Special Climate Summary: October 2002 – June 2003 Cool and Wet in Eastern United States

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1. Introduction

The period October 2002-June 2003 featured exceptionally warm and dry conditions in the western United States, with statewide mean temperatures generally ranking in the top 10% of occurrences (Fig. 1a). Much of this anomalous warmth occurred during October-January in association with a persistent upper-level ridge over western North America. The period also featured anomalously cool and wet conditions in the eastern U.S., with statewide mean temperatures in the coolest 30% of occurrences dating back to 1895 (Fig. 1a), and precipitation totals at record or near-record high levels (Fig. 1b).

The longevity of these exceptionally cool and wet conditions is related to three distinct circulation regimes. The first two regimes cover the period October-May, and are associated with an enhanced subtropical jet stream and increased storm activity across the southeastern United States. During the first regime (October-January) these circulation features are linked to a combination of El Niño and the negative phase of the Arctic Oscillation (AO). During the second regime (April-May) they combined with several Appalachian cold-air damming events to focus the anomalously cold air along the East Coast.

During the third regime (June) a broad trough over the U.S. contributed to a pronounced southward penetration of several major cold fronts, resulting in cool and wet conditions across the eastern half of the country.

Over central and southern Europe warmer and drier than average conditions were observed during April-June. These regions were situated beneath a persistent upper-level ridge and south of the mean jet axis, and experienced a marked reduction in the number and intensity of storms and cold frontal passages during the period.

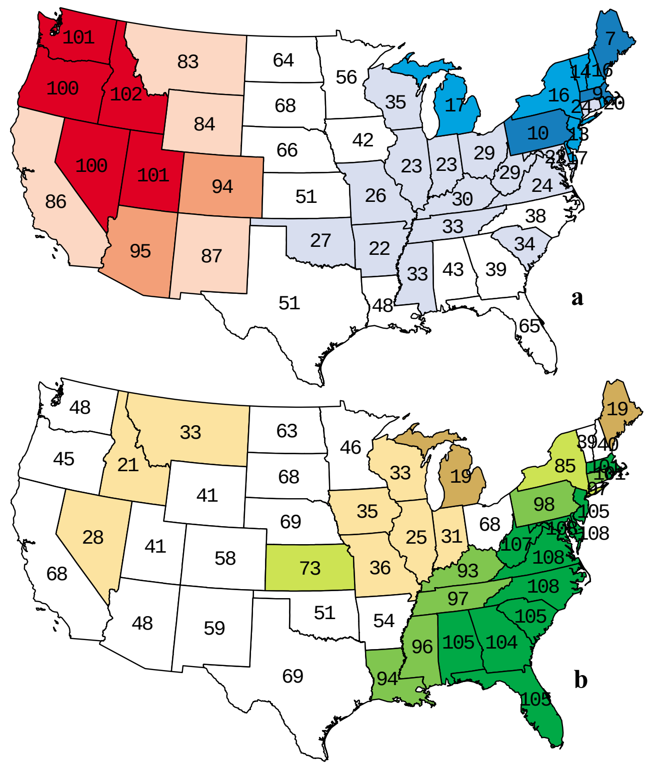

Fig. 1. October 2002 - June 2003: statewide ranks of (a) temperature and (b) precipitation. A rank of 1 represents the coldest or driest period, and a rank of 108 indicates the warmest or wettest period, in the 108-yr record between 1895-2003.

2. October 2002-January 2003 conditions

During October 2002 - January 2003 the anomalously cool and wet conditions across the eastern United States are associated with a pronounced zonal symmetry to the 200-hpa height anomalies (Fig. 2a), with positive anomalies over the polar region and at lower latitudes, and negative anomalies in middle latitudes. This circula-

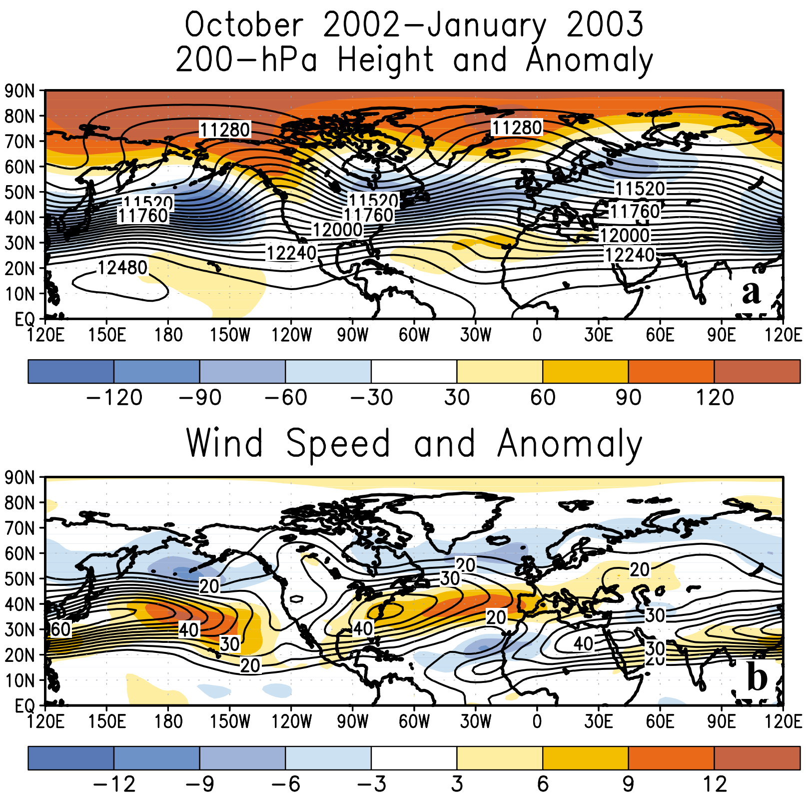

Fig. 2. 200-hPa: October 2002 - January 2003 (a) heights and anomalies (m) and (b) wind speeds and anomalies (m s^{-1}). Anomalies (shading) are departures from the 1971-2000 base period monthly means.

tion includes an amplified ridge-trough pattern over North America that is related to the warmth in the west and cold in the east. It also includes an eastward extension of the East Asian jet stream, an enhanced subtropical jet stream across the southern U.S., and an enhanced North Atlantic jet stream shifted south of normal (Fig. 2b). These conditions are consistent with an enhanced storm track across the southern U.S., and with the anomalously cold and snowy 2002/03 winter in the east.

The height anomaly pattern resembles the negative phase of the Arctic Oscillation (AO), a leading mode of atmospheric variability related to a mass exchange between the middle and high latitudes (Thomson and Wallace 1998, 2000). For the positive phase of the AO, anomalously low pressure covers the polar region and anomalously high pressure spans the central Pacific and Atlantic Oceans (Fig. 3a). Conversely, the negative AO seen during October–January features higher pressure in the polar region and lower pressure in the middle latitudes. This negative AO incorporates aspects of the positive phase of the Pacific/ North American (PNA) teleconnection pattern (Fig. 3b) and the negative phase of the North Atlantic Oscillation (NAO) (opposite anomalies to those shown, Fig. 3c).

The positive PNA pattern seen during the period is also consistent with weak-to-moderate El Niño conditions (Horel and Wallace, 1981). This combination of El Niño and the negative AO highlights how the extratropical climate variability can modulate ENSO teleconnections. For example, El Niño favors above- average winter temperatures across Canada and below-average temperatures over the southeastern United States (Fig. 4a). This temperature pattern can be modified substantially depending on the phase of the NAO, with the negative NAO leading to anomalously cold conditions across the eastern U.S. (Fig. 4b), and the positive NAO leading to anomalous warmth across much of the country (Fig. 4c).

