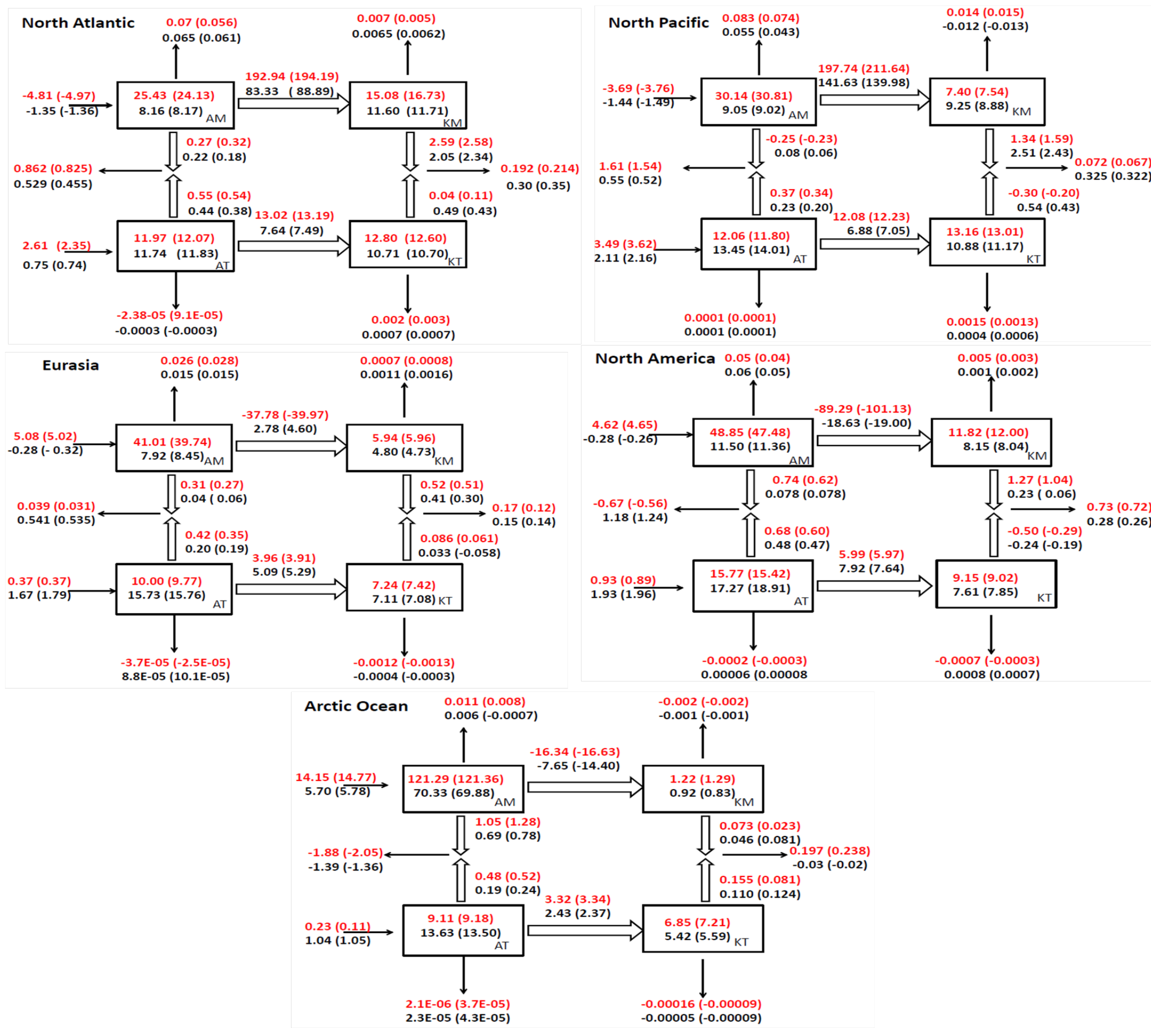

Figure 4.5 Panels showing regional energy balance diagram for each of the sub regions for winter (Red) and spring (Black) in Trex (Conex). Units of the 30 year mean of the terms within the boxes are 10^5 J/m^2 and those on the outside are W/m^2.

