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ORIGINAL PAPER

Spatiotemporal computing of cold wave characteristic in recent 52 years: a case study in Guangdong Province, South China

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Abstract Based on daily air-temperature data of 86 weather stations in recent 52 years (1961–2012) in Guangdong Province, South China, annual cold wave events in each station were calculated. Then, the spatiotemporal characteristics of cold wave over Guangdong Province were thoroughly analyzed by wavelet transform and other statistical analysis method. The results indicate that: (1) The cold wave frequency gradually decreased from north to south, from inland to coastal area and from highland to lower land showing evident regional variance; if there occurred a large range of cold wave, the temperature fall caused by cold wave would be bigger in southwestern area than in the rest of Guangdong Province; (2) 161 regional cold wave events in total invaded Guangdong in recent 52 years. The cold waves can be classified into three invasion paths: north, northeast and west. Most of cold waves took the north path, and a few of them took the west path only; (3) Based on the influence range, the cold wave can be divided into 4 grades. The climatic characteristic of each grade shows that the larger the range of influence was, the more severe the hazard of cold wave would be; (4) Cold wave whose influence range was smaller than 10 % of provincial area happened almost every year, and the frequency was 1.9 annually; cold wave whose influence range was larger than 50 % happened 13 times in recent 52 years; (5) The intensity of cold wave over Guangdong was declining at the rate of 5.5 station-day per year; it also had an inter-decadal oscillation period of 10–14 years, and an obvious inter-annual oscillation period of 3–4 years before 2000; (6) Cold wave frequency of each month varied significantly, 76 % of which occurred during December to

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next February; (7) The snow disaster of 2008 had caused great losses to Guangdong agriculture. But according to the criteria of cold wave, only 22 stations (25 %) of Guangdong actually reached the standard of cold wave. Therefore, the cold disaster index should be additionally considered when analyzing the impact of disaster by cold air process, and the relationship between cold wave and cold disaster is worth further research.

Keywords Cold wave · Spatiotemporal computing · Influence range · Wavelet transform · Morlet wave

1 Introduction

Located in the southern part of mainland China, Guangdong Province is in the low latitude. Relative to the high latitudes, the frequency and extent of the cold air process are slighter. But once the level of the cold air reaches the level of cold wave, strong cooling effect will be caused through the region, which could lead to serious damage to agricultural production. In addition to the impact on agriculture, studies have also shown that cold wave activity has inevitable connection with human body health and mortality (Barnett et al. 2005, 2012; De et al. 2005; Montero et al. 2010). For example, the maximum mortality from cold waves was observed in Toledo and Ciudad Real in Spain with a daily mean of over 11 deaths from 1975 to 2003 (Montero et al. 2010). Therefore, research on cold wave events is of great significance for disaster prevention and mitigation.

At the international level, Radinović and Ćurić (2012) considered air-temperature the most important climatic element for adverse weather phenomena such as cold wave and Radinović et al. (2013) proposed a remediation on the definition of cold wave recommended by International Panel on Climate Change. Other researches on cold wave, such as its impact on plant (Gómez and Souissi 2008), its destruction of animals (Gordon 1951) or its characteristics (Varfi et al. 2009), have also been conducted all these years.

As far as the characteristics of nationwide cold wave in China are concerned, Zhang and Chen (1999) analyzed cold high activities in China, to clearly understand the weather/climate characteristics of cold high; based on the data of 740 national weather stations from 1951 to 2004, the trend that cold wave frequency is declining was revealed by Wang and Ding (2006); using 572 national weather data from 1960 to 2004 and the Arctic oscillation index data, Qian and Zhang (2007) from a new angle of view discovered that the spatial–temporal characteristics of cold wave in China had connection with winter warming. Based on cold wave frequency and intensity sequence data of 160 weather stations in China from 1955 to 2004, Wei (2008) analyzed the characteristic of differences between pre- and post-climate warming and had discussed the connection between cold wave disasters trend and the changes in the Arctic oscillation. Based on weather data of cold air in winter of 1951–2006 and NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) daily reanalysis data, Kang et al. (2010a, b) made a statistical analysis to the climate characteristics of cold wave and its physical characteristics; then, they introduced the clustering method to divide the cold wave types. Sequentially, they proposed an automatic identification and objective forecast method for cold wave, based on TIGGE (THORPEX Interactive Grand Global Ensemble) ensemble forecast products.

Many researches on regional cold wave have also been conducted in recent years. Liu and Xu (2007) analyzed the climate characteristics of cold wave activity in Dalian of 1961 to 2005 and emphatically studied its inter-annual and inter-decadal characteristics. Using the data of temperature and circulation characteristics, Arctic oscillation index and NCAR/NCEP reanalysis data, Chen et al. (2010) studied the climate characteristics of cold wave frequency in Ningxia region and the possible reasons for its change. Applying comparative and wavelet analysis method, Wang et al. (2010) conducted a comprehensive analysis of the cold wave distribution in southeastern Shanxi Province. Mansur (2012) conducted a deep analysis to the spatiotemporal distribution of cold wave, and its formation reasons and effects on agricultural production in southern Xinjiang region from 1949 to 2008.

For cold waves in southern China, Huang (1995) collected statistics on the spatiotemporal/climate characteristic of cold wave and severe cold air in Guangzhou city from 1951 to 1993, and based on observed temperature data and upper air circulation field data, he proposed a new method on predicting cold wave. Lin and Wu (1998) analyzed cold wave characteristic in Guangdong from 1951 to 1994 based on data from 11 representative stations and proposed a cold wave intensity index for analyzing the temporal variation of the cold wave intensity. Zeng and Xie (2003) made an analysis of the climate characteristic of cold wave and severe cold air in Guangdong Province from 1951 to 2008 and studied its relationship with ENSO. Based on observation data of 192 weather stations from southern China's three provinces—Guangdong, Guangxi and Hainan, Wu and Du (2010) made an analysis on southern China's cold wave feature from 1961 to 2008 and analyzed the cold wave intensity variation.

A lot of researches on cold wave have been conducted in recent years. However, with climate warming, cold wave characteristic in Guangdong Province have changed. Besides, previous papers did not make any grading of the cold wave, and comparative analysis of different specific cold wave events was also lacking.

