Tropical rainfall patterns driven by reduced sea ice in high boreal latitudes
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ABSTRACT
Satellite data enabled the Intergovernmental Panel on Climate Change (IPCC), through Report V, to indicate that the regional distribution of sea ice has been reducing in the Northern hemisphere high latitudes. This study assimilated that reduction into a general circulation model of intermediate complexity to simulate the tropical rainfall response. The Northern hemisphere tropospheric wind field simulations presented a clear similarity to the Northern Annular Mode negative phase. In particular, the meridional wind anomalies of the Northern hemisphere Ferrel cell suggest that the energy upsurge due to the boreal sea ice decrease results in an increase in the amplitude of the Rossby waves, thus connecting the polar zone to the tropics. The 500 hPa vertical motion and the rainfall distribution in the tropical belt simulations show a southward displacement of the Atlantic Intertropical Convergence Zone and also the South Atlantic Convergence Zone. Although several studies indicate the Intertropical Convergence Zone is shifted towards the hemisphere most heated by climatic variations, the apparent disagreement with our results can be understood by considering that some continental sectors in the Northern Hemisphere mid-latitudes have shown cooling in recent years, probably in response to the boreal sea ice decrease.

Key words | Northern Annular Mode, sea ice reduction, SPEEDY model, tropical rain

INTRODUCTION
Sea ice is an important Earth climate system component and its obvious reduction in the Northern hemisphere high latitudes is one of the most anticipated consequences of global warming, and a disturbing decrease is expected by the end of this century if current greenhouse gas emission rates continue without effective containment. Without a doubt, Arctic sea ice melting has important consequences for atmospheric circulation and climate due to the energetic imbalance provoked in the boreal seas, as the highly reflective ice cover is replaced by liquid water with a much smaller albedo (Deser et al. 2016; Sorokina et al. 2016). According to the recent Intergovernmental Panel on Climate Change (IPCC) Report V (IPCC 2013), there has been a 3.8% per decade downward trend in the annual average Arctic sea ice coverage over the last four decades.

The connection between polar energy balance variations and tropical atmospheric behaviour occurs through teleconnections, which denote significant temporal correlations between meteorological parameter fluctuations at distant points. These correlations allow establishment of relationships between apparently unrelated climatic anomalies at great distances. Such connections are sustained by the energy transportation and wave propagation both in the atmosphere and the oceans, with the former acting as a bridge and the latter acting as tunnels for these global climate connections (Liu & Alexander 2007).

Although the sea ice coverage, concentration and thickness in the high boreal latitudes have declined sharply in recent decades, colder winters and more snow have been observed for at least the last decade in some Northern
hemisphere mid-latitude continental regions. It is clear the sea ice coverage reduction in the polar regions increases the heat flow from the ocean to the atmosphere, but several studies show that recent atmospheric circulation anomalies resemble the Northern Annular Mode (NAM) negative phase and also the North Atlantic Oscillation (NAO) negative phase, along with warming in more Northern latitudes (Takaya & Nakamura 2008; Vihma 2014; Nakamura et al. 2015; Ruggieri et al. 2017, among other studies). Vihma (2014) suggests that declining Arctic Ocean sea ice and adjacent seas leads to colder winters, especially in Europe, northeast Eurasia and eastern North America. Nakamura et al. (2015) have found evidence that the recent decline in Arctic sea ice results in cold winters in mid-latitude continental regions, associated with an abnormal circulation pattern similar to both NAM and NAO negative phases, and the frequency of these teleconnection negative patterns has increased.

Typically, climate models are fed with historical or idealized data to perform valuable simulations on the Earth climate system behaviour. Due to their simplicity, results from intermediate complexity model, such as the SPEEDY model used here, are useful to understand various types of variability and climate change. Furthermore, this type of simpler model facilitates the clarification of relevant scientific and software issues, which would be computationally very expensive with the latest generation of general circulation models.

