Finch, J., and D. Bikos, 2012: Russian tornado outbreak of 9 June 1984. *Electronic J. Severe Storms Meteor.*, **7** (4), 1–28.

Electronic Journal of
SEVERE STORMS METEOROLOGY

Russian Tornado Outbreak of 9 June 1984

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(Submitted 9 September 2011; in final form 20 August 2012)

ABSTRACT

The tornado outbreak of 9 June 1984 is among the most important tornado events in Russia's history because it was associated with substantial loss of life (400 deaths), and contained one of two F4 tornadoes on record for that country. Also, a 1-kg hailstone was observed, comparable to the heaviest on world record. The synoptic and mesoscale environments are examined and previous studies of this case are revisited to confirm or dispute findings. One of the major findings in dispute is the source of the low-level moist air mass, which is shown to be the Black Sea. Due to the paucity of previous studies, the authors also surveyed the typical sources of low-level moisture for tornado events in the western part of the former Soviet Union.

Despite the limited information available about the tornadoes for this case (at least relative to significant tornado events in the United States), the authors present details from eyewitness accounts, previous studies, and modernized updates from the European Severe Weather Database (ESWD). Satellite data were studied in order to augment this limited information and to refine event locations and times. A map of storm tracks is presented, along with reasons why it differs in some instances from previous studies.

1. Introduction

On 9 June 1984, at least eight tornadic thunderstorms tracked across western Russia, producing severe weather mainly between 0600–1600 UTC (1000–2000 Moscow daylight saving time [MT]). There have been several scientific papers published on Russian tornadoes, some including information about the 9 June 1984 events. Vasiliev et al. (1985a) provided the most detail, documenting five separate areas with tornado or wind damage across Russia. Some of these details suggest that the Ivanovo tornado was violent, which is rare in Russia. According to Snitkovskii (1987), only two events since 1844 were rated as F4 on the Fujita damage scale (Fujita 1971), the Moscow tornado of 29 June 1904 and the Ivanovo tornado that is the focus of this paper. Human deaths from tornadoes in Russia are rare; and multiple tornadoes on the same day are quite uncommon as well. The number of fatalities on 9 June 1984 is reported; however, the details are uncertain and will be discussed in section 5a. Thus, this severe weather event is worthy of further investigation.

Climatological information on Russian tornadoes was presented by Lyakhov (1986), Snitkovskii (1987), Vasiliev et al. (1985a), and Peterson (2000). These works reveal that the majority of tornadoes occur west of the Ural Mountains in western Russia. The tornado season there and in the adjacent republics of eastern Europe generally extends from late April to mid September, with a peak in June and July. Snitkovskii (1987) presented details of all

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tornado reports (including estimates of tornado intensity) from 1844–1986, and a brief summary of surface and 500-hPa patterns accompanying these tornadoes for cases since the 1950s. The typical upper-air pattern for the northwestern part of the former Soviet Union is a deep 500-hPa trough to the west of the affected area with a strong southwesterly jet over the region.

This paper presents the synoptic setting for the 9 June 1984 tornado outbreak, including detailed surface charts using continuity, upper-air charts, composite charts and satellite-image overlays. A modified sounding and hodograph are presented that likely represent the conditions associated with the Ivanovo tornado.

One of the major objectives of this study is to investigate the source of low-level moisture, a topic about which the authors disagree with findings from a previous study. We also expanded this objective to determine the typical source(s) of low-level moisture for F2+ tornado events in western Russia and the adjacent republics of eastern Europe.

Another major objective is to document the locations and times of severe weather reports, noting any discrepancies with Vasiliev et al. (1985a). To do so, the authors used satellite imagery, newspaper descriptions, the European Severe Weather Database (ESWD) (European Severe Storms Laboratory 2011) and information within Vasiliev et al. (1985a) to construct a map of the thunderstorm paths that were associated with tornadoes and/or wind reports and a possible record hailstone weight. The map confirms some findings, but also highlights significant differences with Vasiliev et al. (1985a).

2. Synoptic overview

a. Surface and upper-air evolution

At 0000 UTC 8 June (0400 MT), a 500-hPa longwave trough extended from western Poland to the Adriatic and Mediterranean Seas (Fig. 1). A shortwave trough extended from the northern Adriatic Sea southward through Italy. From 0000 UTC 8 June to 0000 UTC 9 June, this intense shortwave trough progressed eastward through the longwave trough from Italy (0000 UTC 8 June) to Bulgaria (1200 UTC 8 June) to southern Ukraine (0000 UTC 9 June). By 0000 UTC 9 June (0400[MT]) the system already had become negatively tilted and was about to move rapidly to the north-northeast across Ukraine and western Russia.

By 0600 UTC 8 June (Fig. 2), a pre-existent area of surface low pressure (≈1000 hPa MSL), possibly forced by a combination of mid-level downslope flow from the mountainous regions of Bulgaria and coastal effects, was deepening slowly. In response to strong, synoptic-scale forcing ahead of the shortwave trough, surface cyclogenesis commenced along the Romanian coast by 1200 UTC 8 June (Fig. 2).

Surface dewpoints increased to the 18–20°C range along the Romanian and Ukrainian coastlines by 0900 UTC 8 June as low-level moisture was advected onshore by southeasterly to southerly winds from the Black Sea. These dewpoints closely correspond to the climatological sea surface temperatures of the Black Sea (Shapiro 2010) derived from buoy and ship data. Surface analyses for 0900–1200 UTC 8 June show that surface temperatures and dewpoints (30–32 °C and 7–12 °C respectively) were higher and lower respectively in the areas immediately north of the Crimean Mountains (location depicted in Fig. 3). This is likely the result of downslope flow from the Crimean Mountains, which range in elevation from 500–1500 m. A local maximum in low-level moisture was evident along the northwest coast of the Black Sea as shown in the 1200 UTC 8 June Odessa sounding (Fig. 4, in red). Thunderstorms moved into this moist air mass from the southwest. Outflow from these thunderstorms moved northeastward and covered areas from central Ukraine northeastward into central Russia by 1800 UTC 8 June (10 pm MT).

At 0000 UTC 9 June, the deepening surface low was located over northern Ukraine beneath the left-exit region of the 300-hPa jet streak that extended from western Turkey across the western Black Sea (Fig. 5). As the 500-hPa trough became more negatively tilted between 0000 and 1200 UTC 9 June, the surface low moved north-northeastward through 0300 UTC 9 June and then almost due northward between 0300 UTC and 1200 UTC into northwestern Russia (see Fig. 2) before occlusion started. The

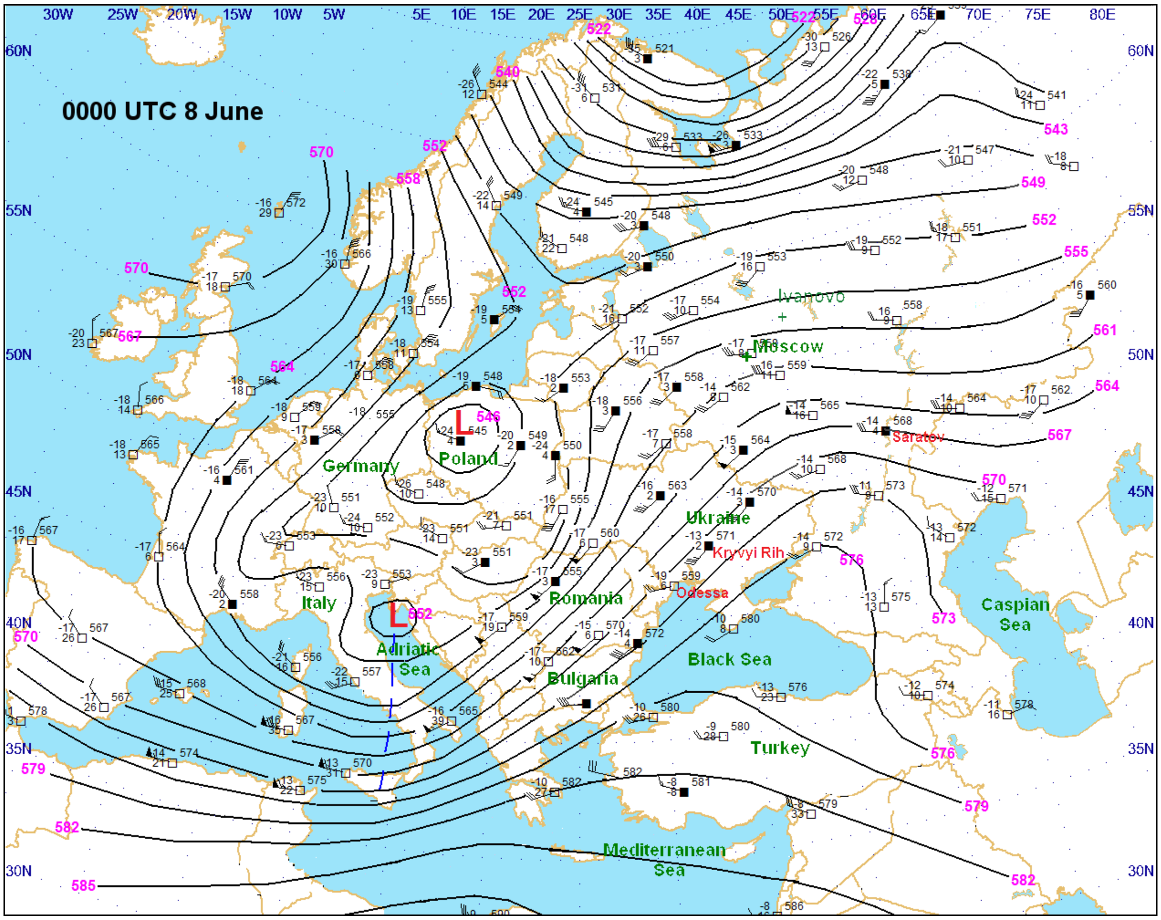


Figure 1. 500-hPa analyses from 0000 UTC 8 June to 1200 UTC 9 June 1984. Heights in dam, temperatures in °C and winds (half barb = 2.5 m s^{-1}, full barb = 5 m s^{-1}, pennant = 25 m s^{-1}). Static (initial) image depicted is 0000 UTC 8 June. *Click image to open animation and enlarge. Countries/cities/seas and latitude/longitude may be toggled on for geographic reference.*

aforementioned outflow boundary stalled after 1800 UTC 8 June and then became a warm front moving northward with the surface low after 0300 UTC 9 June. By 0000 UTC 9 June the surface low had deepened by 9 hPa and increased in speed to 60 km h^{-1} during the last 12 h. The rapid northward movement of the surface low resulted in a strong southerly advection of moisture from the Black Sea into western Russia.

Vertical boundary-layer mixing in the warm sector of the developing low-level cyclone probably diluted the low- level moisture, with a decrease in surface dewpoints immediately north of the Black Sea to 12–16 °C. This reduction in surface dewpoint also may have been partly a result of downslope flow from the Crimean Mountains (Fig. 3), similar to what occurred on 8 June (section 2a); however, this was a localized terrain effect confined to regions immediately north of the Crimean Mountains.

The cold front moved rapidly eastward, and by 0600 UTC extended south-southeastward from the surface low to the eastern extremity of the Black Sea, effectively cutting off the Black Sea from the low-level inflow into the system (see Fig. 2). The fetch farther south in the warm sector was entirely over land by this time. More specifically, for regions >400 km south of the warm front, the combination of strong winds and daytime heating (temperatures 5–10 °C warmer than near the warm front) resulted in greater vertical mixing compared to regions further north, in turn reducing the dewpoints. The 1200 UTC sounding from Saratov (Fig. 6) is representative of this warm, well-mixed air mass.

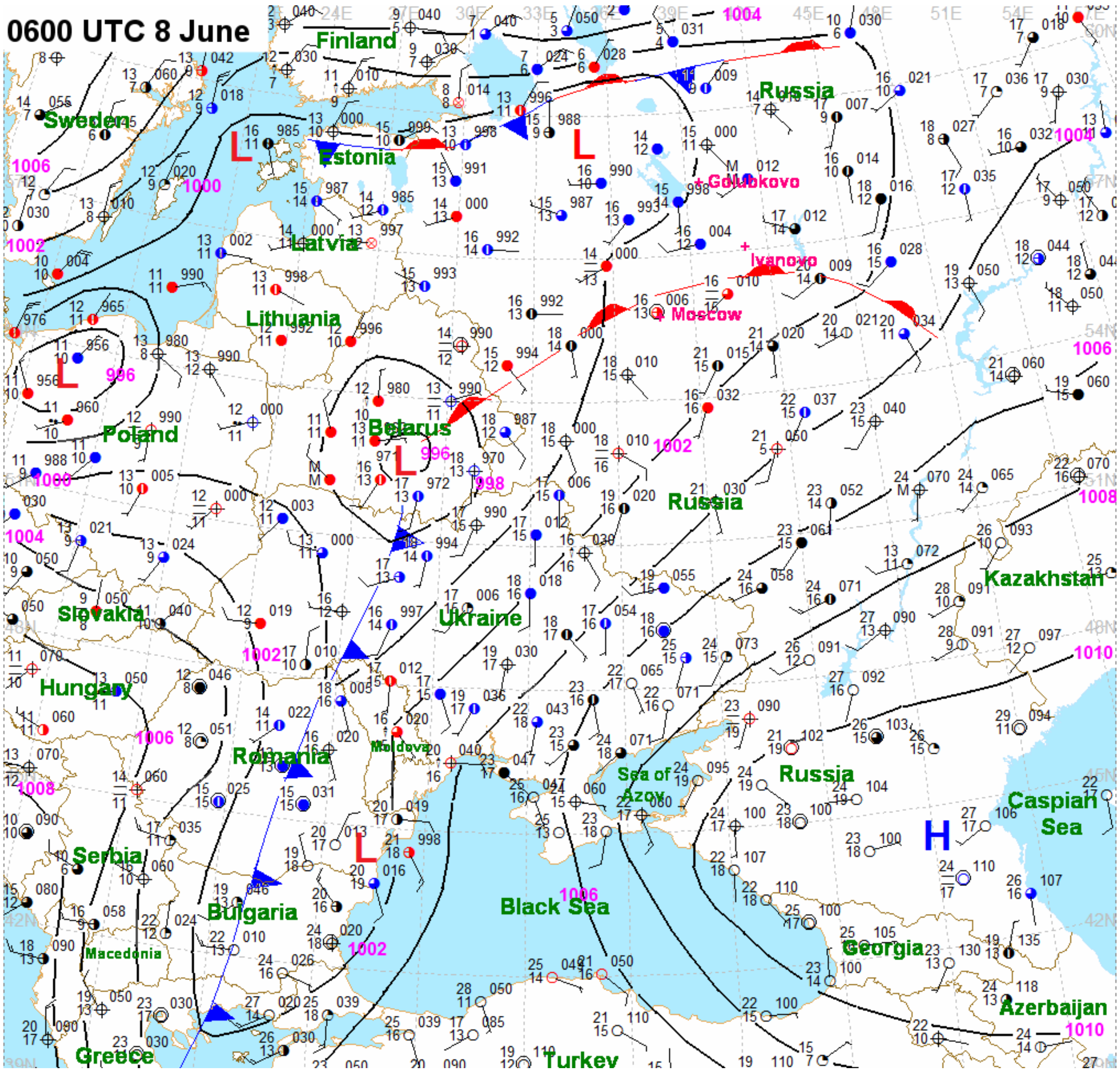


Figure 2. Surface analysis loop from 0600 UTC 8 June to 1500 UTC 9 June 1984 in 3-h intervals. Black lines are MSLP (hPa); fronts are annotated. Static (initial) image depicted is 0600 UTC 8 June. Latitude/longitude lines are labeled. Surface-based (SB) CAPE and mass divergence (10^{-6} s^{-1}) for 0600–1200 UTC 9 June available as an overlay. *Click on the image to open animation and enlarge*. *Countries, cities and seas may be toggled for geographic reference.*

