ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

TORNADOES, SEVERE HAIL, AND THEIR ENVIRONMENTS IN TURKEY

Ph.D. THESIS

Abdullah KAHRAMAN

Meteorological Engineering Department

Atmospheric Sciences Programme

NOVEMBER 2016

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

TÜRKİYE'DE HORTUMLAR, ŞİDDETLİ DOLU HADİSELERİ, VE OLUŞTUKLARI ÇEVRE KOŞULLARI

DOKTORA TEZİ

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KASIM 2016

Abdullah Kahraman, a Ph.D. student of İTÜ Graduate School of Science, Engineering, and Technology, with student ID 511092005, successfully defended the thesis/dissertation entitled "TORNADOES, SEVERE HAIL, AND THEIR ENVIRONMENTS IN TURKEY", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my family,

FOREWORD

A keen interest in severe convective weather, and their frequent occurrence in Turkey led me to prepare this thesis. From the first day observing a giant Black Sea waterspout from my balcony in 1998, to unforgettable 2014 spring, chasing supercells around Oklahoma and Kansas; I have gone to undergraduate and graduate schools of meteorology, studied a lot and anticipated that there is much more to explore about severe storms. I believe that this study will be a fundamental base for severe weather research in Turkey.

I would like to thank my advisor Mikdat Kadıoğlu, for his exceptional support, guidance, and patience during the research process, preparation of the thesis, and my whole graduate school years. I also would like to thank my co-advisor Paul Markowski, who not only excellently supervised my research in the U.S., but also provided wonderful opportunities for further academic development. Special thanks to David M. Schultz, who encouraged me to work on climatologies of severe weather in Turkey, and guided my research in my early graduate years, and Şeyda Tilev-Tanrıöver, for valuable discussions, her effort, and contributions in the Storm Meteorology and Modelling working group at Istanbul Technical University. My thesis committee members Selahattin Incecik, Zafer Aslan, Gürcan Oraltay, and Yurdanur Unal are acknowledged with gratitude for the insights they provided. My sincere thanks go to Yvette Richardson, Chris Nowotarski, Jim Marquis, Alexandra Anderson-Frey, Alicia Klees, Matthew Kumjian and Holly Hamilton from Penn State; Harold Brooks; all the editors and reviewers of the papers I have submitted; and the observers working at Turkish State Meteorological Service, journalists, and volunteers for reporting storms. Finally, for their precious support, I would like to thank Kemal A. Kahraman, Muhammed Kahraman, Ajda Kahraman, Sedef Çakır, Mediha Kılıç, and my parents, Ruziye and Kenan Kahraman.

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Abdullah KAHRAMAN
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ABBREVIATIONS

3-D	: 3-dimensional
AGL	: Above ground level
APR	: April
AUG	: August
CAPE	: Convective Available Potential Energy
CG	: Cloud to Ground
CYAFR	: Cyclones of North African origin
CYBAL	: Cyclones from Balkans
CYBLA	: Cyclones over Black Sea
CYMDC	: Central Mediterranean cyclones
CYMDE	: Eastern Mediterranean cyclones
DCAPE	: Downdraft CAPE
DEC	: December
DWD	: Deutsche Wetterdienst
E	: East
ECMWF	: European Centre for Medium-Range Weather Forecasts
EF	: Enhanced Fujita Scale
EF0	: Tornadoes with Enhanced Fujita Scale ratings of 0
EF1	: Tornadoes with Enhanced Fujita Scale ratings of 1
F	: Fujita Scale
F0	: Tornadoes with Fujita scale ratings of 0
F1	: Tornadoes with Fujita scale ratings of 1
F2	: Tornadoes with Fujita scale ratings of 2
F2+	: Tornadoes with Fujita scale ratings of 2 and higher
EHI	: Energy Helicity Index
EHI01	: Energy Helicity Index calculated with 0-1 km helicity
EHI03	: Energy Helicity Index calculated with 0-3 km helicity
EM-DAT	: Centre for Research on the Epidemiology of Disasters's Emergency Events Database
ERA	: ECMWF Reanalysis
ESWD	: European Severe Weather Database
FEB	: February
Fig	: Figure
H	: Hail intensity scale
IN+EA	: Central and eastern Anatolia
JAN	: January
JUL	: July
JUN	: June
LAR	: Large
LCL	: Lifting Condensation Level
LFC	: Level of Free Convection
LLS	: Low level shear
LST	: Local Standard Time
MAR	: March

MAR+BLA : Marmara and Black Sea coastal regions
MAY : May
MED+EGE : Mediterranean and Aegean coastal regions
MLCAPE : Mixed-Layer Convective Available Potential Energy
MLLCL : Mixed-Layer Lifting Condensation Level
MUCAPE : Most Unstable Convective Available Potential Energy
N : North
NCEP : (United States) National Centers for Environmental Prediction
NCAR : (United States) National Center for Atmospheric Research
NCL : NCAR Command Language
NON : Nonmesocyclonic
NOV : Novermber
OCT : October
ORD : Ordinary
REP : Republic
RUC : Rapid Update Cycle
SBCAPE : Surface-Based Convective Available Potential Energy
SBLCL : Surface-Based Lifting Condensation Level
SCP : Supercell Composite Parameter
SEP : September
SH06 : 0-6 km bulk shear
SRH : Storm Relative Environmental Helicity
SRH01 : 0-1 km Storm Relative Environmental Helicity
SRH03 : 0-3 km Storm Relative Environmental Helicity
STP : Significant Tornado Parameter
SUP : Supercell
TARSIM : Turkish Agricultural Insurance Pool
TOR : Tornado
TorDACH : Tornadoes and downbursts in Germany, Austria, Switzerland
TSMS : Turkish State Meteorological Service
ULL : Upper level low
ULT : Upper level trough
UNK : Unknown
US : United States
USA : United States of America
UTC : Coordinated Universal Time
VLG : Very large
WRF : Weather Research and Forecasting Model
WST : Western inlands of Anatolia

SYMBOLS

t	**:** Time
u,v	**:** Displacement Vector Components

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TORNADOES, SEVERE HAIL, AND THEIR ENVIRONMENTS IN TURKEY

SUMMARY

This thesis investigates the tornadoes, severe hail, and their environmental features in Turkey. Climatologies of tornadoes and severe hail are prepared using various data sources, from official records to newspaper and internet reports, after a rigorous quality control check.

The first part presents the first and most comprehensive climatology of tornadoes in Turkey to date. Tornado reports in Turkey historically have been sporadic and difficult to obtain, but reporting has improved in recent years for a number of reasons. Nonmesocyclonic tornadoes (waterspouts) are relatively common in the fall and winter along the Turkish coastlines, especially the southern and western coastlines of the Mediterranean and Aegean Seas, respectively. In fact, the southern coastline from Antalya to Anamur is likely among the most tornado-prone regions of Europe. Tornadoes in interior Turkey are less common, or at least reported less often. However, Turkey's strongest (and deadliest, despite a relatively low-population density) tornadoes have occurred here, most often in late spring, and are associated with supercells.

The second part focuses on the severe hail occurrences in Turkey. Investigating the spatial and temporal distribution of severe hail is a prerequisite for understanding and ultimately predicting the environmental conditions that are favorable for severe hail. Turkey's severe hail climatology reveals that all parts of the country are vulnerable to severe hail (larger than or equal to 1.5 cm), and it can occur in any season of the year. The largest hailstones exceed 5 cm in diameter and 480 g in mass. Severe hail in Turkey is most likely in May and June, when severe hail is most likely in the interior of the country, especially in the east. Severe hail is least likely in the winter, though when it occurs in winter, it is most likely along the southern and western coasts. The afternoon and early evening hours are the most favorable time of the day for severe hail. The long-term variations in Turkish severe hail events (e.g., the 1960s maximum and early 2000s minimum) are also discussed.

Thermodynamics of severe convective storms in Turkey are similar to relatively stronger than those in Europe, but considerably weaker than those in the US. This can partially be attributed to the latitude, and surrounding warmer seas. For deep layer shear, the situation is similar. However, low level shear appear to be lower. Complex topography of Turkey, being not represented in coarse reanalysis data might have contributed to this, effecting also the SRH values. LCLs are much lower than US environments, and similar to European ones, as expected. Composite parameters can be useful for discriminating severe weather. EHI and especially SCP are found to be useful in discriminating supercell and very large hail environments, as well as mesocyclonic tornado events from other storm categories. However, STP is not found to be a good discriminator for tornado forecasting.

TÜRKİYE'DE HORTUMLAR, ŞİDDETLİ DOLU HADİSELERİ, VE OLUŞTUKLARI ÇEVRE KOŞULLARI

ÖZET

Şiddetli konvektif fırtınalar, dünya genelinde ölümler ve maddi zararlarla sonuçlanan meteorolojik afetlerin önemli bir kısmından sorumludurlar. Ani taşkın ve seller, zarar verici hamleli rüzgarlar, dolu, hortum, yıldırım gibi olaylar şiddetli konvektif fırtınalar ile ilişkilidir. Türkiye'de sadece dolunun neden olduğu tarımsal zararlar yılda 73 milyon doları aşmaktadır.

İçeriklere-dayalı yaklaşıma göre bir konvektif fırtınanın oluşumu için gerekli üç içerik vardır: Kararsızlık, nem ve kaldırma mekanizması. Şiddetli konvektif fırtınalar içinse bunlara ek olarak düşey rüzgar kayması da mevcut olmalıdır. Bu içeriklerin bir bölgede bir an için ne ölçüde bir arada bulunduğu, o bölgede o an için şiddetli konvektif fırtınaların oluşum riskine işaret etmektedir. Bahsedilen içerikler birer meteorolojik parametre değildirler, ancak çeşitli meteorolojik parametrelerle bu içeriklerin mevcut olup olmadığı, mevcutsa hangi mertebede olduğuna dair çıkarımlar yapılabilir. Ancak kullanılacak meteorolojik parametreler daha çok ABD'de yapılan çalışmalarca ve ABD'de görülen koşullar için belirlendiğinden, dünyanın diğer bölgelerinde benzer temsiliyeti ve tutarlılığı sağlayamamaktadır. Bunda sinoptik klimatoloji, coğrafi konum, orta ölçekli süreçler, topoğrafik etkiler, vb pek çok etmen rol oynamaktadır. Bu yüzden şiddetli konvektif fırtınalar için ilgili bölgenin koşulları baz alınarak çalışmalar yapılmalı, bunların nerelerde hangi sıklıkla ve hangi şiddette meydana geldiği tespit edilmeli, ilgili klimatolojiler oluşturulmalı, meydana geldikleri çevre koşulları incelenmeli, ve elde edilen çıkarımlarla tahminlerde kullanılabilecek meteorolojik parametreler ve modeller belirlenmeli ya da geliştirilmelidir.

Konvektif fırtınaların orta uzay ve zaman ölçeklerinde meydana gelmesi, tahminlerindeki en önemli güçlüktür. Günümüzde atmosfer modellerinin gelişimi ile sinoptik ölçekte hava tahmininde başarı oranı oldukça yüksek olup orta ölçekte bu başarı sağlanmış değildir. Bunda halihazırdaki gözlemlerin atmosfer koşullarını tam olarak temsil edememesi, küçük ölçekli topoğrafik etkiler, parametrizasyonlar, model hataları vb rol oynamaktadır. İyi konfigüre edilmiş, 1 km mertebesinde grid aralığıyla çalışan bir orta ölçekli model ile konvektif hücreler simüle edilebilmekteyse de, bu hücrelerin yeri, zamanı, süresi, şiddeti, cinsi doğru olarak tahmin edilememektedir. Bu yüzden özellikle radar ve uydu gözlemleri ile otomatik meteoroloji istasyonlarından alınan anlık verilerin, bir konvektif fırtınanın oluşum ve gelişimi anında tahmincilerce değerlendirilerek çok kısa vadeli tahminlerinin (nowcasting) yapılması meteorolojik uyarıların temelini oluşturmaktadır. Ancak nowcasting tekniklerinin en fazla bir kaç saat mertebesinde bir vadede tahmini mümkün kılmasından ötürü, yapılan uyarılar önlem alınmasını sağlayamamaktadır. Tahmin tutarlı olsa dahi etkilenecek insanlar çoğunlukla afet gerçekleştikten sonra uyarıdan haberdar olmaktadırlar. Sonuç olarak zarar verici hadiselerin oluşma riskinin birkaç gün öncesinden tahmin edilmesi büyük

önem taşımaktadır, ve tahmin için de ilgili bölgenin sinoptik klimatolojisinin bilinmesi, bölgede şiddetli konvektif fırtınaları üreten ya da destekleyen çevre koşullarının ortaya çıkarılması, orta ölçekli süreçlerin incelenmesi, yerel etkilerin ortaya çıkarılması gerekmektedir.

Bu çalışmanın amacı, Türkiye'de oluşan şiddetli konvektif fırtınaların alansal ve zamansal dağılımlarının belirlenmesi, bunların operasyonel tahmininde kullanılabilecek kavramsal model ve/veya fiziksel parametrelerin belirlenmesi ya da geliştirilmesi için ilgili çevre koşullarının araştırılmasıdır. Çalışma, üç ana kısımdan oluşmaktadır. Bunlardan ilk ikisi Türkiye'nin hortum klimatolojisi ve iri taneli dolu klimatolojisini sunmakta, sonuncusu ise hortum ve iri taneli dolu hadiselerinin oluştuğu çevre koşullarını incelemektedir.

Türkiye'de meydana gelen hortum hadiselerine ilişkin kapsamlı bir veritabanı olmaması nedeniyle, ilk olarak çeşitli kaynaklardan veriler toplanmış ve bir veritabanı oluşturulmuştur. Meteoroloji Genel Müdürlüğü Fevk rasatları, European Severe Weather Database, eski gazete arşivleri (Cumhuriyet, Milliyet, Hürriyet, vb), internet taramaları, sosyal medya, Osmanlı Arşivi gibi kaynaklardan elde edilen bilgiler güvenilirlik derecelerine göre sınıflanmış, bunlardan şüpheli olanlar elimine edilerek kalanlar klimatolojiye dahil edilmiştir. Eldeki bilgiler yeterli olduğu durumda hortumlar mezosiklonik ve mezosiklonik olmayan şeklinde iki gruba ayrılmış, kalanları ise "bilinmeyen" kategorisinde değerlendirilmiştir.

1818'den 2013'e kadar gerçekleşen 385 hortum hadisesinin 225'i son 5 yıla ait kayıtlardadır. Bundaki ana neden, iletişimdeki büyük gelişim (internet ve akıllı telefonlar), Türkiye'de hortum oluşumlarına dair farkındalığın oluşmaya başlaması, ve bu çalışma kapsamında aktif olarak veri araştırılmasıdır. Kayıtlardaki trende bakılarak olası bir iklim değişimi ya da değişkenliği üzerine yorum yapmak ise şu noktada güçtür.

Son 5 yılda, en az 7'si mezosiklonik olmak üzere Türkiye'de yılda ortalama 45 hortum hadisesi kayıt edilmiştir. Bu değer 10000 km2'de 0.57 hadiseye karşılık gelmekte, ve Avrupa'daki hortum sıklığıyla uyumlu bir görünüm çizmektedir. Öte yandan, Türkiye'deki hortumların coğrafi dağılımı son derece heterojendir. Akdeniz ve Ege kıyıları en fazla hortumun gözlendiği bölgeler olup (385 hortumun 207'si burada gözlenmiştir), frekans Antalya-Anamur arası bant, yılda 10000 km2'de 19 hortum ile Avrupa'nın en çok hortum görülen bölgelerinin başında yer almaktadır.

Türkiye'de hortumlar farklı bölgelerde farklı mevsimlerde meydana gelmektedir. Akdeniz ve Ege kıyılarındaki hortumların daha çok kış aylarında gerçekleştiği görülmektedir. Bunların önemli bir kısmı mezosiklonik olmayan su hortumlarıdır. Ancak bölgede özellikle Ekim ve Kasım aylarında süper hücreli fırtınalarla ilişkili güçlü hortumlar da gözlenmiştir. Öte yandan, Karadeniz kıyıları yaz sonu ve sonbahar başında daha sıklıkla hortum hadisesine tanık olmaktadır. Bunların da ezici çoğunluğu su hortumlarıdır. İç bölgelerde ise mezosiklonik hortumlar daha ağırlıkla görülmektedirler; daha yıkıcı olan bu hortumlara özellikle Mayıs ve Haziran aylarında rastlanmaktadır.

Hortum kayıtlarına göre, gün içerisinde daha çok öğleden sonra ve akşam saatlerinde bu hadiseye rastlanmaktadır. Bunda konveksiyonel döngü ve rapor edilme değişimlerinin etkili olduğu değerlendirilmektedir.

Zarar vermiş hortum kayıtlarına göre Fujita ölçeğine göre sınıflandırılma yapılmış, bunlar arasında en fazla sayıda hortumun F1 şiddetinde olduğu bulunmuştur. Bu noktada zayıf hortumların (F0) rapor edilmeme oranlarının daha yüksek olduğu değerlendirilmesi yapılabilir. Öte yandan, (en az) F3 şiddetinde en az 4 hortum tespit edilmiştir.

Türkiye'de iri taneli dolu hadiseleri de sıklıkla görülmektedir. Kimi zaman yumruk büyüklüğünde görülmüş, 480 gramlık, hatta daha ağır dolu taneleri rapor edilmiş, zaman zaman yarım metreye ulaşan dolu birikintileri gözlenmiştir. İri taneli dolu binalara ve tarıma verdiği zararın yanısıra zaman zaman yaralanmalara da yol açmış, küçükbaş hayvanların sürüler halinde ölümüne neden olmuştur.

