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Tropical Pacific impacts on cooling North American winters

Michael Sigmond* and John C. Fyfe

The North American continent generally experienced a cooling trend in winter over the early 2000s. This cooling trend represented a significant deviation from expected anthropogenic warming and so requires explanation. Previous studies indicate that climate variations in the tropical Pacific contributed to many mid-latitude climate variations over the early twenty-first century. Here we show using large ensembles of fully coupled, partially coupled and uncoupled model simulations that in northwest North America the winter cooling was primarily a remote response to climate fluctuations in the tropical Pacific. By contrast, in central North America the winter cooling appears to have resulted from a relatively rare fluctuation in mid-latitude circulation that was unrelated to the tropical Pacific. Our results highlight how decadal climate signals—both remote and local in origin—can together offset anthropogenic warming to produce continental-scale cooling.

Northern Hemisphere surface temperature over the 13 winters ending in the winter of 2013–2014 was characterized by cooling over Eurasia and North America (Fig. 1a, ref. 1). In central North America (CNA) the winters of 2009–2010, 2010–2011 and 2013–2014 were particularly cold, with average winter temperatures falling 1.2 to 2.1 °C below the 1981–2010 average (Supplementary Fig. 1a). The cooling trend in CNA was significant when viewed against the expected anthropogenic warming estimated by averaging over a large ensemble of coupled climate model simulations (Fig. 1b and Supplementary Fig. 1b). Motivated by earlier research into the unusually cold winter of 2013–2014[2–4] we explore linkages between decadal variability in the tropical Pacific and wintertime cooling over the northwest and central sectors of North America from 2001–2002 to 2013–2014.

Tropical Pacific surface air temperature (SAT) trends in winter from 2001–2002 to 2013–2014 were characterized by warming in the west Pacific and cooling in the central to east Pacific (Fig. 1a; shading). This weakening of the climatological SAT gradient was associated with strengthening trades (Fig. 1a; arrows)[5]. Apart from their impact on global-mean surface temperature (ref. 6 and references therein) these changes have been linked to several regional climate variations, including warming in northeast Canada and Greenland[7], drying in western North America[8], shifting of the North Atlantic Oscillation (NAO) towards its negative phase[9] and cooling of northwest North America (NWNA, ref. 10). However, it is unclear what role the tropical Pacific has played in winter cooling over central North America.

Winter cooling in the central to east Pacific from 2001–2002 to 2013–2014 was accompanied by decreasing precipitation (Fig. 1a; brown contours). It is well known that latent heating associated with such a situation has the potential to impact North American climate through the generation and transmission of atmospheric Rossby waves[11]. Similarly, the observed warming in the west Pacific, and associated moistening (Fig. 1a; green contours), has the potential to affect the climate over North America[2,3,12]. Here we explore the link between these climate variations in the tropical Pacific and winter cooling over North America using the Canadian Earth System Model version 2 (CanESM2; ref. 13) in various configurations; that is, where the oceans and atmosphere are fully coupled, partially coupled and uncoupled (see Methods). We also consider the Community Earth System Model (CESM1; ref. 14) in its coupled configuration.

Model assessment

We first assess the ability of CanESM2 in its coupled configuration to reproduce the observed linkages between the tropical Pacific and North America. As the decadal trends were characterized by increasing trades and a reduced zonal gradient of tropical Pacific SAT we calculate spatial patterns associated with winter-to-winter fluctuations and 14-year trends in the zonal gradient of tropical Pacific SAT. We consider a large ensemble of simulations with observed historical forcings from 1950–2005 and with RCP8.5 (ref. 15) extensions to 2015 (see Methods). An index of tropical Pacific SAT gradient, ΔSAT, is defined as the SAT averaged over the regions with the largest observed warming (left rectangles in Fig. 2 in the west tropical Pacific) minus the SAT averaged over the region with largest observed cooling (right rectangles in Fig. 2 in the central tropical Pacific) over the winters between 2001–2002 and 2013–2014. As the climatological SAT in the central tropical Pacific is higher than in the west tropical Pacific, an increase in ΔSAT corresponds to a weakening of the climatological zonal SAT gradient. We winter-average and detrend the index and then perform spatial regressions against detrended winter-mean anomalies of SAT, sea level pressure (SLP) and precipitation. For CanESM2, ensemble-averaged regression patterns are displayed in Fig. 2b. We then repeat this analysis for decadal timescales by replacing winter anomalies with 14-year (winter) trends (Fig. 2c,d). Both on interannual and decadal timescales the simulated patterns compare well with the observed patterns shown in Fig. 2a,c. CanESM2 generally reproduces the observed interannual and trend patterns of tropical Pacific precipitation, extratropical SLP and North American surface temperature. A favourable comparison is also obtained using a large ensemble of CESM1 simulations (Supplementary Fig. 2). It should be cautioned that despite agreement with observations at this level there may be unrealistic aspects of the simulations—for example, related to the

