COMMENTS TO THE REVIEWERS AND NEW VERSION OF THE MANUSCRIPT WITH CHANGES

Dear Editor,

I´m sending in a single document the comments to the two reviewers, the new version of the manuscript with changes and the supplementary material with changes

Best,

Luis Gimeno

Comments to Interactive comment on “The perfect pattern of moisture transport for precipitation for Arctic sea ice melting” by Luis Gimeno-Sotelo et al.

Anonymous Referee #1 Received and published: 24 January 2018 “The perfect pattern of moisture transport for precipitation for Arctic sea ice melting”

Before any comments about the text or the figures, I have to say that I do not feel very comfortable with the title of the paper. I would suggest to change the title.

The reviewer is right. We´ll change the title to something less confusing such as “The pattern of long-term changes in the moisture transport for precipitation with Arctic sea ice melting”

Some methodological and conceptual issues: Section 2.2.3: ‘. . .To compute moisture transport for precipitation (MTP) from each source to each sink for the AO, the trajectories of particles from the moisture sources for the Arctic (AR) were followed forward in time from every source region detected by Vazquez et al. (2016) (figure 1c).’ I find that further discussion is needed about this sentence (and paragraph) and what it implies. It is difficult for me to understand why those (and only those) particles are tracked. In fact, my interpretation is that source regions are not source regions anymore since authors follow 10 days into the future all the particles within those regions, had them gained water vapor within those source regions or not. Thus, water does not necessarily come from those regions and they stop being ‘source regions’.

The reviewer is right. This is one of the limitations of the approach when analyzing contribution of remote sources. Particles can gain moisture in the regions placed between the defined moisture source and the target region, even in the target region. We have used extensively the same approach in many papers (see Gimeno et al, 2010 or Gimeno et al, 2013 as examples) and not always put in evidence this limitation in the text. However as our defined moisture regions were identified as the ***major*** *moisture sources in the backward analysis (Vazquez et al, 2016) the contribution of the intermediate regions is much lower. We include figure 2 from Vazquez et al. 2006) that shows that intermediate regions are not net sources (particles reaching the Arctic region lost (not gained) moisture in these regions.*

In any case we will include this limitation in the text of the revised version of the manuscript.

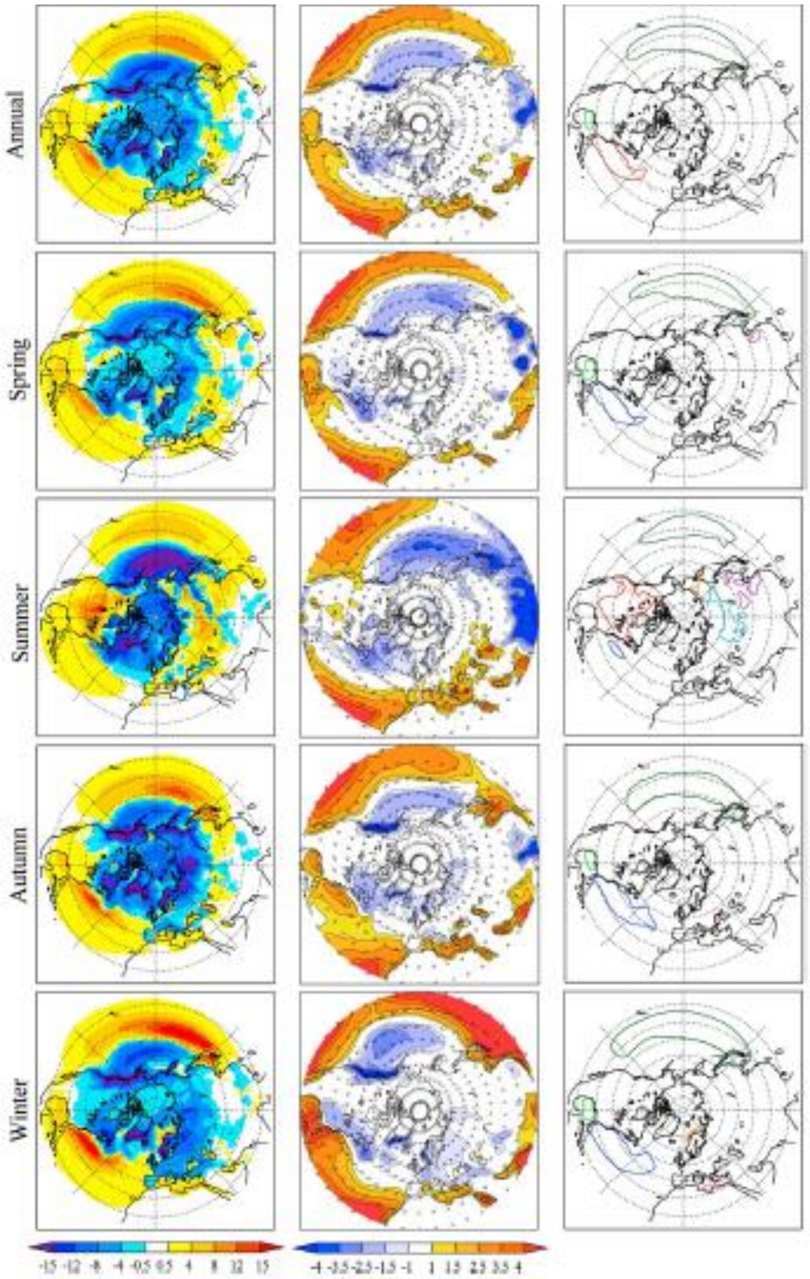

Figure 2. (left column) Climatological annual and seasonal 10 day integrated ($E - P$) values observed for the period 1979–2012, for all the particles bound for the Arctic domain, determined from backward tracking. Red (blue) colors represent moisture sources (sinks). Units are in mm d^{-1}. (middle column) Climatological annual and seasonal vertically integrated moisture flux values (vectors; measured in kg m^{-1} s^{-1}) and respective divergence (shade; measured in mm d^{-1}). Data are from ERA-Interim. (right column) Annual and seasonal moisture sources delimited only for those values of 10 day integrated ($E - P$) greater than 0.4 mm/d. Each contour color represents one source: the dark blue line represents the Atlantic source, light blue the Siberian one, dark green the Pacific, light green the Gulf of Mexico, dark pink the Black Sea, light pink the Caspian Sea, light orange the Eastern Russia source, dark orange the Norwegian and Barents Seas, purple the China source, red the North American source, and garnet the Mediterranean source.

In addition, not all the precipitated water comes from those ‘sources’, so, what happens with other particles that produce precipitation but were not within those ‘source regions’ ten days before precipitation?

We don´t estimate precipitation in the Arctic but contribution of the major sources providing moisture for precipitation. Of course the rest of the particles are responsible for the rest of precipitation

We´ll include a comment on it in the revised version of the manuscript

Another question, are there enough ‘particles’ to properly characterize what happens with the smallest sub-regions defined in figure 1b (I am thinking in the results presented in figure 8)?

The size of the target regions are bigger than many of the regions where the same methodology was used in previous studies. We calculated the average number of particle by source that reach daily the target regions (table below). The number is big enough.

	Central Arctic	*CCA*	*Beaufort*	*Chuckchi*	*E. Siberian*	*Laptev*	*Kara*	*Barents*	*E. Greenland*	*Baffin Bay*	*Hudson Bay*	*St. Law*	*Bering Sea*	*Sea of Okhotsk*
ATL	*4716*	*421,*	*543,*	*572,*	*1102*	*1300*	*2733*	*9256*	*36900*	*40613*	*2961*	*17441*	*1829*	*4157*
PAC	*11059*	*4662*	*11023*	*10358*	*9275*	*2938*	*1698*	*3902*	*17773*	*32785*	*18675*	*15147*	*60348*	*33112*
NA	*21129*	*10426*	*9249*	*3415*	*3421*	*3510*	*4706*	*15336*	*69134*	*141067*	*59233*	*58688*	*6659*	*4794*
SIB	*22220*	*2829*	*9831*	*12078*	*21880*	*17030*	*16358*	*17235*	*7211*	*6184*	*4303*	*1090*	*41223*	*79120*

We´ll write a sentence in the revised paper to address this comment and the table will be included in the supplementary material

Section 2.2.3 (should be 2.2.4): 'circulation types' are identified for four sections selected 'according to the positions of the major sources of moisture'. What are the sizes of those sections? Is there a minimum recommendable size? Is the method used to identify 'circulation types' sensible to the area selected? Are your results robust if you modify (nut much) those sections? Some of those sections share some common areas, does it affect to the latter interpretation of the circulation types? In addition, it would be advisable to identify those four sections in figure 1c.

The size of the sections was 70 ºlatitude x 90ºlongitude. The analysis of changes in circulation types is complementary to the Lagrangian approach to check the coherence of the results. It is obvious that changes in the size of the sections can vary lightly the circulation types (Huth et al., 2008) but probably results of changes in the new types after/before the change point continue to be coherent with Lagrangian approach. We include in this comment a sample of this for the Atlantic section in fall by moving the domain 10º eastward and westward and by extending the domain 10º eastward (similar results, the patterns are very coherent)

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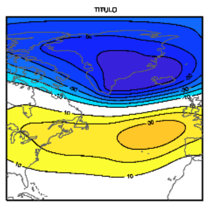
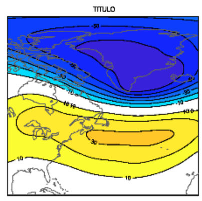
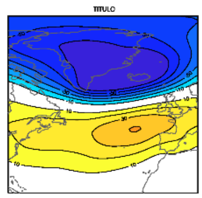
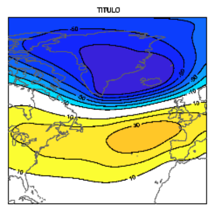
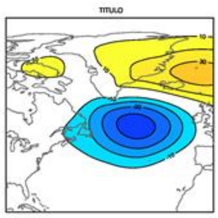
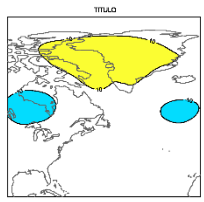
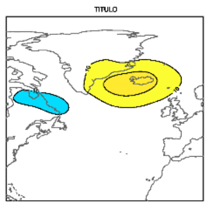
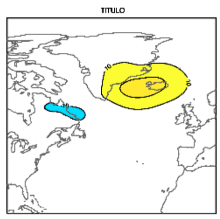
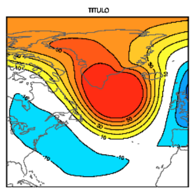
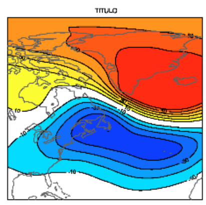
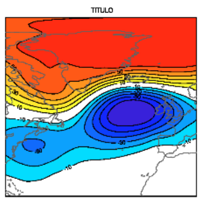
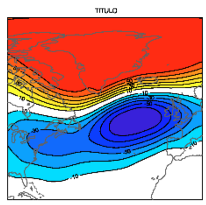
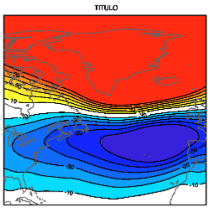
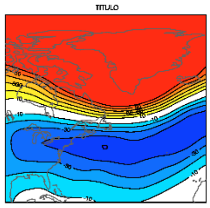
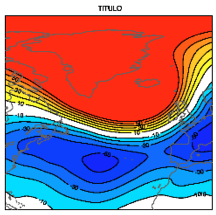
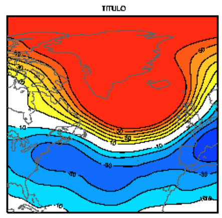
CTC1				
CTC2				
CTC3				

CTC4				

In any case we have taken a domain higher than the used by Fettweiss et al. (2011) (the higher they used was 30ºx30º), who showed no significant differences in the circulation types for 4 different domain sizes. The use of a regional domain centered in the moisture source is justified to account for regional modes instead of annular ones which could not catch details in regional circulation.

We´ll include a discussion on this in the revised version and will change figure 1c as requested

Huth, R. et al. (2008): Classifications of Atmospheric Circulation Patterns – Recent Advances and Applications. Annals of the New York Academy of Sciences: Trends and Directions in Climate Research, 1146, p. 105–152

Authors state that results in figure 6 suggest that 2003 is the most appropriate CP year. I do not find it so obvious. DS and MS series (figure 6) suggest that 2004 would be a better selection. Have authors tested if selecting one year or the other produces any difference? And, when writing about CPs, some explanation about change points identified using BinSeg and PELT should be provided. It is not clear in the text if more than one CP has been identified using those methods nor the implications that the existence of more than one CP in the SIE series would have in the interpretation of the results of this paper.

We include the same analysis for changing 2003 by 2004. As you can see in the figure R2 (the equivalent to figure 7 in the text) results are quite similar. A comment on this will be included in the revised version of the manuscript

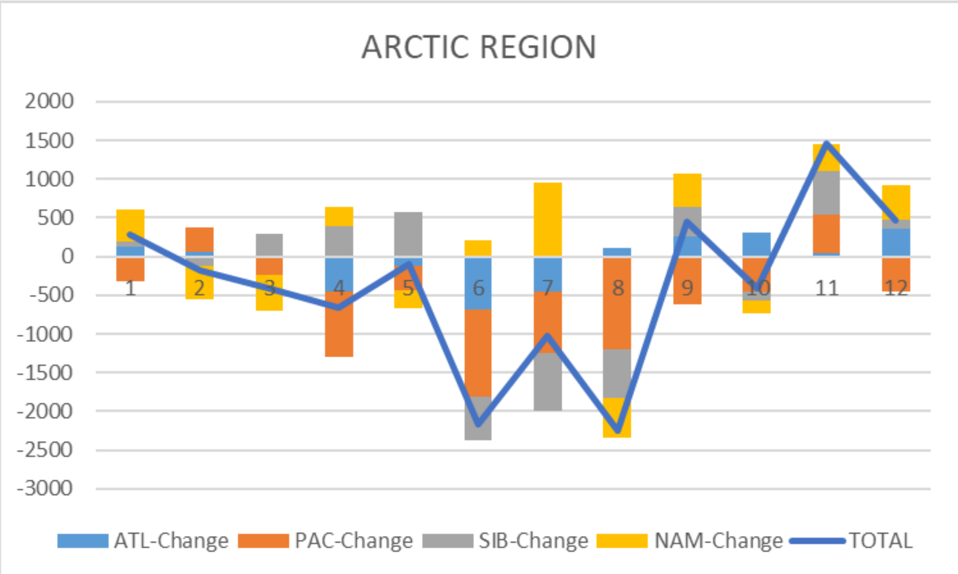


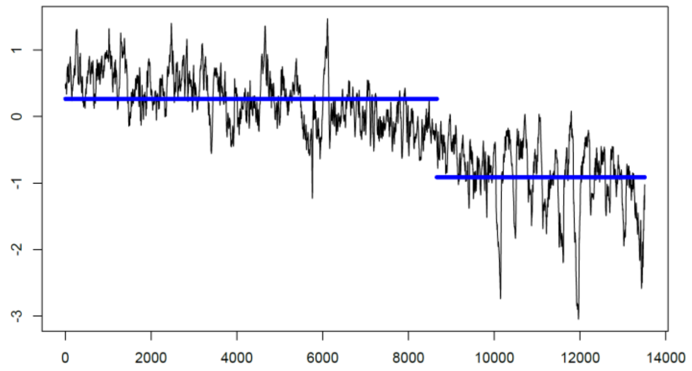
Figure R2 As Figure 7 in the manuscript but with 2004 as change point

In the description of figure 7 we commented the coincidence of change points found by AMOC (only one in the series) with any of the change points found by BinSeg and PELT (multiple change points). These two last approaches identify multiple change points (see the plots for the ADS series as an example of the series with more multiple changes or the plot for the 21 September DS series as an example of only one change in the three approaches, what is the most frequent case in DS and MS series). The idea of the paper is to identify the main change point to compare two periods (one with low ASI and the other with low). It is possible that any of the multiple subperiods identified by the other approaches merits analysis but it is out of the scope of this paper.