Hortum veritabanında olduğu gibi, iri dolu hadiseleri veritabanının oluşturulmasında da resmi kayıtların dışında gazete arşivleri ve internet kayıtları gibi kaynaklar taranmıştır. Çalışmada iri taneli dolu hadiselerine odaklanılmıştır, bu da 1.5 cm ve daha büyük çaptaki doluları kapsamaktadır. Dolu büyüklüğü hakkında, ABD'de olduğu gibi daha çok farklı objelerle mukayese şeklinde kayıtlar mevcuttur. Bunlardan en sık rastlanan fındık büyüklüğünde dolu hadiseleridir. Toplamda 1489 iri taneli dolu hadisesinin 721'i fındık büyüklüğünde şeklinde bildirilmiştir. Bunun hemen ardında, 436 tane ile ceviz büyüklüğü ifadesi yer almaktadır. Literatürde hemen hemen tamamının süper hücreli fırtınalardan meydana geldiği değerlendirilen 4.5 cm ve daha büyük çapta dolular için ise "çok iri" kategorisi oluşturulmuştur. İri dolu hadiseleri, 1.5 cm, 3.0 cm, 4.5 cm ve 6.0 cm eşik değerleri ile birlikte 4 ayrı sınıfta toplanmıştır.

İri dolu klimatolojisi, 1925-2014 yılları arasında toplam 1107 günde meydana gelen 1489 hadiseyi kapsamaktadır. Bunlardan % 8.3'ü çok iri taneli dolu hadiseleridir. Rapor edilmeyen, ya da büyüklük bilgisi belirtilmeyenler düşünüldüğünde, bu sayının çok daha fazla olduğu değerlendirilmektedir. Son yıllarda daha fazla veriye erişimin mümkün olduğu gerçeğinden hareketle, 2009-2013 arasında yılda 10000 km2'de ortalama 0.54 hadisenin gerçekleştiği hesaplanmıştır. Öte yandan, en yüksek frekansın görüldüğü yıllar son yıllar değildir. 1960'larda yılda en az 29 hadise rapor edilmiş, 1963'te bu sayı 74 olmuştur. Bunda o yıllarda Kuzey Atlantik jetinin nispeten güneye inmesinin ve siklon frekansının artmasının rol oynadığı değerlendirilmektedir. 2005'ten sonraki artışın ise olası meteorolojik faktörler dışında internet gibi daha geniş kaynaklardan veri elde edilebilmesine bağlanması mümkündür. Çok iri taneli dolu hadiselerinin yıllara bağlı değişimi değerlendirildiğinde, 1960 sonrasında olduğu gibi öncesinde de benzer frekans gözlenmekte, bu da 1960 öncesi 1.5 cm-4.5 cm arası dolu hadiselerinin gerçekte olduğundan daha az rapor edildiğine işaret etmektedir.

Türkiye'de iri taneli dolu hadiseleri en çok ilkbahar ve yazın görülmektedir. Mayıs ve Haziran aylarında gerçekleşen iri taneli dolu hadisesi sayısı, diğer tüm aylarda gözlenenlerin toplamından daha fazladır. Yine çok iri taneli dolu da en sık Haziran ve Mayıs'ta, daha sonra Temmuz ve Ağustos'ta görülmektedir. En düşük frekans Aralık ayındadır. Bu dağılım, Avrupa'nın güneyindeki diğer ülkelerin dağılımları ile uyumlu bir görünüm arz etmektedir. Sadece Güney Kıbrıs'ta kış ayları pik aylar olup, güney kıyılarımızdaki mevsimsel döngüde de bu fark belirgindir.

İri taneli dolu hadiseleri, hortumlardan farklı olarak, Türkiye'nin hemen hemen tamamında homojen bir dağılım sergilemektedir. Ancak farklı bölgelerde farklı mevsimsellik de mevcuttur. Yukarıda belirtilen genel dağılımın dışında kışın Akdeniz kıyıları, Nisan'da güneydoğu Anadolu'da iri taneli dolu belirgin biçimde görülmektedir. Öte yandan, kuzeydoğu kesimlerde iri dolu riski yaz boyunca sürmektedir. Bu dağılımlar, sadece iri doluları kapsamayan, meteoroloji istasyonlarındaki tüm dolu hadiselerini içeren dolulu gün sayısı istatistikleri ile de örtüşmektedir.

Hortumlarda olduğu gibi, iri taneli dolu hadiselerinde de öğleden sonra ve akşam saatleri günün en riskli saatleri olarak öne çıkmaktadır. Bu durum, yıldırım ve şimşek sensörlerince elde edilen veri ile kıyaslandığında, Türkiye'deki yıldırımların günlük dağılımı ile paralellik göstermektedir.

ERA-Interim reanaliz verisi kullanılarak, veritabanındaki hortum ve iri dolu hadiselerine ait çevre koşulları incelenmiştir. Reanaliz verisi 1979'dan başladığı için 1979-2013 arası 35 yıllık bir zaman dilimi değerlendirilmitşir. 0.75 derece yatay grid aralıklı ve yüzeyin yanısıra 1000 hPa – 100 hPa arası 27 seviye de içeren veri, 00UTC ve 12UTC başlangıç zamanlı 3 saatlik aralıklı tahminler halinde kullanılmıştır.

Hesaplanan parametrelerin çeşitli kategorilere göre dağılımı elde edilmiş, buna göre genel olarak hortum ve iri dolu hadiselerinin 2000 J/kg'a varan CAPE değerlerinde oluştuğu gözlenmiştir. Bu değerler genel olarak ABD'dekilerden düşük olmakla birlikte, Avrupa'da gözlenenlerle aynı seviyede, kimilerinden ise daha yüksektir. CAPE hesaplanmasında kullanılan parsel kalınlaştıkça bu değerler düşmektedir. Her ne kadar mezosiklonik hortumlar, F2+ hortumlar, çok iri dolu taneleri ve süper hücreli fırtınalar esnasında daha fazla CAPE değerleri mevcutsa da, bu parametre tek başına kategoriler arasında büyük bir ayrım göstermemektedir, dolayısıyla sadece CAPE'e dayalı olarak bunların arasındaki farkı tahmin etmek mümkün değildir. Çeşitli tabakalardaki düşey sıcaklık gradyanı ele alındığında ise, mezosiklonik olmayan hortumların 850-700 hPa ve 700-500 hPa gibi yerden yüksek tabakalarda daha az kararsızlığa sahip olduğu belirgindir. Bu tabakalarda ilgili kategorideki lapse rate, diğerlerinden farklı olarak % 75 gibi bir oranla 6.5 K/km altında değerlere sahiptir. Bunda yer (ya da deniz) seviyesindeki yüksek kararsızlığa rağmen hemen yukarıda kararsızlığın mevcut olmadığı, kıyılardaki su hortumları ağırlıktadır.

Türkiye'de mezosiklonik hortumlar ve özellikle F2+ hortumların oluştukları çevre koşullarında, 0-6 km shear değerlerinin medyanı 20 m/s üzerindedir. Bunları süper hücreli fırtınalar, çok iri dolu taneleri ve kategorize edilmemiş hortumlar takip etmektedir. Bu değerler ABD'de gözlenenlerle kıyaslanabilir büyüklükte olup, Avrupa'da gözlenenlere oranla genllikle daha yüksektir. Mezosiklonik olmayan hortumlarsa en düşük shear dağılımına sahip olup, medyan değer 10 m/s civarındadır. Bunlardan % 75'i 15 m/s ve daha az shear ortamında gerçekleşmiştir. Aşağı seviye shear verileri ise, daha önce ABD için yapılan çalışmalardakinden daha düşüktür. Bunda kullanılan reanaliz verisinin karmaşık Türkiye topoğrafyasını iyi temsil etmemesi gibi faktörlerin etkili olduğu değrlendirilmektedir. Avrupa'daki kimi çalışmalarda da benzer sonuçlar mevcuttur. 0-1 km shear dağılımlarına göre, tüm kategorilerde değerler düşük olmakla birlikte, mezosiklonik olmayan hortumlarda en düşük değerler gözlenmiştir. SRH dağılımlarında da 0-3 km'de anlamlı şekilde F2+ ve mezosiklonik hortum kategorileri en yüksek değerlere sahiptir, 1000 m2/s2'yi aşan miktarlarla çok şiddetli hava olaylarının mümkün olduğu göze çarpmaktadır; öte yandan 0-1 km için nispeten düşük değerler gözlenmektedir.

Türkiye'de LCL seviyesi genel olarak tüm fırtına tiplerinde 1500 m'nin altında seyrettiğinden, ABD'de olduğu gibi hortum tahmininde belirleyici bir role sahip değildir. Benzer durum Hollanda gibi Avrupa ülkeleri içi nde geçerlidir. Öte yandan, dolu hadiselerinde hortumlara göre nispeten yüksek bulut tabanı gözlenebilmektedir.

Modern kompozit indeksler ele alındığında, SCP'nin Türkiye'de anlamlı bir dağılımı olduğu söylenebilir. Birimsiz bu indeksin 2 ve daha üstündeki değerlerinde süper hücreli fırtınalar, çok iri taneli dolu hadiseleri ve mezosiklonik hortumlar gözlenmiştir. Mezosiklonik olmayan hortumlarda ise bu değer 0 civarındadır. İri dolu hadiseleri ile çok iri dolu hadiselerini ayırmada da bu indeks başarılı olmaktadır. 0-3 km ve 0-1 km için hesaplanan EHI değerleri de F2+ hortumlar, mezosiklonik hortumlar, çok iri dolu hadiseleri ve süper hücreli fırtınaların tahmininde ayırt edici şekilde kullanılabilir. Öte yandan, ABD'de hortum tahmininde faydalanılan STP'nin Türkiye dağılımları çok düşük değerlerde seyretmektedir. Bunda reanaliz verilerinde özellikle aşağı seviye shear'inin düşük olması etkilidir.

1. INTRODUCTION

Severe convective storms are responsible from an important section of the meteorological hazards causing losses of lives and property worldwide. According to The International Disaster Database, floods and storms are the most frequent disasters throught the last 115 years, with an increasing trend (Figure 1.1). In the database, floods include flash floods, which are usually associated with convective storms.

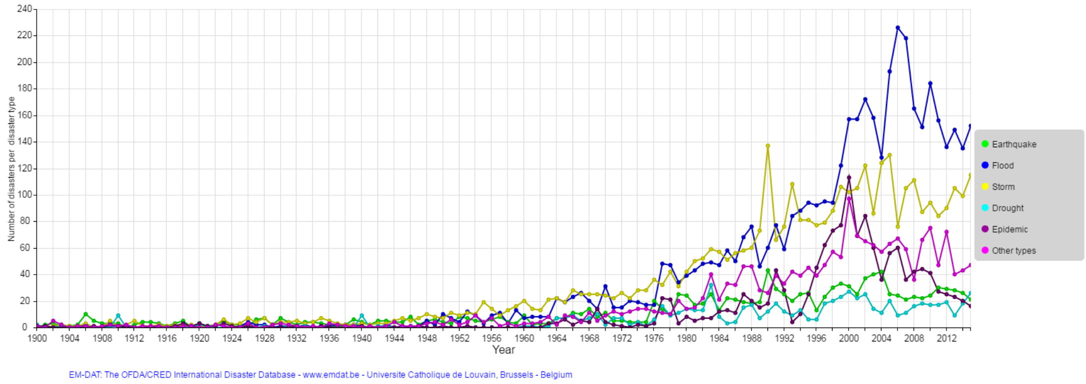

Figure 1.1 : Number of disasters reported between 1900 and 2015 (from EM-DAT, The OFDA/CRED International Disaster Database).

Tornadoes, severe hail, excessive rain causing flash flood and severe wind gusts are associated with different aspects of severe convective storms. However, all are results of mesoscale to microscale processes around deep moist convection. Even if all these processes would be handled satisfactorily, the scale problem makes operational analysis and forecasting a hard work, which is crucial for early warnings and preparedness.

At this time, forecasting of these small scale events heavily depends on nowcasting techniques, which permits early warnings in the order of minutes, or a few hours in advance at best in most of the countries, including Turkey. On the other hand, the Storm Prediction Center in USA makes probabilistic forecasts one to three days in advance. Developing and using appropriate techniques for short range forecasting of severe convective storms in Turkey is possible, and this can shift disaster management paradigms in the country, in terms of preparedness.

1.1 Purpose of Thesis

The purpose of this study is to build tornado and severe hail climatologies of Turkey, and investigate the environmental conditions of these phenomena in order to determine or develop operationally available physical parameters and/or conceptual models to analyse and forecast them.

The concept of the forecast parameters is considered to follow the ingredients-based approach, meaning that they are supposed to be reflecting some form of a particular ingredient of a spesific weather phenomena, so that the forecaster will be able to analyse the physical processes using separate contributors. This is important in particular when some of the ingredients do not exist while some others are very strong in an environment, dominating composite indices and resulting in false alarm rates. One other aspect of this paradigm is that the forecaster can consciously follow how models agree or disagree with observations, i.e. when an ingredient which is not present according to the model output may become available at observations, increasing the risk of severe weather dramatically.

1.2 Significance

Occurence of severe convective storms and related hazards are not comprehensively studied in Turkey. Almost all of the previous studies are case studies, and don’t give an idea of how representative they are of a particular geography and climatology. Locations of tornado and severe hail occurrences, their frequency in a particular location, the intensity distributions, time of the day, and their seasonality, etc. needs to be known. As a part of this study, a severe weather database is built and climatologies of severe weather events are constructed. Knowledge of severe weather risks can shift the paradigms of the government, decision-makers, research community, forecasters, insurence companies and society.

Understanding severe weather environments of Turkey will lead to determining mesoscale mechanisms favoring severe weather events, and these will be some key outcomes of the study not only for researchers, but also for operational forecasters. Determining or developing appropriate physical parameters to be applied to operational mesoscale model outputs will make tremendeneous benefit for risk analysis/probabilistic forecasting of severe weather. Forecasting checklists can be created using these parameters. It can be further investigated how these parameters work for other parts of the world.

1.3 Literature Review

1.3.1 Research on severe convective storms and related hazards: A brief history

Argueably, USA is the country which suffers most from severe convective storms in the world, and most of the research about these storms is performed in this country. It can be discussed that the history of severe weather research goes back as early as the history of meteorology. One can start from kite flight experiments of Benjamin Franklin in 18th century, or collection of tornado reports in the U.S. by John Park Finley in late 1800s and in Germany by Alfred Wegener in early 1900s (Doswell, 2007). However, The Thunderstorm Project in 1940s is usually considered to be a first step in modern severe thunderstorms research, which has been a base for contemporary scientific understanding.

Figure 1.2 : Some researchers of “The Thunderstorm Project” operating a mobile SCR-584 radar in Ohio, 1947 (Kurz, 2012).

The Thunderstorm Project included observations from not only the conventional weather stations and radiosondes, but also weather radars and aircrafts, mantained by US Weather Bureau, US Army Air Force, Navy and National Advisory Committee for Aeronautics (Fig 1.2). Observations in Florida in summer 1946 and in Ohio in summer 1947 are published by Byers and Braham in 1949 as the official summary of the project “The Thunderstorm”. The results showed the three main stages of a thunderstorm cell namely the cumulus stage, mature stage and dissipating stage, the updrafts and downdrafts, and their relationships with surface pressure, as well as gust fronts and outflows. Fig 1.3 is an example from Byers and Braham’s study, depicting the mature stage of the life-cycle of a thunderstorm (1949).

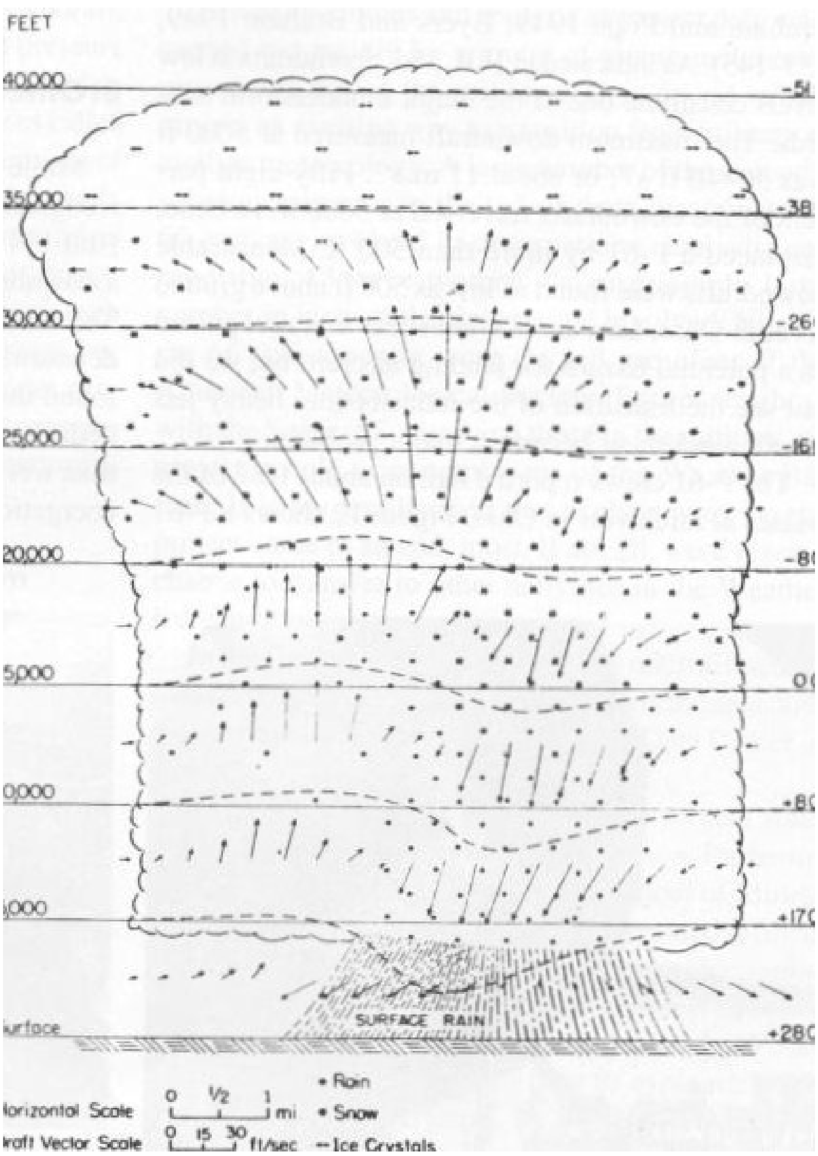

Figure 1.3 : Mature stage of a thunderstorm cell, illustrated by Byers and Braham (1949).