The exit region of the 300-hPa jet streak crossed the cold front (Fig. 5 at 1200 UTC) and contributed to the strong synoptic scale ascent favorable for thunderstorms that developed in the northwestern part of the warm sector (Beebe and Bates 1955). At lower levels, the leading edge of the 700-hPa speed maximum (not shown) contained wind speeds from 25–30 m s^{-1} (50–60 kt), and was moving into the region that experienced severe storms.

The most damaging tornado of the outbreak was in progress a few kilometers north of Ivanovo at 1200 UTC. The Ivanovo storm was located under the exit region of the 300-hPa jet streak (as shown in Fig. 5). The exit region of the upper-level jet was found to be important in severe weather events (Clark et al. 2009) and for possible coupling between upper- and low-level jet streaks (Uccellini and Johnson (1979). The 300-hPa wind at Vologda (250 km to the north-northwest of Ivanovo) may have been influenced by convection since a tornadic storm was located upstream to the south around 1200 UTC. If so, then the wind in the vicinity of the storm may have been stronger than analyzed in Fig. 5.

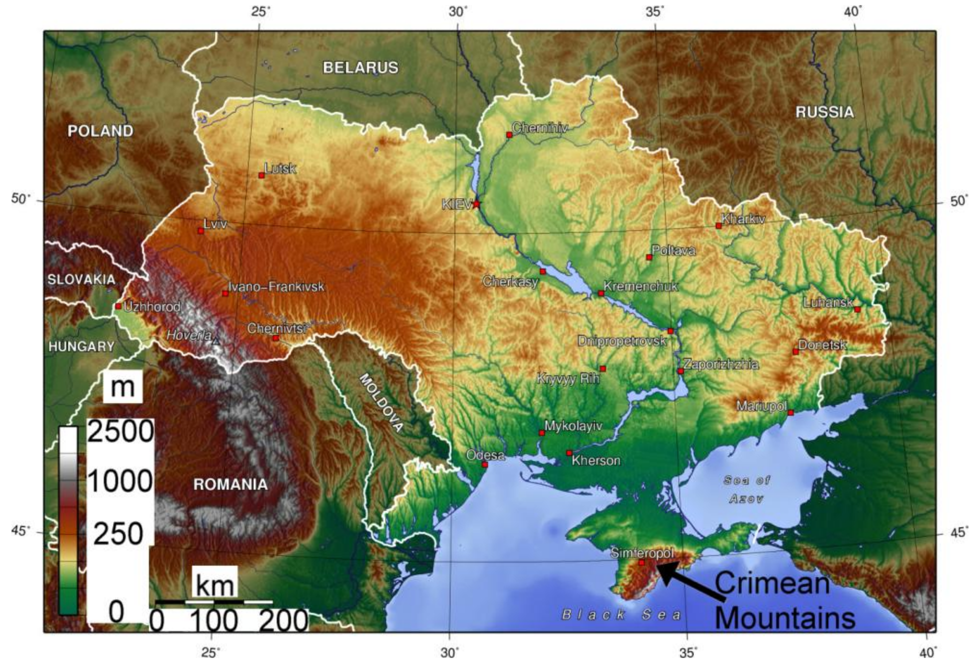


Figure 3. Topographic map of the Ukraine (non-shaded / brighter region). *Click image to enlarge.* Map courtesy of http://www.world-geographics.com

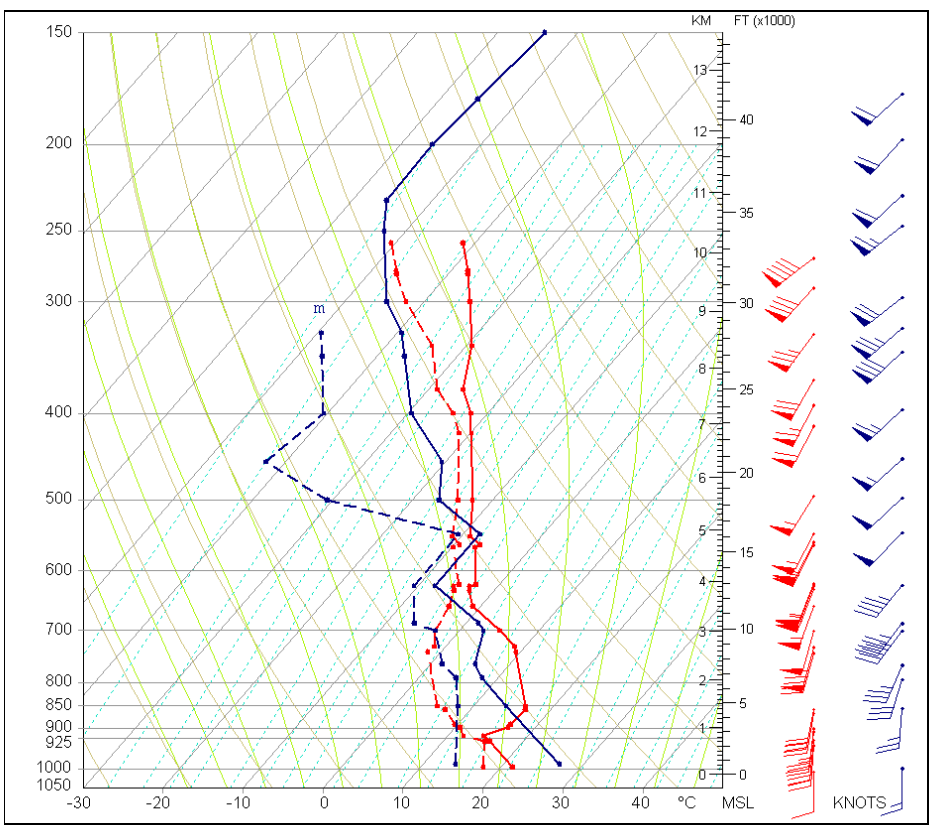


Figure 4. Skew *T*–log*p* diagram of soundings for Odessa (red) and Kryvyi Rih (blue), Russia, valid 1200 UTC 8 June 1984. Temperature (solid line), dewpoint temperature (dashed line) and winds (half barb = 2.5 m s^{-1}, full barb = 5 m s^{-1}, pennant = 25 m s^{-1}). Sounding locations depicted in red font on Fig 1. *Click image to enlarge.*

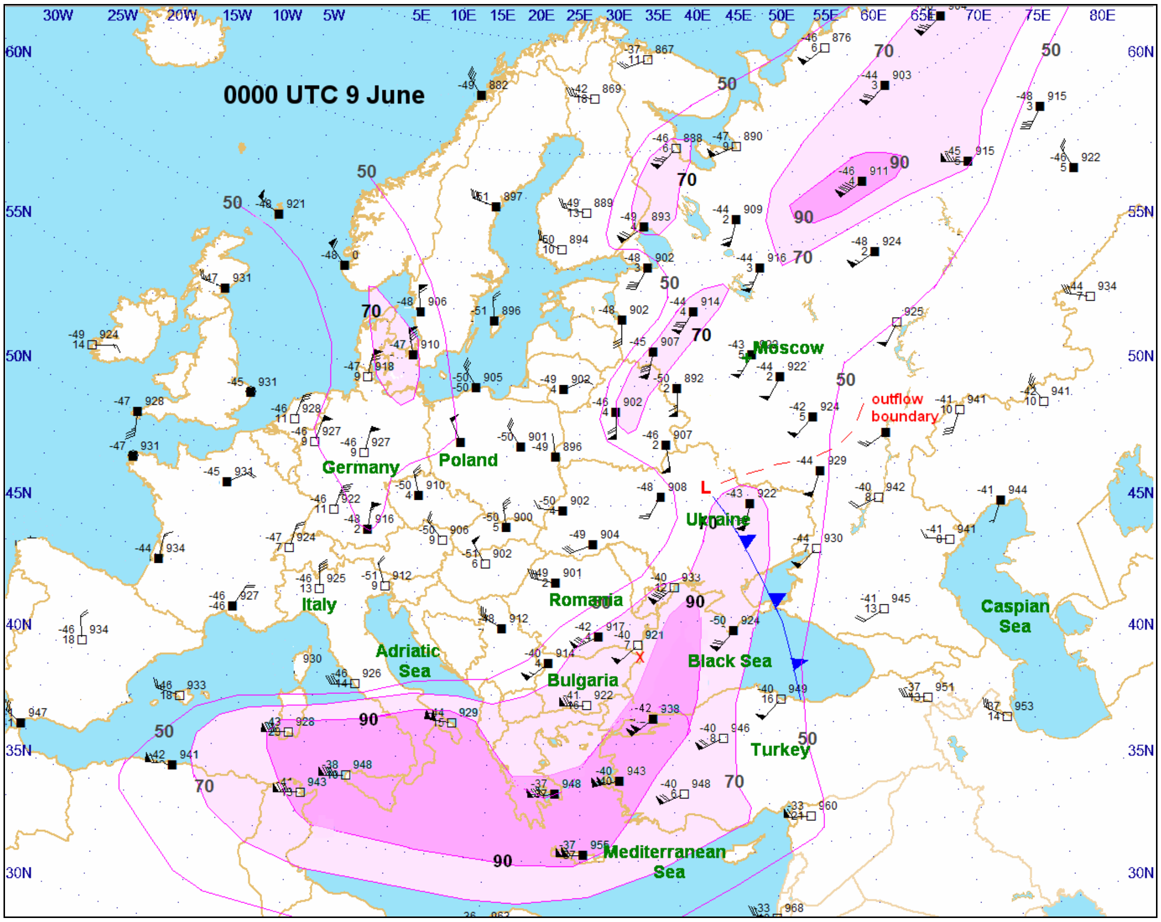


Figure 5. 300-hPa analyses at 0000 UTC (frame 1) and 1200 UTC (frame 2) 9 June 1984 (following Fig. 1 convention). The surface low and fronts are superimposed. Isotachs are shaded and given in kt (divide by 2 for approximate m s^{-1}). The red X denotes a likely error in the observation. Static (initial) image depicted is 0000 UTC 9 June. *Click image to open animation and enlarge*. *The location of the Ivanovo tornado is denoted by a red T at 1200 UTC during the animation.*

Composite charts (Fig. 7) were prepared for 0000 and 1200 UTC 9 June by overlaying the surface features and 45 m s^{-1} (90 kt) isotach at 300 hPa onto the 500-hPa chart. At 0000 UTC (frame 1 of Fig. 7) the surface low over northern Ukraine was located in the left-exit region of the 300-hPa jet streak. The phase lag between the 500-hPa trough and surface low resulted in differential cyclonic vorticity advection over the surface low, resulting in a decrease in the MSLP of the surface low of 8 hPa. The second frame of Fig. 7 shows the same features except for 1200 UTC, illustrating that the Ivanovo tornado was in the warm sector of the surface cyclone (100 km ahead of the cold front) and under the exit region of the 300-hPa jet. Another tornadic storm was located 160 km northwest (320°) of Ivanovo in the left-exit region of the upper-level jet streak.

b. 500-hPa geopotential height anomaly

The 500-hPa geopotential height anomaly and standard deviation for 1200 UTC 9 June were calculated using the NCEP/NCAR reanalysis dataset (Kalnay et al. 1996). First, the long-term (1948–2010) mean 500-hPa height (Fig. 8a) at 55°N 32°E (360 km west- southwest of Moscow) was 567.5 dam. The 500-hPa height at this location was 539 dam (Fig. 8b). The geopotential height anomaly in the center of the 500-hPa trough was 28.5 dam (Fig. 8c). The climatological standard deviation of the height field at this location is 10.7 dam, so the anomaly was 2.7 standard deviations below the mean. In addition, a map of the 500-hPa geopotential height anomaly from the daily mean (0000, 0600, 1200, and 1800 UTC) is shown in Fig. 8c.