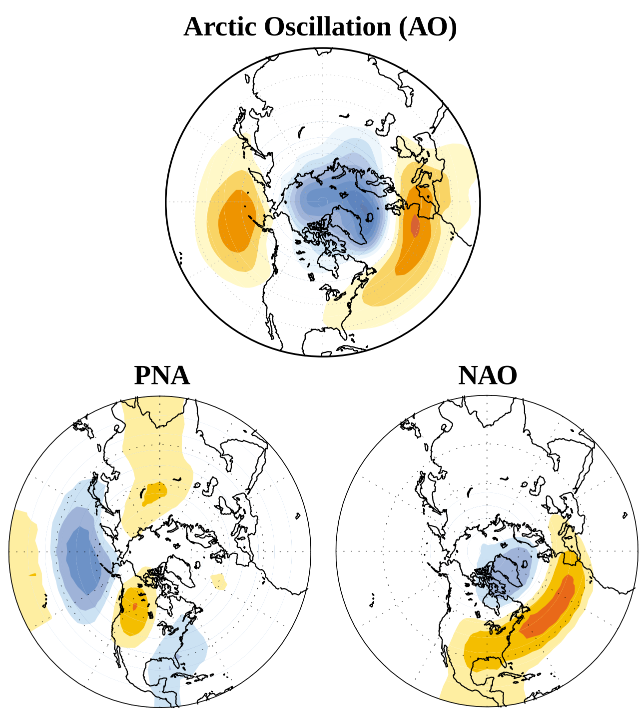

Fig. 3. The positive phases during November-January of (a) the Arctic Oscillation (AO), (b) the Pacific/ North American (PNA) pattern, and (c) the North Atlantic Oscillation (NAO). Positive anomalies are shaded orange and negative anomalies are shaded blue

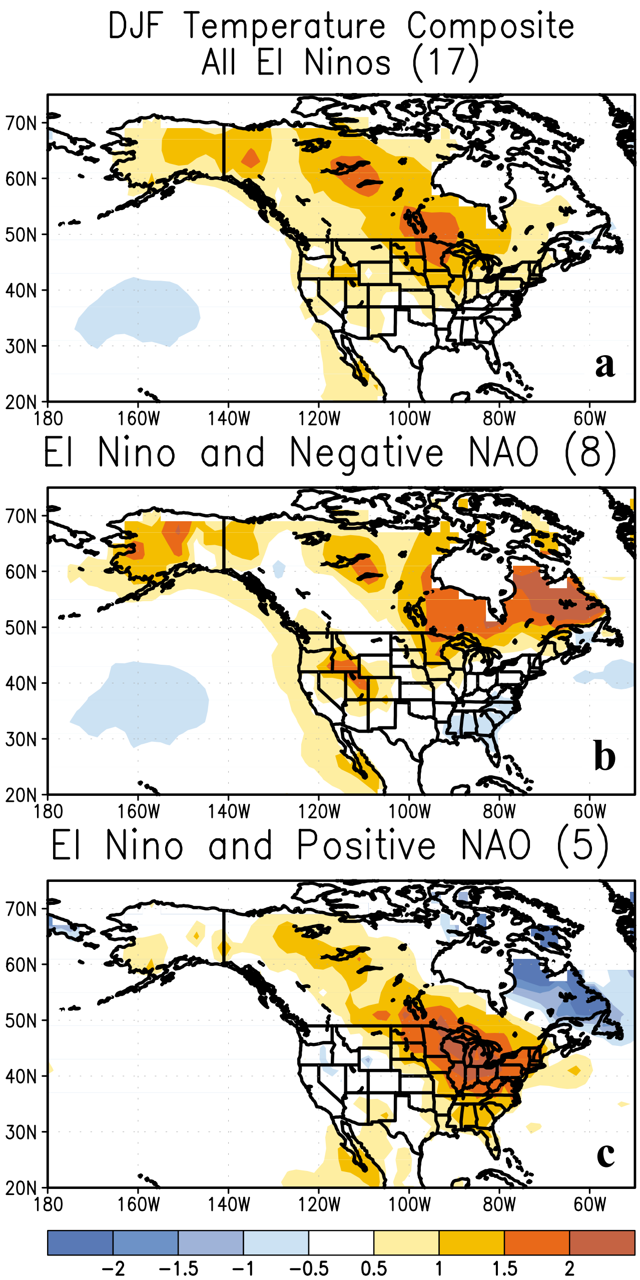

Fig. 4. January-March El Niño composite surface temperature anomalies during: (a) all moderate to strong El Niño's, and the subset of these El Niño's coinciding with the (b) negative and (c) positive phase of the NAO. Red and blue shading indicates warmer and cooler than average conditions, respectively.

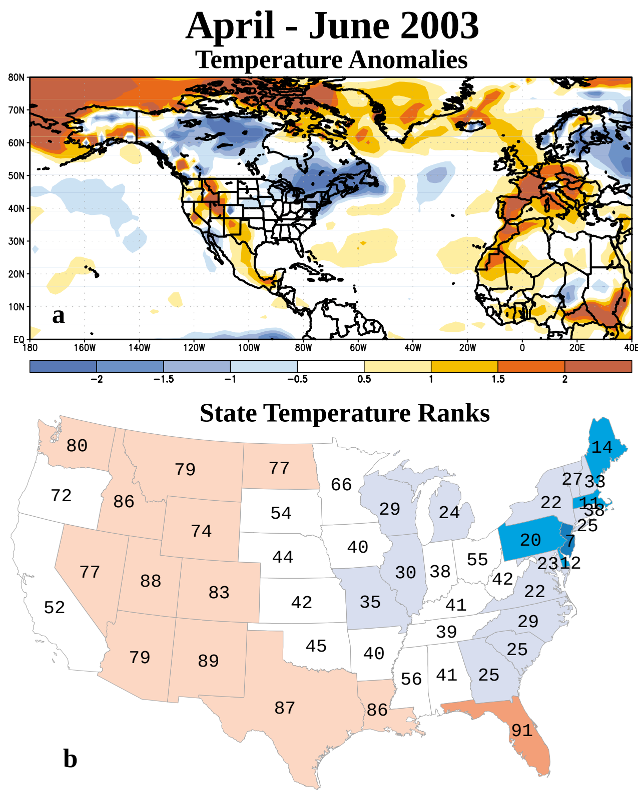

Fig. 5. April-June 2003 (a) surface temperature anomalies and (b) state-wide temperature rankings. A rank of 1 represents the coldest period and a rank of 108 indicates the warmest period in the 108-year record between 1895-2003. Anomalies are departures from the 1971-2000 base period monthly means.

3. April-June 2003 mean temperatures and precipitation

a. United States

During April-June (AMJ) 2003 the largest negative temperature departures (exceeding -2.5°C) covered most of Canada and the extreme northeastern United States (Fig. 5a). In the northeastern U.S. statewide mean temperatures ranked in the coolest 20 percent of occurrences dating back to 1895 (Fig. 5b), with Massachusetts recording its fifth coolest AMJ season on record and New Jersey recorded its seventh coolest. Smaller period mean departures of -1°C covered the Mid-Atlantic States.

Daily surface temperatures at a representative station (Washington D.C.) show distinct cold-air outbreaks in all three months, with the most significant outbreak occurring between mid-May and the end of June when below-average temperatures (Fig. 6a) and measurable rain were recorded nearly every day (Fig. 6b).

Precipitation totals during April-June exceeded 400 mm across the southeastern and eastern U.S. (Fig. 7a), with surpluses exceeding 100 mm throughout the region (Fig. 7b). These totals exceeded 125% of normal from Florida northward to the Ohio valley and eastward to New Jersey, and

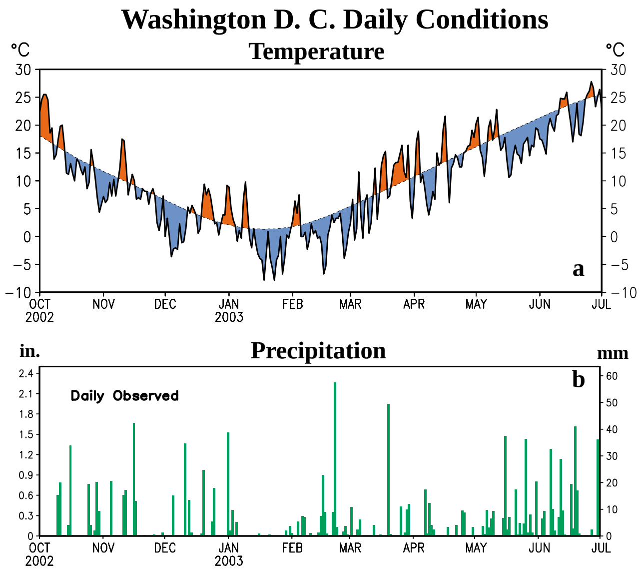

Fig. 6. Daily mean (a) surface temperatures (°C) and (b) precipitation at Washington, D.C. Scale for precipitation is inches (on the left) and mm (on the right).

