Response of Northern Hemisphere Storm Activity to Tropical Pacific SST and Arctic Sea Ice Forcing: Modeling Investigations

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INTRODUCTION

Extratropical synoptic-scale cyclonic storms are a fundamental element comprising daily weather patterns and interactively contribute to large-scale general atmospheric circulation in mid and high latitudes. They can bring about blizzards, snowfall, and gusty winds that impact daily life through infrastructure damage and property loss. Storm activities have prominent regional and seasonal structures, and exhibited daily to interannual variability [*Hoskins and Hodges*, 2002; *Zhang et al.*, 2004, *Bengtsson et al.*, 2006]. Meanwhile, storm tracks and activities have also demonstrated long-term changes in a changing climate.

To improve understanding of regional variability and changes in storm activities over North America and North Hemisphere, we examined impacts of elevated Tropical Pacific SST and declining Arctic sea ice.

MODEL AND STORM FINDING/TRACKING ALGORITHM

- Model: the National Center for Atmospheric Research (NCAR) Community Atmosphere Model (CAM) version 3.1.p2.
- Resolutions: T85 (approximately 1.4° in both latitude and longitude) horizontally with 26 vertical levels.

To analyze storm activities in all the experiments, we employed a storm identification and tracking algorithm (Zhang et al. [2004]) and applied this algorithm to the 6-houly sea level pressure (SLP) outputs from each model ensemble. The principles of this algorithm are:

1) Identify a low SLP center.
2) low center has at least a minimum SLP gradient of 0.15 hPa (100 km)^-1 with the surrounding 8 grid points.
3) Survives for more than 12 hours.

From the outputs of the algorithm we calculated:

- ***Storm Trajectory*** - It is defined from the time of storm generation until dissipation within the study area or from the time when the storm enters the study area until the time it leaves the study area.
- ***Mean Duration*** - Mean duration for each sub-region is the averaged duration throughout the total number of storm trajectories.
- ***Mean Intensity*** - The storm intensity for individual storm was calculated as a difference between the storm's central SLP and the monthly mean SLP at the corresponding location. The mean intensity for each sub-region was obtained by averaging storm intensities throughout their duration and over the number of storm trajectories.

EXPERIMENTS

IMPACTS OF TROPICAL PACIFIC SST ON STORMS

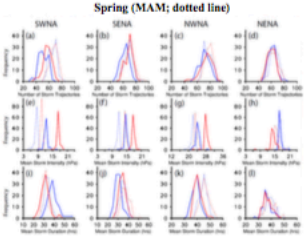
MODELING EXPERIMENT DESIGN

Experiment	Description
ConExp	Climatological SST + Climatological sea ice
SenExp	Positive SST anomalies added to the climatological SST at each grid point over the tropical Pacific region between 10°S and 10°N and from 165°W to 80°W + climatology SST elsewhere + climatology sea ice

- Simulation time: Model run from 1st November to 31st May, with 6-hourly output of selected variables.
- Experiments: 60 ensembles for each of control experiment (ConExp) and sensitivity experiments (SenExp).
- Considering distinct geographic features of climatological storm activity, we divided the North American continent into four sub-regions in this study.
- 95% significant level Student's T–test was performed to examine the statistical significance of the results.

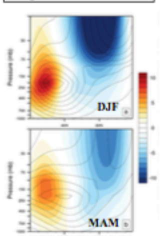
RESULTS

Probability Density Functions (PDFs) for ConExp (Blue) and SenExp (Red) for Winter (DJF; solid line) and Spring (MAM; dotted line)

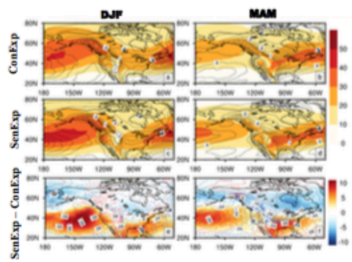


- Trajectory count increases in winter (spring) over SWNA and SENA (NWNA).
- Mean storm intensity increases in winter (spring) over SWNA, SENA, and NWNA (SWNA, SENA).
- Mean duration decreases over SWNA and increases over SENA in winter.

- Transient eddy kinetic energy increase over SWNA and SENA in winter and spring and over NWNA in winter, which is consistent with the statistical results suggesting southward shift of storm track and thus showing the inherent linkage of synoptic scale surface cyclones to large scale background circulation.



Zonally averaged (between 180° and 310°) climatological zonal wind (contours) and the differences between SenExp and ConExp (shaded) across the vertical section along 20°N–80°N for (a) winter and (b) spring.



Transient eddy kinetic energy (KJ/m2, shaded) ; superimposed Eady Growth Rate Maximum (day1, contours) at 775 hPa in ConExp for (a) winter and (b) spring. (c and d) The same as Figures a and b, but for SenExp. The differences between SenExp and ConExp are displayed for (e) winter and (f) spring.

- Strengthening and southward shifting of the subtropical jet stream, particularly in winter, when the tropical Pacific SST increases in SenExp compared to its climatology in ConExp.
- Changed jet stream between 25°N and 40°N can result in an increase in EGRM further southward than its climatology and, in turn, supports the intensified and southward shifted storm tracks found above.
- In addition, the jet stream favors storms developing on its south side, due to the associated large upper-level divergence.
- The northwest-to-southeast aliened background steering flow favors storms to propagate to the south-eastern US.

