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% ABSTRACT

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A growing body of literature finds a change in summer rainfall over China after the late 1970s (the ``South Flood North Drought''). In these months, rainfall characteristically occurs along zonal bands with a meridional tilt (the Meiyu Front). We construct a novel database that tracks all occurrences of frontal rainfall over China on each day from 1951 to 2007 from APHRODITE rain gauge data, and reports their latitude, strength, tilt and width. An unprecedented Meiyu climatology is obtained. In addition, the latitude of frontal events is known to correspond to the position of the tropospheric jet. Therefore, we search for correspondence between front and jet position, and coupled changes in behavior with time. Two robust changes are observed in front behavior between the time periods 1951-1979 and 1980-2007: 1) A significant decrease in the frequency of pre-Meiyu (May) frontal events after 1979 and 2) a southward shift in late season Meiyu events (mid-July to August) found both in the front and jet databases. Our results hold the promise of coupling regional climate change to \nth{21} century global change.

\end{abstract}

\begin{article}

\section{Introduction}

China receives about 60\% of its rainfall from May to August, a period known collectively as the East Asian summer monsoon. The period of peak rainfall within this monsoon lasts from early June to mid-July (usually referred to as ``Meiyu Season'') features a northward-migrating front known as the Meiyu front (lit. ``Plum rains,'' referring to the spectacular growth of plum blossoms in central China after the onset of heavy rains). The corresponding rainy seasons in Japan and Korea are known as Baiu and Changma respectively. A growing volume of evidence suggests a shift in mean rainfall patterns over China beginning in the late 1970s, with increased flooding in the south and droughts in the north (the ``South Flood-North Drought'') \citep{Hu1997,Gong2002,Nigam2013}. A permanent change would have major humanitarian impacts on the densely-populated eastern Chinese plain, where a sizable fraction of the population depends on agriculture. Northern China suffers from substantial depletion of freshwater resources along with increasing demand \citep{Currell2012,Gleeson2012}. The Chinese government has already embarked on a project to reroute water from the Yangtze River to northern China, the South-North Water Transfer Project (\textit{nanshui beidiao gongcheng}), which is expected to become the most expensive hydraulic engineering project ever undertaken and will entail massive human and environmental impact \citep{Magee2011}.

Although summer rainfall in East Asia is referred to as a monsoon, its climatology bears little resemblance to its Indian counterpart or other monsoon circulations worldwide \citep{Ding2005}. Whereas understanding of tropical monsoons has progressed greatly via theoretical studies \citep{Plumb1992,Prive2007,Bordoni2008}, the dynamics that favor the existence of frontal convection over East Asia in summer remain a point of debate, centering around the interplay of the tropospheric jet and Tibetan Plateau \citep{Molnar2010,Sampe2010,Chen2014}. Therefore, no simple template exists for interpreting a change such as the South Flood-North Drought. However, it is known that the migration of the Meiyu front entails a series of large-scale circulation changes \citep{Chen2004}, and furthermore that anomalies in Meiyu front latitude produce corresponding rainfall anomalies \citep{Kosaka2011}. Therefore, a long-term change in rainfall r\'egime such as the South Flood-North Drought should be describable in terms of changes in the characteristics of Meiyu events, such as a shift in latitude, a change in intensity or an earlier or later transition from one stage to the next. In turn, such a characterization may provide insight into the dynamics responsible for the change.

In pursuit of this aim, we have developed a 57-year climatology (1951-2007) of frontal rainfall events in China based on the APHRODITE rain gauge product (described below). We develop a convergent fitting algorithm of daily rainfall maps which returns information about the position and strength of the front, as described in greater detail below. A few previous studies have discussed the statistics of the Meiyu front on decadal and even centennial time scales \citep{Chen2004,Ge2008,Xu2009}, but to our knowledge no author has compiled a multi-decadal daily catalog of events. We use this database to clarify the spatial and temporal characteristics of the South Flood-North Drought, and present it as a tool for future East Asian monsoon research.