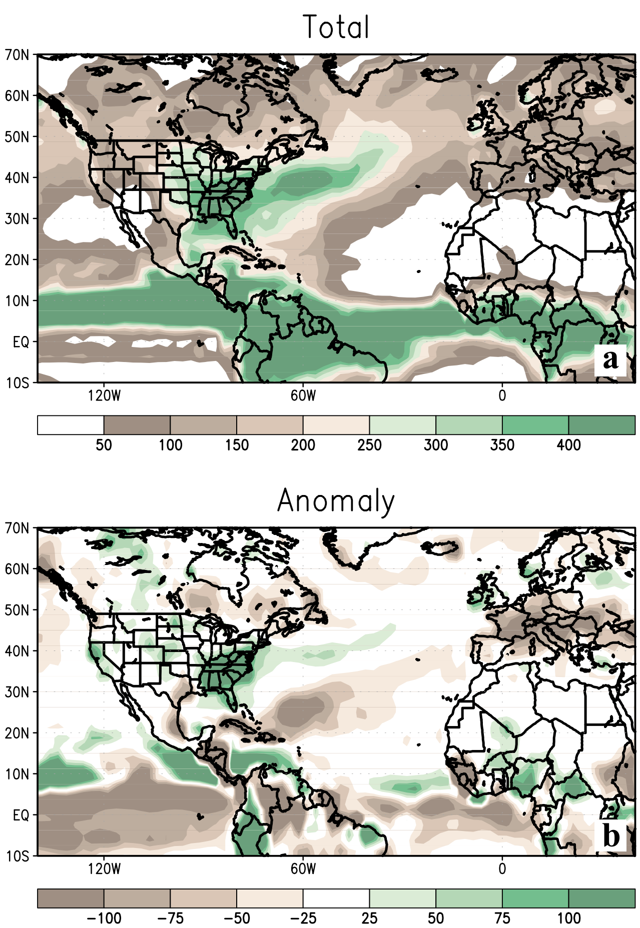

Fig. 7. April-June 2003 precipitation (mm) (a) total and (b) and anomalies. Anomalies are departures from the 1971-2000 climatological mean.

150% of normal from Alabama to Virginia (Fig. 8a).

Virginia and Mississippi experienced their wettest AMJ season on record dating back to 1895 (Fig. 9). Georgia, South Carolina, and North Carolina experienced their second-wettest AMJ season in the record, with near-record totals observed in West Virginia, Kentucky, and Tennessee.

As seen for Washington, D.C. these totals are

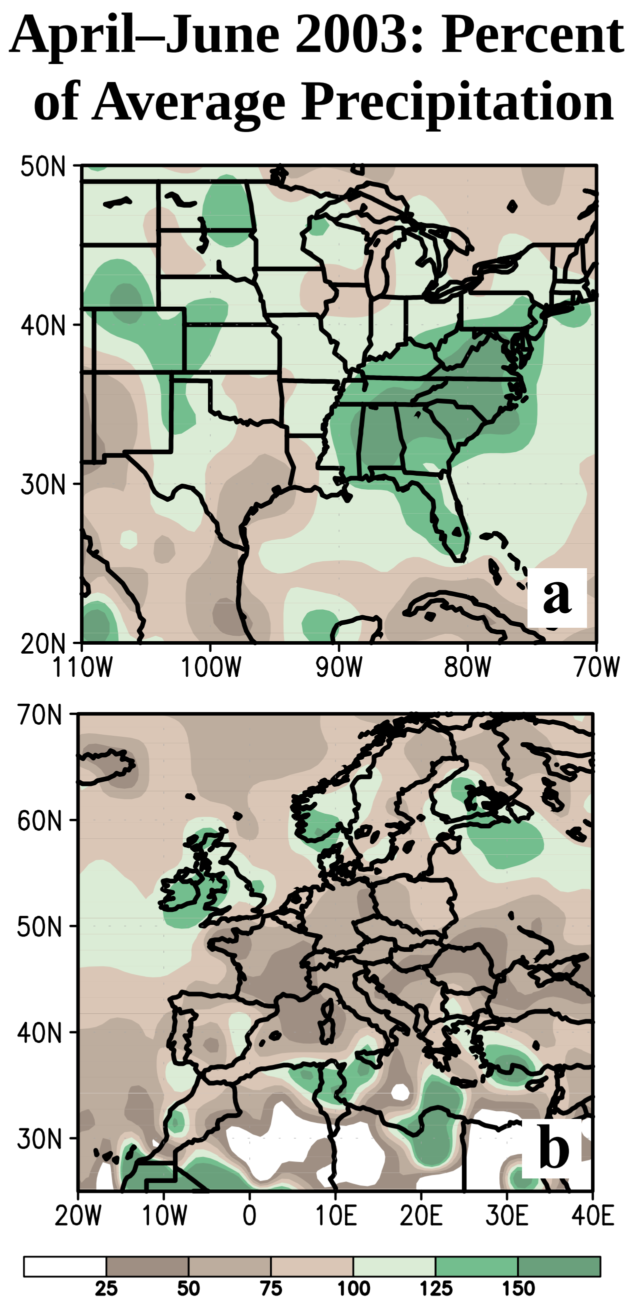

Fig. 8. April-June 2003 percent of normal precipitation for the (a) United States and (b) Europe. Departures are calculated with respect to the 1971-2000 climatological mean

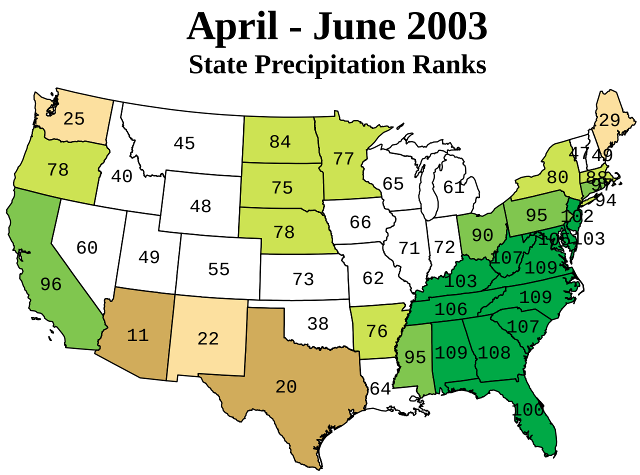

Fig. 9. April-June 2003 state precipitation ranks. A rank of 1 represents the driest period and a ranking of 108 indicates wettest period in the 108-year record between 1895-2003.

related to an increased frequency of precipitation events, as well as to several heavy precipitation events (Fig. 6b). For example, rainfall in the Mid-Atlantic region exceeded 1.0 mm on more than 36 days during the season (Fig. 10a), which is 8-10 days more than the climatological average (Fig. 10b).

At Washington, D.C. measurable rainfall during AMJ occurred on 38 days, with 11 days of rain during April, 19 days of rain during May, and 18 days of rain during June. This station also recorded eleven days with rainfall totals exceeding 12.5 mm (1/2 inch), with ten of these days occurring during the prolonged cold period of mid-May through June.

b. Europe

Southern and central Europe experienced substantially warmer and drier than normal conditions during AMJ 2003, with mean temperatures averaging more than 2.5°C above normal (Fig. 5a). Daily temperatures at a representative station (Rennes) in northwestern France (Fig. 11a) indicate prolonged warm episodes during the period with daily mean temperatures often reaching 5°-7°C above normal. The time series also indicates that the anomalous warmth persisted until mid-September. A near-absence of cold frontal passages is observed throughout this period.