The experiments presented sought a chain of events connecting the Northern Hemisphere high latitude sea ice reductions to the tropical climate, specifically location and intensity changes of the Intertropical Convergence Zone (ITCZ) and the South Atlantic Convergence Zone (SACZ). Thus, the research focuses on atmospheric connections to possibly explain how the high boreal latitudes sea ice reduction could influence precipitation in the Atlantic Ocean tropical sector and tropical Americas.

**METHODOLOGY**

Since 1979, satellite sensors have shown that sea ice cover is declining throughout the four annual seasons in practically all the Northern Hemisphere high latitude seas, with the exception of the Bering Sea during the winter. The IPCC Report V (IPCC 2013) indicates the regional distribution of the high boreal latitude sea ice coverage decrease observed per decade: 9.3% in the Barents Sea; 6.1% East of Greenland; 7.0% West of Greenland; 2.5% in Foxe Bay; 4.6% in the Hudson Bay; and 2.2% in the Arctic Sea (see Figure 1).

**Global model simulations**

To simulate a possible future tropical rainfall climatological scenario, due to the currently observed trend of sea ice reduction in the Northern Hemisphere upper latitudes, the intermediate complexity atmospheric model SPEEDY was integrated with eight vertical layers and the triangular horizontal spectral truncation at full wave number 30 (T30L8), as documented at http://users.ictp.it/~kucharsk/speedy-net.html. SPEEDY is a hydrostatic σ-coordinate, spectral transform model of the vorticity-divergence form, with semi-implicit treatment of gravity waves. The parameterized processes include large-scale condensation; convection; short-wave and long-wave radiation; surface fluxes of momentum, heat and moisture; and vertical diffusion. A simple one-layer thermodynamic model is used to determine land and ice temperature anomalies (Kucharski et al. 2013).

**Figure 1** | Regional distribution of the ice coverage decadal trends (%) in the boreal seas, as indicated by IPCC Report V.
The atmospheric model SPEEDY was fed with boundary condition files, derived from ERA Interim, the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis, in order to determine the fluxes of momentum, heat and moisture at the surface, and the flux of incoming solar radiation at the top of the atmosphere. The integrations started with an initial condition, but because all integrations of the model were made for 110 years discarding the first ten years, the initial condition became totally irrelevant. All input data, both initial and boundary conditions were delivered with the SPEEDY package.

The boundary condition files include the global climatological fields of orography, land-sea mask, sea surface temperatures (averaged from 1979 to 2008), sea ice coverage, land temperature distribution, snow depth, soil wetness, bare-surface albedo in the absence of snow or sea ice and fraction of land-surface covered by vegetation. For the last two fields, annual-mean values are used, while all other fields are specified as monthly means and are linearly interpolated to get daily-updated values. The monthly global distribution of sea ice was used in the control run and was subsequently modified according to the trend indication of the IPCC in order to isolate the disturbed climate forced by the expected changes in sea ice coverage.

Based on the IPCC Report V (IPCC 2013), showing the sea ice decrease percentage per decade in the Northern Hemisphere upper latitudes, and assuming that the global sea ice cover climatology used in SPEEDY corresponded to 1990, Table 1 shows the projected sea ice cover decrease in each region indicated by the IPCC by 2050.

The expected variation was then applied to the SPEEDY model code in the corresponding areas, using the variation factors as presented in the last column of Table 1. Due to model code requirements, these variation factors actually represent the sea ice that is expected to remain, not the ice that will be lost.

This study presents two experiments to generate global climatologies from the model. In the first, identified as IPCC, the Table 1 last column variation factors, referring to the sea ice cover decrease in the Northern Hemisphere high latitude oceans and seas, were simultaneously input to the SPEEDY model code. To examine the model’s sensitivity to how the reducing sea ice could affect the simulated atmospheric behaviour, a second numerical experiment was devised, referred to hereafter as Radical, with a 90% ice reduction in all maritime regions where the IPCC indicated ice shrinkage. Thus, in all regions cited in the IPCC Report V, a variation factor of 0.1 was imposed, which meant that only 10% of the sea ice would remain there in the future.