We also explore links between the behavior of the Meiyu front and subtropical jet, which plays an essential and complex role in East Asian climate both in summer and winter \citep{Yang2002}. In a region featuring a strong wind shear, we expect a band of ascent displaced southward from the core of maximum wind \citep{Holton2004}. Theoretical studies suggest that the high topography of the Tibetan Plateau couples with the jet in nonlinear fashion, amplifying the regional response to global climate anomalies \citep{Nigam1989,Broccoli1992,Park1997}. In summer, past work has argued the timing of the jet's transit north of the Tibetan Plateau dictates the initiation of the monsoon in India and East Asia, both in present-day \citep{Yin1949,Hahn1975,Yeh1959} and on paleoclimate timescales \citep{Chiang2015}. Meridional shifts in the tropospheric jet induce rainfall anomalies in china \citep{Liang1998}, as do changes in its strength \citep{Kwon2007,Du2009,Li2014} On a daily time scale, the jet serves as a waveguide for storms propagating from the Euarasian interior via the ``Silk Road'' teleconnection \citep{Hoskins1993,Ambrizzi1997,Kosaka2012}. Thus, it is reasonable to expect to look for \nth{20} century changes in the tropospheric jet over East Asia in conjunction with Meiyu changes. Therefore, we also compare our Meiyu database with an existing data set of jet counts for 1958-2001, as described in \citet{Schiemann2009}, in search of coupled change.

\section{Methods}

\subsection{Data}

\subsubsection{APHRODITE Rainfall Data}

The APHRO\\_MA\\_V1101 product from APHRODITE (Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation of the Water Resources) \citep{Yatagai2012} includes 57 years (1951-2007) of daily rainfall derived from rain gauge records (and therefore available over land only). Available data are precipitation (PRECIP product, units mm day$^{-1}$) and station coverage (RSTN product) on a .25\textdegree\ $\times$ .25\textdegree\ grid (roughly 25 km spacing) between 60\textdegree E-150\textdegree E and 15\textdegree S-55\textdegree N. We focus on the subregion of land lying within 100\textdegree E-123\textdegree E and 20\textdegree N-40\textdegree N as the area of occurrence of Meiyu events. Rain gauge products present an analytical challenge because the distribution of stations is uneven in space and changes with time. Station density over eastern China improves beginning in the 1970s from X to Y (INSERT ACTUAL NUMBERS). However, the spacing of stations in generally does not exceed 100 km, sufficient to resolve frontal events. APHRODITE lacks the resolution to show characteristics of precipitation systems visible with TRMM satellite data, such as the anchoring of rainfall by low orography \citep{Xu2009}. In compensation, the length of our data set allows us to study decadal change in frontal properties.

\subsubsection{A Database of Jet Counts from \citep{Schiemann2009}}

Our aim is to investigate the relationship between the position of the subtropical westerly jet in eastern China and Meiyu activity. \citep{Schiemann2009} constructed a data set of jet occurrences in the Tibetan Plateau region from the ERA-40 reanalysis. For a given longitude, a jet `count' is defined as a local maximum in the horizontal wind field with magnitude greater than $30$ m s$^{-1}$; further details can be found in section 2 of \citep{Schiemann2009}. Since we are interested in the relationship between jet latitude and Meiyu front activity, we only consider the set of this data in the longitude band $90-130^\circ$E, which encompasses the region of Meiyu front activity. We aggregate the jet counts to produce the average daily jet latitude across this across the longitude band for the entire period of the ERA-40 reanalysis, 1958-2001.

\subsection{Meiyu Detection Algorithm}

For each day from 1 January 1951 to 31 December 2007 (20,819 total), the algorithm determines whether a frontal event is present or not inside the window of 105-123E and 20-40N, and if it exists returns its properties. In addition, it is observed that some days feature two frontal events. If a primary event is detected, the algorithm therefore checks for a secondary fit as well. The algorithm follows the subsequent checklist:

\begin{enumerate}

\item The maximum daily rainfall for each longitude is found. If there exists a 5\textdegree continuous chain of maxima (20 points in a row) exceeding 10 mm/day, we proceed to step 2 and attempt a fit. Otherwise, the day is thrown out.

\item A weighted least-squares linear fit of the \textit{latitudes} of the maxima is attempted, using the intensity of the maxima as weight.

\item A recursive algorithm converges on a best estimate. In each iteration, we find a new set of maxima within \textit{k} degrees of the previous best fit line, and again repeat the weighted linear fit in step 2. $k$ is progressively decreased with each iteration.

