Reliability of the IPCC AR4 Models: A 20th Century Intercomparison of the Freezing/Thawing Index

NSIDC National Snow and Ice Data Center

CIRES

Oliver W. Frauenfeld (oliverf@colorado.edu), Tingjun Zhang, Andrew J. Etringer, and Haiyan Teng

Support from NSF OPP-0229766 and ARC-0612431

Motivation

The annual freezing/thawing index can be used to predict and map permafrost and seasonally frozen ground distribution, active layer and seasonal freeze depths, and has important engineering applications, thereby providing important information on climate variability in cold regions. Most general circulation models (GCMs) do not consider or evaluate permafrost. Therefore, ***we calculate the freezing/thawing index based on projections of surface air temperatures for the permafrost and seasonally frozen ground regions of the Northern Hemisphere***.

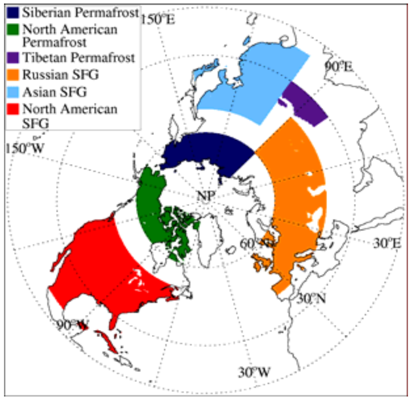

Figure 1. Regions used in this investigation. Not pictured, "Arctic:" land areas north of 50°N, and "Midlatitudes:" land areas from 20°N–50°N.

Goals

We use 5-member ensemble projections of surface air temperatures from the 16 models used in the Intergovernmental Panel on Climate Change (IPPC) Fourth Assessment Report (AR4) to provide an estimate of 21st century freezing/thawing index changes. We make use of four emission scenarios: "commit," "SRESA2," "SRESA1B," and "SRESB1" (see 2001 IPCC report).

An essential consideration in any projections of future climate is the degree to which models can actually reproduce past climate. We evaluate the freezing/thawing index from the IPCC AR4 model simulations' "20th Century Climate in Coupled Models" (20C3M) 5-member ensemble runs based on forcing with 20th century historical records, against our *Frauenfeld et al.* [2007] observed freezing/thawing index data from CRU TS 2.1 (http://nsidc.org/data/ggd649.html).

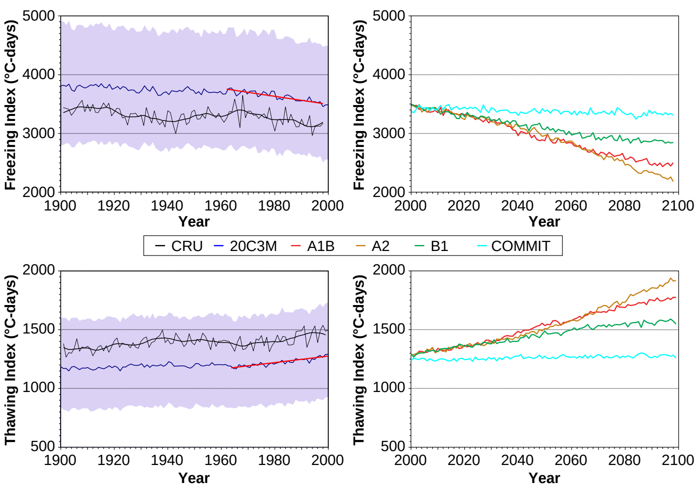

Figure 2. Freezing (top) and thawing (bottom) index time series for "Arctic," 1901–1999 (left) and 2000–2099 (right). CRU time series (black) is smoothed for ease of comparison with 20C3M. Blue shading corresponds to the 1-σ range among the 16 models. The trend line (red, left) corresponds to the objectively determined 1960s breakpoint in 20C3M.

Results

There is a significant cool bias in 20C3M for the Arctic region (Figure 2, left), manifest as freezing index values that are too high, and thawing index values that are too low. Additionally, the interdecadal variability is underestimated in 20C3M. It should be noted that among the eight regions investigated, this "Arctic" domain nonetheless represents a best-case scenario for agreement between observations and models.

