Diminished Summer Arctic Sea Ice Linked to North-Central United States Moisture Extremes

Thomas J. Ballinger[1], Dagmar Budikova[2], Trent W. Ford[3]
[1]Department of Geography, Texas State University, San Marcos, TX; contact: tballinger@txstate.edu
[2]Department of Geography-Geology, Illinois State University, IL
[3]Department of Geography and Environmental Resources, Southern Illinois University, Carbondale, IL

ABSTRACT

This study explores the connection between declining Arctic sea ice and hydroclimatolocal characteristics of the north-central United States (US) between 1979 and 2013. Since 1979, summers with low sea ice conditions have coincided with significant increases in mean, minimum, maximum, and dew point air temperatures. We also find increases in seasonal precipitation, the number of wet days, heavy (>95th percentile) precipitation days, and very heavy (>99th percentile) precipitation days and accumulated precipitation over the region. These moisture changes coincide with atmospheric patterns typically observed during anomalously wet summers, known to prompt flooding across the Upper Mississippi River Valley region (UMRV). Low sea ice summers are associated with enhanced southerly air flow and increased activity of the Great Plains Low Level Jet (GPLLJ), increased occurrence of moist tropical air masses over the UMRV region, and amplified mid-tropospheric flow over the Pacific-North American region with a strong ridge situated over the central-eastern portions of the North American continent. The results suggest that summer Arctic sea ice decline may influence the hydroclimate across the north-central US and add to our growing knowledge of the potential influences that a changing Arctic environment may pose on mid-latitude climates.

INTRODUCTION

Recent observational and modeling studies have suggested potential mechanisms that make the connection between boreal summer Arctic Amplification/sea ice decline and same-season weather conditions in the middle latitudes plausible (e.g., Francis and Vavrus 2012 and 2015; Petoukhov *et al.* 2013; Coumou *et al.* 2015).

The processes include weakening of the zonal mean and thermal winds, declining total eddy kinetic energy of the atmospheric column, a reduction in the mean amplitude of Rossby waves, and an increase in the amplification of quasi-stationary wave numbers 6-8. These modifications have the potential to increase the occurrence of slow-moving meridional flow over North America and the Atlantic Ocean and increase the incidence of persistent weather patterns and extremes throughout the middle latitudes.

OBJECTIVES

This study aims to build on the existing knowledge of Arctic-mid-latitude climate connections by exploring associations between summer Arctic sea ice decline and variability in hydroclimate and extreme precipitation across the north-central portions of the US.

STUDY AREA AND METHODS

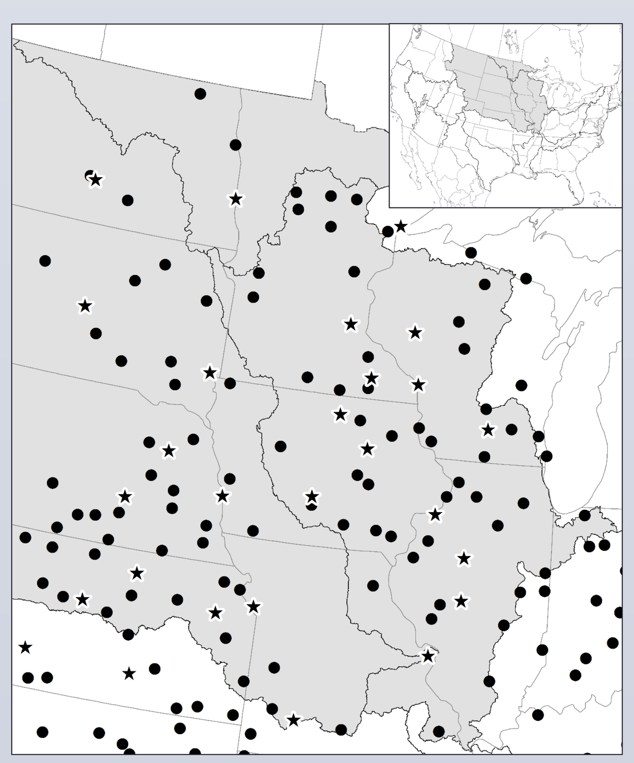

Figure 1: Location of north-central region within the US. This region contains the UMRV, the Souris-Red-Rainy watershed, and large portions of the Missouri River Valley (shaded). Stations used in precipitation analyses are depicted using black dots; stars represent location of first-order weather stations used to analyze changes in temperature and synoptic weather types.