\item Using our final best estimate from step 3, we define the ``quality score'' $Q$ as the fraction of total daily precipitation that falls within 5 degrees of this fit line.

\item As mentioned, we check for a secondary front. We remove all precipitation within the primary front and again apply the front criterion in step 1 to the leftover rainfall map. If passed, steps 2-4 are repeated to find a best estimate for a secondary front.

\item If a secondary front is found, two additional quality scores $Q\_1$ and $Q\_2$ are determined. $Q\_1$ is defined as the fraction of rainfall contained in the primary front \textit{after removing all rainfall associated with the secondary front}. Likewise $Q\_2$ is the Q score of the second front \textit{after removing all rainfall from the primary front}.

\end{enumerate}

In some cases, a fit will be achieved, but its quality will be too poor to include in our statistics. To check for this scenario, we use the quality scores $Q$, $Q\_1$ and $Q\_2$, and the ``Taiwan fraction'' (TW), defined as the percentage of daily rainfall that falls on the island of Taiwan. If $TW > 20\%$, the day is thrown out. Such days are dominated by a local storm reaching Taiwan and rarely exhibit a strong front. Subsequently there are two ways a day may be included:

\begin{enumerate}

\item if $Q>.6$, the day is included in our statistics. If $Q\_2$ also is greater than .6, the day will be classified as a double front day.

\item If $Q<.6$, a day can only be included if both $Q\_1 \mathrm{\textbf{ and }} Q\_2 > .6$. In such cases, the quality of fit is initially obscured by the presence of multiple fronts. We classify the day as a double front day.

\end{enumerate}

%I've defined Q1 as the quality of fit after deleting all rainfall associated with the secondary front, and Q2 likewise as the quality of fit after removal of primary front. I am not sure if this is equivalent to checking if the combination of primary and secondary fit explain over 60% of the rainfall - if so, may be a simpler way of describing.

In practice, days with secondary fronts constitute a small fraction of all days ($>$ 5\%) but are more common during certain seasons (see Figure \ref{dingchan}c).

\subsection{Statistical Significance of Changes in Means}

Two separate Monte Carlo methods are employed to assess the statistical significance of the change in mean between time periods: 1) Bootstrapping with replacement and 2) a permutation test (without replacement) \citep{Good2005}. Given two original sets of observations of size $n\_1$ and $n\_2$, each set is replaced with a new set drawn at random from the original distribution, and then the difference in the mean of the two sets. Therefore, the statistical significance of the actual change in mean can be determined directly by comparison with our newly generated distribution of differences. In general, we use 10,000 iterations and find that increasing the number of iterations past a much lower threshold does not influence results. Past authors have suggested that a permutation test is a stricter test of significance than the bootstrapping methods \citep{Hesterberg2003}. In practice, both methods used provide almost identical results, but the permutation test is consistently stricter by a small amount as suggested by the literature. Therefore, in the subsequent presentation of results, we present the results of the permutation test. Both methods are further described in the appendix. The database of fronts runs from 1951 to 2007, whereas the jet data only spans the years 1958-2001. Therefore, we have repeated all calculations of significant changes in Meiyu behavior for both 1951-1979 versus 1980-2007 and for 1958-1979 versus 1980-2001 to ensure that our results are robust.

%is it necessary to include more in the appendix?

%also - likely need to discuss moving blocks bootstrap in future iterations of manuscript.

