**Atmospheric
Chemistry
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Discussions**

Observed and model simulated 20th century Arctic temperature variability: Canadian Earth System Model CanESM2

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Canadian Earth System Model CanESM2

P. Chylek et al.

Title Page

Abstract	Introduction
Conclusions	References
Tables	Figures

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Abstract

We present simulations of the 20th century Arctic temperature anomaly from the second generation Canadian Earth System Model (CanESM2). The new model couples together an atmosphere-ocean general circulation model, a land-vegetation model and terrestrial and oceanic interactive carbon cycle. It simulates well the observed 20th century Arctic temperature variability that includes the early and late 20th century warming periods and the intervening 1940–1970 period of substantial cooling. The addition of the land-vegetation model and the terrestrial and oceanic interactive carbon cycle to the coupled atmosphere-ocean model improves the agreement with observations from 1900–1970, however, it increases the overestimate of the post 1970 warming. In contrast the older generation coupled atmosphere-ocean general circulation models Canadian CanCM3 and NCAR/LANL CCSM3, used in the IPCC 2007 climate change assessment report, overestimate the rate of the 20th century Arctic warming by factor of two to three and they are unable to reproduce the observed 20th century Arctic climate variability.

1 Introduction

The Arctic is a region where climate change is amplified and therefore more easily detected and identified than in the global average. The observed climate change is driven by external climate forcing as well as by internal unforced natural climate variability. Disentangling the effects of these external and internal components is difficult but necessary for any reliable decadal-scale climate forecast (Keenlyside et al., 2008; Branstator and Selten, 2009; Solomon et al., 2011) and for identification of long-term trends induced by anthropogenic greenhouse gases and other radiative forcings. The effect of natural climate variability is expected to be much stronger in the Arctic than in the global mean due to the positive ice albedo feedback and the influence of meridional heat transported to the Arctic. The accuracy of decadal-scale forecasts of the Arctic

climate critically depends on our ability to delineate the effects of forced and natural climate change in the observed record.

Polar regions occupy a relatively small part of the globe. The climate changes in polar regions are not necessarily manifested in the global mean climate. If the Arctic warms and Antarctica cools (Chylek et al., 2010) the global mean can stay unchanged while changes in polar region may become significant. Since the Arctic region is expected to experience adverse impacts of climate warming (e.g. disappearing summer sea ice, melting of the Greenland ice sheet and associated sea level rise) with global consequences it is essential to know how accurate model simulations of the Arctic climate are. Models that cannot reproduce the past century of Arctic climate variability cannot be expected to provide a reliable projection of future Arctic climate changes.

In this paper we compare the observed 20th century Arctic temperature with the new Canadian Centre for Climate Modeling and Analysis (CCCma) simulations performed within the framework of CMIP5 (Climate Inter-comparison Project Phase 5) that will contribute results to the fifth assessment report of the IPCC. We also discuss simulations by the older CMIP3 models: CCCma third generation coupled atmosphere-ocean general circulation model CanCM3, and the NCAR coupled atmosphere-ocean CCSM3 model (NCAR atmospheric general circulation model coupled to the Los Alamos National Laboratory ocean and ice model) which contributed to the IPCC 2007 report.

2 CMIP3 simulations of 20th century Arctic climate

The Climate Models Inter-comparison Project Phase 3 (CMIP3) contains 63 individual simulations of the 20th century temperature (20C3M) produced by twenty coupled climate models forced by the known past century forcing (Meehl et al., 2007). The model simulations of the 20th century climate start with a control run where all the forcing agents are held constant at their pre-industrial level and the model is run for several hundred years to settle in a statistical steady state. The variability found in this control simulation characterizes the intrinsic model variability. To simulate anthropogenic

warming the model is then forced by prescribed 20th century forcing that evolves with time. This is usually done several times starting from different initial states of the control run. Each individual simulation represents model response to changing radiative forcing agents, and an intrinsic model variability (uncorrelated between different simulations). Averaging over several model simulations is expected to average out the effect of intrinsic model variability and to produce the model response to applied forcing which can then be compared to observations.