Precipitation deficits across central and southern Europe averaged 100 mm or more during AMJ

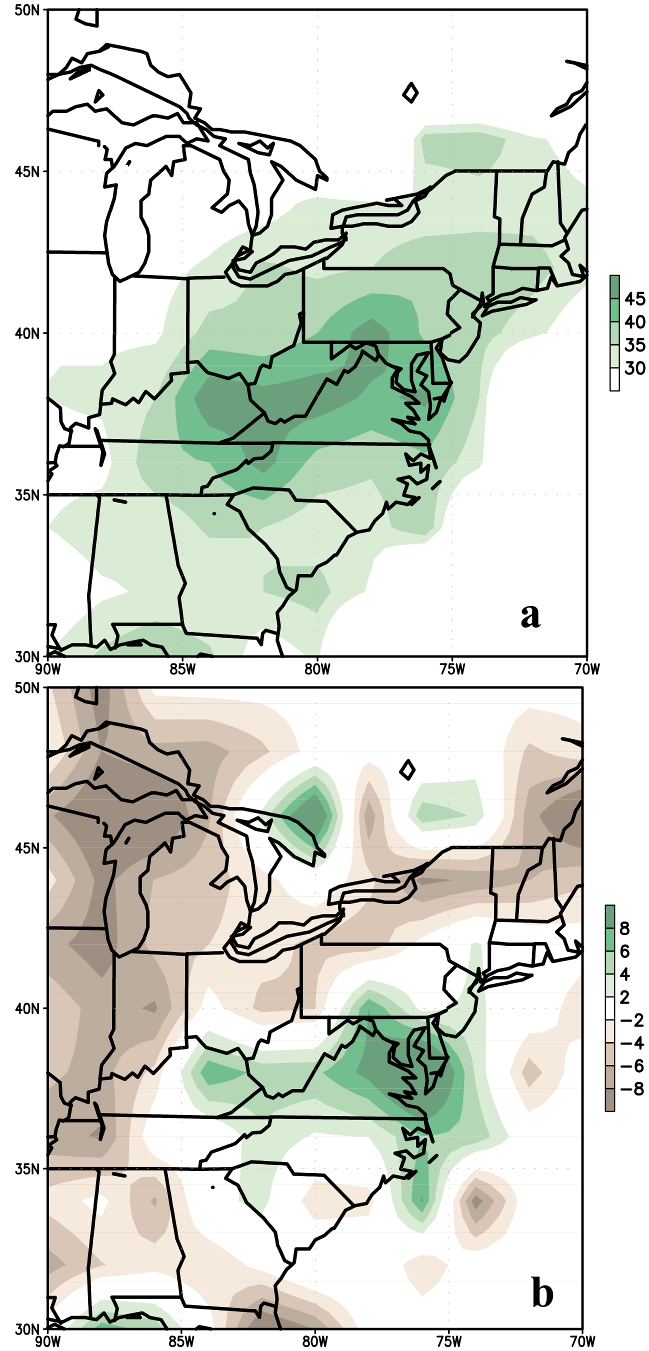

Fig. 10. Number of days during April-June 2003 with precipitation exceeding 1.0 mm: (a) total and (b) anomaly. Anomalies are departures from the 1948-2001 base period seasonal mean.

2003 (Fig. 7b). Seasonal totals were generally less than 75% of normal, with portions of southern and Eastern Europe recording less than 50% of normal rainfall (Fig. 8b). At Nimes in southeastern France measurable rainfall occurred on only four days during April and on two days during May, and on only one day during June and July combined (Fig. 11b).

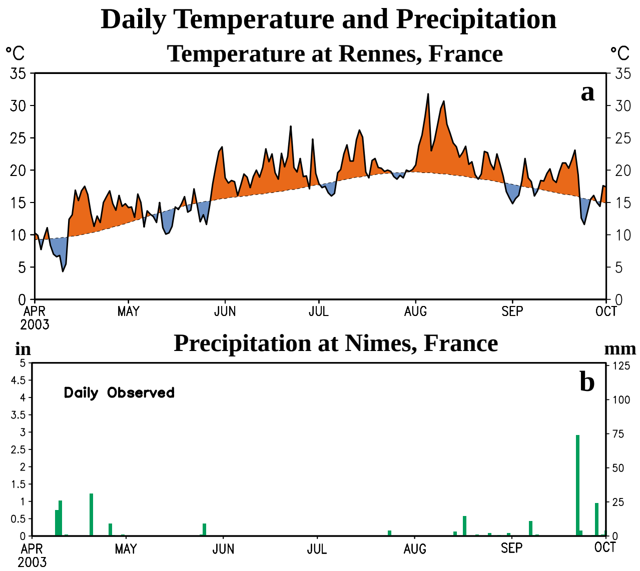

Fig. 11. Daily mean (a) surface temperatures at Rennes, France (°C) and (b) precipitation at Nimes, France. Scale for precipitation is inches (on the left) and mm (on the right).

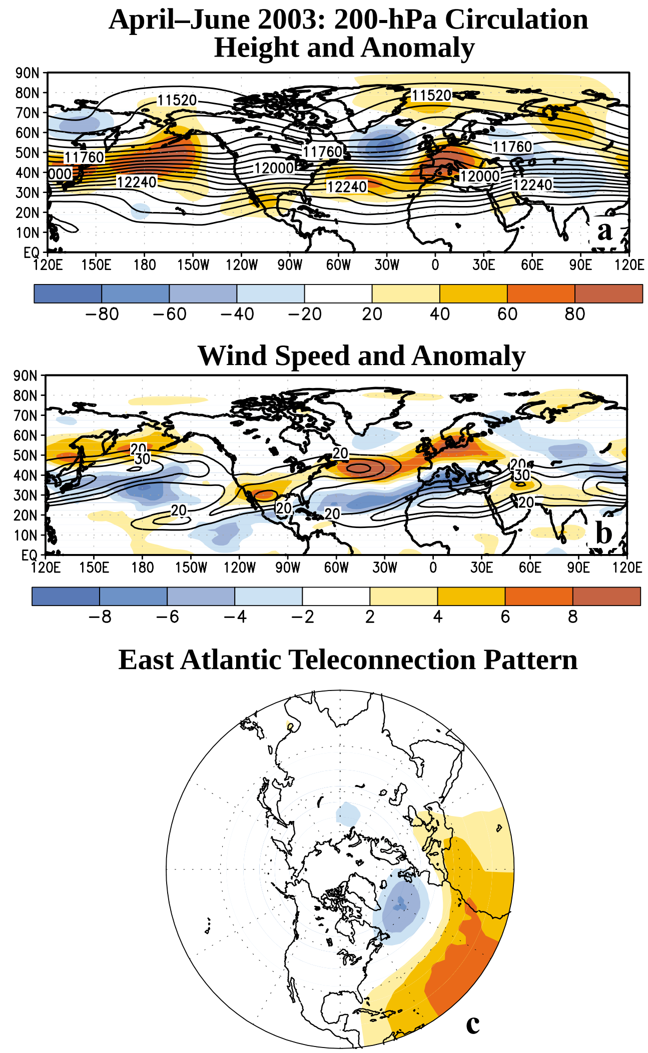

Fig. 12. April-June 2003: 200-hPa (a) heights and anomalies (m), and (b) wind speed and anomalies (m s^{-1}). (c) 500-hpa loading (or anomaly) pattern illustrating the positive phase of the East Atlantic teleconnection pattern based on April-June seasonal 500-hPa height anomalies from 1950-2000. Positive anomalies are shaded orange/ red and negative anomalies are shaded blue.