Canadian Centre for Climate Modelling and Analysis, Environment and Climate Change Canada, Victoria, British Columbia V8W 2Y2, Canada.
*e-mail: michael.sigmond@canada.ca

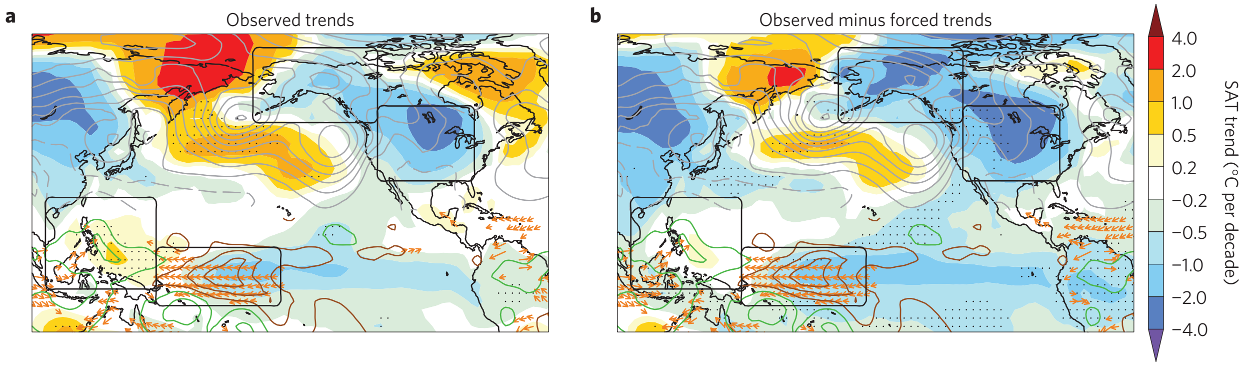

Figure 1 | Observed winter trends from 2001–2002 to 2013–2014. a,**b**, Linear trends in SAT (shading; dots represent significance at the 95% level), surface wind stress (arrows, plotted only south of 20° N and where zonal wind stress trends are larger than 1.5×10^{-2} Pa per decade), precipitation (coloured contours, plotted only south of 20° N) and SLP (grey contours, plotted only north of 20° N). **a**, Observations. **b**, Observations relative to the forced response derived from the fully coupled CanESM2 simulations. Contour interval for precipitation is 2 mm d^{-1} per decade (. . ., −3, −1, 1, . . .), and green (brown) contours denote moistening (drying). Contour interval for SLP is 0.8 hPa per decade (. . ., −1.2, −0.4, 0.4, . . .), and solid (dashed) contours denote positive (negative) values. For observational sources see Methods.