In this paper, using temperature observation data in winter season from 1961 to 2012 of all the 86 national weather stations in Guangdong Province, we calculated every cold wave event happened in each sites as defined. And then, we did an analysis of spatiotemporal characteristic on each grade of cold wave; we finally chose several severe cold wave events for comparative analysis on its climate features. The work of this paper might have important meaning for understanding the characteristics of cold wave in economically developed Guangdong Province of China.

2 Data, area and methods

2.1 Criterion of cold wave

The criteria of single-station cold wave adopted in this paper (Table 1) are cited from "Standards for Major Disastrous Weather in Guangdong Province" (Lin 2006) which is used in meteorological operation of Guangdong, that is, temperature fall ≥8 °C in 24 h, or

Table 1 Grading criteria of cold air

Cold air level	24-h temperature fall	48-h temperature fall	Minimum temperature
Cold wave	≥8°	≥8°	≤5°
Severe cold air	≥8°	≥8°	>5°
	[6,8)	[8,10)	≤7°
Moderate cold air	[4,6)	–	–
Weak cold air	[0,4)	–	–

$\geq$10 °C in 48 h, and the minimum temperature below 5 °C; the beginning day of cold wave event is the day in which the weather condition is in line with the criteria; the ending day is the day in which daily average temperature $\geq$12 °C and minimum temperature >5 °C.

For criteria of regional cold wave, Chen et al. (2010) defined that when 12 stations (48 % of the total station number) fall within the standard of cold wave, it is a regional cold wave process for Ningxia district. Wu and Du (2010) defined that it is a cold wave event over southern China if cold wave happens in more than 1 station among 192 representative stations.

For criteria of cold wave over Guangdong Province, Huang (1995) defined that when cold wave happens over Guangzhou city, it is a cold wave event over Guangdong; Lin and Wu (1998) defined that it is a cold wave activity over Guangdong if cold wave happens in more than 1 station among 11 representative stations.

We think that, if regional cold wave is calculated based on most of the criteria mentioned above, the results of the division might be vague or incorrect, because cold wave that happened in a small region might be ignored, or might be recognized as a big-scale cold wave. Therefore, in this paper, the definition by Wu and Du (2010) and that by Lin and Wu (1998) is adopted. The only difference is that the representative station number is 86, which is the total number of Guangdong national-level weather station. The first day that the cold wave occurred in some station is taken as the beginning date of such cold wave event; the last day that the cold wave ended in the last station is taken as the ending date. The total number of stations that cold wave occurred (taken as range under cold wave influence) is also recorded.

2.2 Data and research area

Cold wave mainly happened from October till March of the next year over Guangdong Province, so 86 weather station's daily average/minimum air-temperature data between October 1st and March 31st from 1961 to 2012 are used in this paper. Based on the criteria described above, the cold wave that happened annually from October of this year till March of the next year for each station was computed. Data are acquired from Guangdong Meteorological Information Center. Guangdong Province, a coastal province, located in southernmost part of mainland China (Fig. 1), with a population of 104.3 million and area of 179,770 km^2, is chosen as the research area in this paper. In the north area of Guangdong Province, there are many rugged mountains and adjacent to its south is vast South China Sea. Located in the tropical and sub-tropical monsoon climate area, Guangdong is alternately influenced by low-latitude tropical weather system and mid-/high-latitude weather system which leads to complex and changeable weather and climate. Therefore, typhoon, rainstorm, cold disaster, heat wave, drought, etc. and secondary disaster caused by them often happened.

2.3 Definition of variables

1. Range of cold wave influence: $R = N/86 \times 100\ \%$. R is the influence range of cold wave. N is the total number of stations that cold wave occurred. The total number of national weather stations in Guangdong Province is 86.
2. Days of cold wave in single station (site): $d(i)$, that is, the day counts from the beginning date of the cold wave till the ending date.

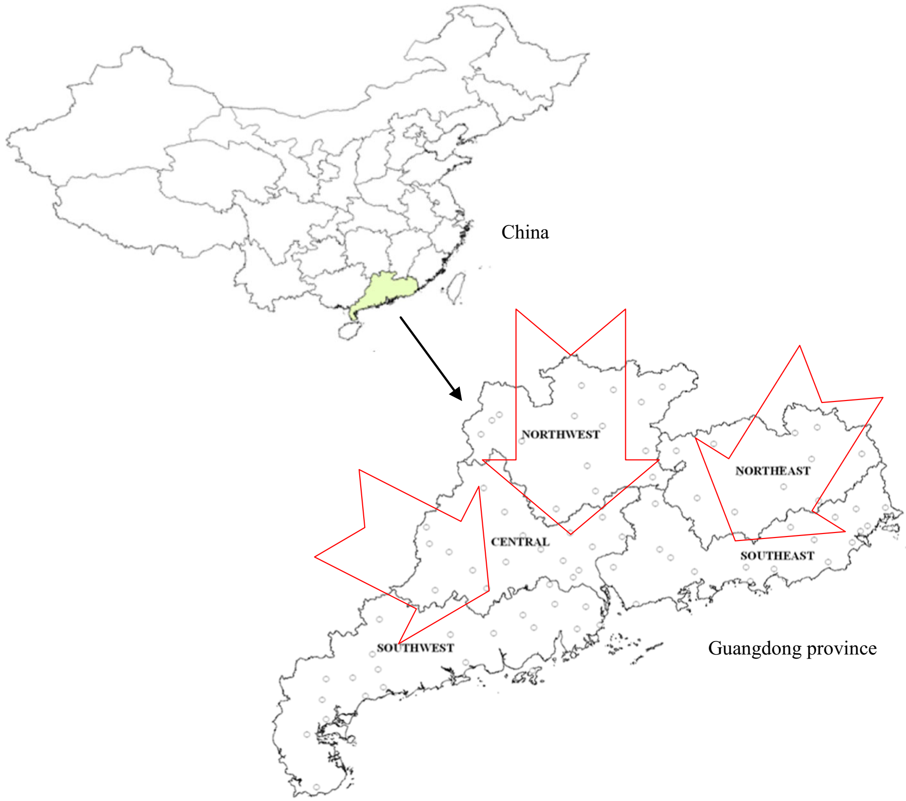

Fig. 1 Position of Guangdong Province in China and Guangdong's climatic classification. Note: Circles in map indicate the 86 weather stations. The number of stations in each region is: northwest—15, northeast—12, central—19, southeast—18 and southwest—22 (Table 2). These three arrow shapes denote the cold wave invasion paths, respectively—northeast, north, west

