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Summary

During the past 130 years the global mean surface air temperature has risen by about 0.75 K. Due to feedbacks – including the snow/ice albedo feedback – the warming in the Arctic is expected to proceed at a faster rate than the global average. Climate model simulations suggest that this Arctic amplification produces warming that is two to three times larger than the global mean. Understanding the Arctic amplification is essential for projections of future Arctic climate including sea ice extent and melting of the Greenland ice sheet. We use the temperature records from the Arctic stations to show that (a) the Arctic amplification is larger at latitudes above 70°N compared to those within 64-70°N belt, and that, surprisingly; (b) the ratio of the Arctic to global rate of temperature change is not constant but varies on the decadal timescale. This time dependence will affect future projections of climate changes in the Arctic.

The twentieth century increase in global mean temperature has been well documented (about 0.75 K increase between 1880 and 2008) and has been attributed to a combination of natural and anthropogenic influences[1]. The instrumental temperature record has been roughly reproduced by a set of Atmosphere-Ocean General Circulation Models (AOGCMs) that are also being used to make projections of future temperature changes due to expected increase in atmospheric greenhouse gases[1]. The past climate records as well as climate model simulations have suggested a link between the Arctic and global climate change[2-12].

The observed global mean temperature change since 1880 has a combination of causes including increasing greenhouse gases[1], variation in the aerosol optical depth[13-15], natural and anthropogenic surface albedo changes[16], variability of solar radiation[17-21], variability of atmosphere-ocean circulation[22-24] and volcanic activity[25, 26]. Some of the causes act on an interdecadal scale while others are limited to a few years. One of the robust features of the AOGCMs is the finding that the temperature increase in the polar region is larger than the global increase at least partially due to the ice/snow-albedo feedback. The ice/snow-albedo temperature feedback operates mostly during the sunlit summer months when the contracting sea ice extent allows more solar energy to be absorbed by the Arctic Ocean. Specifically the surface air temperature change in the Arctic region is expected to be about two to three times the global mean[1, 8]. This robust feature of the AOGCMs has been challenged in the past[2, 27] as well as by a recent analysis[17] of the observed surface temperature records suggesting that the recent anthropogenic warming has been more pronounced at the lower and middle latitudes (from 45°S to 50°N) than in polar regions. Finally a recent attribution study[12] showed that IPCC climate models reproduced well the observed Arctic warming since about 1970, however, they failed to reproduce the large warming during the early part of the 20th century and the strong Arctic cooling during 1940 -1970.

The main objective of this work is to use the surface air temperature measurement time series to investigate observational evidence in support of Arctic amplification. A second goal is to find how short term forcing, lasting only a year or two, like the 1991 Mt. Pinatubo volcanic eruption and the strong 1998 El Nino affect the Arctic temperature.

Data

We consider the Arctic temperature[28] above 64°N. To maintain at least a modest latitudinal variability in Arctic temperatures, we divide it into two belts: the low Arctic from 64°N to 70°N and the high Arctic from 70°N to 80°N. The average near surface air temperature within each belt has been calculated as an average of distributed meteorological stations having almost uninterrupted long-term temperature records. We use annual and seasonal station averages to avoid gridding artifacts. There is fairly good coverage from Arctic land stations since about 1950 with just a few stations with continuous observations since around 1880. The seasonal averages and annual temperature data[29] for individual stations (with outliers already removed) are obtained from the NASA GISS site (http://data.giss.nasa.gov/gistemp/).

We calculate the low Arctic (64 to 70°N) temperature anomaly for the years 1950-2008 using the temperature records of 25 stations **(Fig. 1)** listed in the **Table 1**. We have selected only those stations with records up to the year 2008 that are at least 95%

complete. The missing data are treated as missing and no interpolation is performed. A subset of eight stations with sufficiently long records (at least 1882-2008) is used to calculate the Arctic temperature anomaly within the 64-70°N belt from 1880-2008.

The correlation coefficient (for the years 1950-2008) between un-smoothed annual temperatures of the 1950-2008 time series (calculated from all 25 stations) and the 1950-2008 time series (calculated using only 8 stations having long term records) is 0.94, suggesting that even the long term time series stations (1880-2008) represent reasonably well the average temperature anomaly within the 64 to 70°N belt. The high Arctic temperature anomaly (70 to 90°N) has been calculated only for the years 1950-2008 using twelve stations (Fig. 1).