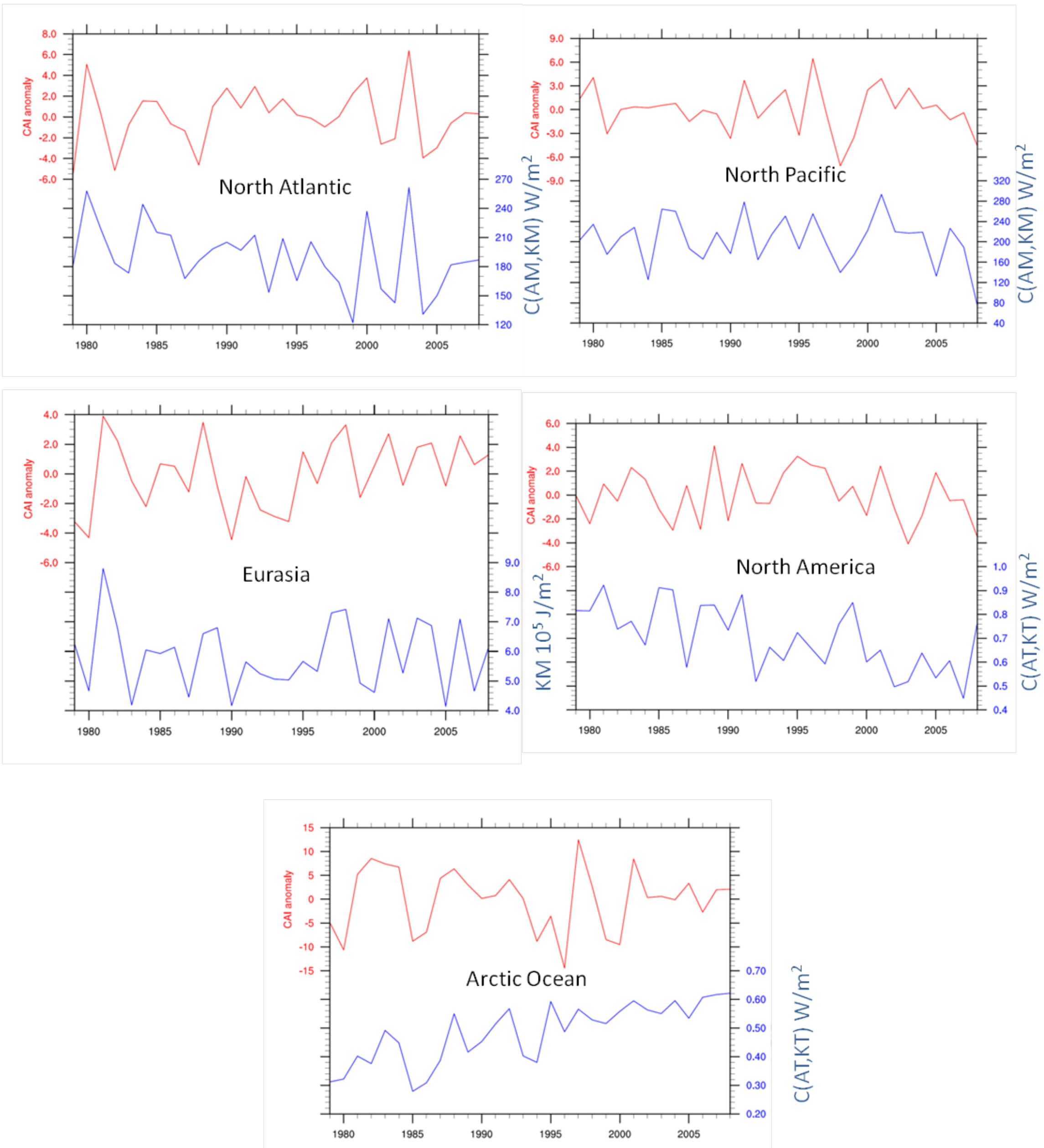

Figure 4.6 Plot shows, time series of CAI anomaly (red) and the area mean of highest co-related energy balance term (blue) for each the sub region in DJF.

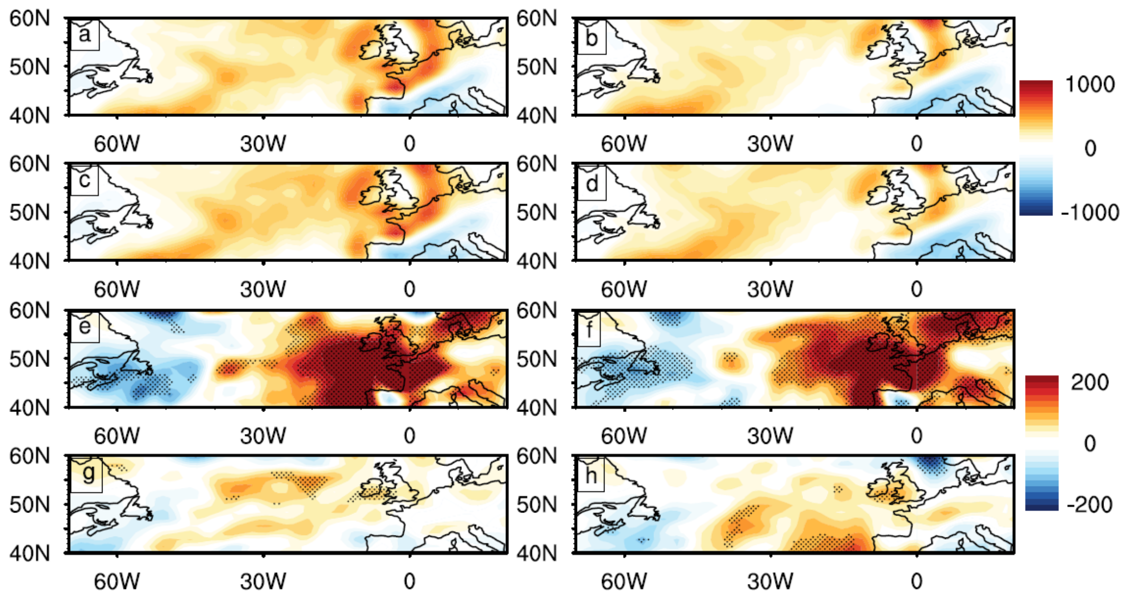

Figure 4.7 Plot showing the rate of conversion between Mean APE and Mean KE (W/m^2) over North Atlantic in winter : a) composite mean of positive years in Conex, b) composite mean of negative years in Conex, c) composite mean of positive years of Trex, d) composite years of negative years of Trex, e) Difference (Positive years of Conex – Negative years of Conex), f) Difference (Positive years of Trex – Negative years of Trex), g) Difference (Positive years of Trex – Positive years of Conex) and h) Difference (Negative years of Trex – Negative years of Conex). Dots represent greater or equal to 95% statistically significant areas.

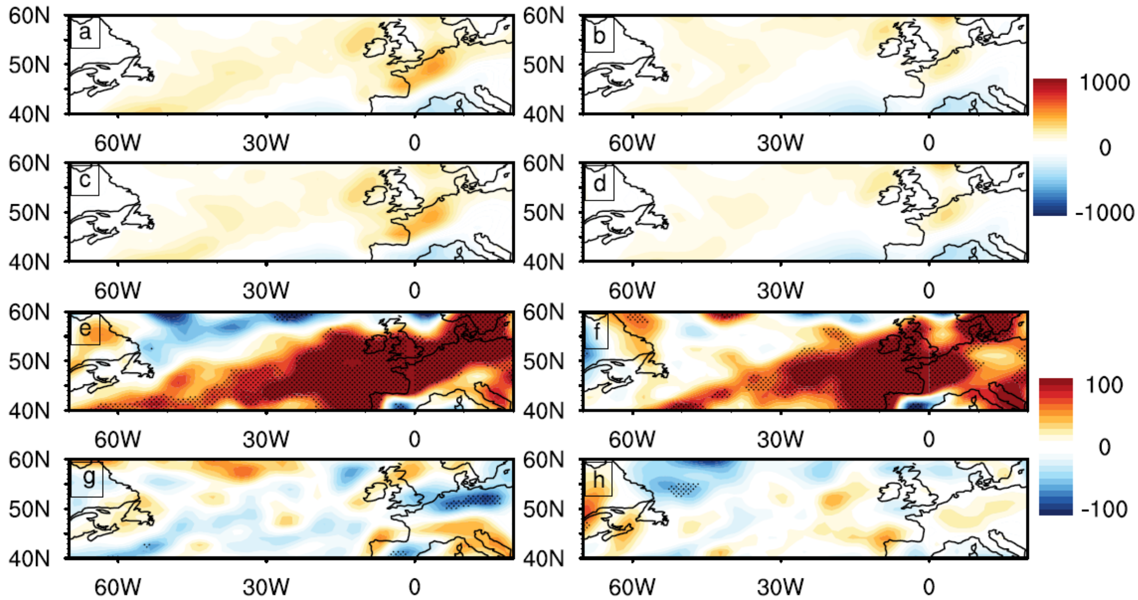

Figure 4.8 Plot showing the rate of conversion between Mean APE and Mean KE (W/m^2) over North Atlantic in spring : a) composite mean of positive years in Conex, b) composite mean of negative years in Conex, c) composite mean of positive years of Trex, d) composite years of negative years of Trex, e) Difference (Positive years of Conex – Negative years of Conex), f) Difference (Positive years of Trex – Negative years of Trex), g) Difference (Positive years of Trex – Positive years of Conex) and h) Difference (Negative years of Trex – Negative years of Conex). Dots represent greater or equal to 95% statistically significant areas.