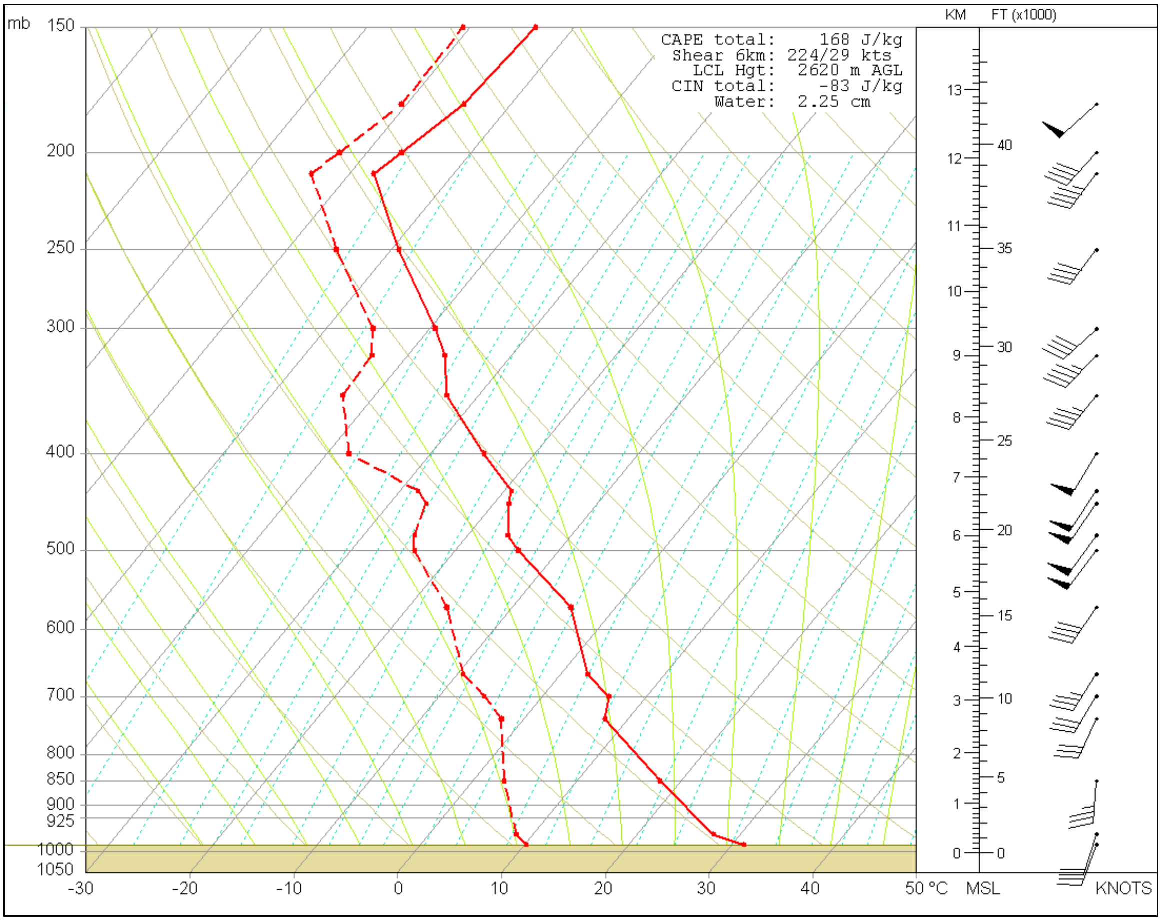


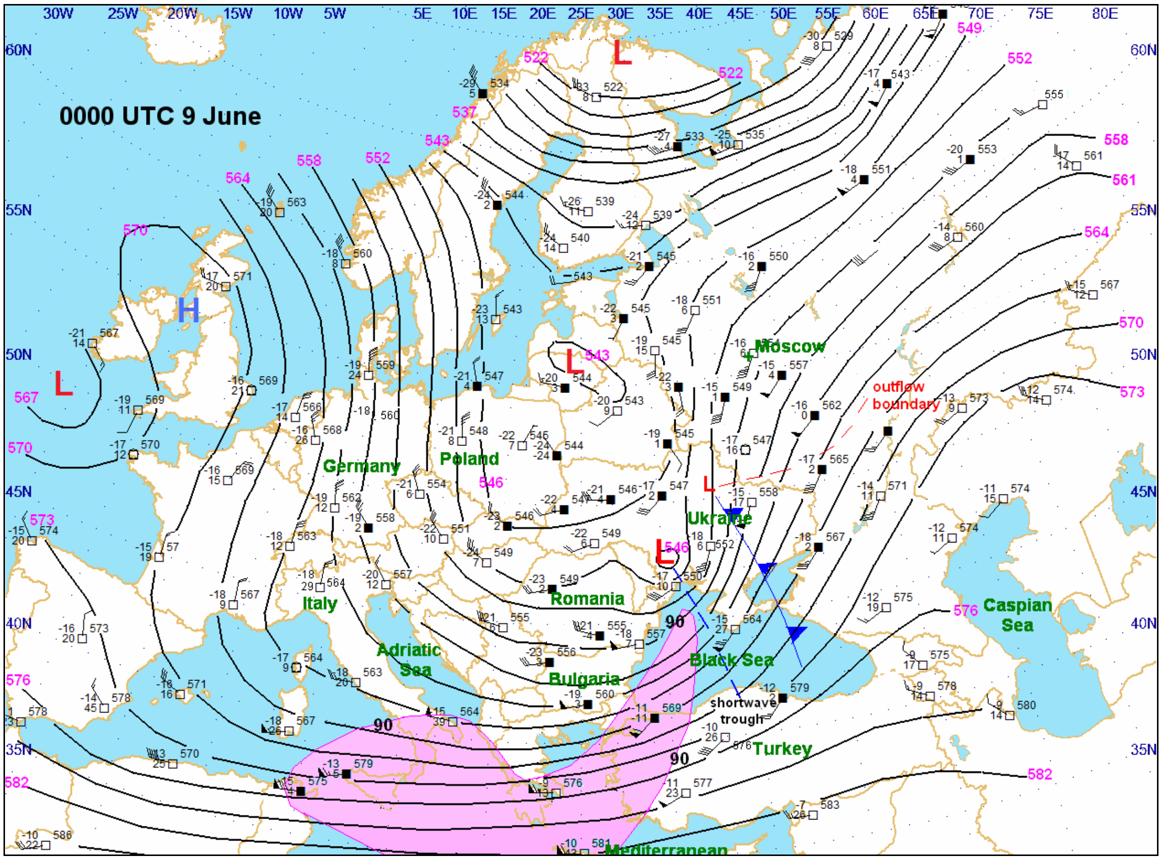
Figure 6. Skew *T*–log*p* diagram of the sounding for Saratov, Russia valid 1200 UTC 9 June 1984. Temperature (red solid line), dewpoint (red dashed line) and winds (half barb = 2.5 m s^{-1}, full barb = 5 m s^{-1}, pennant = 25 m s^{-1}). Location of Saratov depicted in red font on Fig. 1.

Although only slightly different from the 1200 UTC analysis (standard deviation of 2.5 in comparison to 2.7), it illustrates the magnitude and areal extent of the height anomaly (Fig. 8c). These results indicate that the 500-hPa trough was unusually strong for early June. In fact, besides 1984, the next lowest 500-hPa geopotential height at this location for 9 June (1948–2010) was 542 dam in 1982.

3. Low-level moisture source

As mentioned in section 2a, the primary low-level moisture source for this case was the Black Sea. To illustrate this, precipitable water (PW) values and 925-hPa wind vectors are shown in Fig. 9 for 6–9 June. On 6 June, there were small plumes of moisture immediately downstream of the Adriatic and Black Seas, with maximum values ranging from 24–30 mm. By 7 June, the moisture plume downstream of the Black Sea became more pronounced, with values between 25–33 mm. By 8 June, the moisture plume just north (downstream) of the Black Sea increased in areal extent with PW values around 30 mm. The magnitude of the PW increased between 3–5 mm from 7–8 June over a broad area north of the Black Sea. There was also a secondary maximum of PW over the Caspian Sea. By 9 June, the moisture plume from the Black Sea had advected far downstream (northeastward) as the surface low intensified and moved north-northeastward into western Russia.

The NOAA-7 Advanced Very High Resolution Radiometer (AVHRR) satellite data for 6 June 1984 (Fig. 10) show sea surface temperature (SST) values mainly between



<u>Figure 7</u>. Composite 500-hPa analyses for 0000 and 1200 UTC 9 June 1984 (following Fig. 1 convention) with 300-hPa 45 m s^{-1} (90 kt) isotach shaded and surface features annotated. The location of the Ivanovo tornado at 1200 UTC is shown by a red T in the animation. C*lick image to open animation and enlarge*.

18–19 °C with a few pockets around 20 °C. This date was chosen because there was an image after sunrise with little sun glint, along with mostly clear skies. The AVHRR satellite SST values closely correspond to the SST data from Shapiro (2010), which indicate values around 19–20 °C. SST values for 9 June would be slightly less since the data from Shapiro (2010) were centered on 15 June.

These two independent data sets increase confidence in a mean SST value ≈19 °C. Dewpoint values in this range were realized along the northwest coast of the Black Sea on 8 June before cyclogenesis had occurred. Then by 9 June, during cyclogenesis, this moist air mass moved northward with the surface low and warm front, with slightly lower dewpoints in the 15–17 °C range. These lesser values are due to the large distance from the Black Sea (1300 km). However, near the surface low and warm front this factor was offset by 1) temperatures that remained cool enough to avoid deep vertical mixing, as discussed in section 2a, 2) low-level mass convergence (see overlay of mass divergence in Fig. 2), and 3) local evapotranspiration. The magnitude of evapotranspiration is uncertain; however, since early June is well within the growing season for this region, abundant vegetation coverage was likely. Therefore, evapotranspiration likely played a role in enhancing low-level moisture.

To provide more confidence in the source of the low-level moisture for this event, the HYSPLIT model (Draxler and Rolph 2011) was used with input from the global reanalysis dataset (Kalnay et al. 1996). A backward trajectory from Ivanovo, Russia was run at 1200 UTC 9 June 1984 going back 96 h (Fig. 11). Parcels from three different heights at low levels (100, 250 and 500 m AGL) clearly have origins over the Black Sea. As a further test to the hypothesis that the moisture for the Ivanovo

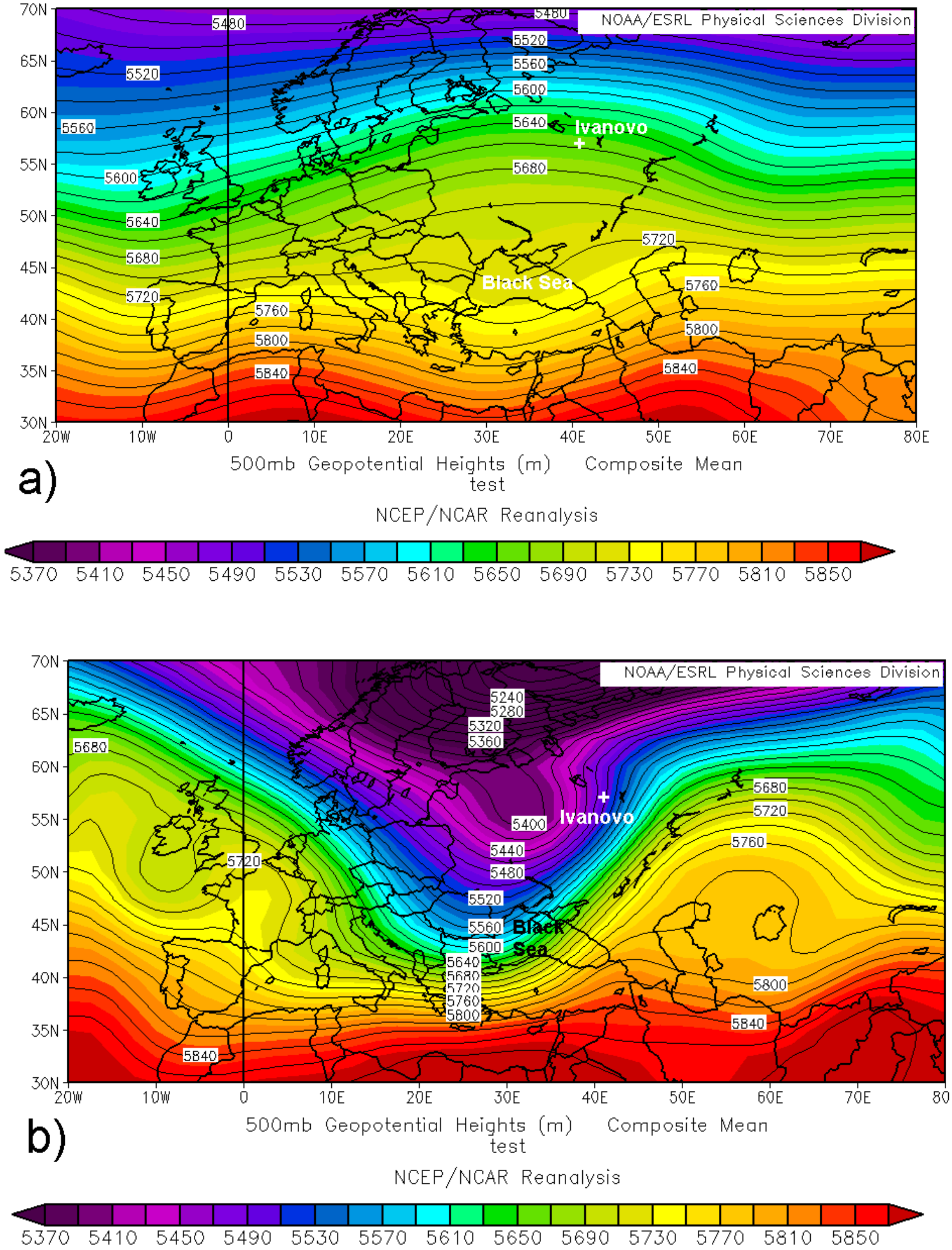


Figure 8. 500-hPa geopotential fields: a) Long-term (1948–2010) mean height for 1200 UTC 9 June, b) height for 1200 UTC 9 June 1984, c) height anomaly (m) for 9 June 1984 (daily mean). Imagery provided by the NOAA/ESRL Physical Sciences Division from http://www.esrl.noaa.gov/psd.

