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Key Points:
- Atmospheric circulation contributed to the observed boreal winter cooling
- Recent winter cooling is overestimated due to incomplete observational coverage
- Accounting for both implies positive corrections to temperature trends

Supporting Information:
- Text S1 and Figures S1–S7

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Contributions of atmospheric circulation variability and data coverage bias to the warming hiatus

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Abstract The warming hiatus shows a strong seasonal and geographical asymmetry, with cooling in the Northern Hemisphere winter, especially over land, and warming elsewhere and in the other seasons. We show that the characteristics of the Northern Hemisphere winter cooling in 1998–2012 can mostly be explained by missing observations and by internal variability in the atmospheric circulation of the Northern Hemisphere extratropics. Estimates of the annual and seasonal temperature trends in 1998–2012 obtained by considering the concurrent effects of unforced natural variability and of coverage bias are much closer to the corresponding long-term trends. Reanalyses suggest that the coverage bias was exceptionally pronounced during recent years and that an area of strong warming was missed due to the incomplete observational coverage. Coupled Model Intercomparison Project Phase 5 climate models indicate that trends in atmospheric circulation during the hiatus period did not occur as a response to anthropogenic forcing.

1. Introduction

The global warming trend appears to have slackened or even halted since about 1998, in clear contrast with the strong warming signal projected by the Coupled Model Intercomparison Project Phase 5 (CMIP5) multimodel mean for recent years [e.g., *Easterling and Wehner*, 2009; *Meehl et al.*, 2011; *Fyfe et al.*, 2013; *Huber and Knutti*, 2014]. Under current anthropogenic forcing short periods with enhanced or reduced warming are common in both observations and model simulations as a consequence of natural climate variability. Furthermore, it was shown that atmospheric dynamics played a major role in the strong wintertime positive temperature trend in the period 1965–2000 over high northern latitudes [*Wallace et al.*, 2012].

Many factors have been suggested to contribute to this warming hiatus, including changes in solar radiative forcing [*Lean and Rind*, 2009], tropospheric [*Kaufmann et al.*, 2011] and stratospheric aerosols [*Solomon et al.*, 2010], internal variability resulting from El Niño [*Fyfe et al.*, 2013; *Kosaka and Xie*, 2013; *Risbey and Lewandowsky*, 2014], the dynamics of the Atlantic [*Keenlyside et al.*, 2008; *Chen and Tung*, 2014] and the Equatorial Pacific oceans [*Meehl et al.*, 2011, 2014; *Trenberth et al.*, 2014], wind stress variability [*England et al.*, 2014; *Watanabe et al.*, 2014], or a combination of those [*Trenberth and Fasullo*, 2013; *Huber and Knutti*, 2014; *Schmidt et al.*, 2014]. In addition, deficiencies due to the incomplete observational coverage have led to an underestimation of recent surface warming trends [*Cowtan and Way*, 2014]. Although the above factors can account for the reduced warming trends at the global scale, only few previous studies [e.g., *Cohen and Barlow*, 2005; *Cohen et al.*, 2009, 2012a; *Kosaka and Xie*, 2013; *Delworth et al.*, 2015] proposed mechanisms explaining the spatial and temporal characteristics of the current slowdown in the rate of global warming, which is characterized by a Northern Hemisphere wintertime cooling, mostly over land, and statistically significant warming in the other seasons [*Cohen et al.*, 2012b]. December, January, and February (DJF) and annual mean temperature trends for the hiatus period 1998–2012 are shown in Figure S1 in the supporting information. Here we identify the processes that contributed to the seasonal and geographical asymmetry of the hiatus and estimate their contributions to the observed temperature trends.

2. Data and Methods

We quantify how internal atmospheric variability in the extratropical Northern Hemisphere (20–90°N) contributed to the spatial and seasonal patterns of the hiatus in the period 1998–2012 and how temperature trends were impacted by coverage bias. We use five different reanalysis data sets, namely European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim [*Dee et al.*, 2011], Japan Meteorological Agency (JMA) Japanese 55-year