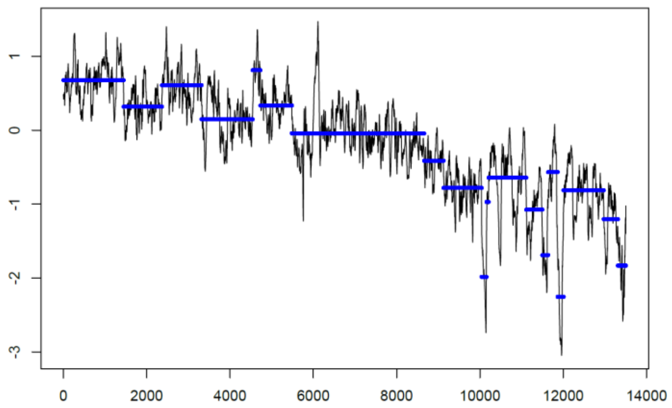
In any case we will include a comment in the revised version to suggest this for future work

ADS series

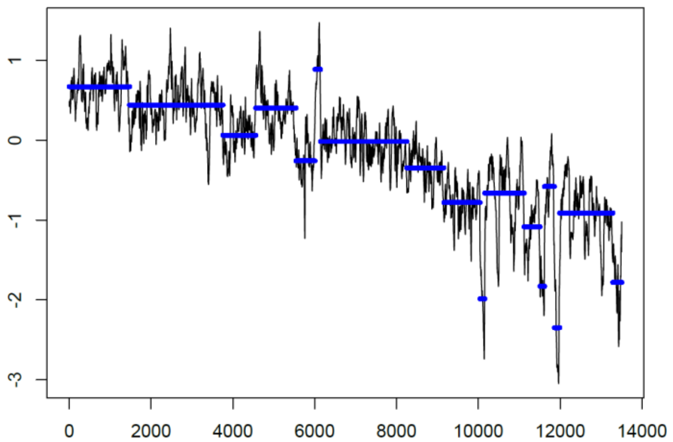
AMOC



BinSeg

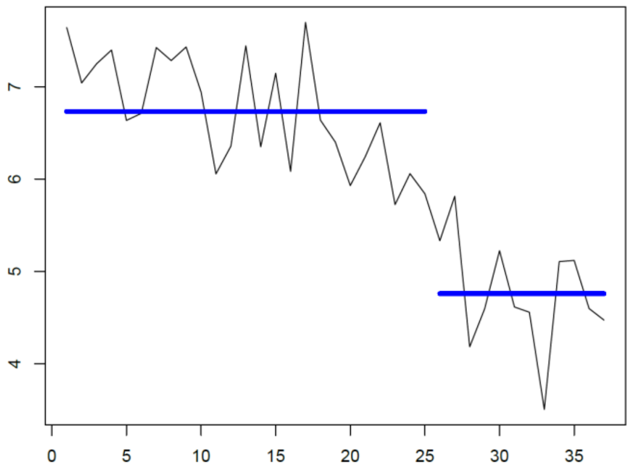


Pelt

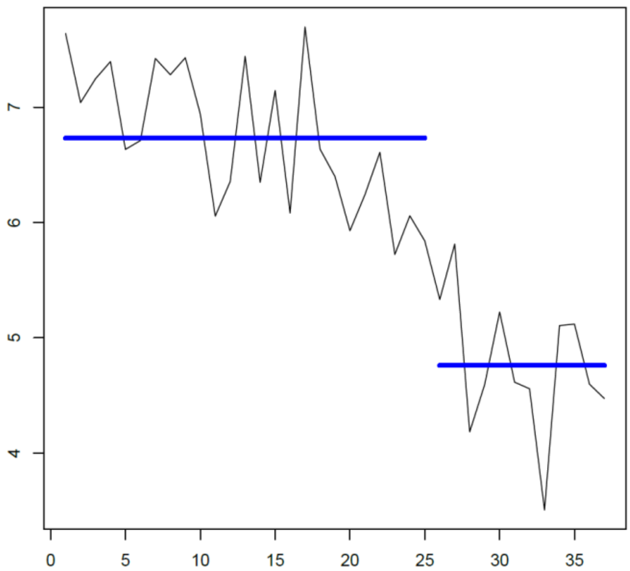


21 September DS series

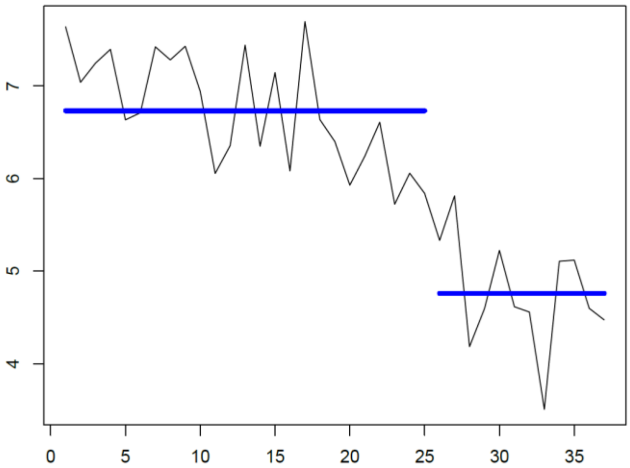
AMOC



BinSeg



Pelt



Some additional comments and typos: P7, paragraph describing figure 7: It is not explained anywhere that figure 7 includes the differences between mean values of MTP until 2003 and mean values after 2003 for every source region (this is my interpretation of what is represented in figure 7). The caption of figure 7 doesn't include this information either. Same comments can be applied to figure 8.

We´ll do in the revised version of the manuscript

I would suggest to re-plot figures 7 and 8 in order to include the information from the table in figure 7 and from table 1. It would be as easy as to plot with a thick (or filled) bar those differences that are statistically significant and with a thinner (empty) bar those differences that are not. In addition, plotting with a thicker line the horizontal bar indicating the 0 mm/day level would help to notice which sources increase/decrease their MTP contribution.

We´ll do in the revised version of the manuscript for Figure 7, not possible for figure 8 (we keep the significativity table) because of the small size of the component figures

Finally, no information about the statistical significance of the differences in total MTP is provided anywhere (again, it could be indicated by using a continuous or discontinuous line)

Indicated with a red asterisk in the new figure 7

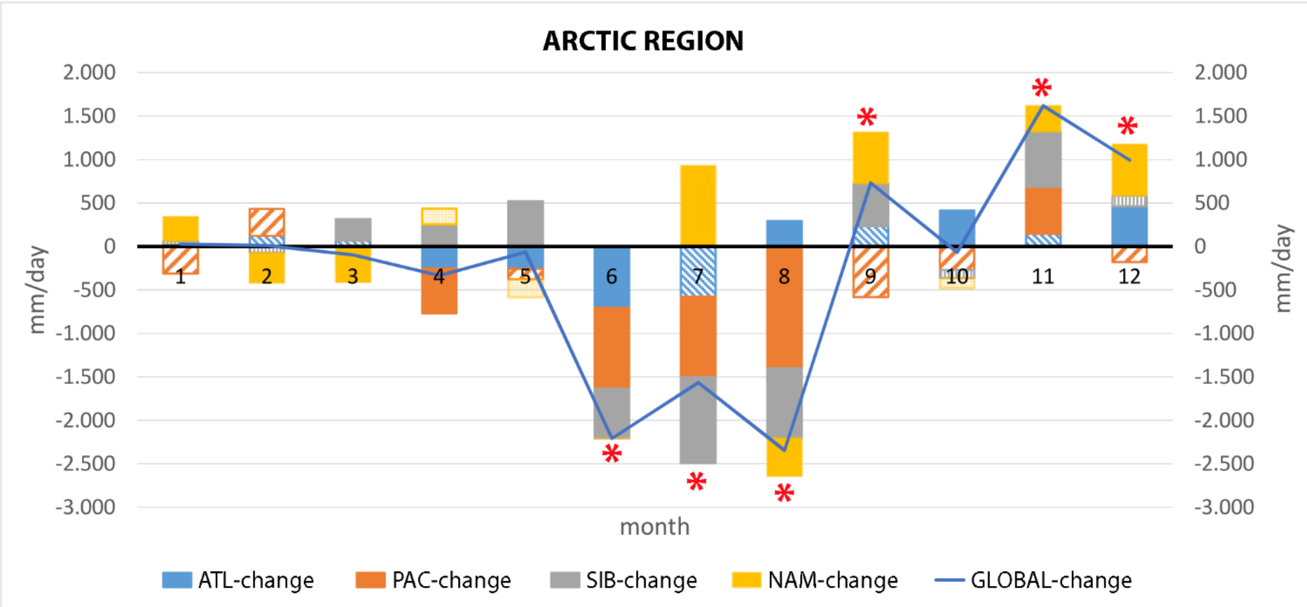


Figure 7. Differences between mean values of Moisture transport for precipitation (MTP) until 2003 and mean values after 2003 for every source region. Filled bars show those differences that are statistically significant at the 95% confidence level for decreases after the CP. Statistical significance of the differences in total MTP (sum of the four sources) is displayed with a red cross

It would be easier to follow the comments in the text if Figure S1 and figure 9 included some labeled meridians (or at least, some longitudes in the outer area of the maps).

We´ll do in the revised version of the manuscript

TYPOS

We´ll correct the typos and minor changes in the revised version of the manuscript

Table S2: Are changes in the frequency of each class statistically significant?

We have used a z-test to compare two sample proportions (Sprinthall, 2011). Statistical significant changes has been now included in Table S2 using asterisks

- *Sprinthall, R. C. (2011). Basic Statistical Analysis (9th ed.). Pearson Education. ISBN 978-0-205-05217-2.*

Comments to Interactive comment on "The perfect pattern of moisture transport for precipitation for Arctic sea ice melting" by Luis Gimeno-Sotelo et al.

Anonymous Referee #2 Received and published: 6 March 2018 "The perfect pattern of moisture transport for precipitation for Arctic sea ice melting"

First, I find the title confusing and even misleading. Which perfect pattern is meant? Also, the statement "moisture transport for precipitation for Arctic sea ice melting" sounds rather awkward. I suggest to modify the title.

The reviewer is right. The term "perfect pattern" is disconcerting. We´ll change the title to something less confusing such as "The pattern of long-term changes in the moisture transport for precipitation with Arctic sea ice melting". We prefer to keep the term moisture transport for precipitation because it is the usual term in previous studies using the same methodology

The authors present a detailed analysis with clear graphical representations, however methodology description is unfortunately too vague to appreciate and understand the results. I invite the authors to explain the concept of the change points in relationship to its application to the Arctic sea ice extent data. Further, it is not clear how the results shown in Fig 6 have been obtained and how these results can be interpreted.

We have used several methods to estimate change points in sea ice extension to detect when the main long-range change occurred. As usual in time series analysis a change point detection tries to identify times when the time series in mean or variance changed. In this case we were interested mainly in mean changes (in the Arctic sea extension the change means decrease, higher values before the change point and lower after it)

Three different change point detections were used for different sea ice extension time series, as explained in the manuscript. As an example we´ll included in the paper a new figure (above) for two series and one method, AMOC. The top plot represents the 13505-values Arctic ice extent anomalies series consisting of all days from 1st January 1980 to 31st December 2016. There are two horizontal lines in the left panel representing the mean of the values before and after the change point identified by the AMOC method (8660th day-22th September 2003). Those means are 0.27 and -0.91, respectively. The graphic at the bottom portrays the 444-values Arctic ice extent anomalies series consisting of all months from January 1980 to December 2016. As in the previous one, in the left panel there are two horizontal lines which correspond to the mean of the data before and after the AMOC change point (286-October 2003). Those means are 0.41 and -0.74, respectively.

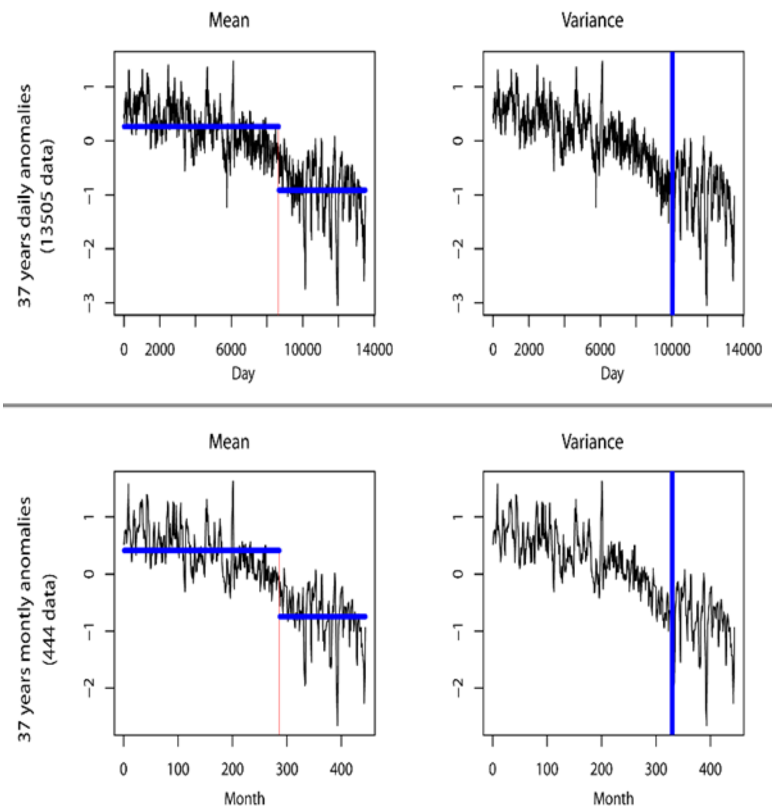


Figure 6 tries to summarize results of the change points estimation in mean identified by the AMOC method for the four different kinds of series of Arctic ice extent anomalies from 1980 to 2016 (as described in the methods section). So:

**A blue point refers to the change points in DS; for instance, the 21 July daily anomaly series (size of the series: 37 data points, representing 37 annual anomalies of the values of the sea ice extension for the 37 values on 21 July); occurred in 2004.*

** A red line portrays change points in the MS (July–October). For instance, for July monthly anomaly series (size of each series: 37 data points, representing 37 annual anomalies of the values of the sea ice extension for the 37 values in the average monthly July); occurred in 2004.*

** The single green square corresponds to the change point in the ADS, only one series of all daily anomalies (size of the series: 13,505 data points) built by ordering the daily anomalies in DS from 1 January 1980 to 31 December 2016 and the change point occurred the 22nd September 2003*

** The single purple line represents the change point in the AMS, only one series of all monthly anomalies (size of the series: 444 data points) built by ordering the monthly anomalies in MS from January 1980 to December 2016 and the change occurred in October 2003*

This plot was designed to show the big coherence of results for the different built series, what permitted us to select 2003 as the CHANGE POINT of the sea ice extent for our analysis

We´ll try to explain a bit more the figure 6 with examples in the revised paper to do easier the reading and interpretation of the results

Section 3.2 text is very descriptive and lacks interpretation. The methodology of the E-P analysis along the trajectories also needs to be better described. The moisture source regions are predefined from another study without any explanation - I invite the authors to explain the method in more details.

In view to not enlarge the paper with wide methodological description (what has been done in many of our previous papers) we preferred to condense the information, lacking any details that probable difficult the correct understanding of the approach and the own meaning of the MTP, we´ll extend this description in the revised paper

The wording itself "moisture transport for precipitation" sounds confusing and has to be rephrased and better defined.

We prefer to keep the term moisture transport for precipitation because it is the usual term in previous studies using the same methodology, however we´ll try to explain better its meaning

The sentence explaining the methodology ("Then, we selected all particles losing moisture, $(e - p) < 0$, at the sinks (whole Arctic or any of the subregions), and by adding $e - p$ for all of these particles, we estimated moisture transport for precipitation from the source to the sink $(E - P) < 0$ at daily, monthly or yearly scales.") needs more clarification with an extended explanation.

We´ll extend the explanation in the revised paper

This approach also doesn't imply that precipitation results exclusively from the moisture transport and local paper moisture re-circulation can also contribute.

Of course, and this is without any doubt an important contribution, but not addressed in this study, limited to the influence of remote sources. We´ll add any sentence in the revised manuscript to account for this, which is important for the correct interpretation of the results

I find a lot of similarities of this manuscript with another article by a coauthor of the present article Vasquez et al 2017 (www.mdpi.com/2073-4433/8/2/32/pdf), which is not somehow in the reference list. Can the authors put this manuscript in context of Vasquez et al 2017 explaining the novelty of the results?

Although the objective of Vazquez et al. (2017) was too to analyze the effect of moisture transport on the Arctic ice melting and the Lagrangian approach is the same both studies differ a lot. In Vazquez et al. (2017) we analyzed the influence of the transport on the two most important sea ice minimum events (2007 and 2012) and the analysis is based mostly on an analysis of anomalies. In this paper we analyzed the long-term changes in the moisture transport concurrent with long-term changes in sea ice (sea ice decline). However we´ll add a comment on this in the introduction to contextualize the study.

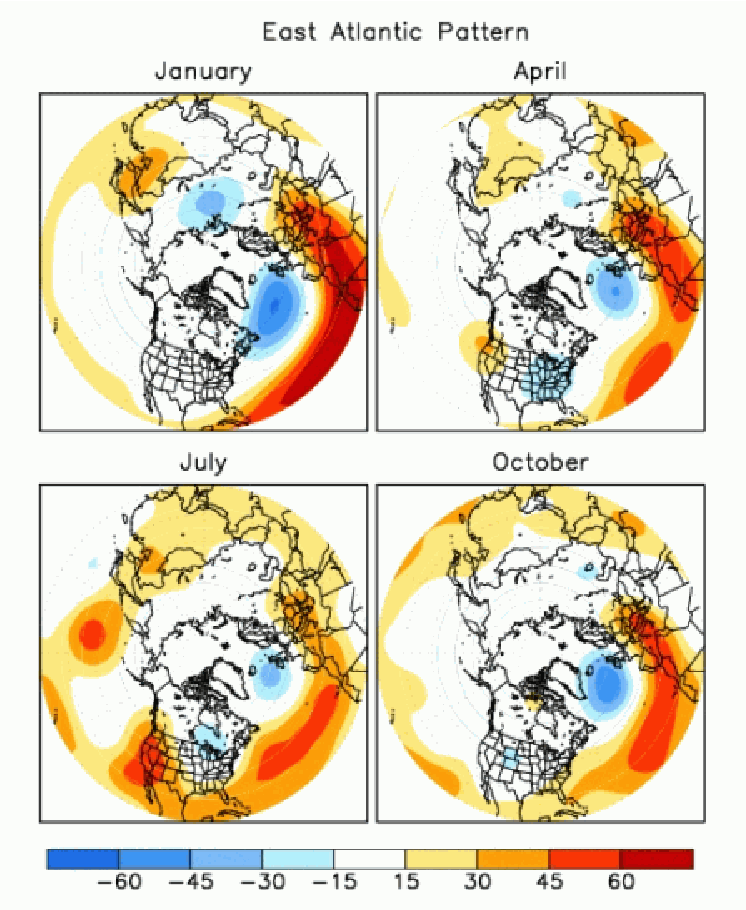
"We grouped individual days into four circulation types using the methodology developed by Fettweis et al. (2011) and explained in the Data and Methods sections." - in the Methods section the authors mention five (not four) circulation types and give no further explanations (which types, how they were defined...). Abbreviations used for the circulation types are not explained.