Owing to these potential biases in the model, we next assess the correspondence of the 20C3M simulations against CRU for Northern Hemisphere climatologies. We also calculate trends for the recent decades (since 1960s breakpoint).

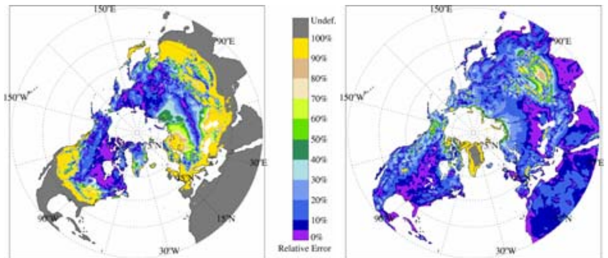

Figure 3. The % relative error (RE) between 20C3M and CRU for 1901–1999 (left, freezing index; right, thawing index). Cold season (left): much of the Eurasian Arctic and the Tibetan Plateau is too cold in the models, while midlatitudes are too warm—indicated by high REs. Warm season (right): the models are also too cold, though REs tend to be much lower.

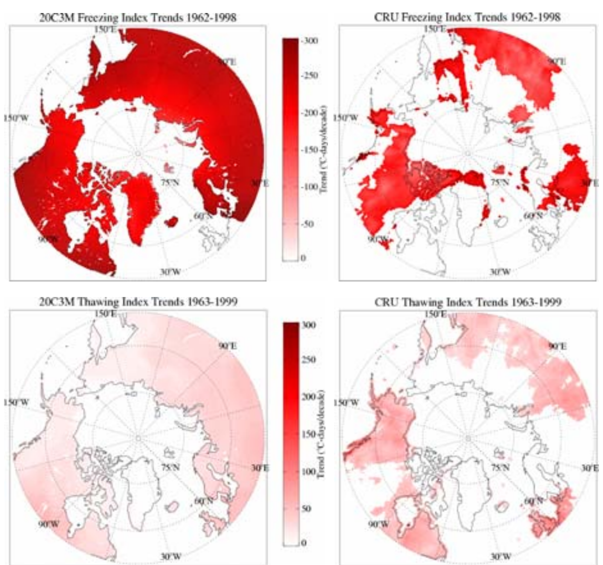

Figure 4. Freezing index trends over recent decades (top) are stronger and significant (95%-level) over all land areas in 20C3M (left), while observations (right) indicate significant trends only over certain regions. Similarly, during the warm season, thawing index trends (bottom) are again significant over all land areas, though weaker than observed trends. In general, warm season trends are much weaker than for the cold season, which is correctly captured in 20C3M.

Table 1. Correlations between freezing/thawing index from 20C3M and CRU, CAI, and ERA-40; statistically significant *R*s (95%-level) are bold; significantly equal means (1958–1998, *t*-tests) are italicized.

Domain	CRU		CAI		ERA-40	
Arctic	**0.59**	***0.64***	**0.61**	***0.59***	**0.52**	**0.54**
Midlatitudes	**0.59**	**0.74**	***0.64***	**0.77**	**0.50**	**0.51**
Permafrost Regions						
North America	**0.33**	***0.52***	**0.33**	**0.51**	*0.23*	**0.45**
Tibetan Plateau	**0.43**	**0.35**	**0.63**	**0.63**	0.10	0.18
Siberia	0.17	**0.39**	0.27	**0.32**	0.15	0.27
Seasonally Frozen Ground Regions						
North America	***0.34***	**0.58**	**0.32**	**0.54**	**0.32**	**0.49**
Asia	**0.51**	**0.59**	**0.52**	**0.64**	**0.46**	**0.44**
Russia	***0.50***	**0.52**	***0.51***	**0.44**	**0.48**	**0.45**

Table 2. Root mean squared error (RMSE) for the 1958–1998 freezing/thawing index between 20C3M and CRU, CAI, and ERA-40.

Domain	CRU		CAI		ERA-40	
Arctic	312	46	360	44	395	175
Midlatitudes	47	359	46	293	98	588
Permafrost Regions						
North America	518	66	522	110	254	142
Tibetan Plateau	724	229	874	582	723	192
Siberia	266	155	314	94	761	238
Seasonally Frozen Ground Regions						
North America	67	345	79	199	93	711
Asia	171	521	112	412	279	776
Russia	149	286	*150*	181	184	334

Are these large and significant differences between the models and observations due to shortcomings in CRU? The above tables provide: correlations, *t*-tests, and RMS errors between 20C3M and the freezing/thawing index from: CRU, Legates and Willmott CAI version 1.02 T_{air}, and ERA-40.