Wang et al. (2007) analyzed 63 individual simulations of the 20th century Arctic winter temperature obtained from the CMIP3 project and found that a total of nine models (CCSM3, CRISO-Mk3.0, INM-CM3.0, ECHO-G, PCM, CGCM3.1(T47), CGCM3.1(T63), CNRM-CM3 and UKMO-HadCM3) produced better than average simulations of the observed Arctic 20th century temperature variability in at least one of their realizations. The CCSM3 model (National Center for Atmospheric Research Atmospheric General Circulation Model coupled to the Los Alamos National Laboratory ocean model) and the Canadian CGCM3 were among the models characterized as the better models for the Arctic (Wang et al., 2007).

3 Canadian CMIP5 models: coupled atmosphere-ocean general circulation model CanCM4, and the earth system model CanESM2

The atmospheric component of CanCM4 is the fourth generation atmospheric general circulation model, which has 35 layers from the surface up to 1 hPa. New with respect to the CCCma third generation model CanCM3 (Scinocca et al., 2008) are the correlated-k distribution radiation algorithm (Li and Barker, 2005), an accurate aerosol optical property parameterization, aerosol direct and indirect radiative effects using a prognostic bulk aerosol scheme, and a new shallow convection scheme (von Salzen and McFarlane 2002).

The CanCM4 ocean component differs from that of CanCM3 in that it has 40 levels with approximately 10 m resolution in the upper ocean. Diapycnal ocean mixing is

represented by the K-profile parameterization (Large et al., 1994) and a tidally-driven mixing parameterization similar to that of Simmons et al. (2004). Horizontal friction is described by anisotropic viscosity (Large et al., 2001), and subsurface heating by penetrating shortwave radiation is dependent on the model's prognostic ocean chlorophyll as described in Zahariev et al. (2008), where the model's interactive ocean carbon cycle is also described.

Canadian Earth System Model CanESM2 combines the CanCM4 model and the terrestrial carbon cycle based on the Canadian Terrestrial Ecosystem Model (CTEM) (Arora and Boer, 2010) which models the land-atmosphere carbon exchange. The CTEM models all primary terrestrial ecosystem processes including land use change based on historical changes in crop areas.

The concentrations of greenhouse gases and solar variability are based on the CMIP5 recommendations. In addition the effects of volcanic eruptions are included.

4 Arctic 20th century temperature anomaly

The Arctic 20th century observed mean temperature anomaly with respect to the 1900–2000 average using the NASA GISS temperature data (Hansen et al., 2010) north of 64°N based on meteorological stations (http://data.giss.nasa.gov/gistemp/) is shown in Fig. 1 (a thick black line in all panels). The first three panels show simulations of the 20th century Arctic temperature anomaly with the Canadian third generation coupled atmosphere-ocean model CanCM3 used in the IPCC 2007 report (Fig. 1a), the same simulation with the fourth generation model CanCM4 (Fig. 1b), and the simulation with the Canadian Earth System Model CanESM2 (Fig. 1c). The individual simulations (five for CanCM3 and CanESM2 and three for CanCM4 model) are shown in thin color lines and thick red lines are models ensemble means.

Comparing the observed Arctic temperature variability with models simulations, it is apparent that the CanCM3 simulations and their ensemble average do not capture the amplitude of the early 20th century warming period and the following (1940–1970) cooling.