3. Beginning/ending date of regional cold wave: the first day that the cold wave occurred in the first station is taken as the beginning date of regional cold wave event; the last day that the cold wave ended in the last station is taken as the ending date.
4. Station-day counts of regional cold wave: $D = \sum_{i=1}^{N} d(i)$. D is the total counts of all station's cold wave days, whose unit is *station-day*. N is the station counts where cold wave happened. $d(i)$ is the days of cold wave in each single station. Such station-day count is used for describing the intensity of each regional cold wave in this paper.
5. Averaging duration of each regional cold wave: Dcourse $= D(i)/N$. Dcourse is the averaging duration of each regional cold wave event, which is the result of station-day counts ($D(i)$) of each regional cold wave divided by total station counts (N), and the unit is Days.
6. Annual station-day counts of all cold wave: Dyear $= \sum_{i=1}^{N} D(i)$. Dyear is the sum number for station-day counts of all the regional cold wave events, whose unit is: *station-day*. n is the counts of regional cold wave, $D(i)$ is the station-day counts of each regional cold wave event. Such annual station-day count is used for describing the total intensity of each year's regional cold wave in this paper.

2.4 Periodical analysis method (Huang 2004)

In this paper, cycle of cold wave intensity variation was analyzed, based on wavelet transform with the Morlet wavelet as mother function. The wavelet transform is a two-dimensional mathematical transform that has been comprehensively applied in signal processing. To make inner product of one signal and a wavelet group, we can obtain the wavelet coefficients in the time–frequency domain. These wavelet coefficients reveal the signal's time–frequency distribution. If the mother function $\psi(t)$ is given, the wavelet transform of cold wave intensity $x(t)$ is:

$$\omega_f(a,b) = |a|^{-\frac{1}{2}} \int_{-\infty}^{\infty} x(t)\bar{\Psi}\left(\frac{t-b}{a}\right)\mathrm{d}t$$

where a is the frequency parameter and b represents translations in time. $\bar{\Psi}\left(\frac{t-b}{a}\right)$ is the wavelet transform function, which is generated by dilations and translations of wavelet mother function $\psi(t)$. $x(t)$ is the temporal series of cold wave intensity, and $\omega_f(a, b)$ are the wavelet transform coefficients.

The wavelet mother function has various forms, such as Haar, Mexican Hat, Morlet. The Morlet wavelet transform function is described as

$$\psi(t) = e^{-\beta^2 t^2/2} \cos \pi t$$

The sub-wavelet after dilations and translations of mother wavelet is:

$$\psi_{a,b}(t) = \exp\left[-\frac{\beta^2 (t-b)^2}{a^2}\right] \cos\left[\frac{\pi(t-b)}{a}\right]$$

3 Results and discussion

3.1 Spatial computing of cold wave

3.1.1 Spatial characteristics of single-site cold wave frequency

In recent 52 years, in total 2136 single-site cold wave occurred in Guangdong Province; that is, 41.1 single-site cold wave annually. If it is divided by all of Guangdong's weather station number 86, the averaged cold wave is 0.5 annually. Of which, the probability of cold wave invading northwestern and northeastern Guangdong is highest—0.9 times annually; The probability in central Guangdong is moderate—0.4 times annually; the probability in southwest and southeast is the lowest—0.2 annually (Table 2).

In meteorology, 30 years' averaged value of each element is taken as climate background. In this paper, 30 years' annually averaged (1981–2010) cold wave frequency of each station was calculated. Figure 2 depicts that cold wave frequency gradually decreased from north to south and from inland to coastal area, showing evident regional variance. Frequency in most of northern region could reach 0.5 times per year. The biggest frequency occurs in Lianshan station in northwestern part, which is 1.6 times per year (48 times in 30 years). The frequency in the southwestern and southeastern region is relatively

Table 2 Spatial distribution of cold wave invading Guangdong during 1961–2012

	Sum	Northwest	Northeast	Center	Southwest	Southeast
Total	2136	736	582	406	207	205
Annual	41.1	14.2	11.2	7.8	4.0	3.9
Station count	86	15	12	19	22	18
Annual single site	0.5	0.9	0.9	0.4	0.2	0.2

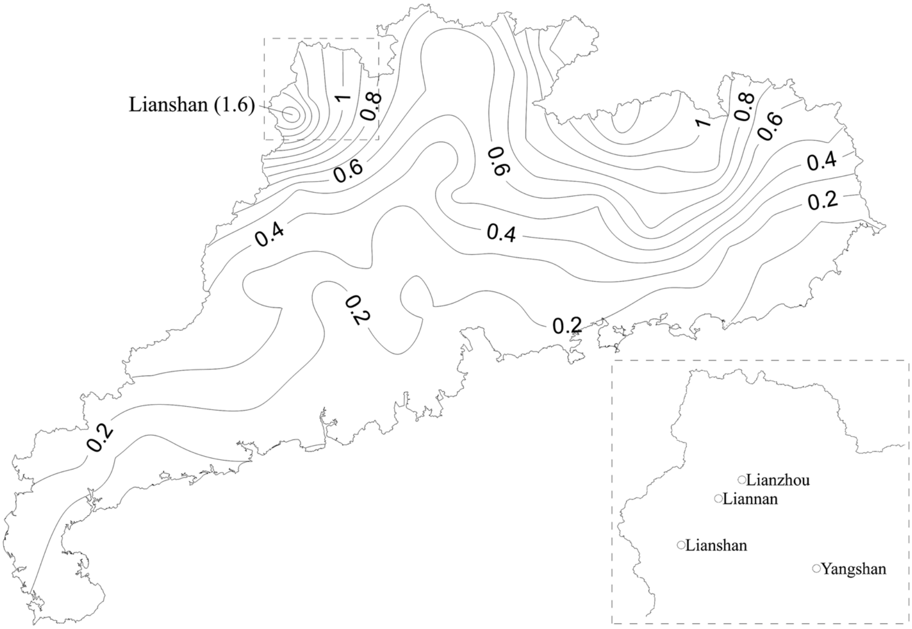

Fig. 2 Distribution of 30 years' annually averaged cold wave frequency in Guangdong