First we limit our investigation to large episodic changes in internal climate modes or climate forcings (lasting a few years) that will dominate the transient temperature response. For this purpose we use the largest recent volcanic eruption in terms of stratospheric aerosol loading (Mt. Pinatubo in 1991) and the strongest El Nino event which occurred in 1998. The other causes of climate change – the solar irradiance changes, increasing greenhouse gases, variability of aerosol atmospheric loading, surface albedo changes, and changes in oceanic thermohaline circulation – vary the temperature only slowly within the considered short interval. Thus the temperature changes within a year or two of the considered "fast" event are likely dominated by that event and only weakly affected by other causes.

Mount Pinatubo Volcanic Eruption

We first analyze the effect of the Mt Pinatubo eruption on the mean global surface air temperature. **Figure 2a** shows the annual global mean temperature anomaly with respect to the 1950-2008 average and its five-year running mean. The year of the Mt Pinatubo eruption (1991) and the two following years (1992 and 1993) are denoted by the rectangular boxes (a similar mark in the year 1998 denotes the El Nino year). We note that the year of eruption is followed by two years (1992 and 1993) of cooler global temperatures. The global temperature decrease after the eruption is more evident when the long-term temperature variability is removed from the data by subtracting the 21-year running average (**Fig. 2b**). The Mt Pinatubo eruption is followed by two cold years[23] when the mean global temperature stays about 0.15K below 21-year running mean (the standard deviation is 0.10 K).

The mean of the annual Arctic temperature within the 64 to 70°N and 70 to 80°N latitudinal belts is shown in **Fig. 2c and 2d**. The cooling due to the 1991 Mt Pinatubo eruption appears only within the year of 1992 (compared to the two years signal in the global mean temperature) that in both belts is about 0.6 K below the long term average (the standard deviation is 0.5 K in the 64-70°N and 0.4 K in the 70-80°N belts).

The volcanic sulfate aerosol can affect the Arctic temperature by changes that occur directly within the Arctic region (local radiation budget) and by changes that occur outside the Arctic but are transported to the Arctic by atmosphere and ocean circulation. The direct aerosol effect (solar radiation is reflected by the sulfate aerosol back to space) can be effective only during the months of sunlight. Depending on the optical properties of the aerosol and on the surface albedo the effect may be cooling, warming or no change of an atmospheric column[20-31]. During the summer and fall months when a considerable part of Arctic Ocean is ice free (low albedo), the expected direct aerosol effect is cooling.

The temperature data suggest no statistically significant temperature change within the December to February (DJF) and March to May (MAM) seasons for the post Mt Pinatubo years 1992 and 1993 **(Fig. 3a and 3b)**. It is only in the summer (JJA) and the autumn (SON) seasons **(Fig. 3c and 3d)** of the year following the eruption that the temperature is affected by the volcanic aerosol. The summer temperature is about 0.6 K below the 1950-2008 average and the autumn temperature is 2.2K below the average. The temperature behavior within the 70 to 80°N belt (not shown) is very similar with no statistically significant changes during the winter (DJF) and spring (MAM) months, about 0.5 K cooling during the summer (JJA) and 0.7 K cooling during the autumn (SON) of 1992. We note that the summer cooling is about the same in both latitudinal belts, while the autumn cooling is larger in the 64 to 70°N compared to 70 to 90°N belt (2.2 K compared to 0.7 K). The fact that the Arctic cooling is observed just during 1992 suggests that the stratospheric aerosol might have dissipated over the Arctic before the summer of 1993 and thus no direct aerosol effect could arise. The lack of cooling during the winter and spring 1992 seasons and in the whole of 1993 suggests that the cooling at lower latitudes which persisted into 1993 did not propagate efficiently to the Arctic region.

El Nino of 1998

The strongest El Nino in the last few decades occurred in 1998. The perturbation in the equatorial Pacific caused significant temperature and precipitation anomalies in various regions around the world. The 1998 El Nino produced a globally averaged warming peak of about 0.2 K above the 21 year running average (Fig. 2b). However there is no indication of the El Nino signal in the Arctic annual or seasonal temperature record (Figs. 2c, 2d, and 3) suggesting that the strong 1998 El Nino effect did not extend to the Arctic region, or was offset by local cooling processes.

Long Term Temperature Trends

The ratio of the Arctic to the mean global temperature trend is an important parameter characterizing the main feature of the latitudinal distribution of the recent warming. The correct latitudinal distribution of the warming in models is essential for predicting the future melting of the Greenland ice sheet, sea ice, and permafrost. Recent analysis of observational data[18] raised some doubts related to the generally accepted assumption that the polar anthropogenic warming is about two to three times the mean global warming.