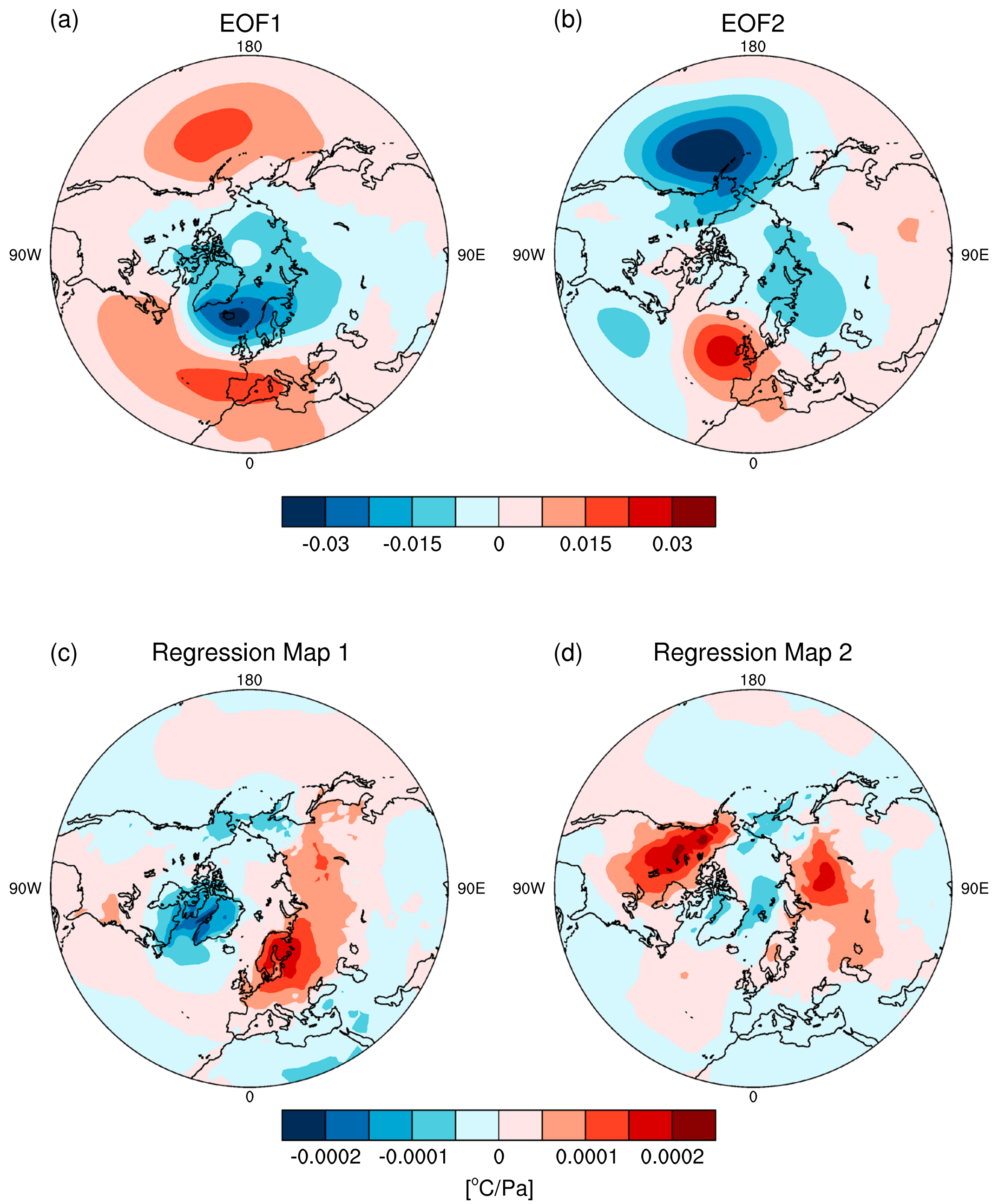

Figure 1. The (a) first and (b) second leading modes of monthly detrended sea level pressure variability and (c and d) their effect on detrended mean winter near-surface temperatures as computed from ERA-Interim in the period 1980–1997.