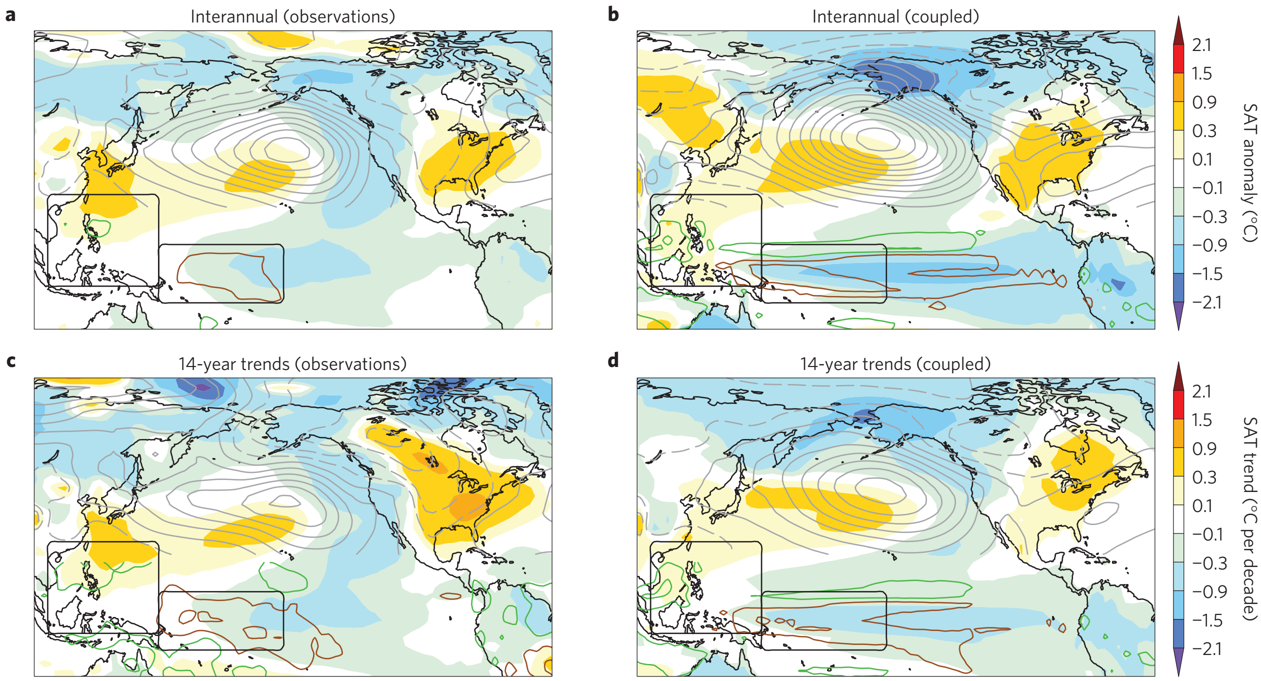

Figure 2 | Anomalies associated with a weakened tropical Pacific temperature gradient on interannual and decadal timescales. a,**b**, Regressions of ΔSAT against SAT (shading), precipitation (coloured contours, plotted only south of 20° N) and SLP (grey contours, plotted only north of 20° N). **a**, Observations. **b**, Results from CanESM2. ΔSAT regression patterns correspond to a positive anomaly (weakened temperature gradient). Regressions are based on detrended winter-mean time series between 1950–1951 and 2009–2010, and for CanESM2 the ensemble-mean patterns are shown. Contour interval for precipitation is 2 mm d^{-1} (. . ., −3, −1, 1, . . .), and green (brown) contours denote wet (dry) anomalies. Contour interval for SLP is 0.4 hPa (. . ., −0.6, −0.2, 0.2, . . .), and solid (dashed) contours denote positive (negative) values. **c**,**d**, Same as **a** and **b**, except that the regressions are based on 14-year overlapping trends instead of interannual anomalies. Contour interval is 1 mm d^{-1} per decade (. . ., −1.5, −0.5, 0.5, . . .) for precipitation. Contour level for SLP is 0.4 hPa per decade (. . ., −0.6, −0.2, 0.2, . . .).

representation of deep convection—that impact the extratropical response to tropical SST anomalies. Finally, we note that this regression analysis reveals that a weakening of the tropical Pacific SAT zonal gradient is associated with winter warming rather than cooling over central North America.