4. April-June 2003 atmospheric circulation

The mean 200-hPa circulation during AMJ 2003 features above-average heights across the central North Pacific, and from the southwestern United States and Mexico eastward to central Europe, and below-average heights over the higher latitudes of the central North Atlantic (Fig. 12a). For the European sector this circulation is associated with an enhanced and nearly zonal jet stream from southeastern Canada to northern France (Figs. 12b), and with a persistent ridge over Europe. South of the mean jet axis the reduction in the number and intensity of storms and cold frontal passages associated with this circulation contributed to well above-average temperatures and below- average rain across central and southern Europe. These conditions are consistent with the positive phase of the springtime East Atlantic teleconnection pattern (Fig. 12c).

For the Pacific/ North American sector the circulation features an anomalous anticyclonic curvature to the East Asian jet stream (Fig. 12b), with the jet axis and associated exit region extending southeastward into the base of the mean upper-level trough upstream of California. This trough axis also comprises the cyclonic shear side of the entrance region of an enhanced subtropical jet stream, which extends across the southern United States.

This overall circulation contributed to increased storm activity over the southern U.S., with many of these storms subsequently moving along the U.S. east coast (Figs. 13a) on the cyclonic shear side of the amplified subtropical jet (see Serreze (1995) and Serreze et al. (1997) for a discussion of the stormtracks program). This anomalous storm track (Fig. 13b) helps to account for the above-average precipitation across southeastern and eastern U.S. during the season.

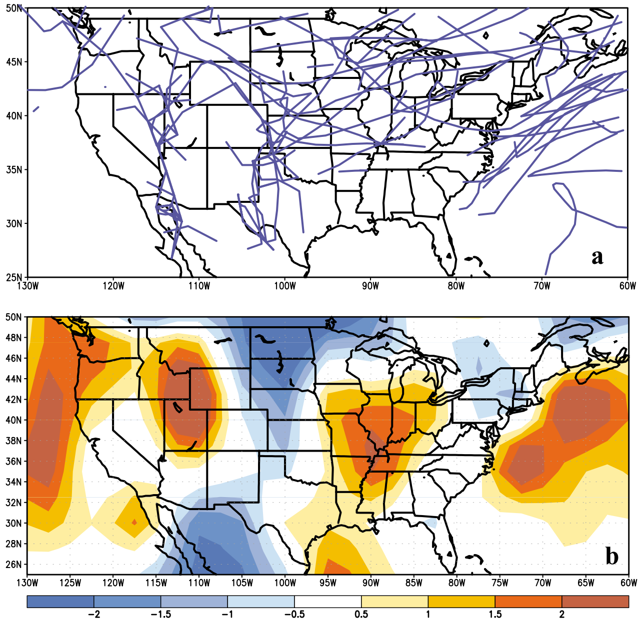

Fig. 13. April-June 2003 storm tracks (a) total and (b) anomaly. Anomalies are departures from the 1948-2001 climatological mean number of storm tracks counted in each 5° latitude x 5° longitude box.

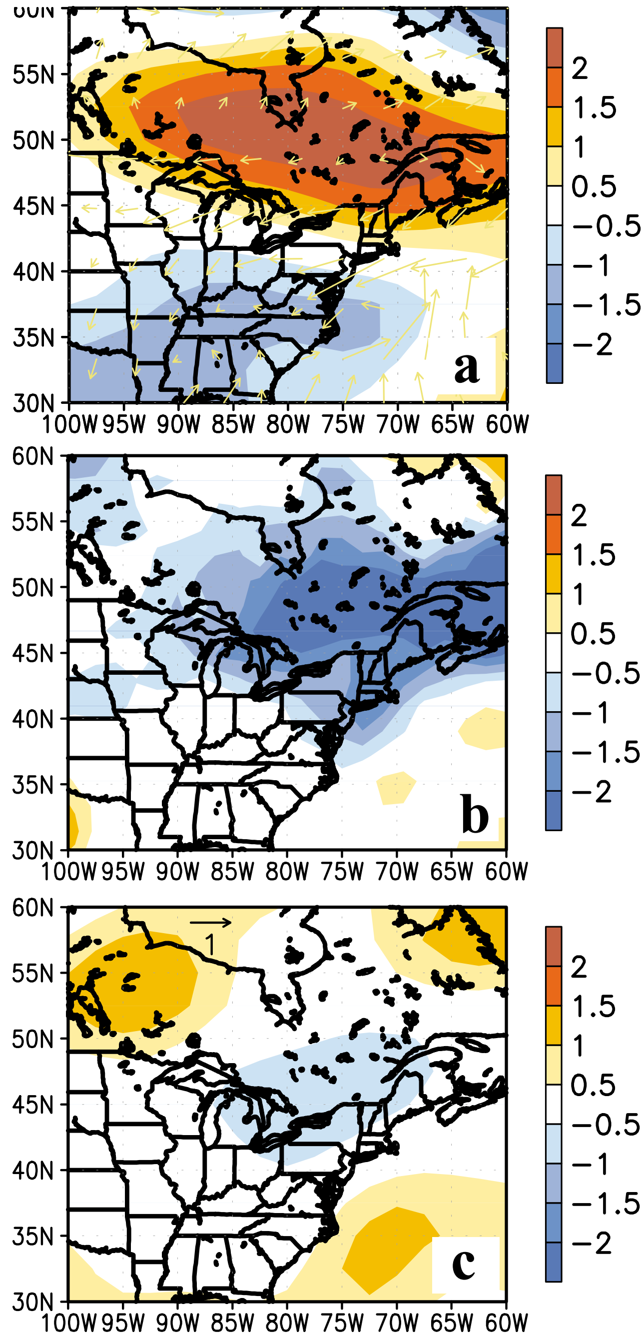

Fig. 14. April-June 2003 anomalous (a) sea-level pressure (hPa) and vector wind, (b) 1000-hPa temperature (°C), and (c) 925 hPa temperature (°C). Anomalies are departures from the 1971-2000 base period means.

The season also featured a dipole pattern of sea-level pressure (SLP) anomalies, with higher SLP over eastern Canada and the northeastern U.S. and lower SLP over the southeastern U.S. (Fig. 14a). This dipole is consistent with below-average temperatures across southeastern Canada and the northeastern U.S. (Figs. 14b, c), and with the enhanced low-latitude storm track.

It is also associated with a frontal boundary off the east coast, which delineates cold, easterly flow in the northeast and Mid-Atlantic regions. Below-average SSTs (exceeding 2°C below average) along the coast likely helped to maintain the exceptionally cold temperatures in these regions (Fig. 15).

At 1000-hPa the anomalously cold air extends southwestward from New England to the Carolina's. However, no such signal is evident just above the peak of the Appalachian Mountains at 925-hPa (Fig. 11c). This shallowness of the cold air, combined with the mean easterly flow impinging on the eastern slopes of the Appalachian Mountains, is suggestive of a meso-scale phenomenon known as Appalachian cold-air damming (Forbes 1986, Bell and Bosart 1988).