The reviewer is right; there is an error in the number of classes. It will be corrected in the manuscript. More details on the circulation types methodology will be included in the revised version of the manuscript.

The abbreviations will be included in the methods section.

What does it mean "the positive phase of the East Atlantic pattern" or " the negative phase of the East Atlantic/western Russia"?

You are right. We have supposed readers familiar with teleconnection patterns and their phases. According to the NOAA definition "The term teleconnection pattern alludes to a to a recurring and persistent large-scale pattern of pressure and circulation anomalies that spans vast geographical areas. These patterns have strong influence on temperature, rainfall, storm tracks, and jet stream location/ intensity over vast areas and consequently are often assumed as responsible for abnormal weather patterns occurring simultaneously over seemingly vast distances". We included in the main text of the manuscript the known web page from NOAA http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml where the patterns are described and their phases plotted. For instance, the East Atlantic pattern consists of a north-south dipole of anomaly centers spanning the North Atlantic from east to west with the positive phase with positive anomalies in the south pole, the one placed in the subtropics (see figure below)



We´ll describe a bit in the revised version of the manuscript what a teleconnection pattern is and the structure of those patterns referred in the main text

I find that many statements in the Conclusions are not supported by the results. A major change seems to occur in 2003 - however unclear how this was obtained and what does it mean exactly (from the conclusions one can deduce that it means a drastic sea ice decline - I suppose the "change point" technique allows to detect that the mean SIE over the period after 2003 is significantly smaller than before). And the "perfect pattern of MTP for Arctic sea ice melting consists of a general decrease in moisture transport in summer and an increase in fall and early winter", as stated in the Conclusions section, refers to this year as I understand (no longer mentioned in the Conclusions).

We´ll re-write these sentences in the conclusions. You are right, the 2003 change means a drastic sea ice decline and a decrease in moisture transport in summer and an increase in fall and early winter after 2003 vs before 2003

"This pattern is not only statistically significant but also consistent with Eulerian flux diagnosis, changes in circulation type frequency, and known mechanisms affecting snowfall or rainfall on ice in the Arctic." - which other known mechanisms affecting precipitation the authors refer to?

Basically we are referring to the mechanisms summarized in the introduction

"Snowfall on sea ice enhances thermal insulation and thus reduces sea ice growth in winter (Leppäranta, 1993), but increases the surface albedo and thus reduces melt in spring and summer (Cheng et al., 2008). In contrast, rainfall is generally related to sea ice melt, and for both snowfall and rainfall, flooding over the ice favors the formation of superimposed ice and potentially increases in the Arctic sea ice thickness"

The implications of these mechanism coherent with our results would be:

A lower MTP in early summer (as occurred since 2003) is consistent with lower precipitation in snowfall decreasing the surface albedo and thus increasing melt (Cheng et al., 2008)

A lower MTP in late summer (as occurred since 2003) is consistent with less probability of occurrence of rainfall storms with possible flooding over the ice which would favor the formation of superimposed ice

A higher MTP in early fall (September) (as occurred since 2003) is consistent with higher precipitation as rainfall, something generally related to sea ice melt

A higher MTP in late fall and early winter (as occurred since 2003) is consistent with higher precipitation as snowfall, enhancing thermal insulation and thus reducing sea ice growth in (Leppäranta, 1993)

Of course to check these implications rigorously is clearly out of the scope of this manuscript, since it would imply to know details over the precipitation form (snow or rain) for the different Arctic regions with good temporal and geographical resolution, and even to analyze specific precipitation episodes to know if these are responsible for flooding or not.

The comment in the conclusion has as objective to reinforce the creditability of the significant results from the Lagrangian analysis.

We´ll extend the comment in the line of described in this comment

"it is clear beyond doubt that an increment in moisture transport during this month favours ice melting, regardless of the source of moisture." - how is that clear? September's increase in MTP according to the methodology used here (if I understood correctly) means increased local precipitation vs evaporation (not necessarily increased moisture transport), and its impact to the SIE has not been established in this study. There are previous studies showing that the linkage can be the other way that precipitation has increased because of the decreased sea ice extent (eg, Bintanja, R. & Selten, F. M. Future increases in Arctic precipitation linked to local evaporation and sea ice retreat. Nature 509, 479–482 (2014).).

Not at all. I´m afraid that the reviewer has not understood properly the methodology and the meaning of MTP, probably for any lack of detail in the explanation of it (see previous comments). We´ll extend this explanation to avoid fails in the interpretation of the results. An increment in MTP in our study means exactly an increment in the moisture transported from the four major remote sources which then result in precipitation in the target region (Arctic region, subregions…). Changes in the precipitation in the Arctic could be of course due to changes in the moisture transport from remote sources but also and not less important to changes in evaporation from the own Arctic (a major factor, according to previous studies, but not evaluated in this paper).

We´ll try to clarify this in the revised version of the manuscript to avoid misunderstanding in the interpretation of the results

"Snowfall is the dominant (almost unique) form of precipitation during most of the year, with the exception of late summer." - there is frequent rain during summer (and not only later summer), especially in the peripheral Arctic regions. Even in the central Arctic rain can occur in the very beginning of the melt period (like during SHEBA, eg Perovich et al 2002).

We´ll re-write this to avoid so categorical affirmation

" when precipitation is produced in the form of snowfall on sea ice, it enhances thermal insulation, and reduces sea ice growth in winter (Leppäranta, 1993), but increases the surface albedo, and thus reduces melt in spring and summer (Cheng et al., 2008). These phenomena justify the opposite change in moisture transport for fall and winter versus spring." - how can these phenomena justify any changes in moisture transport?

These phenomena do not justify changes in the moisture transport but changes in the effect of precipitation on the sea ice. As we estimate changes in the moisture transport for precipitation (MTP), higher MTP results in more precipitation, this is the basis of the argument.

The manuscript has to be checked for language and consistency - there are many vague, incomplete phrases.

The first version was edited by a professional English service, in any case we´ll check carefully the revised version of the manuscript

~~*The perfect pattern of moisture transport for precipitation for Arctic sea ice melting*~~
The pattern of long-term changes in the moisture transport for precipitation with Arctic sea ice melting

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Abstract. *In this study we use the term moisture transport for precipitation (MTP) for a target region as the moisture coming to this region from its major moisture sources that then results in precipitation over it.* We have identified the patterns of *change in* moisture transport for precipitation over the Arctic region, the Arctic Ocean, and its 13 main subdomains *concurrent with the major* ~~, which better fit with~~ sea ice decline *occurred in 2003*. ~~For this purpose, we studied the different patterns of moisture transport for the case of high/low Arctic sea ice (ASI) extension linked to periods before/after the main change point (CP) in the extension of sea ice.~~ The pattern consists of a general decrease in moisture transport in summer and enhanced moisture transport in autumn and early winter, with different contributions depending on the moisture source and ocean subregion. The pattern is not only statistically significant but also consistent with Eulerian fluxes diagnosis, changes in the frequency of circulation types, and *any of the* known mechanisms of the effects of *the increments of precipitation as* snowfall or rainfall on ice in the Arctic. The results of this paper also reveal that the assumed and partially documented enhanced poleward moisture transport from lower latitudes as a consequence of increased moisture from climate change seems to be less simple and constant than typically recognized in relation to enhanced Arctic precipitation throughout the year in the present climate.

1 Introduction

The shrinking of the cryosphere since the 1970s is among the most robust signals of climate change identified in the last IPCC Assessment *(IPCC, 2013)*. There is little doubt that this change is a result of global warming caused by increased anthropogenic greenhouse gas emissions *(AR5; IPCC, 2013)*. The Arctic is of particular scientific and environmental interest; the rise in Arctic near-surface temperature doubles the global average in almost all months *(e.g., Screen and Simmonds, 2010; Tang et al., 2014, Cohen et al., 2014)*. Without doubt, the most important indicator of Arctic climate change is sea ice extent, which is characterised by a very significant decline since the 1970s *(Tang et al., 2014; IPCC, 2013)*. This decline has accelerated in recent decades in terms of both extent and thickness to the point where a summer ice-free Arctic Ocean is expected to occur within the next few decades *(IPCC, 2013)*. Changes in atmospheric and oceanic circulation with implications for Arctic mid-latitude climate or reductions and shifts in the distribution of oceanic and terrestrial fauna are among the most concerning and already apparent impacts of this decline in sea ice (Screen and Simmonds, 2010; Post et al, 2013). The scientific mechanisms involved in Arctic sea ice extension (SIE) are multiple and varied; atmospheric processes *(Ogi and Wallace, 2007; Rigor et al., 2002)* interact closely and nonlinearly with hydrological and oceanographic processes *(Zhang et al.,1999; Årthun et al., 2012; Zhang et al., 2012)*. Changes in atmospheric circulation can affect SIE via dynamical (e.g. changes of surface winds) or thermodynamic factors (i.e. changes in heat and moisture fluxes in the Arctic *(Tjernström et al., 2015; Ding et al., 2017)*. ~~.~~*A*~~a~~*m*ong these effects, change in moisture transport has emerged as one of the most important with respect to the greenhouse effect *(Koenigk et al., 2013; Graversen and Burtu, 2016;~~,~~ Vihma, 2016)*, and is related to SIE decline through hydrological mechanisms such as changes in Arctic river discharges *(Zhang et al., 2012)*, radiative mechanisms such as anomalous downward longwave radiation at the surface *(Woods et al., 2013; Park et al., 2015a; Mortin et al., 2016; Woods and Caballero, 2016;~~,~~ Lee et al., 2017)*, or meteorological mechanisms such as changes in the frequency and intensity of cyclones crossing the Arctic *(Rinke et al., 2017)*. Because the effects of enhanced moisture transport on Arctic ice are diverse, there is no direct relationship between enhanced transport and SIE decline. Anomalously high moisture transport into the Arctic is associated with intense surface winds, and increment in moisture content and induced radiative warming, which lead to decreased SIE *(Kapsch et al., 2013; Park et al., 2015b)*. However, anomalous moisture transport can result in anomalous precipitation, and in this case, the relation between enhanced moisture transport and diminished SIE is unclear because changes in precipitation are not always related to SIE in the same way, depending on the type of precipitation and the season. Snowfall on sea ice enhances thermal insulation and thus reduces sea ice growth in winter *(Leppäranta, 1993)*, but increases the surface albedo and thus reduces melt in spring and summer *(Cheng et al., 2008)*. In contrast, rainfall is generally related to sea ice melt, and for both snowfall and rainfall, flooding over the ice favours the formation of superimposed ice and potentially increases in the Arctic sea ice thickness.

In this study we use the term moisture transport for precipitation (MTP) for a target region as the moisture coming to this region from its major moisture sources that then results in precipitation over it~~.~~. W~~In this article, w~~e focus on identifying the patterns of moisture transport for precipitation in the Arctic region (AR), the Arctic Ocean (AO) as a whole, and its 13 main subdomains, which fit better with sea ice decline. For this purpose, we have studied the different patterns of moisture transport for the cases of high and low SIE linked to periods before and after the main change point (CP) in the extension of sea ice. *The study differs significantly from our previous work, Vazquez et al. (2017), in which we analyzed the influence of the transport of moisture on the two most important sea ice minimum events (2007 and 2012) based mostly on an analysis of anomalies. In this paper we analyzed the long-term changes in the moisture transport concurrent with long-term changes in sea ice (sea ice decline).*

2 Data and Methods

2.1 Data

The target region in this study comprises the AR (figure 1a) as defined by Roberts et al. (2010) and used by *Vazquez et al. (2016*), the AO as a whole, and its 13 main subdomains as defined in figure 1b (Boisvert et al., 2015). The analysed period was from 1 January 1980 to 31 December 2016. For Arctic SIE, we used daily, monthly and annual data from the U.S. National Snow and Ice Data Center (Fetterer, 2016), and to implement the Lagrangian approach, by which moisture transport is estimated to approximate vertical integrated moisture fluxes and circulation types, we used the European Centre for Medium-Range Weather Forecasts (ECMWF) interim Re-Analysis (ERA-Interim) *(Dee et al., 2011).* Data from this reanalysis cover the period from January 1979 to the present and extending forward continuously in near-real time. These data are available at six-hour intervals at a 1° x 1° spatial resolution in latitude and longitude for 61 vertical levels (1000 to 0.1 hPa). The ERA-Interim reanalysis is typically considered to have the highest quality relative to other reanalysis data for the water cycle *(Lorenz and Kunstmann, 2012)* and is especially appropriate over the Arctic region *(Jakobson et al., 2012),* with better representation of mass fluxes including water vapor *(Graversen et al., 2011).*

2.2 Methods

2.2.1 Calculation of sea ice extension anomalies

Daily, monthly and annual data of sea ice extension from 1980 to 2016 taken from the National Snow and Ice Data Center *(Fetterer, 2016)* were used to build four different series of ice extension anomalies for the whole Arctic Ocean (AO) and its 13 subregions. These four series were constructed as follows:

DS: 365 daily anomaly series (size of each series: 37 data points); for each daily value, the average for the same calendar day over the 37-year period is subtracted (for instance, the series for 21 September comprises the anomaly of each 21 September vs. the average of the 37 data points from this date)

MS: 12 monthly anomaly series (size of each series: 37 data points); for each monthly value, the average for the same month over the 37-year period is subtracted (for instance the series for September results of the anomaly of each September vs the average of the 37 September data points).

ADS: one series of all daily anomalies (size of the series: 13,505 data points) built by ordering the daily anomalies in DS from 1 January 1980 to 31 December 2016.

AMS: one series of all monthly anomalies (size of the series: 444 data points) built by ordering the monthly anomalies in MS from January 1980 to December 2016.

2.2.2 Detection of change points in Arctic sea ice extension

We have used several methods to estimate change points in Arctic sea ice (ASI) extension to detect when the main long-range change occurred. As usual in time series analysis a change point detection tries to identify times when the time series in mean or variance changed. In this case we were interested mainly in changes in mean (in the Arctic sea ice extension the change in mean is equivalent to a decrease, higher ASI extension values before the change point and lower after it).

Change points of each of these series for the AO were calculated using three different methods, one detecting single change points (At Most One Change, AMOC) and two detecting multiple change points (BinSeg and PELT).

AMOC uses ~~employs~~ a test to detect a hypothesised single change point (CP). The null hypothesis refers to no change point, and its maximum log-likelihood is given by $\boldsymbol{log\ p\ (y_{1:n}|\widehat{\theta_1})}$, where p(·) is the probability density function associated with the distribution of the data and $\widehat{\boldsymbol{\theta}}$ is the maximum likelihood estimate of the parameters. For the alternative hypothesis, a change point at $\boldsymbol{\tau_1}$ is considered, with $\boldsymbol{\tau_1} \in \{\mathbf{1}, \mathbf{2}, \ldots, \boldsymbol{n} - \mathbf{1}\}$. The expression for the maximum log-likelihood for a given $\boldsymbol{\tau_1}$ is $\boldsymbol{ML(\tau_1)} = \mathbf{log}\,\boldsymbol{p}(\boldsymbol{y}_{1:\tau_1}|\widehat{\boldsymbol{\theta_1}}) + \mathbf{log}\,\boldsymbol{p}\left(\boldsymbol{y}_{(\tau_1+1):n}|\widehat{\boldsymbol{\theta_2}}\right)$.

Taking into account that the CP location is discrete in nature, $\mathbf{max}\,\boldsymbol{\tau_1}\,\boldsymbol{ML(\tau_1)}$ is the maximum log-likelihood value under the alternative hypothesis, where the maximum is taken over all possible change-point locations. Consequently, the test statistic is $\boldsymbol{\lambda} = \mathbf{2}[\mathbf{max}\,\boldsymbol{\tau_1}\,\boldsymbol{ML(\tau_1)} - \mathbf{log}\,\boldsymbol{p}(\boldsymbol{y_{1:n}}|\widehat{\boldsymbol{\theta}})]$. The null hypothesis is rejected if $\boldsymbol{\lambda}$ > C, where C is a threshold of our choice. When detecting a CP, its position is estimated as $\widehat{\boldsymbol{\tau_1}}$, which is the value of $\widehat{\boldsymbol{\tau_1}}$ that maximises $\boldsymbol{ML(\tau_1)}$.