Reanalysis (JRA-55) [*Ebita et al.*, 2011], National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) Reanalysis 1 [*Kalnay et al.*, 1996], NCEP/Department of Energy (DOE) Reanalysis 2 [*Kanamitsu et al.*, 2002], and National Oceanic and Atmospheric Administration (NOAA) Twentieth Century Reanalysis [*Compo et al.*, 2011]. In order to determine the circulation-induced contribution to temperatures, we apply a dynamical adjustment technique by the following steps. The most prominent circulation patterns are first identified for each season separately by performing an empirical orthogonal function (EOF) analysis on monthly detrended sea level pressure data over all the available years before the reference hiatus period (thus excluding data from 1998 onward). The temperature contribution related to each EOF is then estimated by linearly regressing monthly detrended temperature anomalies (with respect to the period 1979–2008) on the corresponding principal component. Multiplying the regression maps by their associated principal components yields the monthly effect on temperatures induced by each of the orthogonal circulation modes. Finally, the

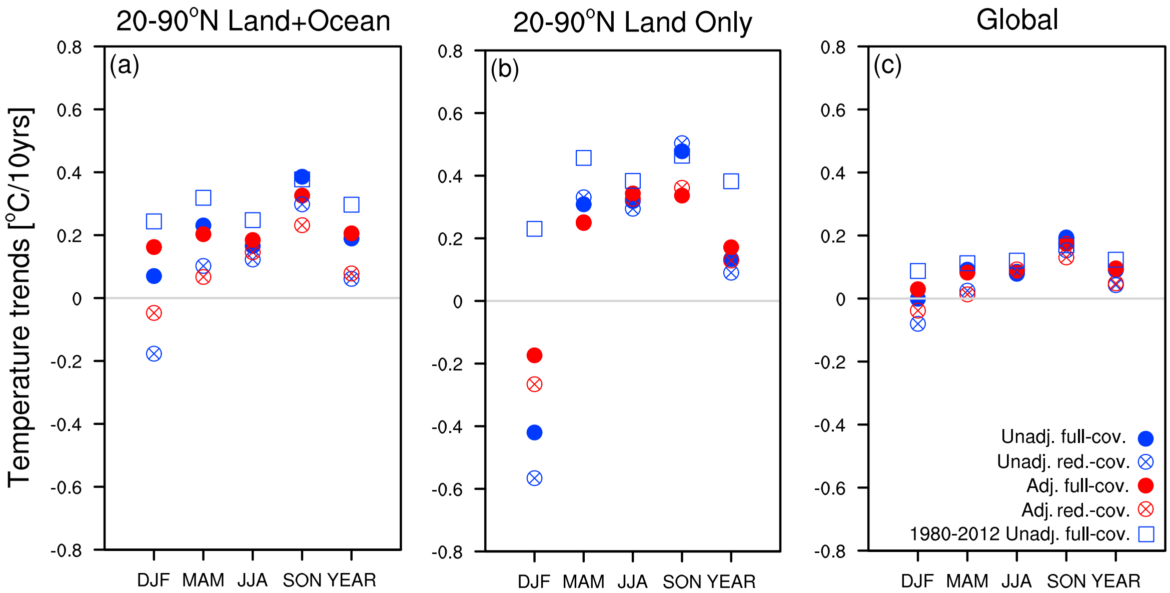

Figure 2. Seasonal and annual mean temperature trends (°C per 10 years) in the period 1998–2012 (a) for the domain 20°–90°N, (b) for the same region but land only, and (c) for the entire globe. Closed blue circles indicate the values directly computed from the ERA-Interim reanalysis and closed red circles their dynamically adjusted counterparts. Open circles represent coverage-biased estimates computed from unadjusted (open, blue) and dynamically adjusted (open, red) temperatures by prescribing the HadCRUT4 observational coverage in the reanalysis data set. Blue squares indicate the 1980–2012 long-term trends computed from the full-coverage reanalysis.

temperature contributions by the leading EOFs are removed on a monthly basis from reanalysis anomalies and seasonal temperature trends are computed. The effect of circulation on annual trends is estimated in an analogous way, but performing an empirical orthogonal function analysis over all months in the years before 1998. The two leading EOFs of detrended sea level pressure in winter as computed from the ERA-Interim reanalysis (Figures 1a and 1b), respectively, account for approximately 25% and 15% of the total variance. The first mode resembles the Arctic Oscillation/Northern Annular Mode [*Thompson and Wallace*, 1998]. The imprint of the two modes on winter near-surface temperature anomalies is particularly pronounced over land, especially across large stretches of Eurasia and North America (Figures 1c and 1d). The overall effect of these circulation patterns on the mean temperature across the entire domain is quantified by the area-weighted averages of the corresponding regression maps. During winters in the period 1998–2012 the two leading modes of variability shifted toward their negative phase (Figure S2), thus contributing cooling in the regions over which the regression maps are positive. By dynamically adjusting temperature anomalies it is possible to account for this effect, i.e., to estimate what temperature trends would have been if circulation had been close to the climatological mean state. These adjusted trends are more representative of the temperature response to external forcing.