In general, correlations are highest and RMSEs lowest between CRU and 20C3M, i.e. we are not biasing our results by using this particular observational data set; *t*-tests also indicate that the models have significantly different means in virtually all regions, for all data sets.

Table 3. 1958–1999 trends in freezing (top) and thawing (bottom) index in °C-days/decade; bold if statistically significant (95%-level). Since 20C3M represents 5-member ensembles of 16 models, the time series are greatly smoothed. Indicated also, therefore, in parentheses, are the normalized trends, to allow for more accurate comparison between regions and data sets.

Domain	CRU		CAI		ERA-40		20C3M	
Arctic	**−63**	**(−0.44)**	**−76**	**(−0.48)**	**−52**	**(−0.39)**	**−56**	**(−0.70)**
Midlatitudes	**−19**	**(−0.43)**	**−28**	**(−0.52)**	**−13**	**(−0.34)**	**−11**	**(−0.62)**
Permafrost Regions								
North America	**−98**	**(−0.40)**	**−113**	**(−0.43)**	**−92**	**(−0.37)**	**−72**	**(−0.63)**
Tibetan Plateau	**−34**	**(−0.30)**	**−236**	**(−0.63)**	3	(0.02)	**−52**	**(−0.65)**
Siberia	−60	(−0.25)	**−96**	**(−0.34)**	−55	(−0.21)	**−63**	**(−0.66)**
Seasonally Frozen Ground Regions								
North America	**−20**	**(−0.28)**	−17	(−0.23)	−14	(−0.25)	**−13**	**(−0.55)**
Asia	**−36**	**(−0.41)**	**−45**	**(−0.45)**	**−26**	**(−0.35)**	**−14**	**(−0.43)**
Russia	−35	(−0.22)	−38	(−0.22)	−27	(−0.18)	**−25**	**(−0.48)**

Domain	CRU		CAI		ERA-40		20C3M	
Arctic	**25**	**(0.44)**	**23**	**(0.42)**	**18**	**(0.32)**	**22**	**(0.70)**
Midlatitudes	**43**	**(0.46)**	**47**	**(0.49)**	17	(0.20)	**47**	**(0.69)**
Permafrost Regions								
North America	**31**	**(0.42)**	**30**	**(0.42)**	**19**	**(0.29)**	**14**	**(0.59)**
Tibetan Plateau	5	(0.10)	**192**	**(0.58)**	0	(−0.01)	**17**	**(0.60)**
Siberia	15	(0.24)	**17**	**(0.27)**	10	(0.15)	**16**	**(0.58)**
Seasonally Frozen Ground Regions								
North America	**34**	**(0.37)**	**31**	**(0.33)**	19	(0.22)	**47**	**(0.67)**
Asia	**34**	**(0.34)**	**42**	**(0.42)**	22	(0.21)	**32**	**(0.63)**
Russia	**48**	**(0.39)**	**36**	**(0.32)**	**30**	**(0.27)**	**40**	**(0.66)**

Trends suggest the IPCC models are statistically significantly warming for all Northern Hemisphere permafrost and seasonally frozen ground regions. However, the three observational data sets indicate distinct regional differences, suggesting that the models may be over-estimating historical warming in the 20th century. Furthermore, when calculating the normalized trends (accounting for lower standard deviation in the smoother model time series), the 20C3M model trends are much greater in all instances, almost twice the magnitude of the observed trends in many cases.

Conclusions

We note some significant differences between models and observations over the 20th century. The models are too cold (higher freezing indices) in high latitudes/altitudes during the cold season, and too warm in middle latitudes. During the warm season, the models are too cold (lower thawing indices) over most of the Northern Hemisphere. ***Trends over recent decades are greatly overestimated by the models*** as well, resulting in ***too much warming that is too widespread***. While we do show the freezing/thawing index for the Arctic for various emission scenarios over the 21st century in Figure 2, ***we urge caution given the potential model shortcomings over the 20th century***.