The annual mean Arctic temperature within the 64 to 70°N latitudinal belt and the mean global surface air temperature (data from the NASA GISS site) for the time span 1880-2008 is shown in **Fig. 4a**. The correlation coefficient between the annual un-smoothed Arctic temperature and the mean global temperature is 0.77 for the whole 1880-2008 time span and rises to 0.83 for the five year running averages. It is apparent that there are three distinct time intervals in the Arctic temperature record: warming trends from 1880-1940 and 1970-2008 separated by a cooling from 1940-1970.

The rate of the mean annual Arctic air temperature increase within 64-70°N is 0.35 K/decade from 1880-1940 and 0.40 K/decade from 1970-2008 (**Table 2**). The decreasing trend from 1940 to 1970 is -0.36 K/decade. Note that the absolute value of the Arctic temperature rate of change (warming or cooling) has changed only little between 0.35 to

0.40 K/decade during the three distinct periods within the 1880-2008 time span. At the seasonal resolution the largest increases or decreases of temperature occurred during the winter season and smallest during the summer (Table 2) indicating an importance of the large-scale dynamics[28].

The mean global surface air temperature rate of increase (Fig. 4a) was around 0.042 K/decade from 1880-1940 and 0.16 K/decade from 1970 to 2008. The cooling rate from 1940 to 1970 is –0.023 K/decade. The change of breakpoints in 1940 and 1970 by +/- 5 years does not make a significant difference in reported slopes. The rate of increase in the mean global temperature from 1970-2008 is about a factor of four larger compared to 1880-1940. This increase by a factor of four – caused presumably mainly by the increase in the atmospheric concentration of greenhouse gases – observed in the mean global temperature is not seen in the Arctic where the rate of warming in 1970-2008 is essentially same as the rate from 1880-1940 (0.40 K/decade compared to 0.35 K/decade). Possible causes of currently increasing global temperature, in addition to the anthropogenic warming due to increase in atmospheric greenhouse gases concentration[12], include post 1975 decrease of tropospheric sulfate aerosols[19-21], and changes in the atmospheric and North Atlantic circulation[13].

Due to fourfold changes in the rate of global temperature increase and effectively no change in the rate of the Arctic temperature change, the ratio of the long term average Arctic to mean global temperature change has not been a constant during the time span of instrumental data. The observed temperature changes suggest that the ratio of the Arctic to global mean temperature was about 8 from1880 –1940, around 16 during the cooling period from 1940-1970 and around 2.4 during the 1970-2008 warming.

The present day value of the Arctic to mean global warming deduced from the observed data is in agreement with the results of the climate models[12, 32]. The fact that this ratio was much different in the past suggests that there are physical processes and/or changes in the atmosphere/ocean circulation (e.g. Atlantic Multidecadal Oscillation) that are not yet fully understood and very likely not properly described by the current AOGCMs.

The high Arctic (70 to 80°N) temperature is available only from around 1948 **(Fig. 4b)** due to an insufficient number of stations in earlier years. The time span 1948 to 1970 is too short to provide any meaningful trend. Consequently only the increasing temperature period from 1970 to 2008 is used in our analysis. The high Arctic temperature did rise at the rate of 0.55 K/decade during 1970-2008 years. This is a higher rate of warming compared to 0.40 K/decade warming of the 64 to 70°N belt within the same time period. The ratio of the high Arctic (70 to 80°N) temperature trend to the mean global temperature trend in this time interval is 3.4. The ratio of the high Arctic (above 70°N) to global mean temperature change is higher than the same ratio for the 64 to 70°N belt, suggesting that the current Arctic warming proceeds at a higher pace at the high latitudes (above 70°N). This is likely due to a stronger sea ice albedo effect at higher latitudes. The maximum rate of warming in the high Arctic (above 70°N) occurs during the autumn seasons at the rate of 0.67 K/decade. A likely explanation is a minimum sea ice extent in September combined with a peak in surface ocean temperature (heated by a direct sunshine from spring to autumn).

Observations suggest that the current (since about 1970) ratio of the Arctic to mean global temperature change is around 2.5 for the 64 to 70°N latitudinal belt and around 3.4

for region north of 70°N. These values are in an agreement with recent AOGCMs results[14]. The ratio was, however, much different during the early warming period 1880-1940 when it was close to 8 (and close to 16 during the 1940-1970 cooling phase).