It was suggested that the recent slowdown of global warming has been overestimated due to the incomplete spatial coverage of temperature measurements in several regions of the globe, in particular over the Arctic [*Cowtan and Way*, 2014]. Figure S3 shows the percentage of missing monthly observations in HadCRUT4 [*Morice et al.*, 2012] for DJF and annual data in the period 1998–2012. We test how the coverage bias influenced the observed temperature trends together with their spatial and temporal characteristics by interpolating the unadjusted and dynamically adjusted reanalysis temperatures to the HadCRUT4 spatial resolution (i.e., $5 \times 5°$ on a regular latitude/longitude grid) and masking out all the grid points where observations are missing. We thereby obtain four distinct sets of monthly temperature anomalies (i.e., unadjusted and dynamically adjusted temperature anomalies, with complete and incomplete coverage). We compute the area-weighted average of temperature anomalies at each time step for the entire globe and for the full and land-only northern hemispheric domain (20–90°N). The annual and seasonal mean values of the time series are estimated, then performing a linear regression for identifying the trends.

3. Results and Discussion

A strong asymmetry in temperature trends between seasons is found in the reduced-coverage version of ERA-Interim, obtained by introducing the HadCRUT4 coverage bias in the reanalysis (Figure 2). A marked

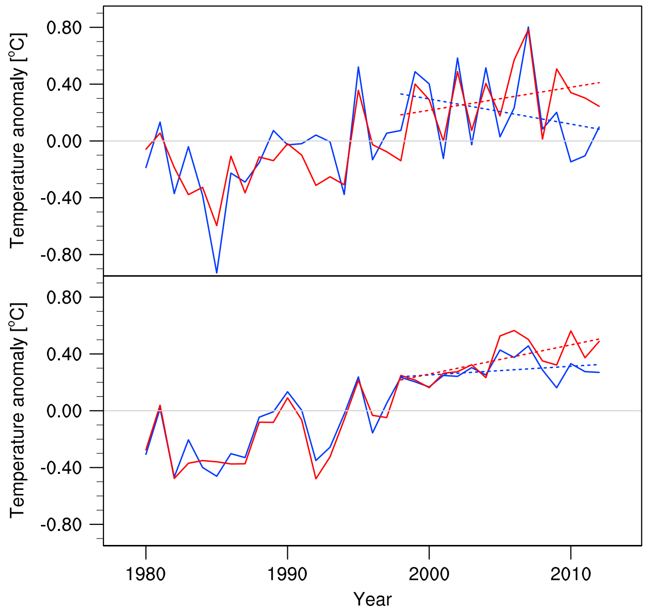

Figure 3. Temperature anomalies in the ERA-Interim reanalysis with respect to the period 1979–2008 for (a) Northern Hemisphere extratropics (20–90°N) winter and (b) annual mean data. Solid blue lines indicate temperatures from the unadjusted, reduced-coverage reanalysis obtained by prescribing HadCRUT4 observational data coverage. Solid red lines denote temperatures from the dynamically adjusted, full-coverage version of the data set. Dashed blue and red lines represent the corresponding linear trends in the period 1998–2012.

cooling is found in winter, in contrast with the warming or near-zero trends in the other seasons. Consistent with recent findings [*Cohen et al.*, 2012b], this trend dissimilarity across seasons is particularly pronounced over land. Accounting for the effects of both circulation in the Northern Hemisphere extratropics and coverage bias implies a strong positive correction to the negative DJF and the near-zero annual mean temperature trends in the period 1998–2012, as highlighted in Figure 3. Dynamically adjusted full-coverage DJF and annual trends are substantially closer to the long-term trends in the period 1980–2012, indicating that the anomalous trends in the leading modes of the northern hemispheric circulation and the incomplete coverage in the HadCRUT4 data critically contributed to the observed temperature records. The detected winter cooling in recent years was partly an artifact of missing data and was partly caused by anomalous circulation. Even at the global-scale temperature trends in reanalyses are corrected to positive values in line with the long-term trends when removing the contributions of natural variability in the Northern Hemisphere extratropics and the coverage bias (Figure 2c). When dealing with global temperature data, the coverage bias is estimated by taking into account the effect of missing observations across all latitudes, but a dynamical adjustment is only applied in the Northern Hemisphere extratropics. Figure S4 shows the contributions of atmospheric circulation and coverage bias separately for DJF and annual mean temperature anomalies averaged over 20–90°N, 20–90°N land, and the global domain.