5. April-May 2003 Appalachian cold-air damming

a. Temperature

Appalachian cold-air damming is an important part of the eastern United States climate variability. Cold-air damming was observed on ten days

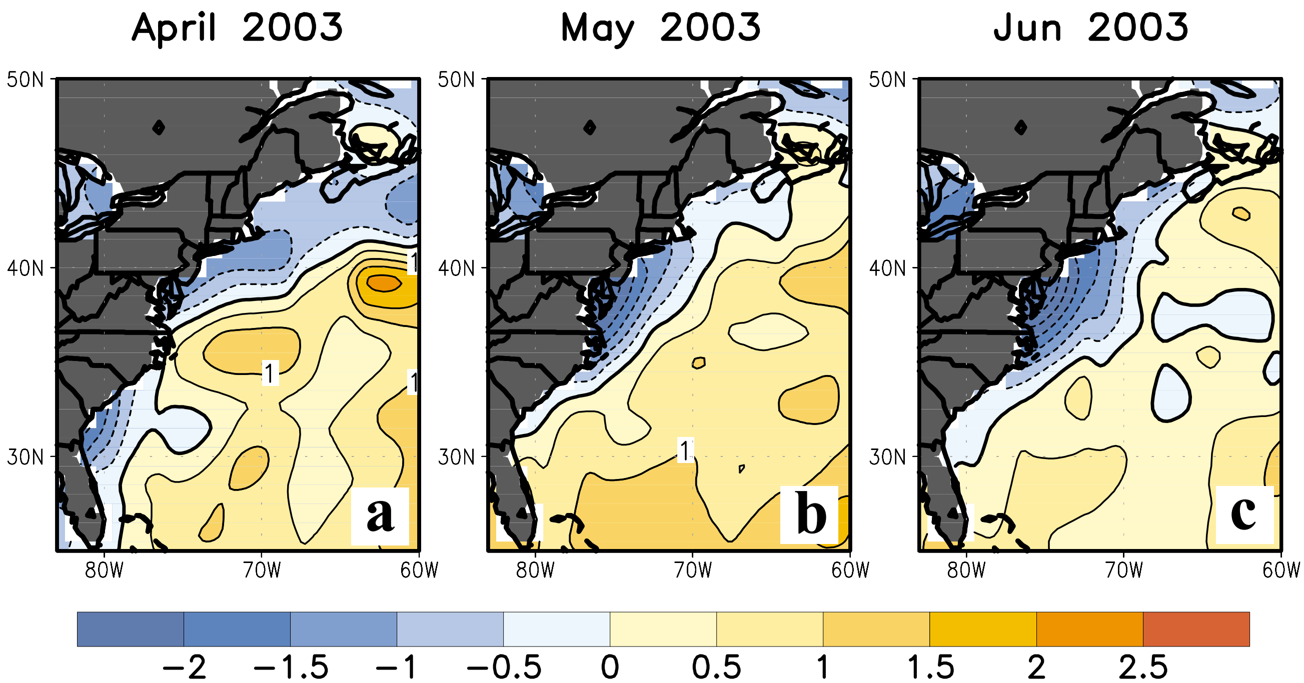

Fig. 15. Monthly sea surface temperatures anomalies (°C) for (a) April, (b) May, and (c) June 2003. Anomalies are departures from the 1971-2000 base period monthly means.

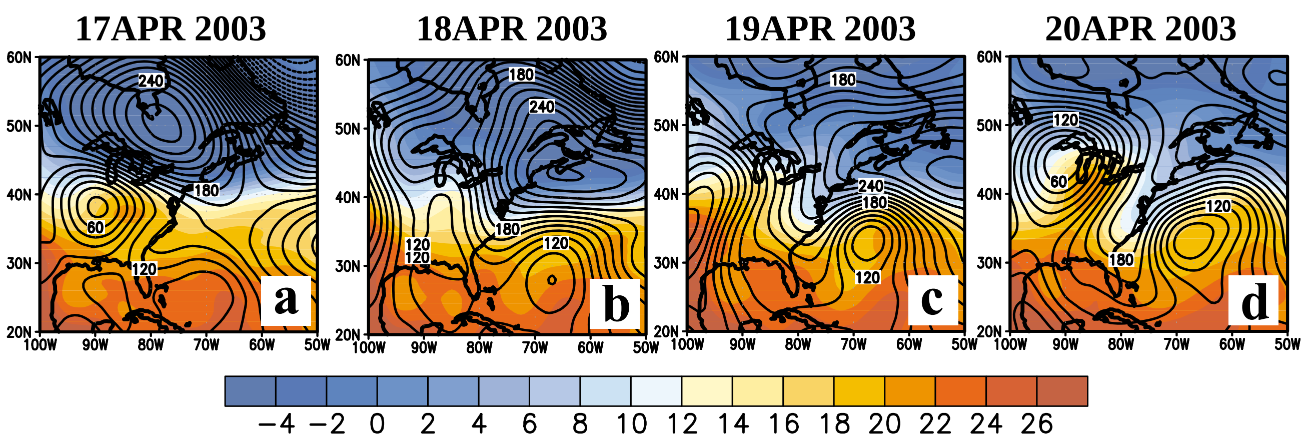

Fig. 16. Daily 1000-hPa heights (m, contours) and temperatures (°C, shading) for (a) 17 April, (b) 18 April, (c) 19 April, and (d) 20 April 2003.

during both April and May 2003, which is approximately twice the climatological average (Bell and Bosart 1988, Bailey et al. 2003). These damming events occurred on 3, 8-10, 18-21 (Fig. 16), and 29 April, and 4-5 and 16-23 May, and accounted for the main cold-air outbreaks in the mid-Atlantic region in both months.

Cold-air damming episodes are often associated with east coast cyclogenesis. A classic cold-air damming/ east-coast cyclogenesis event began on 17 April 2003, as high pressure and cold temperatures moved over southeastern Canada, and a developing low- pressure center moved into the southeastern U.S. (Fig. 16a).

In the Mid-Atlantic region this pressure pattern is associated with strong easterly geostrophic flow impinging on the eastern slopes of the Appalachian Mountains. Being unable to pass over the mountains, this cold air turns southward and accelerates down the large-scale pressure gradient approximately parallel to the mountains (Bell and Bosart 1988). One day later a shallow dome of cold air and its associated pressure ridge (indicated by a "U"-shape in the sea-level isobars) extend southward to central Georgia between the surface and the approximate peak of the mountains near 930-