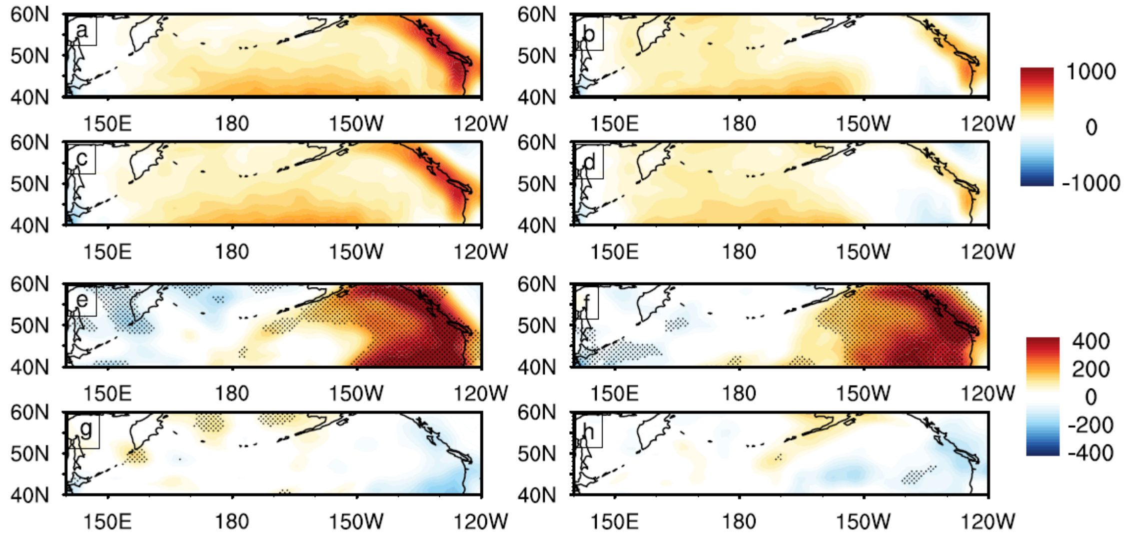

Figure 4.9 Plot showing, the rate of conversion between Mean APE and Mean KE (W/m^2) over North Pacific in winter : a) composite mean of positive years in Conex, b) composite mean of negative years in Conex, c) composite mean of positive years of Trex, d) composite years of negative years of Trex, e) Difference (Positive years of Conex – Negative years of Conex), f) Difference (Positive years of Trex – Negative years of Trex), g) Difference (Positive years of Trex – Positive years of Conex) and h) Difference (Negative years of Trex – Negative years of Conex). Dots represent greater or equal to 95% statistically significant areas.

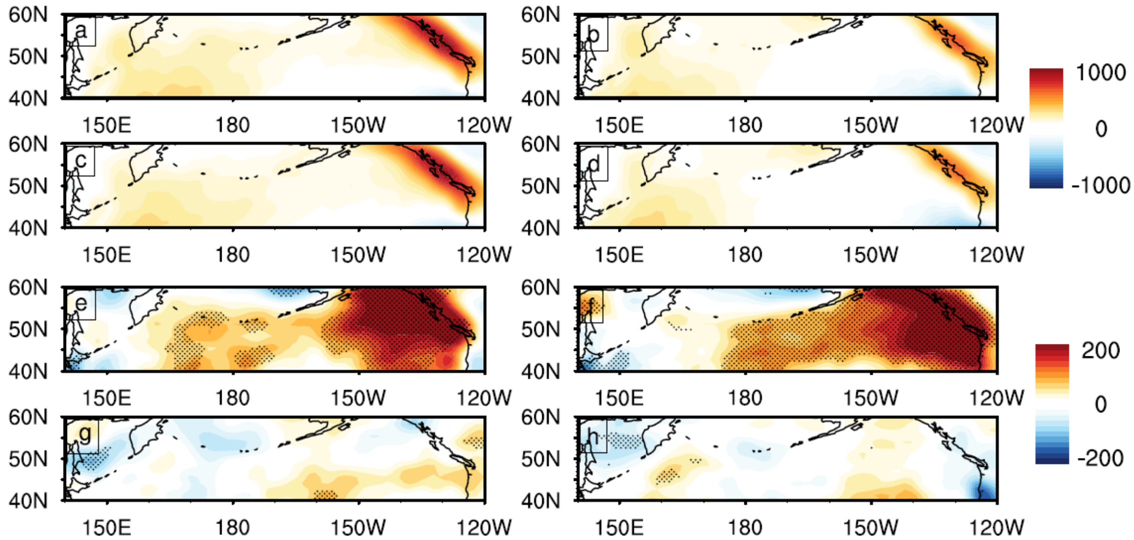

Figure 4.10 Plot showing, the rate of conversion between Mean APE and Mean KE (W/m^2) over North Pacific in spring : a) composite mean of positive years in Conex, b) composite mean of negative years in Conex, c) composite mean of positive years of Trex, d) composite years of negative years of Trex, e) Difference (Positive years of Conex – Negative years of Conex), f) Difference (Positive years of Trex – Negative years of Trex), g) Difference (Positive years of Trex – Positive years of Conex) and h) Difference (Negative years of Trex – Negative years of Conex). Dots represent greater or equal to 95% statistically significant areas.

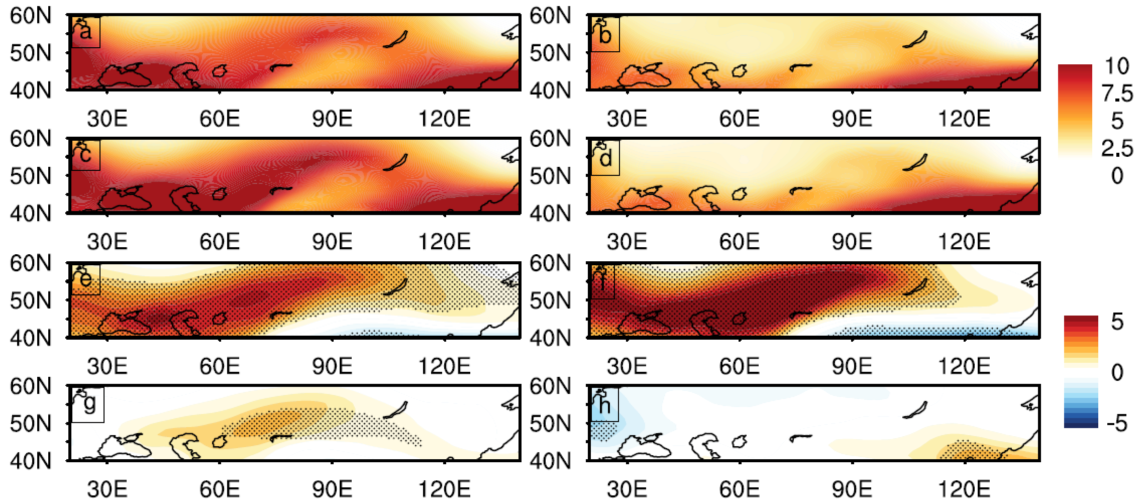

Figure 4.11 Plot showing, mean KE (10^5 J/m^2) over Eurasia in winter : a) composite mean of positive years in Conex, b) composite mean of negative years in Conex, c) composite mean of positive years of Trex, d) composite years of negative years of Trex, e) Difference (Positive years of Conex – Negative years of Conex), f) Difference (Positive years of Trex – Negative years of Trex), g) Difference (Positive years of Trex – Positive years of Conex) and h) Difference (Negative years of Trex – Negative years of Conex). Dots represent greater or equal to 95% statistically significant areas.