Simulated trends over the early twenty-first century

Having established that the models used in our study reproduce the observed linkages between the tropical Pacific and North America, we now investigate their simulated trends in the early twenty-first century. First we employ the ensemble of fully coupled CanESM2 simulations to explore potential links between variations in the simulated ΔSAT trend and variations in the simulated SAT trend averaged over NWNA (over the period from 2001–2002 to 2013–2014). The red dot in Fig. 3a, representing observed trends, shows a positive trend in ΔSAT (corresponding to a weakening zonal temperature gradient) and a relatively small cooling trend over NWNA (see Fig. 1a). The ellipse in Fig. 3a encompasses 95% of the simulated trends. The line is the best linear approximation between the simulated trends. The observed trends lie within the range of simulated trends, and are situated very close to the best linear approximation between the simulated trends. This indicates

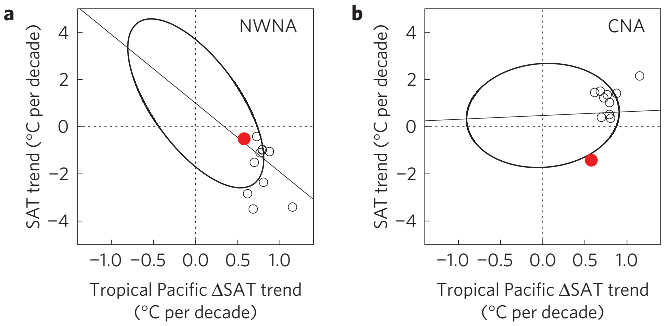

Figure 3 | Simulated and observed winter trends from 2001–2002 to 2013–2014 in North American SAT and the tropical Pacific SAT gradient. **a**,**b**, SAT trends averaged over northwest North America (**a**) and central North America (**b**) versus trends in the tropical Pacific ΔSAT. The red dot represents the observations. The trends in the ensemble of fully coupled model simulations are depicted by the ellipses (encompassing 95% of the ensemble members) and the straight line (representing the best linear fit). The open circles denote the trends in the pacemaker simulations.

that had the simulated tropical Pacific variability in the model been aligned in time with that observed then it would have probably simulated the observed cooling over NWNA. This is our first line of evidence that the observed winter cooling over NWNA from 2001–2002 to 2013–2014 was a remote response to decadal changes in the tropical Pacific. Our second line of evidence is obtained from an ensemble of partially coupled CanESM2 simulations where surface wind stress in the tropics is constrained to follow its observed monthly evolution from January 1979[16] (see Methods). The values of ΔSAT and NWNA-averaged SAT trends are displayed in Fig. 3a as open circles. In all of these so-called 'pacemaker' experiments, the observed trade wind intensification and associated ΔSAT increase is associated with cooling surface temperatures over NWNA. These results are consistent with relationships that exist between winter-to-winter fluctuations and 14-year trends in ΔSAT and NWNA SAT (Fig. 2). Supplementary Fig. 3a shows that the pacemaker experiments not only capture the decadal cooling trend but also the interannual variability in NWNA SAT.

Figure 3b displays corresponding results for CNA. In observations there was a relatively large cooling coincident with a positive trend in tropical Pacific ΔSAT. In this case, the

