The link between the Victoria mode in the preceding boreal winter and spring precipitation over the southeastern USA and Gulf of Mexico

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ABSTRACT

The sea surface temperature anomalies (SSTAs) associated with the Victoria mode (VM) can persist into the following season and then influence climate variability in the tropical Pacific. This paper demonstrates the connection between the preceding boreal winter VM and precipitation in the following spring over the southeastern United States (SE USA) and the Gulf of Mexico (GM). The results indicate that a positive (negative) preceding winter VM is usually followed by increased (reduced) precipitation over the SE USA and GM during the following spring. The corresponding mechanism is similar, but slightly different to, the seasonal footprinting mechanism. For positive VM cases, the preceding-winter VM-related SSTAs appear to persist into the following spring via air–sea interactions, which then induce low-level convergence and vigorous ascending motion, leading to an adjustment of the zonal and meridional circulation. This adjustment can then influence the local Hadley cell by weakening the downward branch. These anomalous patterns of vertical airflow enhance spring precipitation over the SE USA and GM under suitable moisture conditions. Hence, this work demonstrates that the preceding-winter VM has the potential to regulate precipitation over the SE USA and GM in the following spring.

1. Introduction

The Victoria mode (VM) is the second empirical orthogonal function mode (EOF2) of sea surface temperature anomalies (SSTAs) in the North Pacific north of 20°N (Bond et al. 2003; Ding et al., “The Victoria Mode”, 2015), and is distinct from the Pacific Decadal Oscillation (Mantua et al. 1997; Zhang, Wallace, and Battisti 1997), which is the leading mode of North Pacific climate variability (figure not shown). The VM exhibits a tripole structure that is characterized by a band of positive SSTAs extending from the west coast of North America to the central tropical Pacific, a band of negative SSTAs extending from the central North Pacific to the northwestern tropical Pacific, and another band of positive SSTAs in the Pacific north of 35°N (Bond et al. 2003; Ding et al., “The Victoria Mode”, 2015) Figure 1(a). The VM index (VMI) is the corresponding time coefficient of the EOF2 of the monthly SST field over the North Pacific (20–61°N, 100°E–100°W) (Bond et al. 2003; Ding et al., “The Victoria Mode”, “The Impact of South Pacific”, 2015). Previous studies indicate that the VM is driven by the North Pacific Oscillation (NPO; Walker and Bliss 1932; Rogers 1981; Ding et al., “The Victoria Mode”, “The Impact of South Pacific”, 2015).

KEYWORDS

Victoria mode; spring precipitation; southeastern USA; Gulf of Mexico; air–sea interaction

ARTICLE HISTORY

Received 6 February 2016
Revised 8 March 2016
Accepted 28 March 2016

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Arkin (1997) was used to validate the results for precipitation. The GPCP and CMAP datasets contain monthly precipitation data at a horizontal resolution of 2.5° × 2.5°. (2) Atmospheric variables are from the NCEP–NCAR reanalysis (Kalnay et al. 1996), which has a horizontal resolution of 2.5° × 2.5°. (3) SST data are from the HadISST data-set, gridded at a resolution of 1° × 1° (Rayner et al. 2006). (4) The ENSO index (Ninõ3) is from the NOAA CPC website. In addition, we calculated the vertical integration of the anomalous moisture flux fields between the sea level and 300 hPa (Behera, Krishnan, and Yamagata 1999; Nnamchi and Li 2011).

We analyzed the period from 1979 to 2014, for which satellite records are available. The significance of the correlation between two autocorrelated time series was assessed using the effective number of degrees of freedom.

3. Results

3.1. Connections between the preceding winter VM and spring precipitation

Ding et al., “The Victoria Mode”, (2015) suggested that the VM, as an ocean bridge through which extratropical atmospheric variability in the North Pacific affects tropical variability, is more closely linked than the NPO to the development of ENSO. The VM can trigger the onset of ENSO via surface air–sea coupling and the evolution of subsurface ocean temperature anomalies along the equator. Meanwhile, the spring VM has been linked to variability in Pacific ITCZ precipitation during the following summer (Ding et al., “The Impact of South Pacific”, 2015). In positive VM cases, SSTAs in the subtropics associated with the spring VM persist until summer and develop towards the equator, inducing low-level convergence that leads to enhanced precipitation over the central-eastern Pacific ITCZ region.