In 1951, Morris Tepper used mesonetworks for his “Tornado Project” over Plains of USA.

Ernest J. Fawbush and Robert C. Miller investigated severe convective storms and related phenomena such as tornadoes, large hail, gusty winds, and published their results in 1953 and 1954. These studies were on determining the environmental conditions of the atmosphere during tornado cases, hail size forecasting methods, wind gust forecasting approach in order to be able to make forecasts of severe weather (Fawbush and Miller, 1953a, 1953b, 1954a, 1954b). Fig 1.4 shows an example of a composite chart from their article “Forecasting Tornadoes”. Miller later published a technical report named “Notes on Analysis and Severe-Storm Forecasting Procedures of the Air Force Global Weather Central”, an extensive guide for forecasters (1972). Another similar guide was published by Crisp (1979).

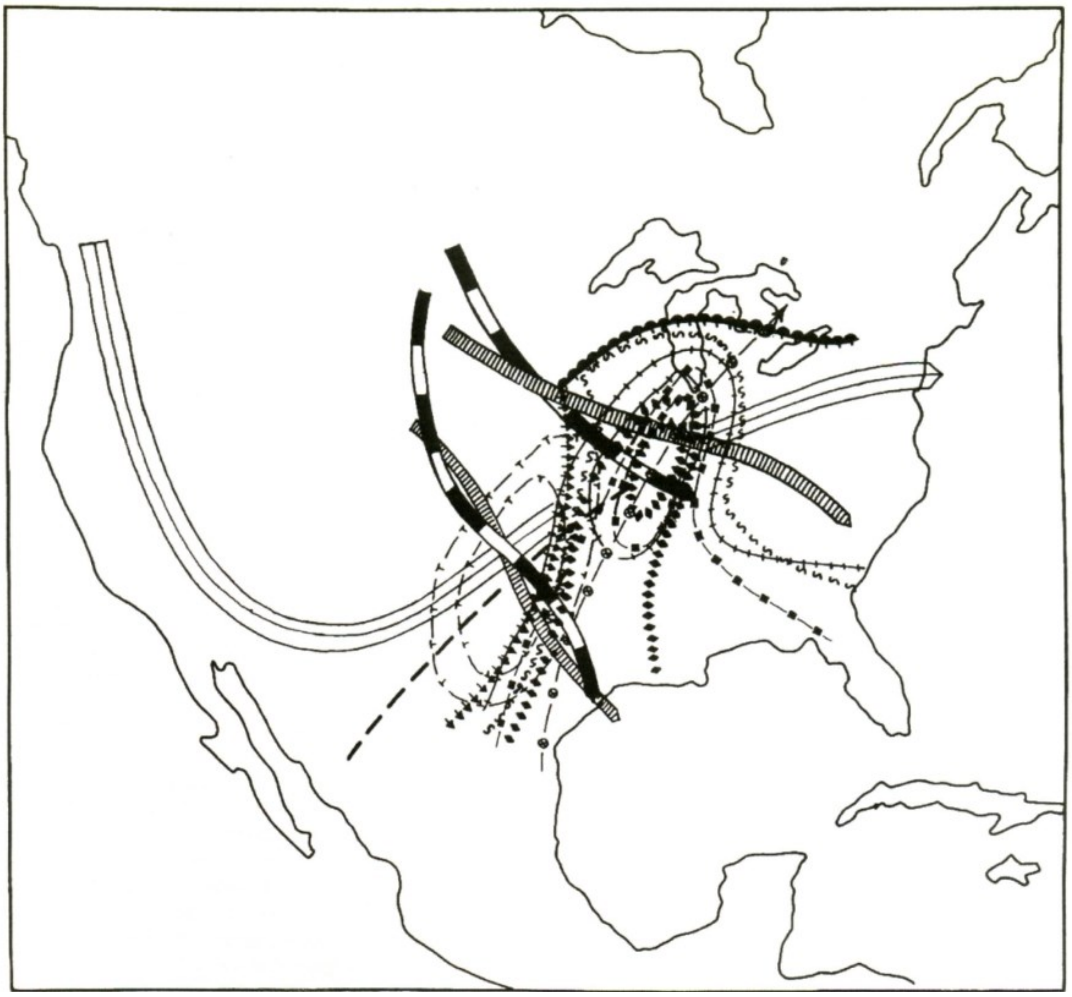

Figure 1.4 : A composite chart example from Fawbush and Miller (1953a).

Tetsuya Fujita's studies are accepted as milestones in severe convective storms research. He used mesoscale analysis using the mesonetwork data from plains to create his famous conceptual models. He published a detailed analysis on squal lines (Fig 1.5) in 1955, and his conceptual model of the tornadic storm (which is now called supercell) in 1960. He was the first to explain storm-generated cold pools of air (1963). His manual of downburst identification was published in 1978 (Fig 1.6). Discovering microbursts, using photogrammetry for quantitative analysis of severe storms, detecting and naming "wall" and "tail" cloud formations, devising the internationally accepted standard for measuring tornado severity are some important notes to be mentioned about him.

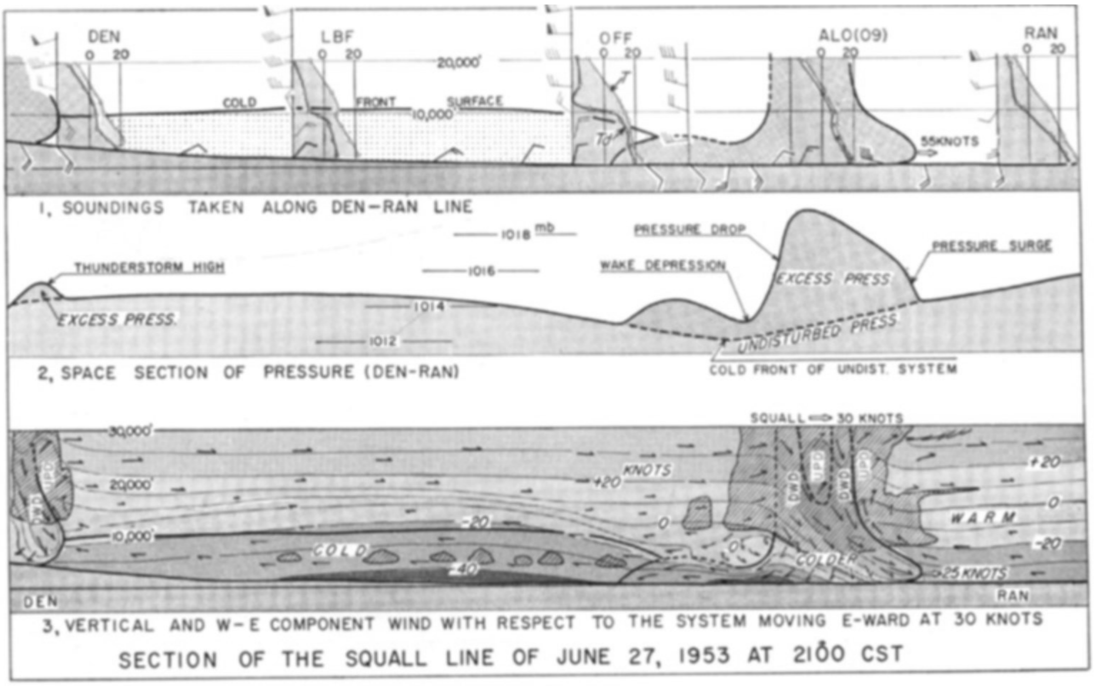

Figure 1.5 : Fujita's illustration of "East-west cross section of the squall-line of June 27, 1953 at 2100 CST" from his study (1955).

Keith Browning published a conceptual model of kinematic airflow and precipitation trajectories within severe local storms (supercells) in 1964. He used radar data to understand the internal structure of these storms, and mentioned the relationship between supercells and vertical wind shear.

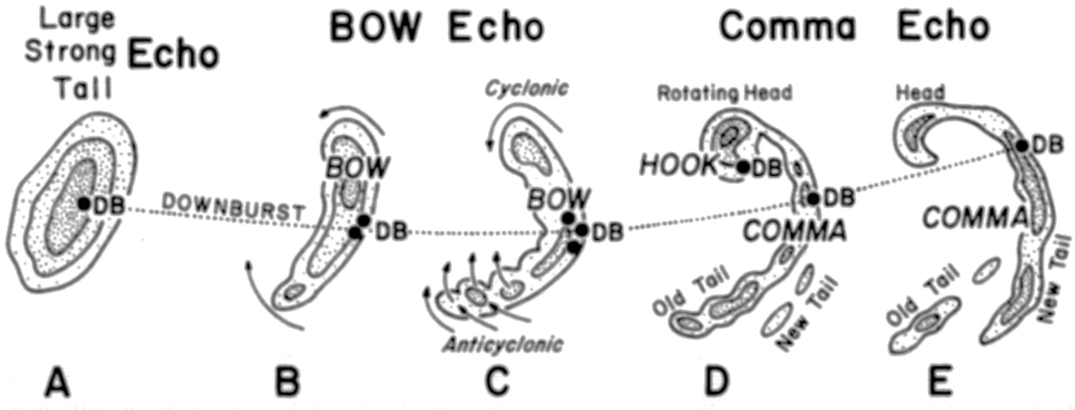

Figure 1.6 : Fujita's illustration of "bow" and "comma" echoes associated with strong and extensive downbursts (1978).

In 1970s, development of Doppler radars and 3-D numerical cloud models as well as scientific storm chasing resulted in a revolutionary better understanding of severe storms according to Doswell (2007). Among other studies with Doppler radar data usage, Rodger A. Brown et al. published their study about tornado detection by a Doppler Radar (1978). Meanwhile, Robert E. Schlesinger, and right after, Joseph Klemp and Robert B. Wilhelmson simulated splitting storms using three dimensional idealized models (1978). Later on, Morris L. Weisman and Joseph B. Klemp studied the effects of vertical wind shear and buoyancy on convective storm structure and evolution (1982). Short lived single cells, certain types of multicells and rotating supercells were successfully simulated by varying the magnitude of buoyant energy and one-directional vertical shear over a wide range of environmental conditions associated with severe storms. Two years later, they published another paper on the structure and classification of numerically simulated convective storms in directionally varying wind shears (1984). Fig 1.7 shows an example from one of their model outputs, depicting the horizontal flow around a left flank cell relative to the 6 km mean wind.

Foote and Frank created a conceptual model of the airflow around a hailstorm in Colorado (1982).

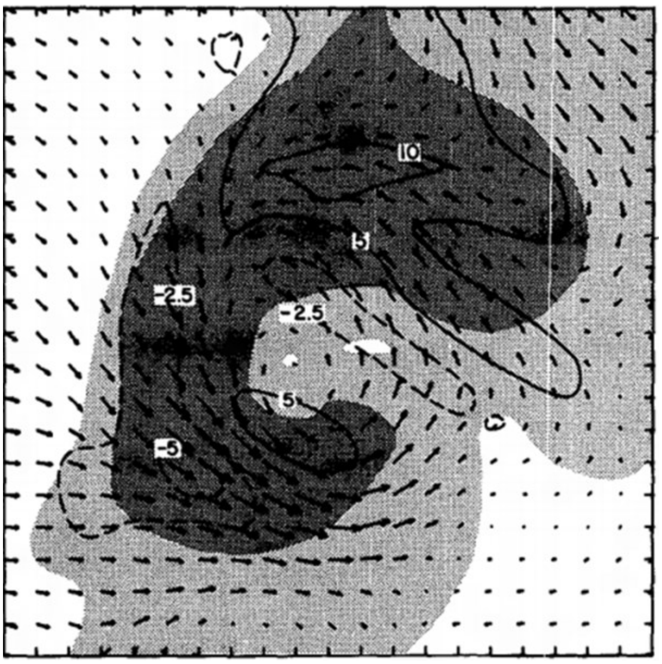

Figure 1.7 : Structure of dominant left flank cell at mid troposphere from Weisman and Klemp, 1984.

1.3.2 Severe weather climatologies in Europe

Nikolai Dotzek's survey on average tornadic activity in Europe, which is conducted among the European Conference on Severe Storms 2002 participants showed that a total of 329 tornadoes over land and water per year are observed in Europe (2003), and an estimated total is about 700. Tornadoes over land occur 1170 times in USA, and 169 in Europe, with an estimate of 304 according to the study. Turkey is not inside the 28 countries included in the dataset.

Nikolai Dotzek built a climatology of tornadoes in Germany, using the TorDACH database up to the year 2000 (2001). The climatology includes 517 tornadoes, mostly occuring on afternoon and early evening hours, with a seasonal maximum in July. Four to seven tornadoes occur per year, and the most severe tornado has been classified as F4. Dotzek mentions that most of the weak tornadoes are not reported, and with a statistical approach, he finds out the true number of tornadoes each year should be around 15 to 25. Increasing surface roughness and terrain height favour tornadoes by enhancing the low level (horizontal) vorticity.

2.7 tornadoes on average occur in Austria per year, according to Holzer, although there are considerable amount of unreported cases (2001). Daytime peak is in the late afternoon, and July is the month with the most records. There are spesific regions because of orographical effects, and the geographical distribution is not homogeneous, with east part showing a more frequent distribution.

Between 1989 and 1999, 27 tornadoes and 54 waterspouts are reported in Balearic Islands (Gaya et al, 2001). September and October are the months with the highest frequency, typical track length is 4 km, and afternoon to evening hours have the peak. Their discussion includes the idea that tornadoes and waterspouts occur usually during colder air masses.

Izolda Marcinoniene's tornado climatology of Lithuania consists of 23 records of Lithuanian Hydrometeorological Service, in the period of 1950-2002 (2003). Spring and summer months in the year and between 12-15UTC in a day show the peak in the dataset. The strongest tornado observed on 29th of May, 1981 is rated as F2, and analysed in the study.

Ireland's tornado climatology is published by John Tyrell in 2003. The climatology consisted of three years data between 1999-2001, part of the analysis including the data since 1950. He suggests that although the classical environmental conditions do not imply severe convective activity frequently, Ireland has an active tornado regime. Typically ten tornadoes are observed each year in Ireland, mostly occuring in August. Intensities vary between F0 and F3, afternoon hours having the peak.

Michalis V. Sioutas and Alexander G. Keul studied the synoptic and mesoscale conditions associated with 28 waterspout cases around Adriatic, Ionian and Eagean, during summer and fall 2002 (2007). 12 of the waterspouts occured between 06 to 08 UTC. "Longwave Trough" and "Closed Low" weather types dominated Adriatic waterspouts, and Ionian waterspouts only occured during "Southwest Flow" and "Closed Low" classes. "Short Wave Trough" and "Closed Low" are the types mostly observed during Eagean waterspouts.

Dario B. Giaiotti and friends built a climatology of tornadoes and waterspouts for Italy in 2007. They used ten years data collected by amateurs. Summer and autumn are the seasons with most tornadoes, and flat areas observe more tornadoes than rough orographic areas. According to the authors, the tornadoes in Italy are weaker than those in other countries, and the CAPE-SRH diagrams as well as shear magnitude diagrams show different characteristics than those obtained for USA.

Czech Republic experienced 307 tornadoes in 264 tornado days from 1119 to 2010 (Brazdil et al, 2012). Yearly average from the last 10 years is 4.6 tornado days and 5.6 cases. Summer is the most tornadic season, and most of the reports are EF1.

Jenni Rauhala, Harold Brooks and David M. Schultz constructed a climatology of tornadoes for Finland in 2012. The 1796-2007 dataset consists of 298 records, all occuring between April and November, 169 of which are from the recent years i.e. between 1997-2007. These recent years' data indicate that averagely 14 cases occur in Finland every year, and F2 or stronger ones once every two years. Between 17 to 19 is the peak time of the day for tornadoes. Hail climatology of Friuli Venezia Giulia plain in Italy has been built using hailpad network established in 1988 (Giaiotti et al., 2003). Most of the cases occured between 12 and 18 UTC, and in June and July. Large scale circulation relevant to hail occurences is also discussed in the study.

According to Sioutas and friends, hail is a spring and summer phenomenon in northern Greece (2009). A mean number of 8 hail days was recorded by the hailpad network. Maxima of hail occurence are located at higher elevation areas close to the lee of the mountains. About 86 % of the hailstones were smaller than 11 mm.

Webb et al. performed an extensive climatological survey and hazard assesment for severe hailstorms in Britain and Ireland using 2500 hailstorm cases since 1141 (2009). 75 years between 1930 to 2004 are examined in respect of seasonal frequency and geographical distribution. The highest frequency of significant, damaging storms (H2 or more intensity with hailstones usually over 15 mm diameter) is in central and eastern England, with the East Midlands, East Anglia. These hailstorms occured mostly between May and August, having a peak on June. 12-15 UTC is the diurnal maxima of H4-5 intensity cases between 1800-2004.

Jari-Petteri Tuovinen et al constructed a climatology of severe hail in Finland using newspaper records, storm-spotter and eyewitness reports (2009). 1 May to 14 September is covered in the climatology during the 77 year period of 1930-2006. 84 % of the 240 severe hail cases occured from late June to early August, July being the peak month. Afternoon and early evening hours are the most favourable times for these occurences, and southern to western parts of the country have more reports than other sides. Annual average of severe hail days is 5, and severe hail cases is 10 according to the most recent 10 years of data.