Data from National Centers for Environmental Prediction Climate Forecast System Reanalysis

The use of reanalyses in meteorology was a huge step forward in the 1990s, because the gridded datasets available before 1995 were created by constantly changed models and by different methods of analysis, even manual analyses prior to 1965. The most prominent reanalyses in world meteorology were conducted by the US environmental agencies National
Centers for Environmental Prediction (NCEP) and Goddard Space Flight Center/National Aeronautics and Space Administration, the Japan Meteorological Agency and the European ECMWF consortium with the basic objective of producing global multiannual fields of atmospheric variables using a single state-of-art system for data assimilation and also a unique model.

The present study uses monthly means of zonal and meridional wind components, vertical motion at 500 hPa and tropical rain, obtained from the NCEP Climate Forecast System (CFS) Reanalysis (Saha et al. 2010) in order to diagnose eventual similarities between boreal ice reduction and negative events of the NAM as suggested by the literature. The construction of composites of meteorological variables associated with the phases of the NAM followed the usual methodology, taking into account weighted averages of each variable during the positive and negative phases of the NAM separately. The difference between such composites referring to the negative and positive phases of NAM was then calculated, thus highlighting how the negative phase of the NAM affects the meteorological variables diagnosed.

RESULTS AND DISCUSSION

Effects of sea ice reduction on Northern Hemisphere meridional wind

Based on the intuition that the Ferrel cell should be the atmospheric bridge linking the high boreal latitudes with the tropical belt, its horizontal branches were analysed. The modelled behaviour of the meridional wind component at 850 and 200 hPa was analysed, as shown in Figures 2 and 3, for the so-called IPCC and Radical simulations implemented in the SPEEDY model. The arrows represent the vector differences of the meridional wind between the experiments with regional Arctic ice decrease and the control run. Together with the vectors, the images present shades whose colours indicate the positive and negative differences for the meridional wind component in the Northern hemisphere Ferrel cell using the following criteria: at 850 hPa the meridional component is usually from the south ($v > 0$) and therefore a strengthening (weakening) of the Ferrel cell lower branch must be positive (negative); at 200 hPa, the meridional component is usually from the north ($v < 0$) and therefore a strengthening (weakening) of the Ferrel cell upper branch should be negative (positive). In short, blue indicates the Ferrel cell strengthening, while red indicates its weakening.

In Figure 2, regarding the Ferrel cell inferior branch, blue represents the strengthening of the winds from the...
south or the weakening of the winds from the north, while red represents the strengthening of the winds from the north or the weakening of the winds from the south.

Figure 3 refers to the Ferrel cell upper branch; blue represents the strengthening of the winds from the north or the weakening of the winds from the south, while the red represents the strengthening of the winds from the south or the weakening of the winds from the north.

The Ferrel cell connects the polar region to the tropical belt and the meridional wind simulations show sectors with accelerations and decelerations throughout the Northern Hemisphere mid-latitudes, as in Figures 2 and 3. This anomalous sectorization in the meridional wind component of the Ferrel cell can be understood as an increase in the amplitude of Rossby waves in response to the available energy increase in the simulated system due to the maritime polar ice decrease. The principal discrepancies between the configurations of the realistic (IPCC) and Radical tests may be due to the excessively strong reduction of Western Hemisphere ice imposed in the Radical experiment, where the IPCC indicates less severe sea ice reductions.

Unlike the figures above, in which the colours and arrow directions represent differences between the SPEEDY model experiments with polar sea ice reductions and the control run, Figure 4 below shows the differences between the composites of the NAM meridional component, through its negative minus positive events. The data used herein are from the NCEP CFS reanalyses for the December–January–February quarter over the last 36 years. Therefore, since the data come from observations, the values represent the prominence of negative NAM events of the meridional winds throughout the Ferrel cell. Composites were implemented for the NAO (not shown), presenting very similar characteristics.

In Figure 4, the arrows indicate accelerations and decelerations due to differences between the NAM negative and positive phases, while the coloured shading indicates whether such variations in the meridional wind component accelerate or decelerate the Ferrel cell from its normal condition. The similarities between the composites of the NAM in Figure 4 and the simulations shown in Figures 2 and 3 indicate that the sea ice reduction in the high boreal latitudes in the recent decades coincides with the prominence of the NAM negative phase. Although not shown here, the same seems to be true in comparison with NAO.

