also be used as an efficient tool for the study of low-frequency variation signals above the IDO scales, using data taken with instruments.

b. Over the past 150 years, the warming trend dominates in the hemispheric annual mean temperature variability. As significant 40 – 70 – yr IDOs are superimposed on the warming background of the annual mean temperature in NH, making important contribution to the undulation of the warming process. The warming in the 1920's and 1930's and the cooling from 1940's to 1970's may be the result of IDO intertwining with background trends. It is noted the IDO signals peaked in the 1990's and began declining afterwards. It may affect the rate at which the global climate warms up in future.

c. The warming trend is more stable and significant in SH, though with insignificant IDO signals; the linear warming is less significant and stable and the warming rate smaller in NH, due to the presence of the significant 40 – 70 – yr IDO there.

d. The linear warming rate and stability are always higher in winter than in summer in either hemisphere, especially in NH. For the mean temperature in both winter and summer in NH, a 40 – 70 – yr IDO is superimposed on the warming trend. The IDO is more significant in summer with relative specific gravity larger than the background warming. As it may lead to changes in the tendency of background warming, researchers on global changes and future climate should pay more attention to it. For the ocean, the IDO signals are more obvious than land but the linear warming rate is a little lower than land, though with higher significance and stability.

e. The quasi – 9 – 10 yr signal is mainly found in the series of sea surface temperature in NH without much difference from season to season and consistent amplitude, phase and time-dependent transformation between winter and summer. For the amplitude of variation, the decadal signal is small for the period 1900 – 1950 but large from the 1860' s to early 20^{th} century and in the 1970' s.

f. From the 240-yr results of the control experiment with the HadCM2 at the Hadley center, we know the observed warming trend is independent of the natural variability within the air-sea system itself. The IDO may be its inherent oscillation, which can be simulated by HadCM2 to some extent.

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