1.3.3 Current understanding of environmental conditions of severe convective storms

Paul Markowski and Yvette Richardson (2010) explain why vertical wind shear is related with the type, lifetime and severity of a storm with the notion of separateness of the updraft and downdraft regions, and development of dynamic vertical pressure gradients. When 0-6 km shear is under 10 m/s, storm type is single cell: new cells can not be initiated by gust front and convection is short lived. Between 10 and 20 m/s of shear values, multicells are dominant: new cells are initiated usually at downshear flank along the gust front, with system propagation being driven by gust front lifting. Above 20 m/s shear, supercells are likely with persistant updrafts and vertical pressure gradients governed propagation. Other factors which have much smaller effects on storm type are mentioned as vertical distribution of buoyancy, moisture and shear, etc.

Erik N. Rasmussen and David O. Blanchard have used a so called "proximity-inflow method" in their study on baseline climatology of parameters for convective storms (1998). This method is based on the idea that a sounding to be used for analysing the environmental conditions should be at the inflow section of a meteorological event in order to reduce the efects of the convection itself to the parameters. Proximity is taken as 400 km according to the wind direction of the low level, within a 150 degrees angle. Using 6000 0000 UTC soundings that have nonzero CAPE from 1992, they showed that severe storms have larger CAPE values than ordinary ones (Fig 1.8). Only a quarter of ordinary storms have over 1094 j/kg CAPE, while slightly more than half of the supercells with and without F2 or higher-rated (significant) tornadoes exceed this value. However, it is hard to discriminate significantly tornadic or other supercells using CAPE. It can be mentioned that the distribution for significantly tornadic ones are skewed farther toward higher values though. In the same study, the deep layer shear also is examined to be able to discriminate between the ordinary storms and supercells with and without significant tornadoes (Fig 1.9) when the CAPE is nonzero. More than half of the ordinary storms are under 25th percentile of others, whose medians are around 19 m/s. However, severe storms with and without significant tornadoes show similar results again. Regarding the energy helicity index (EHI), which is defined by Hart and Korotky (1991) and Davies (1993) as

$$EHI = \frac{(CAPE)\ (SRH)}{1.6 \times 10^5}. \qquad (1.1)$$

they suggest that likelihood of significant tornadoes increase with increasing values (Fig 1.10), and EHI is a good discriminator between all three classes of storms. For ORD soundings, 90% have EHI <0.77, while only about 60% of SUP soundings have EHI <0.77, and less than one third of TOR soundings have values less than 0.77. TOR soundings are very strongly distinguished in the neighborhood of EHI=1.5, where approximately half of TOR supercells have values greater than 1.5 and only 10% of SUP soundings have values larger than In the same study, they hypothesize that relatively low values of boundary layer relative humidity support more low-level cooling through the evaporation of rain, leading to stronger outflow. Relatively dry boundary layers are characterized by higher LCLs, and the distributions in Fig. 1.11 are consistent with the subjective storm intercept observations. According to the figure, half of the TOR soundings have LCLs below 800 m, while half of the SUP soundings have LCLs above 1200 m. They note that LCL, as with most of the parameters explored in the study, could have major variation on small time and space scales (Markowski et al. 1998) that are not well sampled with network soundings. Actual LCL heights near tornadic supercells may be considerably lower than found.

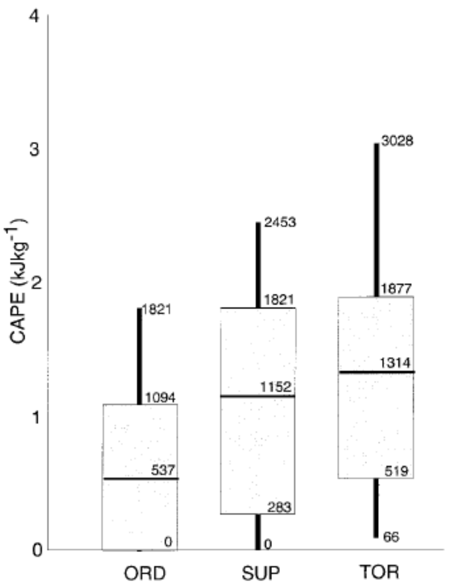

Figure 1.8 : CAPE for soundings associated with nonsupercell “ordinary” storms (ORD), supercells without significant (F2 or higher) tornadoes (SUP) and supercells with significant (F2 or higher) tornadoes (TOR). Boxes denote 25th to 75th percentiles, horizontal bar the median, whiskers extend to the 10th and 90th percentiles (Rasmussen and Blanchard, 1998).

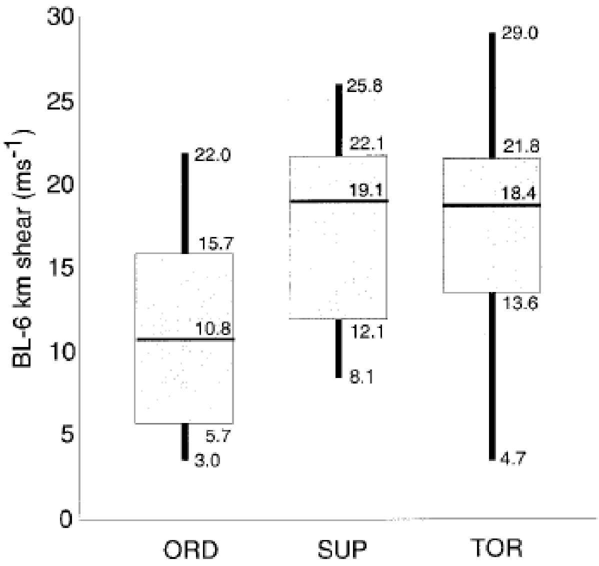

Figure 1.9 : Difference between mean boundary layer and 6 km winds associated with nonsupercell "ordinary" storms (ORD), supercells without significant (F2 or higher) tornadoes (SUP) and supercells with significant (F2 or higher) tornadoes (TOR). Boxes denote 25th to 75th percentiles, horizontal bar the median, whiskers extend to the 10th and 90th percentiles (Rasmussen and Blanchard, 1998).

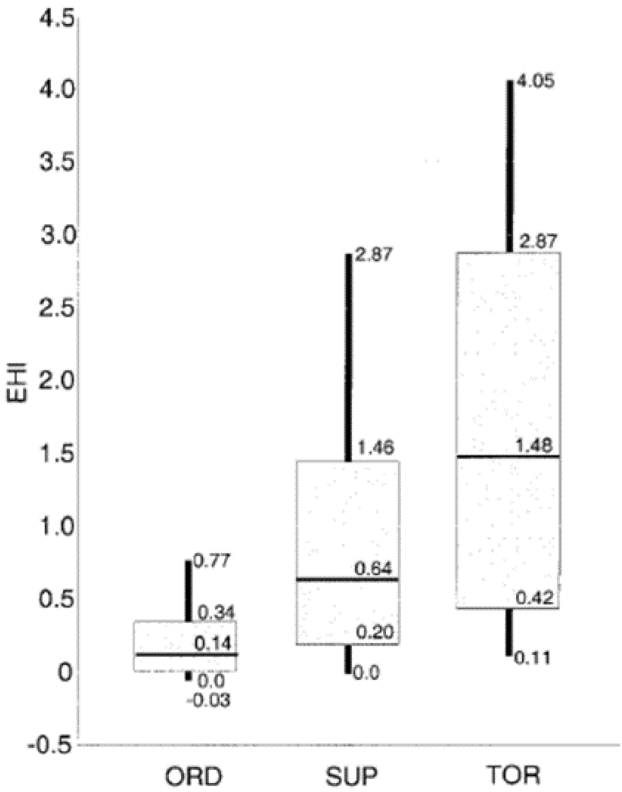

Figure 1.10 : Energy Helicity Index associated with nonsupercell "ordinary" storms (ORD), supercells without significant (F2 or higher) tornadoes (SUP) and supercells with significant (F2 or higher) tornadoes (TOR). Boxes denote 25th to 75th percentiles, horizontal bar the median, whiskers extend to the 10th and 90th percentiles (Rasmussen and Blanchard, 1998).

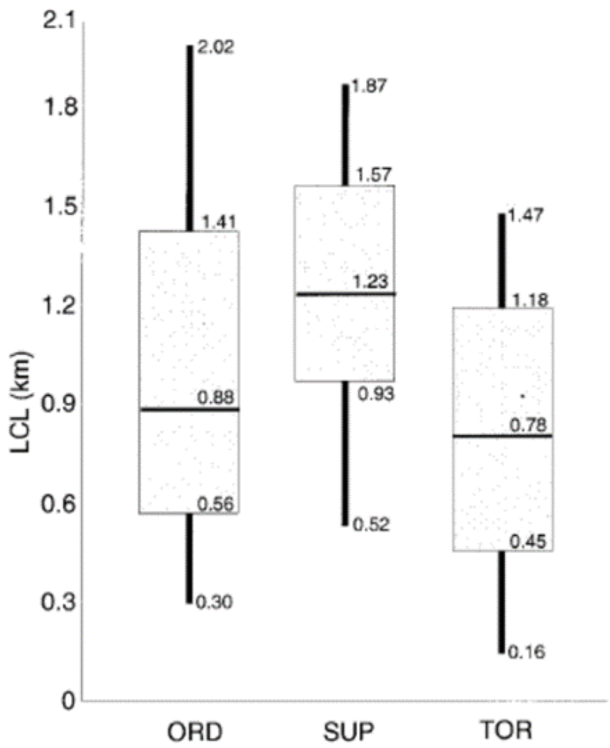

Figure 1.11 : LCL associated with nonsupercell "ordinary" storms (ORD), supercells without significant (F2 or higher) tornadoes (SUP) and supercells with significant (F2 or higher) tornadoes (TOR). Boxes denote 25th to 75th percentiles, horizontal bar the median, whiskers extend to the 10th and 90th percentiles (Rasmussen and Blanchard, 1998).

Craven and Brooks (2004) studied 60090 0000 UTC proximity soundings from 1997-1999. In their study, proximity is defined as 185 km, and six categories are defined as no thunder with zero and nonzero MUCAPE (0-1 CG strikes), general thunder (more than one CG strike), severe (0.75~1.99" hail and/or 50~64 kt gust and/or wind damage and/or F0 or F1 tornado), significant hail/wind (equal or bigger than 2" hail and/or higher than 65 kt gust) and significant tornado (F2¨F5 tornado). They showed that there is an impressive difference between significant tornado events and other five categories when the 0-1 km shear is considered (Fig 1.11). More than three fourth of significant tornado events occured with low level shear higher than that of significant hail/wind events and other categories. Furthermore, the seasonal variability graph (Fig 1.12) implies that low level shear during significant tornado cases does not change according to the time of the year as much. LCL height for the lowest 100 hPa parcel indicates that significant tornadoes occur in lower cloud base environments (Fig 1.13). In the same study, they also depicted the parameter combinations such as 0-1 km shear vs MLLCL, significant severe parameter and strong tornado parameter. The latter is defined as

$$STP = \frac{(MLCAPE)*(0 - 1\ km\ shear)*(0 - 6\ km\ shear)}{MLLCL*DCAPE} \tag{1.2}$$

and resulted in the fact that much more than half of the strong/violent tornadoes occured with values higher than 0.25 m/s-2 while more than three fourth of other events occured lower than that (Fig 1.14).

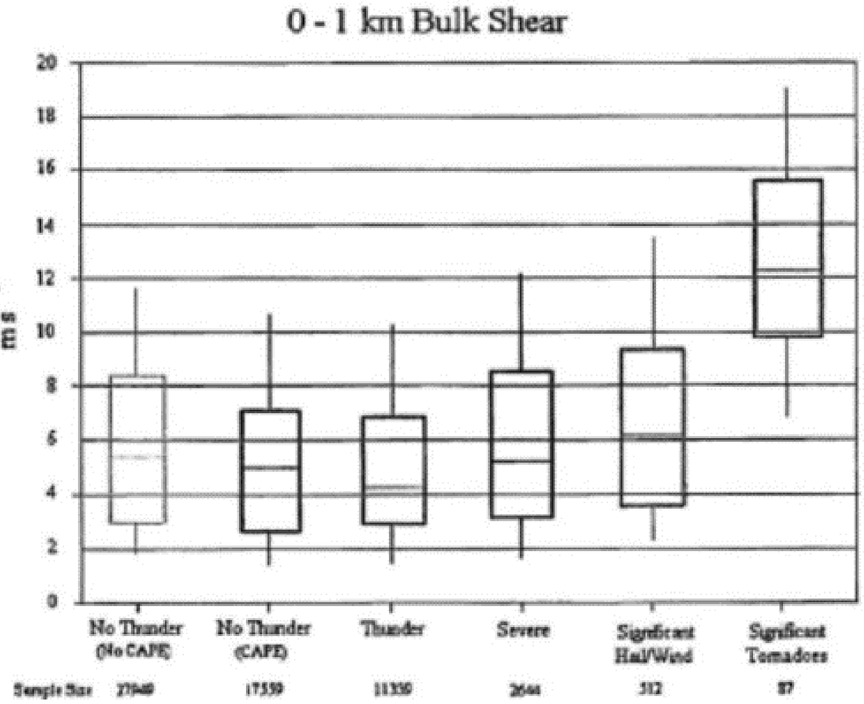

Figure 1.12 : 0-1 km shear versus storm categories. (Craven and Brooks, 2004).

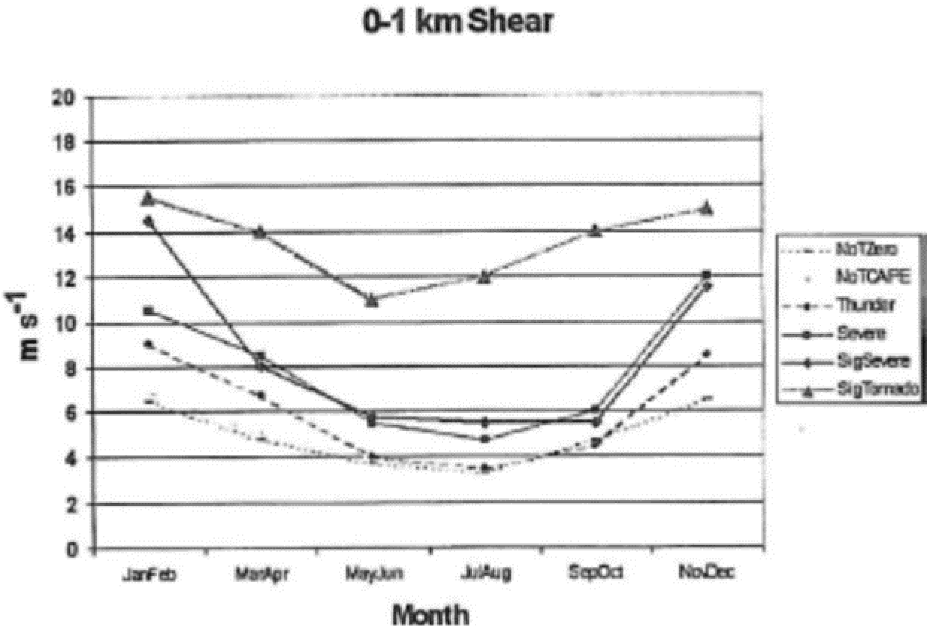

Figure 1.13 : Seasonal variation in 0-1 km shear for storm categories. (Craven and Brooks, 2004).

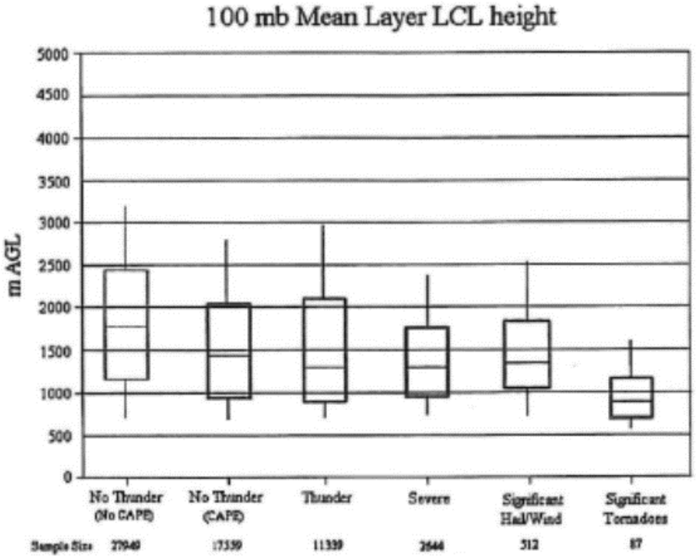

Figure 1.14 : 100 hPa mean layer LCL height for storm categories (Craven and Brooks, 2004).

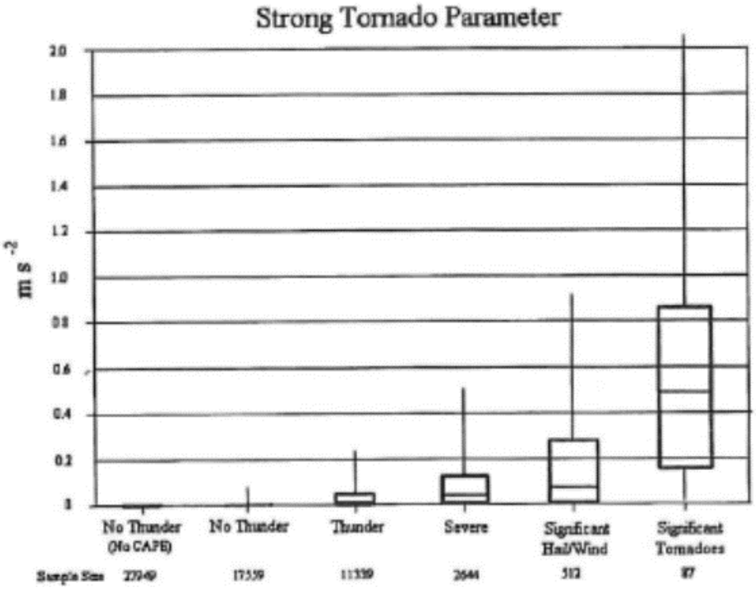

Figure 1.15 : Strong Tornado Parameter versus storm categories (Craven and Brooks, 2004).