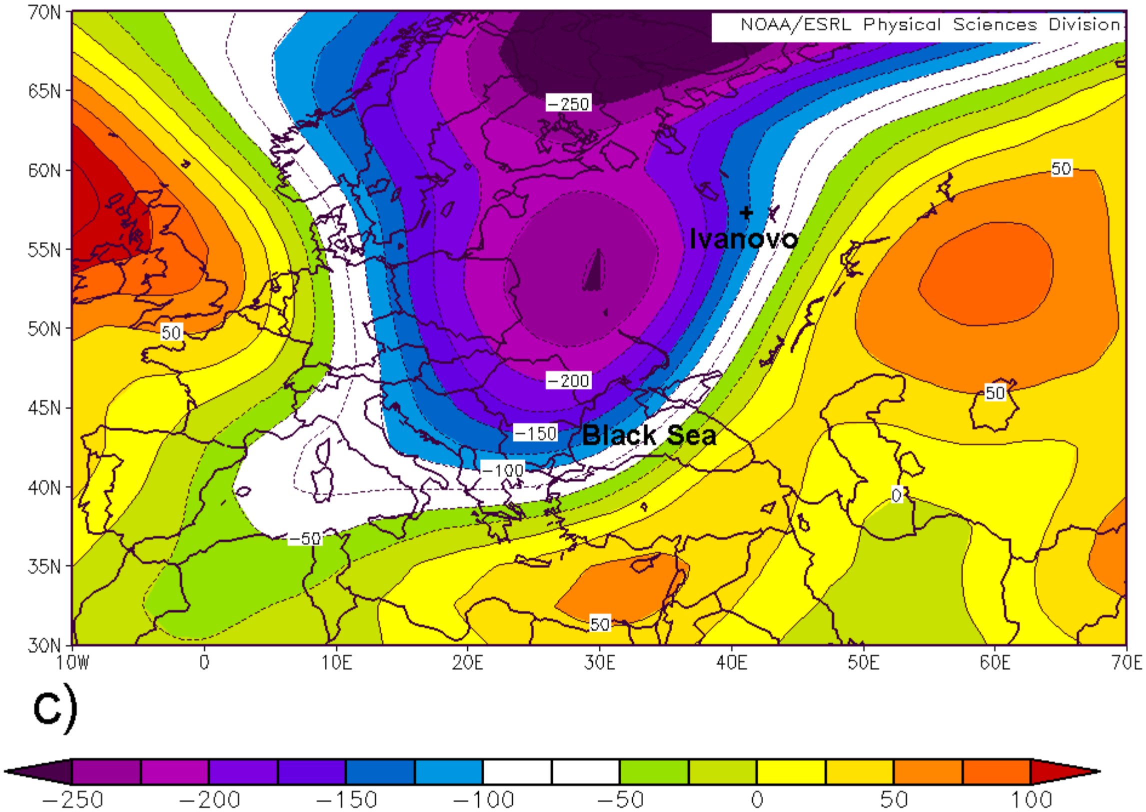


Figure 8. Continued.

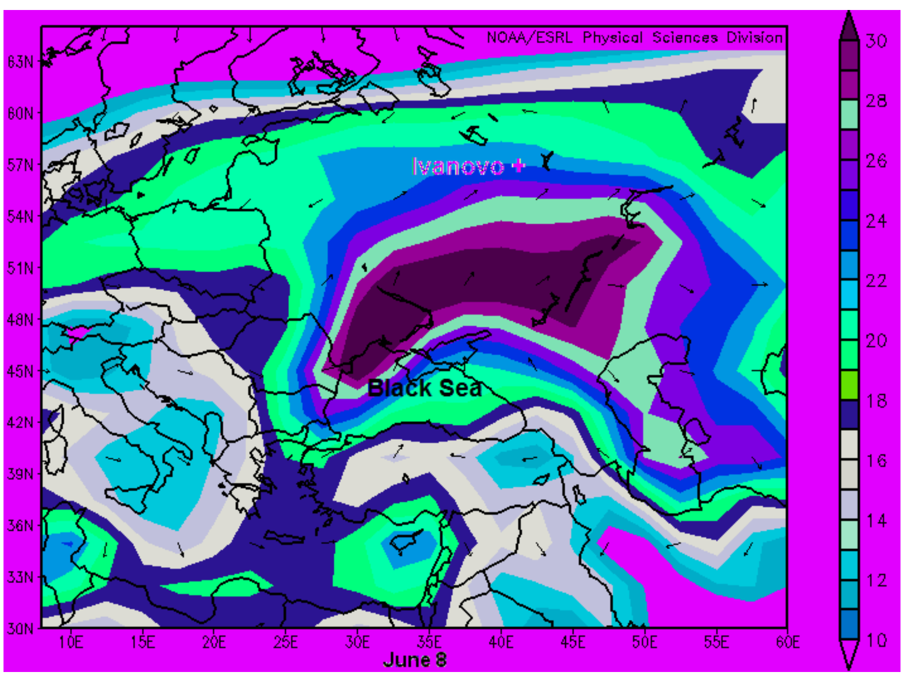


Figure 9. Mean PW (mm) overlaid with mean 925-hPa winds for 6–9 June 1984. Static (initial) image depicted is 8 June. Charts generated from the NCEP/NCAR reanalysis dataset (Kalnay et al. 1996, via http://www.esrl.noaa.gov/psd/data/composites/day/). *Click image to open animation and enlarge*.

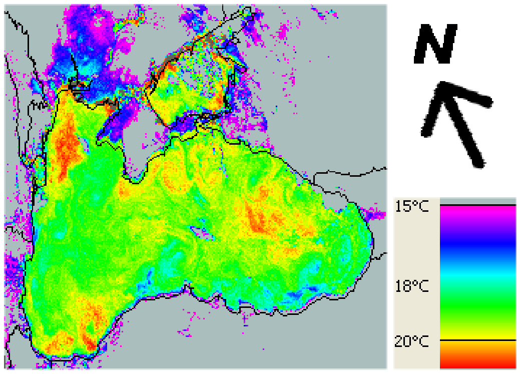


Figure 10. NOAA-7 AVHRR sea surface temperature (°C) from 0200 UTC 6 June 1984. *Click image to enlarge.*

tornado originated off of the Black Sea, forward trajectories at different start times and locations were investigated (Fig. 12). The locations of the forward trajectories are indicated by the yellow + signs, with the source region 1 starting on June 5 at 1200 UTC (run out to 96 h), source region 2 on June 6 at 1200 UTC (run out to 72 h) and source region 3 on June 7 at 1200 UTC (run out to 48 h). The Black Sea source region (3) moved towards the vicinity of Ivanovo by the time of the event (1200 UTC 9 June). Source region 2 originated off the Mediterranean Sea (east of Greece) and moved northeastward then eastward so that it would not be near Ivanovo by the time of the tornado event. Meanwhile, at source region 1, the 100- and 250-m AGL parcels moved northeastward then eastward, so that they would not be near Ivanovo at the time of the event. The parcel at 500 m AGL (green line) did make it to near Ivanovo by the time of the event. This is >3 km AGL at this time, however, rendering the parcel unrepresentative of boundary-layer moisture. Although the Mediterranean Sea cannot be ruled out as a secondary contributor, these results strongly suggest that the Black Sea was the predominant source of low-level moisture for this tornado event.

These findings concerning the source of low-level moisture disagree with Vasiliev et al. (1985b), who stated on page 4: "A polar front passed through Romania and Bulgaria and separated very warm continental tropical air, which picked up moisture at the bottom over the Mediterranean, from the polar air mass." In contrast, multiple independent data sources strongly indicate that the Black Sea was the primary source of low-level moisture.

Very little information is available in the literature regarding the source of low-level moisture for severe weather events in Russia. The literature typically states that the source of moisture was a tropical air mass, but without specifics on the associated body of water or source region for the moisture. This paucity of scientific studies motivated the question: what is the typical source region of the low-level moist air mass with tornado events in the western part of the former Soviet Union?

In order to address that question, the source of the low-level moist air mass was analyzed for 32 tornado cases (F2 or greater) between 1950 and 1986 in the region of interest that includes Estonia, Latvia, Lithuania, Belarus, Moldova, and the Ukraine in addition to western Russia (for geographic reference see Fig. 2). The tornado events considered are from Snitkovskii (1987). The source of the low-level moisture was assessed using PW, 925 hPa wind vectors, and backward trajectories from the NCEP/NCAR reanalysis dataset (Kalnay et al. 1996) produced at the NOAA/ESRL Physical Sciences Division. The relative maximum in moisture in the vicinity of each tornado event was traced back in time to determine the moisture source subjectively.

Table 1 summarizes the moisture source for the tornado events that affected the region of interest. We can conclude from the data: 1) the importance of the Black Sea as a moisture source, and; 2) that it is common for the Black Sea to be the primary moisture source. In a progressive trough pattern, the Mediterranean frequently was a moisture source; however, as the trough progressed eastward, the Black Sea played an increasing role due to low-level southerly flow. Often, the moisture would increase due to 1) advection from the Black Sea, and 2) convergence accompanying a deepening surface low over the area. The Black Sea played no clear role as the moisture source in only 9% of the cases, compared to 57% for the Mediterranean Sea.

Figure 11. HYSPLIT model backward trajectories for 1200 UTC 9 June 1984 from Ivanovo, Russia. Backward trajectories go back 96 h. Initial trajectory heights are 100 m (red), 250 m (blue), 500 m (green) AGL. Background image courtesy Google. *Click on image to enlarge*.

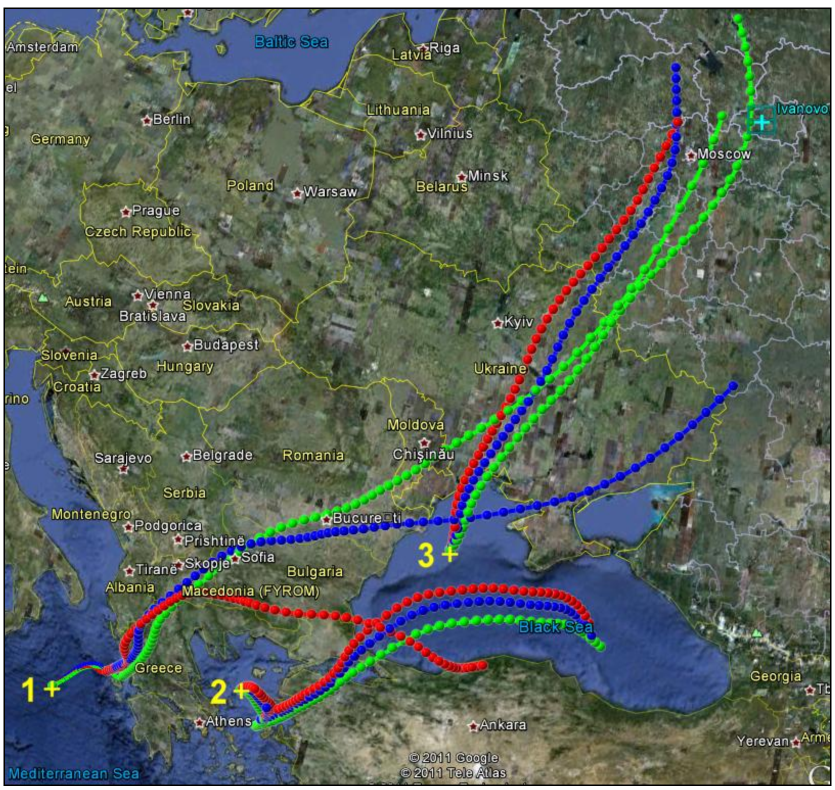


Figure 12. HYSPLIT forward trajectories with starting locations indicated by yellow + symbols. Initial times and number of hours run for source region 1) 1200 UTC 5 June , 96 h, 2) 1200 UTC 6 June, 72 h, 3) 1200 UTC 7 June, 48 h. Location of Ivanovo indicated by the cyan + symbol. Initial trajectory heights are 100 m (red), 250 m (blue), 500 m (green) AGL. Background image courtesy Google. *Click image to enlarge.*

Table 1: Percentage of tornado cases (F2 or greater from 1948–1986 in the region of interest) associated with the stated moisture source. Based on 32 cases from Snitkovskii (1987).

Primary moisture source	Percentage of cases
Black Sea only	16
Mediterranean Sea only	6
Caspian Sea only	3
Black and Mediterranean Seas	21
Black and Caspian Seas	38
A combination of the Black, Mediterranean and Caspian Seas	16

4. Modified sounding and hodograph

To further assess the thermodynamic and kinematic environments of the tornadic storms, a sounding was derived for Ivanovo at 1200 UTC 9 June. The nearest available sounding locations are Vologda (250 km to the north-northwest), Tambov (475 km to the south) and Ryazan (275 km to the south). Ivanovo was chosen as the sounding location since it is where the most intense tornadic storm was located at 1200 UTC. The mid- to upper-level thermal profile at these sounding sites were very similar; therefore, sounding modification yielded surface-based (SB) CAPE values that were not substantially different. There was a gradient in upper-level wind speed near Ivanovo, which was the greatest source of uncertainty.

Another consideration is that convection was occurring upstream of Vologda, where weaker winds were observed than further south. Therefore, there are two possibilities for why the upper-level winds were generally weaker at Vologda: 1) this is where the strong gradient in upper levels winds existed, with Vologda being on the weaker side or 2) the convection south of Vologda was at least partly responsible for the weaker winds at Vologda. We assumed hypothesis #1, knowing that if #2 was true, then the upper-level winds could have been even stronger. The mid and upper-level winds on the modified sounding are mostly an average, except with a slight bias on the higher side between Vologda and the stronger winds at Ryazan and Tambov. The reason for the slight bias is that Ivanovo was most likely at the leading edge of the mid to upper-level jet streak. The modified sounding for Ivanovo (Fig. 13) has a SBCAPE value of 2329 J kg^{-1}, lifted condensation level (LCL) of 761 m AGL and zero convective inhibition.