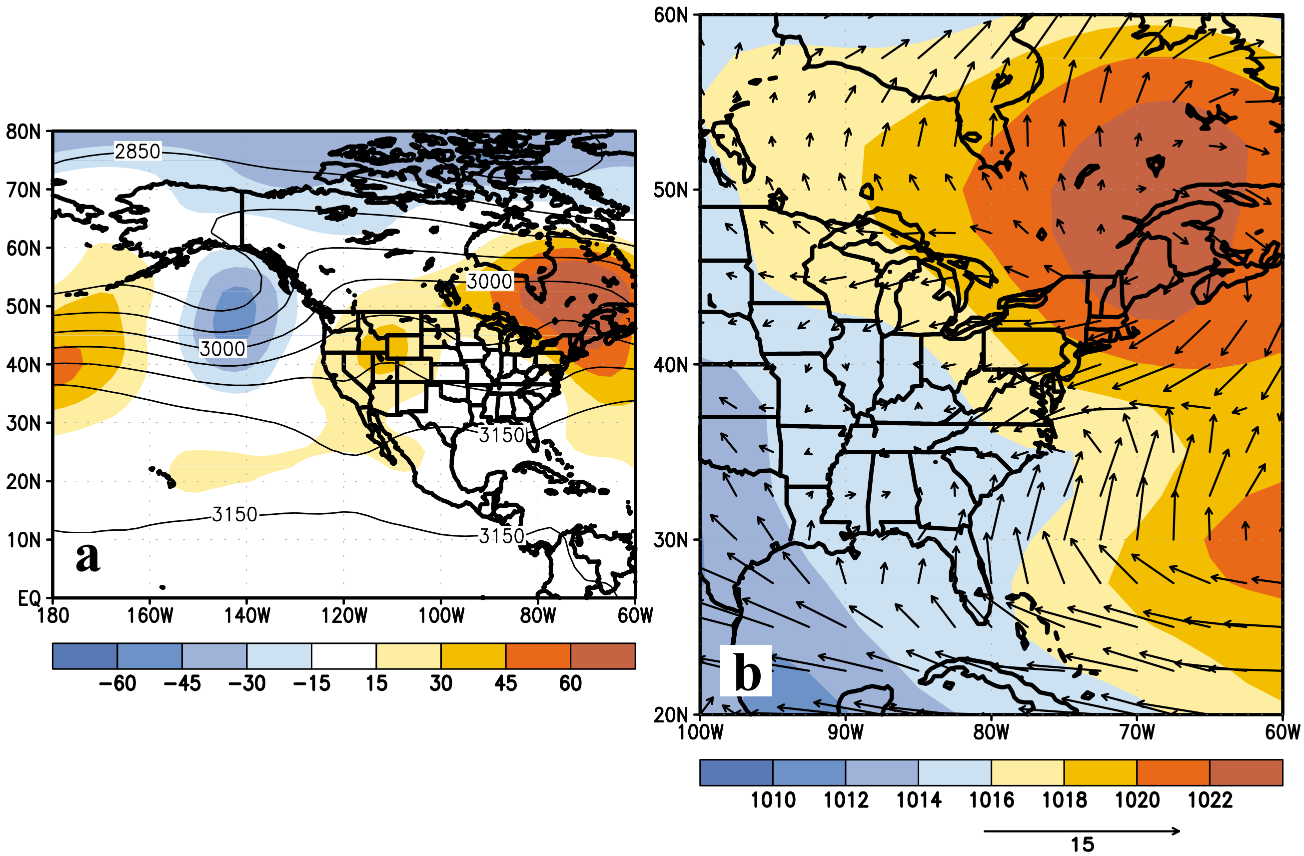

Fig. 17. April-May 2003 composite conditions when daily precipitation totals were at least 6.0 mm in the mid-Atlantic region (35°–40°N, 75°–77.5°W): (a) 700-hPa heights (m, contour) and anomalies (shaded), (b) sea level pressure (hPa) and vector winds (m s^{-1}). Anomalies are departures from the 1979-1995 base period daily means.

hPa (Fig. 16b).

During this period the cyclonic circulation has re-developed off the east coast. During the next two days the pressure ridge and cold dome become better defined as a major east coast storm forms (Figs. 16c, d).

b. Precipitation

Cold-air damming events can influence the precipitation distribution associated with east-coast storms. For example, as upper-level troughs traverse the southern U.S. the southeasterly flow of warm, moist air ahead of the trough axis is forced to rise over the cold dome instead of by orographic uplift closer to the mountain slopes. Also, as the upper-level trough strengthens along the east coast the strong convergence zone (termed a coastal front, Bosart 1975, Stauffer and Warner 1987) between the cold dome and the warm, moist air being brought northward can act to focus heavy precipitation along the eastern seaboard.

For the days during April-May 2003 when precipitation totals exceeded 6.0 mm in the Mid-Atlantic region, the composite daily mean conditions (Fig. 17, 18) are consistent with an enhanced low-latitude storm track and a low-level circulation favorable for both cold-air damming and east coast cyclogenesis. At 925-hPa (Fig. 18b) the mean warm frontal position is displaced to the northwest of the surface frontal position separating cold northeasterly winds from the southerly flow farther south, indicating that precipitation in this region is associated with a significant flow of warm, moist air over the cold dome.

For the dry days in the Mid-Atlantic region opposite circulation anomalies at 700-hPa are seen across eastern North America (Figs. 19a), with below-average heights across eastern Canada and above-average heights over the Mid-Atlantic. The mean sea-level pressure field and north-south pressure gradient is also reversed from the wet periods (Fig. 19b). These conditions are accompanied by a strong low-level anticyclonic flow of mild air extending from the Gulf of Mexico into most of the eastern United States.

The associated mean warm-frontal position is located over the extreme northeastern U.S. during these periods, which helps to confine anomalously cold air to eastern Canada and northern New England (Fig. 20). These conditions are neither associated with nor conducive to a low-latitude storm track, cold-air damming, or east coast cyclogenesis.

During June rainfall in the Mid-Atlantic region is linked to the passage of

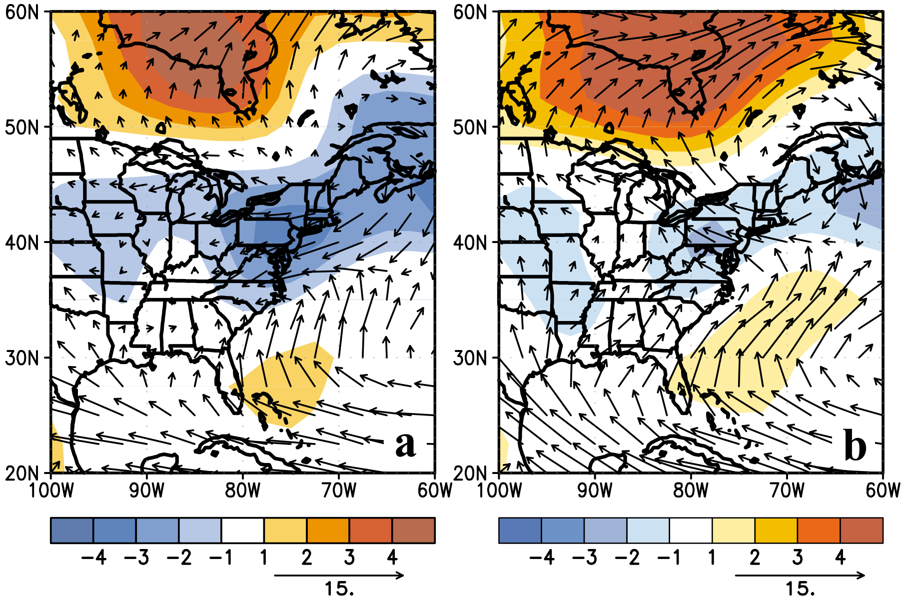

Fig. 18. April-May 2003 anomalous temperatures (°C) and total vector wind (m s^{-1}) at (a) 1000-hPa and (b) 925-hPa when daily precipitation totals were at least 6.0 mm in the mid-Atlantic region (35°–40°N, 75°–77.5°W). Anomalies are departures from the 1979-1995 base period daily means.