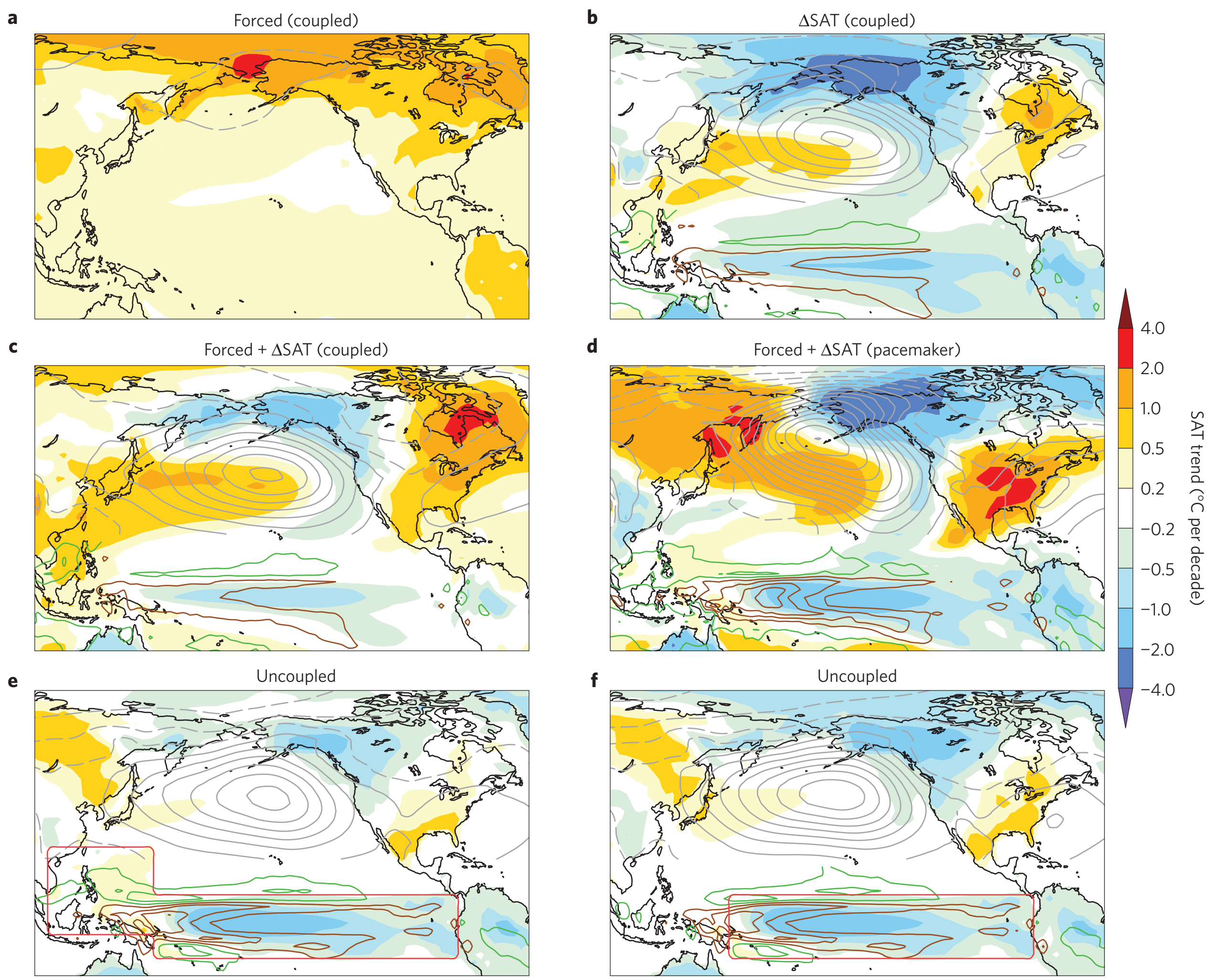

Figure 4 | Climate trends in winter from 2001–2002 to 2013–2014 from fully coupled, partially coupled and uncoupled model simulations. **a**–**c**, Forced (**a**) and tropical-Pacific-related climate trends (**b**) as derived from the fully coupled simulations, and their sum (**c**). **d**, Climate trends in the pacemaker simulations. **e**,**f**, Climate response to the SST perturbations from the pacemaker simulations (displayed in **d**) in the corresponding uncoupled model, where the SST perturbations are restricted to the areas denoted by the red boxes in each case. Shading represents SAT trends, grey contours denote SLP trends and green (brown) contours denote moistening (drying). Contour intervals identical to those in Fig. 1.