BinSeg and PELT: by summing the likelihood for each of the $\boldsymbol{m}$ segments, the likelihood test statistic can be extended to multiple changes. However, there is a problem in identifying the maximum of $\boldsymbol{ML(\tau_{1:m})}$ over all possible combinations of $\boldsymbol{\tau_{1:m}}$. The most common approach to resolve this problem is to minimise

$$\sum_{i=1}^{m+1}\left[C(\boldsymbol{y}_{(\tau_{i-1}+1):\tau_i})\right] + \boldsymbol{\beta f(m)} \quad (1)$$

where C is a cost function for a segment, such as the negative log-likelihood, and $\boldsymbol{\beta f(m)}$ is a penalty to guard against over fitting. The BinSeg (binary segmentation) method starts with applying a single CP test statistic to the entire data set. If a CP is identified, the data are then split into two at the CP location. The single CP process is repeated for the two new data sets, before and after the change. If CPs are identified in either of the new data sets, they are split further. This procedure continues until no CPs are found in any parts of the data. This process is an approximate minimisation of (1) with $\boldsymbol{f(m) = m}$, as any CP locations are conditional on CPs identified previously. The segment neighbourhood algorithm precisely minimises the expression given by (1) using a dynamic programming technique to obtain the optimal segmentation for $(\boldsymbol{m} + \mathbf{1})$ CPs reusing the information calculated for $\boldsymbol{m}$ change points. The PELT (pruned exact linear time) method is similar to that of the segment neighbourhood algorithm in that it provides an exact segmentation. We have used the PELT algorithm instead of the segment neighbourhood method as it has proven to be more computationally efficient. The reason for this greater efficiency is the use of dynamic programming and pruning in the algorithm's construction.

A full description of these methods and the subroutines in R used in this study can be found in *Killick and Eckley (2014).*

The three different change point methods were used for the four different ASI ice extension time series defined in point 2.2.1. . Figure 2 illustrates the detection of the change point in mean for two series (ADS and AMS) using AMOC method. The top plot represents the 13505-values Arctic ice extent anomalies series consisting of all days from 1st January 1980 to 31st December 2016 (ADS series). There are two horizontal lines representing the mean of the values before and after the change point identified by the AMOC method (the 8660th day that correspond to -22th September 2003). Those means are 0.27 and -0.91, respectively. The graphic at the bottom portrays the 444-values Arctic ice extent anomalies series consisting of all months from January 1980 to December 2016 (AMS series). As in the previous one, there are two horizontal lines, which correspond to the mean of the data before and after the AMOC change point (the 286th month of the series, that is -October 2003). Those means are 0.41 and -0.74, respectively.

2.2.3 Estimation of the Lagrangian moisture transport from the main sources

In this study, we used a Lagrangian approach to calculate moisture transport from the main moisture sources as detected by *Vazquez et al. (2016)* (figure 1c) for the AR, AO, and its 13 subregions. This approach is based on the particle dispersion model FLEXPART v9.0 (i.e., the FLEXible PARTicle dispersion model of Stohl and James (2004, 2005)) forced by ERA-Interim data from the ECMWF. This approach has been used extensively in moisture transport analysis *(e.g., Gimeno et al., 2010; 2013)*, and a review of its advantages and disadvantages versus other approaches for tracking water vapor was summarised by *Gimeno et al. (2012 and 2016).* To briefly summarise this method, the atmosphere is divided into so-called particles (finite elements of volume with equal mass) and individual three-dimensional trajectories are tracked backward or forward in time for 10 days, the average residence time of water vapor in the atmosphere *(Numaguti, 1999).* Then, taking into account the changes in ($\boldsymbol{q}$) for each particle along its trajectory, the net rate of change of water vapour ($\boldsymbol{e-p}$) for every particle, $(\boldsymbol{e-p}) = \boldsymbol{m}(\boldsymbol{dq}/\boldsymbol{dt})$, is estimated, with $\boldsymbol{e}$ and $\boldsymbol{p}$ representing evaporation and precipitation, respectively. The total atmospheric moisture budget ($\boldsymbol{E-P}$) is estimated by adding up ($\boldsymbol{e-p}$) for all particles over a given area at each time step used in the analysis. *If we follow the particles backward in time for a target region, positive (E-P) values identify the main moisture sources for this target region, if we followthe particles forward in time from a source region, negative (E-P) values identify the main moisture sinks of the source region. In this study we have used four predefined moisture sources, those identified as the major sources of moisture for the Arctic region (AR) in Vazquez et al (2016) following backward in time all the particles reaching the AR for the period 1980-2012 and taking the regions showing positive (E-P) values greater than 90th percentile (taking into account global values of positive E-P). Then, t*To compute moisture transport for precipitation (MTP) from each of these four sources to each sink for the AO, the trajectories of particles from the moisture sources for the Arctic (AR) were followed forward in time from every source region detected by *Vazquez et al. (2016)* (figure 1c).-.This was done for 6 hours in the period 1980–2016. Then, we selected all particles losing moisture, $(e-p) < 0$, at the sinks (whole Arctic or any of the sub-regions), and by adding $e-p$ for all of these particles, we estimated moisture transport for precipitation from the source to the sink ((E − P) < 0) at daily, monthly or yearly scales. A schematic illustration of this approach is displayed in figure 3~~2~~. *A couple of clarifications on this approach are necessary to avoid misunderstandings of the results. The first one is that particles can gain moisture in the regions placed between the defined as the major moisture sources and the target region, even in the target region itself. However as our defined moisture regions were identified as the major moisture sources in the backward analysis (Vazquez et al, 2016) the contribution of the intermediate regions is much lower. A look at figure 2 from Vazquez et al.(2016) shows that intermediate regions are not net sources (particles reaching the Arctic region lost (not gained) in average moisture in these regions. In any case not all the precipitated water comes from the major sources, those particles that were not within those major source regions ten days before precipitation are responsible for the rest of precipitation, including the particles coming from the own Arctic region, which account for the important contribution of local moisture re-circulation. The second clarification is concerned with the size of the target regions and the number of particles reaching them. As commented in the seminal description of the approach (Stohl and James, 2004, 2005), this works better for large regions. The size of the target regions in this study (Arctic region and subregions) is bigger than in many of the regions where the same methodology was used in previous studies (e.g. Ramos et al., 2016 or* Wegmann *et al, 2015) and the average number of particles by source that reach daily the target regions big enough (see **Table S1** in the supplementary material).*

2.2.4 ~~3~~ Identification of circulation types

The patterns of (E − P) < 0 can change daily in association with variations in atmospheric circulation. To evaluate the relationship between this variability and the moisture supply generated from each source of moisture, we identified different circulation types *(CTCs)* over the areas of interest using a~~n applied~~ methodology developed by *Fettweis et al. (2011).* This approach consists of an automated circulation type classification based on a correlation analysis whereby atmospheric circulation is categorised into a convenient number of four~~ive~~ discrete circulation types in the present study. For each pair of days, a similarity index based on the ~~Spearman rank~~ correlation coefficient was calculated for the purpose of grouping days that showed similar circulation patterns *(Belleflamme et al., 2012).* The first category contains the greatest number of similar days, where similarity is defined by a particular threshold (0.95 for the first class). After establishing the first class, the same procedure was applied for the remaining days using a lower similarity threshold to find the second and then all other classes. The complete procedure was repeated for different thresholds to optimise the percentage of variance explained (Philipp et al., 2010). This method is termed a "leader" algorithm because each class is represented by a leader pattern considered as the reference day (Philipp et al., 2010). In this study, we used the geopotential height field at 850 hPa from ERA-Interim. Because our aim was to find and analyse different circulation patterns affecting the Arctic system linked to each source of moisture, the northern hemisphere from 20º to 90ºN was divided into sections according to the positions of the major sources of moisture (figure 1c). *The size of the sections was 70 ºlatitude x 90ºlongitude.* Thus, the circulation type classification was obtained seasonally for each of these sections. *The use of a regional domain centered in the moisture source is justified to account for regional modes instead of annular ones, which could not catch details in regional circulation. As changes in the size of the sections can vary lightly the circulation types (Huth et al., 2008) we performed a sensibility analysis (not shown) by moving the domain 10ª eastward and westward and by extending the domain 10º eastward with (similar results, what showed that the patterns are very coherent).*

3 Results

3.1 Climatological moisture transport for precipitation (MTP) to the Arctic region (AR) and Arctic Ocean (AO) subregions

Figure 4~~3~~ displays the seasonal cycle of MTP to the AR from four major sources (Atlantic, Pacific, Siberia, and North America) and the relative contributions of each. MTP to the AR exhibits a marked seasonal cycle with a maximum in summer and a minimum in winter; MTP doubles in the highest month (August) relative to the lowest month (February). The percentage of the contribution from each source is relatively constant throughout the year, with the Pacific, North America, Siberia, and the Atlantic contributing about 35%, 30%, 20%, and 15%, respectively.

The seasonal cycle is quite similar for eight of the 13 AO subregions (figure 5~~4~~), with two other regions (Barents and the Central Arctic) exhibiting similar maxima, but with minima in May, and another (Chukchi) with two minima in March and November, and finally Greenland with a minimum in May but no clear maximum in summer, extending the typical summer high values to fall and winter~~ (Greenland)~~. The relative contributions of each moisture source are very diverse, with three general patterns: one with the~~ a dominating~~ closest source dominating (a Pacific source for Bering, Chukchi, and Okhostk, a North American source for the Canadian Islands and Hudson, and a Siberian source for Kara and Laptev), another pattern where two sources share importance throughout the year (Atlantic and Siberian sources for Baffin and Greenland, and Pacific and North American sources for Beaufort), and a third where the Siberian source shares importance with two or more sources (Barents, Central Arctic, and East Siberia).

The relative importance of each ocean subregion on MTP to the AO (estimated as the sum of the 13 subregion) is shown in figure 6~~5~~ where the percentage of moisture transport to the whole AO is displayed by region and month. There are four regions where the aggregated MTP received represents more than 60% of the MTP received for the whole Arctic. Those regions are Greenland, Baffin, Bering, and the Central Arctic, in order of importance. The contributions of Baffin, Bering, and the Central Arctic vary little throughout the year, representing about 20%, 12% and 10% of the MTP received for the whole Arctic, respectively, whereas the contribution of Greenland has a marked seasonal cycle with values around 25% for fall and winter, and 10–15% in spring and summer, seasons when two other sources gain importance, Hudson and Okhotsk, with percentages close to 10%. The almost constant contribution of Barents throughout the year is non-negligible, around 5%. The remaining sources have contributions lesser than 5%.

3.2 Moisture transport after and before Arctic sea ice change points

Figure 7~~6~~ summarises the identified change points (CPs) in means identified using the AMOC method in the four series of whole Arctic sea ice extent anomalies (DS, MS, ADS, and AMS) from 1980 to 2016.
Blue points refer to the change points in DS; for instance, the 21 July daily anomaly series (size of the series: 37 data points, representing 37 annual anomalies of the values of the sea ice extension for the 37 values on 21 July); occurred in 2004. DS only has CPs in the period from July to October~~; blue points therefore refer to the CPs in the daily series in this period.~~ . These CPs occurred mostly in 2004, the first part of September in 2006, and the last week of October in 2003. The results of both the BinSeg and PELT methods (results not shown) coincide for every day except for 17 September (2004 based on AMOC and 2006 for the other methods). The red bands in figure 7~~6~~ portray the CPs in the MS data set (July–October). *For instance, for July monthly anomaly series (size of each series: 37 data points, representing 37 annual anomalies of the values of the sea ice extension for the 37 values in the average monthly July); occurred in 2004.* These CPs occurred in 2004 for July and September, a little earlier (2001) for August, and a little later (2005) for October. Both the BinSeg and PELT methods coincide in every month except for October (2005 based on AMOC and BinSeg, and 2006 for PELT). The single green square corresponds to the CP in the 13,505-value series consisting of all days from 1 January 1980 to 31 December 2016 (ADS). The CP occurred on 22 September 2003, and was identified by the BinSeg, although not by PELT (the closest ones are 4 August 2002 and 26 January 2005). The single purple line represents the CP in the 444-value series consisting of all months from January 1980 to December 2016 (AMS). This CP occurred in October 2003. The results of both the BinSeg and PELT methods coincide for this CP, and it is the only one for both. Overall, the results in figure 7 ~~6~~ suggest that 2003 is the most appropriate year for analysis of differences in moisture transport after and before a single CP date. The average values for ADS before/after the CP were 0.27/−0.91 and for AMS were 0.41/−0.74. *The analysis of changes in MTP for the multiple sub-periods identified by BingSeg and PELT would merit analysis, but it is out of the objective of this paper.*

The ~~top panel of~~ Figure 8~~7~~ portrays the differences between mean values of MTP until 2003 and mean values after 2003 for every source region ~~MTP from the four main Arctic moisture sources~~ (figure 1c) ~~until 2003 and from the following year (2004) onward~~ for the AR, which includes continental and oceanic areas (figure 1a). The quantities in the plot result from averaging daily values of MTP. The statistical significance of the differences ~~(table in figure 7 bottom)~~ has been estimated by comparing daily values of MTP before and after the CP, and the sample size is large enough (30 x 23 years vs 30 x 13 years) to permit application of the Student *t*-test. The pattern of changes in MTP before and after the change point for the AR shows no significant changes in late winter and spring, a significant decrease in MTP in summer, and increased MTP in fall and early winter, with the exception of October. The summer decrease is statistically significant ~~(marked with blue crosses in the table of Figure 7)~~ for the contributions of Pacific and Siberian sources throughout the entire summer, for the Atlantic source in early summer, and for the North American source in late summer. The fall–early winter increase is statistically significant (red crosses) for the contributions of the North American source in three months (September, November, and December), for the Siberian and the Atlantic sources in two months (September and November; and October and December, respectively), and for the Pacific source only in one month (November). *As~~-~~, according to figure 7~~,~~ mainly for DS and MS, 2004 could also be interpreted as the main change point, we tested results of changes in MTP by changing 2003 by 2004 with almost identical results (not shown).*

These results are coherent with any of the mechanism referred in the introduction. So, ~~-~~i) a ~~-~~lower MTP in early summer (as occurred since 2003) is consistent with lower precipitation as snowfall which would result in a decreasing in the surface albedo and thus increasing melt (Cheng et al., 2008); ~~-~~ii) a lower MTP in late summer (as occurred since 2003) is consistent with less probability of occurrence of rainfall storms with possible flooding over the ice which would favor the formation of superimposed ice and consequently is consistent with increasing melt; ~~-~~iii) a higher MTP in early fall (September) (as occurred since 2003) is consistent with higher precipitation as rainfall, something generally related to sea ice melt; and ~~-~~iv) a higher MTP in late fall and early winter (as occurred since 2003) is consistent with higher precipitation as snowfall, enhancing thermal insulation and thus reducing sea ice growth in (Leppäranta, 1993). The rigorous checking of these implications merits further analysis but it is out of the scope of this manuscript, since it would imply to know details over the precipitation form (snow or rain) for the different Arctic regions with good temporal and geographical resolution, and even to analyze specific precipitation episodes to know if these are responsible for flooding or not.

However, because Arctic ice cover is extensive in geographical domain covering the subregion affected by very different atmospheric circulation patterns, this pattern of change in MTP could ~~not~~ be *non-*homogeneous for the entire AO and its subregions. Finer-scale analysis can be done by restricting the analysis to oceanic areas only (the 13 Arctic oceanic subregions and the whole Arctic Ocean defined as the sum of these regions, figure 1b). *The differences between mean values of MTP until 2003 and mean values after 2003 for every source region* ~~The pattern of changes in MTP before and after the change point~~ for the AO (figure 9~~8~~ top left) is quite similar to the AR without significant changes in late winter and spring, with decreased MTP in summer and increased MTP in fall and early winter, now also including October. Small differences are observed in the contributions of each source to the change of MTP toward the AO, with the Pacific source becoming much less important for the summer decrease and more important in the fall increased. The consistent increment is especially remarkable after the change point of MTP for all the moisture sources in September, the month when extension of Arctic sea ice is lowest.
The analysis by subregion allowed us to identify which subregions contributed most to change in MTP in the AO. As in the case of the AR, the statistical significance of the differences (Table 1) has been estimated by comparing daily values of moisture transport before and after the CP. The diminished contribution of the Atlantic source to the AO in June and July is mainly attributed to the reduction of transport to Greenland; this decrease is not observed in August because of the compensation of

the decrease to Greenland by the increase to Baffin. A moderate increase in October and a small decrease in December were also attributed to changes occurring in Greenland. The slightly decreased contribution of the Pacific to the AO in summer was caused by the compensation of the decreased contribution of Bering (strong decrease) with a strong increase in the contribution of Okhotsk, with some influence of other regions such as Beaufort (decrease) and East Siberian (increase). There is greater concordance in fall and winter, with generally slight increments, which resulted in a small increase in the contribution of the Pacific to the AO. The greatly decreased contribution of the Siberian source to the AO in summer is attributed mainly to the strong decrease of MTP to the Central Arctic and Laptev, and the generally slight increment of the contribution of the Siberian source for these regions in fall and early winter (with the exception of October); these changes result in similar behaviour for the AO. The different changes of the contribution of the North American source to the AO in July (increase) and August (decrease) reproduce the common changes observed in the contributions to Baffin and Hudson. The slight increase in contribution to the AO in September and October again is attributed to compensation of the increased to Hudson with a strong decrease in September to the Canadian Islands and slight decreased in October to Baffin and Barents; the increased contribution of this source to the AO in December is the result of increased contribution to the Central Arctic and Barents, partially compensated by slight decrease to Hudson and Baffin.