Our results are not an artifact of our splitting the Arctic temperature into two belts and of our way to calculate an average temperature of the belts. If we use the NASA GISS 64-90°N temperature (http://data.giss.nasa.gov/gistemp/) instead, the values of Arctic amplifications are very similar: 8, 15 and 3 K/decade for the time spans 1880-1940, 1940-1970 and 1970-2008.

Summary and Discussion

Our analysis of the Arctic temperature time series suggests that the ratio of change of the Arctic to mean global temperature increase was around 8 during the warming from 1880-1940 and has been reduced to around 2.5 and 3.4 for latitudinal belts between 64-70°N and 70-80°N during the current 1970-2008 warning period. This reduction of the Arctic amplification occurred because of an increase in the rate of global warming from 0.04/decade during 1880-1940 to an about 0.16 K/decade during 1970-2008, while the rate of Arctic warming increase only slightly from 0.35 to 0.40 K/decade. This suggests that the recent accelerated global climate change – caused presumably by anthropogenic increase in greenhouse gases – has not yet been effectively communicated to the Arctic region. Regional climate variability apparently dominates the Arctic climate change. The Arctic temperature changes seem to be at least partially decoupled from the global temperature change.

The recent warming of 1970-2008 proceeded at a faster rate at high Arctic above 70°N compared to the 64-70°N belt (0.55K/decade compared to 0.40K/decade). We attribute this accelerated pace of warming in the high Arctic to a positive sea ice (snow/ice albedo) feedback. The largest temperature changes within the high Arctic occurred during the autumn consistent with increased rate of sea ice reduction and direct solar heating of the open part of the Arctic Ocean during minimum sea ice extent. On the other hand the largest temperature changes within the 64-70°N belt occurred during the winter likely due to changes in the large scale atmosphere/ocean circulation. On average the high Arctic rate of temperature change is about 1.4-1.5 faster then a corresponding rate within the 64-70°N belt.

The1991 Mt Pinatubo volcanic eruption cooled the mean global temperature by around 0.15 K during the years 1992 and 1993, and cooled both Arctic belts (64-70°N and 70-80°N) by around 0.6K, however, for one year only (1992). This one year Arctic cooling was limited to the summer and autumn months and is attributed mainly to a direct aerosol effect. On the other hand there is no Arctic temperature signal that can be related to the strong 1998 El Nino.

Our analysis suggests that the ratio of the Arctic to global temperature change varies on a decadal time scale and that it depends on the type of forcing considered. The commonly held assumption of a factor of 2-3 in the Arctic amplification has been valid for the current warming period (1970-2008) only.

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Table 1: List of Arctic meteorological stations, their coordinates and time span of data.

High Arctic	Station	Longitude	Latitude N	Time Span
1	Barrow	156.8W	71.3	1901-2008
2	Resolute	95.0W	74.7	1947-2008
3	Eureka	85.9W	80.0	1947-2008
4	Danmarkshavn	18.7W	76.8	1951-2008
5	Jan Mayen	8.7W	70.9	1921-2008
6	Svalbard/Isfjord	15.5E	78.2	1912-2008
7	Bjornoya	19.0E	74.5	1949-2008
8	Vardo	31.1E	70.4	1880-2008
9	Vize	77.0E	79.5	1951-2008
10	Dikson	80.4E	73.5	1916-2008
11	Hatanga	102.5E	72.0	1929-2008
12	Kotel	137.9E	76.0	1933-2008
Low Arctic				
13	Mys Uelen	169.8W	66.2	1918-2008
14	Kotzebue	166.2W	66.9	1897-2008
15	Nome	165.4W	64.5	1906-2008
16	Fairbanks	147.9W	64.8	1929-2008
17	Coppermine	115.1W	67.8	1930-2008
18	Nuuk	51.8W	64.2	1880-2008
19	Angammassalik	37.6W	65.6	1895-2008
20	Reykjavik	21.9W	64.1	1901-2008