A modified hodograph also was constructed for Ivanovo at 1200 UTC (Fig. 14). The storm motion vector was derived using visible satellite imagery and Bunkers et al. (2000) method. The sequence of visible satellite images was used to determine the speed and direction of movement of the storm that affected Ivanovo. This method yielded a storm motion of 195° at 26 m s^{-1} (50 kt). The storm motion calculated from Bunkers method yielded a storm motion of 200° at 23 m s^{-1} (45 kt). We used 195° for the storm motion since the direction from the satellite imagery method agreed with the orientation of the tornado path in Fig. 15 and the damage locations. For the storm speed, we used a value slightly less than the average of the two methods (24 m s^{-1}) to be consistent with hypothesis #1 from the preceding paragraph. The 0–6 km shear was 31 m s^{-1} (60 kt), a value that clearly supports supercell convective mode (Rasmussen and Blanchard 1998). The storm-relative environmental helicity (SREH) was 307 m^2 s^{-2} for the 0–3 km layer and 193 m^2 s^{-2} for the 0–1 km layer. The combination of shear, SBCAPE, and LCL heights is favorable for tornadic supercells (Rasmussen and Blanchard 1998).

5. Storm events relative to surface synoptic features—A satellite perspective

a. Summary

Many thunderstorms affected western Russia during the afternoon and evening of 9 June 1984. At least eight of these produced documented tornado or wind damage. Vasiliev et al. (1985a) documented five strips of wind and tornado damage. Due to limited evidence on the storm tracks, there is high uncertainty in how continuous the wind damage was with any of these storms and existing documentation focuses mainly on urban areas. Information concerning the number of injuries and fatalities is very limited. A death toll of 400 was reported by diplomats (*Süddeutsche Zeitung*, 1984). Peterson (2000) also indicated 400 deaths.

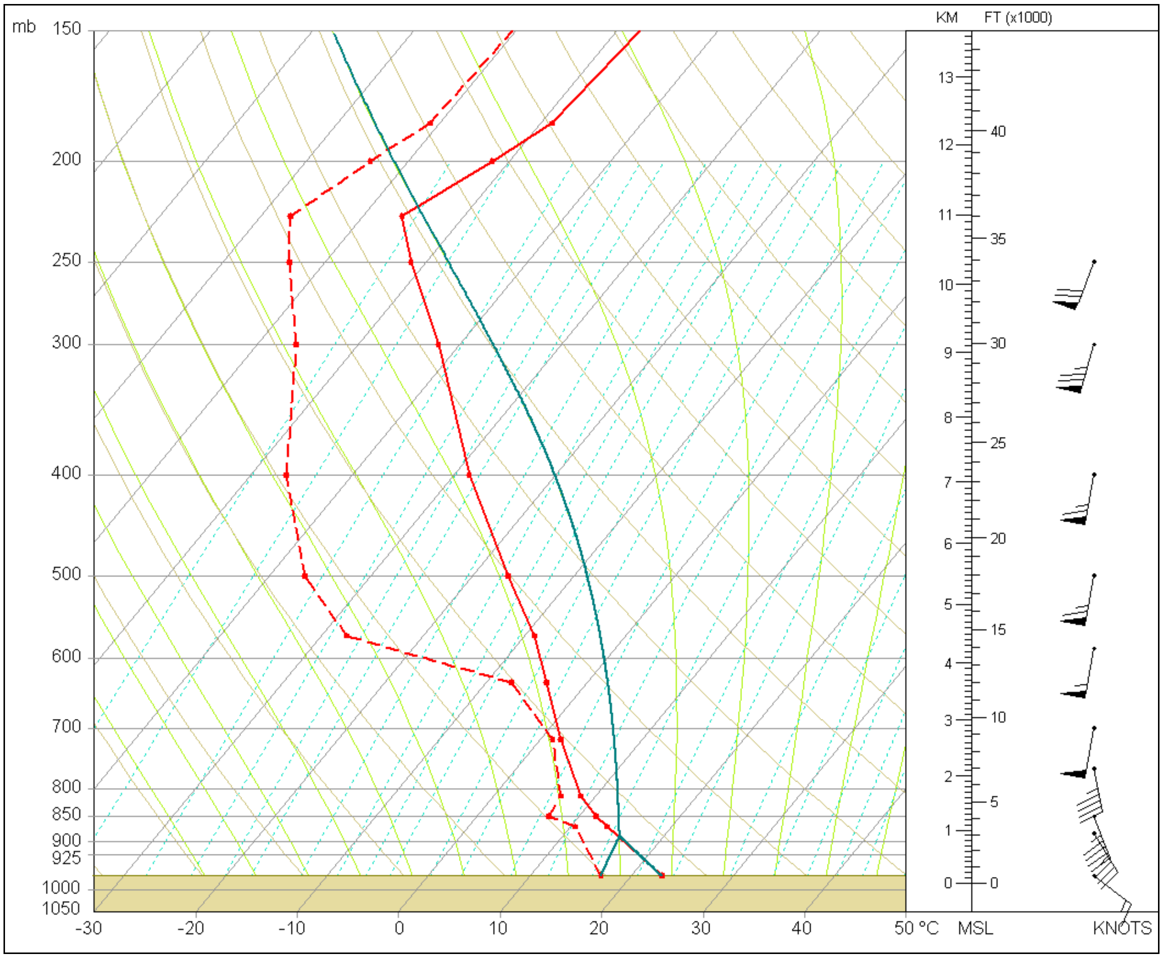


Figure 13. As in Fig. 6 but a derived sounding for Ivanovo, Russia valid 1200 UTC 9 June 1984. Lifted parcel indicated by turquoise line. Location of Ivanovo depicted in Fig. 2.

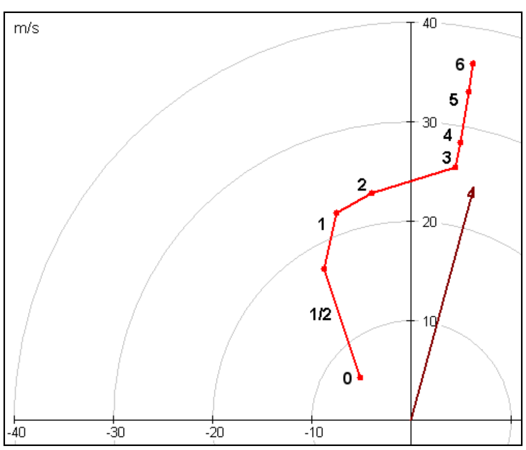


Figure 14. Modified hodograph for Ivanovo, Russia valid 1200 UTC 9 June 1984. Storm motion vector is 195° at 24 m s^{-1} (47 kt). Values along the red line are height AGL (km).

However, it is not clear whether this total is just for the Ivanovo tornado or for all the tornadoes on 9 June. The local Russian newspapers discuss the loss of human life but without specific death tolls.

Meteosat-2 satellite imagery were analyzed for 9 June 1984 to: 1) estimate the locations and times that the tornadic storms initiated, 2) aid in the approximation of storm motion vectors, 3) help to determine the surface initiating boundaries and 4) ascertain certain storm features. Satellite interpretation was especially important since radar data were not available. A visible satellite loop is presented in Fig. 15 that identifies the various thunderstorms (labeled A–H denoting the different thunderstorms that produced damaging winds and tornadoes). Information presented in Figure 15, Vasiliev et al. (1985a), and the ESWD were used to prepare

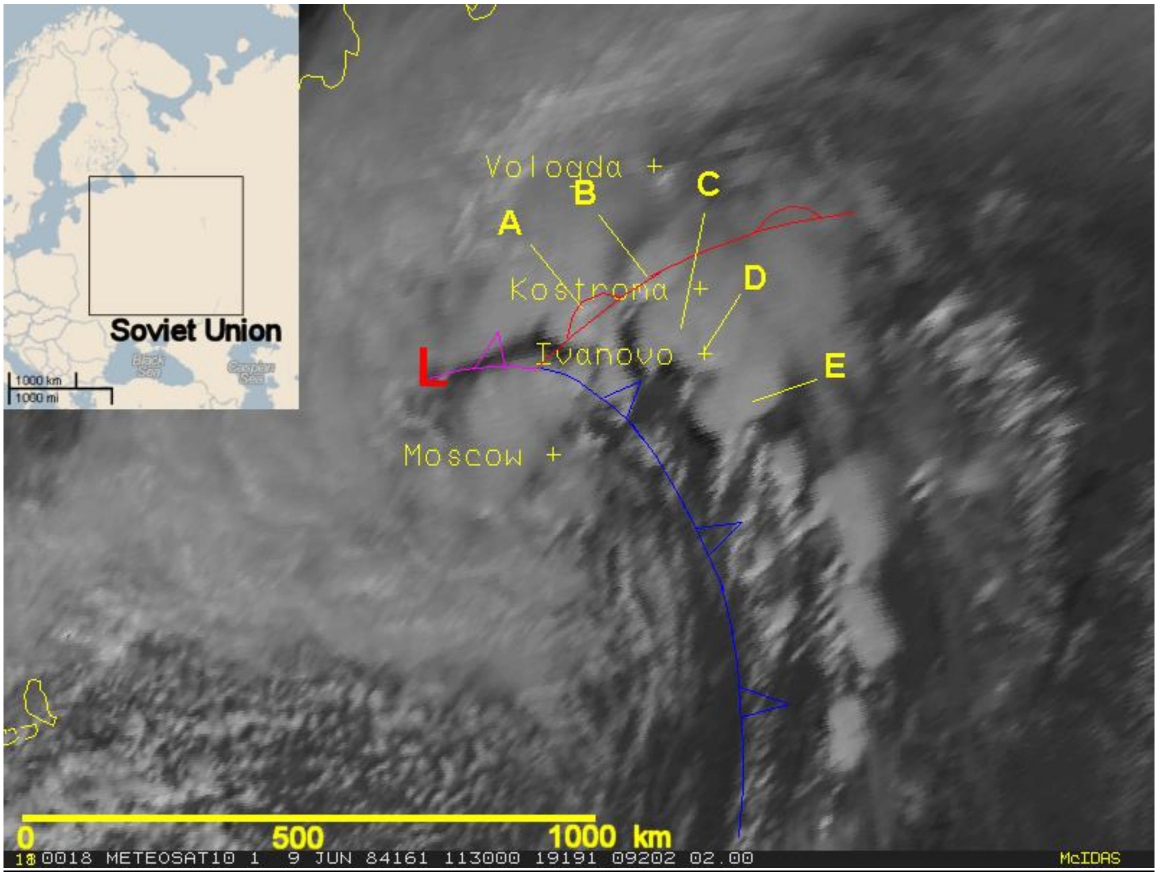


Figure 15. Meteosat-2 visible satellite imagery from 0530–1430 UTC 9 June 1984. Static (initial) image depicted is 1130 UTC. Storm labels (A–H) also correspond to the labels in Fig. 16. Inset (upper left) depicts area displayed in satellite imagery within the Soviet Union. *Click image to open animation and enlarge*. *Cities, frontal boundaries, storm labels, SBCAPE (0600, 0900 and 1200 UTC), 300-hPa isotachs (at 1200 UTC, in kt, divide by 2 for approximate m s^{-1}) and latitude/longitude are shown as overlays*.

individual storm paths plotted onto Google Maps™ (Fig. 16) that were associated with tornado damage or damaging winds. Both Figures 15 and 16 use corresponding storm labels (A–H) for the storms and storm paths. Storms F and G were omitted from Fig. 15 since the proximity of several storms made identification in the visible satellite imagery difficult. The storm path initial point and estimated location times in Fig. 16 were approximated using visible satellite imagery with a parallax correction of 15 km to the southwest. Rather than address storms A through H in west–east succession, the majority of the discussion on storm events will proceed in the order that storms initiated, in order to match the visible satellite loop and to avoid discussing various storms at different times.

