Changes in Northern Hemisphere Winter Storm Tracks under the Background of Arctic Amplification

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1. Background and Motivation

Storm tracks are defined as the preferred regions of extratropical synoptic-scale disturbances. Previous studies could not reach a consensus on how storm tracks have changed in recent decades or how it will be changed in the future. Several studies have shown a northward shift of both the North Atlantic storm track (NAST) and the North Pacific storm track (NPST) in recent decades (Bender et al. 2012) and in the future (Yin 2005), while others have demonstrated a weakening trend in the NAST (e.g., Lee et al. 2012), or a strengthening and extension of southern flank of the NAST (Harvey et al. 2015). Previous studies also leave us uncertain whether the recent change in storm tracks is related to the Arctic warming. Although convincing evidence has been provided in the affirmative (e.g., Francis and Vavrus 2012, 2015), some investigators have argued that Arctic amplification may not be a dominant factor controlling the mid-latitude weather (e.g., Barnes and Screen 2015). In addition, the analyses of possible contribution of mid-latitude variation to changes in the Arctic surface air temperature (Ts) were focused primarily on an intraseasonal timescale (e.g., Yoo et al. 2012).

In this study, we

1. **revisit the interdecadal change in storm tracks based on three statistical metrics and verify the possible mechanism with a model simulation,**
2. **hypothesize that Arctic amplification would result in changes in baroclinicity and hence influence the storm track activity (STA). We test our hypothesis using a high-resolution reanalysis and simulations from the Community Earth System Model Large Ensemble (CESM-LE, Kay et al. 2015) project,**
3. **examine the potential feedback of changes in the NAST on Arctic amplification on the interdecadal timescale.**

2. Interdecadal change in storm tracks

Warm-cold differences of Ts and storm tracks

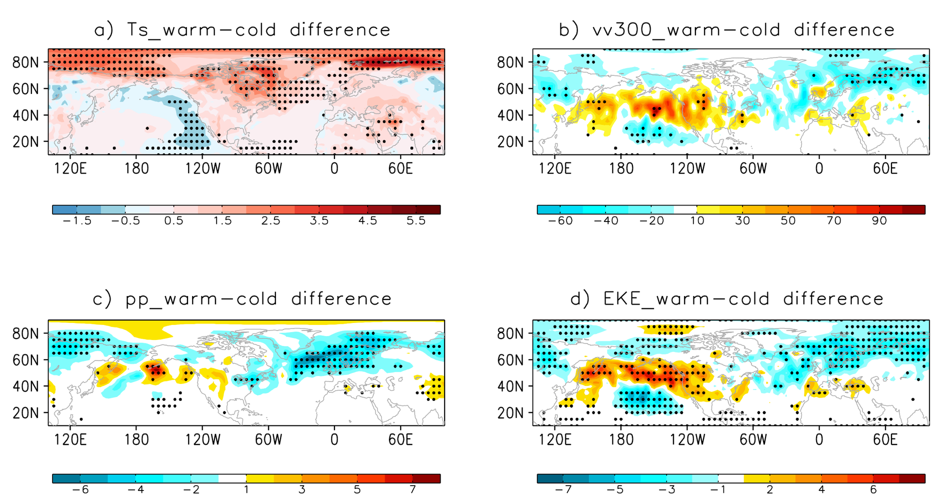


FIG. 1. The warm-cold differences (1997/98-2014/15 mean minus 1979/80-1996/97 mean) of (a) Ts (interval: 0.5 K) and storm tracks defined by the (b) vv300 (interval: 10 m^2 s^{-2}), (c) *pp* (interval: 1 hPa^2) and (d) EKE (interval: 1 m^2 s^{-2}) during October to March. Dotted areas indicate differences exceeding the 95% significance level according to the Student *t* test.