Many studies have focused on the correlation between the VM and the tropical Pacific climate system (Ding et al., “The Victoria Mode”, “The Impact of South Pacific”, 2015). Wang et al. (2010) found that spring precipitation over the southeastern United States (SE USA) is affected by SST patterns in the Pacific. However, they did not address the effect of the preceding winter (December–January–February: DJF) VM on spring (March–April–May: MAM) precipitation. In this study, we explore a possible connection between the preceding winter VM and following spring precipitation over the SE USA and the Gulf of Mexico (GM) with the ENSO signal removed.

2. Data description

The following datasets were used in this study: (1) Precipitation data were obtained from the GPCP (Huffman et al. 1997), and the CMAP data-set (Xie and Arkin 1997) was used to validate the results for precipitation. The GPCP and CMAP datasets contain monthly precipitation data at a horizontal resolution of 2.5° × 2.5°. (2) Atmospheric variables are from the NCEP–NCAR reanalysis (Kalnay et al. 1996), which has a horizontal resolution of 2.5° × 2.5°. (3) SST data are from the HadISST data-set, gridded at a resolution of 1° × 1° (Rayner et al. 2006). (4) The ENSO index (Ninõ3) is from the NOAA CPC website. In addition, we calculated the vertical integration of the anomalous moisture flux fields between the sea level and 300 hPa (Behera, Krishnan, and Yamagata 1999; Nnamchi and Li 2011).

We analyzed the period from 1979 to 2014, for which satellite records are available. The significance of the correlation between two autocorrelated time series was assessed using the effective number of degrees of freedom.

Figure 1. Correlation maps of the preceding winter VMI-DJF showing the three-month averaged SSTAs (shaded) and 850 hPa wind anomalies (vectors) for (a) DJF and (b) MAM. Note: Positive (red) and negative (blue) SSTAs, with correlation significant at the 0.05 level, are shaded. Only 850 hPa wind vectors significant at the 0.1 level are shown.
We represent spring precipitation using the area-averaged precipitation index (PI), which is defined as the standardized area-averaged spring precipitation for the Box region (Figure 2(c)). The preceding winter VM has a marked positive correlation with precipitation anomalies over the above region at a confidence level greater than 99%, with a correlation coefficient of 0.51. This result proves the reliability of the relationship between the preceding winter VM and spring precipitation.

To further confirm the connection between the preceding winter VM and spring precipitation over the SE USA and GM, we regressed the preceding winter North Pacific SSTA onto the PI, shown in Figure 2(c). The regression of the SSTA (Figure 2(e)) shows a well-defined dipole structure over the North Pacific poleward of 20°N, which closely resembles the VM-related SSTA pattern in Figure 1(a). It appears that the VM SST pattern bears a resemblance to the optimal initial SST condition that is likely to lead to spring precipitation anomalies over the SE USA and GM. A positive (negative) VM event in the preceding winter tends to be followed by more (less) precipitation during the following spring over this region. This result agrees with the positive correlation observed between the preceding winter VM and spring precipitation.
with the conclusions from Figure 2(a) and (c), and further supports the existence of a close relationship between the preceding winter VM and following spring precipitation over the SE USA and GM.

Similar correlation maps and regression patterns were also obtained when using the CMAP data-set (Figure 2(b), (d), and (f)). These consistent results demonstrate that the spring precipitation anomalies over the SE USA and GM are closely related to the VM from the previous winter. Thus, the preceding winter VM is one possible factor that affects spring precipitation over the SE USA and GM.

### 3.2. Spring atmospheric circulation anomalies associated with the preceding winter VM

The distribution of precipitation is closely associated with the combined effect of the water vapor conditions and vertical motion. To explain the above-mentioned link between the preceding winter VM and spring precipitation over the SE USA and GM, we present the following spring meteorological variable anomalies that are correlated with the preceding winter VM (Figure 3(a–d)).