Table 3 Cold wave frequency of 4 representative stations

Station name	Longitude	Latitude	Altitude	Frequency 1971–2000	Frequency 1981–2010	Frequency 1961–2012
Yangshan	112.633	24.483	70.5	1.03	0.90	1.19
Lianzhou	112.367	24.800	131.5	1.10	1.13	1.25
Liannan	112.283	24.733	174.4	1.13	1.17	1.25
Lianshan	112.150	24.567	300.6	1.47	1.60	1.69

small, which is only 0.1 times per year (2 times in 30 years). The maximum frequency is 23 times larger than minimum frequency.

As for understanding the dependence of the cold waves over lower lands and highlands, we selected a region (Fig. 2) with 4 stations, which have approximate longitude and latitude, but obviously different altitude. The results (Table 3) show that cold wave frequency in Yangshan which is in lower land (70.5 m) was relatively small: the frequency of

1961–2012 was 1.19 per year; the frequency in Lianshan which is in highland (300.6 m) was relatively bigger: it is 1.69 per year for 1961–2012. It can be deduced that topography is also an important factor for cold wave occurrence.

3.1.2 Distribution of temperature fall caused by cold wave

Figure 3 shows the pattern of 30 years' averaged temperature fall caused by cold wave in Guangdong. It depicts that temperature fall in most of southwestern region is larger than 15 °C, while that of Leizhou peninsula is greater than 16 °C. The averaged temperature fall in this region is obviously larger than that of the rest of Guangdong Province. It might be because that before the cold wave is coming, the temperature in southwest is generally higher than other region; if the cold wave system is strong enough to invade into southwestern region, it will cause bigger temperature fall, which might lead to bigger damage to crop planted there. Taking the cold wave in January 1993 for example, with cold air spreading to the southernmost of Guangdong Province, the minimum temperature of Gaozhou city which is a main area for banana planting maintained in 1–4 °C for three days. Area of plant under freeze injury reached 34,000 ha, among them banana is 19,700 ha. Among all planted banana, almost 60 % were frozen to death, leading to 300–400 million economic loss.

3.1.3 Invasion path and grading of cold wave

In recent 52 years, totally 161 regional cold wave have invaded Guangdong Province. Three paths (Pan 2000) for cold wave invasion could be seen based on the spatial

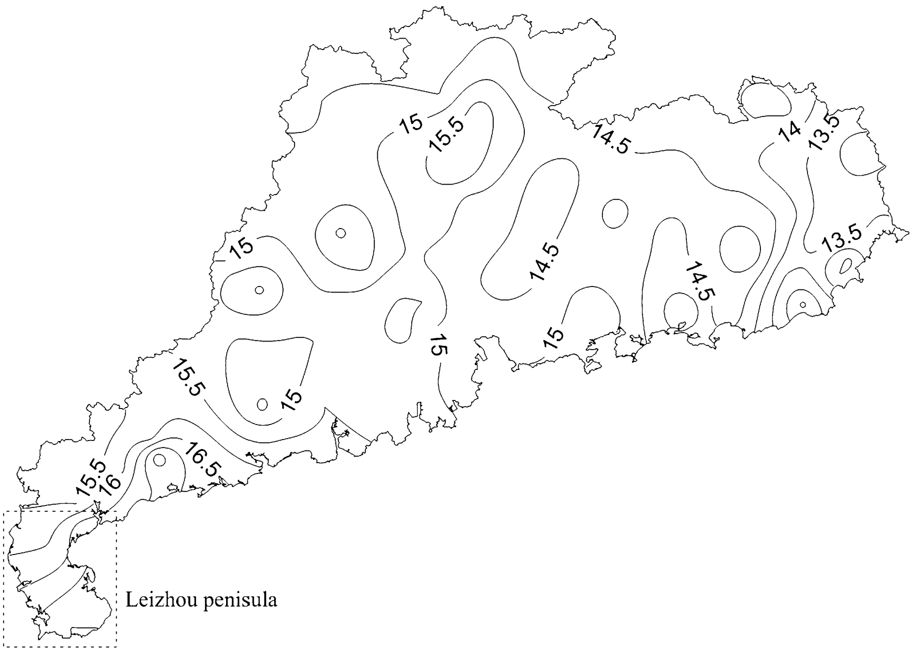

Fig. 3 Distribution of 30 years' averaged temperature fall caused by cold wave in Guangdong

Table 4 Sum of invading cold wave in different paths in recent 52 years

	Northeast	North	West	Else
Cold wave times	28	77	4	3
Percentage frequency	26 %	70 %	4 %	–

"Else" represents the cold wave that can hardly be defined

Table 5 Times of regional cold wave with different influence ranges

	Below 10 %	10–20 %	20–50 %	Above 50 %	Sum
Total times	101	25	22	13	161
Annual times	1.9	0.5	0.4	0.3	3.1

distribution mentioned above—north, northeast and west (Fig. 1). The cold wave that mainly covered northwestern station and invaded into the whole province is defined as north path cold wave; the one which mainly covered northeastern station and invaded into central or southeastern region is defined as northeast path cold wave; and the cold wave that mainly occurred in southwestern region is defined as western path cold wave.

The results (Table 4) show that most of cold wave took the northern path; the number that it occurred is 77 times in total to be exact (70 % of all cold waves). Such kind of cold wave has the following features: severe, large region of influence, which usually covers the whole province (e.g., the influence range of cold wave in December 1991 and that in December 1976, respectively, cover 94 and 93 % of whole Guangdong). Less numbers of cold wave took the northeastern path, and the number is 28 times (26 %). The least number of cold wave took the western path; the number is only 4 times (4 %), and it is slight and influenced small range (<10 %).