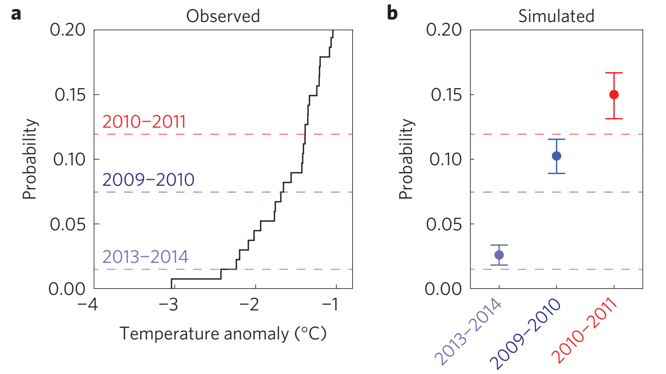

Figure 5 | Probability of an unusually cold central North American winter. **a**, Probability of a CNA winter from 1881 to 2014 being as cold as the three coldest winters from 2001 to 2014. Here the observations have been detrended using a least-square fit of a third-order polynomial. The probability p of a winter being as cold as the 2010–2011, 2009–2010 or 2013–2014 winter is respectively $p = 0.12$, 0.07 and 0.02. **b**, Probability of a CNA winter in an uncoupled control simulation that is as cold as a $p = 0.12$, 0.07 or 0.02 winter in an uncoupled perturbed experiment (with reduced tropical Pacific SAT gradient). The control and perturbation simulations are each 1100 years long. The solid circles show the probabilities from the control simulations. The errors bars show the 5–95% range having resampled (with replacement) the control simulation 200 times. This figure shows that reduced tropical Pacific SAT gradient seen in observations causes a statistically significant reduction in the probability of unusually cold CNA winters.

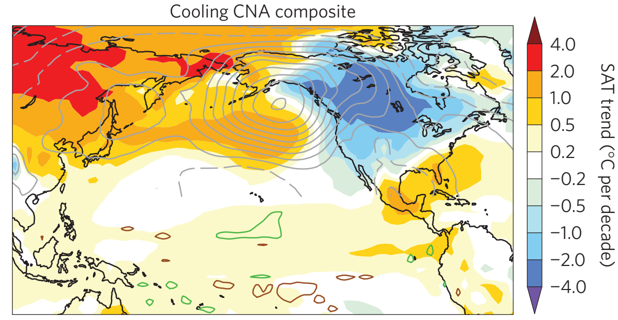

Figure 6 | Composite of climate trends in fully coupled simulations with the largest central North American winter cooling. The simulated climate trends averaged over the five ensemble members of fully coupled CanESM2 simulations with the largest winter cooling in central North America. Variables and contour intervals are identical to those in Fig. 4.

observed trends lie outside of the range of coupled model simulated trends and are far away from the best linear approximation between the simulated trends in the ensemble of coupled simulations. Moreover, the observed CNA-average trend shows a cooling, whereas the pacemaker experiments indicate systematic warming (see also Supplementary Fig. 3b). In short, this is counter-evidence to the notion that the observed winter cooling over CNA from 2001–2002 to 2013–2014 was a remote response to decadal changes in the tropical Pacific.

To further investigate these findings we present spatial maps of the externally forced climate trend (Fig. 4a), the tropical Pacific related climate trend (Fig. 4b) and their sum (Fig. 4c). Here the externally forced maps are obtained as ensemble-mean trends over the large ensemble of fully coupled CanESM2 simulations. We note that, within the plotting ranges used in Fig. 4, the externally forced trends in precipitation are unseen. The tropical Pacific related trends are obtained by performing a gridpoint-by-gridpoint regression between trends in ΔSAT and trends in SLP, SAT or precipitation. The resulting regression coefficients are then multiplied by the observed trend in ΔSAT. By this approach the cooling in the central to east tropical Pacific can be explained by cooling associated with decadal variations in trade winds and ΔSAT overwhelming the externally forced warming. On the other hand, decadal timescale warming in the west tropical Pacific augments anthropogenic warming. Precipitation trends are found to have a negligible external forcing contribution, implying that the early twenty-first century tropical Pacific precipitation variations were the result of decadal variations in ΔSAT.

Figure 4b,c confirms the notion that these decadal variations in tropical Pacific precipitation have shaped the recent mid-latitude SLP and SAT patterns through atmospheric Rossby wave generation and transmission[3,9–11]. Indeed, it appears that the Aleutian Low weakening observed over the early twenty-first century (Fig. 1a), arguably the most pronounced feature in recent Northern Hemisphere SLP trends, can be attributed to tropical Pacific climate variations. Moreover, the associated advection of cold air was sufficient to overcome the externally forced warming to cause cooling over NWNA. By contrast, tropical Pacific related SLP trends over the east coast of North America drove southwesterly winds to produce warming, rather than cooling, over CNA. Hence, tropical Pacific variability cannot explain the observed winter cooling over CNA. Results from the CESM1 simulations confirm these conclusions (Supplementary Fig. 4). These conclusions are also supported by our pacemaker experiments where surface wind stresses in the tropics were constrained to follow their observed monthly evolution (Fig. 4d).