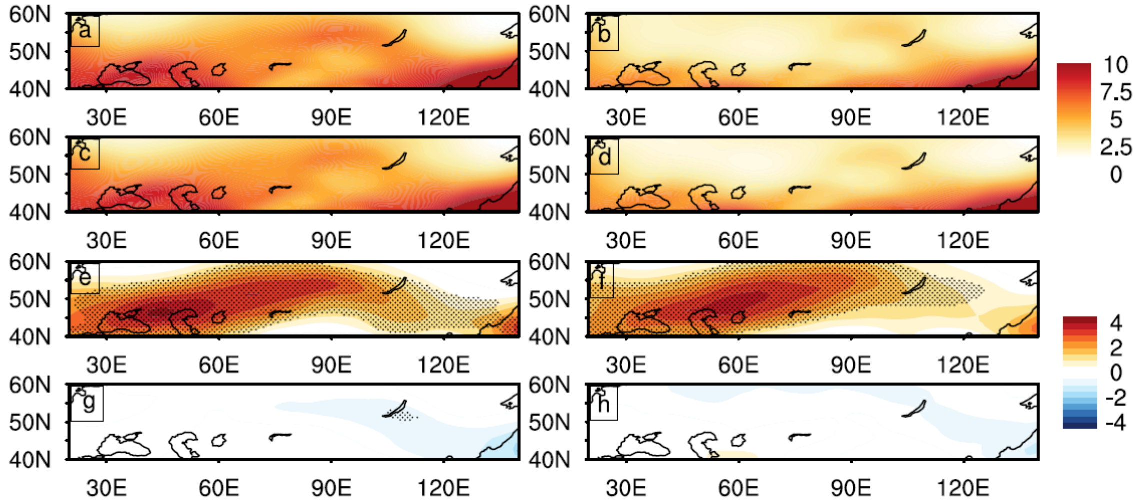

Figure 4.12 Plot showing, mean KE (10^5 J/m^2) over Eurasia in spring: a) composite mean of positive years in Conex, b) composite mean of negative years in Conex, c) composite mean of positive years of Trex, d) composite years of negative years of Trex, e) Difference (Positive years of Conex – Negative years of Conex), f) Difference (Positive years of Trex – Negative years of Trex), g) Difference (Positive years of Trex – Positive years of Conex) and h) Difference (Negative years of Trex – Negative years of Conex). Dots represent greater or equal to 95% statistically significant areas.

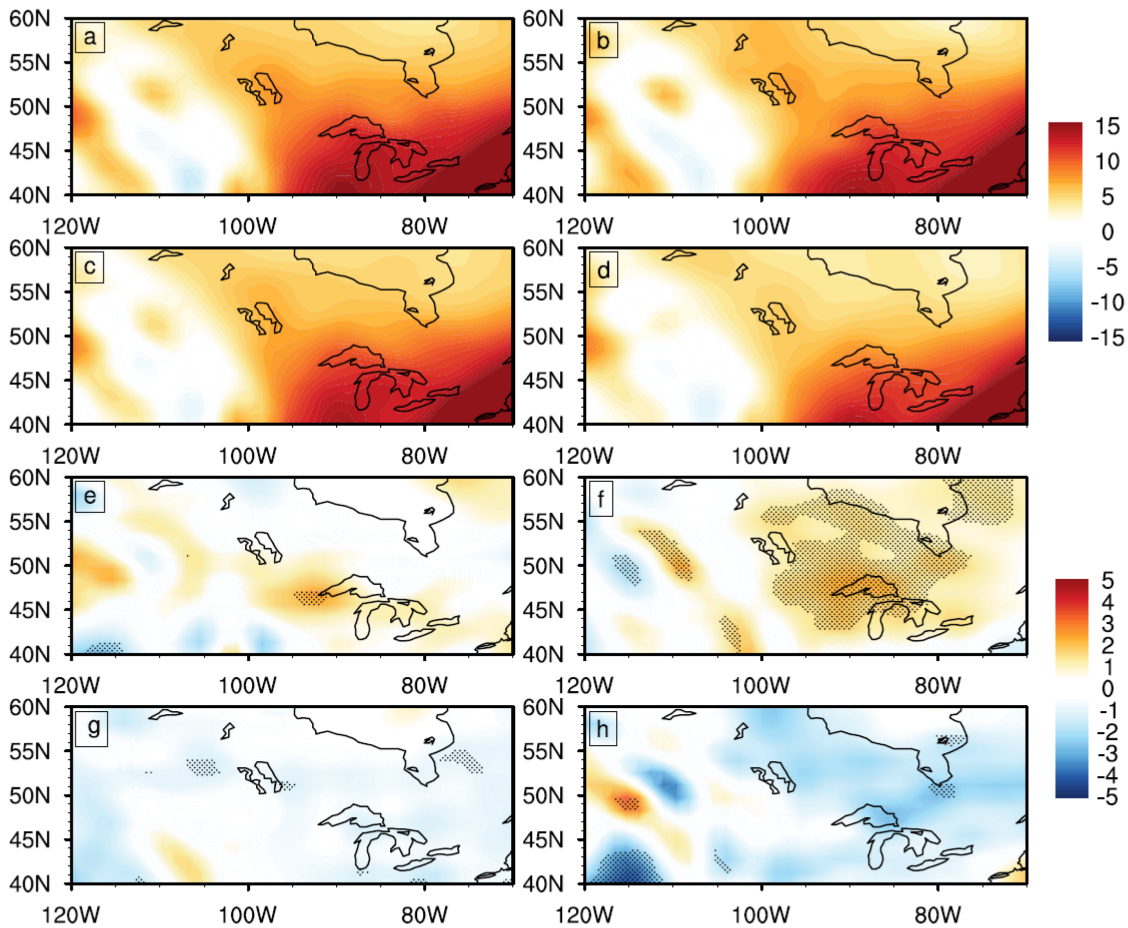

Figure 4.13 Plot showing the rate of conversion between transient eddy APE and transient eddy KE (W/m^2) over North America in winter : a) composite mean of positive years in Conex, b) composite mean of negative years in Conex, c) composite mean of positive years of Trex, d) composite years of negative years of Trex, e) Difference (Positive years of Conex – Negative years of Conex), f) Difference (Positive years of Trex – Negative years of Trex), g) Difference (Positive years of Trex – Positive years of Conex) and h) Difference (Negative years of Trex – Negative years of Conex). Dots represent greater or equal to 95% statistically significant areas.