Among the 161 regional cold waves in recent 52 years, most of them invaded a relatively small range- only several counties. The percentage of cold wave whose influence range covered more than 10 stations is less than 40 %. As for objective description of regional cold wave, we suppose that cold wave should be classified. In this paper, all the cold wave events were divided into 4 classes: below 10, 10–20, 20–50 and above 50 %, based on influence range. The results (Table 5) show that in recent 52 years, most of the cold waves' influence range is below 10 %; it is 101 times in total and 1.9 annually. Cold wave whose influence range is 10–20 or 20–50 % happened 25 times and 22 times separately, that is 0.5 and 0.4 annually. Cold wave whose influence range is above 50 % happened least, that is 13 times totally, 0.3 annually.

3.1.4 Features of all classes of cold wave

Based on the grading described above, we performed a statistical analysis of the influenced station counts and some temperature indexes. The results (Table 6) show that the averaged cold wave duration whose influence range is larger than 50 % is much longer than that of the rest. The averaged duration is 10 days versus 7 days of each kind. 24-h temperature fall, 48-h fall and process temperature fall are bigger if the cold wave grade is higher. Correspondingly, mean temperature and minimum temperature are smaller. It could be concluded that with the influence range getting larger, the intensity of such cold wave is getting stronger. Therefore, influence range can be used as an important index for judging the cold wave intensity.

Table 6 Features of each grade of cold wave

Influence range	Station counts	Station-day counts	24-h temperature fall	48-h temperature fall	Process temperature fall	Mean temperature	Minimum temperature
Above 50 %	66	684	9.0	13.4	16.4	6.9	1.4
20–50 %	27	189	9.0	12.6	14.1	7.6	2.0
10–20 %	12	87	8.4	11.9	13.2	8.0	2.4
Below 10 %	4	27	7.8	11.2	12.7	8.6	2.9

24-/48-h or process temperature fall denotes average of maximum 24-/48-h air-temperature fall and averaged process air-temperature fall. Mean and minimum temperature stand for the average of multi-station air-temperature during the cold wave process

3.2 Temporal computing of cold wave

3.2.1 Single-site cold wave frequency by climate change

As for understanding the change in single-site cold wave frequency under the background of climate change, cold wave frequency for each station of 1971–2000 (past 30 years) was also computed, in addition to the calculation of that of 1981–2010 (recent 30 years). The difference between these two results shows that only in three stations in northwestern region, the number of cold waves in recent 30 years was bigger than that of the past 30 years—Lianshan (4 times), Liannan, Lianzhou (1 time). The number got smaller in rest of the region—almost half of the rest decreased 4–7 times, Dapu in northeast region decreased 8 times. It can be concluded that the climate is getting warmer in Guangdong Province.

3.2.2 Inter-annual change of cold wave frequency

Based on the grading mentioned above in 2.4, counts for all cold wave grades were calculated. As can be seen in Fig. 4, cold wave of influence range below 10 % almost happened every year; it is 1.9 annually. Cold wave of influence range above 50 %

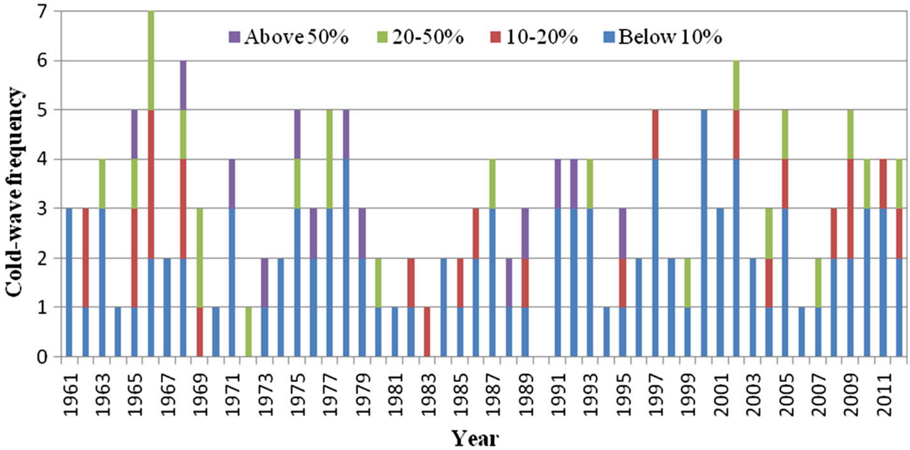

Fig. 4 Inter-annual change of cold wave times in Guangdong in recent 52 years

happened only 13 times in the past 52 years, once at most in 1 year. Furthermore, cold wave of influence range above 50 % never happened again after 1996. In addition, cold wave did not happen in 1990.

3.2.3 Inter-annual change of station-day counts-based cold wave intensity

Lin and Wu (1998) have defined a cold wave composite index based on maximum temperature fall, extreme minimum temperature and duration of temperature declination. However, this index is generated by standardization based on averaged value of all years' cold wave, which only reveals the variance relative to multi-years' average. Moreover, the computing process of this index seems to be complicated and is difficult to apply. Therefore, this method was not adopted in this paper. On the contrary, as we mentioned above, both influence range and duration can reflect the intensity of cold wave, while station-day counts reflects combined effect of cold wave both in space and in time. By supposing that it can preferably reflect the combined influence of all cold wave events, station-day counts was taken as the index for annual cold wave intensity in this paper.

As can be seen in Fig. 5, there is an obvious decrease trend in cold wave station-day counts. Linear trend shows that the decline rate is 5.5 station-day per year. Ten-year moving average was big in late 70 s to early 80 s, decreased afterward and grew a little in 90 s. But after 2000, this value stayed in a low level. In addition, this averaged count for recent 30 years (1981–2010) was 271 station-day, which was much smaller than that of the past 30 years (1971–2000)—394 station-day. As can be seen from many statistical results, cold wave impact in Guangdong was declining, which can be seen from that the influence range was getting smaller and the influence duration getting shorter, both claiming the trend of warming up in Guangdong.