It is clear that tropical Pacific SAT trends played an important role in early twenty-first century mid-latitude climate trends, particularly over NWNA. We ask if this is due to cooling in the central to east Pacific, a well-known source region of mid-latitude climate variations, or due to warming in the west tropical Pacific, hypothesized in previous studies to be an even more important source region[2,3,17,18]? To address this question we employ uncoupled simulations using CanESM2. We perform control runs with prescribed SST and sea ice averaged over the period between 1997 and 2007, and simulations that use the control SST and sea ice, except over the key regions denoted by the red boxes in Fig. 4e,f. In those regions the SST trends are multiplied by 13 years and added to the control values. Each simulation is 100 years long and uses 2002 radiative forcings. Figure 4e,f shows the response (experiment minus control) for uncoupled runs where the SST and sea ice were taken from the ensemble mean of the pacemaker experiments. Figure 4e shows that perturbed SSTs in the tropical Pacific account for almost all of the climate trends in the partially coupled simulations (see Fig. 4d); including the pattern of tropical Pacific moistening and drying, Aleutian Low weakening and NWNA cooling. These responses remain essentially unchanged when the SST perturbation is limited to the central to eastern Pacific (Fig. 4f); implicating this region as the main source of tropical-Pacific-induced mid-latitude climate trends. In response to warming in only the west tropical Pacific a slight warming of CNA is found (not shown), contradicting the notion that west tropical Pacific warming was responsible for the observed CNA winter cooling from 2001–2002 to 2013–2004. Similar conclusions are obtained from uncoupled simulations with prescribed observed (instead of simulated) tropical Pacific SST trends (Supplementary Fig. 5).

Impact on the probability of unusually cold winters

Our analysis indicates that tropical Pacific changes during the early twenty-first century produced a warming impact over CNA. This impact is seen in the ensemble average of our partially coupled simulations and in the time average of our uncoupled simulations. Following speculation in ref. 3, we explore the impact of tropical

Pacific changes on the probability of the unusually cold CNA winters observed in recent years. Based on detrended observations from 1881 to 2014 we estimate the probability of a CNA winter being as cold as the three coldest winters from 2001 to 2014; where detrending is accomplished by subtracting a least-square fit of a third-order polynomial. The probability p of a winter being as cold as 2010–2011, 2009–2010 or 2013–2014 is respectively $p=0.12$, 0.07 and 0.02 (see Fig. 5a). Using our uncoupled simulations, we investigate the speculation of ref. 3 that the probability of these unusually cold winters may have increased due to the tropical Pacific changes. To arrive at statistically robust conclusions, we extended the uncoupled control simulation and the simulation with SST changes in the tropical Pacific region shown in Fig. 4e to 1,100 years each, where the SST and sea-ice fields were taken from observations. Figure 5b shows the probability of a winter in the control simulation that is as cold as a $p=0.12$, 0.07 or 0.02 winter in the perturbed experiment. Since these probabilities are higher in the control than in the perturbed experiment, this indicates a reduced probability of unusually cold winters associated with changes in the tropical Pacific. We find that it is respectively 1.3, 1.4 and 1.6 times less likely to find a $p=0.12$, 0.07 or 0.02 winter in the perturbed simulation than in the control simulation. Hence, our results contradict the notion that tropical Pacific changes have increased the probability of the unusually cold winters observed in recent years.

Cause of winter cooling

If the recent CNA winter cooling cannot be attributed to tropical variability, then what was its cause? To address this question we return to the large ensemble of coupled CanESM2 simulations and note that in three of 100 ensemble members a stronger than observed CNA winter cooling was simulated. Figure 6 shows the average simulated climate trends over the five ensemble members with the largest CNA winter cooling. The CNA winter cooling in this composite is approximately equal to that in observations. As in observations this cooling is the result of northerly winds associated with a ridge of increased SLP over the west coast of North America and CNA. The composite shows that outside the mid-latitudes there are no climate trends that are substantially different from the forced response (displayed in Fig. 4a). This indicates that the observed CNA winter cooling over the early twenty-first century was not a response to decadal changes in the tropical Pacific, but was instead the result of a local internally generated fluctuation in circulation that was unrelated to the tropical Pacific.