21	Akureyri	18.1W	65.7	1881-2008
22	Bodo Vi	14.4E	67.3	1880-2008
23	Tromo	19.0E	69.5	1880-2008
24	Haparanda	24.1E	65.8	1880-2008
25	Sodankyla	26.6E	67.4	1908-2008
26	Murmansk	33.0E	69.0	1918-2008
27	Arkhangelsk	40.7E	64.5	1880-2008
28	Narjan-Mar	53.0E	67.6	1926-2008
29	Salehard	66.7E	66.5	1882-2008
30	Tarko Sale	77.8E	64.9	1937-2008
31	Turuhansk	87.9E	65.8	1881-2008
32	Tura	100.2E	64.3	1928-2008
33	Olenek	112.4E	68.5	1935-2008
34	Dzardzan	124.0E	68.7	1936-2008
35	Verhojansk	133.4E	67.5	1885-2008
36	Zyrjanka	150.9E	65.7	1935-2008
37	Anadyr	177.6E	64.8	1898-2008

Table 2: Seasonal (MAM, JJA, SON, and DJF) and annual (ANN) rate of change of Arctic temperature (in K/decade) within 64-70°N and 70-80°N belts for time intervals indicated (columns 1 to 6), global annual temperature rate of change (column 7), Arctic amplification (column 8), and a ratio of change in high Arctic (70-80°N) to low arctic (64-70°N) belt (last column).

	MAM Arctic	JJA Arctic	SON Arctic	DJF Arctic	ANN Arctic	ANN Global	Arctic Amplification	High/Low Arctic
64-70°N								
1880-1940	0.30	0.29	0.38	0.46	0.35	0.042	8.3	
1940-1970	-0.26	-0.26	-0.36	-0.56	-0.36	-0.023	15.7	1.5
1970-2008	0.33	0.32	0.42	0.51	0.40	0.165	2.4	1.4
70-80°N								
1970-2008	0.58	0.30	0.67	0.57	0.55	0.042	3.3	
1948-1970					-0.53	-0.023	23.0	

Figure Captions

Fig. 1: Fig. 1: Map of Arctic stations (circles: 70-80°N; triangles: 64-70°N; double circles and double triangles: stations with records starting near 1880). The numbers correspond to the station numbers given in the first column of Table 1.

Fig. 2: (a) Annual mean temperature anomaly and its five-year running average (thick line). (b) Annual mean temperature anomaly with a long term 21-yaer running average removed. (c) Annual low Arctic (64 to 70°N) and (d) high Arctic (70 to 80°N) temperature anomaly. All temperature anomalies in this figure are with respect to the 1950-2008 average. The year of the Mount Pinatubo eruption, the two following years, and the year of the 1998 El Nino are denoted by the rectangular boxes.

Fig. 3: Seasonal temperature anomaly (a) winter, (b) spring, (c) summer, and (d) autumn, of the low Arctic (64 to 70°N) with respect to the 1950-2008 average. The year of the Mount Pinatubo eruption, the two following years, and the year of the 1998 El Nino are denoted by the rectangular boxes.

Fig. 4: (a) The mean stations temperature anomaly within the low Arctic (64 to 70°N) latitudinal belt (squares) and the mean of the global surface air temperature anomaly (diamonds) within the time span 1880-2008 and the corresponding five-year running averages (thick solid lines). The anomalies are with respect to the 1880-2008 average. (b) The same for the high Arctic belt. The anomalies are with respect to the 1950-2008 average.