3.2.4 Periodicity analysis of cold wave intensity

As mentioned above in 3.3, annual cold wave intensity can be reflected by sum of station-day counts of all cold wave events. In order to analyze the periodic change of cold wave intensity, we used Morlet wavelet analysis tool to do wavelet transform to yearly data (1961–2012) of station-day counts; we got distribution (Fig. 6) for wavelet coefficient of

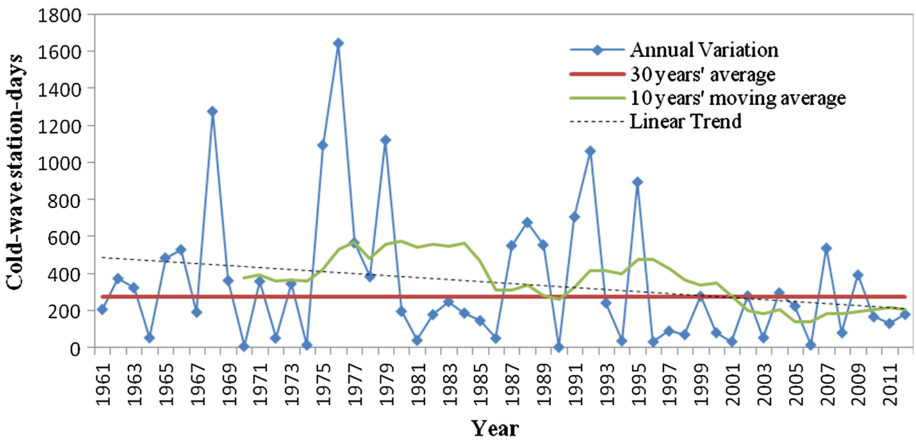

Fig. 5 Inter-annual change of cold wave station-day counts

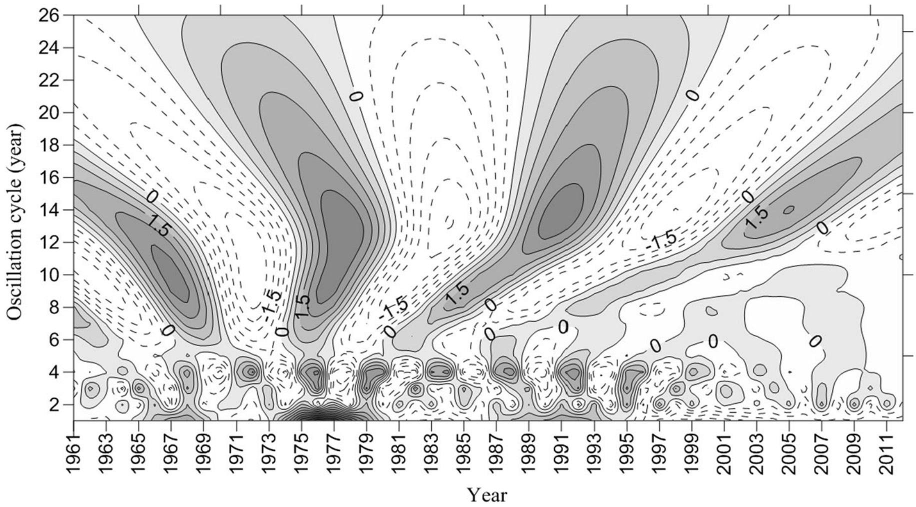

Fig. 6 Distribution for wavelet coefficient of yearly station-day counts

yearly station-day counts' every oscillation period. Values in the figure represent wavelet coefficient; positive values indicate stronger oscillation; negative values indicate weaker oscillation. The results show that cold wave intensity in Guangdong has an inter-decadal oscillation period of 10–14 years, which is similar to the conclusion of 14-year oscillation by Wang et al. (2010) in an analysis of the cold wave in southeastern Shanxi Province. Besides, there is an obvious inter-annual oscillation period of 3–4 years pre-2000.

3.2.5 Monthly distribution of regional cold wave's beginning date

Cold wave mainly happened from October till March of the next year over Guangdong Province. Beginning date for each regional cold wave and its monthly distribution were calculated in this paper. The results (Fig. 7) show that the possibility that cold wave would occur on October is the least; in recent 52 years, only one small range of cold wave occurred in October—it is on October 30, 1978, with a 3-day duration, influencing 7 stations. As season advanced, it is more possible that cold wave would happen. The frequency of cold wave reached the peak on February and significantly reduced in March.

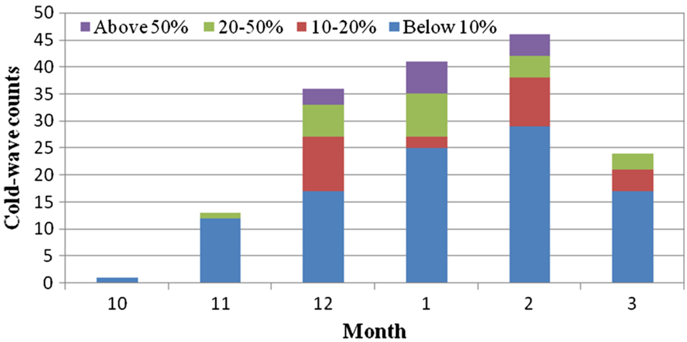

Fig. 7 Monthly distribution of regional cold wave's beginning date in recent 52 years

The percentage of total counts of cold wave occurred during December to next February reached 76 %. As can be seen, cold wave occurred the most in winter—December to next February, less in spring—March, and the least in autumn—October to November. Such conclusion is similar to the one by Lin and Wu (1998), that is 77.6 % of cold wave occurs in December to next February. It can be concluded that cold wave which originates in winter from high-latitude region, such as Siberia in Russia, is the strongest, which could reach Guangdong Province. However, cold wave in spring or autumn is weaker; it rapidly weakens before or after it reaches Guangdong.

3.3 Cases of large-range cold wave

As can be known from 2.5 above, influence range could preferably reflect cold wave intensity. Therefore, some cases whose influence range is larger than 50 % were selected for analysis in the part, and relevant indexes were calculated (Table 7: sorted by influence range in reverse order). As we described in 3.1.3, cold waves that took the northern invasion path were generally severe and large-region influential. Therefore, cold wave selected in this part all took the invasion path of north except for the one happened in January 1993. Description of several obvious cold wave events was listed below.