Figure 3(a) displays the correlation between the VMI-DJF and spring specific humidity at 700 hPa. During positive VM cases, positive anomalies are centered over the SE USA and GM, indicating that the air is wetter over this region. Furthermore, Figure 3(b) indicates that the vertically integrated moisture flux field characterizes much of the specific humidity anomaly pattern. The vector of the moisture flux shows that the moisture transport induced by the preceding winter’s VM is centered over the GM. The majority of the region is dominated by strong southerly winds, which promote the moisture transport from the GM.

When the preceding winter VM is positive, anomalous upward motion prevails over the SE USA and GM (Figure 3(c)). The correlation between the VMI-DJF and spring divergence at 200 hPa is displayed in Figure 3(d). The configuration of the divergence field in the upper troposphere matches these upward motion anomalies well. The vertical motion associated with the positive preceding winter VM is consistent with the vapor conditions that favor the spring precipitation pattern in Figure 2(a) and (b).

To summarize, in the case of a positive preceding winter VM, the anomalous horizontal divergence at 200 hPa favors ascending motion of wetter air over the SE USA and GM. The combination of favorable vapor conditions, vertical motion, and the divergence field generates increased precipitation in this region.

### 3.3. Possible physical mechanisms

As mentioned above, the preceding winter VM has the potential to influence the following spring precipitation over the SE USA and GM. However, the question remains as to exactly how the winter VM affects the SE USA and GM during the following spring. To provide a physical
These significant SST and wind anomalies in the North Pacific north of 20°N decrease quickly in the following spring (Figure 1(b)). In contrast, SSTAs in the subtropical central-eastern North Pacific (10–20°N) can persist from the preceding winter and into spring (Figure 1(b)) via surface air–sea interactions associated with the VM (Ding, Li, and Tseng 2015; Ding et al., “The Impact of South Pacific”, 2015). Specifically, anomalous southwesterlies associated with the VM during the preceding winter reduce the upward latent heat flux (figure not shown) and subsequently warm the ocean from the northeastern Pacific to the equatorial central Pacific.

In response to the warming induced by the above processes in the central-eastern tropical Pacific, strong anomalous southwesterlies in the central-western tropical Pacific strengthen (Figure 1(b)), leading to convergence at 850 hPa with the center located in the central-eastern North Pacific (Figure 4(a)). These convergence zones in the lower tropospheric layers cause vigorous ascending motion centered near the dateline (10°S–10°N, 170°E–170°W). Meanwhile, significant descending motion occurs over the tropical eastern Pacific off the west coast of Colombia and Ecuador ((10°S–10°N, 95–80°W); Figure 4(b)). This anomalous east–west oriented circulation resembles the Walker circulation across the tropical Pacific, resulting in enhancement of the latter. In addition, the increased convection and precipitation caused by low-level convergence in the central-eastern North Pacific may intensify the release of the latent heat of condensation into the atmosphere, which favors the ascending motion, convective precipitation, and so on (Ding et al., “The Impact of South Pacific”, 2015).

 Adjustment of the Walker circulation also influences the meridional circulation over the region 95–80°W, which is the longitudinal band of the Box region. Following the increased Walker circulation, the sinking airflow over the tropical eastern Pacific off the west coast of Colombia and Ecuador is strengthened (Figure 4(c)). Subsequently, this enhanced downward motion is superposed onto the upward branch of the local Hadley cell in the tropical eastern Pacific, weakening the latter and thereby leading to anomalous ascending motion and precipitation over the SE USA and GM (Figure 4(c)).

Note that significant anomalous southerlies are seen over the Box region (Figure 4(c)), which is consistent with anomalous rising airflow there, indicating that the abundant supply of water vapor over the SE USA and GM is closely linked to the ascending motion over this region, and together they encourage the generation of local precipitation. In general, our interpretation is that a large-scale convergence over the central-eastern North Pacific induced by the VM plays an important role in causing anomalous ascending motion and increased precipitation over the SE USA and GM.