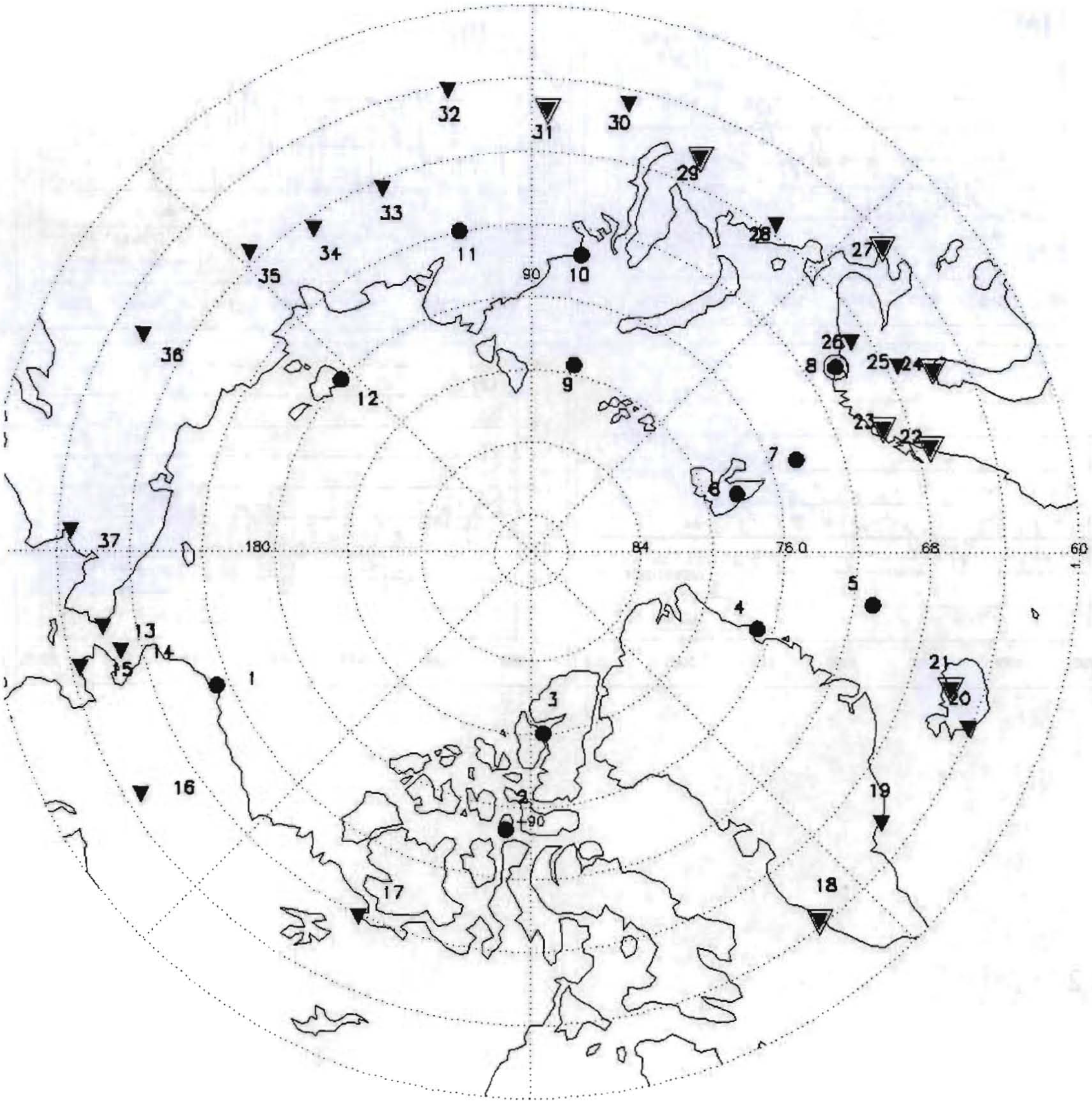
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Fig. 1

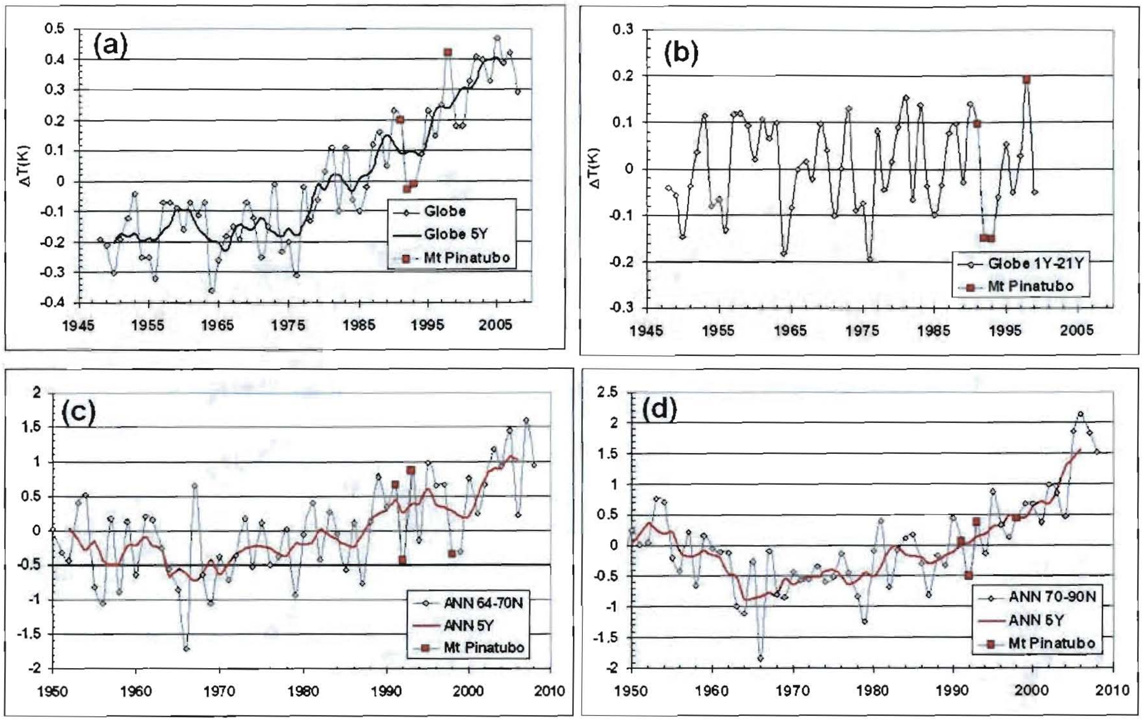
(a)
ΔT(K)
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
1945
1955
1965
1975
1985
1995
2005
Globe
Globe 5Y
Mt Pinatubo
(b)
ΔT(K)
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
Globe 1Y-21Y
Mt Pinatubo
(c)
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
1950
1960
1970
1980
1990
2000
2010
ANN 64-70N
ANN 5Y
Mt Pinatubo
(d)
2.5
ANN 70-90N
ANN 5Y
Mt Pinatubo