3.3 Checking the Lagrangian results by analysing changes in vertical integrated moisture fluxes and atmospheric circulation patterns after and before Arctic sea ice change points

It is useful to check the results derived from the Lagrangian approach to estimate MTP with other Eulerian approach such as the computation of vertical integrated moisture flux (VIMF). Supplemental figure S1 shows the climatological VIMF by month in the period from June to December (left panel) and the difference between the periods after the CP and before the CP for the zonal component (central panel) and the meridional component of VIMF (right panel). This methodology cannot estimate specific changes in the MTP from each source to each sink as the more sophisticated Lagrangian approach does, but it is able to show whether patterns are compatible with the identified changes. For instance, in June (figure 109), the Atlantic source provides moisture for precipitation in the subregion of the Arctic Ocean named Greenland in our study, as revealed by the flux vectors in the top panel. However, the track of moisture from the source to the sink is clearly hinderdifficulted for the period after the CP relative to the period before the CP, as revealed by negative values of the zonal component (blue colours in middle figure 109) in the band 45–60ºN latitude (less moisture transported from west to east, the direction of the source–receptor path) and negative values of meridional winds (blue colours in bottom figure 109) in the band 20–60ºW longitude (less moisture transported from south to north, the direction of the source–receptor path). We have done this analysis for each month, and for source and sink areas, and the patterns can explain all the significant results found in the Lagrangian analysis with almost absolute agreement (figure S1).

An additional demonstration of the robustness of these results can be derived by analysing the changes in atmospheric circulation responsible for changes in moisture transport. Changes in MTP may be related either to alterations in moisture sources caused by changes in circulation patterns, or to changes in the intensity of the moisture sources because of enhanced evaporation, or to a combination of these two mechanisms. At a daily scale, changes in intensity are negligible, but changes in circulation may be significant. Thus, to analyse whether there are important differences in MTP from sources to sinks associated with different circulation patterns, and how such differences could affect MTP in the AR, we grouped individual days into four circulation types using the methodology developed by *Fetttweis et al. (2011*) and explained in the Data and Methods sections. We have separated the analysis into four sectors centred on the four sources of moisture to the AR to filter out annular effects, as we are interested in regional influences.

Supplemental figure S2 shows the summer and fall types of circulation centred on the four source areas (Atlantic, Pacific, Siberia, and North America), with each individual map representing the anomalies of geopotential height at 850 hPa (Z850) for the four different classes found (from CTC1 to CTC4, with the percentage of days grouped). The average MTPs for each class before and after the CP are summarised in Table S2~~1~~, whereas changes in the frequency of each class before and after the CP are shown in Table S3~~2~~ *(statistical significant changes were calculated using a z-test to compare two sample proportions -Sprinthall, 2011-)*. One of these sectors and one season can serve us as an example of these results: the Atlantic during summer (figure 11~~0~~). The anomalies of geopotential height at 850 hPa (Z850) for the four different classes found (figure 11~~0~~ top) show patterns that resemble the known teleconnection patterns in the region (*Barnston and Livezey, 1987* and http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml). ~~.~~ *The term teleconnection pattern alludes to a recurring and persistent large-scale pattern of geopotential height and circulation anomalies over large geographical areas and with strong influence on meteorological varaibles including rainfall.*~~.~~ Thus, CTC1 has a zonal dipolar structure that resembles the positive phase of the East Atlantic pattern *(a north-south dipole of anomaly centers-positive in the southern one-spanning the North Atlantic)*, closely related to enhanced precipitation on Greenland; CTC2 is slightly similar to the negative phase of the East Atlantic/western Russia, *(negative- height anomalies located over Europe and northern China, and positive height anomalies located over the central North Atlantic and north of the Caspian Sea),* associated with enhanced precipitation on Barents; CTC3 resembles the negative phase of the North Atlantic Oscillation *(an above-normal heights across the high latitudes of the North Atlantic and below-normal heights over the central North Atlantic and western Europe),*~~,~~ related to diminished precipitation on Greenland and enhanced precipitation on Barents, and CTC4 is similar to the positive phase of the Scandinavian pattern *(positive height anomalies over Scandinavia and western Russia)* associated with diminished precipitation on Barents. The middle panel of figure 11~~0~~ shows the average MTP for each class in the summer months from the Atlantic source to the AO (dark blue line) and the two dominant subregions, Barents and Greenland (light blue and orange lines, respectively). CTC1 is the circulation type responsible for the highest MTP in the three summer months, and CTC3 and CTC4 are responsible for the lowest MTP, depending on the month. The change of frequency of these classes representing circulation types before and after the CP (Figure 11~~0~~ bottom) shows a decrease of the days belonging to CTC1, with the highest MTP from 40 to 25.4 days, and an increase of days belonging to CTC3 (from 9.58 to 15.15) and CTC4 (from 4.62 to 5.85), the two classes with the lowest MTP. These results are absolutely consistent with our Lagrangian results of changes in MTP.

A similar analysis to the one for this sector, moisture source region, and season can be done for all the significant results found in the Lagrangian analysis with very good agreement.

4 Concluding remarks~~sions~~

This study shows that a drastic Arctic sea ice decline occurred in 2003 and that this decline was accompanied by a change in the ~~e perfect pattern of MTP for Arctic sea ice melting consists of a general decrease in~~ moisture transport *from the main Arctic moisture sources, which then results in precipitation over the Arctic (MTP). The pattern of change consists of a general decrease after vs before 2003 in the moisture transport* in summer and an increase in fall and early winter, with different contributions depending on the moisture source and ocean subregion~~.~~. This pattern *of change in the moisture transport* is not only statistically significant but also consistent with Eulerian flux diagnosis, changes in circulation type frequency, and *any of the* known mechanisms affecting snowfall or rainfall on ice in the Arctic. The consistent increment after the CP of MTP for all moisture sources in September, the month when extension of Arctic sea ice is lowest, is particularly remarkable. ~~Thus, it is clear beyond doubt that an increment in moisture transport during this month favours ice melting, regardless of the source of moisture.~~

These results suggest that ice-melting at a multiyear scale is favoured by a decrease in moisture transport in summer and an increase in fall and early winter.

~~These results are notable because of their consistence with mechanisms related to precipitation and ice cover. It is important to note that we have estimated MTP such that so any relationship of our results with sea ice must be interpreted in terms of changes in precipitation caused by changes in moisture transport and the effect of precipitation on ice cover. Snowfall is the dominant (almost unique) form of precipitation during most of the year, with the exception of late summer. As noted in the introduction, when precipitation is produced in the form of snowfall on sea ice, it enhances thermal insulation, and reduces sea ice growth in winter *(Leppäranta, 1993)*, but increases the surface albedo, and thus reduces melt in spring and summer *(Cheng et al., 2008)*. These phenomena justify the opposite change in moisture transport for fall and winter versus spring. However, in late summer and early fall, precipitation as rain gains importance, and rainfall is generally related to sea ice melting.~~

The results of this paper also reveal another important conclusion: the assumed and partially documented enhanced poleward moisture transport from lower latitudes as a consequence of increased moisture from climate change *(Zhang et al., 2013)* has not been simple or constant in its links with enhanced Arctic precipitation throughout the year in the present climate. Major moisture sources for the Arctic did not provide more moisture for precipitation to the Arctic in summer after 2003, the change point (CP) for Arctic sea ice, than before, although they did provide more moisture in fall and early winter. Because the enhanced Arctic precipitation projected by most models for the end of the century *(Bintaja and Selten, 2014)* is partly attributed to enhanced poleward moisture transport from latitudes lower than 70ºN *(Bintanja and Andry, 2017),* where the major sources studied herein are located, our results raise questions of whether this change has occurred so simply in the current climate, and these questions merit further study.

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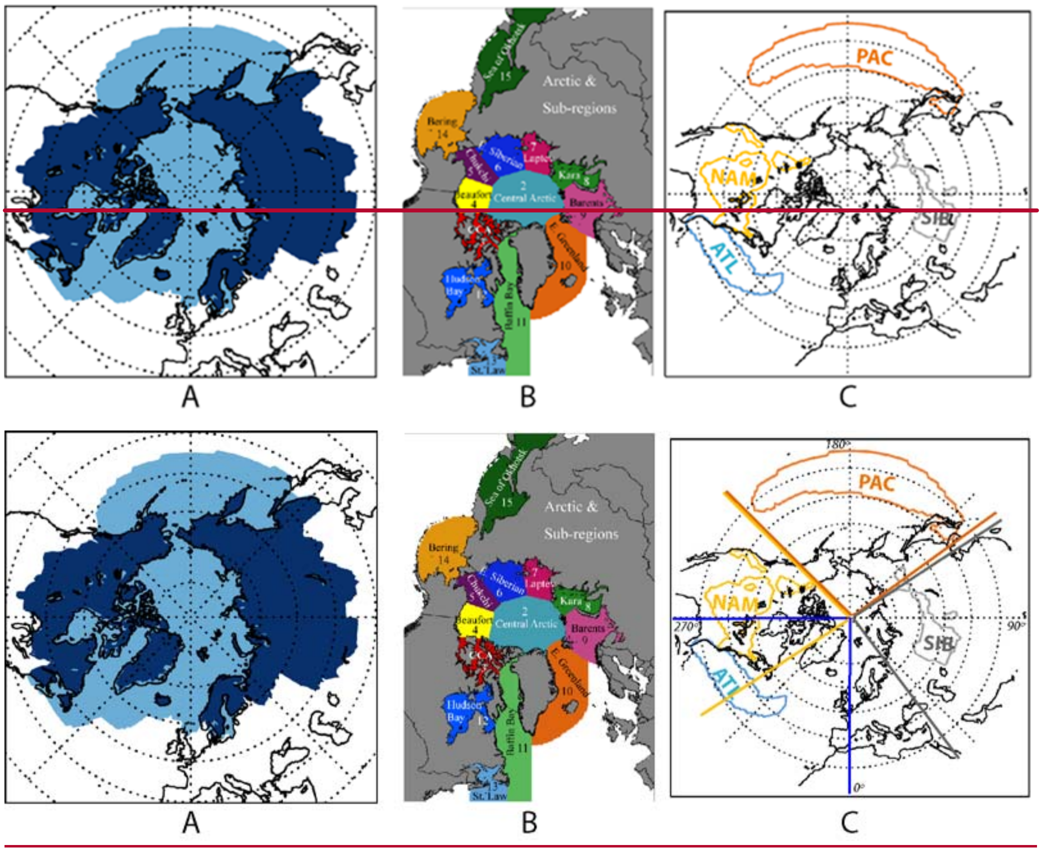


Figure 1. A) The Arctic region (AR) included in the present work defined following the definition of Roberts et al. (2010). B) The Arctic Ocean (OA) and its 13 subregions as described by Boisvert et al. (2015). C) Major moisture sources for the Arctic as detected by Vazquez et al. (2016). The coloured longitudinal~~atitudinal~~ lines mark the areas used for the types of circulation analysis in figure 11.

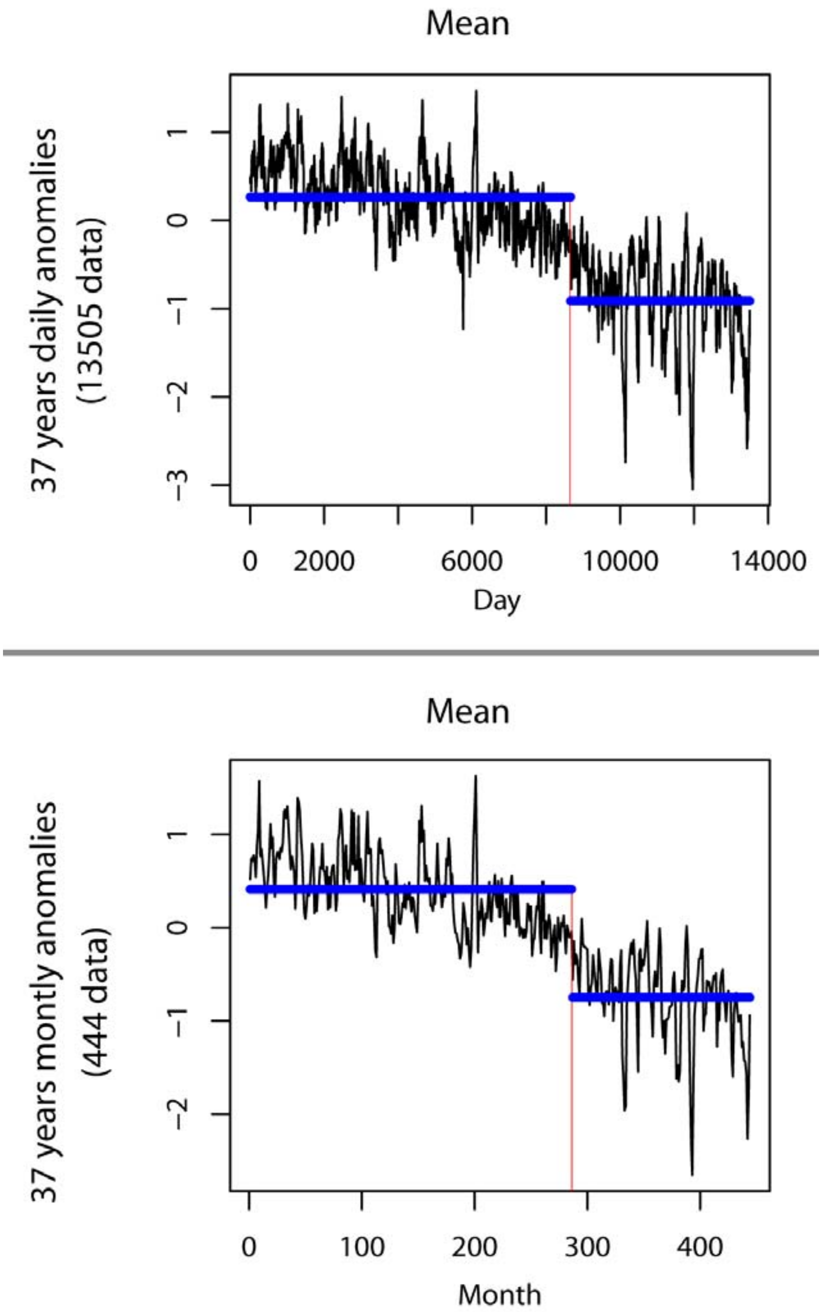


Figure 2. Example of change point detection in mean for two series and one method, AMOC. Top plot represents the change points in ADS series. The two horizontal lines represent the mean of the values before and after the change point identified by the AMOC method (8660th day - 22th September 2003). Those means are 0.27 and -0.91, respectively. Bottom plot represents the change points in AMS series. The two horizontal lines represent the mean of the values before and after the change point identified by the AMOC method (286th month - October 2003). Those means are 0.41 and -0.74, respectively.

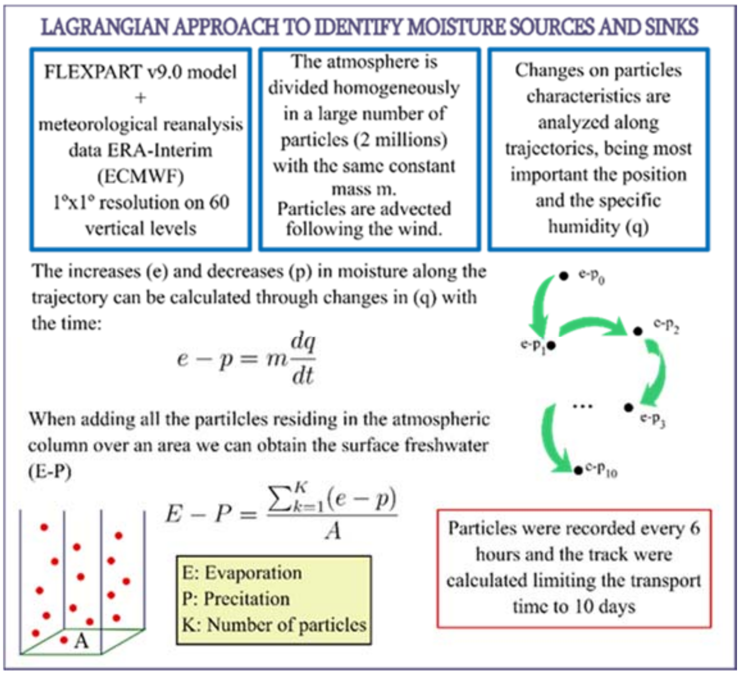


Figure 32. A scheme of the Lagrangian approach used to estimate moisture transport.

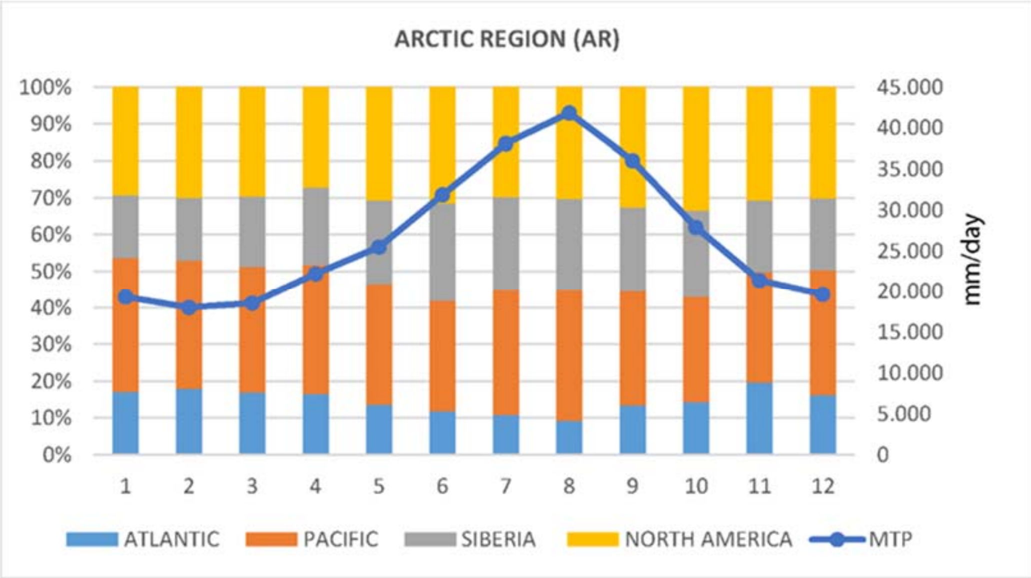


Figure 43. Seasonal cycle of moisture transport for precipitation (MTP) to the Arctic region (AR) from the four major sources (Atlantic, Pacific, Siberia, and North America). Values at the right represent absolute values of transport, and those at the left indicate the relative contribution of each source by percentage.