The agreement between the observed and model simulated 20th century Arctic temperature is significantly improved by the fourth generation Canadian coupled atmosphere-ocean general circulation model CanCM4 (Fig. 1b). The amplitude as well as the timing of the early 20th century warming and the following cooling period is now in a much better agreement with observations. As a measure of agreement between the model ensemble mean and the observations we use the variance of the difference of the observed and modeled temperature anomaly (with respect to 1900–2000 mean), which is $0.13 \, K^2$ for the CanCM4 model compared to $0.31 \, K^2$ for the third generation model CanCM3. The inclusion of CTEM (a dynamic vegetation and transition from CanCM4 to CanESM2) does not improve further the agreement between the observed and modeled temperature anomaly leaving the variance of $0.13 \, K^2$ unchanged.

Figure 1 also shows (panel d) the eight individual simulations and the ensemble average of the 20th century Arctic temperature anomaly produced by the CCSM3 model (NCAR atmospheric GCM coupled to the LANL ocean model). The model is unable to reproduce the 20th century Arctic temperature variability similarly to the Canadian CanCM3.

All individual CanCM4 and CanESM2 simulations (Fig. 1b and c) reproduce reasonably well the 20th century Arctic temperature anomaly including the early century warming and subsequent 1940–1970 significant cooling. In contrast the individual simulations of the CMIP3 models (CanCM3 and CCSM3) cannot reproduce the early 20th century warming and the subsequent cooling periods (Fig. 1a and d).

A significant improvement of the CanCM4 and CanESM2 models compared to the CMIP3 generation models (CanCM3 and CCSM3) is further demonstrated by comparing ensemble averages of model simulations. Figure 2a and b shows the five year moving averages of the temperature anomaly of the ensemble means of the considered models (colored curves) together with the observed temperature (black curve) anomaly.

We note that a single linear fit to 20th century Arctic temperature does not capture the richness of Artic temperature variability. Figure 2c shows three clearly different

P. Chylek et al.

Title Page

Abstract	Introduction
Conclusions	References
Tables	Figures

|◄ | ►|

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

temperature trend regimes with 1900–1940 and 1970–2000 warming periods inter-rupted by an equally steep 1940–1970 cooling period. A three-piece linear fit describes the Arctic temperature variability more accurately. The Arctic amplification has a signif-icantly different value in each of the three segments (Chylek et al., 2009).

5   Arctic 20th century warming trend

The 20th century warming trend based on the NASA GISS data for the region north of $64°$ N is 0.08 K decade^{-1} (Fig. 3 red column in each panel). Trends of individual model simulations are shown in the yellow columns, and model ensemble averages in the black columns. It is apparent that all of the CanCM4 and CanESM2 (CMIP5 models) individual simulations do reproduce the observed 20th century Arctic temperature trend reasonably well (Fig. 3b and c).

On the other hand the individual CanCM3 and CCSM3 (CMIP3 models) simulations show the 20th century warming trends between 0.17 and 0.26 K decade^{-1} (Fig. 3). Thus the individual CanCM3 and CCSM3 (NCAR/LANL) simulations and their ensem-ble averages overestimate the observed 20th century Arctic temperature trend by a factor of two to three.

A comparison of model simulations with observations within each of the distinct warming and cooling periods (1900–1940, 1940–1970, and 1970–2000) is summa-rized in Table 1. In general the CMIP5 models (CanCM4 and CanESM2) simulate tem-perature variability much better than CMIP3 models (CanCM3 and CCSM3), although the temperature peak in the early part of the 20th century is still significantly under-estimated. The CanCM4 model with the added vegetation and carbon cycle (which becomes CanESM2) performs better than the CanCM4 alone within the 1900–1940 and 1940–1970 periods. However, the CanESM2 overestimates by over 50% the rate of the 1970–2000 warming (Table 1) which may make its application to future Arctic climate somewhat problematic.

6   Summary and discussion

We have compared the Canadian CMIP5 generation models (coupled atmosphere-ocean general circulation model CanCM4 and the Earth System Model CanESM2 that includes dynamic vegetation) simulations of the Arctic 20th century temperature variability with the observed Arctic temperature. We found that the model simulations and the observed 20th century Arctic temperature variability (including the early 20th century warming) are in a reasonable agreement. This represents a considerable improvement compared to the earlier version of the Canadian CanCM3 and the NCAR/LANL CCSM3 models (used in the IPCC 2007 report) which do not reproduce the early 20th century warming (1900–1940) and the subsequent cooling period (1940–1970).