There are substantial differences in these results compared to the findings in Vasiliev et al. (1985a). Two of the storms in Vasiliev et al. (1985a) are hypothesized to be four storms. Storms labeled A/B and C/D in Figure 16 were claimed to have been caused by the same thunderstorms that we labeled as separate storms. Based on satellite imagery and newspaper reports, we decided that these damage areas could not have been caused by the same storm. Vasiliev et al. (1985a) assumed that storm A curved to the east and then back north again along our storm B path. We found evidence that these were two separate storms and the reasoning will be detailed later in this section. We also believe this to be true of storms C and D for reasons described below. Vasiliev et al. (1985a) considered the damage from storms A–D to be caused by tornadoes, storms E and H by strong

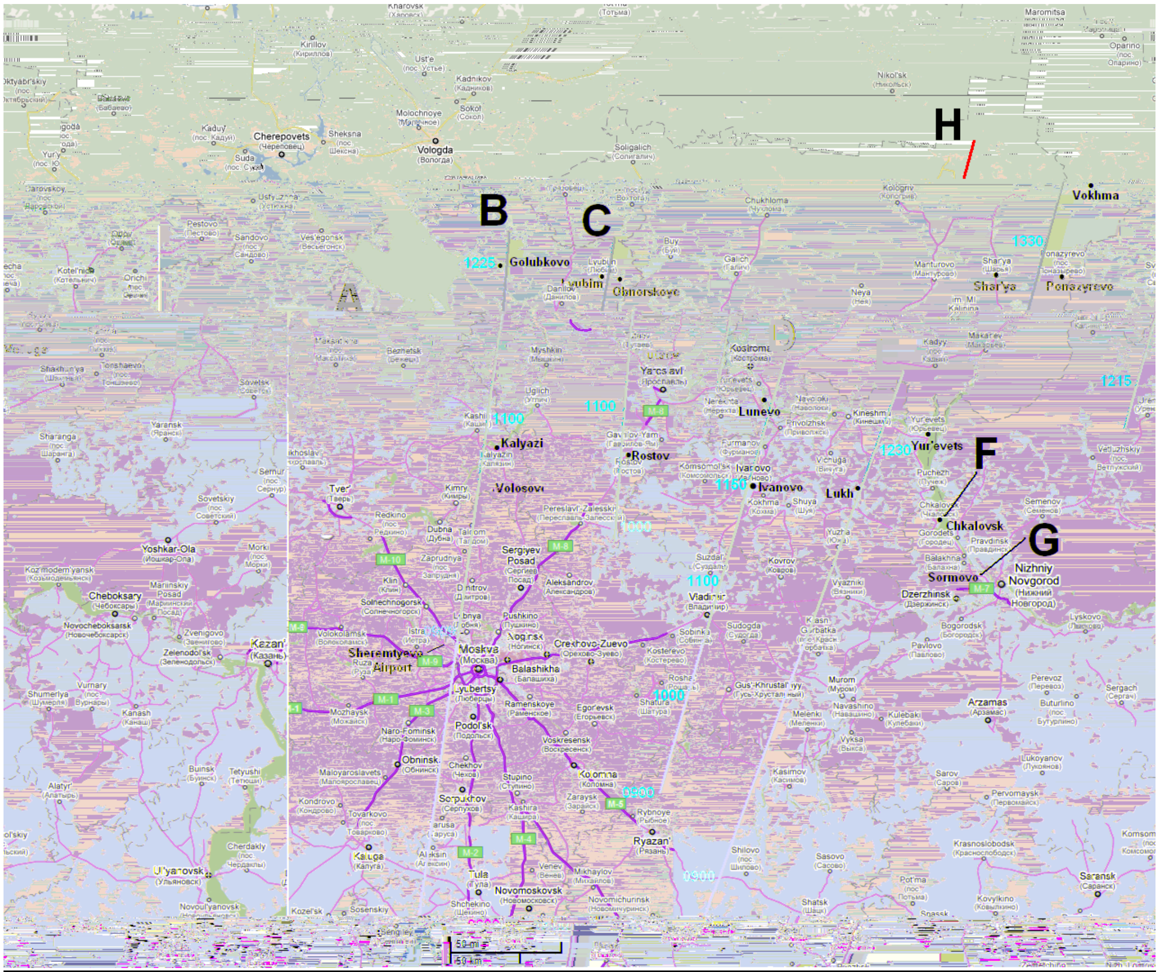


Figure 16. Storm tracks (A–G) that produced wind damage on 9 June 1984. Times plotted next to the storm tracks are in UTC. Towns highlighted in bold are referred to in the text. Background image courtesy Google. *Click image to enlarge*.

winds or tornadoes, and storms F and G by strong winds (without specifying tornadic or nontornadic winds).

b. Analysis of severe weather

The first tornado-producing thunderstorm (storm A in Figs. 15 and 16) developed around 0530 UTC 9 June and is evident in the Meteosat-2 visible loop (Fig. 15). Visible imagery from 0600–1100 UTC indicates that this may have been a cluster of thunderstorms, with the tornadic part on the southeastern edge of the cluster. This convection developed in the left-exit region of the upper-level jet, but only slightly displaced northward and westward from the strongest mid-level flow (700–500-hPa), so that storm motion was still rapid. At 0600 UTC (10 am MT) this storm was 220 km south-southwest of Moscow (Fig. 16) or 130 km east of the surface low and just south of the warm front (Fig. 15). SBCAPE calculations were hand-analyzed for 0600, 0900 and 1200 UTC using surface observations along with objectively analyzed soundings. The SBCAPE near this storm was about 1000 J kg^{-1} (toggle on CAPE at 0600 UTC in Fig. 15).

The eastern part of this storm cluster moved north-northeastward at 20–22 m s^{-1}, as approximated from Fig. 15 imagery and from the arrival time at Sheremetyevo airport. The 0830 UTC visible satellite image (see Fig. 15) shows this thunderstorm cluster about 30 km south-southwest of the center of Moscow and just south of the warm front. Several buildings and hangars were heavily damaged and trees were uprooted near and at Sheremetyevo airport in the northern suburbs of Moscow (Fig. 16) at 0909 UTC according to Alimov et al. (1984) as well as Vasiliev et al. (1985a). The tornado at Sheremetyevo is listed as F1 in Snitkovskii (1987) and ESWD, with a path length of 10 km and path width of 10–20 m.

After passing through Moscow, this storm continued north-northeastward to the Kalyazin area by 1100 UTC or about 145 km north-northeast of Moscow where trees were downed (Fig. 16). Between Moscow and Kalyazin, a tornado caused unspecified damage near Volosovo (Snitkovskii 1987). In ESWD the position of Volosovo appears to have an incorrect latitude and longitude. Since this storm was moving slightly faster than the warm front, it crossed the front into cooler air after 1230 UTC (supported by Fig. 15).

Other thunderstorms rapidly developed in the warm sector farther southeast between 0800–0900 UTC (Fig. 15). Storms D and E developed just ahead of a prefrontal trough (use toggle switch for fronts at 0900 UTC in Fig. 15 to see the dashed brown line). The SBCAPE (use toggle switch for CAPE at 0900 UTC in Fig. 15) was between 1500–2000 J kg^{-1} at 0900 UTC in vicinity of these storms. However, after 0900 UTC, storms D and E moved into a region with SBCAPE exceeding 2000 J kg^{-1}. Storm D was located about 60 km north-northeast of Ryazan, Russia at 0930 UTC or about 215 km south-southwest of Ivanovo. This storm moved north-northeastward (toward 15°) at ≈26 m s^{-1}, as determined by successive visible satellite images (Fig. 15) and from the 1150 UTC time of arrival at Ivanovo (accounting for parallax). The tornadic phase of this storm was between 1130–1230 UTC from 15 km southwest of Ivanovo through Lunevo, a skipping or continuous path of about 80 km.

Even though Snitkovskii (1987) documents a path length of 160 km, Vasiliev et al. (1985a) states that the tornado "re-emerged at Lunevo with particular strength". Therefore, there is conflicting information as to the path length and continuity of the tornado(es) from southwest of Ivanovo to Lunevo. This path length of 160 km may be too long since there is no evidence of tornadic damage north-northeast of Lunevo. In Ivanovo, a 320 000-kg crane was lifted 3 m and cast aside and a 50 000-kg water tank was hurled 200 m (Lyakhov, 1986). Snitkovskii (1987) indicated a F4 rating for the Ivanovo tornado, while ESWD assigned a F5 rating. According to Lyakhov (1986), "asphalt was pulled up and scattered on a highway near Ivanovo". A photo of the Ivanovo tornado that appeared in Vasiliev et al. (1985b) is shown in Fig. 17. A detailed description of the tornado(es) associated with storm D is provided in the Appendix.

In the 1130 UTC visible image (Fig. 15 at 1130 UTC), note the line of towering cumulus clouds above the rear-flank downdraft (RFD) on the south flank of storm D. This is a common satellite signature of a severe storm (Weaver and Purdom 1995; Weaver and Lindsey 2004). Additional satellite evidence of a severe storm was observed on the polar-orbiting NOAA-7 satellite AVHRR infrared image (Fig. 18). The enhanced-V signature (McCann 1983) is readily apparent on the storm that was associated with the Ivanovo tornado.

Storm D was within the 700–500-hPa wind-speed maximum and thus moved a little faster than the storm that affected Moscow. Satellite based estimation of the storm motion of the adjacent storm to the southeast (storm E) was 25 m s^{-1}, which increases the confidence of our estimates. Storm E (80 km further east) caused a strip of tree damage east of Lukh and west of Yurevets (Vasiliev et al. 1985a) between 1150–1245 UTC. There are no F-scale ratings of this tornado in the literature or ESWD.

The area of convection denoted by B at 0930 UTC eventually developed into a tornadic storm by 1000 UTC about 135 km northeast of Moscow (Fig. 15). The storm initiated well ahead of a prefrontal trough in the warm sector (toggle on fronts in Fig. 15); therefore, it is not clear if any surface boundary played an initiating role. The initial convection with this storm developed around 0900 UTC in an area with SBCAPE between 1500–2000 J kg^{-1} (Fig. 15). A tornado was reported southwest of Rostov according to Vasiliev et al. (1985a) around 1030 UTC (based on Fig. 15). The SBCAPE around storm B stayed between 1500–2000 J kg^{-1} as the warm front moved northward along with the storm until eventually the storm moved into the cool air. Vasiliev et al. (1985a) describes storms A and B as one continuous event. More specifically, they describe the storm that eventually strikes Golubkovo (storm B) as the same storm that affected Moscow (storm A).

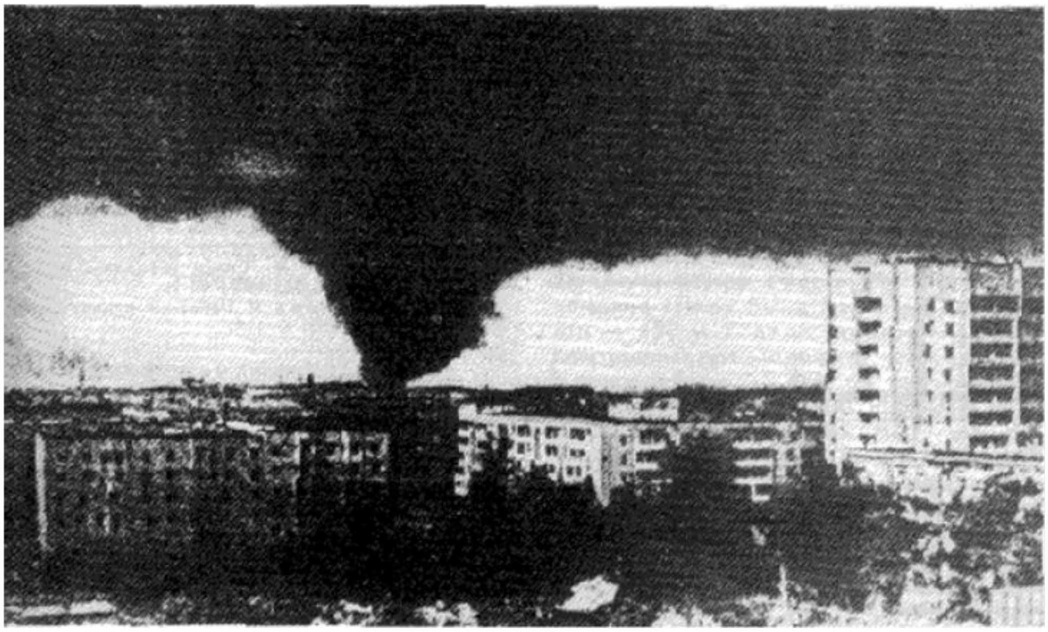


Figure 17. Photograph of the Ivanovo tornado of 9 June 1984, from Vasiliev et al. (1985b).

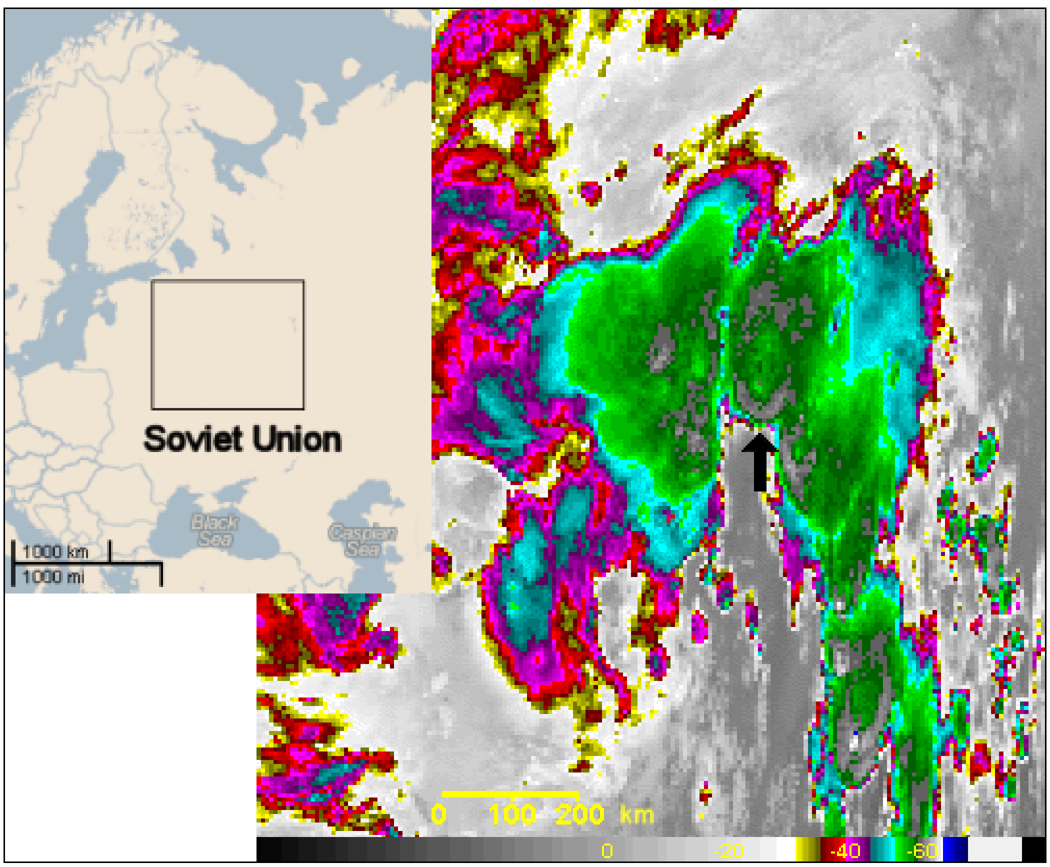


Figure 18. NOAA-7 AVHRR infrared image at ≈1200 UTC 9 June 1984. Black arrow indicates the tornadic storm (labeled D in Fig. 16) affecting Ivanovo, Russia at about this time. Brightness temperature scale given in °C. Inset (upper left) depicts area displayed in satellite imagery within the Soviet Union.