\section{Results}

\subsection{Meiyu Climatology}

Figure \ref{dingchan} shows climatological precipitation over eastern China, averaged over $100^\circ-123^\circ$E. This produces a plot similar to Figure 7 in \citet{Ding2005}, but focusing on eastern China. China receives a substantial fraction of its yearly precipitation outside of summer, unlike a traditional monsoon circulation. Figure \ref{dingchan}b shows a H\"ovmoller diagram of the latitudes occupied by the Meiyu Front over all 57 years, including both primary and secondary events, expressed as a percentage with a 5-day smoothing and 2\textdegree\ smoothing. From May to September, three periods of roughly constant behavior are observed, with two intervening abrupt transitions: 1) the period of the front's northward migration during days 161-200 (June 10-July 19), and 2) a sudden reduction in intensity and frequency of frontal events in northern China around day 200 (July 19), after which double front events become much more common (Figure \ref{dingchan}d). The three periods are equivalent to those described in \citet{Ding2005}. Figure \ref{dingchan} demonstrates that frontal rainfall events over China can occur in any month, with their intensity and probability of occurrence minimizing in January (12 mm day$^{-1}$ and 10\% occurrence) and maximizing in late June (31 mm day$^{-1}$ and 80\% occurrence). However, as seen in Figure \ref{dingchan}c, frontal events are generally more common in spring (mid-March to mid-July) than in fall (mid-July to mid-November). The mean tilt of the front is approximately 8 degrees. Some periods of heavy rainfall, in particular the August peak in rainfall over Southern China (over 10 mm day$^{-1}$ around 20\textdegree N), do not feature a corresponding surge in Meiyu events. Our results can be compared with the event catalog of \citet{Xu2009}, which agrees with our results on the timing of the northward transition of the Meiyu front.

We defined 5 periods of Meiyu behavior as demarcated in Figure \ref{dingchan}: 1) The ``Spring Rains'' for days 60-120 (March 1-April 30), as previously studied in \citet{Tian1998}; 2) The ``Pre-Meiyu,'' days 121-160 (May 1-June 9, Ding and Chan stage 1); 3) Meiyu season from days 161 to 200 (June 10-July 19, Ding and Chan stage 2); 4) The Post-Meiyu from days 201-273 during which double fronts are common (July 20-September 30, Ding and Chan stage 3) and 5) the ``Fall Rains,'' days 274-320 (October 1-November 16), during which the front returns south. Frontal characteristics during each time period are reported in Table \ref{changes\_table}. Meiyu season and the Fall Rains mark the climatological passage of the jet northward and southward of the Tibetan Plateau respectively, but rainfall amounts, Meiyu occurrence and frontal intensity are much higher in the former than the latter. This asymmetry deserves further study.

\subsection{Meiyu Changes between 1951-1979 and 1980-2007}

We use bootstrapping with replacement and a permutation test to calculate the statistical significance of differences between 1951-1979 and 1980-2007 for each of the five time periods described above, as well as for the full year. The results are visible in Figure \ref{changes} and Table \ref{changes\_table}. The greatest change in frontal behavior has occurred during pre-Meiyu season (days 121-160, or May 1-June 9), when the probability of observing a frontal event has declined from $60.7\% \pm 1.5\%$ to $52.2\% \pm 1.6\%$ (statistical significance of $p < .0002$). This change is also seen in figure \ref{changes}a and b as a decrease in rainfall and frontal frequency over central China. The change in pre-Meiyu rainfall in the late \nth{20} century has previously been reported by \citet{Xin2006} and \citet{Wang2009}.

In addition, a southward shift in mean frontal latitude has occurred during the post-Meiyu (days 201-273, or July 20-Sep 30). Mean latitude from 1951-1979 was $29.9^\circ \textrm{N} \pm .3^\circ$ versus $29.3^\circ \textrm{N} \pm .4^\circ$, a difference significant at a 95\% confidence level. Again, we observe a corresponding increase in rainfall and Meiyu event frequency during 1980-2007 relative to 1951-1979, this time over central China, and decreases in both over northern China. As a result of the increase in rainfall over central China during July-August, yearly main rainfall has also increased, in spite of the opposing change in pre-Meiyu rainfall over central China. A statistically significant southward shift is also found for the whole year, as shown in Table \ref{changes\_table}, but the signal is dominated by the change in post-Meiyu frontal behavior. The spatial pattern of this change corresponds more closely to the usual template of the ``South Flood-North Drought." Unlike \citep{Yu2010}, our catalog does not exhibit a decrease in intensity of Yangtze River region frontal events during July-August.