- Constructed composite maps of various surface and atmospheric conditions based on differences between high, low, and neutral sea ice conditions
- Statistical significance of the anomaly differences between various precipitation, temperature, and atmospheric conditions are assessed using a t-test and bootstrapping of 1000 samples
- Reported are one-tailed significance levels in excess of 90%

DATA

Data Sources for Boreal Summer (JJA) 1979-2013

- Arctic Sea Ice Concentration (SIC): HadISST (Rayner *et al.* 2003) time series are de-trended and categorized into SIC-high (SIC+)), SIC-neutral (SICneu), and SIC-low (SIC-) summers; SIC+ included 10 highest ice summers, SIC- included 10 lowest ice summers, remaining 25 years were characterized as neutral

SIC Phase	Years
SIC^+	1983, 1992, 1994, 1996, 1999, 2000, 2001, 2004, 2009, 2013
SIC^-	1980, 1981, 1990, 1993, 1995, 2005, 2007, 2008, 2011, 2012
SIC^{neu}	1979, 1982, 1984, 1985, 1986, 1987, 1988, 1989, 1991, 1997, 1998, 2000, 2002, 2003, 2006, 2010

- Total precipitation: Daily station USHCN (Hughes et al. 1992; Figure 1) derived variables: SPI (McKee et al. 1993), number of wet days, number of heavy precipitation days (>95th percentile), number of very heavy precipitation days (>99th percentile), rainfall accumulations during heavy and very heavy rain days, and precipitation intensity measured by Simple Daily Intensity Index (SDII)
- Frequency of Moist Tropical (MT) synoptic weather types from the Spatial Synoptic Classification (Sheridan 2002) across 27 first-order weather stations (Figure 1)
- Average, minimum, and maximum surface air temperature and dew point temperature: Smith et al. (2011)
- Atmospheric variables from the NCEP/NCAR reanalysis (Kalnay et al. 1996) include geopotential height, vector winds, wind speeds at 500 and 300 hPa levels, 850 hPa meridional and vector winds, 850 hPa moisture flux, and total column precipitable water
- All anomalies are computed based on the 1981-2010 period

RESULTS: AIR AND DEW POINT TEMPERATURE TENDENCIES

Table 1. Summary of increases in temperature tendencies (T – surface air temperature, Td – dew point temperature) associated with (a) low ice years (SIC^- minus SIC^{neu}) and (b) differences between low and high ice years (SIC^- minus SIC^+). Statistical significance (sig.) is tested at the 90% confidence level.

(a)	Number of Stations (n)			
	Study Area (n=27)		UMRV (n=12)	
	# Increases	# Sig. Increases	# Increases	# Sig. Increases
T_{avg}	23 (85%)	20 (74%)	10 (83%)	8 (67%)
T_{min}	24 (89%)	21 (78%)	11 (92%)	10 (83%)
T_{max}	21 (78%)	19 (70%)	11 (92%)	8 (67%)
Td_{avg}	22 (81%)	12 (44%)	10 (83%)	6 (50%)
Td_{min}	21 (78%)	14 (52%)	10 (83%)	5 (42%)
Td_{max}	22 (81%)	11 (41%)	10 (83%)	5 (42%)

(b)	Number of Stations (n)			
	Study Area (n=27)		UMRV (n=12)	
	# Increases	# Sig. Increases	# Increases	# Sig. Increases
T_{avg}	27 (100%)	27 (100%)	12 (100%)	12 (100%)
T_{min}	27 (100%)	27 (100%)	12 (100%)	12 (100%)
T_{max}	27 (100%)	27 (100%)	12 (100%)	12 (100%)
Td_{avg}	17 (63%)	15 (56%)	10 (83%)	10 (83%)
Td_{min}	15 (56%)	10 (37%)	10 (83%)	5 (42%)
Td_{max}	18 (67%)	16 (59%)	10 (83%)	9 (75%)

Table 2. Number of stations exhibiting different MT air mass type frequency anomalies of >0, ≥+2, ≤0, and ≤-2 days per year for Arctic sea ice summers (JJA), 1979-2013: (a) SIC^- minus SIC^{neu}, and (b) SIC^- minus SIC^+). The asterisk (*) indicates two stations where MT++ days are not observed during SIC^- and SIC^+ years.