**Effects of sea ice reduction on Northern Hemisphere zonal wind**

Variations in tropospheric zonal wind simulations due to sea ice reductions in the boreal latitudes are analysed below. The vertical profiles of the zonal average of the zonal wind in January are presented in Figure 5, as a result of the 2050 projected simulations for the realistic reductions indicated by the IPCC, as well as for the 90% decrease in ice in all boreal seas.
Zonal wind decelerations can be observed between latitudes 50 and 70°N, in the modelled troposphere, coinciding with accelerations southward of 50°N and northward of 70°N. This pattern also appears in the Radical experiment, which suggests this is a coherent response to the polar sea ice coverage shrinkage. Although not shown, this zonal wind variation pattern also appears in the simulations of the other seasons, being more intense in the spring (April) and less intense in the fall (October). As discussed above, these zonal wind variations in the Northern Hemisphere troposphere also suggest that the energy input due to the polar sea ice coverage shrinkage increases the Rossby waves’ amplitude.

The difference of the tropospheric zonal wind composites for the negative minus positive phases of the NAM during December–January–February is shown in Figure 6, these profiles being similar to those obtained in the boreal sea ice decrease simulations.

The literature points out the NAM negative phase predominance would be a possible response to the climate change due to greenhouse gases increased release into the atmosphere (Nakamura et al. 2015, among others). Therefore, climate response to the CO₂ increase in the atmosphere during recent decades seems to have led to an ice cover reduction in the polar seas and also to tropospheric circumpolar circulation changes in the mid-latitudes associated with the NAM negative phase. The representation of the negative minus positive phase difference of the NAO, although not presented here, shows a similar configuration. Deser et al. (2016) indicate that the decrease in the amount of sea ice weakens the westerly tropospheric winds along the polar side of the eddy-driven jet, while on the south side a small intensification occurs. This response is stronger in winter and is associated with a north–south temperature gradient reduction due to the increasing warming of the lower Arctic troposphere, influencing the Rossby wave north–south meanders and associated synoptic activity.

Effects of sea ice reduction on tropical vertical motion

The last dynamic link between the Arctic sea ice reduction and the tropical rain patterns is diagnosed herein through the vertical motion field throughout the tropical belt shown in Figure 7.

Figure 7 clearly shows shifts in the ITCZ position as well as a kind of compensating subsidence sector in the subtropical belt, probably in response to the significant intensification of upward movements in some ITCZ sectors. It is worth highlighting such subsiding sectors in the Mexican mainland, the southeastern USA, the Gulf of Mexico, the Caribbean Sea and a large area.

Figure 4 | Composites highlighting the effect of NAM negative events in the meridional wind (m/s) in December–January–February: (a) 850 hPa and (b) 200 hPa. Data source: NCEP CFS Reanalysis. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wcc.2018.066.
Figure 5 | Latitude–height cross sections showing the zonal average of the zonal wind (m/s) for the SPEEDY outputs in January for (a) IPCC and (b) Radical experiments.
in northern Argentina, which is a major food producer. Another highlight is the apparent displacement to the south of the west sector of the Atlantic ITCZ, favouring the rains in Northeast Brazil.

Figure 8 presents the difference of the vertical motion composites for the NAM negative minus positive events throughout the tropical belt in December–January–February, for the last 36 years.
In the Indian peninsula and Indian Ocean there are several discrepancies in the comparison between simulation depicted in Figure 7 and results presented in Figure 8. On the other side, there are many similarities in the tropical belt of the oceans Pacific and Atlantic, including the shift of ITCZ and SACZ southward, which are two very important patterns for Brazilian rainfall. The vertical motion field composite concerning the NAO negative events is similar, although it is not shown here.

Effects of sea ice reduction on tropical precipitation

Figure 9 illustrates the rainfall simulations on tropical South America and its surroundings, following the boreal sea ice reduction indicated in the IPCC Report V and also with respect to the Radical 90% abatement of Northern Hemisphere polar marine ice.