Brooks et al (2003) used NCAR/NCEP reanalysis data as proximity soundings to analyse the spatial distribution of severe thunderstorm and tornado environments. CAPE and 0-6 km wind shear as well as 2-4 km AGL lapse rate are used as parameters for severe thunderstorms and 0-1 km shear and LCL are used for tornadic severe storms (in addition to those of severe thunderstorms). Distribution pattern of severe storm environments from these data agreed well over USA with earlier studies, however there was an eastward shift of the maxima of tornadic storms. Their application of these parameters to Europe resulted in favourable environments for severe storms to be in the South part of the continent (note that Turkey is not included in the Europe charts). An area from Spain to Germany and from there to Balkans as well as North of Black Sea is found to be important, emphasizing Spanish plains and a region from northern Italy to Bosnia, although the rates being half of the peaks in the USA. The most favourable significant tornado environments are the region near Bosnia, France, western Germany and Ukraine, with values comparable to those in the northern USA, which is at a similar latitude.

Pieter H. Groenemeijer and A. Van Delden (2006) studied large hail and tornado environments around Netherlands, using 66365 radiosonde soundings from six stations betweeen 1975 and 2003. They showed that CAPE of the parcel with highest equivalent potential temperature below 500 hPa level is a good parameter to discriminate large hail events (Fig 1.16). Significant tornadoes in Netherlands occur when low level shear is much stronger than other cases, and weak ones in lower values of low level shear, according to their results (Fig 1.17). However, LCL is not a good discriminator for tornadic storms as it is in USA (Fig 1.18). Their idea is that this may be because of the LCL height difference between Netherlands and USA, i.e. Netherlands experience storms with rather low LCLs than USA does.

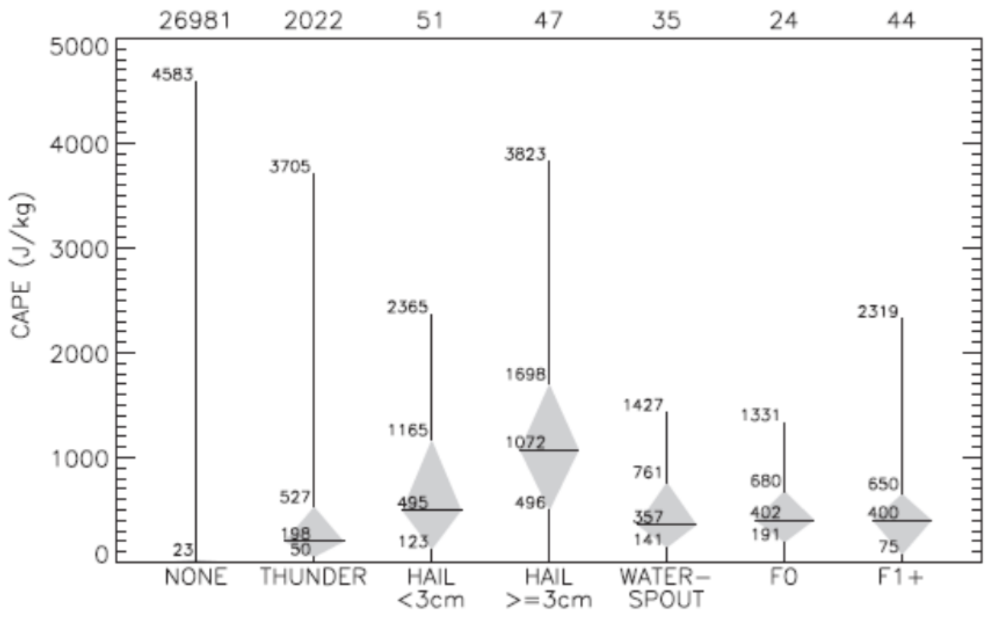

Figure 1.16 : Distribution of CAPE values which are calculated using the parcel with highest equivalent potential temperature in the surface-500 hPa layer among seven categories of weather. The boxes extend to the 25th and 75th percentiles, and the whiskers Show the maximum and minimum values. Number of the sounding samples for each category are on the top of the figure (Groenemeijer, Delden, 2006).

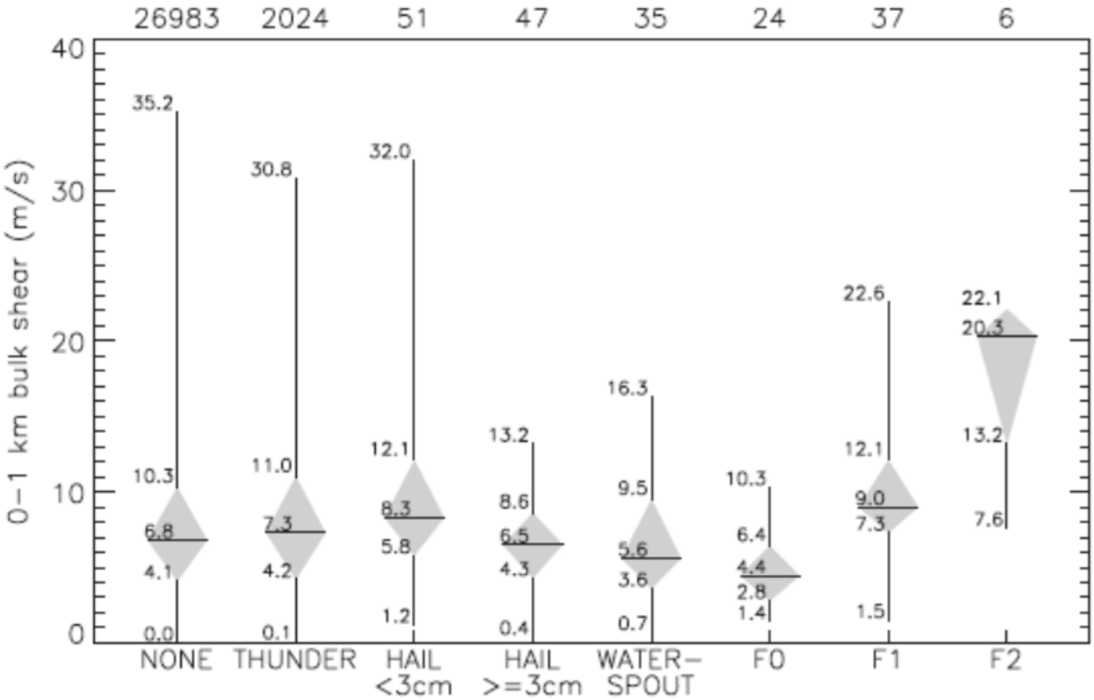

Figure 1.17 : Distribution of 0-1 km bulk shear for seven categories of weather. The boxes extend to the 25th and 75th percentiles, and the whiskers Show the maximum and minimum values. Number of the sounding samples for each category are on the top of the figure (Groenemeijer, Delden, 2006).

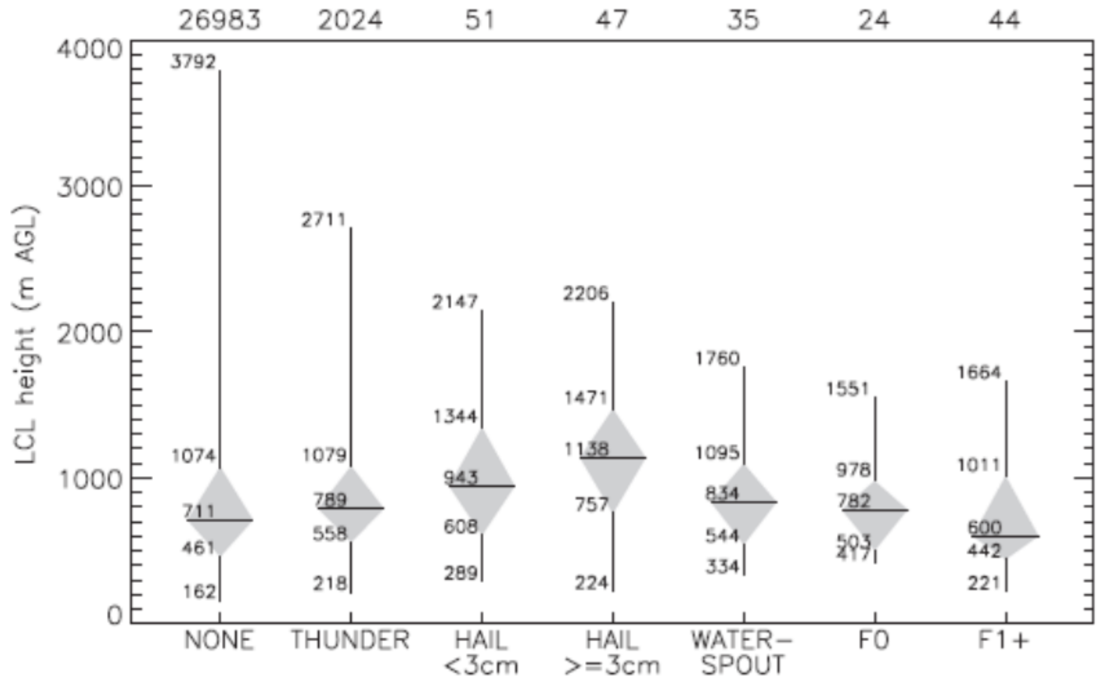

Figure 1.18 : LCL height (AGL) for seven categories of weather. The boxes extend to the 25th and 75th percentiles, and the whiskers Show the maximum and minimum values. Number of the sounding samples for each category are on the top of the figure (Groenemeijer, Delden, 2006).

Peter Bissolli et al (2007) studied tornadoes occuring in Germany and their relation with particular weather conditions, using an objective weather type classification of DWD with 40 classes. The classification criteria are 700 hPa wind (5 classes), second spatial derivative of geopotential height at 950 and 500 hPa (2 classes for eachlevel), and PW derived from five levels temperature and humidity fields (two classes). According to their results, southwesterly and wet weather types enhance the tornado frequency, and thunderstorm days as well as PW are not good tornado predictors.

In a very recent study of Harold E. Brooks (2012), impacts of climate change on severe storms and tornadoes are investigated using large scale environmental conditions from reanalysis data and climate projections. CAPE will increase and wind shear will decrease in the future according to climate models, as the surface and boundary layer temperature will increase and equator-to-pole temperature gradient will decrease. The increase in CAPE will more than offset the decrease in 0-6 km shear over USA, meaning that severe storms will be favoured more by the environmental conditions. On the other hand, tornadoes and severe hail are supposed to be seen with same frequency, and number of severe wind events to increase.

1.4 Hypothesis

Like other mid-latitude locations on earth, severe weather such as tornadoes and large hail occur in Turkey. The environmental characteristics favouring these weather events should be comparable to those in the United States or Europe, therefore, it is possible to categorize the proximity soundings and weather phases and ultimately have a forecasting approach for them.

2. TORNADO CLIMATOLOGY OF TURKEY[1]

2.1 Introduction

This paper presents what is believed to be the most comprehensive climatology of tornadoes in Turkey to date. [The only other known compilation is available on the Turkish Meteorological Services Web page (in Turkish) at http://www.dmi.gov.tr/FILES/arastirma/afetler/hortum.pdf. It consists of 31 tornadoes recorded between 1940 and 2010.] The climatology spans the years 1818–2013. Tornado climatologies recently have been published for several European countries, including Ireland, the United Kingdom, Lithuania, former Soviet Union, France,Germany,Austria, the Czech Republic, Hungary, Greece, Spain, Portugal, Italy, and the Balaeric Islands [see Rauhala et al. (2012) and the references therein for a comprehensive summary]. The lack of formal documentation of Turkish tornadoes is perhaps in part because they are regarded as extremely rare and exceptional weather events.

Tornadoes have been blamed for at least 31 fatalities and 204 injuries in Turkey. The killer tornadoes in Ankara in 2004, Agrı in 2005, Balıkesir in 2011, Elazıg and Antalya in 2012, and Mardin and Mersin in 2013 are notable recent examples. Other major tornadoes in Turkey include the 1997 Kayseri tornado, which uprooted thousands of large trees; the 1988 Cxorum tornado, which lifted a car a significant distance and killed two; and the killer tornadoes in Istanbul and Konya in 1914 and 1959, respectively. Though events such as these deservedly attract considerable public attention in their aftermath, the events tend to be quickly forgotten. There remains an overall lack of awareness of tornadoes, for example, media reports of ‘‘the first tornado in Turkey’’ abound. The purpose of this article is to document the geographical,

[1] This chapter is based on the paper Abdullah Kahraman, Paul M. Markowski (2014). Tornado Climatology of Turkey. Monthly Weather Review, Vol:142, June 2014, pages 2345-2352. DOI:10.1175/MWR-D-13-00364.1.

annual, and diurnal distributions of tornadoes in Turkey. It is believed that tornado forecasting in Turkey would benefit from a better understanding and increased appreciation of the local tornado climatology.

The data collection process and methods used to construct the tornado climatology for Turkey are described in section 2. The results and summary are presented in sections 3 and 4, respectively.

2.2 Data and Methods

Following Rauhala et al. (2012), the concept of tornado case is used, where a case potentially can include more than one tornado if the tornadoes occur in close proximity to each other. Rauhala et al.'s (2012) approach was adopted because the exact number, location, or timing of each individual tornado is not known in some cases. This is a particularly common issue for offshore waterspout cases, which can sometimes include a dozen or more tornadoes (these occurrences would dominate the database if they were counted as individual cases). On the other hand, for a regional outbreak of tornadoes occurring on a single day, multiple tornado cases may be tallied. In other words, separate tornado cases are identified if it can be determined that tornadoes were associated with different storms or the starting points of successive tornadoes can be resolved from the available reports.

Building a tornado climatology for Turkey proved to be a challenging task, as there is no official database of tornadoes such as Storm Data in the United States. It is likely that the climatology suffers from potentially significant underreporting given the low population density in many parts of Turkey (especially eastern Turkey), the absence (until very recently) of an operational radar network, and a lack of storm spotting (let alone chasing) activities.

One major source of data was the Turkish State Meteorological Service (TSMS), which operates meteorological stations in Turkey. The stations report exceptional weather events in addition to routine observations, which are archived separately. A total of 59 tornado cases were found by manually searching this archive from 1939 to 2012. The European Severe Weather Database (ESWD; Brooks and Dotzek 2008; Dotzek et al. 2009) was also a major contributor to the tornado records used in the development of the tornado climatology for Turkey; 118 cases were obtained from the database.

Another major source of records was historical newspaper archives. In Turkey, two mainstream newspapers, Milliyet and Cumhuriyet, maintain digitized archives. The Milliyet archive is accessible via a free membership and contains newspapers from 3 May 1950 to 30 June 2004. The archive was searched for the Turkish word hortum (which is literally translated as hose), and typographically similar words such as hontum and horturn, in order to reach possible lost records especially with older fonts owing to some of the deficiencies of digitalizing technology. This search resulted in 46 tornado cases. The Cumhuriyet archive, which requires purchasing a membership for access, contains newspapers from 1 January 1930 to almost the present date. A search of that archive identified 33 additional tornado cases. The online archives of two additional media sources, Hurriyet and the Cihan News Agency, which each span roughly the last decade, resulted in 13 more cases. Another 149 cases were found via the Google and Yahoo! search engines, mostly through additional news websites, video-sharing websites, and social networks. Newspaper and Internet records had to be scrutinized to ensure their reliability, and some records lacked essential information. In other cases, the information from these sources was further investigated, sometimes via interviews with locals who experienced the event. For example, some news stories were accompanied by photos that were not necessarily obtained from the event being reported. In other cases, damage was exaggerated, or what was clearly nontornadic straight-line wind damage was reported as resulting from a tornado. Moreover, words like kasırga (a word occasionally used for hurricanes and gale-force winds in Turkish, and sometimes for tornadoes as well), fırtına (refers to a storm or severe wind), or siklon (which means cyclone) have also been used in reports documenting some tornado events, which further complicated the compilation of historical tornado records.

Additional tornado reports were obtained from Gilbert (1823) and the Ottoman Archives. The two oldest tornado records for Turkey originate from these sources. A tornado in Cxes¸me in early December 1818 is described in Gilbert’s work, and is also documented in Wegener’s (1917) landmark publication on European tornadoes. A tornado that killed two people in Istanbul on 19 June 1914 is documented in the Ottoman Archives. This tornado is also discussed by Kocaturk (2012).

Cases were classified as ‘‘verified,’’ ‘‘very likely,’’ and ‘‘possible,’’ depending on the credibility of the report and weight of the evidence. Of the 421 tornado cases, 77 cases (18%) were classified as verified, 308 cases (73%) were classified as very likely, and 36 cases (9%) were classified as possible. Existence of reliable video and/or photos of tornado cases, with credible timestamps and locations given, garnered a verified classification. The very likely classification was applied to cases for which photos or videos of the tornado damage, or a credible eyewitness report, were available. The possible category was used for cases in which considerable uncertainty existed regarding the veracity of the report(s); these cases were not included in the climatology.

When possible, tornado cases were classified as ‘‘likely mesocyclonic’’ and ‘‘likely nonmesocyclonic,’’ depending on clues in radar imagery (available only in rare cases, even after the installation of operational radars, given the gaps in coverage that remain), satellite imagery, ancillary severe weather reports (e.g., very large hail observed near the tornado would suggest a mesocyclonic tornado), or photographic/video evidence of the tornado, if it existed.