(a)	Number of Stations			
MT types	>0	≥+2	≤0	≤-2
MT	16	5	11	3
MT+	17	1	10	1
MT++	19	0	8	0
Sum of All MT	17	11	10	2
(b)	**Number of Stations**			
MT types	>0	≥+2	≤0	≤-2
MT	22	15	5	1
MT+	13	3	14	4
MT++*	16	0	9	0
Sum of All MT	22	17	5	1

RESULTS: PRECIPITATION CHARACTERISTICS

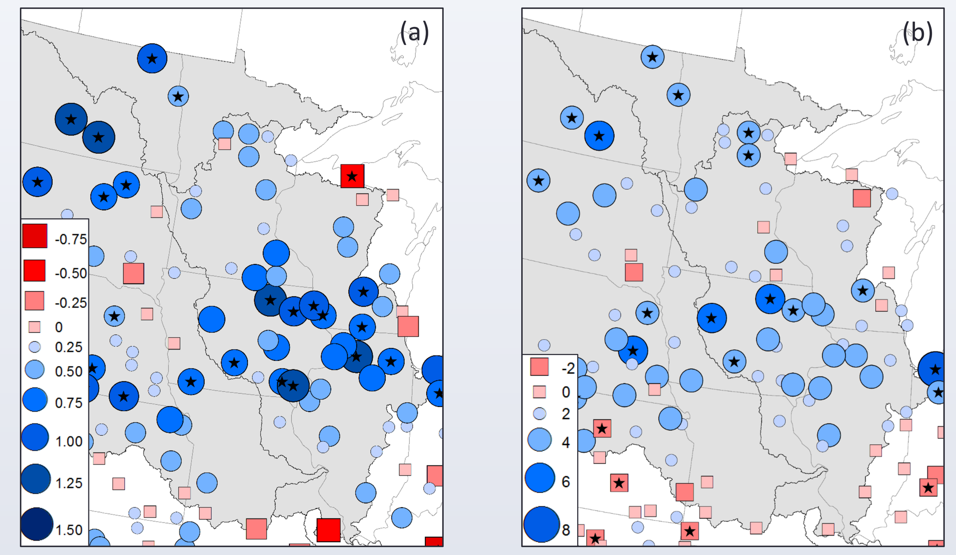

Figure 2. 1979-2013 JJA composite mean anomaly differences associated with SIC^- minus SIC^{neu} conditions for (a) SPI, and (b) number of wet days. Stations where statistically significant differences are observed are shown with an asterisk.

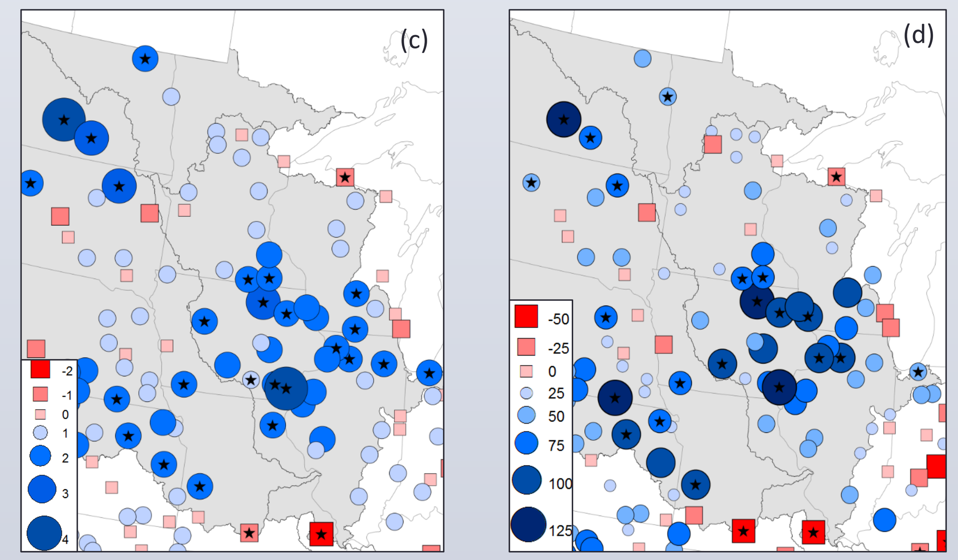

Figure 2 cont'd. 1979-2013 JJA composite mean anomaly differences associated with SIC^- minus SIC^{neu} conditions for (c) number of heavy rain days, and (d) heavy rain day accumulations (mm). Stations where statistically significant differences are observed are shown with an asterisk.