Figure 4. (a) Correlation map of the VMI-DJF with the MAM-averaged 850 hPa divergence anomalies. Correlation significant at the 0.1 level is shaded. (b) Correlation map of the VMI-DJF with anomalies of the meridional mean spring (MAM) zonal wind and omega components for 10°S–10°N. The green lines indicate the longitudinal band of the Box region. (c) Correlation map of the VMI-DJF with anomalies of the zonal mean spring (MAM) meridional wind and omega components for 95–80°W. The green lines indicate the latitudinal band of the Box region. In (b, c), the omega value with the vector is multiplied by 10. Shading represents significance above the 0.1 level.

Figure 1(a) and (b) present the correlation between the VMI-DJF and SST and the 850-hPa wind anomalies in the winter and following spring. During winter, the positive VM is accompanied by a dipole-like SSTA pattern in the North Pacific north of 20°N, and a subtropical (0°–20°N) band of positive SSTAs extending from the northeastern Pacific to the tropical central Pacific (Figure 1(a)). The related wind anomalies resemble those associated with the NPO (Walker and Bliss 1932; Rogers 1981). This result is consistent with those reported by Vimont, Wallace, and Battisti (2003), Vimont, Battisti, and Hirst (2003), Alexander et al. (2010), and Ding et al., “The Victoria Mode,” (2015).
4. Conclusions and discussion

This paper focuses on the relationship between the preceding winter VM and precipitation over the SE USA and GM during the following spring. Our analysis demonstrates that the VM may have a marked effect on the interannual variation in spring precipitation over this region. A positive preceding winter VM is related to an intensified Walker circulation across the tropical eastern Pacific and a suppressed local Hadley cell within the longitude of the Box region. The related anomalous upward motion over the Box region, which contains large amounts of water vapor, dominates the SE USA and GM. The configuration of the atmospheric circulation and the water vapor conditions is consistent with the positive precipitation anomalies over the SE USA and GM.

In brief, the underlying physical processes associated with the influence of the preceding winter VM on spring precipitation over the SE USA and GM are similar, but slightly different to, the seasonal footprinting mechanism (SFM). The SFM was proposed by Vimont, Battisti, and Hirst (2001), Vimont, Wallace, and Battisti (2003), Vimont, Battisti, and Hirst (2003) to explain the effects of the NPO-like variability during a particular winter on ENSO during the following winter. The preceding winter VM SST pattern displayed in Figure 1a closely resembles the SST footprint reported by Vimont, Battisti, and Hirst (2001), Vimont, Wallace, and Battisti (2003), Vimont, Battisti, and Hirst (2003). However, here we emphasize the linkage between the VM and precipitation over the SE USA and GM. Specifically, the preceding winter VM signal can persist into the following spring, inducing anomalous southwesterlies that have a potential effect on the circulation in the central-eastern tropical Pacific through air–sea interaction. Thus, the Walker circulation and local Hadley cell act as an atmospheric bridge, which allows the North Pacific VM to influence precipitation over the SE USA and GM during the following spring.

Our analysis suggests that the preceding winter VM provides an additional source of predictability for downscaled seasonal predictions of the following spring precipitation over the SE USA and GM. Nevertheless, the problem of how to construct a prediction model for the following spring precipitation based on the preceding winter VM remains; additional study is required in this area. Moreover, given that the VM is closely correlated with ENSO (Ding et al., “The Victoria Mode,” 2015), and ENSO could significantly influence precipitation over the USA (Ting and Wang 1997; Gutzler, Kann, and Thornbrugh 2002; Wang et al. 2010, 2012; Ciancarelli et al. 2014), the question naturally arises as to whether the effect of the VM and ENSO on the precipitation over the SE USA and GM are independent. Further research into this issue is also necessary.

Acknowledgements

The authors thank Dr Sen Zhao for calculating the vertical integration of the anomalous moisture flux fields.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was jointly supported by the China Special Fund for Meteorological Research in the Public Interest [grant number GYHY201506013]; the National Basic Research Program of China [973 Program, grant number 2012CB955200]; the National Natural Science Foundation of China for Excellent Young Scholars [grant number 41522502]; the National Natural Science Foundation of China [grant number 41475037], and the Strategic Priority Research Program of the Chinese Academy of Sciences [grant number XDA11010303].

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