3.3.1 Cold wave in December 1991

Late December, a cold wave process—81 stations influenced, averaged 7.7 days of duration—invaded Guangdong. Most area to the north of the Tropic of Cancer suffered snow and freezing rain. The depth of snow reached 5–10 cm in plain and 30–40 cm in mountainous area. Its process temperature fall distribution was: northern north and coastal south 13.6–17 °C, rest district 17–20.2 °C. Extreme minimum temperature distribution was: north

Table 7 Features of large-range cold wave events with influence range over 50 %

Beginning date	Ending date	Station counts	Station-day counts	Averaged days of duration invaded	Process temp. fall	Mean temp.	Extreme minimum temp.	Extreme low temp. records
1991-12-25	1992-1-27	81	623	8	17.2	7.2	−5.5	−7.3
1976-12-25	1977-2-25	80	1574	20	18.1	7.1	−3.9	−7.3
1996-2-17	1996-3-1	76	774	10	18.6	6.3	−0.6	−3.0
1980-1-29	1980-2-17	74	1082	15	15.9	6.3	−2.6	−3.8
1990-1-31	1990-2-9	72	418	6	13.1	7.5	−1.4	−3.8
1969-1-29	1969-2-12	66	701	11	18.6	5.8	−3.8	−3.8
1974-2-24	1974-3-3	66	320	5	15.5	7	−2.4	−2.4
1979-1-29	1979-2-8	65	335	5	13.9	8.1	−1.9	−3.8
1993-1-15	1993-2-6	62	993	16	13.8	7.3	−3.1	−5.5
1975-12-9	1976-1-20	58	906	16	19.8	6.9	−5.2	−7.3
1989-1-11	1989-2-14	58	668	12	16.2	6.9	−1.1	−7.3
1972-2-3	1972-2-15	49	314	6	16.7	6.2	−2.9	−3.8
1966-2-22	1966-2-28	49	181	4	15.8	7.6	−0.1	−2.4

Process temp fall denotes averaged process air-temperature fall. Mean temperature stands for the average of multi-station air-temperature during the cold wave process

−5.5 to 0 °C, coastal southwest 3–4.5 °C, rest district 0–3 °C; the extreme minimum temperature of 10 stations including Lianshan (−5.5 °C), Xingning (−3.5 °C), Jiaoling (−2.9 °C), Wuhua (−2.4 °C) set lowest historical records. According to statistics, 1.8 billion RMB of economic loss was caused by such cold wave event; potatoes, corns, aquatic products, tropical plants had suffered different severity levels of damage (Pan 2000).

3.3.2 *Cold wave in December 1976*

Late December, a cold wave event—with 80 stations influenced and averaged 19.7 days of duration, invaded Guangdong. There is little sunlight appearing in the whole of Guangdong Province more than a month. Its 48-h temperature fall distribution is as follows: northern northwest, western central-west, eastern east 8.3–13 °C, rest district 13–14.8 °C. Process temperature fall distribution was: part of north and coastal south 11.8–17 °C, northwest 19–22 °C, rest district 17°–19°. Extreme minimum temperature distribution was: north −3.9° to 0°, coastal southwest 2–5.8 °C, rest district 0–2 °C; the extreme minimum temperature of Doumen (2 °C) and Zhuhai (2.5 °C) set lowest historical records.

3.3.3 *Cold wave in December 1996*

Late February, a cold wave event—76 stations influenced, averaged 10 days of duration, invaded Guangdong. Because the weather was warm before the cold wave invasion, the whole of Guangdong Province suffered rapid temperature fall. Its 48-h temperature fall distribution was: southeast 7.3–14 °C, rest district 14–18.7 °C. Process temperature fall distribution was: eastern southeast 11.1–17 °C, rest district 17°–21°. Extreme minimum temperature distribution was: north −0.2° to 2°, south 3–6.5 °C, rest district 2–3 °C; the extreme minimum temperature of Xinhui (2.5 °C), Xinyi (2.6 °C), Lianjiang (3 °C) and Zhanjiang (3.8 °C) set lowest historical records.

February 19th to 21st northern Guangdong had experienced 3 days of snow, ice and frost. According to statistics, 21 districts—1.2 million people, 340,000 ha plants—suffered from the disaster. Aquatic breeding, planting and forestry had suffered from serious damage. 4.7 billion agricultural economic loss was caused by such a cold wave event (Pan 2000).

3.3.4 *Cold wave in December 1980*

Late January, a cold wave event—74 stations influenced, averaged 14.6 days of duration, invaded Guangdong. Its 48-h temperature fall distribution was: Leizhou peninsula 5.4 °C, western southwest, eastern east, part of central 12–14 °C, rest district 14–17.7 °C. Process temperature fall distribution was: Leizhou peninsula 7.4 °C, southeast, part of southwest 11.1–16 °C, rest district 16°–18.4°. Extreme minimum temperature distribution was: central south 2°–5.6°, north −2.6° to 2°; the extreme minimum temperature of Wengyuan (−1.9 °C), Xingning (−1.4 °C) and Jiaoling (−0.9 °C) set the lowest historical records.

3.3.5 *Snow disaster of southern China in 2008*

Snow disaster of southern China in 2008 was a large-range natural disaster of low temperature, sleet and freezing that happened in south China from middle of January to late of February 2008, which was caused by continuous cold air processes. During the disaster, much of the crops and trees were damaged and thousands of passengers and cars were blocked on highways. Even worse, in some areas, the electrical wire was disconnected. It caused direct economic losses of about 150 billion RMB in China (Chen et al. 2011). The influence range in Guangdong almost covered the whole province, but what should be noticed is that based on the criteria of Guangdong cold wave, there are only 22 stations which reached the standard of cold wave in Guangdong Province, so that such cold wave process should not be taken as an actual cold wave process. Its 48-h temperature fall distribution was: southwest, northern east 10–16.5 °C, rest district 6–10 °C. Process temperature fall distribution was: northwest, northern northeast 15–18.6 °C, south, eastern northwest 8–13 °C, rest district 13–15 °C. Extreme minimum temperature distribution was: north −2.9 to 3 °C, coastal south 5–7.3 °C, rest district 3–5 °C.