RESULTS: PRECIPITATION CHARACTERISTICS

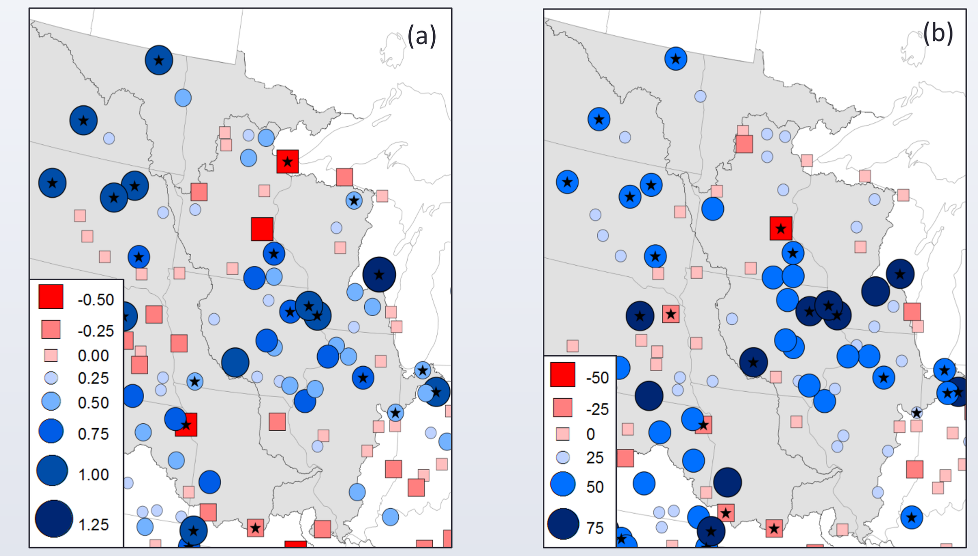

Figure 3. 1979-2013 JJA composite mean anomaly differences associated with SIC^- minus SIC^{neu} conditions for (a) number of very heavy rain days, and (b) rain accumulations during very heavy days (mm). Stations where statistically significant differences are observed are shown with an asterisk.

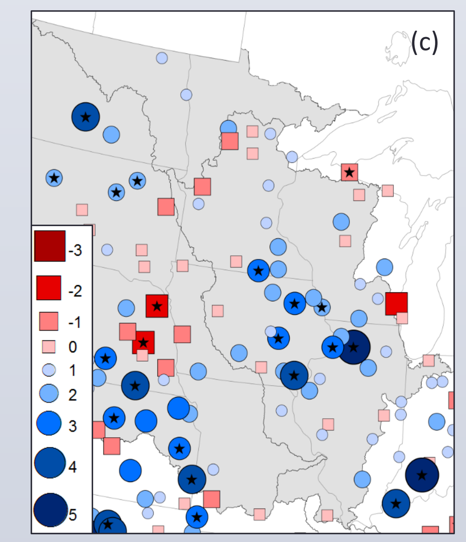

Figure 3 cont'd. 1979-2013 JJA composite mean anomaly differences associated with SIC^- minus SIC^{neu} conditions for (c) precipitation intensity as measured by SDII (mm/day). Stations where statistically significant differences are observed are shown with an asterisk.

RESULTS: ATMOSPHERIC CONDITIONS

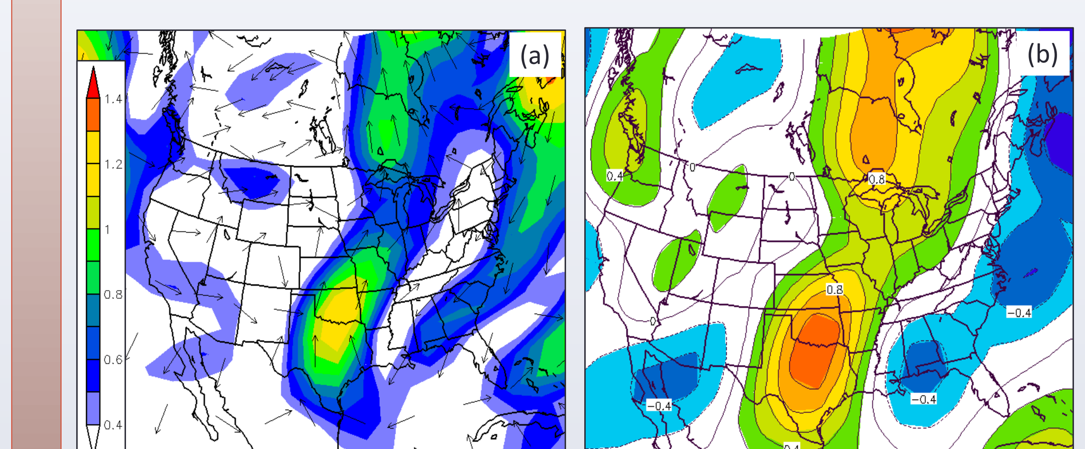

Figure 4. 1979-2013 JJA composite mean anomaly differences associated with SIC^- minus SIC^{neu} conditions for (a) 850 hPa vector winds (m/s), and (b) 850 hPa meridional wind (m/s).