There are some discrepancies between these two simulations, but the Atlantic ITCZ and the SACZ southward shift are very consistent, suggesting that both are responses to the available energy increase in the atmosphere in the Arctic region following the sea ice reduction, as observed in recent decades. Again, contrary to the common results indicating that the ITCZ is shifted toward the warmer hemisphere, here the ITCZ is shifted southward, probably due to the temperature field rearrangement in the Northern Hemisphere mid-latitudes in response to the boreal marine ice reduction (Deser et al. 2016, among others).

Figure 10 shows the composite of the effect of the NAM negative minus positive events on tropical rainfall. The rainfall variations impact in NAM negative events seems to be very weak in tropical South America, but it is significant in the ITCZ southward shift, favouring rainfall over Northeast Brazil, a response very consistent with previous results.

CONCLUSIONS

The objective of this study was to search for possible atmospheric mechanisms that connect the changes in the Northern Hemisphere polar and subpolar sea ice with the tropical belt rainfall patterns. Even with the limitations of a very simple general atmospheric circulation model, the results show how the Northern Hemisphere Ferrel cell seems to act as a bridge between sea ice cover variations in the high boreal latitudes and tropical rainfall patterns, mainly to the ITCZ and the SACZ. The analyses were based on two simulation types with the SPEEDY model, in addition to the control run: (1) Arctic and sub-Arctic sea ice reductions input to the model code accordingly to the IPCC Report V; and (2) a Radical experiment, in which these same boreal seas had a 90% decrease in ice.

The main result is the indication that the Northern Hemisphere Ferrel cell responds to the sea ice cover shrinkage in the high boreal latitudes by increasing the amplitude of Rossby waves, as shown in the meridional component field anomalies.
Figure 9 | Difference between tropical precipitation (mm/day) for sea ice reduction minus control run in January, (a) for IPCC indications and (b) for Radical 90% reduction in polar sea ice.
of the wind at 850 and 200 hPa. This enables the temperature and pressure fields to be reordered (not shown here), as proposed in the literature (Sorokina et al. 2016). These changes in the Northern Hemisphere planetary wave structures are also evident in the simulated profiles of the tropospheric zonal wind component.

Although several studies have demonstrated the ITCZ is shifted towards the hemisphere most warmed by climatic variations (Chiang & Bitz 2005; Cvijanovic et al. 2013, among others), in the simulations presented herein, the Atlantic ITCZ is clearly shifted southward in response to the Arctic region sea ice reduction. This apparent contradiction can be explained by the fact that the first reaction to the sea ice decrease is a continental cooling in the Northern Hemisphere mid-latitudes, especially in Europe, Northeast Eurasia and Northern North America (Vihma 2014; Nakamura et al. 2015). Therefore, it seems that the tropospheric wind field rearrangement may explain the ‘warm Arctic – cold continents’ pattern that has been associated with the sea ice reduction (Ruggieri et al. 2017).

As several recent articles have pointed out, a higher frequency of NAM (and NAO) negative phases appears to be a natural response to global climate change. This study uses the zonal and meridional tropospheric wind composites in the Northern Hemisphere mid-latitudes, as well as the vertical motion in 500 hPa and tropical precipitation, highlighting the NAM negative phase. All these composites have a close resemblance to the changes in the same variables simulated by the model. It is likely that neither the NAM and NAO negative events nor the boreal sea ice reduction are the cause of each other, but both must be caused by the global climate change observed in recent decades and attributed by the majority of the scientific community to the high amounts of CO₂ released into the atmosphere by human activities.

The simulation results and the subsequent diagnoses indicate that energy exchange variations between the surface and the atmosphere, even in remote regions such as the Northern Hemisphere high latitudes, can affect tropical rainfall patterns, especially in the ITCZ. Obviously, the model tests presented here were too simple to determine exactly what these effects are. Nevertheless, it is reasonable to expect that the Amazon and Northeastern Brazilian rainfall has been and will continue to be affected by global climate change.
climate change (Kucharski et al. 2006). Furthermore, the SACZ appears to be shifted by remote forces such as the changes explored herein.

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