2.3 Results

The climatology of Turkish tornadoes consists of 385 verified and very likely cases from 1818 to 2013 (Fig. 2.1). More than half of the cases (225) are from the last 5 years. The recent upward trend in tornado cases is presumed to reflect technological advances in communications (e.g., Internet and smart phones), a growing awareness of tornado occurrences in Turkey, and the efforts of the lead author in documenting Turkish tornadoes,[2] rather than an abrupt change in the regional climate. The distribution of the cases throughout the years is greatly affected by the inhomogeneous sources and low probability of accessing old records, whether they exist or not (there is an overall lack of old records, likely because of a limited historical appreciation that tornadoes occur in Turkey).

The distribution of tornado damage intensity peaks at F1, though the distribution should be viewed with caution because intensities are unavailable for 223 tornado

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[2] Approximately one-third of the ESWD reports of tornadoes from Turkey were submitted by the lead author.

cases (Fig. 2.2). The most extreme tornado damage observed in Turkey is F3 (four cases). As in all assessments of tornado damage, the usual caveats apply concerning the relationship between wind speed and damage (Fujita 1971; Doswell et al. 2009; Feuerstein et al. 2011; Edwards et al. 2013). Moreover, as in the sparsely populated

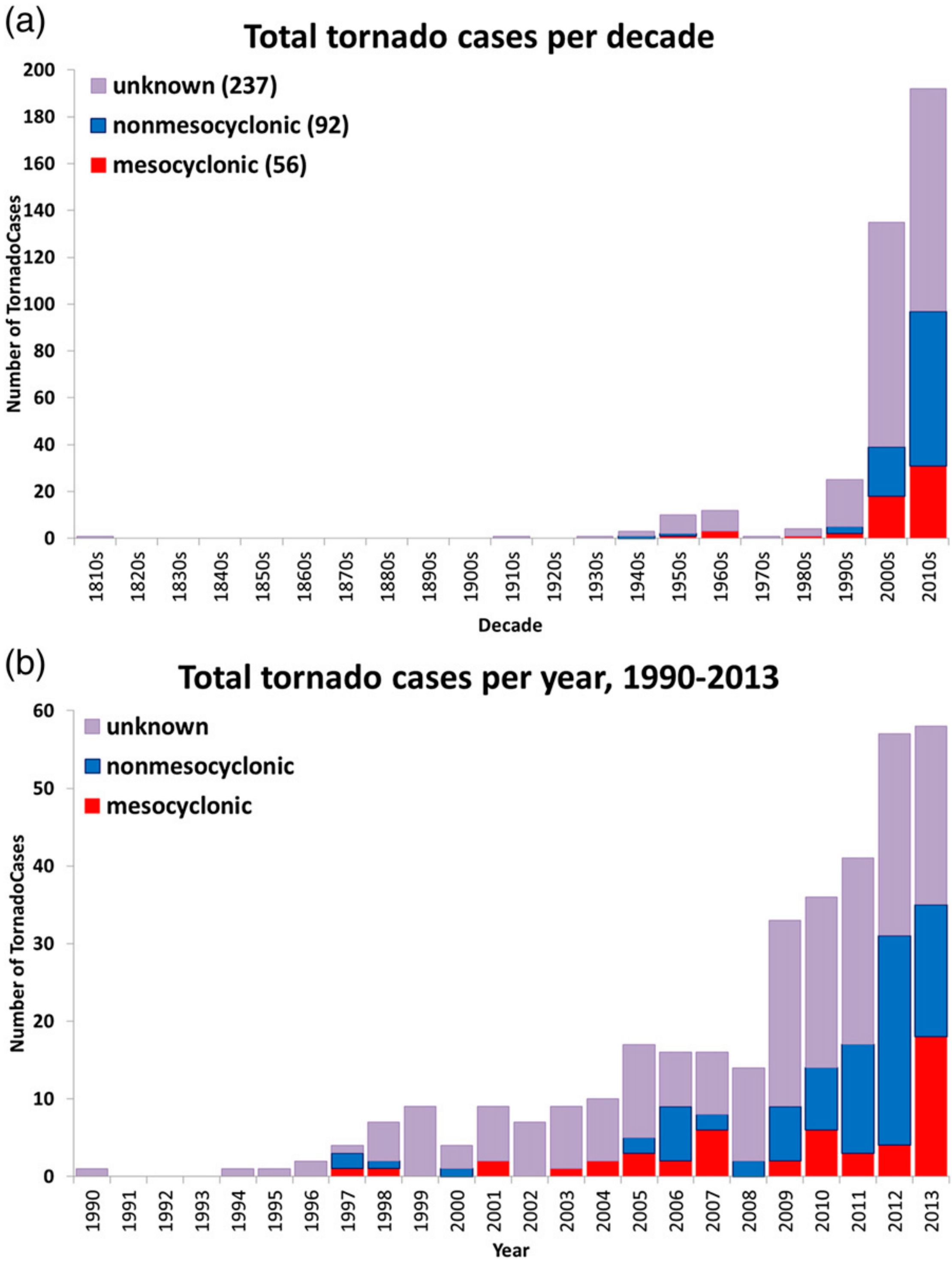

Figure 2.1 : Total tornado cases (a) per decade and (b) per year during 1990–2013.

Great Plains region of the United States, the intensity of many tornadoes occurring in low-population-density regions of Turkey is likely underestimated.

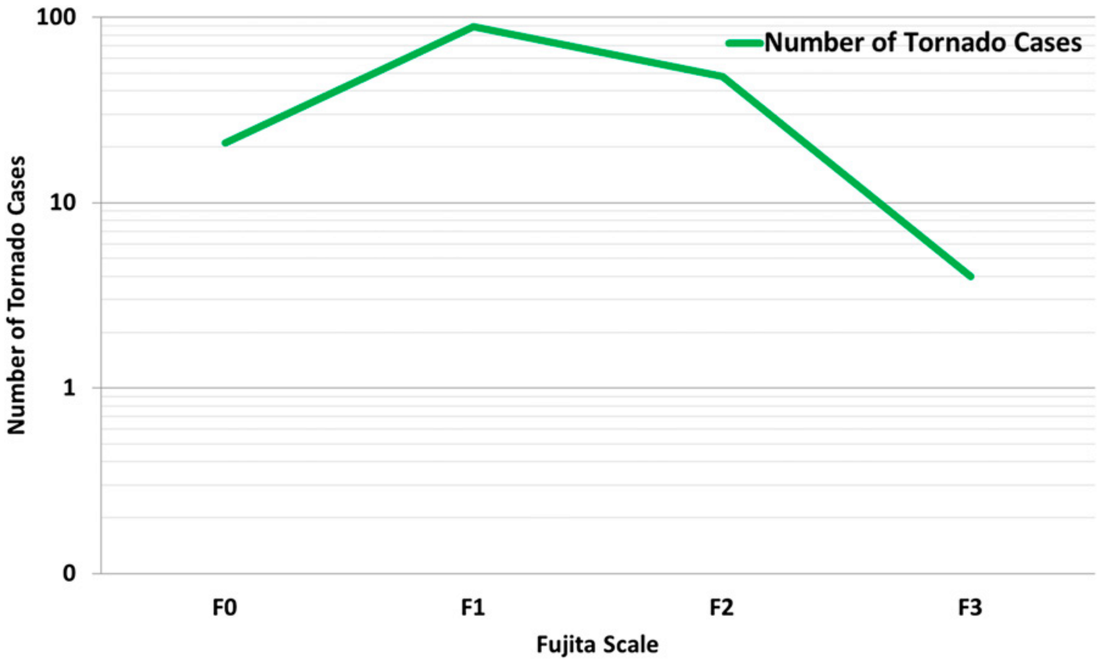

Figure 2.2 : Intensity distribution of tornado cases in Turkey.

The longest-lived tornado is reported to have persisted for 30 min. The longest-confirmed path is 20 km; however, a 60-km path in one case is possible, which is presently reported as two different tornadoes. Information about path widths is difficult to obtain, given that damage widths are usually not reported. Of the cases for which path widths are known (25 cases), the widest tornado had a diameter of 400 m.

There are 56 cases identified as likely mesocyclonic and 92 cases categorized as likely nonmesocyclonic. Taking only last 5 years into account (considering these data to be the most representative), the annual average number of tornado cases in Turkey is 45, of which 7 are likely mesocyclonic. This equates to 0.57 tornado cases per 10 000 square kilometers per year, which is comparable[3] to the tornado densities that have been estimated in prior European tornado climatologies (e.g., Holzer 2001; Sioutas 2011). However, the spatial distribution of reported tornadoes in Turkey is extremely heterogeneous, such that a much higher tornado density is found along the coast, and

[3] The comparison to other studies is not a direct comparison given that tornado cases (this study) are being compared to tornadoes (other studies).

a significantly a smaller tornado density exists in the interior, where low population densities may have contributed to underreporting (Fig. 2.3).

The tornadoes along the Mediterranean (MED; southern) and Aegean (EGE; western) coasts (MED+EGE; Fig. 2.3) dominate the tornado climatology (207 of the 385 cases). Tornado cases are most numerous along the southern coast between Antalya and Anamur. Along this; 210-km segment of the coastline, roughly a dozen tornado cases per year have occurred on average in the past 5 years, implying a tornado density of approximately 19 tornado cases per 10 000 square kilometers (within a 30-km-wide corridor along this segment of the coastline). Comparisons to previously published tornado climatologies for European countries (e.g., Dotzek 2001; Holzer 2001; Gaya et al. 2001; Tyrrell 2003; Marcinoniene 2003; Sioutas et al. 2006; Bissolli et al. 2007; Szilard 2007; Sioutas and Keul 2007; Giaiotti et al. 2007; Sioutas 2011; Gaya 2011), as well as plots of tornadoes that are recorded in the ESWD (http://eswd.eu), suggest that this stretch of Turkish coastline is among the most tornado-prone regions of Europe, though many of these vortices remain offshore as waterspouts. The EGE has nearly the same climate as the MED, but with a considerably lower tornado frequency.

Within both the southern and western coastal regions (MED+EGE), tornadoes are predominantly nonmesocyclonic, weak (F0–F1), and are most frequently observed in the winter months, having a peak in December and January (Fig. 2.4a). Although a significant fraction of the ‘‘unknown’’ tornadoes are likely waterspouts not associated with mesocyclones, supercellular convection also occasionally occurs in this region in winter. Therefore, it is likely that at least some of the unknown cases are tornadoes associated with mesocyclones. The summer months are the least favorable time of the year in this region, likely owing to the region being under the influence of subsidence associated with the Azores anticyclone.

A third coastal region comprises the Black Sea coast in the north (BLA) and the Marmara coastal region in the northwest (MAR; Fig. 2.3). Waterspouts during summer and autumn dominate the dataset here, though three mesocyclonic tornadoes have also been observed (Fig. 2.4c). In winter, the frequency gradually decreases, and practically vanishes in April and May.

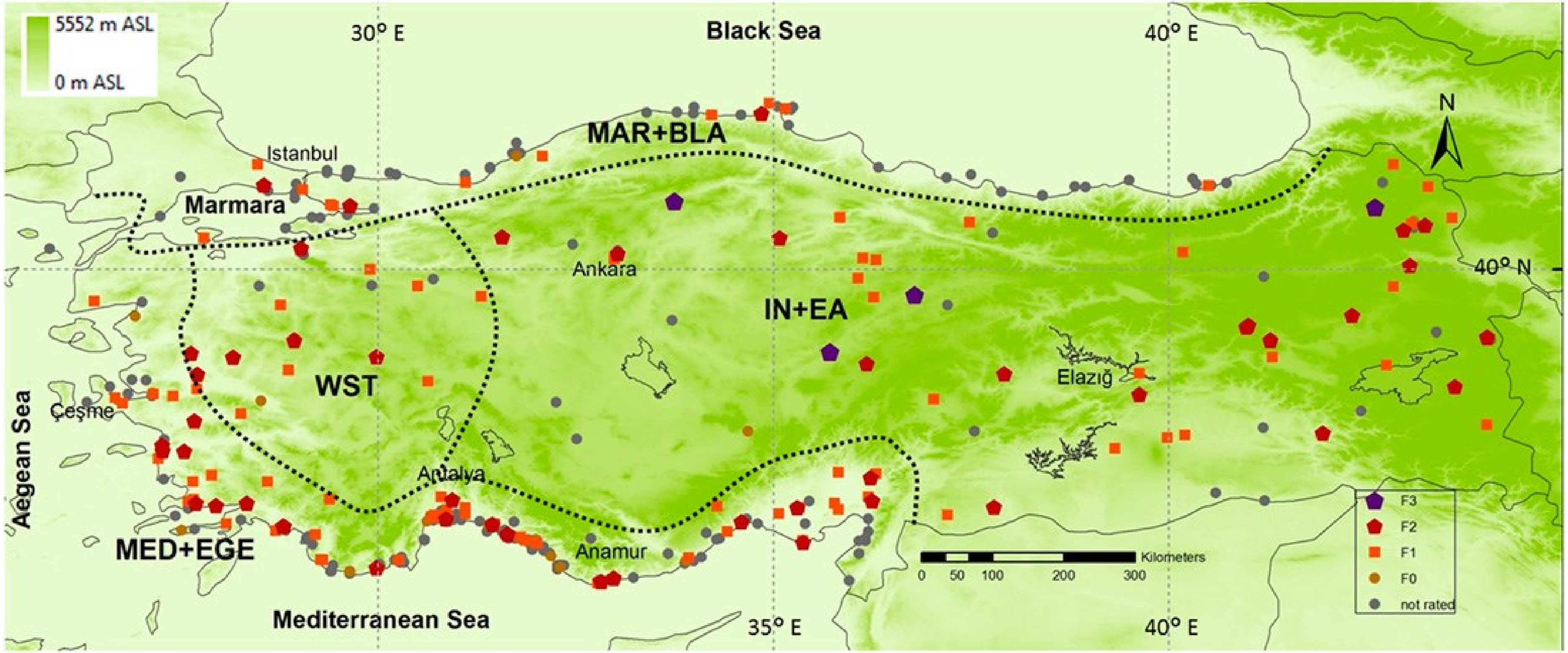

Figure 2.3 : Geographical distribution of tornado cases over Turkey. ‘‘MAR+BLA’’ and ‘‘MED+EGE’’ refer to the coastal regions around the Marmara and Black Seas and Mediterranean and Aegean Seas, respectively. The central and eastern inlands of the Anatolian Peninsula are labeled as ‘‘IN+EA,’’ and the western inlands are labeled as ‘‘WST’’.

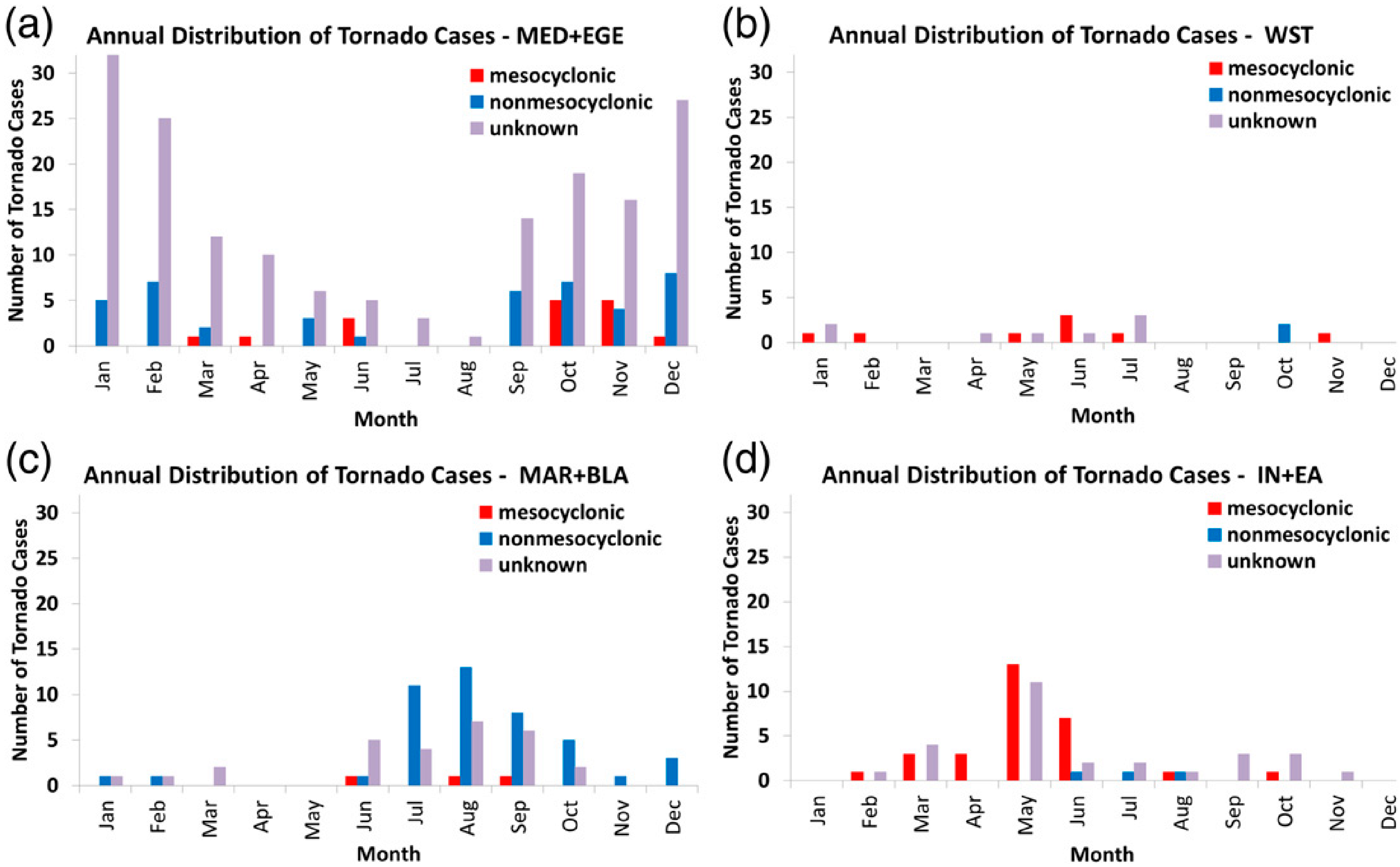

Figure 2.4 : As in Fig. 2.3, but for the number of tornado cases for each month and region.