\section{Jet Changes between 1951-1979 and 1980-2007}

In this section we show that the jet latitude covaries with the latitude of Meiyu events, and that we observe changes in the jet transition behavior corresponding to changes in Meiyu activity demonstrated above and to the ``South Flood-North Drought'' pattern. A full climatology of the jet can be seen in \citet{Schiemann2009}. From April to June, the mean jet position migrates northward, from a position anchored to the southern flank of the Tibetan Plateau to a position on the northward flank. During this transition period, the pre-Meiyu and Meiyu stages of intense rainfall occur in succession in eastern China. The period of frequent double front occurrences seen in Figure \ref{dingchan} corresponds to the time of maximal northward extent and low variance in jet latitude. Finally, during the ``Fall rains'' in October and November the jet shifts back southward of the Tibetan Plateau, with frontal events correspondingly shifting southward, but only a weak rainfall response.

In Figure \ref{jet\_seasonal}, we show the mean jet latitude from April to October in the region $90-130^\circ$E, averaged over the years 1958-1979 (blue solid line) and 1980-2001 (dashed red line). Bootstrapped 95\% confidence intervals are shaded in blue and red, respectively. The most notable difference between the two time periods is in May, when the jet is at $\approx 41^\circ$N in 1958-1979, while is is almost $2$ degrees further south in 1980-2001. This corresponds to the `pre-Meiyu' period, and the time of the greatest change in Meiyu activity, as shown in Figure \ref{changes}. In contrast, during Meiyu season, the mean jet latitude is nearly identical in both time periods, and we see no significant change in Meiyu events. During the post-Meiyu (days 201-273), when the mean latitude of Meiyu events has shifted south during 1980-2007, the mean latitude of the jet is consistently southward during 1980-2001 relative to 1958-1979 and attains 95\% significance at several times. As mentioned in the methodology, the two principal changes in Meiyu behavior were also calculated using the shorter time periods of 1958-1979 versus 1980-2001 (Table \ref{changes\_table} shows 1951-1979 versus 1980-2007), and remain statistically significant.

%not sure how to do it exactly, but we could calculate the statistical significance of the consistent monthlong southward shift of the jet - in total, I suspect it would far exceed a 95% confidence level.

The covariance of Meiyu front positions and tropospheric jet latitudes in the climatological mean also suggests a dynamical reason for the covariance of their anomalies. The period of peak rainfall and peak frontal frequency corresponds directly to the period when the westerly jet is impinging on the Tibetan Plateau upstream. When the jet moves further north to its preferred summer position northward of the Tibetan Plateau, it is no longer deflected and the front is significantly weaker, and we transition to a preferred double-front state as seen in Figure 1b. If we perturb the entire seasonal cycle of jet latitude southward, we would expect the jet to begin impinging on the Tibetan Plateau later (a later start to the Pre-Meiyu season) and a southward shift in the occurrence latitude of Meiyu events in mid-summer (during the Post-Meiyu). In fact, these are the two major findings from considering changes in our Meiyu catalog. In the annual mean, we propose that the effect of the more southerly position of the jet has been to reduce the amount of precipitation in northern China, and increase the amount in southern China, producing the ``South Flood-North Drought'' pattern of response.

\section{A secondary shift: 1979-1993 v 1994-2007}

In addition to the change in China rainfall in the late 1970s, authors have reported an earlier onset of the pre-Meiyu season over the period 1994-2008 relative to 1979-1993 \citep{Kajikawa2012}, as well as associated changes such as an increase in rainfall over southeastern China and an increase in the passage of tropical cyclones \citep{Kwon2007,Chang2014}. We repeat the analysis of Section 4 for the two time periods 1979-1993 and 1994-2007 (see appendix). A shift in intensity is found during Meiyu season (days 156-200, June 5-July19) from 28.1 to 31.1 mm day$^{-1}$, with significance level $p<.0001$. Furthermore, the same time period also sees a shift in latitude of events southward from 29.54\textdegree\ to 28.71\textdegree\ with $p=.0011$. However, unlike the 70s shift, no significant change is observed in the frequency of Meiyu events ($63.3\pm 1.9\%$ for 1979-1993, $64.0\pm 2.0\%$ for 1994-2007) and there is no significant change in jet latitude. Thus, the character of the mid-90s shift is found to differ fundamentally from the 70s shift (a change in the \textit{intensity} of events during Meiyu season in the former with no jet change, versus a change in \textit{frequency} of pre-Meiyu events and a statistically significant jet shift). \citet{Biasutti2011} points out that apparent changes in the intensity of rainfall on daily or monthly time scales result instead from frequency changes at the hourly scale. Thus, the 90s shift could possibly reflect a change in the duration of Meiyu storms when they occur.