Occurrence frequency of poleward displaced NPST and negative phases of the NAST

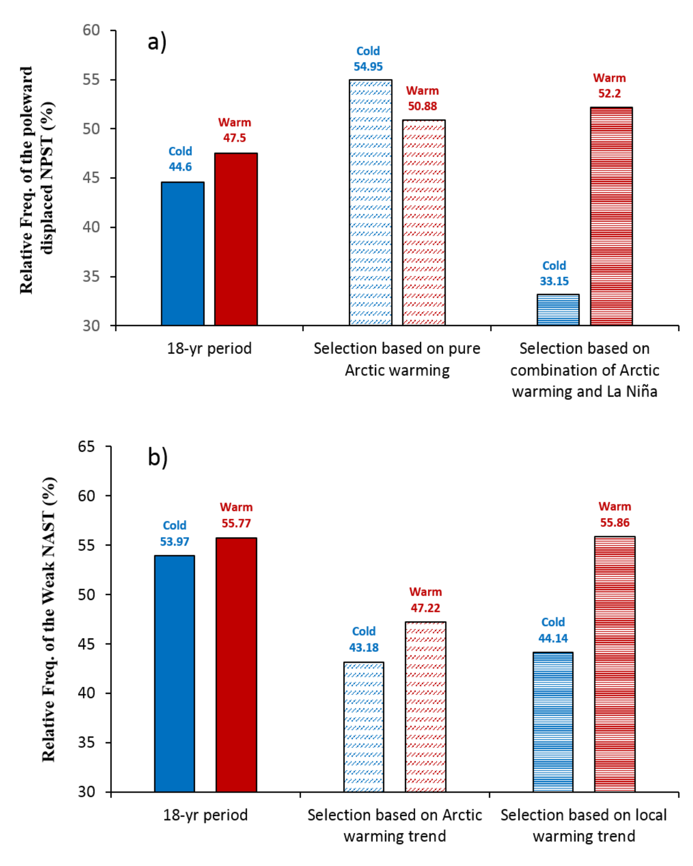
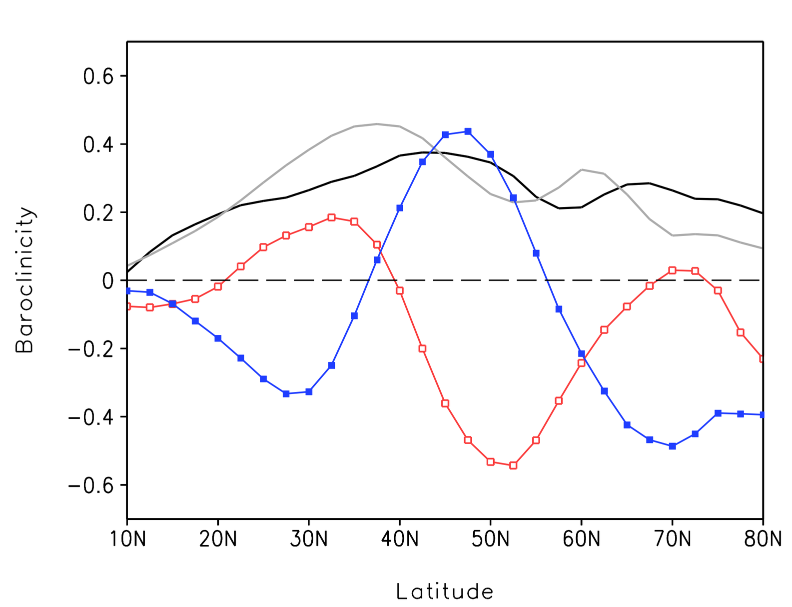


FIG. 2. (a) Relative occurrence frequency of poleward displaced NPST over the (left) cold and warm periods, cold and warm Arctic years (middle) without and (right) with influence of strong ENSO events. (b) Relative occurrence frequency of negative phases of the NAST over the (left) cold and warm periods, cold and warm Arctic years selected based on (middle) the entire and (right) the local Arctic (160°-20°W, 60°-90°N) warming trend.