Tornado cases are less common in the interior of Turkey [westernmost inlands (WST) and central and eastern inlands (IN+EA)] than along the coastlines (MED+EGE and MAR+BLA; Fig. 2.3), especially the southern and western coastlines (Figs. 2.4b,d). Most tornadoes in the inlands are believed to be associated with the mesocyclones of supercells. Turkey's most intense and deadly tornadoes have occurred in the IN+EA (Fig. 2.3), with all four F3 tornadoes occurring here. It seems likely that the tornado frequency is underestimated here owing to the general low-population density of this region. It is also possible that tornadoes have been able to inflict greater damage in this region owing to substandard construction of dwellings. A distinct maximum in tornado cases in the IN+EA occurs in May, followed by June (Fig. 2.4d), and no tornado observations exist for December and January. In the WST (Fig. 2.3), the peak months are June and July.

May and June are the peak months for mesocyclonic tornadoes, with a secondary peak in October and November (Fig. 2.5a). The secondary maximum for mesocyclonic

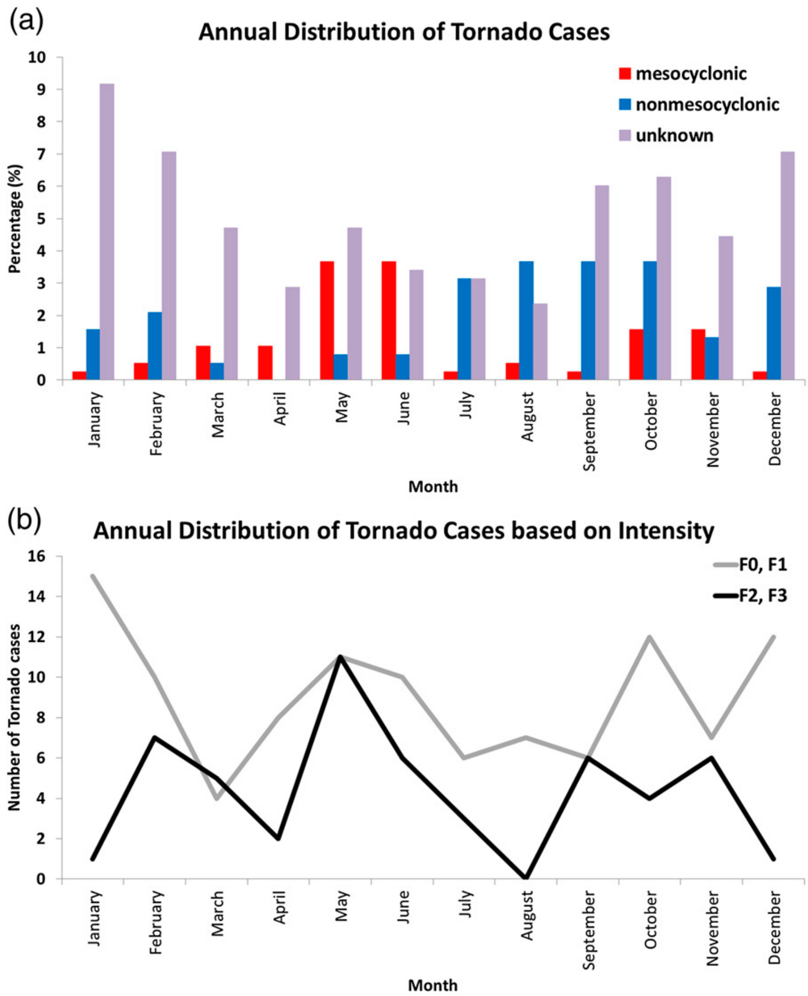

Figure 2.5 : Annual distribution of tornado cases in Turkey.

tornadoes in October and November can be attributed to the return of extratropical cyclone passages (which are largely absent in the summer months) and the severe weather ingredients they tend to bring together (e.g., strong vertical shear and significant convective available potential energy). Nonmesocyclonic tornado frequency (which mainly reflects the occurrences of waterspouts on the Mediterranean, Aegean, and Black Sea coastlines) is a maximum from July to October and a minimum from March to June (Fig. 2.5a).

For the relatively small sample of strong tornadoes (F2+), such tornadoes are most likely to occur in May, though there is a secondary maximum in February (most of these occur along the southern coast) and during September–November (Fig. 2.5b). Tornadoes are most likely in Turkey in the afternoon [local standard (daylight saving) time is 2 (3) h ahead of UTC]. Mesocyclonic and strong tornadoes are most likely between 0900 and 1500 UTC (1200–1800 local time, except in winter; Figs. 2.6a,b).

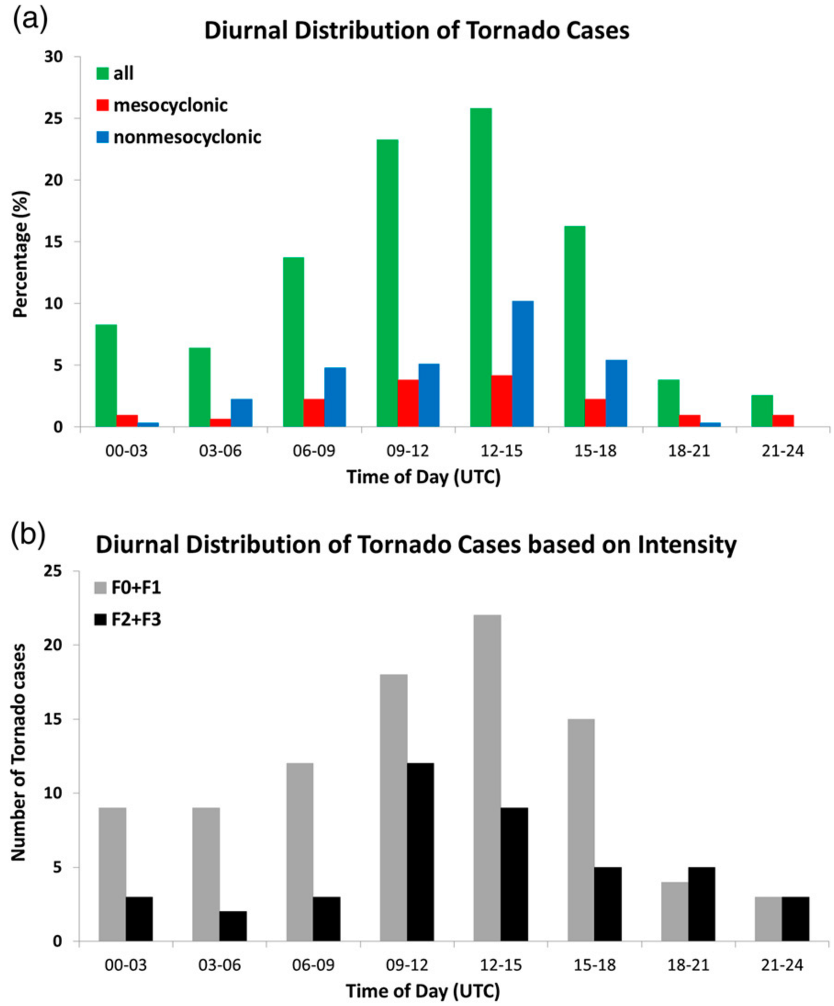

Figure 2.6 : Diurnal distribution of tornado cases in Turkey.

3. SEVERE HAIL CLIMATOLOGY OF TURKEY[4]

3.1 Introduction

Insured losses owing to hail damage in Turkey accounted for over 60% of all weather-related insured losses during 2007–13 [$73 million (U.S. dollars) in 2013], according to the Turkish Agricultural Insurance Pool (TARSIM; TARSIM 2014; Fig. 3.1). The vast majority of the losses have been related to agriculture, which plays an important role in Turkey's economy (over $60 billion per year, or about 10% of the Turkish gross domestic product). A quarter of the working population (over 6 million) is engaged in the agricultural sector.

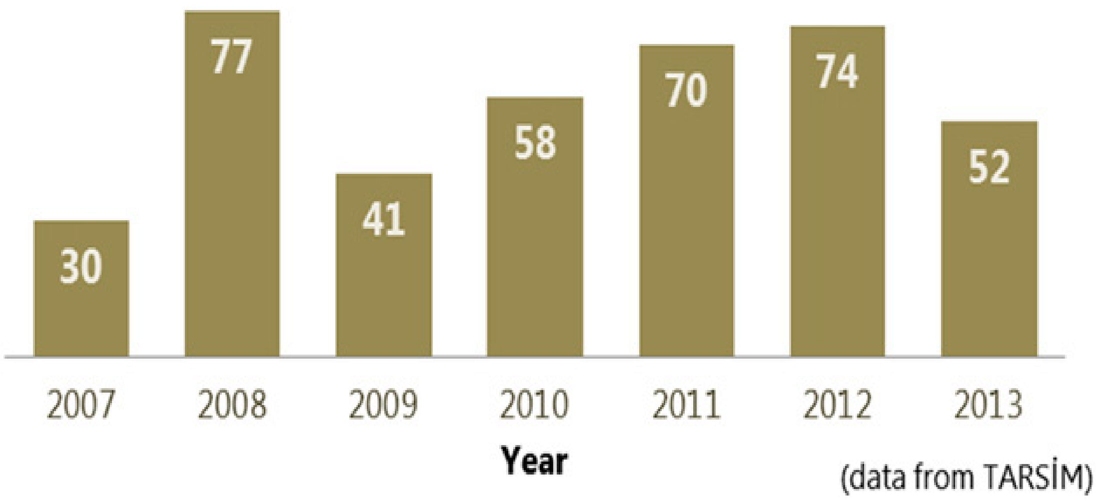

Figure 3.1 : Percentage of all insured agricultural losses due to hail damage in Turkey during 2007–13 (data from TARSIM).

Turkey's worst hailstorms have been as devastating as severe hail events in the United States. For example, the 19 June 1932 hailstorm in Inebolu (near the northern coast of Turkey; see Fig. 3.2 for locations), reportedly contained hailstones as massive as 480

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[4] This chapter is based on the paper Abdullah Kahraman, Şeyda Tilev-Tanriover, Mikdat Kadıoğlu, David M. Schultz, Paul M. Markowski (2016). Monthly Weather Review, Vol:144, January 2016, pages 337-346. DOI: 10.1175/MWR-D-15-0337.1 .

g, which broke windows and damaged roofs. The 15 June 1943 hailstorm that struck Aksehir and surrounding villages in the interior of Turkey produced a half-meter accumulation of hail, destroying nearly all crops within the hail swath. A hailstorm on 26 April 1963 in Diyarbakır (southeastern Turkey) resulted in dozens of injuries and damaged homes, and another hailstorm on 31 May 1972 in Tunceli (eastern Turkey) killed hundreds of sheep and goats. The 6 June 1975 hailstorm in Karabiga (northwestern Turkey) produced hailstones with diameters in excess of 5 cm, and killed hundreds of cattle, damaged buildings, and possibly killed two people (it is unclear whether the victims were killed by the hail or an accompanying flash flood).

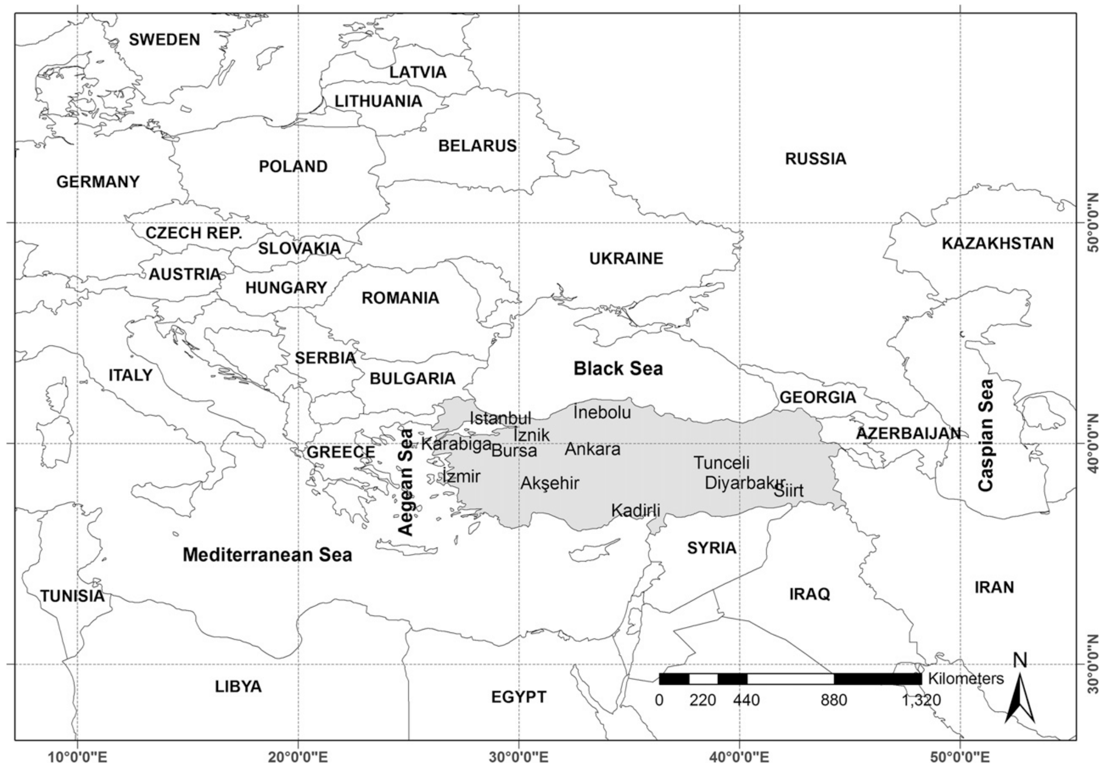


Figure 3.2 : Location of Turkey (gray shaded) and cities mentioned in the paper.

A climatology of hail derived from the Turkish State Meteorological Service's (TSMS) database was included in a previous study by Ceylan (2007). Ceylan (2007) investigated the statistics of two different datasets: 17 661 hail observations from Turkish meteorological stations during 1967–2004 and 824 cases of damaging hail [referred to as ''hail disasters'' by Ceylan (2007)] during 1940–2004. With respect to the first dataset, there was an average of 425 hail occurrences per year, but with decreasing frequency between 1967 and 2004. In the damaging hail dataset, the frequency of occurrences increased during 1961–83, decreased during 1983–96, and increased once again during 1997–2004. The individual cases from that dataset are no longer available to us.

Owing to improvements in communications in recent years, it is now possible to obtain more information about local severe weather events than a decade ago. The Internet and widespread usage of smart phones have greatly increased reporting in Turkey. Furthermore, newspaper archives have been digitized, enabling much more efficient searches of historical events using keywords.

The purpose of this study is to present an updated climatology of hail in Turkey that exploits the aforementioned improvements in severe weather documentation. In contrast to the prior work that focused on hail damage in Turkey (damage was often the result of significant accumulations of small hail), the present paper documents what we refer to as severe hail—hailstones with diameters equal to or larger than approximately 1.5cm (the reason for the qualifier approximately will be explained in section 3.2).

Documenting the occurrence of severe hail in Turkey is a necessary first step toward developing an understanding of the environments and processes conducive to its formation there. Forecasts of severe hail in Turkey cannot be improved without this understanding.

Definitions, data sources, and analysis methods are discussed in section 3.2. The findings from the climatology are presented in section 3.3. Conclusions are presented in section 3.4.

3.2 Data and methods

This section describes the definitions used in this study. It also describes the sources of data for the 1489 severe hail cases. In this study, the term ‘‘case’’ or ‘‘event’’ implies a specific severe hail occurrence on the ground, which is observed by one or more people, supposedly from a single storm cell (this will be defined in more detail in section 3.2.3). The term ‘‘report’’ indicates the observation of one or more severe hail case. Although rare, one report may include more than one case, and one case may be reported more than once. The numbers given in the paper pertain to cases rather than reports.

3.2.1 Definitions of severe hail, very large hail, and large hail

Before developing a climatology of severe hail, careful consideration must be given to how severe hail will be defined. Hail severity usually is defined by hail diameter, even though not all of wide-ranging impacts of hailstorms are dependent on hailstone diameter only. A number of previous studies discussed this issue and mentioned other factors such as the wind speed during a hailstorm and the quantity of the hail on the ground (Webb et al. 2001, 2009; Sioutas et al. 2009). In addition to these, some studies have defined hail severity in terms of the kinetic energy of the hailstones (e.g., Vinet 2001; Eccel et al. 2012), which increases rapidly with hailstone diameter given that both mass and terminal fall speed increase with hailstone diameter.

Another measure of severity can be the depth of the hail accumulation. For example, the European Severe Weather Database (ESWD; Brooks and Dotzek 2008; Dotzek et al. 2009) includes hailstones ‘‘having a diameter (in the longest direction) of 2.0 cm or more and/or smaller hailstones that form a layer of 2.0cm thickness or more on flat parts of the earth's surface.’’ In the United States, the National Weather Service, since 2010, has defined severe hail to have a diameter equal to or exceeding 1 in. (about 2.5 cm) [prior to 2010, the threshold was a diameter of 0.75 in. (1.9 cm)]. Some prior studies have analyzed all hail regardless of severity. For example, Giaiotti et al. (2003) used data from a special hailpad network in the Friuli–Venezia–Giulia region of Italy, and Etkin and Brun (1999), Zhang et al. (2008), Suwala and Bednorz (2013), and Mezher et al. (2012) have documented hail statistics obtained from surface meteorological stations in Canada, China, central Europe, and Argentina, respectively.