Figure 45. Same as in figure 3, but for each of the 13 subregions of the Arctic Ocean (AO).

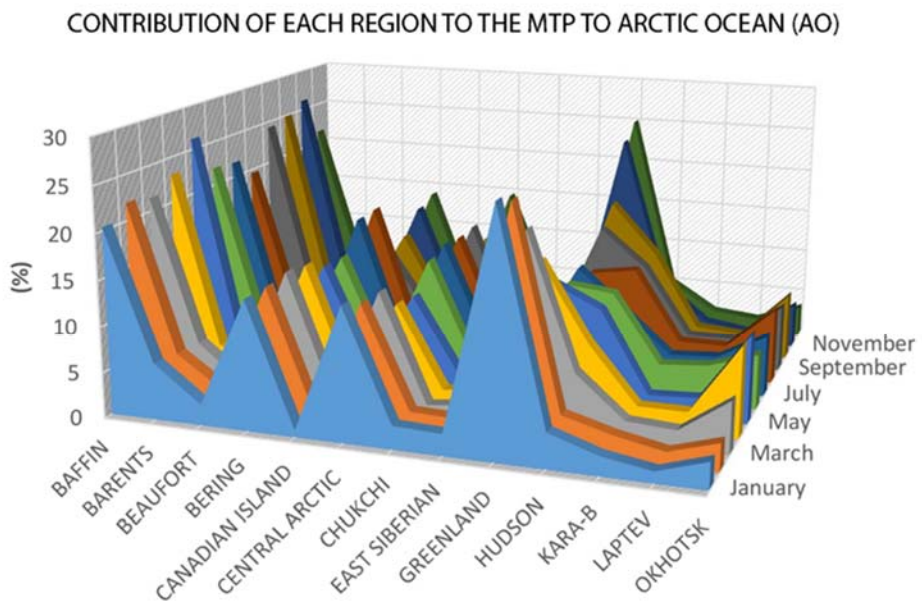


Figure 65. Percentage of moisture transport for precipitation to the whole Arctic Ocean by subregion and month.

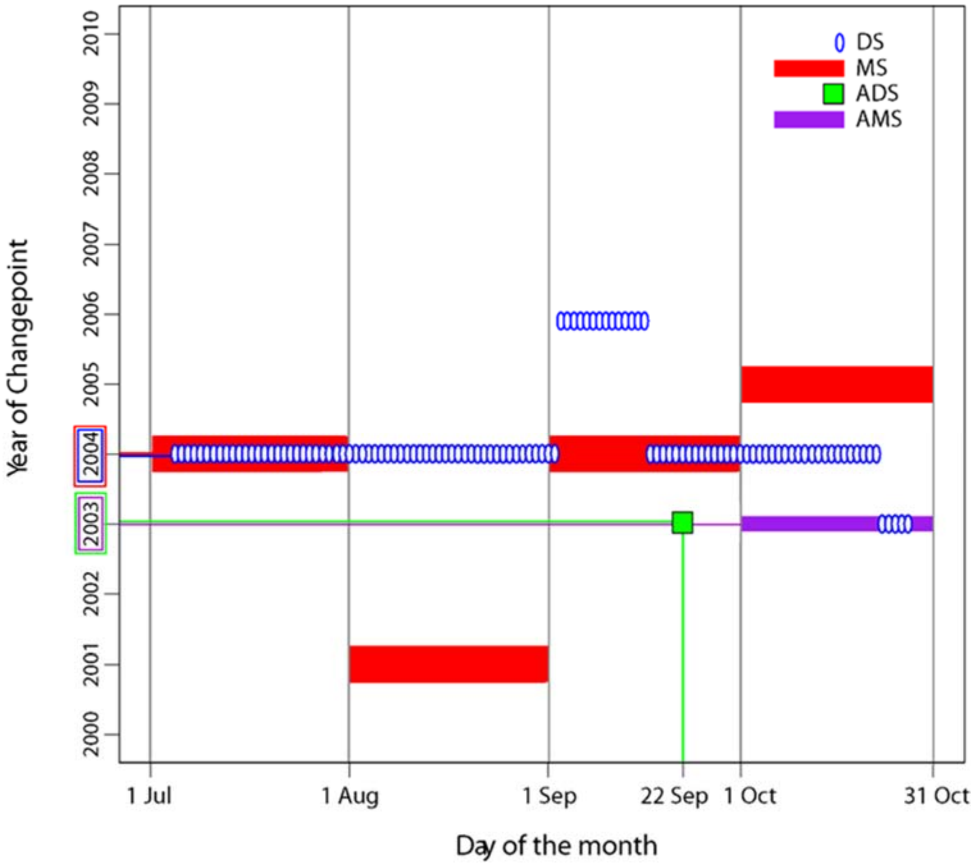
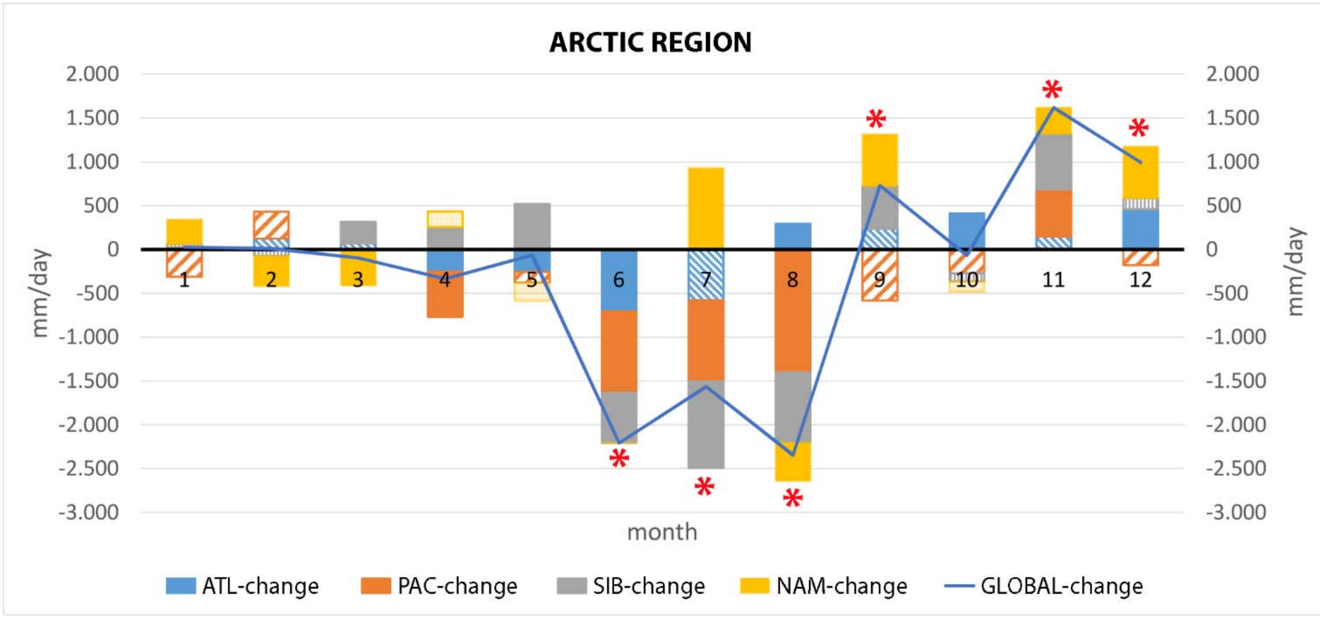
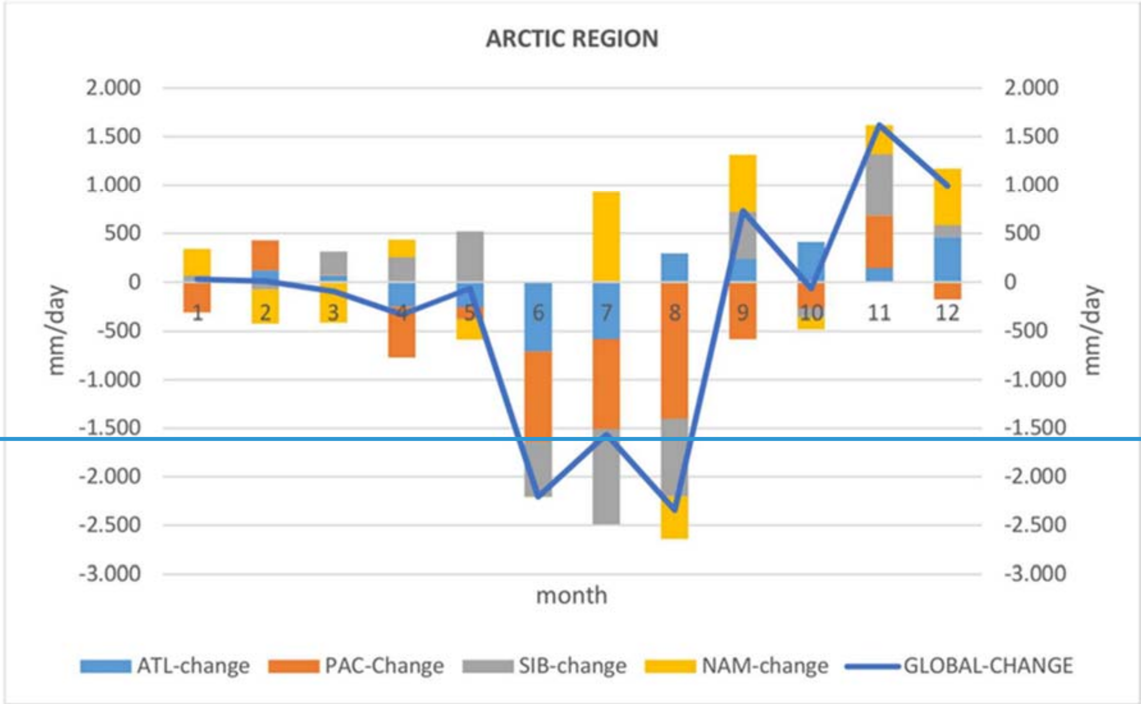


Figure 76. Summary of the identified change points (CPs) in means identified using the AMOC method with the four series of ice extent anomalies for the whole Arctic (DS, MS, ADS, and AMS) from 1980 to 2016. The blue points refer to the change points in DS; the red lines portray change points in the MS (July–October). The green square corresponds to the change point in the ADS, and the purple line represents the change point in the AMS.


ARCTIC REGION
2.000
1.500
1.000
500
0
-500
-1.000
-1.500
-2.000
-2.500
-3.000
mm/day
1
2
3
4
5
6
7
8
9
10
11
12
month
ATL-change
PAC-change
SIB-change
NAM-change
GLOBAL-change



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ATLANTIC SOURCE				X	X	X		X		X		X
PACIFIC SOURCE				X		X	X	X			X	
SIBERIAN SOURCE			X	X	X	X	X	X	X		X	
NORTH AMERICA SOURCE	X	X	X				X	X	X		X	X

Figure 87. (top) Differences between mean values of Moisture transport for precipitation (MTP) until 2003 and mean values after 2003 for every source region. Filled bars show those differences that are statistically significant at the 95% confidence level for decreases after the CP. Statistical significance of the differences in total MTP (sum of the four sources) is displayed with a red asterisk. Moisture transport for precipitation (MTP) from the four main Arctic moisture sources until 2003 (change point, CP) and from the following year onward for the Arctic region (AR); (bottom) summary of the statistical significance of the differences estimated by comparing daily values of moisture transport before and after the CP, based on the Student *t* test. Red crosses indicate statistical significance at the 95% confidence level for increases after the CP; blue crosses indicate statistical significance at the 95% confidence level for decreases after the CP

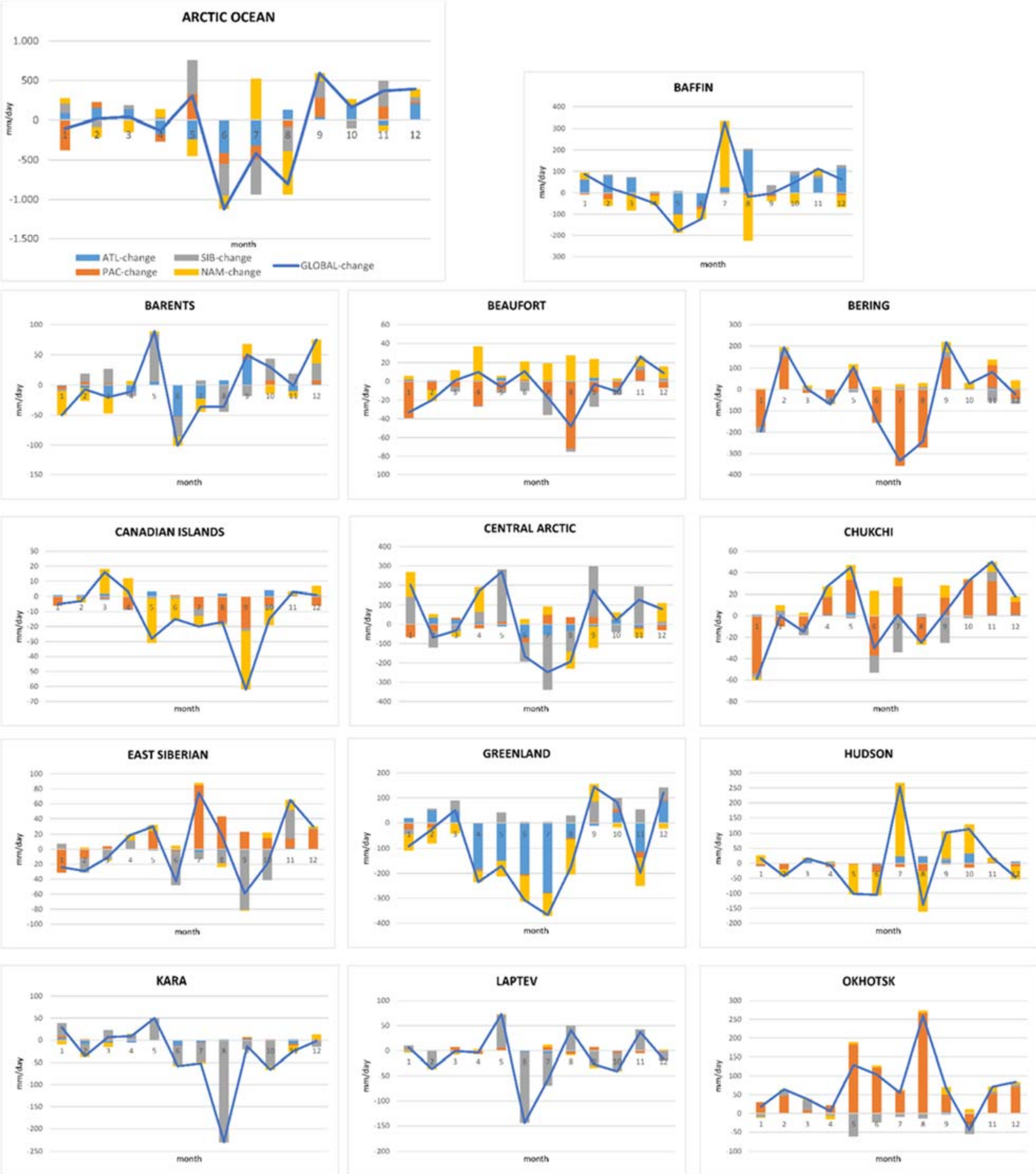
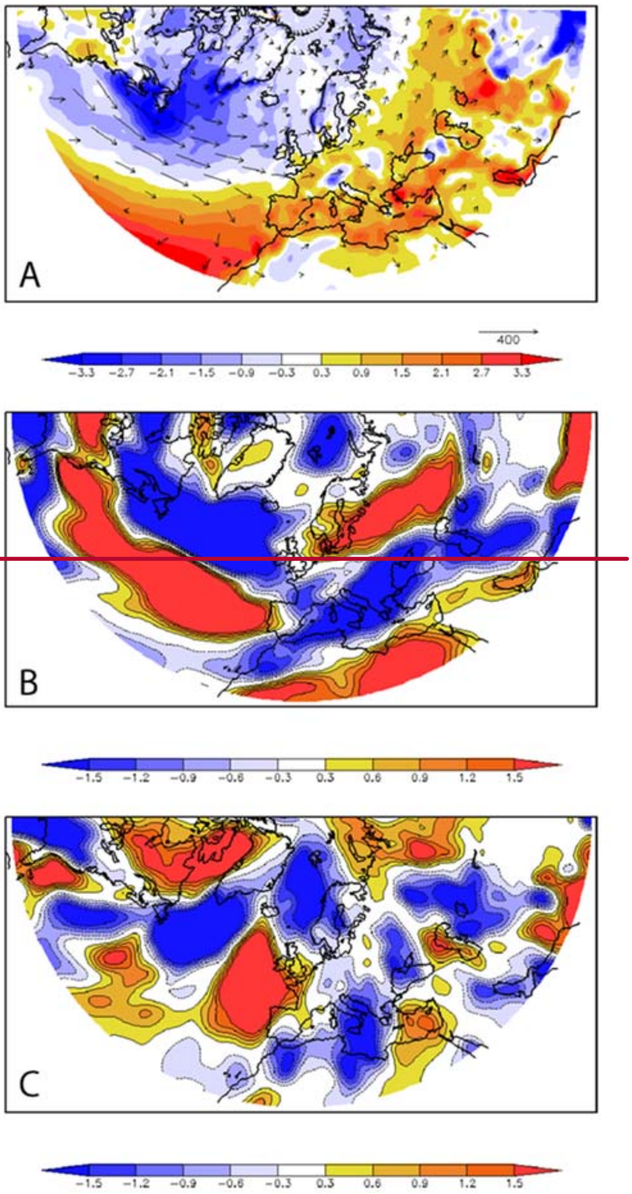

ARCTIC OCEAN
ATL-change
SIB-change
PAC-change
NAM-change
GLOBAL-change
mm/day
month
BAFFIN
BARENTS
BEAUFORT
BERING
CANADIAN ISLANDS
CENTRAL ARCTIC
CHUKCHI
EAST SIBERIAN
GREENLAND
HUDSON
KARA
LAPTEV
OKHOTSK

Figure 98. -Differences between mean values of Moisture transport for precipitation (MTP) until 2003 and mean values after 2003 for every source region As figure 7 for the Arctic Ocean (AO) and its 13 subregions. Statistical significance of the differences is displayed in Table I.