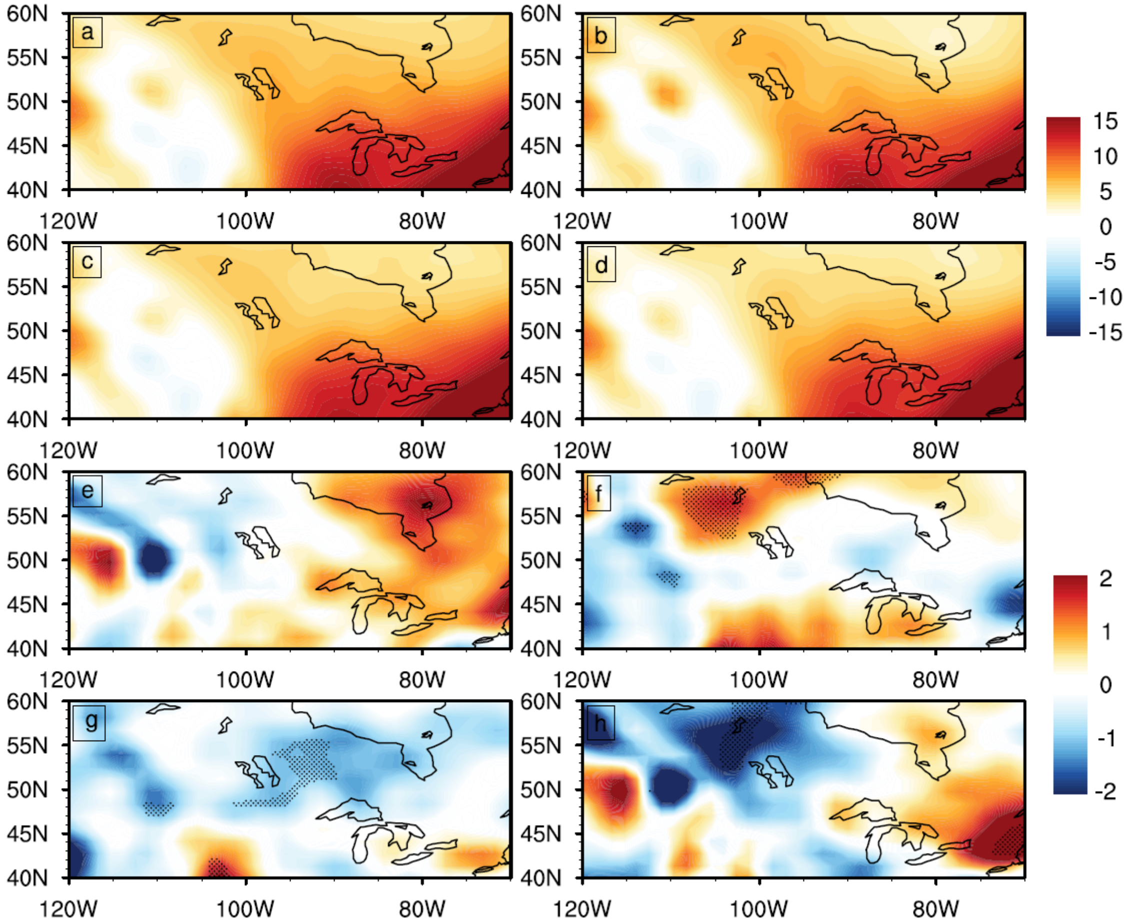

Figure 4.14 Plot shows, the rate of conversion between transient eddy APE and transient eddy KE (W/m^2) over North America in spring : a) composite mean of positive years in Conex, b) composite mean of negative years in Conex, c) composite mean of positive years of Trex, d) composite years of negative years of Trex, e) Difference (Positive years of Conex – Negative years of Conex), f) Difference (Positive years of Trex – Negative years of Trex), g) Difference (Positive years of Trex – Positive years of Conex) and h) Difference (Negative years of Trex – Negative years of Conex). Dots represent greater or equal to 95% statistically significant areas.

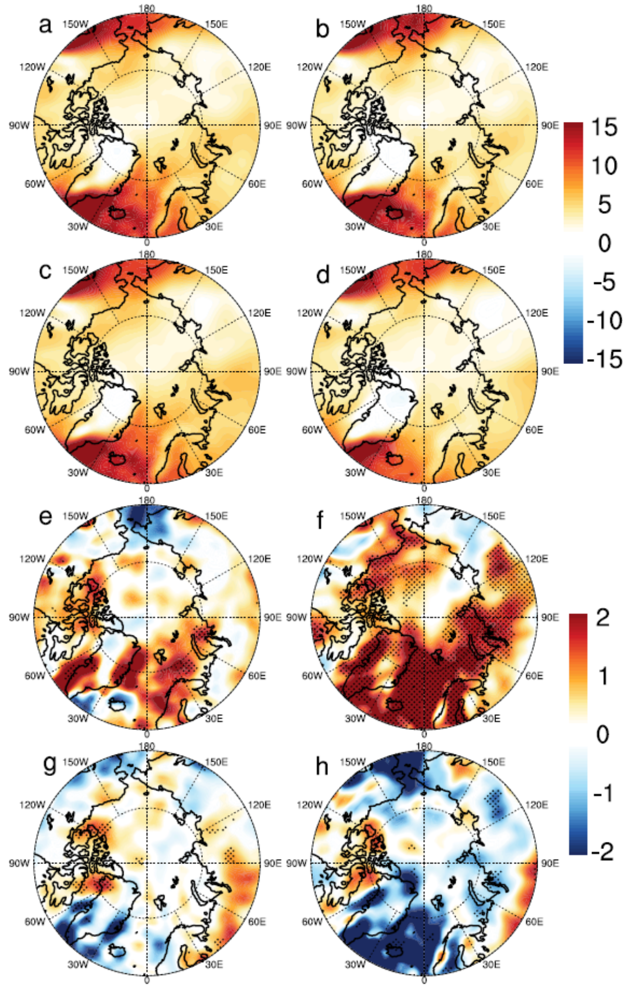

Figure 4.15 Plot showing the rate of conversion between transient eddy APE and transient eddy KE (W/m^2) over Arctic Ocean in winter : a) composite mean of positive years in Conex, b) composite mean of negative years in Conex, c) composite mean of positive years of Trex, d) composite years of negative years of Trex, e) Difference (Positive years of Conex – Negative years of Conex), f) Difference (Positive years of Trex – Negative years of Trex), g) Difference (Positive years of Trex – Positive years of Conex) and h) Difference (Negative years of Trex – Negative years of Conex). Dots represent greater or equal to 95% statistically significant areas.