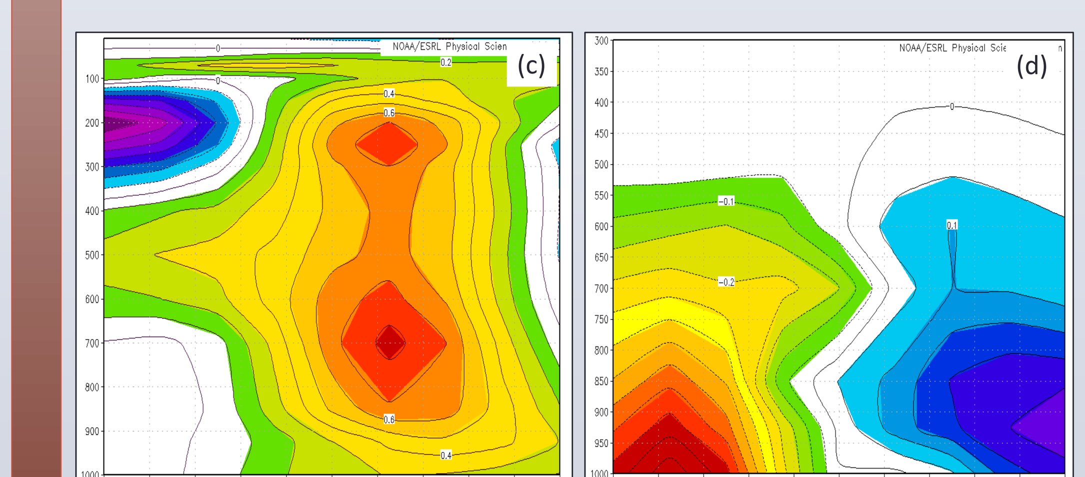

Figure 4 cont'd. 1979-2013 JJA composite mean anomaly differences associated with SIC^- minus SIC^{neu} conditions for (c) meridional wind (m/s) cross-section (30°N-45°N; 90°W-110°W) and (d) specific humidity (g/kg) cross-section (30°N-45°N; 90°W-110°W).

RESULTS: ATMOSPHERIC CONDITIONS

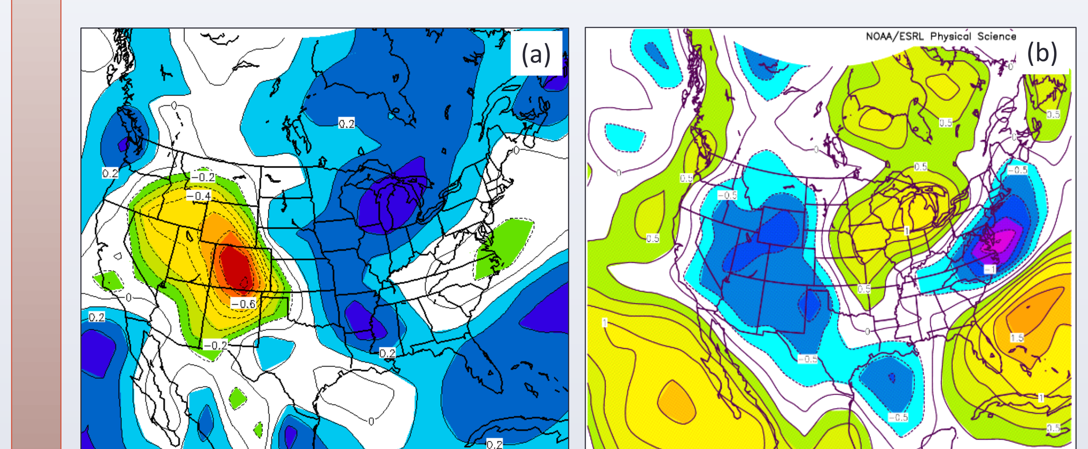

Figure 5. 1979-2013 JJA composite mean anomaly differences associated with SIC^- minus SIC^{neu} conditions for (a) 850 hPa specific humidity (g/kg), and (b) precipitable water (kg/m²) for the atmospheric column.