- Eady Growth Rate Maximum (EGRM) shifts southeastward from the Aleutian Islands to western North America, particularly in winter.
- Considerably increased EGRM occurs from southeastern Alaska and western Canada to California.
- EGRM also increases substantially from the southern U.S. to the east coast, with the largest increase in spring.

Details can be found at:
Basu, S., X. Zhang, I. Polyakov, and U. S. Bhatt (2013), North American winter-spring storms: Modeling investigation on tropical Pacific sea surface temperature impacts, Geophys. Res. Lett., 40,5228–5233, doi:10.1002/grl.50990. :

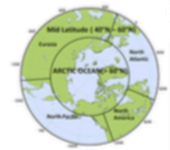
CONCLUSION

1. In response to anomalous surface boundary forcing such as elevated tropical Pacific SST like El Niño the winter-spring storms over North American exhibit a southward shift.
2. Elevated tropical Pacific SSTs cause a southward shift and intensification of the subtropical jet stream which favors an increased vertical wind sheer to the south of the climatological jet stream.
3. Increased vertical wind sheer enhances baroclinicity, upper level divergence and hence supports the development of surface storms.
4. Increased storm activity also causes an increase in the EKE over the regions located south of the climatological storm track.

IMPACTS OF ARCTIC SEA ICE DECLINING TREND ON STORMS

MODELING EXPERIMENT DESIGN

Experiment	Description
ConExp (Observed Sea ice)	Observed sea ice (January 1979 – December 2008) over Arctic + climatology SST + climatology sea ice in SH
TrExp (Sea ice Trend)	Linearly prescribed sea ice over Arctic for January 1979 to December 2008 based on trend + climatological sea ice over SH + climatology SST



- Domain expanded to whole North Hemisphere with 5 regions :

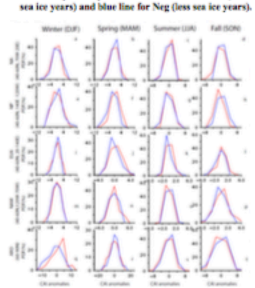
Mid Latitude (40°N to 60°N) and Arctic (70°N to 90°N).

- Mid latitude is further classified into: **North Atlantic (70°W to 20°E) , North Pacific (140°E to 120°W), Eurasia (20°E to 140°E) and North America (120°W to 70°W)**
- Simulation time: Model run from 1st January, 1978 to 31st December, 2007 with 6-hourly output of selected variables.

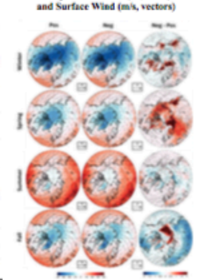
RESULTS

OBSERVED SEA ICE FORCING

Probability Density Function - Red lines for Pos (more sea ice years) and blue line for Neg (less sea ice years).



Composite Analysis Surface Air Temperature - SAT (°C, color) and Surface Wind (m/s, vectors)



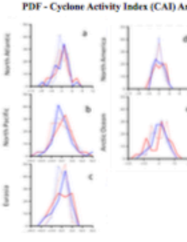
- Increased storm activity over the Arctic region in Spring, Summer and Fall.
- Decreased storm activity over Eurasia in Spring, Summer and Fall.

Similar composite analysis : Total Precipitation, Cloud Cover, Sea Level Pressure, Longwave, Shortwave, Latent Heat, Sensible Heat

- Warmer and wetter Arctic in Spring, Summer and Fall.
- Intensification of anticyclone over Eurasia – colder in Fall and Winter and warmer in Spring.

SEA ICE TREND FORCING

PDF - Cyclone Activity Index (CAI) Anomaly



- Bimodal distribution in Trex
- Overall weakening of storms
- Increased extreme positive and extreme negative storms in Trex

Trex (red); Conex (blue) in winter (solid) & spring (dotted)

Energy Balance of the Atmosphere

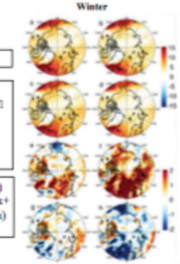
Composite Analysis

Years of storm activity greater than ± 1 std. deviations are grouped: Conex+, Conex-, Trex+, Trex- ("+" extreme positive storms; "-" extreme negative storms in Conex and Trex

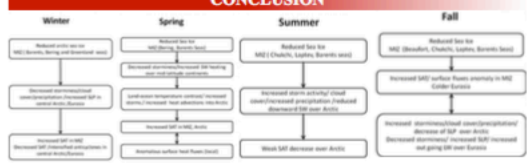
a) Conex+, b) Conex- , c) Trex+, d) Trex-, e) Conex+ - Conex-, f) Trex+ – Trex-, g) Trex+ – Conex+ and h) Trex- - Conex-

Rate of conversion between transient eddy APE and transient eddy KE (W/m²) over Arctic Ocean

Winter



CONCLUSION



CONCLUSION

- An overall weakening of the storm activity over the mid-latitudes and the Arctic, but an increase in extreme storm events that is defined by a criterion of extreme positive cyclone activity index anomaly.
- Conversion rate between the transient available potential and kinetic energy over the Arctic increases due to the long-term sea-ice declining trend, supporting the increase in extreme storm events.