Table 8 Grading criteria of cold disaster

Cold disaster level	Process temperature fall	Minimum temperature
Heavy	≥10°	≤0°
	≥8°	≤−2°
Moderate	≥10°	≤5°
	≥8°	≤2°
Light	≥8°	≤5°

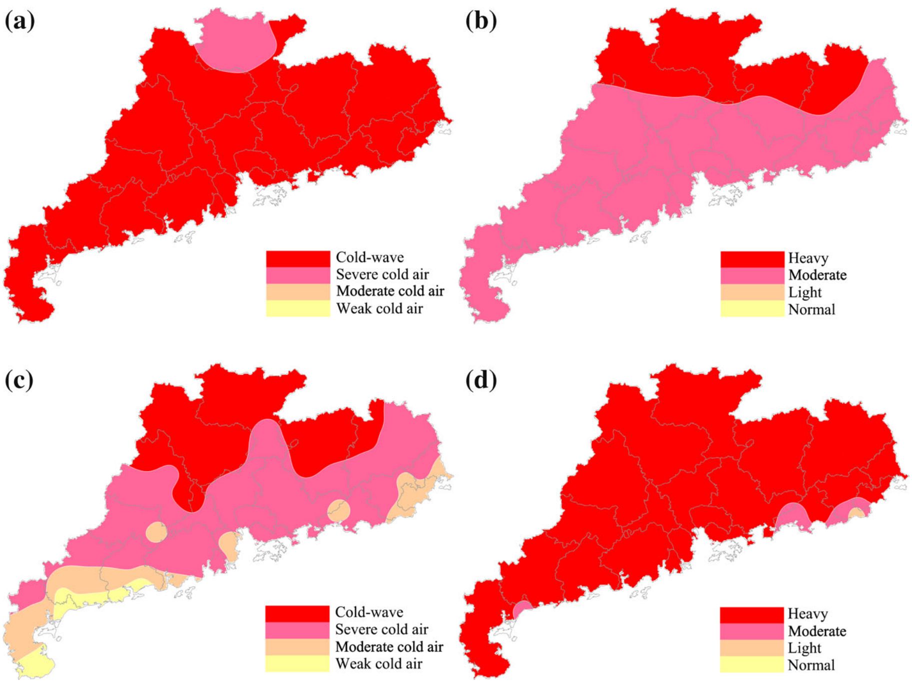

Fig. 8 Distribution of cold air levels (*left*) and cold disaster levels (*right*). *Note*: **a**, **b** represent cold wave event in 1991; **c**, **d** represent snow disaster in 2008

3.4 Cold wave and cold disaster

Cold wave is the highest level of cold air process; cold disaster (including levels of normal, light, moderate and heavy) is natural disaster that cold air process might cause and impact agriculture. There is obvious difference between them (criteria for cold wave, see Table 1; criteria for cold disaster, see Table 8): impact on agriculture or mankind activity. As can be seen by comparing cold air and cold disaster distribution figures of cold wave in 1991 and snow disaster in 2008 (Fig. 8), the cold wave process in 1991 had very large influence range—81 stations reached the standard of cold wave, but only 21 stations suffered heavy cold disaster. The snow disaster in 2008 caused heavy cold disaster to 82 stations, but only 22 stations reached the standard of cold wave. Just as Wang et al. (2004) mentioned, it could be deduced that, though the criteria of cold wave was widely used in metrological operation or research work, its limitation in reflecting the cold damage could not be ignored. Therefore, cold disaster index should be additionally considered in analyzing the cold air impact; the relationship between cold wave and cold disaster would deserve further research too.

4 Conclusions

All cold wave events which happened in Guangdong Province in recent 52 years were studied. And their spatiotemporal characteristics were thoroughly analyzed. Conclusions are listed below:

1. The cold wave frequency gradually decreased from north to south, from inland to coastal area and from highland to lower land, showing evident regional variance; if there occurred a large range of cold wave, the temperature fall caused by cold wave would be bigger in southwestern area than in the rest of Guangdong Province;
2. One hundred and sixty-one regional cold wave events invaded Guangdong in recent 52 years. There are three paths for cold wave invasion: north, northeast and west. Most of cold wave took the northern path (70 %), less took the northeastern path (26 %), and least took the western path (4 %);
3. Based on the influence range, regional cold wave can be divided into 4 grades: below 10, 10–20, 20–50 and above 50 %. The climatic characteristic of all grades shows that the larger the range of influence is, the severer the cold wave would be. Therefore, influence range can be used as an important index for judging the cold wave intensity.
4. As for cold wave counts for each station, the number of cold waves in recent 30 years (1981–2010) was smaller than that of the past 30 years (1971–2000) at most stations. In terms of regional cold wave process, cold wave whose influence range is smaller than 10 % happened almost every year and the frequency was 1.9 annually; cold wave whose influence range is larger than 50 % happened 13 times in recent 52 years, once at most annually; and cold wave with influence range above 50 % never happened again after 1996;
5. Station-day counts was proposed as the evaluation index for annual cold wave intensity in this paper. The research found that the intensity of cold wave over Guangdong was declining at the rate of 5.5 station-day per year; it also has an inter-decadal oscillation period of 10–14 years, and an obvious inter-annual oscillation period of 3–4 years pre-2000;

6. Cold wave frequency of each month varies significantly; as season advanced between December to next February, it is more likely that cold wave would happen. The frequency of cold wave reached the top on February and significantly reduced on March. Seventy-six percentage of cold wave occurred during December to next February;
7. The defining criteria of cold wave (see Sect. 2.1) can reflect severe temperature fall event but have limitation in reflecting several continuous cold air processes. For example, the snow disaster of 2008 had caused a great loss to Guangdong agriculture. But according to the criteria of cold wave, only 22 stations (25 %) of Guangdong actually reached the standard of cold wave. Therefore, the winter cold disaster index should be additionally considered when analyzing the disaster-causing impact by cold air process, and the relationship between cold wave and cold disaster is worth further research.

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