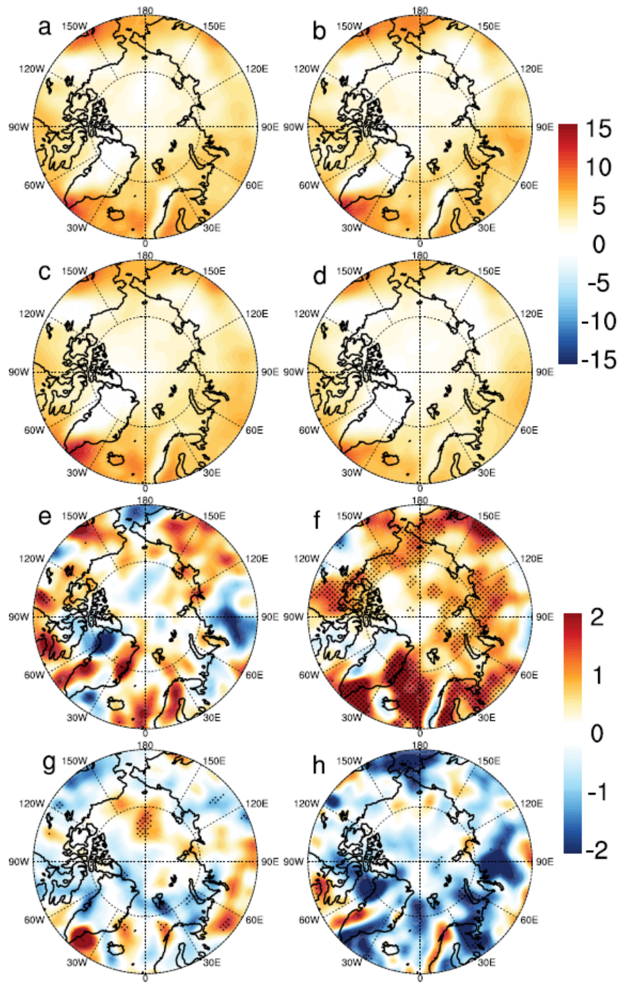

Figure 4.16 Plot shows, the rate of conversion between transient eddy APE and transient eddy KE (W/m^2) over Arctic Ocean in spring : a) composite mean of positive years in Conex, b) composite mean of negative years in Conex, c) composite mean of positive years of Trex, d) composite years of negative years of Trex, e) Difference (Positive years of Conex – Negative years of Conex), f) Difference (Positive years of Trex – Negative years of Trex), g) Difference (Positive years of Trex – Positive years of Conex) and h) Difference (Negative years of Trex – Negative years of Conex). Dots represent greater or equal to 95% statistically significant areas.

Chapter 5 Summary and Conclusions

5.1 Background and Motivation

Extratropical cyclones are associated with extreme weather events such as blizzards, gusts, flood, freezing rain etc and occur over mid- and high-latitudes. These weather events are well known for their ability to disrupt normal life by causing property and infrastructure damage and causing hazardous travel conditions. Extratropical storms are most prominent over certain geographical regions located over mid-latitudes and the Arctic and these regions are known as storm tracks. Each of these regions exhibits different temporal variability. For example, over Eurasia storms have gotten weaker with time [Zhang et al. 2012]. There are many gaps in our existing knowledge of changes in storm activities over the Northern Hemisphere. According to our hypothesis for this study, in addition to a warming climate these changes can be caused by anomalous surface boundary forcing such as SST or Arctic sea ice.

One of the potential anomalous surface forcing is elevated tropical Pacific SST associated with El Niño. From previous studies it was found that direct and indirect effects of the elevated tropical Pacific SST includes a southward shift of the jet stream and a southward shift and eastward extension of the storm track over the east Pacific [Trenberth et al., 1993; Hoerling, 1994; Straus et al., 1997; Zhang et al., 1999; Orlanski, 2005; Eichler et al., 2006; Compo, 2010]. But the impact of elevated tropical Pacific SST on North American storm activities has not been fully investigated. Thus, in this thesis we studied the response of winter-spring storm activities over North America to elevated tropical Pacific SSTs.

Another potential surface forcing is Arctic sea ice. Changes in Arctic sea ice impacts the atmospheric circulation and weather patterns [Zhang et al. 2008, Overland et al. 2010] and causes anomalous surface fluxes. But the role of Arctic sea ice in changing storm activity over the Northern Hemisphere is not fully yet understood. So in this thesis we showed the impacts of reduced Arctic sea ice on storm activities over the mid-latitudes and the Arctic and corresponding changes in surface climate parameters. Due to global warming, the Arctic Ocean is undergoing a rapid loss of sea ice. There have been no studies to distinctly identify the responses of Northern Hemisphere storm activity to the declining trend of Arctic sea ice. Thus, in this thesis we conducted a comprehensive analysis of the response of Northern Hemispheric extratropical storm activity to the long term trend of Arctic sea ice.

5.2 Key Scientific Findings and Conclusions

In this thesis we conducted an integrated evaluation of the contribution of SST and Arctic sea ice on changes in Northern Hemisphere storm activities. In order to do that we performed modeling experiments using the NCAR CAM 3.1_p2 model and analyzed 6-hourly outputs of selected variables. In our analysis we applied a storm identification and tracking algorithm, which first identified and then tracked each storm following a Lagrangian approach and then we linked those changes in storm activity to the general circulation of the atmosphere. The key findings from our study are as follows:

1) Elevated tropical Pacific SST causes an increase in storm activity over the southern part of North America (Figure 5.1).

2) Reduced Arctic sea ice causes increased storminess over the Arctic in all seasons (except winter) whereas the storm activity decreases over the mid-latitudes in all seasons (Figure 5.2).

3) The long-term declining trend of Arctic sea ice causes an overall decrease in Northern Hemispheric storm activity but there is an increase in the extreme storm events (Figure 5.3).

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. 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. Increased vertical wind sheer enhances baroclinicity, upper level divergence and hence supports the development of surface storms. Increased storm activity also causes an increase in the EKE over the regions located south of the climatological storm track.

Apart from SST, evaluation of another large natural forcing – changes in Arctic sea ice on Northern Hemispheric storm activities was done. The rapid loss of Arctic sea ice due to a warming climate has many consequences on climate and weather patterns. Due to the widespread impact of Arctic sea ice on global climate we studied the entire Northern Hemisphere storm activity in this experiment. In response to reduced Arctic sea ice there is increased storminess over the Arctic in contrast to a decreased storm activity over the mid-latitudes in most seasons. During a reduced Arctic sea ice condition in winter, the storm activity decreased over the central Arctic and Eurasia. The decreased storminess associated with increased SLP (i.e. intensification of anticyclones in the central Arctic and Eurasia) causes decreases of precipitation and SAT in winter. In spring, a dramatic warming occurs over the Arctic and mid-latitudes. Anomalous sensible and latent heat fluxes in the MIZ, partially contribute to this warming. Also, decreased storminess, associated with intensified anticyclones, reduced cloud cover over the mid-latitudes results in enhanced heating from the downward shortwave radiation over the mid-latitude continents. This land-ocean temperature contrast paves the way for increased storm activity in the Arctic. The advection of heat associated with increased storminess over the Arctic also contributes to the warming. In summer, reduced Arctic sea ice causes increased storminess, increased cloud cover and decreased downward SW, increased precipitation which causes a moderate cooling over the Arctic. In fall, reduced Arctic sea ice causes increased storminess over the Arctic. The anomalous surface heat fluxes contribute to higher SAT in the MIZ. The decreased storminess causes intensification of anticyclones in association with clear sky and enhanced cooling due to outgoing LW over Eurasia.