- **Ts**: Arctic amplification (two maximum warming with one located over eastern Canada and western Greenland, and the other over the Barents-Kara Sea), a La Niña-like pattern in the Pacific.
  Storm tracks: A significant poleward shift of the NPST and a striking weakening trend in the NAST.
- **The poleward-shifted NPST:** an increase in the warm Arctic period, a 4.07% decrease during pure Arctic warming years, and a significant increase (19.05%) during the warm Arctic years with strong La Niña events.
  The negative phase of the NAST: an increase from the cold to warm period, more obviously for the case of local Arctic Ts change.

3. Mechanism of the recent changes in storm tracks

Change in baroclinicity over the North Atlantic and North Pacific



- **The North Atlantic**: a significant decrease in the baroclinicity over 40°-70°N during the warm period, exactly in the same region where the largest weakening in the NAST is observed.
  The North Pacific: a tripolar change in the baroclinicity which comprises an increase to the north (40°-60°N) and a decrease to the south (20°-40°N) of the climatological NPST. This also matches the observed poleward shift of the NPST.

Possible influence of the Arctic warming on the NAST
Plausible contribution of La Niña-like SST change to the poleward shift of the NPST over Arctic amplification

FIG. 3. Climatology of longitudinal-mean baroclinicity over the North Atlantic (black line, 90°W-0°) and North Pacific (gray line, 120°E-120°W), and their corresponding changes (red line with open box for the North Atlantic, blue line with filled box for the North Pacific) between the warm and cold periods. The baroclinicity is defined as negative temperature gradient integrated from the surface to 400 hPa. The original values of changes are multiplied by 100 while the climatology are maintained as original values.

4. Model simulation of the change in storm tracks

Ensemble mean of changes in Ts and storm tracks

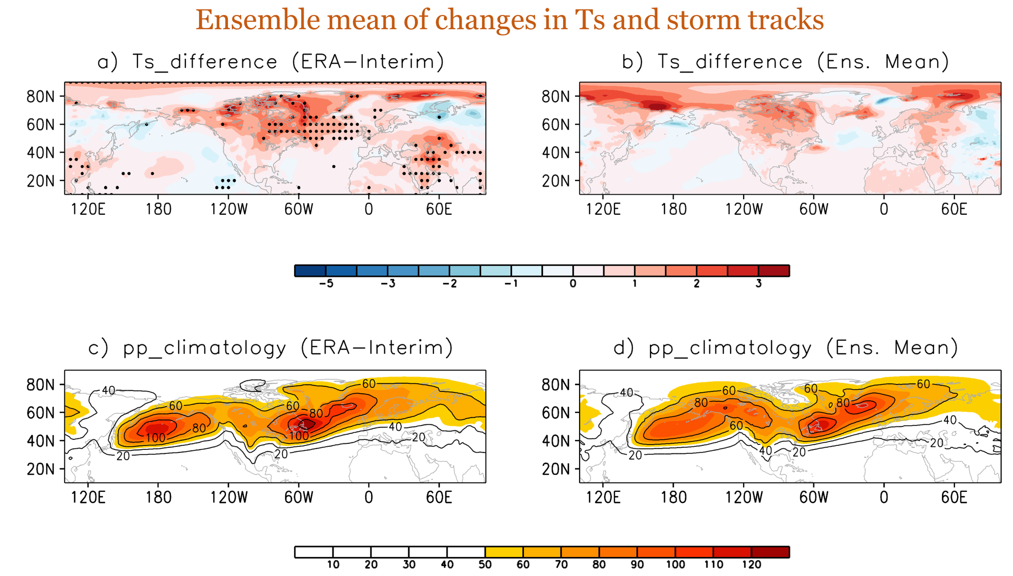


FIG. 4. Differences of Ts (shading, interval: 0.5 K) based on the (a) ERA-Interim and (b) 33-number ensemble mean derived from the CESM-LE between 1997/98-2004/05 and 1979/80-1996/97. Climatology of storm tracks (hPa^2) based on the (c) ERA-Interim and (d) 33-number ensemble mean for the period 1979/80-2004/05.