A reason for the large improvement of the CanCM4 and CanESM2 20th century Arctic simulations over those by the CanCM3 and the NCAR/LANL CCSM3 is currently not clear. Likely candidates include more realistic treatment of atmospheric aerosols (Mishchenko et al., 2010), surface use changes (Pielke et al., 2002, 2007) and clouds, and perhaps a better characterization of 50–80 yr climate modes related to the Atlantic Multidecadal Oscillations (Polyakov and Johnson, 2000; Dijkstra et al., 2006; Chylek et al., 2009, 2010, 2011).

Since the earlier (CMIP3) CanCM3 and CCSM3 (NCAR/LANL) models are not able to reproduce the 20th century Arctic temperature variability and since their simulated 20th century warming trend is 2 to 3 times higher that the observed warming trend, applications of these models for projections of the future Arctic climate (Arctic temperature, sea ice extent, Greenland ice sheet melt or sea level rise) has to be taken with great caution. Similar reservations apply to regional Arctic models that are driven by boundary conditions produced by these CMIP3 generation models.

The CanCM4 and CanESM2 models' ability to reproduce the past Arctic temperature behavior is no guarantee of a skillful prediction of the Arctic future climate change. To reproduce the past is a necessary, but not a sufficient condition for a successful future forecast. On the other hand, the earlier CMIP3 models (CanCM3 or the NCAR/LANL CCSM3) are clearly a poor choice for the Arctic climate forecast.

We note that the addition of a dynamic land-vegetation model to the coupled atmosphere-ocean general circulation model does improve the agreement between simulated and observed early 20th century warming (1900–1940) and the subsequent cooling (1940–1970), however it also increases the overestimate of the late (1970–2000) warming rate compared to the observed one.

The new Canadian CMIP5 models (CanCM4 and CanESM2) do show a significant improvement in reproducing the 20th century Arctic temperature variability. To identify all the processes responsible for this improvement further detailed diagnostics and additional simulations are needed. It will be interesting to see how other CMIP5 models will be able to reproduce the observed 20th century Arctic temperature variability, and, when appropriate, what is the source of model improvements compared to the CMIP3 simulations.

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Canadian Earth System Model CanESM2

P. Chylek et al.

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◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper

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Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Table 1. Rates of temperature change per decade in three distinct Arctic temperature trend sections in K decade^{-1} (rows 3 to 5) or in % with respect to observed change according to the NASA GISS data (rows 7 to 9). Numbers in parenthesis indicate a model trend in a direction opposite to observation (model warming instead of observed cooling).

Model	CanCM3 CCCma	CanCM4 CCCma	CanESM2 CCCma	CCSM3 NCAR	NASA GISS
	K decade^{-1}	K decade^{-1}	K decade^{-1}	K decade^{-1}	K decade^{-1}
1900–1940	0.15	0.13	0.19	0.13	0.43
1940–1970	[0.08]	−0.21	−0.25	[0.13]	−0.35
1970–2000	0.44	0.41	0.55	0.33	0.35
	%	%	%	%	%
1900–1940	35	30	41	31	100
1940–1970	[−21]	60	71	[−37]	100
1970–2000	124	116	156	93	100