Fig. 2

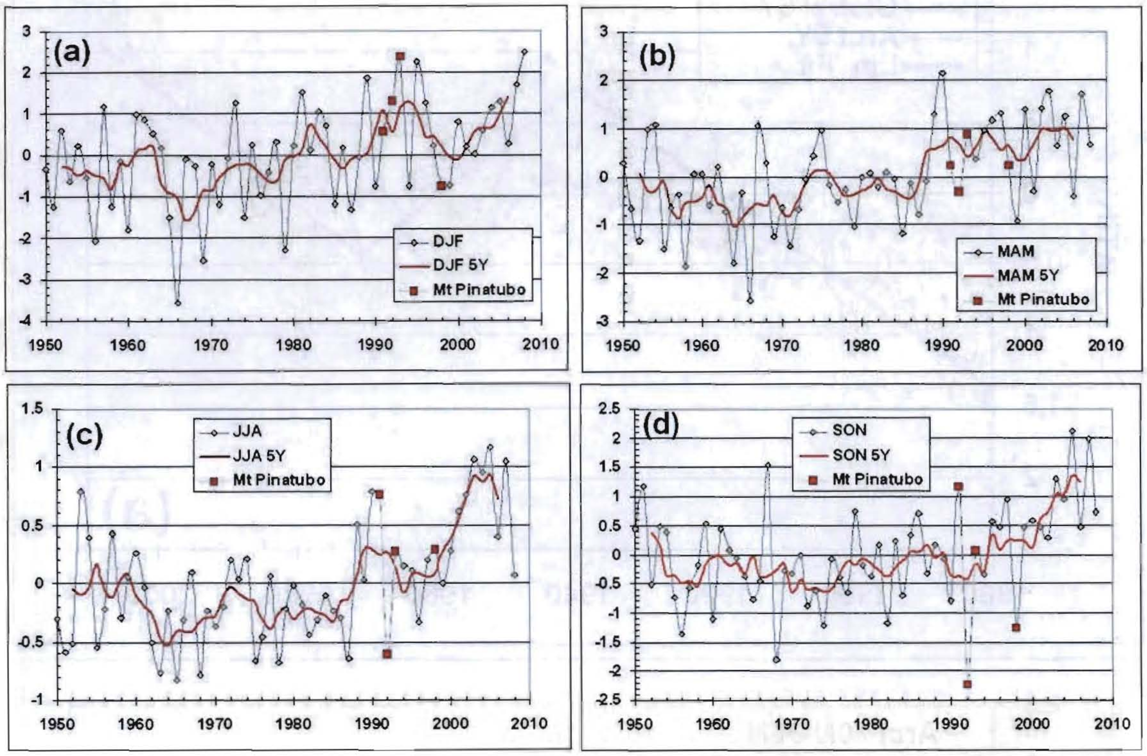
(a)
3
2
1
0
-1
-2
-3
-4
1950
1960
1970
1980
1990
2000
2010
DJF
DJF 5Y
Mt Pinatubo
(b)
3
2
1
0
-1
-2
-3
1950
1960
1970
1980
1990
2000
2010
MAM
MAM 5Y
Mt Pinatubo
(c)
1.5
1
0.5
0
-0.5
-1
1950
1960
1970
1980
1990
2000
2010
JJA
JJA 5Y
Mt Pinatubo
(d)
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
1950
1960
1970
1980
1990
2000
2010
SON
SON 5Y
Mt Pinatubo