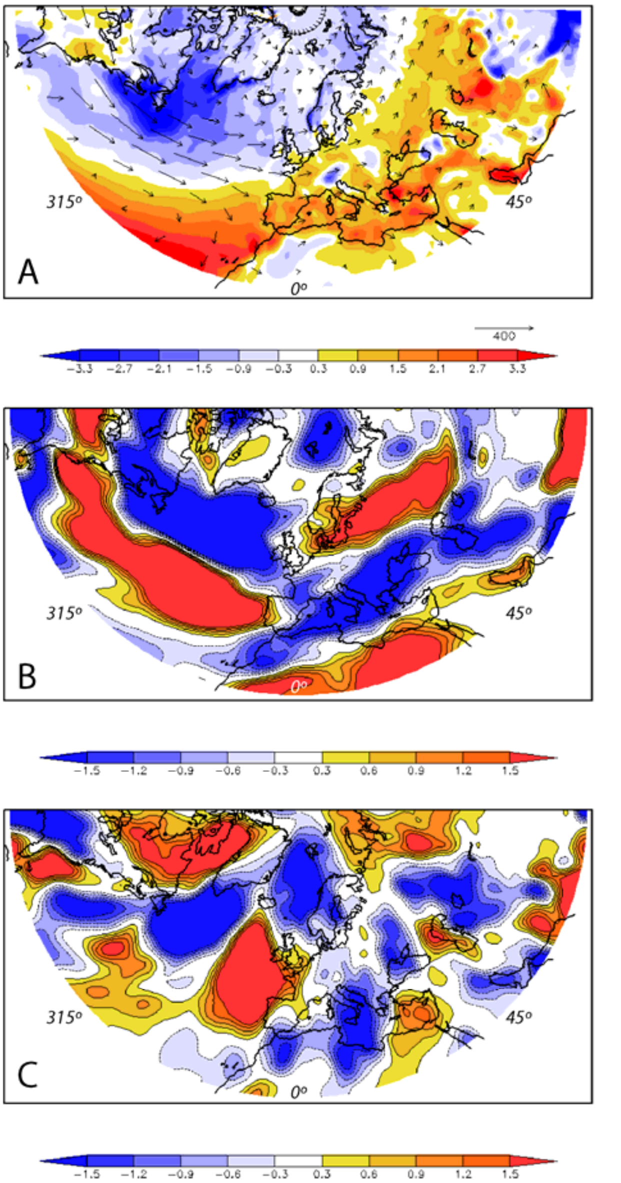
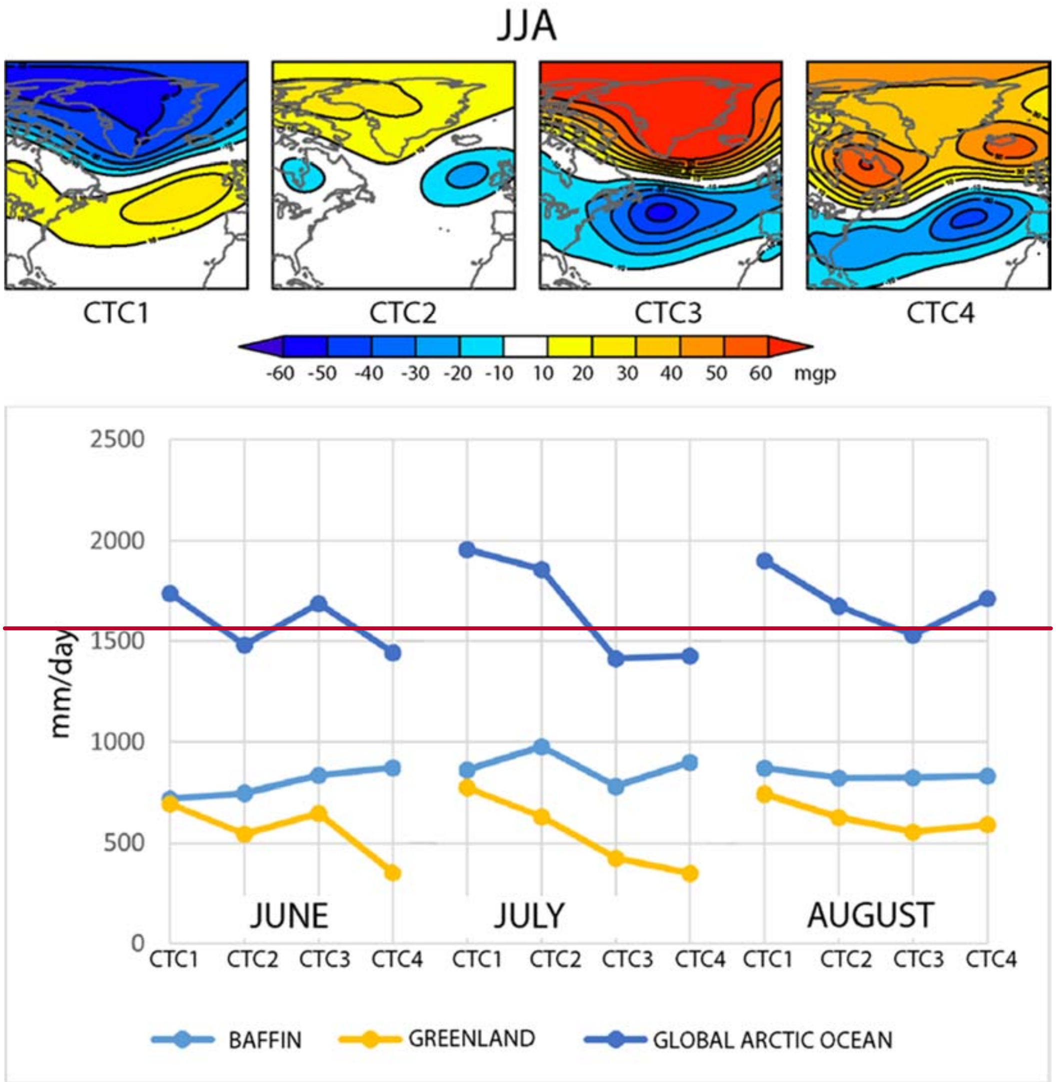
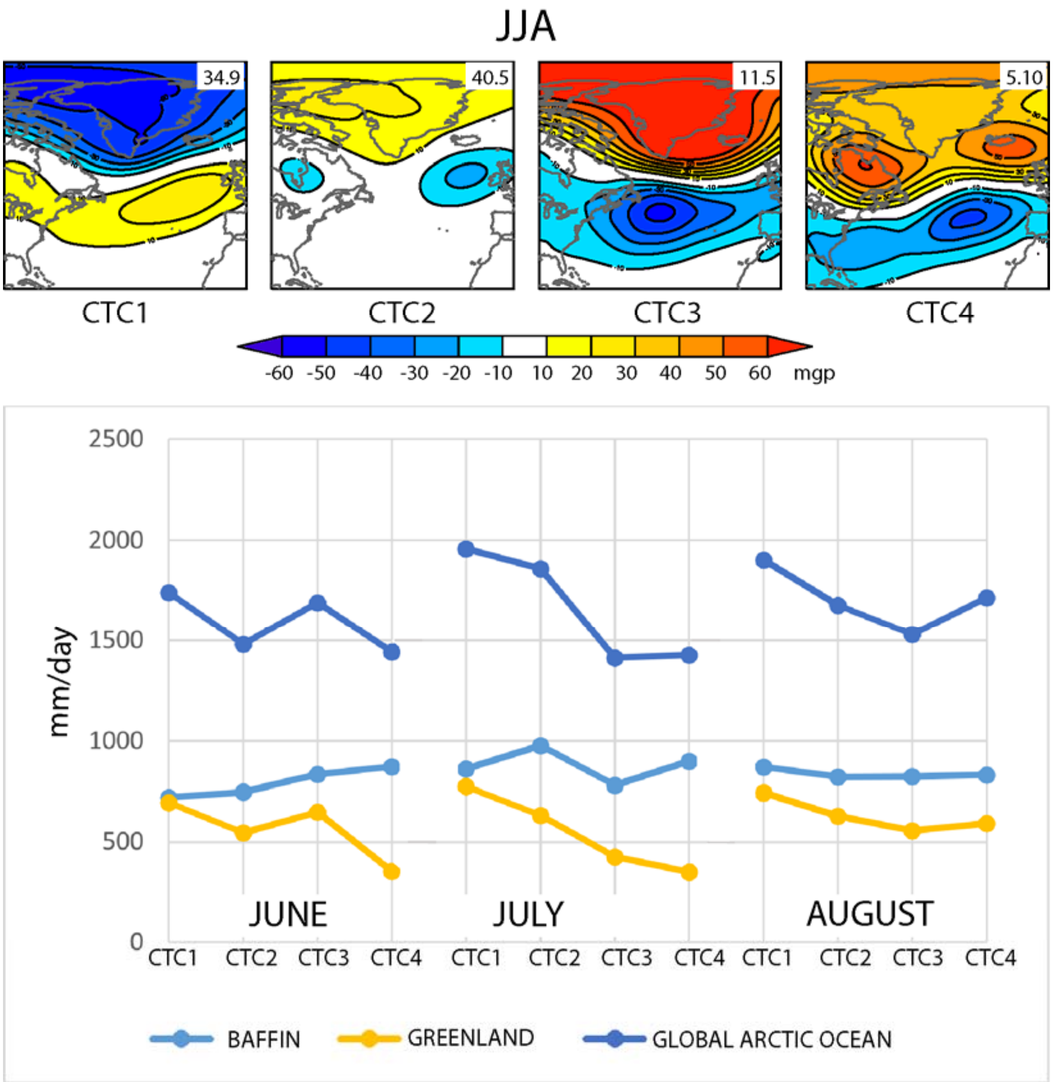


Figure 10 ~~9~~. A) The climatological vertical integrated moisture flux (VIMF) (vector, kg/m/s) and its divergence (shaded, mm/yr) in June for the European sector, B) the difference between the periods after vs before the CP for the zonal component of VIMF, and C) as for b but for the meridional component of VIMF.



	CTC1	CTC2	CTC3	CTC4
before	40	37,79	9,58	4,62
after	25,54	45,46	15,15	5,85



	CTC1	CTC2	CTC3	CTC4
before	40	37,79	9,58	4,62
after	25,54	45,46	15,15	5,85

Figure 110. (top) Anomalies of geopotential height at 850 hPa (Z850) for the four types of circulation centred in the Atlantic sector in summer (classes CTC1 to CTC4), and the percentages of days grouped in each class. (middle) Average moisture transport for precipitation (MTP) for each class and summer months from the Atlantic source to the Arctic Ocean (AO), and the two dominant subregions, Barents and Greenland. (bottom) Change of frequency of these circulation types (classes) before and after the change point.

ATLANTIC SOURCE	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baffin			X		X			X				X
Barents			X			X	X		X			
Beaufort	X		X		X				X	X	X	X
Bering		X	X		X		X		X		X	X
Canadian	X	X	X		X			X		X		X
Central Arctic		X	X			X	X	X		X		
Chukchi	X				X			X	X		X	X
East Siberian			X		X	X	X	X			X	
Greenland				X	X	X	X				X	X
Hudson			X				X	X		X		
Kara	X	X	X	X		X					X	
Laptev	X	X				X	X	X		X		X
Okhotsk		X				X		X	X		X	X
PACIFIC SOURCE	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baffin		X		X		X		X				
Barents	X								X	X		X
Beaufort	X			X				X			X	
Bering	X	X				X	X	X	X		X	
Canadian	X			X			X	X	X	X		X
Central Arctic	X	X										
Chukchi	X				X	X				X	X	
East Siberian	X				X		X	X	X	X		X
Greenland	X	X		X		X		X		X		X
Hudson		X		X		X	X	X		X		X
Kara	X	X	X						X	X	X	
Laptev			X	X	X			X	X	X	X	
Okhotsk	X	X			X		X	X			X	X
SIBERIAN SOURCE	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baffin		X	X		X			X	X	X	X	X
Barents			X		X			X		X		X
Beaufort			X		X	X	X		X	X	X	
Bering	X	X		X	X				X		X	X
Canadian			X	X			X		X	X	X	
Central Arctic	X	X					X		X		X	
Chukchi			X			X	X		X		X	
East Siberian		X	X			X			X	X	X	
Greenland	X		X		X			X	X	X	X	X
Hudson	X	X	X					X	X	X	X	X
Kara	X	X	X		X			X		X		X
Laptev	X	X			X	X	X			X	X	X
Okhotsk	X	X	X		X	X				X		
NORTH AMERICA SOURCE	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baffin			X		X		X	X				X
Barents	X		X			X	X		X			X
Beaufort		X	X	X			X	X			X	X
Bering		X			X	X	X		X	X	X	X
Canadian			X	X	X	X			X			
Central Arctic	X			X				X	X			X
Chukchi				X	X	X	X		X		X	
East Siberian				X	X					X	X	
Greenland					X	X	X	X			X	
Hudson		X			X		X	X	X	X		X
Kara	X	X	X			X				X	X	X
Laptev	X		X				X		X			X
Okhotsk		X	X		X	X			X	X	X	X

Table I. Summary of the statistical significance of the MTP differences estimated by comparing daily values of moisture transport before and after the CP, based on the Student t-test. Red crosses indicate statistical significance at the 95% confidence level for increases after the CP; blue crosses indicate statistical significance at the 95% confidence level for decreases after the CP.