Our analysis shows how remotely and locally generated decadal climate variations have offset anthropogenic warming to produce North American winter cooling over the early twenty-first century. Similar to the slowdown in the rise of global-mean surface temperature[6], this cooling is very likely to be a temporary feature, as future decadal variations could be opposite in sign and amplify anthropogenic warming of North American winters.

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions

M.S. designed and performed the uncoupled simulations, helped to carry out the analysis and wrote the initial draft. J.C.F. helped design the pacemaker experiments, helped with the analysis and edited the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to M.S.

Competing financial interests

The authors declare no competing financial interests.

Methods

Observations. The observational products to quantify boreal winter trends in the early twenty-first century are GISTEMP (ref. 19, SAT), ERA-interim (ref. 20; SLP and surface wind stress) and the Global Precipitation Climatology Project version 2.2 (ref. 21, precipitation). The surface wind stress of ERA-interim, also used to force the pacemaker experiments (described below), was shown to be consistent with several observational data sets in the tropical Pacific[22]. For the model evaluation presented in Fig. 2 and Supplementary Fig. 2 we used 1950–2010 SAT, SLP and precipitation data from the twentieth century reanalysis project[23]. GISTEMP SAT data are also used for the analysis presented in Fig. 5.

Fully coupled simulations. Large ensembles of coupled simulations were performed with the Canadian Earth System Model version 2 (CanESM2)[13] and the Community Earth System Model version 1 (CESM1)[14], which included historical forcings from 1950–2005 and with RCP8.5 (ref. 15) extensions to 2015. Two sets of 50 members were run with CanESM2, one with natural and anthropogenic historical forcings (hereafter referred to as the Historical ensemble) and one with only natural forcings (hereafter referred to as the HistoricalNat ensemble). Anthropogenic forcings include changes in greenhouse gases, anthropogenic aerosols, tropospheric and stratospheric ozone and land use (for example, deforestation). Climate trends resulting from external forcings were calculated as the ensemble mean of the Historical ensemble. Climate trends associated with the tropical Pacific variations were derived from all 100 ensemble members. Before combining the two 50-member sets, the forced component was added to each member of the HistoricalNat ensemble. Details of the 30-member CESM1 ensemble can be found in ref. 24.

Partially coupled simulations. These so-called 'pacemaker' simulations were performed with an updated version of CanESM2 that includes an improved (spatially variable) representation of ocean mesoscale eddy transfer coefficients and are described in detail in ref. 16. From a historical simulation, two sets of five simulations were branched off in the year 1979. In these simulations the wind stress felt by the ocean between 35° S and 35° N was replaced with the monthly evolution in ERA-interim, thus representing the effects of trade wind intensification in the early twenty-first century. The two subsets both included anthropogenic historical forcings, but only one of them also included natural (that is, solar and volcanic) forcings. Comparison of ensemble-mean climate trends in the two subsets (not shown) reveals that, over the 2002–2014 period considered here, the impacts of natural forcings are negligible, justifying our approach to combine the two sets into one 10-member ensemble.

Uncoupled simulations. The uncoupled simulations were performed with the atmospheric component of CanESM2, CanAM4 (ref. 25). Hundred-year time-slice simulations were run with annually repeating boundary conditions based on the SST and sea-ice fields simulated in the pacemaker runs (Fig. 4e,f) and HadISST[26] observations (Supplementary Fig. 5). The control run used prescribed 1997–2007 SST and sea-ice climatology and external forcing representative of 2002. The SST field was then perturbed by adding the 2002–2014 winter trends (multiplied by 13 years) in specific key regions of the tropical Pacific, while keeping the external forcings fixed to 2002 values. Finally, the climatological differences between the perturbation and control runs are scaled by a factor 10/13 to convert the trends to units per decade. The control runs and simulations with SST perturbations in the entire tropical Pacific were extended to 1100 years to evaluate the impact of the tropical Pacific temperature trends on the probability of extreme cold winters (Fig. 5).

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