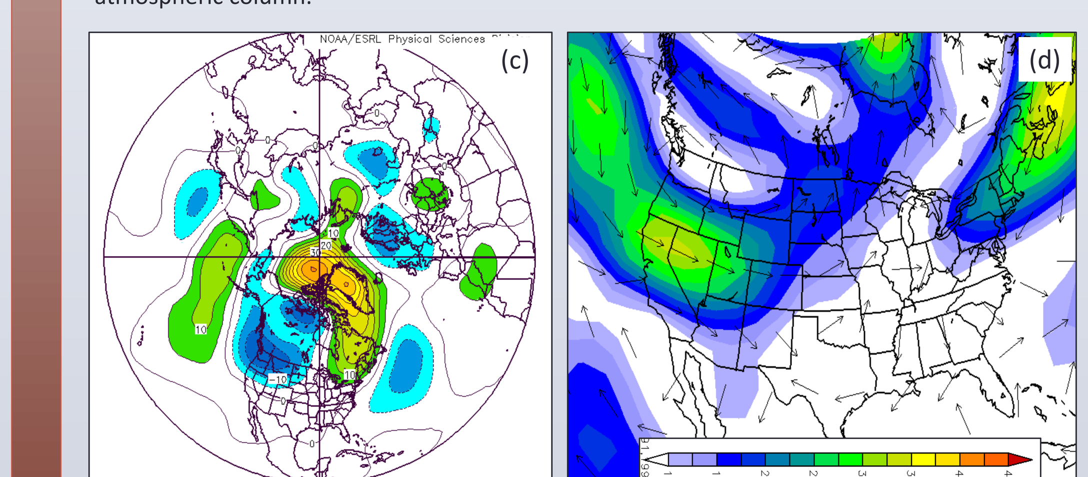

Figure 5 cont'd. 1979-2013 JJA composite mean anomaly differences associated with SIC^- minus SIC^{neu} conditions for (c) 500 hPa geopotential height (m), and (d) 300 hPa vector winds (m/s).

SUMMARY AND CONCLUDING STATEMENTS

Low summer sea ice conditions have coincided with notable changes in the hydroclimatology of the north-central US and the UMRV region over the past 35 years. The hydroclimatic anomalies observed during low-ice summers across the study area, including the UMRV region, coincide with various notable changes in synoptic-scale atmospheric circulation including:

1. Increased flow of southerly warm and moisture-rich air into the north-central US from the Gulf of Mexico indicative of a well-developed and active GPLLJ. Weaver and Nigam (2008) linked its activity to the negative phase of the NAO, which has been coincident with recent Arctic sea ice decline (Overland *et al.* 2012). Negative phase NAO has also coincided with weaker zonal mean jets and stronger meandering of the polar jet similar to what we observe in this study. Increased meandering of the jet has been hypothesized as a response to a reduced meridional thermal gradient stemming from Arctic sea ice reductions (Overland *et al.*, 2012, Coumou *et al.*, 2014; Hall *et al.*, 2015).
2. Enhanced meridional flow of the polar jet over the North American continent with a trough situated over the northwestern sections of the US to the west of the study area that brings frontal systems and storms into the UMRV, and a ridge situated over the eastern section of the continent. Budikova and Chechi (2016) argue that such an atmospheric pattern may be suggestive of increased jet waviness due to reduced summer Arctic sea ice cover and Northern Hemispheric meridional temperature gradient, when compared to a relatively zonal flow typically observed during average summers. Coumou *et al.* (2014 and 2015), and Francis and Vavrus (2015) argue that such a planetary wave amplification may weaken the overall zonal mean jet and slow down the propagation of Rossby waves.
3. Southerly air flow from the Gulf of Mexico at lower levels and westerly flow from the Pacific Ocean at the jet level merge over the study area just to the south-west of the UMRV region enhancing the atmospheric moisture content and precipitation over the area.

Over the past three decades, this region of the US has experienced some of the largest increases in annual total precipitation, heavy precipitation events, and rising trends in flood magnitude (Walsh *et al.*, 2014). Climate modeling studies under various increasing greenhouse gas scenarios predict many of these precipitation trends to continue into the future along with the shrinking Arctic cryosphere (Walsh *et al.*, 2014). The results of this study suggest that Arctic sea ice loss may act to further enhance central US summer precipitation and potentially increase the incidence of flooding across the UMRV region through its influence on the activity of the GPLLJ and modifications of the upper-level atmospheric flow.

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