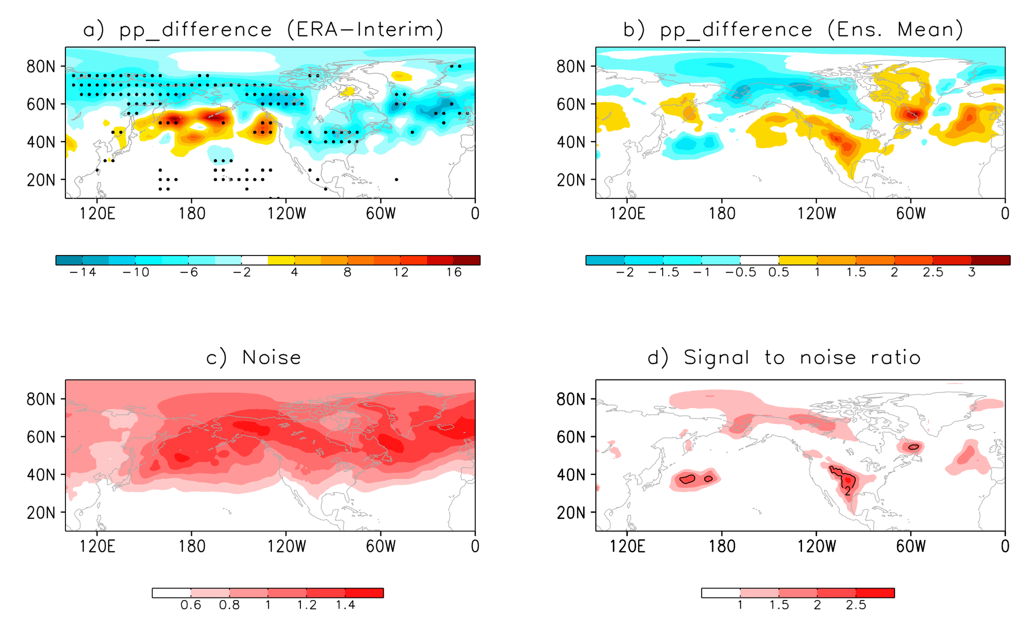


FIG. 5. (a), (b) Same as Fig. 4a and b, but for storm tracks (hPa^2). (c) Noise is defined as the standard deviation of difference across the individual ensemble members, while the signal to noise ratio (d) is the ratio of absolute value of (b) divided by (c). The ratio larger than 2 is encircled by black contour.