\section{Conclusion}

We have created a 57-year climatology of frontal rainfall over China including information such as frequency of rainfall, latitude, intensity, tilt, width and length. No prior study has categorically analyzed such an extent of data. Furthermore, we have isolated two statistically robust changes that occur between the years 1951-1979 and 1980-2007: 1) A decrease in the frequency of frontal events during the pre-Meiyu season (days 121-155, or May 1-June 5), significant at $p < .0002$; 2) A southward shift in front latitude during the post-Meiyu (days 201-273, or July 20-Sep 30), significant at a 95\% confidence level. Each of these is associated also with a statistically significant change in jet latitude between the two time periods. Many of these results have been individually reported in previous work. \citet{Xuan2011} also report a southward shift in the westerly jet in July, as well as an increase in rainfall over the Yangtze Valley. \citet{Yu2004} found a shift in the July-August latitude of the tropospheric jet and suggested a link with the ``South Flood-North Drought.'' However, no previous study has shown a comprehensive set of changes in late \nth{20} century Meiyu behavior with changes in the tropospheric jet.

We argue that the ``South Flood-North Drought'' reflects changes in the seasonal cycle of East Asian summer monsoon precipitation and the tropospheric jet. This interpretation can be viewed as a modern analog of the ``Spring Jet'' hypothesis described in \citet{Chiang2015}. In that work, changes in East Asian rainfall on paleoclimate time scales are ascribed to modulations in the seasonal cycle of the tropospheric jet. Here, we attribute the sharp decrease in front frequency during the pre-Meiyu and the southward shift of events during the post-Meiyu during 1980-2007 to a southward shift in the jet's seasonal cycle, which delays the onset of the pre-Meiyu and decreases the jet's northward extent.

Many other potential mechanisms have been suggested for the ``South Flood-North Drought.'' These include changes in Indian and Pacific Ocean SST, a decrease in sensible heating from the Tibetan Plateau (CITE), aerosol forcing \citep{Song2014} and decadal modes of natural variability \citep{Zhang1999,Xin2006,Lei2014}. \cite{Zhou2009} found that the variability contained in the South Flood-North Drought was distinct from other patterns of \nth{20} century variability. \citet{Qu2012} proposed that changes in Indian Ocean SST lead to meridional shifts in the jet over East Asia. The proposed pivotal role of the tropospheric jet's seasonal cycle does not supplant the previous hypotheses, but rather supplies further observations that they must address.

In the global mean, observations show that the tropospheric jet is shifting poleward, in tandem with mid-latitude tropospheric heating, an increase in subtropical static stability, a northward shift in mean ITCZ latitude and the expansion of the Hadley circulation \citep{Fu2006,Archer2008}. In contrast, we find a contrary trend at the regional level: The jet has shifted southward over East Asia at the end of the \nth{20} century. Other work also finds a southward shift of the tropospheric jet relative to the Tibetan Plateau during summer \citep{Yu2007}. Recent work proposes that the observed changes in tropical Pacific convection and SST have led to meridional displacement of the tropospheric jet across the entire tropical Pacific \citep{Park2014a}. Thus, both observations (a global poleward trend in jet latitude and a regional equatorward shift) may be compatible given the spatial distribution of \nth{20} century warming.

The anticipated relation of regional climate change and global mean change under \nth{21} century warming is unclear-- the CMIP5 model suite does not come to a consensus on the sign of future summer rainfall changes in East Asia \citep{Christensen2011}. However, in this study, we have demonstrated a robust connection between local rainfall changes in eastern China to a global-scale dynamical phenomenon-- the westerly jet. The trend of poleward expansion of the Hadley Cell is found to continue under \nth{21} century global warming in models \citep{Lu2007,Kang2012}, but a recent study with CMIP 3 and CMIP 5 finds that anomalous heating of the eastern Pacific warm pool under global warming will lead to a further southward shift of the jet over the Pacific Ocean \citep{Park2014}. By linking the ``South Flood-North Drought'' with the seasonal cycle of the tropospheric jet, we open up the possibility of improved projection of East Asian rainfall change by studying the global scale change in the tropospheric jet.