Arctic sea ice can change due to natural variability and the long term trend. We performed a comprehensive study of the impact of the long-term declining trend of Arctic sea ice on Northern Hemispheric storm activities. In response to the declining trend of Arctic sea ice there was an overall decrease in storm activity over the Northern Hemisphere, but with increased extreme storm events. The loss of Arctic sea ice due to the declining trend causes an enlarged area of open water. The newly opened water resulted in anomalous heating of the surface and lower troposphere which resulted in an increased convective activity and baroclinically driven synoptic circulation, leading to faster conversion between transient available potential energy (AT) and transient kinetic energy (KT) over the Arctic. The increased conversion of AT to KT resulted in an increased number of extreme storms over the Arctic in the model simulation forced by the long term trend of Arctic sea ice. There was an increased conversion rate of mean available potential (AM) and mean kinetic energy (KM) over the North Atlantic and North Pacific, which resulted in increased extreme storm events, as indicated by our statistical analysis. The declining Arctic sea ice affects the mid-latitude atmospheric circulation, which resulted in an increased vertical velocity contributing to the increased conversion between AM and KM. The reduced sea ice affects the downstream propagation of Rossby wave trains towards Eurasia and East Asia, impacts regional westerlies, vertical circulation and conversion between AM and KM. This change in conversion rate corresponds well to our finding of increased extreme storms over Eurasia with declining Arctic sea ice.

The occurrence of cyclones has significant implications for human society, properties and natural ecosystems. They also cause hazardous travel conditions contributing to huge economic impacts. Thus, in this integrated contribution of the two biggest natural forcings such as SST and Arctic sea ice it was shown that interannual variabilities like El Niño can modulate a southward shift of the storms over North America however, long term variabilities like Arctic sea ice causes increased storminess over the Arctic region with a weakened storm activity over the mid-latitude. But the long term trend of Arctic sea ice causes decreased storm activity over middle and high latitudes with an increased occurrence of extreme storm events. Thus our modeling study provides an assessment and prediction of cyclones in the context of global warming forcing and will further facilitate the decision making processes. Careful analysis of our results will also help us to further advance our knowledge of the changes in storm activity over the Northern Hemisphere in a warming climate.

5.3 Future Work

There is a great need to study the variability of each of the major storm tracks over the Northern Hemisphere with individual details and to understand changes in dynamical processes of the atmosphere that control storm activity as each of these storm tracks has different variability over time. Storms are associated with the transport of heat and moisture across the latitudes. We have shown that increased (decreased) storm activity causes increased (decreased) precipitation and snowfall and induces changes in surface air temperature so it is important to study the changes in transport processes especially for the Arctic, which is the center of attraction for climate studies under a warming climate.

Recent studies have predicted a sea-ice free Arctic summer in the near future in conjunction with global warming. It has been observed that the growth and decay of Arctic sea ice affects the global circulation and weather patterns. So the loss of Arctic sea ice will further influence the storm activity over the Northern Hemisphere, as a result our group is currently investigating the future projections of storm activity over each of the storm tracks under different warming scenarios such as RCP 4.5 and RCP 8.5 from the CMIP5 model simulations. A thorough investigation of future storm activities over the Arctic and mid-latitude will help us to better understand the changes and variability of extratropical cyclones at the end of the 21st century. In near future, the Arctic will be the center of attraction for oil, uranium and other mineral industries so it is important to better predict and forecast the changes in storm activity over the Arctic and the adjoining high latitudes. The rapid loss of Arctic sea ice can also lead to a loss of natural habitat for Arctic wildlife and marine life and hence can disturb the polar ecosystem.

Finally, it is necessary to develop better communication between climate science and society. It is absolutely necessary to enhance awareness of the climate science among the stake holders, policy makers, general public and industrialists as the storms affect every person and industry. This process of interactive understanding will bridge the gap between climate scientists and society as climate scientists will also have a detailed knowledge of the need of the industrialists, stakeholders and property owners.

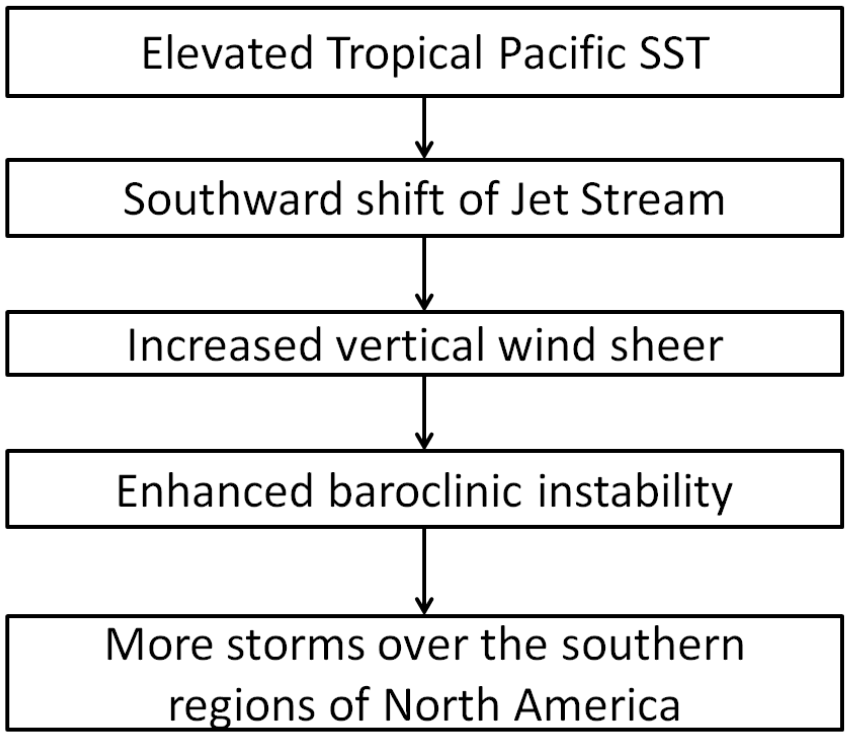

Figure 5.1 Sequence of physical processes associated with changes in storm activity over North America due to elevated tropical Pacific SST.