Fig. 3

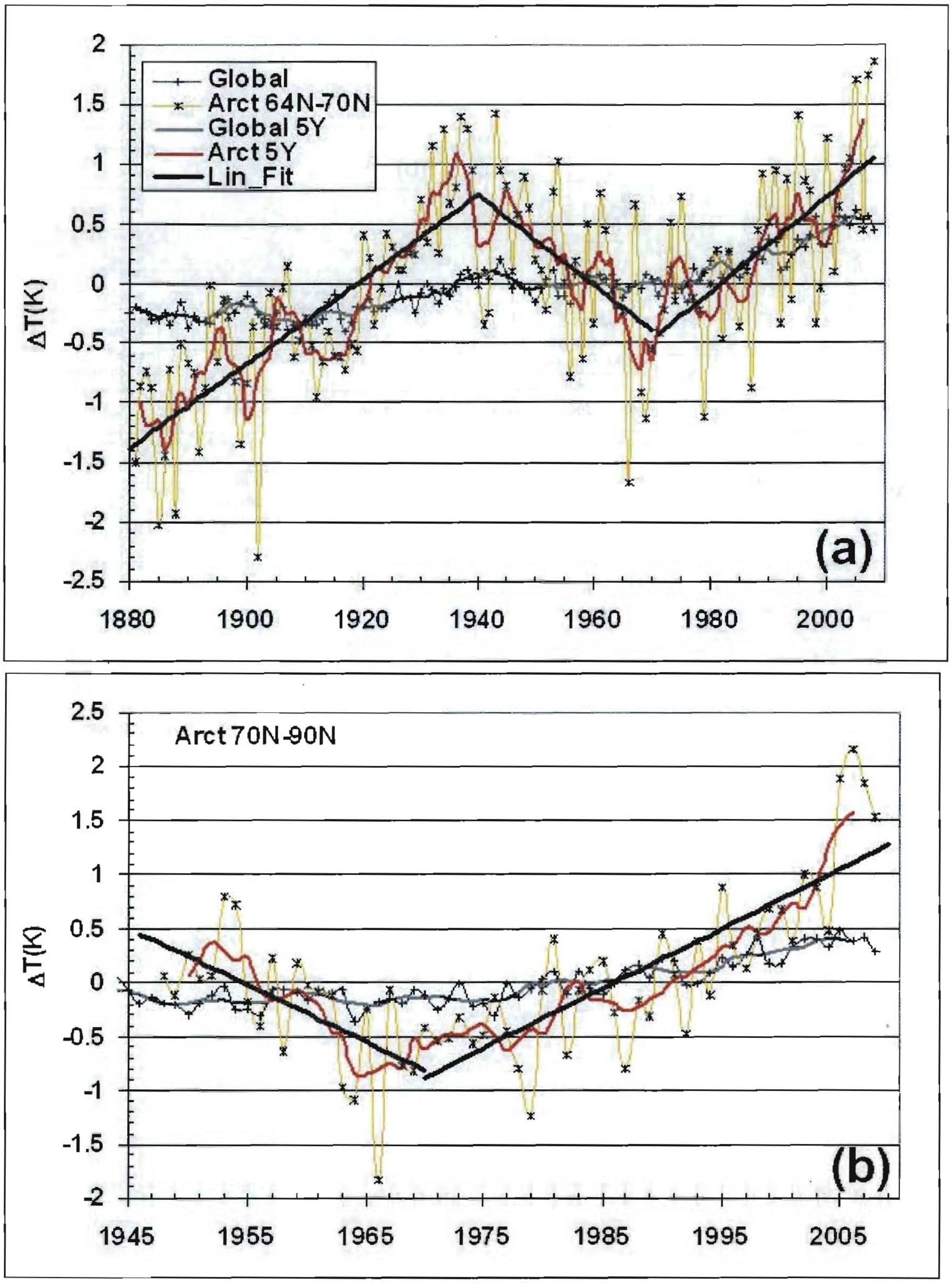
Global
Arct 64N-70N
Global 5Y
Arct 5Y
Lin_Fit
ΔT(K)
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
1880
1900
1920
1940
1960
1980
2000
(a)
Arct 70N-90N
ΔT(K)
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
1945
1955
1965
1975
1985
1995
2005
(b)

Fig. 4