Best simulations of changes in Ts and storm tracks

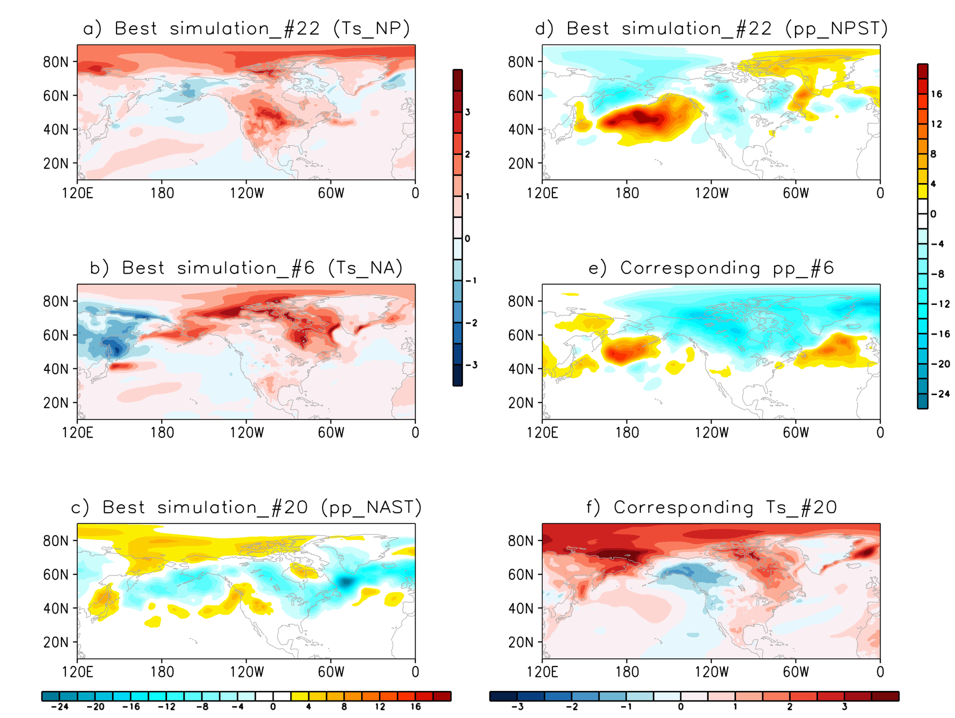


FIG. 6. Simulations of changes in a) Ts over the North Pacific, b) Ts over the North Atlantic (K), c) the NAST and d) the NPST (hPa^2) that have highest spatial correlation coefficients with the observations. e)-f) Corresponding simulations of the *pp* and Ts.

- **Simulation of Ts**: a maximum warming near the New Siberian Islands and an unobserved cooling over the northern North Atlantic (around 30°W, 55°N).
- **Simulation of storm tracks**: a meridional dipole change in the NAST, and an eastward shift of the NPST.
- When the La Niña-like change in SST is reproduced by the model, a significant poleward shift of the NPST could be materialized (#22). When an intense warming over northeastern North America is simulated (#6) and the cooling bias is weaker and shifts to far south (#20), a uniform weakening of the NAST is reproduced similar to the observed change.

5. Future projections of Ts and storm tracks

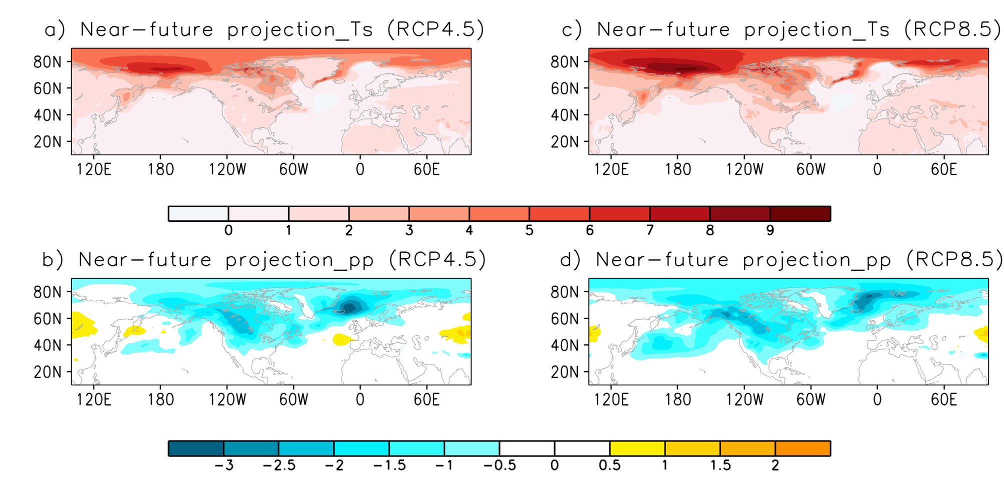


FIG. 7. Near-future projections of (a), (c) Ts (shading, interval: 1 K) and (b), (d) storm tracks (shading, interval: 0.5 hPa^2) under the RCP4.5 and RCP8.5 scenarios, which is derived as differences between the 15-number ensemble mean of RCP4.5/RCP8.5 for the period of 2016/17-2039/40 and that of the historical runs for 1997/98-2004/05.

- a warmer planet under the influence of increasing greenhouse gases, and a significant weakening of both the NAST and the NPST.