Based on the visible satellite imagery and locations of damage, however, the authors believe that two separate storms caused the damage in these areas. According to Vasiliev et al. (1985a), this tornadic storm caused areas of tree damage from 30 km southwest of Rostov to Golubkovo (160 km path length that may or may not have been continuous).

Hailstones with storm B near Tutayev were as large as 15 cm in diameter and weighed up to 1 kg (Lyakhov 1986, Vasiliev et al. 1985b). Based on the arrival time of the storm near Tutayev in the visible satellite imagery, the giant hail occurred around 1140 UTC. This hailstone is comparable to the world record, which is the 1-kg hailstone recorded in the Gopalganj district of Bangladesh on 14 April 1986 (*Bangladesh Observer*, 15 April 1986). For comparison purposes, the hailstone that fell in Vivian, SD on 23 July 2010 was measured to be 0.88 kg (NCDC 2010). The accuracy of the Tutayev hailstone weight may be questioned since the details of this report are lacking; however, it is still comparable to the heaviest hailstone on record.

Tornado damage occurred later at Golubkovo around 1225 UTC as storm B moved toward north 5° east at 20–22 m s^{-1}. Snitkovskii (1987) documented a path width of 300–600 m, a path length of 100 km and a damage rating of F3. This tornado also is rated F3 in the ESWD. Thirty-one homes were destroyed and 260 buildings heavily damaged in the countryside of the Yaroslavl region (*Moscow News*, 22–29 July 1984). This was probably the tornado between Rostov and Golubkovo. Human casualties were reported but without a specific death toll. This storm was initially in the warm sector but eventually crossed the warm front after passing Golubkovo (Fig. 15).

By 1130 UTC, storms A, B, D and E are discernible in the visible imagery (Fig. 15). Storm A was moving north of the warm front, with storms A and C becoming obscured by anvil cirrus from adjacent storms. Alimov et al. (1984) stated that tornadic damage occurred 10 to 13 km southwest of Kostroma (storm C). Vasiliev et al. (1985a) mentions that additional damage near Lyubim and Obnorskoye was caused by storm D. However, this damage is offset to the west by 30–40 km and it is more likely that this damage was caused by storm C.

Storms F and G, which developed around 1100 UTC, are not shown in Fig. 15 since it was difficult to identify these in the visible satellite imagery. According to ESWD there was F2 damage around Chkalvosk (caused by storm F) which was not mentioned in Snitkovskii (1987). Vasiliev et al. (1985a) reported a swath of tree damage near Sormovo (storm G), but there is no F-scale rating for this tornado in the literature.

Storm H developed around 1200 UTC well to the northeast of the prefrontal trough in the warm sector and moved to the north-northeast at about 22 m s^{-1}. The SBCAPE was >2000 J kg^{-1} near this storm (toggle on CAPE in Fig. 15). Unspecified damage was reported near Vetluga (ESWD) and trees were damaged in a swath from east of Sharya to west of Vokhma (Vasiliev et al. 1985a). There is no F-scale rating applied to this tornado in the literature. Four different tornadoes are listed in ESWD associated with this storm but only one tornado is mentioned in Snitkovskii (1987)**.**

Vasiliev et al. (1985a) mentions other areas of wind damage farther south and east in Russia, but there are no accounts of damage. The ESWD mentions tornadoes in this area, but it is unclear how they were able to list these events as tornadoes. For example, the ESWD lists five other tornadoes farther south and east of the region of interest, two of which were identified as F2; however, there were no details available for any of these tornadoes.

6. Conclusions

The severe weather event of 9 June 1984 in western Russia was noteworthy in that it was associated with a F4 tornado (only one of two in Russian records) and hail up to 1 kg in weight. There was substantial loss of life and damage from this event as well. This study investigates the following aspects of the 9 June 1984 tornado outbreak: the major synoptic scale features, the initiation and movement of thunderstorms relative to these features, the near-storm environment associated with the Ivanovo tornado, the source of low-level moisture, and documentation of severe weather reports. A map of thunderstorm paths is presented which is based on satellite imagery, newspaper descriptions, ESWD and information within Vasiliev et al. (1985a). The results confirm some findings from Vasiliev et al. (1985a), but also highlight significant differences.

The authors identified the Black Sea as the primary moisture source, with a possible secondary contribution from the Mediterranean Sea. This finding disagrees with Vasiliev et al. (1985a) which stated that the moisture source was the Mediterranean Sea. Additionally, the paucity of previous studies on the source of low-level moisture for tornado events in the western part of the former Soviet Union served as motivation to identify it for 32 F2 or greater historical tornado events. The Black Sea commonly has been the primary source of low-level moisture, as we observed in the 9 June 1984 event.

An anomalously strong and progressive shortwave trough and associated jet streak moved north-northeastward through western Russia. The surface cyclone deepened considerably while propagating from eastern Romania to west of Moscow. The leading edge of the upper-level jet crossed various low-level convergence boundaries and supported severe thunderstorms.

Most of the storms initiated in the northwestern extremity of the warm sector. Several of the storms developed along a prefrontal trough, including the Ivanovo storm. Two thunderstorms eventually crossed the warm front and into cooler air after producing damaging tornadoes in the warm sector and near the warm front.

An analysis of a modified sounding and hodograph for Ivanovo depicted a favorable near-storm environment for severe thunderstorms. Low-level moisture from the Black Sea and daytime heating contributed to the development of SBCAPE ranging from 1500–2300 J kg^{-1}. Backed low-level winds in the vicinity of the surface low, along with strong mid to upper-level winds, resulted in estimated 0–3 km AGL SREH values around 300 m^2 s^{-2}. In addition to the supportive synoptic and mesoscale patterns, this combination of shear and CAPE provided a favorable environment for significant tornadoes and extremely large hail.

APPENDIX

The following description of the Ivanovo tornado (storm D) appeared in Vasiliev et al. (1985a):

"At 3:45 pm a new, very dark cloud appeared with a funnel-shaped protrusion, which descended to the ground, swaying from side to side. Almost touching the ground, the funnel grew rapidly and began to suck objects up, then it repeatedly rose and descended. The rapidly spinning funnel, like an elephant's trunk, was clearly visible, as was its tossing of objects high above the ground; it sounded like a strong whistle and rumble, similar to a jet engine. This phenomenon resembled a boiler—the funnel shone from inside. From the "trunk", smaller arms detached, which first moved away from the funnel, then back toward it. The mother cloud from which the trunk had descended rapidly moved north, and in a strip with a width of about 500 m, the tornado tore away the roofs of houses, and broke/uprooted trees, posts and power lines supports. Sturdy wooden houses, and especially their roofs, were destroyed; heavy railroad cars were overturned; cars, buses, trolleys and other objects were picked up, flipped and dumped onto their sides. The tornado appeared about 15 km south of Ivanovo on the boundary between the forest and the fields. It moved toward the western suburbs of Ivanovo, then entered the forest, continuing the strip of uprooted and broke-off trees. The trees that were broken off were broken at a height of 1 to 3 m. Trees were laid flat in the direction the tornado was traveling—to the north. The rotation of the tornado was clockwise on the edges of the path, and counterclockwise in some places. In an hour the tornado was approximately 60 km north-northeast of Ivanovo, on the hilly banks of the Volga, in the tourist center Lunevo, where it reappeared with particular strength. Fir trees were uprooted; pine trees and birches broken off; wood-frame houses collapsed; a 50-ton water tower tank was thrown 200 m onto its side. As in the outskirts of Ivanovo, concrete and large brick structures were not destroyed, but had their roofs torn off and glass broken out."

The following description of the tornado at Lunevo (storm D) published in an article titled "120 Minutes of a Tornado" from *Izvestia* (Alimov et al. 1984):

"Wind with severe hail moved in a line a kilometer wide. As if hewn, the huge power line supports fell, ancient trees snapped like matches, cars were flung about, 150-cubic meter steel water containers rose into the air a good hundred meters and were carried for a kilometer. Industrial buildings were destroyed, and in a few places even one-story stone buildings did not stay standing; they were reduced to their foundations."

ACKNOWLEDGMENTS

Digital Atmosphere (meteorological plotting software developed by Tim Vasquez) was used to plot surface, upper air data and analysis fields. Google Maps was used to plot the paths of the storms. The authors wish to acknowledge Thilo Kuehne for detailed analyses of some of the tornadoes that took place on 9 June 1984 that appeared in ESWD. Lisa McLendon translated text between Russian and English. The authors gratefully acknowledge the NOAA Air Resources Laboratory (ARL) for the provision of the HYSPLIT transport and dispersion model and/or READY website used in this publication: (http://www.arl.noaa.gov/ready.php).

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REVIEWER COMMENTS

[Authors' responses in *blue italics.*]

REVIEWER A (Steven R. Silberberg):

Initial Review:

Recommendation: Accept with minor revision.

Substantive comments:

1. Summary

This is an excellent paper documenting the synoptic, mesoscale, and climatological aspects of a very rare severe tornado outbreak in Russia on June 9, 1984. The authors have made unique contributions that advance our understanding of the event. In particular the authors made exceptional use of data sources available during 1984, references published just after the event, the use of advances in data availability such as the use of the NCEP/NCAR reanalysis and the use of Digital Atmosphere to apply state-of-the-art meteorological analysis software to this case, and reconstruction techniques to determine tornado tracks, CAPE and helicity from nearby soundings.

To follow along with EJSSM review guidelines with respect to scientific content, the authors made excellent use of references in support of their assertions demonstrating their mastery of the paper's topic and advancing our understanding of this rare tornado outbreak. The authors went further and used references along with further original data analysis to develop tornado tracks and the climatological source of low-level moisture for Russian tornado outbreaks of F2 or greater.

There are some unsupported speculations and conflicting/confusing scientific explanations with regard to moisture and the processes which produce low-level moisture changes which are detailed in section 2A below. Suggestions to help resolve this issue through rewriting and some calculations are made in the section 2A to assist in getting the paper published as soon as possible.

The paper is well-written and data sources and methods are well-documented, such that a reader can reproduce the results. The paper greatly extends work already published on this topic and uses new data sources and original analysis methods to advance our understanding of this tornado outbreak and, as mentioned above, advance our understanding of the climatological source of low-level moisture for Russian tornado outbreaks of F2 or greater. Comparisons with existing work are clear and unambiguous such that the advances made in this paper are easy to see and understand.

With regard to quality of presentation guidelines, the quality of figures is excellent and makes excellent use of electronic media advantages. It was a pleasure to view the figures, loop them, and toggle overlays on and off in an effort to understand the key points being made in the paper. The paper is well written, organized, and complete.

2. Scientific Content

A. The evolution of the moisture field and the scientific processes which are responsible for the evolution of the moisture field conflict with the explanations provided on pages 6 and 12 in the original manuscript. On p. 6, second to last sentence, point #2 vertical mixing in the warm sector of the cyclone is hypothesized to explain the decrease in surface dewpoint 900–1600 km north of the Black Sea on 9 June, but no scientific evidence is presented to support this hypothesis. Please provide support for the vertical mixing hypothesis.

The text on p. 12 in the first paragraph, second sentence mentions strong mixing in the warm sector of the developing low-level cyclone due to strong surface winds as a reason for the dilution of low-level moisture in the vertical and a decrease in surface dewpoint temperatures immediately north of the Black Sea. The reviewer requests that evidence to show the dilution of low-level moisture in the vertical be presented.

Additionally, in the first paragraph on p. 12 in the sentence which begins with, "Further north in the warm sector…" states that surface dewpoint temperatures remained from 15 to 17 deg C…despite surface winds of 8–15 m s^{-1}. The reviewer is confused that vertical mixing due to strong surface wind is cited as a scientific reason for the reduction in surface dewpoints north of the Black Sea, yet no reduction in surface dewpoint was observed despite the strong surface wind in the warm sector.

We organized the discussion between the northern sector (near the warm front) and southern sector (in the well-mixed boundary layer region). We stressed that the main difference between these two regions was the temperature difference. We inserted a sounding (Fig. 6) that represents the southern sector. We removed redundancy by putting the majority of our discussion earlier (page 6) and inserting a summarizing sentence "As discussed in section 2a" in section 3 (page 12).

We also stressed that the flow was moving over land instead of the Black Sea as it was earlier: As previously noted, the fetch further south in the warm sector was entirely over land by this time since the cold front had passed east of the Black Sea. We removed the sentence "This maintenance of higher dewpoints was also in spite of an increase in elevation from near sea-level to the 100–250 m range," since we thought it was insignificant. We wanted more emphasis on the other points in this section.

The last sentence of the first paragraph on p. 12 mentions that low-level moisture convergence and local evapotranspiration may have allowed moisture to accumulate locally to explain why surface dewpoints remained the same in the warm sector of the intensifying cyclone. The reviewer suggests that scientific calculations of water vapor mixing, advection, moisture convergence, and an estimate of local evapotranspiration be provided to support these scientific assertions which conflict with each other.

Moisture convergence was added as an overlay to Figure 2, and we do believe this played a significant role, in combination with the other factors discussed. The big question mark in our mind is evapotranspiration, we did add this sentence:

"The magnitude of evapotranspiration is uncertain; however, since early June is well within the growing season for this region, abundant vegetation coverage was likely. Therefore, evapotranspiration likely played a role in enhancing low-level moisture."

Since we're quite uncertain as to the role of evapotranspiration, we tried to convey our uncertainty in our text. We did attempt to make some rough estimate of ET using the Penman-Monteith equation, and came up with numbers around 7 to 8 mm day^{-1}. Rather than going into the details of this estimate and the large uncertainty associated with it, we think it's best to state what we did so as not to detract too much from our main point, which is the Black Sea being the primary source of low-level moisture for this event.

Is there another way to explain the evolution of water vapor? Was there a two step process, one near the Black Sea during initial cyclogenesis, and a second further north in the warm sector during rapid cyclogenesis? The reviewer believes that these points need to be reconciled and explained a little more carefully with supporting calculations because this is a key scientific issue in the paper. If the reviewer has misunderstood, please explain.