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◀◀ | ▶▶

◀ | ▶

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion
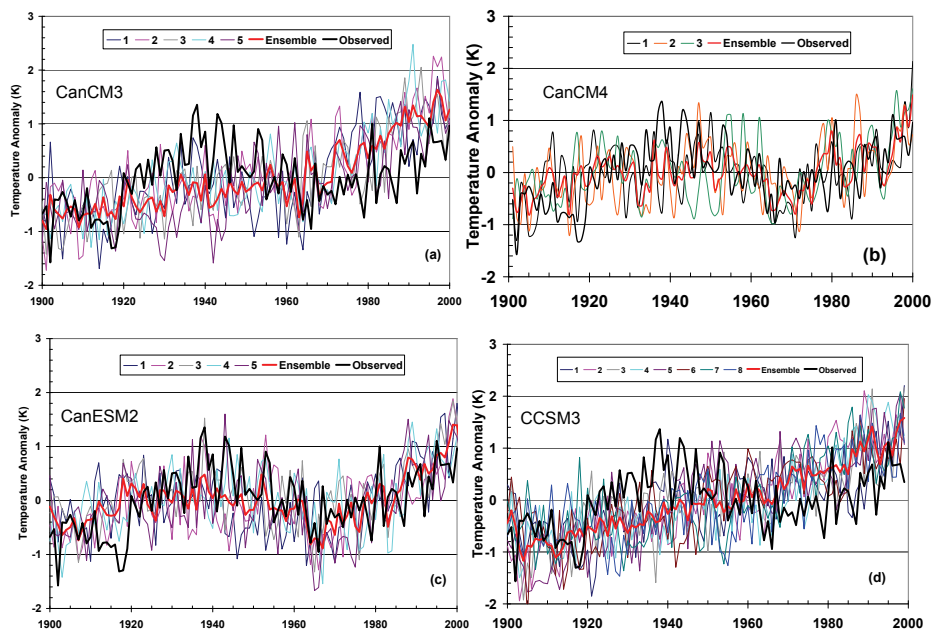
Fig. 1. Observed mean Arctic 20th century annual temperature anomaly (thick black line) compared to model individual simulations (thin colored lines) and model ensemble average (thick red line) for **(a)** the Canadian coupled atmosphere-ocean general circulation model CanCM3 model (five simulations), **(b)** Canadian CanCM4 model (three simulations), **(c)** the Canadian Earth System Model CanESM2 (five simulations), and **(d)** NCAR/LANL coupled atmosphere-ocean general circulation model CCSM3 (eight simulations). The considered CMIP5 models (CanCM4 and Can ESM2) reproduce the 20th century Arctic temperature variability much better than the considered CMIP3 models (CanCM3 and CCSM3).
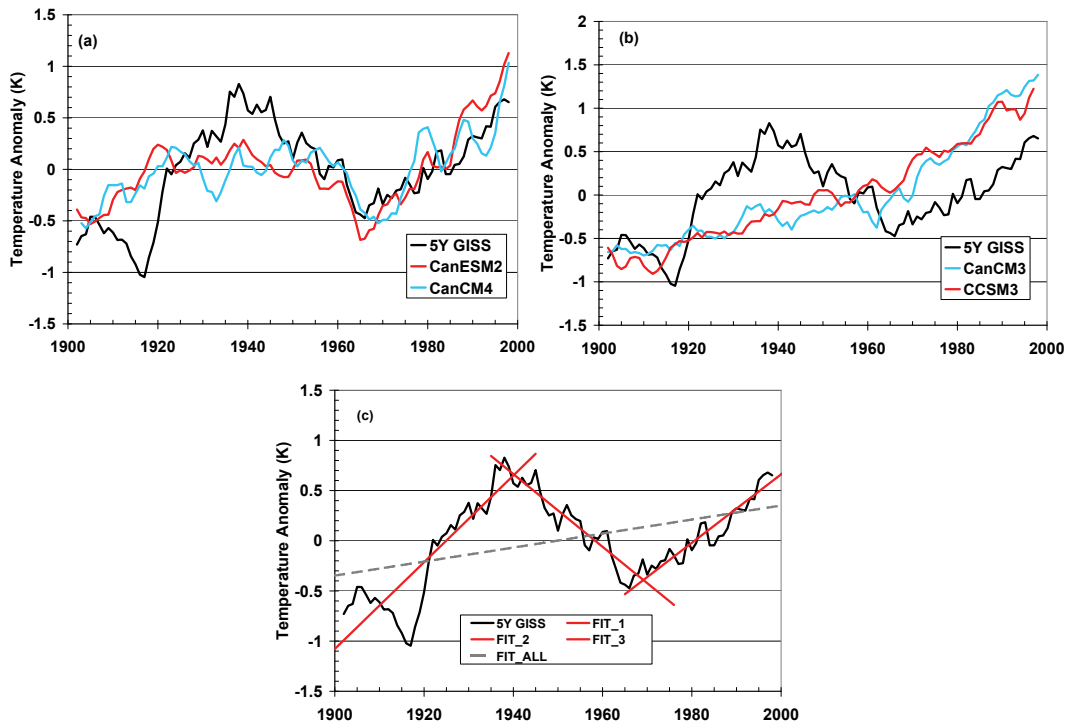
Fig. 2. Five year moving average of the 20th century observed Arctic temperature anomaly (black thick line) together with **(a)** the Canadian CanCM4 (blue) and CanESM2 (red) simulation ensemble average, and **(b)** the CanCM3 (blue), and the NCAR/LANL CCSM3 (red) simulation ensemble average, and **(c)** the Arctic 20th century temperature variability (black) is captured much better by a three piece linear fit (red) than a simple linear trend (dashed black line).