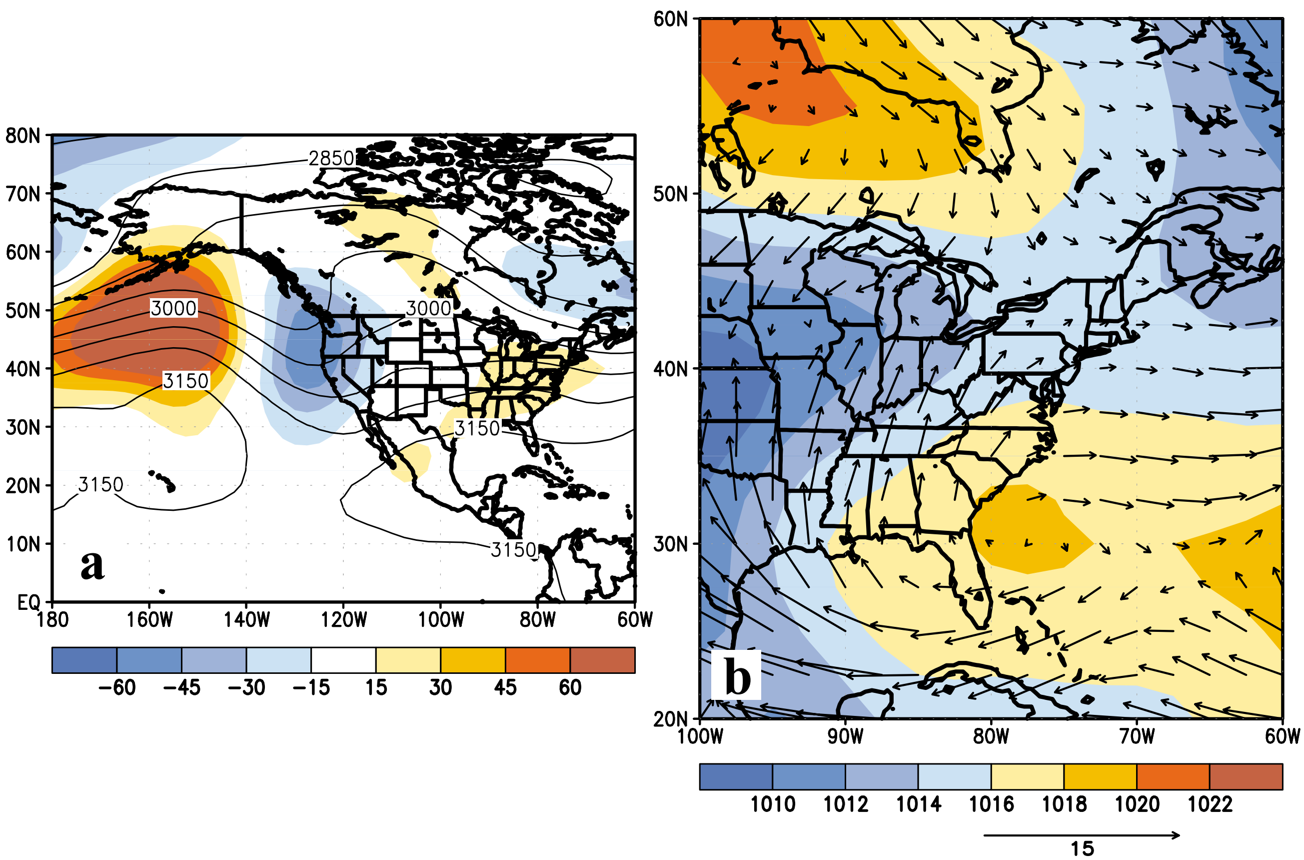

Fig. 19. April-May 2003 composites for days when less than 1.0 mm of rain was observed in the mid-Atlantic region (35°–40°N, 75°–77.5°W): (a) 700-hPa heights (m, contour) and anomalies (shaded), (b) sea level pressure (hPa) and vector winds (m s^{-1}). Anomalies are departures from the 1979-1995 base period daily means.

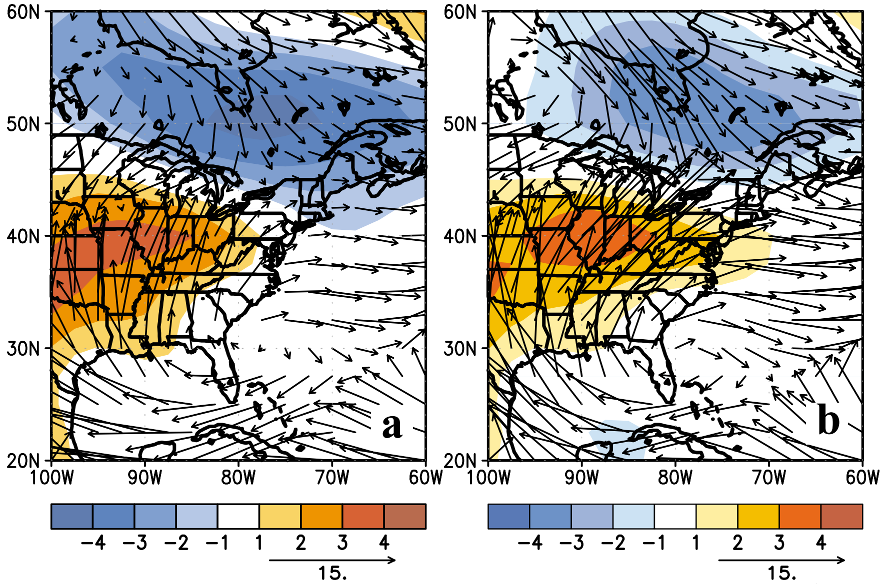

Fig. 20. April-May 2003 anomalous temperatures (°C) and total vector wind (m s^{-1}) at (a) 1000-hPa and (b) 925-hPa when less than 1.0 mm of rain was observed in the mid-Atlantic region (35°–40°N, 75°–77.5°W). Anomalies are departures from the 1979-1995 base period daily means.

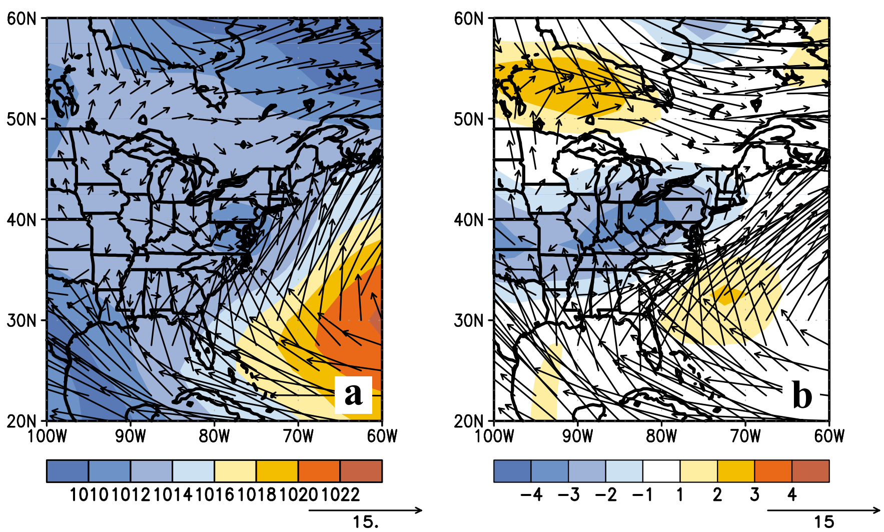

Fig. 21. June 2003 composite conditions for days with precipitation > 6.0 mm in the mid-Atlantic region (35°–40°N, 75°–77.5°W): (a) SLP (hPa, shading) and total vector winds, and (b) 925-hPa anomalous temperatures (°C) and total winds. Anomalies are departures from the 1979-1995 base period daily means.

several cold fronts that span the north-south extent of the U.S. (Fig. 21). A pronounced confluence zone between northwesterly flow over the central and eastern U.S. and broad southerly flow along the east coast defines the mean position of these cold fronts during the rainy periods. These frontal passages are also the primary cause of the anomalously cool conditions across the eastern half of the U.S. during the month.

6. Discussion

The eastern United States experienced exceptionally cool and wet conditions during October 2002 - June 2003 in response to three distinct circulation regimes. The first two regimes covered the period October-May and are associated with an enhanced subtropical jet stream and increased storm activity along the southern United States.

During the first circulation regime (October-January) these conditions are linked to a combination of El Niño and the negative phase of the Arctic Oscillation (AO). These combined modes incorporate a positive phase of the Pacific/ North American (PNA) teleconnection pattern and negative phase of the North Atlantic Oscillation (NAO). The associated circulation features included an amplified ridge-trough system across central North America, an enhanced jet stream across the southern U.S., and a corresponding shift in the main storm track to the southern and eastern states. This anomalous circulation resulted in exceptionally warm temperatures in the West, and cool and wet conditions in the East.

The second circulation regime (April-May) featured increased Appalachian cold-air damming, as opposed to large-scale Canadian cold-air outbreaks. These damming episodes, combined with the enhanced jet stream and storm track across the southeastern United States, contributed to continued cool and wet conditions in the East. No links to either the AO or El Niño are identified for this period.

During the third circulation regime (June) cool and wet conditions spanned the eastern half of the U.S. in response to the passage of several major cold frontal passages. The southward extent of these frontal systems is related to a broad upper-level trough over the central U.S.

Over the North Atlantic the mean upper-level circulation during October 2002 – June 2003 featured below-average heights at high latitudes and above-average heights in the middle latitudes. This circulation is associated with an overall southward shift of the North Atlantic jet stream and storm track, and a more zonal orientation of that jet from the eastern North America to Europe. This circulation was particularly prominent during October-January, and resulted in anomalously warm conditions across central and southern Europe.

During April-June 2003 similar height anomalies over the North Atlantic were combined with a persistent upper-level ridge across Europe. Central and southern Europe experienced anomalously warm and dry conditions during this period due to their location beneath the upper-level ridge and south of the mean jet axis. This area of the flow is known to be associated with large-scale sinking motion, and with a reduction in the number and intensity of storms, precipitation events, and cold frontal passages. The exceptionally warm and dry weather subsequently persisted until mid-September.

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