6. The potential feedback of the NAST on Arctic amplification

Relative contribution of different-timescale moisture transport to the Arctic warming

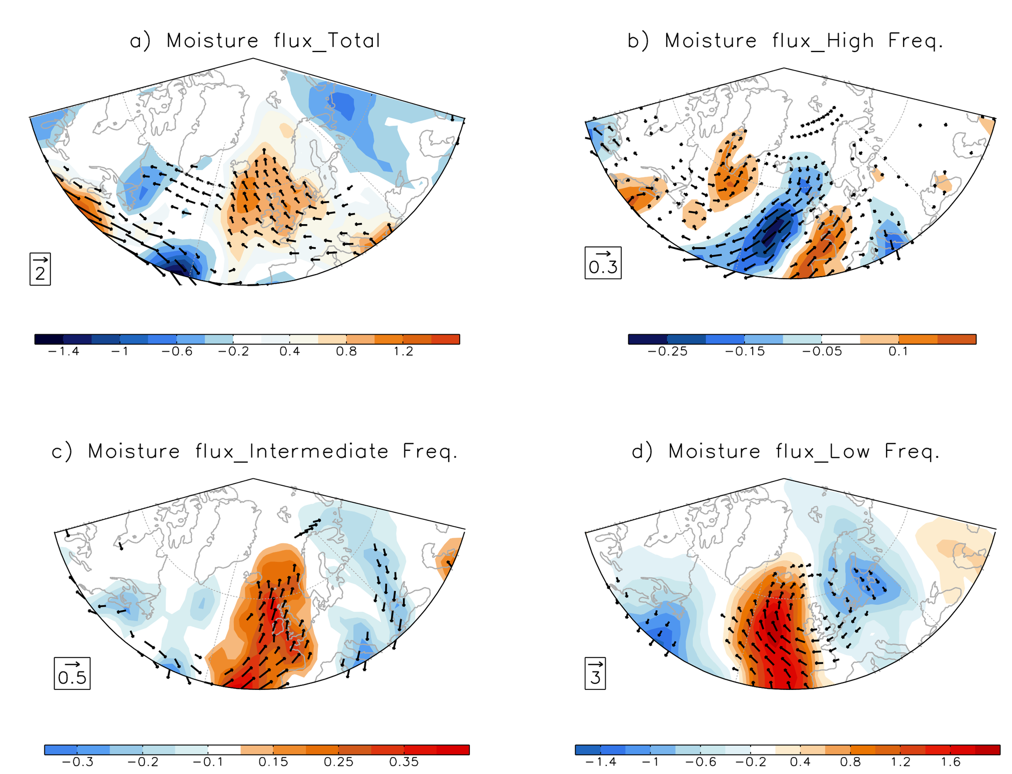


FIG. 8. Composite maps of a) $\overline{V}q' + V'\overline{q} + V'q'$, b) $\overline{V}q^H + V^H\overline{q} + V^Hq^H$, c) $\overline{V}q^I + V^I\overline{q} + V^Iq^I$, d) $\overline{V}q^L + V^L\overline{q} + V^Lq^L$ (vector, unit: ×10 kg m^{-1} s^{-1}, only values exceeding the 95% significance level are shown) for the warm Arctic years. Shading indicates the meridional transport.