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

|◄ | ►|

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion
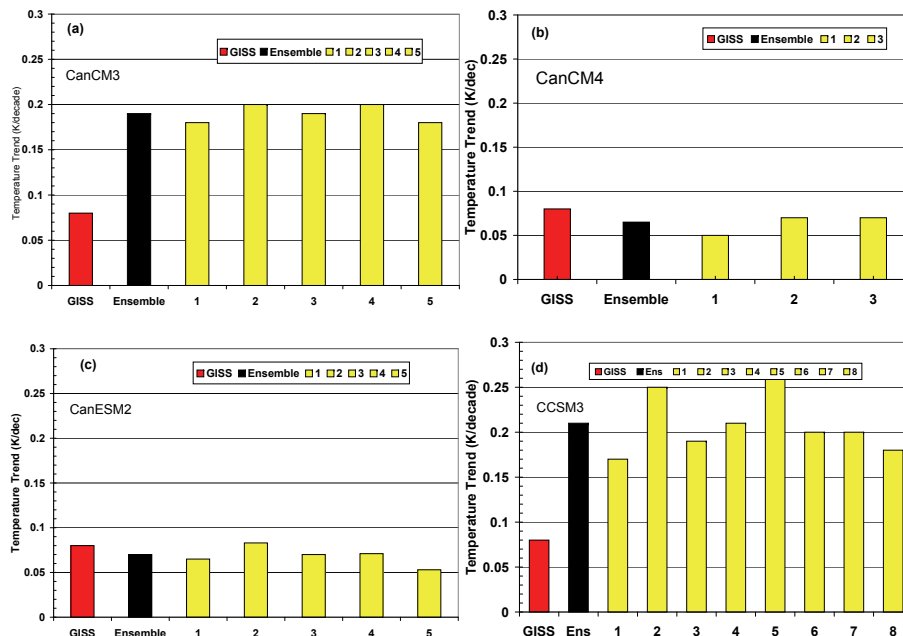
Fig. 3. The Arctic 20th century observed temperature trend (red column) compared with the trends of models' individual simulations (yellow columns) and the trends of models ensemble averages (black columns) for **(a)** Canadian CanCM3 model, **(b)** Canadian CanCM4, **(c)** Canadian CanESM2, and **(d)** NCAR/LANL CCSM3 model. The CMIP5 models (CanCM4 and CanESM2) match reasonably well the observed temperature trend, while the CMIP3 models (CanCM3 and CCSM3) used in the IPCC 2007 report overestimate the 20th century Arctic temperature trend by a factor of two to three.