A separation of the effects of the coverage bias and the anomalous circulation reveals that they both substantially contributed to the observed DJF trends (Figure 2). The incomplete observational coverage led to a considerable underestimation of the actual temperature trends, although its effect was smaller over land due to the higher density of observations. The DJF trend over northern hemispheric land was thus mainly affected by atmospheric circulation, as shown in Figure 2b.

As the effect of the leading modes of atmospheric variability in middle and high latitudes is stronger in the cold months than during the rest of the year, the dynamical contribution to temperatures is more pronounced during the winter season. DJF trends were thus impacted by both atmospheric variability and incomplete coverage, while annual trends were mainly affected by coverage bias. All the results discussed so far are consistent across reanalyses, as shown in Figure S5.

The sign of the contributions obtained from dynamical adjustment in DJF is consistent with the winter trends of the two leading modes of variability for detrended sea level pressure, which in the period 1998–2012 shifted toward their negative phase (Figure S2). This led to anomalous cooling across large stretches of northern Eurasia. In many other regions such as the Pacific sector and vast areas of the Atlantic, the temperature trends induced by the two leading modes of variability partly compensated each other.

Reanalyses suggest that the contribution of coverage bias was particularly pronounced in DJF, as missing observations in the Arctic region led to a considerable underestimation of the effect of the polar amplification on temperature trends. Moreover, the impact of coverage bias was enhanced by the decreasing number of available observations since the early 1990s [*Morice et al.*, 2012]. The effect of missing observations is expected to change in time not only due to the time-varying coverage but also as a consequence of atmospheric variability, which can critically affect short-term temperature trends, especially on local and regional scales. However, anomalous atmospheric circulation in recent years played only a secondary role in enhancing the effect of the incomplete observational coverage on the reconstruction of temperature trends, with the only exception of the land-only northern hemispheric winter trend (Figure 2b). This effect is quantified by the difference between the distance of the two blue dots and of the two red dots in Figure 2, respectively, representing the impact of coverage bias estimated when including and excluding the effect of circulation.

Overall, the phase of the leading circulation modes contributed to the observed northern hemispheric winter cooling. Likewise, it was argued that atmospheric variability played a major role in amplifying the strong wintertime positive temperature trend in the period 1965–2000 over northern high latitudes [*Wallace et al.*, 2012]. This implies that the northern hemispheric winter temperature trends were enhanced by atmospheric circulation up to 2000 and damped thereafter. These results are in line with earlier studies showing that anthropogenic climate change can be regionally obscured or enhanced by natural variability, even on timescales of several decades [*Deser et al.*, 2012, 2014]. This form of uncertainty is largely irreducible and hinders the identification of changes in the frequency and intensity of climatic extremes, especially on local and regional scales [*Fischer et al.*, 2013; *Fischer and Knutti*, 2014].

It was suggested that the anomalous circulation trends were partly a response to anthropogenic forcing through the rapid reduction of sea ice cover in the Northern Hemisphere [*Outten and Esau*, 2011; *Liu et al.*, 2012; *Tang et al.*, 2013]. The decline of Arctic sea ice should have played a role in the recent wintertime cooling by indirectly forcing a negative phase of the Arctic Oscillation through a change in Eurasian snow cover caused by a warmer and moister atmosphere at higher latitudes [*Cohen et al.*, 2012b, 2014]. Under the assumption that models can capture this forced response in atmospheric circulation, we should expect transient climate simulations to show significant long-term trends consistent with the trends in the principal components of the leading EOFs during the hiatus period. To test to what extent CMIP5 models can reproduce the observed circulation trends we consider simulations under both the historical and the Representative Concentration Pathway RCP8.5 forcing and we project the simulated monthly detrended sea level pressure fields on the two leading modes of variability obtained from ERA-Interim. In most of the models we find individual 15 year periods with principal component trends as large as the ones estimated for the hiatus years. However, no evidence is found that the reduced temperature trends during the hiatus period are a consequence of anthropogenic forcing, as neither the historical nor the RCP8.5 simulations show significant long-term trends in the principal components of the first two EOF modes. The robustness of the simulated trends is tested for both winter and annual data by introducing a measure defined as the ratio of the multimodel mean to the multimodel standard deviation of trends. As these ratios are smaller than 1 the changes in atmospheric circulation in the period 1998–2012 are not attributable to anthropogenic forcing.