Yes, we also included trajectories, see new Fig. 11. We used a backward trajectory from Ivanovo going back 96 h at three different low-level heights. The trajectories clearly show the Black Sea being the origin of the low-level moist air mass.

In addition, we also used forward trajectories—see new figure 12—from 3 different locations (indicated by the yellow + signs) starting at 3 different times in order to address the hypothesis: does any of the low-level moisture for the Ivanovo event come from the Mediterranean? The easternmost starting location over the Black Sea clearly moves towards the Ivanovo region. The starting location over the Mediterranean east of Greece moves northeast but then eastward, so that it does not make it close to Ivanovo by the time *of the event. The starting location over the Mediterranean west of Greece, the parcels at 100 and 250 m move northeast then eastward, again looking unlikely that they would be close to Ivanovo by the time of the event. The highest level parcel at 500 m does make it towards the Ivanovo region by the time of interest; however the parcel is at 3.4 km by that time so that it's unlikely to be representative of boundary layer moisture. Based on this, we have even greater confidence in the Black Sea being the moisture source. The Mediterranean still cannot be completely ruled out, but the Black Sea plays the more significant role.*

Since we did not use trajectories at the initial submission, but started using this based on reviewer comments, we also re-analyzed the 32 F2 or greater tornado cases to track the source of the low-level moist air mass used in constructing Table 1. The inclusion of trajectories, in addition to the previous analysis method of inspection of precipitable water and low-level wind vectors, made the subjective assessment of the origin of the low-level moist air mass more accurate from our viewpoint. Here is the difference between the old method and new (including trajectory analysis) methods:

Moisture source	**Percentage of cases (new)**	**Percentage of cases (old)**
Black Sea only	16	19
Mediterranean Sea only	6	3
Caspian Sea only	3	6
Black and Mediterranean Seas	21	41
Black and Caspian Seas	38	19
A combination of the Black, Mediterranean and Caspian Seas	16	13

The main consequence of using the trajectories was to determine that some of the cases clearly did not come from the Mediterranean (i.e., the trajectory was coming from the east or southeast), also the Caspian Sea could not be ruled out as a moisture source for the same reason. This resulted in some of the categories shifting from "Black and Mediterranean Seas" to "Black and Caspian Seas".

In our conclusions we edited this sentence: "Low level winds and the distribution of precipitable water in the days leading up to June 9 identify the Black Sea as the primary moisture source, with a possible secondary contribution from the Caspian Sea," to this:"Trajectories, low-level winds, and the distribution of precipitable water in the days leading up to 9 June identify the Black Sea as the primary moisture source, with a possible secondary contribution from the Mediterranean Sea." Our justification for this is the inclusion of the trajectories, which were not used for the initial submission. We did not find any trajectories southeast of Ivanovo that would lead us to believe that the Caspian Sea played any role. However, based on the forward trajectories, the Mediterranean Sea cannot be completely ruled out as a moisture source. Note, this does not change the most important part of our argument, that the Black Sea was the primary moisture source.

Please note that the reviewer agrees with the authors and Figs. 2, 3, 8, 11, 12, that the Mediterranean moisture source cited by Vasiliev (1985b) is not correct and that the primary moisture source of low-level moisture for this event was the Black Sea.

B. Are the mean precipitable water maps in Fig. 11 for 0000 UTC, 1200 UTC, or an average of 00 and 12 UTC? They are excellent figures.

An average of 00 and 12 UTC. We're not sure if this info is needed in the figure caption?

[Minor comments omitted...]

Second review:

Recommendation: Accept.

General comments: Revisions of this manuscript are excellent and further strengthen the authors' scientific points. I wish to thank the authors for doing an excellent job in rewriting the manuscript, incorporating suggestions, conducting the trajectory calculations, and reclassification using the trajectory calculations. Great work. This manuscript is ready for publication.

REVIEWER B (John Hanesiak)

Overview: The study documents and summarizes the key synoptic (and some limited mesoscale) aspects and processes that contributed to the tornado outbreak of June 9, 1984 in western Russia. The study also contained details of the tornado tracks, times of occurrence and locations. The outbreak killed many people and had other major impacts. It is argued that the Black Sea was a major moisture contributor to the event.

Although the article requires some major revision, the study is worthy of appearing in EJSSM based upon it providing some insight into a rare significant tornado outbreak event in Russia.

Recommendation: Accept with major revision

Substantive comments:

Scientific Merit/Contribution: Although this article does not necessarily significantly enhance our current understanding of severe weather events as a whole, it could be argued that the moisture source analysis (that requires some further "beefing up") and some of the other detailed analysis does provide at least some insight for the region in question.

Quality of Presentation: The authors have done a reasonable job in the quality of figures, English, organization, and, for the most part, completeness. It may be appropriate for the authors to expand their moisture source analysis to make the article more "complete" (see comments below).

Article Length / # of Figures: The existing article can be shortened by 1-2 pages by editing some of the sections that have too much detail in them (see below for specific comments). There are also too many non-critical figures in my view (see specific comments below).

1) The paper does NOT provide any explicit objective(s) of the article in the abstract nor the Introduction. It states what analysis it contains, however, the reader has no idea about the actual objective(s) of the study.

We added some additional details in the introduction to more fully address the objectives:

One of the major objectives of this study is to investigate the source of low-level moisture. This is particularly important since the authors disagree with findings from a previous study regarding the source of low-level moisture. We also expanded this objective to determine the typical source(s) of low-level moisture for tornado (F2 or greater) events in western Russia and the adjacent republics of eastern Europe. Another major objective is to thoroughly document the locations and times of severe weather reports, noting any discrepancies with Vasiliev et al. (1985a). To accomplish this objective, the authors utilized satellite imagery, newspaper descriptions, ESWD and information within Vasiliev et al. (1985a) to construct a map of the thunderstorm paths. The map confirms some findings, but also highlights significant differences with Vasiliev et al. (1985a). The map presents paths of thunderstorms that were associated tornadoes and/or wind reports, along with a notable hail report with is comparable to the heaviest hailstone on record.

2) In conjunction with (1) above, the article also does not make it clear how it is different than the other

articles on this same event (i.e. by Vasiliev et al.) - at least it is not entirely clear to me. If the authors would state their objective(s), this issue would likely be addressed as well. One objective could potentially be related to how this article is different than Vasiliev et al. and if the results are slightly different for this case, for example.

There are four significant differences between this article and that of Vasiliev et al (1985b):

1) Vasiliev et al. postulated that the source of moisture for the Ivanovo event came from the Mediterranean Sea. One of the objectives for this article is to present sufficient evidence to dispute this hypothesis. The "sufficient evidence" has been enhanced by the use of trajectories and additional soundings to show the Black Sea as the primary source of moisture for the Ivanovo event.

2) The authors believe some of the Vasiliev et al. tornado paths were in error. Our objective was to develop a tornado map and present sufficient evidence (i.e., visible satellite imagery, newspaper articles, ESWD reports etc.) for the map presented in this article and note where there are discrepancies between this article and that of Vasiliev et al.

3) Unlike Vasiliev et al., we also documented where the severe reports occurred in relation to the low-level convergence boundaries and upper-air features. We added this sentence at the end of section 1:
"In addition to the severe weather reports, the authors document where the tornadoes occurred relative to the initiating low-level convergence boundaries and upper-air features."

4) Although not stated explicitly as an "objective", this paper utilizes looping capabilities of multiple datasets which was not available in Vasiliev et al. 1985b. We're able to demonstrate how the storms moved relative to surface/upper air features. Vasiliev et al. 1985b showed one or two very crude surface charts which are very difficult to read. The paper does not mention where the storms are relative to the boundaries. Instability is only mentioned in subjective wording, without any mention of CAPE values. The same can be said of the vertical wind shear.

3) Section 3: The analysis and conclusions of this section is of primary concern to this reviewer. The authors contend that the Black Sea was **the** major moisture source for this event but do not in any way attempt to quantify this at all (using either tracers or diagnostic moisture transport/advection calculations from model data). Other tornado events were examined to produce Table 1; however, the primary method of determining the source region in each case was subjective.

We have included trajectory analyses as well as additional soundings to assess the source of the low-level moist air mass.

As for the soundings, early in section 2a we included the 1200 UTC 8 June soundings from Odessa and Kryvhi Rih along with discussion.

As for the trajectories, we used a backward trajectory (see new figure 11) from Ivanovo going back 96 hours at three different low-level heights. The trajectories clearly show the Black Sea being the origin of the low-level moist air mass. In addition, we also used forward trajectories - see new Fig. 12—from 3 different locations (indicated by the yellow + signs) starting at 3 different times in order to address the hypothesis – does any of the low-level moisture for the Ivanovo event come from the Mediterranean? The easternmost starting location over the Black Sea clearly moves towards the Ivanovo region. The starting location over the Mediterranean east of Greece moves northeast but then eastward, so that it does not make it close to Ivanovo by the time of the event. The starting location over the Mediterranean west of Greece, the parcels at 100 and 250 m move northeast then eastward, again looking unlikely that they would be close to Ivanovo by the time of the event. The highest level parcel at 500 m does make it towards the Ivanovo region by the time of interest, however the parcel is at 3.4 km by that time so that it's unlikely to be representative of boundary layer moisture. Based on this, we have even greater confidence in the Black Sea being the moisture source. The Mediterranean still cannot be completely ruled out, but the Black Sea plays the more significant role.

Regarding Table 1 which looks at other cases, with the inclusion of trajectory analysis in addition to the other data that was used (precipitable water and low-level wind vectors), we re-analyzed the 32 tornado cases of interest. The main consequence of using the trajectories was to determine that some of the cases clearly did not come from the Mediterranean (i.e., the trajectory was coming from the east or southeast), also the Caspian Sea could not be ruled out as a moisture source for the same reason. This resulted in some of the categories shifting from "Black and Mediterranean Seas" to "Black and Caspian Seas". Here is the difference between the old method and new (including trajectory analysis) methods:

Moisture source	**Percentage of cases (new)**	**Percentage of cases (old)**
Black Sea only	16	19
Mediterranean Sea only	6	3
Caspian Sea only	3	6
Black and Mediterranean Seas	21	41
Black and Caspian Seas	38	19
A combination of the Black, Mediterranean and Caspian Seas	16	13

We believe this is more accurate than the data from the old table due to the inclusion of trajectories.

In our conclusions we edited this sentence "Low level winds and the distribution of precipitable water in the days leading up to June 9 identify the Black Sea as the primary moisture source, with a possible secondary contribution from the Caspian Sea."
To this:
"Trajectories, low-level winds, and the distribution of precipitable water in the days leading up to 9 June identify the Black Sea as the primary moisture source, with a possible secondary contribution from the Mediterranean Sea."
Our justification for this is the inclusion of the trajectories, which were not used for the initial submission. We did not find any trajectories southeast of Ivanovo that would lead us to believe that the Caspian Sea played any role. However, based on the forward trajectories, the Mediterranean Sea cannot be completely ruled out as a moisture source. Note, this does not change the most important part of our argument, that the Black Sea was the primary moisture source.

More quantitative analysis is needed. For example, given the substantial troughing (strong meridional flow) at almost all levels of the June 1984 event, one could argue that moisture advection from further south and west would also have played a role in this event that wrapped up into this deep intensifying low - as somewhat indicated by Fig 11.

See above regarding the note on trajectories.

We did a number of other forward trajectories that are not shown in the paper, including in the eastern Mediterranean south of Turkey and found that these trajectories went south and east.

As well, do the authors have any information as to the physiographic nature of the region (local moisture sources such as smaller open water sources and vegetation/crop transpiration) at this time of year in western Russia? I suspect in June that crops (if any are actively growing in this region) would potentially contribute some low level moisture as well. The authors have one sentence that states "Also, low-level moisture convergence and local evapotranspiration may have allowed moisture to accumulate locally." More information about local vegetation/open water moisture sources should be investigated to some degree by the authors in my view—at least state how plentiful crops or other seasonal vegetation and small open water bodies may have been in this region. Quantifying local moisture via evapotranspiration is difficult; however, knowing how much of the region is covered by various vegetation types/open water bodies would provide some insight into this issue. The reviewer does not dispute that the Black Sea may have contributed to low level moisture for this case, however, the authors need to provide more information regarding other possible sources (and quantifying advection as best they can), as suggested above.

Moisture convergence was added as an overlay to Figure 2, and we do believe this played a significant role, in combination with the other factors discussed. The big question mark in our mind is evapotranspiration, we did add this sentence:
"The magnitude of evapotranspiration is uncertain; however, since early June is well within the growing season for this region, abundant vegetation coverage was likely. Therefore, evapotranspiration likely played a role in enhancing low-level moisture."

Since we're quite uncertain as to the role of evapotranspiration, we tried to convey the uncertainty in our text. We did attempt to make some rough estimate of ET using the Penman-Monteith equation, and came up with numbers around 7 to 8 mm day^{-1}. Rather than going into the details of this estimate and the large uncertainty associated with it, we think it's best to state what we did so as not to detract too much from our main point, which is the Black Sea being the primary source of low-level moisture for this event.

[Minor comments omitted...]

Second review:

Recommendation: Accept with minor revisions.

General Comments: The paper is vastly improved from its original version and includes most suggestions made by the reviewers. The authors have presented a nice overview of this important event and provided useful insight into its nature, impacts and causes as well as comparisons to other tornado events with respect to moisture sources. It is for these reasons that this reviewer suggests acceptance for publication. I have only two more suggestions for the author's consideration prior to final publication, indicated below.

[*[Minor comment omitted...]*

Substantive Comment:

Conclusions: the conclusions should restate the article's main objectives and organize the discussion somewhat around those objectives to make the point of the paper perfectly clear. None of the objectives are referred to at all in the conclusions section. Other key points (that are not explicit objectives) can be inserted where appropriate.

We made major edits to the conclusions and I think it sounds a lot better.