Feedback of the NAST towards Arctic amplification

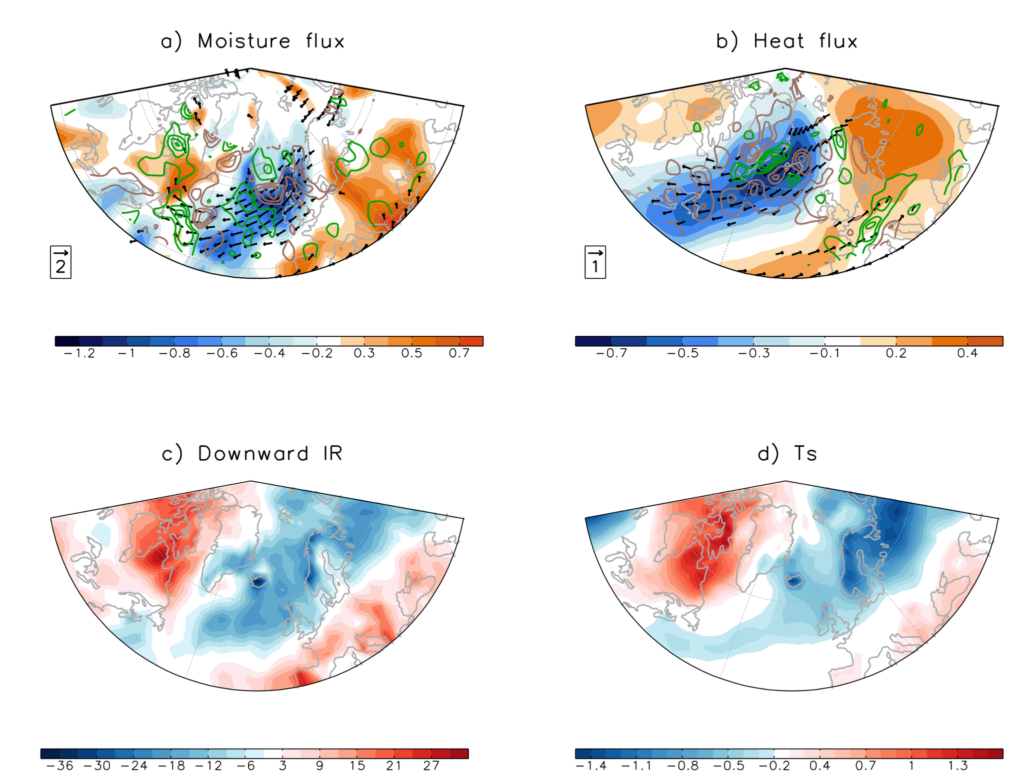


FIG. 9. Composite maps of the anomalous (a) moisture flux (vector, ×10 kg m^{-1} s^{-1}), (b) heat flux (vector, ×10 kg K m^{-1} s^{-1}), (c) downward infrared radiation (shading, interval: 3 W m^{-2}), and (d) Ts (shading, interval: 0.2 K) associated with the negative phase of the intense NAST. For the moisture and heat fluxes, only fluxes exceeding the 95% significance level according to the Student's *t* test are shown. Shading in (a), (b) denotes the meridional transport, while contours indicate anomalous convergence (green) and divergence (brown) of integrated moisture and heat flux.

- An anomalous equatorward moisture transport is found in the North Atlantic for the high-frequency component, but an intensified poleward transport is detected in the low- and intermediate-frequency components. A weakening in storm activities during the warm Arctic years.
- Equatorward moisture transport anomalies take less humidity away from the Arctic near North America and hence bring less humidity to northern Europe. This warms the former region but cools the latter one.
  Fewer storm events in the North Atlantic will strengthen the warming over the Arctic near North America by increasing the downward IR as a positive feedback but will hinder the warming over North Europe.

7. Conclusion

1. The interdecadal weakening of the NAST in recent decades is shown to be a result of the decreased baroclinicity associated with recent Arctic amplification; while the poleward shift of the NPST is found to be influenced by the La Niña-like change in SST.
2. 33 simulations derived from the CESM-LE project, although with some biases in storm track and Ts simulations, support the observed relationship between the NAST and Ts over northeastern North America, as well as the link between the NPST and the ENSO.
3. The near-future projections of Ts and storm tracks suggest that Arctic amplification will still be dominant in the future, and storm tracks will continue to weaken, which alludes to fewer storm events over the mid-latitudes.
4. The anomalous equatorward moisture flux associated with the weakening trend of the NAST would enhance the warming over its upstream region and hinder the warming over its downstream region via modulation of the downward infrared radiation.

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