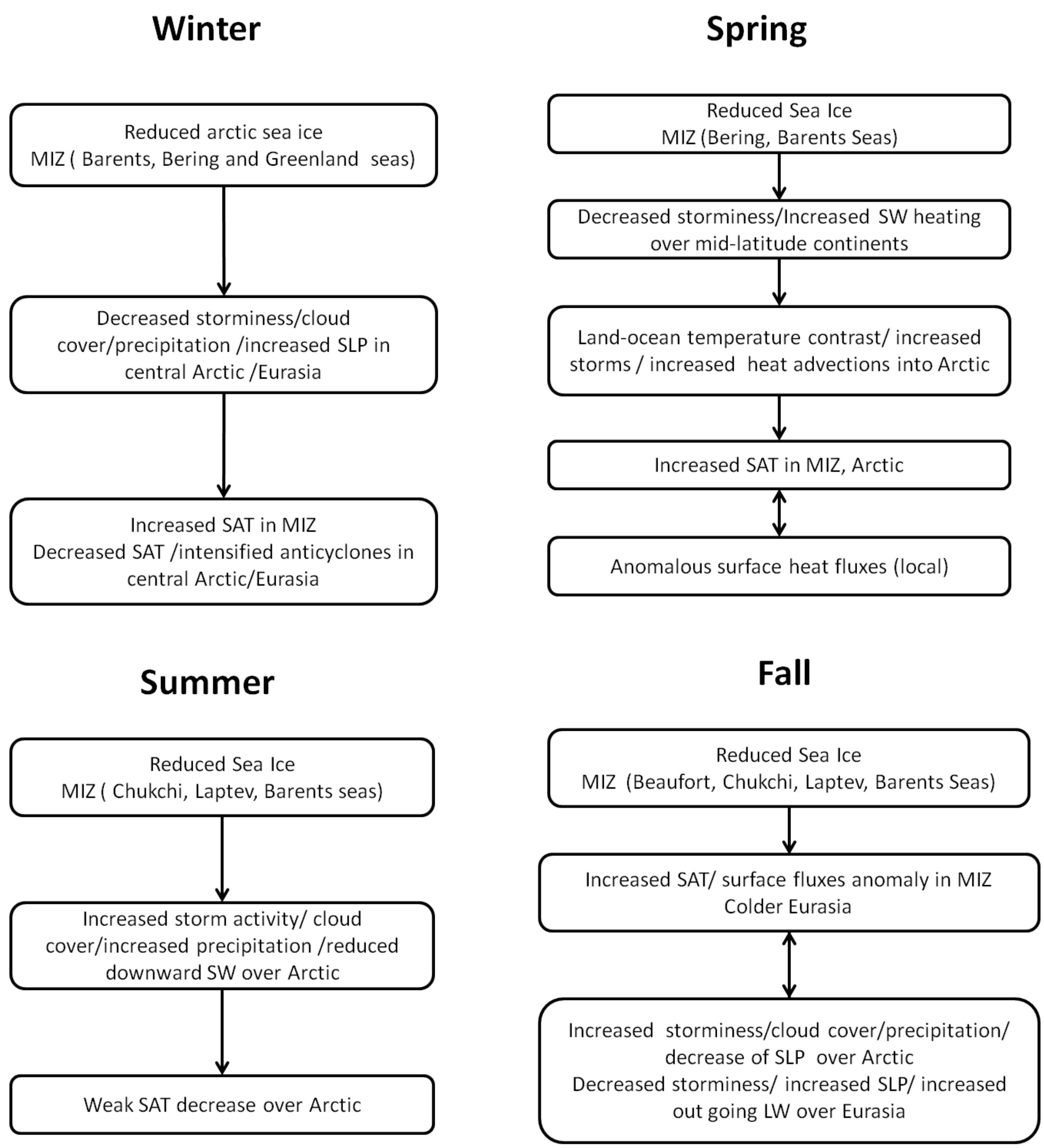

Figure 5.2 Sequence of events linking the reduced Arctic sea ice, storm activity and the most prominent surface climate changes.

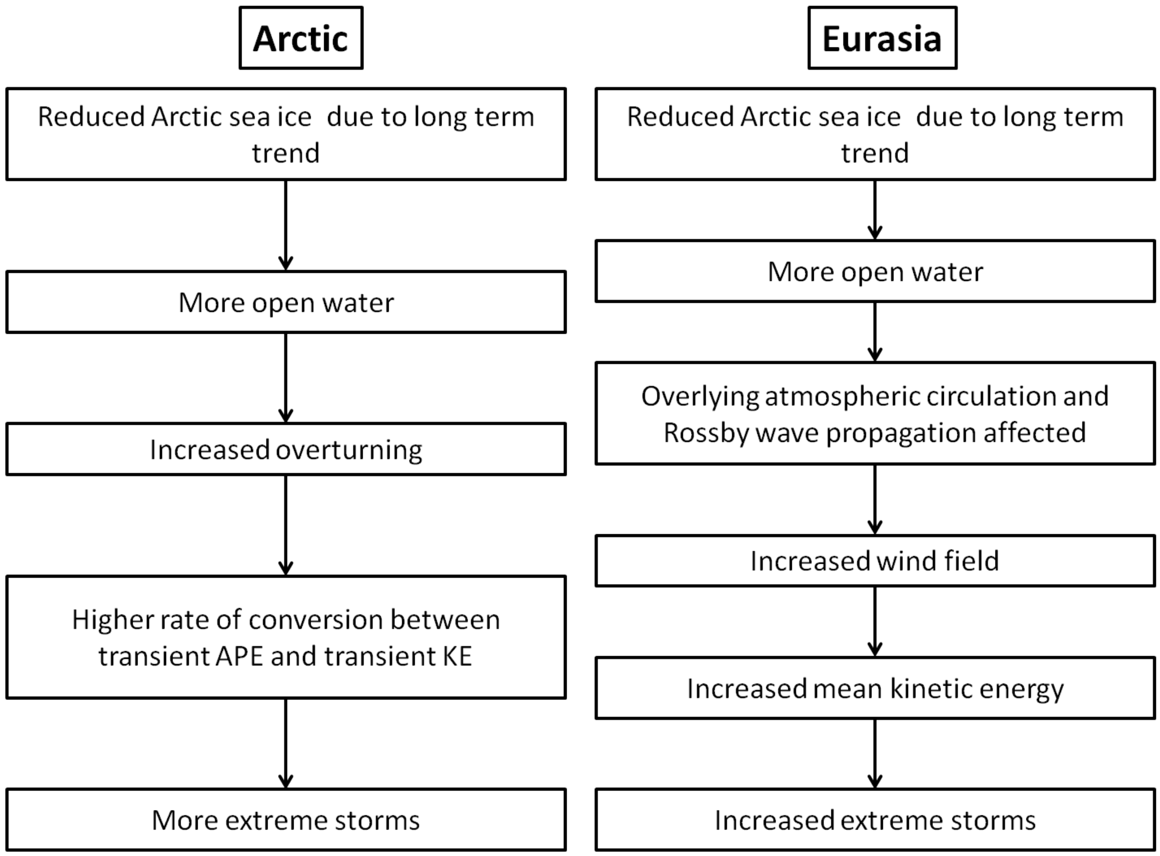

Figure 5.3 Sequence of possible mechanisms for increased extreme storm events over the Arctic and Eurasia in response to sea ice change.

Contribution to Chapters

In Chapter 2 the model simulations, analysis of scientific findings and preparation of figures was done by Soumik Basu. The experimental design, text refining and understanding the physical processes were done by Soumik Basu in conjunction with Dr. Xiangdong Zhang. Comments and suggestions for the paper were obtained from Dr. Uma Bhatt and Dr. Igor Polyakov.

In Chapter 3 the model simulations, analysis of scientific results, figure preparation was performed by Soumik Basu. Experimental design was done by Soumik Basu with the help of Dr. Xiangdong Zhang. Text refining and organization of the paper was done by Soumik Basu in conjunction with Dr. Xiangdong Zhang and Dr. Igor Polyakov.

In chapter 4 the model experiments, scientific analysis and preparation of figures were done by Soumik Basu. Experiment design, understanding the underlying mechanisms and text refining was done by Soumik Basu with help from Dr. Xiangdong Zhang.