~~The perfect pattern of moisture transport for precipitation for Arctic sea ice melting~~

The pattern of long-term changes in the moisture transport for precipitation with Arctic sea ice melting

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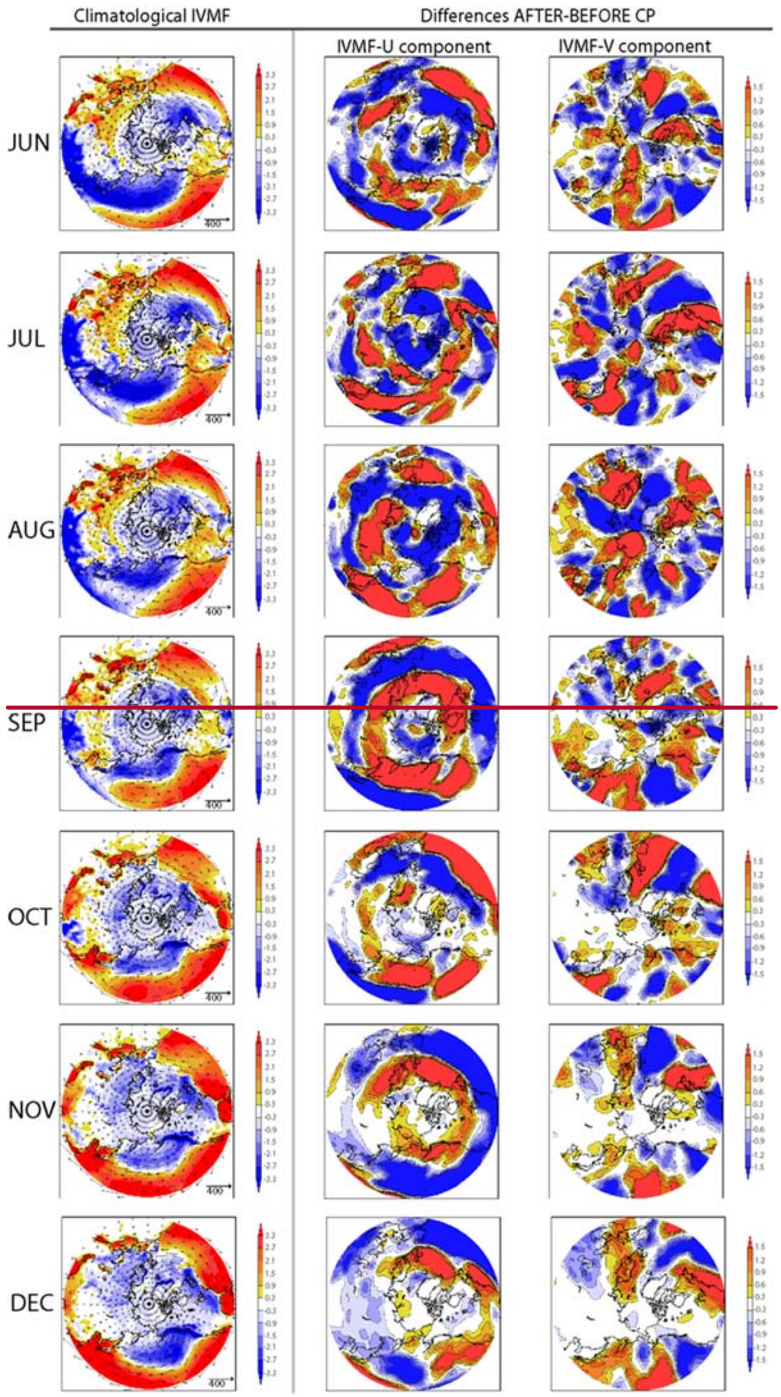
(Supplementary material)


Climatological IVMF
Differences AFTER-BEFORE CP
IVMF-U component
IVMF-V component
JUN
JUL
AUG
SEP
OCT
NOV
DEC

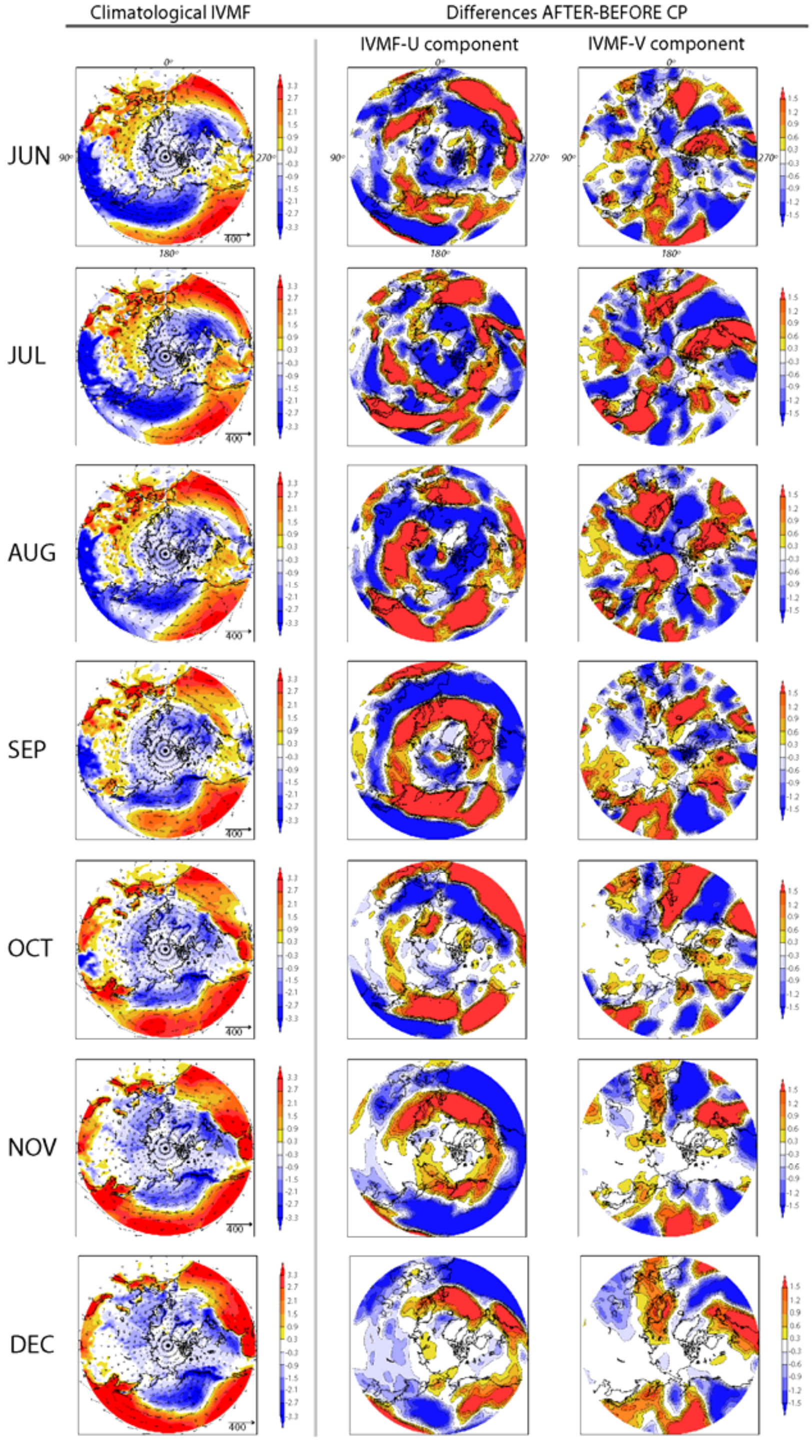


Figure S1. Left) The climatological vertical integrated moisture flux (VIMF) (vector, kg/m/s) and its divergence (shaded, mm/yr) by month from June to December, middle) the difference between the periods after vs before the CP for the zonal component of VIMF, and right) as in the middle panel but for the meridional component of VIMF.

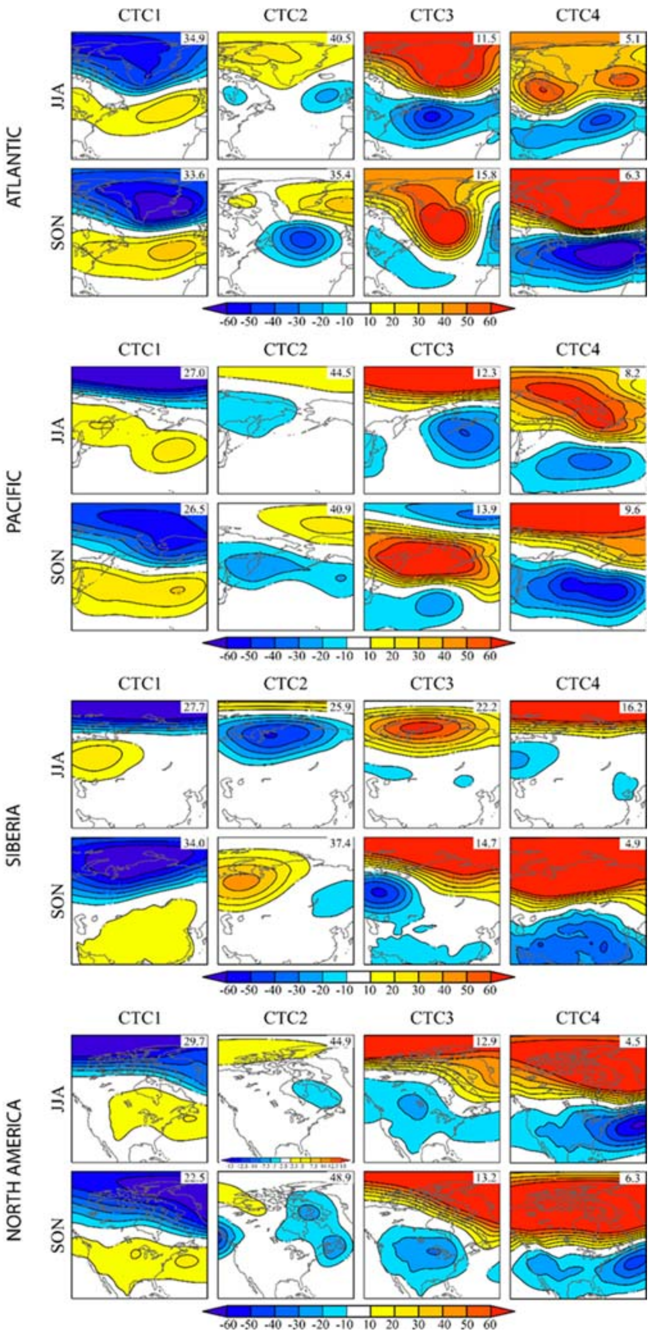


Figure S2. Anomalies of geopotential height at 850 hPa (Z850) for the four classes representing types of circulation (classes CTC1 to CTC4), and sector centred on the major source together with the percentage of days grouped in each class

	Atlantic Ocean	Pacific Ocean	North America	Siberia
BAFFIN	40613	32785	141067	6184
BARENTS	9256	3902	15336	17235
BEAUFORT	534	11023	9249	9831
BERING	1829	60348	6659	41223
CANADIAN ISLAND	421	4662	10426	2829
CENTRAL ARCTIC	4716	11059	21129	22220
CHUKCHI	572	10358	3415	12078
EAST SIBERIAN	1102	9275	21880	3421
GREENLAND	36900	17773	69134	7211
HUDSON	2961	18675	59233	4303
KARA-B	2733	1698	4706	16358
LAPTEV	1300	2938	3510	17030
OKHOTSK	4157	33112	4794	79120

Table S1. Average ***number of particles by source that reached daily the target regions***

Month	Mode	Atlantic Before/After	Mode	Pacific Before/After	Mode	Siberian Before/After	Mode	North America Before/After
June	CTC1	3903/3552	CTC1	8961/8436	CTC1	8034/7237	CTC1	10450/9289
	CTC2	3626/2907	CTC2	10028/9016	CTC2	8371/8530	CTC2	10140/9962
	CTC3	4196/2919	CTC3	8895/8463	CTC3	8348/7431	CTC3	10016/10473
	CTC4	3200/3276	CTC4	9918/7881	CTC4	9422/8055	CTC4	8918/10746
July	CTC1	4184/3820	CTC1	1354/13634	CTC1	9122/8767	CTC1	11475/12694
	CTC2	4088/3550	CTC2	12983/11148	CTC2	10662/8853	CTC2	11278/12008
	CTC3	3980/2669	CTC3	12666/12940	CTC3	9381/8200	CTC3	11563/12502
	CTC4	3427/3424	CTC4	12996/9504	CTC4	10224/9430	CTC4	9363/11271
August	CTC1	4018/4659	CTC1	15962/14527	CTC1	9771/8707	CTC1	13017/13145
	CTC2	3763/4021	CTC2	14467/13273	CTC2	11564/10554	CTC2	12258/12211
	CTC3	3559/3530	CTC3	14714/11736	CTC3	9884/9195	CTC3	12852/10896
	CTC4	3731/4383	CTC4	13338/13179	CTC4	10660/10466	CTC4	11864/11193

Month	Mode	Atlantic Before/After	Mode	Pacific Before/After	Mode	Siberian Before/After	Mode	North America Before/After
September	CTC1	4827/4955	CTC1	11648/10974	CTC1	8091/9588	CTC1	11863/13180
	CTC2	4877/5255	CTC2	10401/10737	CTC2	8324/8306	CTC2	11865/12180
	CTC3	4865/5145	CTC3	12545/10308	CTC3	8479/8762	CTC3	11302/11433
	CTC4	4316/4655	CTC4	9760/8969	CTC4	7848/9054	CTC4	11125/11095
October	CTC1	3854/4270	CTC1	8009/8121	CTC1	6703/6429	CTC1	9474/8931
	CTC2	4097/4545	CTC2	7792/7600	CTC2	6321/6524	CTC2	9343/9328
	CTC3	4132/4710	CTC3	8904/7721	CTC3	6952/6728	CTC3	9541/9394
	CTC4	3097/4076	CTC4	7712/7157	CTC4	5785/5520	CTC4	8386/8715
November	CTC1	4182/4447	CTC1	6418/6869	CTC1	4472/5181	CTC1	6484/7059
	CTC2	4080/4467	CTC2	6275/6214	CTC2	3859/4578	CTC2	6684/6796
	CTC3	5052/4025	CTC3	7551/8996	CTC3	4319/4361	CTC3	6336/6618
	CTC4	3600/4493	CTC4	6408/7374	CTC4	3008/2990	CTC4	6105/6612

Table S2. Average moisture transport for precipitation (MTP) for each class representing circulation types before and after the 2003 change point

	CTC	Atlantic	Mode	Pacific	Mode	Siberian	Mode	North America
June	CTC1	9.30/5.31*	CTC1	6.5/6.69	CTC1	9.38/8	CTC1	7.75/4.92*
	CTC2	12.67/13.61	CTC2	16.29/14.61	CTC2	10.41/9.85	CTC2	14.71/13.54
	CTC3	5.38/7.38*	CTC3	4.54/6.46*	CTC3	5.62/6.77	CTC3	4.5/8.46*
	CTC4	2.67/3.69	CTC4	2.67/2.23	CTC4	4.58/5.38	CTC4	3.04/3.08
July	CTC1	14.08/9.85*	CTC1	11.17/8.62*	CTC1	9.04/6.23*	CTC1	10.63/7.85*
	CTC2	14.17/16.23*	CTC2	13.13/14.62	CTC2	6.63/7.23	CTC2	16.83/16.31
	CTC3	1.75/3.54*	CTC3	3.79/5.54*	CTC3	9.54/10.38	CTC3	3/6.23*
	CTC4	1/1.38	CTC4	2.92/2.23	CTC4	5.79/7.15	CTC4	0.54/0.62
August	CTC1	16.63/10.38*	CTC1	10.92/8.77*	CTC1	9.83/12.54*	CTC1	15.58/9.08*
	CTC2	11/15.62*	CTC2	13.92/17.46*	CTC2	8.17/10*	CTC2	13/15.69*
	CTC3	2.45/4.24*	CTC3	2.63/2.77	CTC3	7.67/4*	CTC3	1.83/4.92*
	CTC4	0.96/0.77	CTC4	3.54/2*	CTC4	5.33/4.46	CTC4	0.58/1.31*
Summer	CTC1	40/25.50*	CTC1	28.58/24.08*	CTC1	28.25/26.77	CTC1	33.96/21.84*
	CTC2	37.79/45.46*	CTC2	43.33/46.69*	CTC2	25.21/27.08	CTC2	44.54/45.53
	CTC3	9.58/15.15*	CTC3	10.96/14.77*	CTC3	22.83/21.15	CTC3	9.33/19.61*
	CTC4	4.62/5.85	CTC4	9.12/6.46*	CTC4	15.71/17	CTC4	4.17/5
September	CTC1	11.13/16.08*	CTC1	7.83/10.46*	CTC1	6.29/5.38	CTC1	6.38/8.31*
	CTC2	12.67/9.08*	CTC2	12.17/12.54	CTC2	12.5/13.54	CTC2	16.67/16.54
	CTC3	5.08/4.46	CTC3	7.75/5.46*	CTC3	7.21/7.84	CTC3	4.92/3.61
	CTC4	1.12/0.38*	CTC4	2.25/1.54	CTC4	4.00/3.23	CTC4	2.04/1.54
October	CTC1	11.17/8.46*	CTC1	10.33/11.08	CTC1	15.38/14.23	CTC1	8.25/5.31*
	CTC2	12.00/12.84	CTC2	13.88/13.15	CTC2	11.25/12.15	CTC2	15.75/15.23
	CTC3	5.50/5.00	CTC3	4.17/2.46*	CTC3	3.67/3.85	CTC3	4.46/7.23*
	CTC4	2.33/4.69*	CTC4	2.62/4.31*	CTC4	0.71/0.77	CTC4	2.54/3.23
November	CTC1	10.21/11.08	CTC1	6.71/8.08	CTC1	12.33/14.31*	CTC1	7.92/8.92
	CTC2	12.37/10.38*	CTC2	15.71/13.69*	CTC2	13.46/12.08	CTC2	16.67/16.84
	CTC3	4.67/7.23*	CTC3	2.59/5.00*	CTC3	4.00/2.77*	CTC3	3.08/3.77
	CTC4	2.75/1.31*	CTC4	5.00/3.23*	CTC4	0.21/0.85*	CTC4	2.33/0.46*
Autumn	CTC1	32.51/35.62*	CTC1	24.87/29.62*	CTC1	34.00/33.92	CTC1	22.55/22.54
	CTC2	37.04/32.26*	CTC2	41.76/39.38	CTC2	37.35/37.77	CTC2	49.09/48.61
	CTC3	15.25/16.83	CTC3	14.51/12.92	CTC3	14.88/14.46	CTC3	12.46/14.61
	CTC4	6.20/6.38	CTC4	9.87/9.08	CTC4	4.92/4.85	CTC4	6.91/5.23*

Table S3. Changes in the frequency of each class (days per month) before and after the CP. Blue/red coloured numbers indicate decreased/increased frequency of the class after the CP. Colours in the CTC cells are related to the order relationship of the 1980–2016 average MTP value for each CTC (in decreasing order: red, orange, green, and blue).

Asterisks indicate statistical significance at the 95% confidence level *using a z-test to compare two sample proportions (Sprinthall, 2011).*