4. Robustness of the Results and Caveats

The results discussed here are robust across all the five reanalyses examined. In all data sets DJF trends are strongly affected by both atmospheric circulation and coverage bias, while the effect of missing observations generally prevails in other seasons and for annual data (Figure S5). The difference across the data sets in the number of years available for computing the EOFs leads to somewhat different representations of circulation modes, but they are consistent across reanalyses. In all cases the leading mode of detrended sea level pressure variability closely resembles the Arctic Oscillation, while the successive modes computed from different data sets are all characterized by similar centers of action. In all reanalyses the dynamical adjustment of the first two modes of variability results in a positive change in winter temperature trends and the contribution of circulation is largely independent of the number of empirical orthogonal functions accounted for. We test the robustness of the results obtained from dynamical adjustment by considering all the EOFs explaining more than 5% of the variance of detrended sea level pressure. This leads to including the first six EOFs in all seasons, cumulatively accounting in winter for approximately 73% of the variance of detrended sea level pressure. The resulting trends computed for ERA-Interim are presented in Figures S6 and S7 in the supporting information. Figure S6 shows the trends obtained by removing the first two and six modes of atmospheric circulation. The corresponding maps for winter temperature trends in the extratropical Northern Hemisphere are presented in Figure S7. The first two

EOFs have the largest effect on trend adjustment, while further modes of variability are responsible for only minor contributions.

Reanalyses are well known to be affected by artificial variability and discontinuities, leading to errors in the quantification of temperature trends in recent decades [*Simmons et al.*, 2004; *Sterl*, 2004; *Screen and Simmonds*, 2011]. While the exact magnitude of the impact of coverage bias still involves substantial uncertainty, the corrections obtained here are generally consistent across reanalyses. Estimates of the effect of coverage bias are particularly robust for recent winter and annual temperature trends, which were in all cases underestimated due to missing observations (Figure S5).

Note that regression-based methods as the one used in dynamical adjustment do not necessarily imply causality. Our implicit assumption is that internal variability in temperature is at least partly driven by atmospheric variability. This is well established in particular during cold months, in which the effect of circulation on temperatures is dominant [*Vautard and Yiou*, 2009; *Cattiaux et al.*, 2012]. On the other hand, there is the possibility that temperature anomalies may feedback on sea level pressure, especially during the warm months and over land [*Fischer et al.*, 2007].

The method applied here relies on the assumption that circulation is not critically affected by anthropogenic forcing at the time scales considered or that the forced component in natural variability is small. Previous studies have shown that in the Northern Hemisphere, the forced response of sea level pressure over land is less than 1 hPa for the next 50 years [*Deser et al.*, 2014]. Consistently, the CMIP5 models show no clear trends over the 21st century for the first two circulation modes presented in Figure 1.

Our analysis primarily focuses on the extratropical Northern Hemisphere, as the hiatus was shown to be mainly a boreal winter phenomenon [*Cohen et al.*, 2012b]. The study of the effect of atmospheric circulation on temperature records in the Northern Hemisphere tropics and in the Southern Hemisphere is beyond the scope of this work.

5. Conclusions

We show that taking into account the effects of coverage bias and of atmospheric circulation in the Northern Hemisphere extratropics results in reanalysis temperature trends in the period 1998–2012 being closer to the long-term trends. This explains a large fraction of the observed boreal winter hiatus. Hemispheric and global DJF trends were affected by both atmospheric dynamics and the coverage bias, while winter cooling over Northern Hemisphere land was mainly caused by circulation. Trends in other seasons and for annual data were predominantly impacted by the coverage bias, whose effect was enhanced by the decreasing number of available observations since the early 1990s. Climate models suggest that the recent circulation trends were likely due to internal variability and not a consequence of anthropogenic forcing. The results highlight that short-term trends, especially in smaller regions and for particular seasons, are not necessarily reflecting long-term forced trends and that comparison between models and observations as well as local near-term projections must carefully consider natural variability.

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ERRATUM

In the originally published version of this article, Figures 2 and 3, and supporting Figures S4, S5, and S6, contained errors. The figure files and Supporting Information files have since been corrected, and this version may be considered the authoritative version of record.