Ideally, the present study would adopt a 2-cm diameter threshold for severe hail to facilitate comparison to other hail climatologies in Europe. However, the available hail reports from Turkey rarely include quantitative size information. Instead, 98% (1465) of the 1489 severe hail cases compare hail sizes to familiar objects such as hazelnuts, chestnuts, olives, walnuts, and eggs, which obviously have a range of diameters.

‘‘Hazelnutsized hail’’ represents the most commonly reported severe hail size (721 out of 1489 cases) in the Turkish records. Even though most hazelnut diameters fall short of 2 cm (hazelnut diameters are more typically about 1.5 cm), in the TSMS data, severe damage (especially to crops) is commonly reported with this size. Moreover, the reports also sometimes merely document average rather than maximum hailstone diameter.

After considerable deliberation, hazelnut-sized hail is included in the climatology given the reported damage, uncertainty of maximum/average size during the events, and number of hail reports of that size. A walnut-sized hail threshold also was considered—‘‘walnut-sized hail’’ also is commonly referenced in Turkey (436 out of 1489 cases), and walnuts would logically be the next size increment up from hazelnuts—but was dismissed because walnuts tend to have diameters considerably larger than 2 cm. Such quantized reports of severe hail size is not an issue only for Turkey; Schaefer et al. (2004) show that more than 75% of large hail reports (defined as 0.75 in. before 2010) in the U.S. dataset describes hail size with three objects (dime/penny, quarter, and golf ball).

A subset of severe hail is classified in this study as very large hail, nominally equal to or larger than 4.5 cm in diameter. This category includes hail sizes compared to an egg (this is among the most common descriptions with 75 occasions), tangerine, fist, goose egg, and cigarette pack, among others. The determination of the 4.5-cm egg-sized threshold followed a similar approach to that of 1.5-cm hazelnut-sized threshold mentioned above.

Large hail is classified as hail with diameters equal to or greater than 1.5 cm and less than or equal to 4.4 cm. Thus, the severe hail classification scheme presented in this paper is sum of the two classes: large hail and very large hail. Whenever the term hail is used in this article without qualifier, it is intended to mean all hail regardless of size (the sum of severe hail and nonsevere hail).

Table 3.1 summarizes the severity criteria used in the study. No matter how severe the reported hail damage, hail reports without any accompanying size description almost always are excluded from the climatology [the lone exceptions are reports of hailstones breaking windows and hailstones having ‘‘sizes not seen before’’ (5 of 1489 cases), which are placed in the 3.0–4.4-cm bin]. Moreover, as in any hail study, a reported hailstone diameter probably should be regarded as a typical or maximum observed hail diameter, though larger (and smaller) than observed hailstones might exist from a specific storm.

Table 3.1 : Hail classification scheme for the Turkish severe hail climatology.

Class	Nonsevere	Severe			
Size	Small	Large		Very large	
Diameter (d) (cm)	d < 1.5	1.5≤d<3.0	3.0≤d<4.5	4.5≤d<6.0	d≥6.0
Sample keywords	Pea	Hazelnut, grape	Walnut, chestnut	Egg	Orange, fist

3.2.2 Origin of severe hail reports

Considering the relatively small spatial and temporal scale of hailstorms, any climatology based on observations will be limited by underreporting, especially in less-populated regions (e.g., the mountains in eastern Turkey). The higher number of reports around metropolitan areas such as Istanbul, Ankara, Izmir, and Bursa can be partially attributed to the high population density. The population of Turkey has risen from 13.6 million in 1927 to 76.7 million in 2013 (based on data from the Turkish Statistical Institute), with an impressive shift between rural and urban populations, as 24% of people in 1927 were living in urban areas and 76% were living in urban areas in 2010. Population density in the Istanbul province is 2725 people/km^2 (slightly lower than Washington, D.C.), whereas it is only 11 people/km^2 in the Tunceli province (similar to Nevada or Utah).

Underreporting may also be significant in areas without agriculture or other vulnerability to hail. According to Turkish Statistical Institute data, as of 2013, 26.5 % of Turkey is arable/cultivated (in 2004, the figure was 23.1 %). Reporting biases are further complicated by the fact that agricultural vulnerability to hail varies seasonally and as a function of crop type. Although there is no way to ensure that all severe weather occurrences have been captured, the climatology presented herein has been derived from hail reports obtained from a diverse mix of sources in order to capture as many events as possible, similar to the approach used by Tuovinen et al. (2009).

The most important source for the severe hail reports was the TSMS archive. The TSMS has maintained 459 different meteorological stations throughout Turkey since 1930, though fewer are operational at any given time (243 are in operation at the present time). In addition to making routine climatological observations, the TSMS meteorological stations report hazardous weather phenomena such as hail in their local areas. These reports include a written description (usually just a sentence or two, but occasionally longer entries are made) of the event and any injuries and property damage. Severe hail cases were obtained from a manual search of this archive from 1939 to 2012 by the first two authors. The search produced 1083 severe hail cases. Furthermore, the TSMS database contains hail frequency (all hail, not just severe hail) statistics by month during 1960–2013. These data were used to provide context for the locations of severe hail reports. Another 142 severe hail cases (during 2001–14) were obtained from the ESWD.

Digital archives of two national mainstream newspapers, Cumhuriyet and Milliyet were also combed for hail records. Currently, these are the only two national newspapers that maintain digitized archives. The keywords used for searching were ‘‘dolu yağdı’’ (hail fallen), ‘‘dolu yağışı’’ (hail precipitation), ‘‘büyüklüğünde dolu’’ (hail with size of), rather than only ‘‘dolu,’’ which is the literal translation of ‘‘hail’’ in Turkish (only searching for dolu was problematic because the word has popular alternative meanings such as ‘‘full’’). The Cumhuriyet archive, which is accessible via a paid membership, goes back as far as 1 January 1930 and was the source of 98 additional severe hail cases. A search of the Milliyet archive, which is freely accessible and contains articles from 3 May 1950 to 30 June 2004, yielded 20 more severe hail cases. Online records of Hürriyet and Sabah, two other national mainstream newspapers, were also searched. Although these searches were limited to roughly the last decade (the archives extend back to 8 July 1997 and 1 January 1997, respectively), these sources provided 40 and 12 new cases, respectively. Hardcopy archives of Cumhuriyet and another periodical, Aksam, also were searched manually starting in 1929, which is the first year the Latin alphabet was used in Turkey. This search added two additional severe hail cases to the climatology.

A search of additional Internet news websites in Turkey, with the Google.com.tr search engine, yielded 92 additional severe hail cases. Obviously, the credibility of Internet reports is often questionable. When available, satellite and radar images were used to verify the presence of a convective cloud or high reflectivity at the location of a severe hail report. It was also possible to investigate the reliability of the information via interactions with eyewitnesses using social media (Twitter and Facebook) in 17 cases. In some other cases, the municipality or local administration offices were called (since 2010) to verify the information found on the Internet. All these efforts yielded 1489 severe hail cases, of which 320 (21 %) had multiple sources (cases mostly from recent years in which Internet reports abound).

3.2.3 Definitions of severe hail day and severe hail case

The term severe hail day is used in this study to refer to a day with at least one severe hail report, as in Tuovinen et al. (2009). When multiple severe hail reports are within 20 km of each other on a single day, they are merged into a single case. Some single severe hail cases might be the result of multiple storms, but the number of such instances is likely small. A storm with a long hail swath might be responsible for multiple severe hail cases if there are gaps in the severe hail reports along the storm's path that exceed 20 km. We suspect that a few such storms have been responsible formultiple severe hail cases in the climatology. Because the exact times of the severe hail reports are generally unknown (times are available for only 587 out of 1489 cases, or 39 %), a time criterion like those used in previous studies could not be applied in this study. For example, hail studies in the United States (Schaefer et al. 2004) and Finland (Tuovinen et al. 2009) attributed a report to a new event if 15 min elapsed since the previous report, with 16-km and 20-km distance criteria, respectively.

3.3 Results

The climatology includes 1489 severe hail cases on 1107 severe hail days (days with at least one severe hail case) in Turkey during 1925–2014, of which 124 (8.3 %) were classified as very large. These numbers correspond to 16.5 cases per year or 0.21 cases 10 000 km^2/yr, and 12.3 days/yr or 0.17 days 10 000 km^2/yr. The actual frequency must be higher given the large number of hail damage reports without size information and other severe hail events that may not have been reported at all. However, the annual average over the last 5 years of the dataset (2009–13), which may be more representative of the true frequency given the much greater availability of Internet reports, is 42 cases, or 0.54 cases 10 000 km^2/yr, and 29 days, or 0.37 days 10 000 km^2/yr.

3.3.1 Severe hail cases by year

Between 0 and 74 severe hail cases per year were documented during 1925–2014 (Fig. 3.3). Severe hail cases were most numerous in the 1960s, during which every year had at least 29 severe hail events (74 severe hail cases were reported in 1963). The 1970s

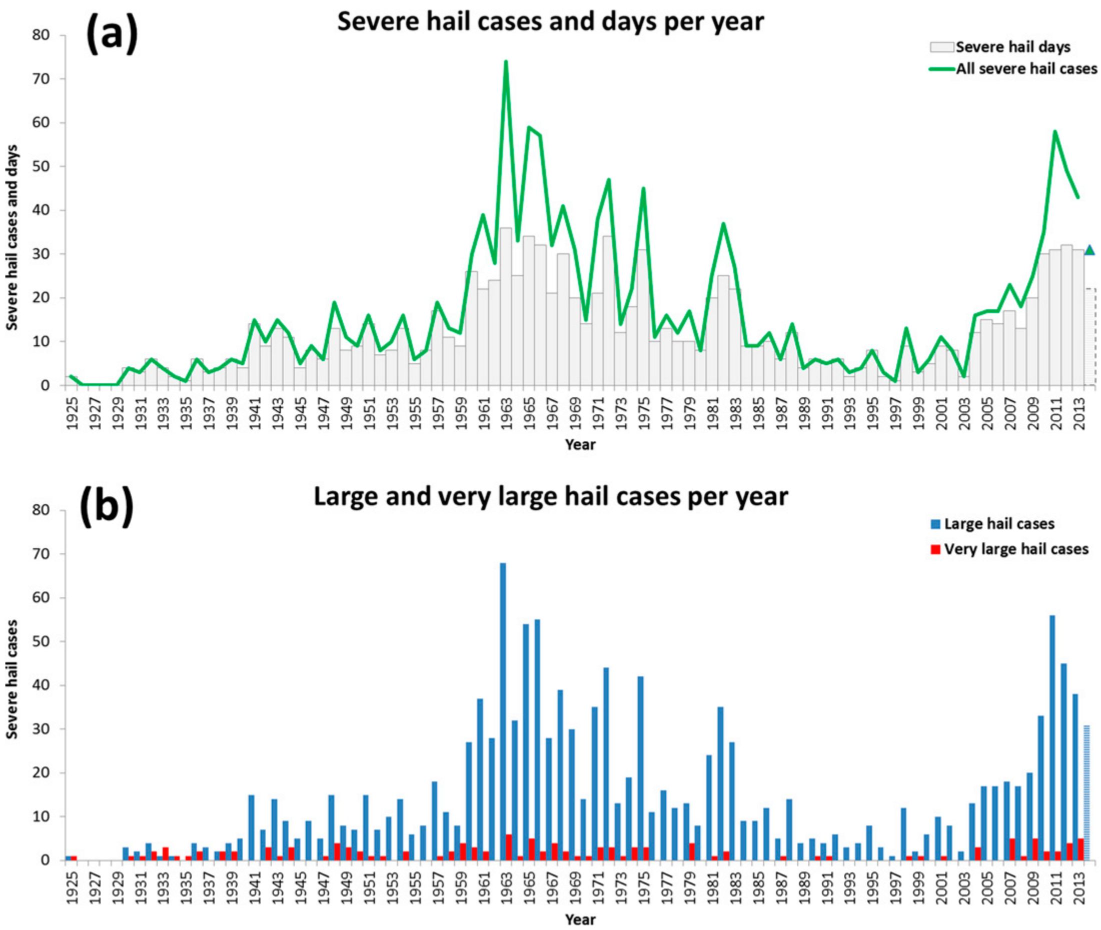


Figure 3.3 : (a) Severe hail cases and days and (b) large and very large hail cases in Turkey per year, 1925–2014 (the 2014 data are through 27 May).

and 1980s generally featured a decline in cases to pre-1960s levels. Curiously, a similar trend in the long-term precipitation records of Turkey exists, as they also show a peak in the 1960s and decrease afterward (Türkes 1996; Toros 2012). Furthermore, lightning fatalities and injuries also increased in the 1960s in the country (Tilev-Tanriover et al. 2015). Although the underlying reasons for more frequent severe hail environments are not yet known, the track of extratropical cyclones might play a role. A shift of the North Atlantic jet stream's latitude in spring from about 45.8 N (during roughly 1960–80) to about 48.8 N (during roughly 1980–2000), with 1 m/s faster speeds in the 1960s on average (Woollings et al. 2014), may be related to the precipitation and severe hail frequency trends. Since 2005, there has been an increase in the frequency of severe hail reports. From 2005 to 2013, the annual number of severe hail cases has increased from 17 to 43, and the annual number of severe hail days has increased from 12 to 32. Though we cannot rule out that meteorological factors partly contributed to the recent increase in the frequency of the cases, the trends likely also have been heavily influenced by changes in the availability of hail reports. For example, the availability of cases has greatly increased in the last decade owing to the Internet; 249 of 301 cases (83 %) during 2004–13 originate from online sources (search engines, social media, newspaper archives, and the ESWD), whereas there are none before 1998.

The trend in severe hail days roughly follows that of the severe hail cases, with a correlation coefficient of 0.97 (Fig. 3.3a). However, days with more than one case increase in peak periods (e.g., during the 1960s and 2010s), which can be attributed to regional outbreaks or wider sources of information (especially for the recent years). The leading year is 1963 with 36 severe hail days, followed by 1965 and 1972 (34 severe hail days occurred in both of these years).

The trend in the frequency of very large hail cases compared to large hail cases over the period of the climatology (Fig. 3.3b) indicates a possible underreporting of severe hail before 1960. Though the frequency of very large hail is roughly steady throughout the climatology, the frequency of large hail is lower prior to roughly 1960 (we might naively expect that very large hail is unlikely to be unreported owing to its likelihood of having an impact). A similar argument has been made for the underreporting of F0/EF0 tornadoes (the F and EF ratings refer to the Fujita and enhanced Fujita scales, respectively), in that the number of tornadoes rated F1/EF1 or higher has exhibited little upward trend since the 1950s, whereas the number of F0/EF0 tornadoes has dramatically risen (Kelly et al. 1978; Feuerstein et al. 2005; Verbout et al. 2006). The peak year is 1963 with 6 very large hail cases; 55 (62 %) of the years in the climatology have very large hail cases.

3.3.2 Hail size distribution

The frequency of occurrence of many rare events, such as tornadoes, extreme precipitation, and severe winds, are known to approximately follow a log–linear decline with increasing intensity (Brooks and Doswell 2001; Brooks and Stensrud 2000). Following the approach described by Brooks and Doswell (2001) for tornadoes, the percentages of hail sizes are plotted on a log–linear plot (Fig. 3.4). The near-constant slope of the line in Fig. 3.4 indicates that the distribution of hail sizes equal to or exceeding 3 cm is not biased by size. The slightly smaller slope for the smallest hail sizes likely indicates an underreporting bias.

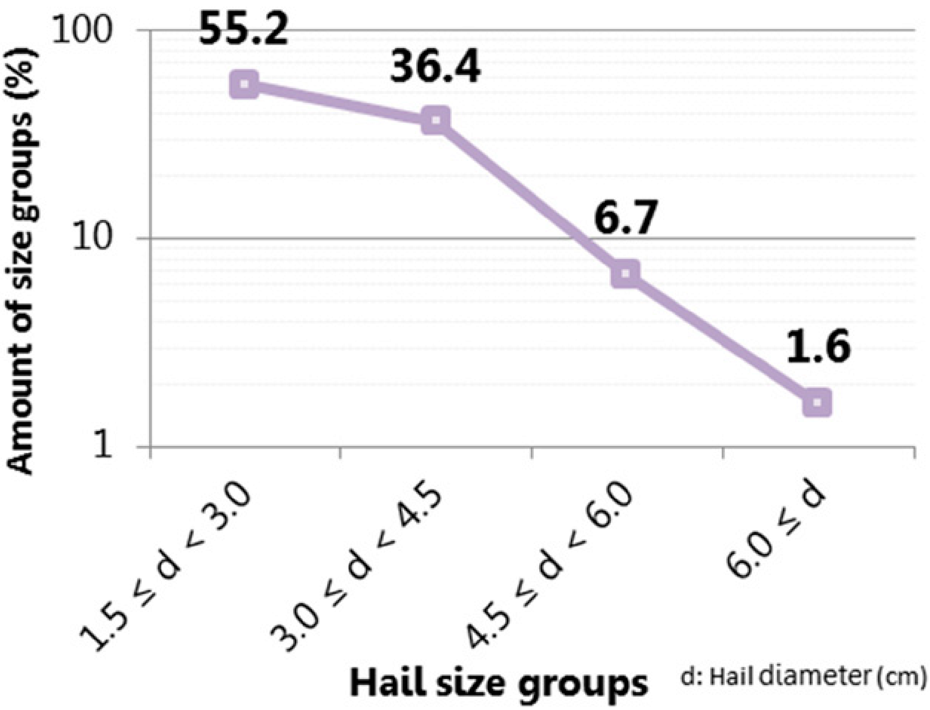


Figure 3.4 : Size distribution of severe hail cases in Turkey.

Of the severe hail cases in Turkey, 55 % (821 cases) involve hailstone diameters smaller than 3.0 cm, and 36 % (542 cases) are associated with hailstone diameters between 3.0 and 4.4 cm, inclusive (Fig. 3.4). There are 24 very large hail cases involving hailstone diameters equal to or larger than 6.0 cm (1.6 % of all severe hail cases).

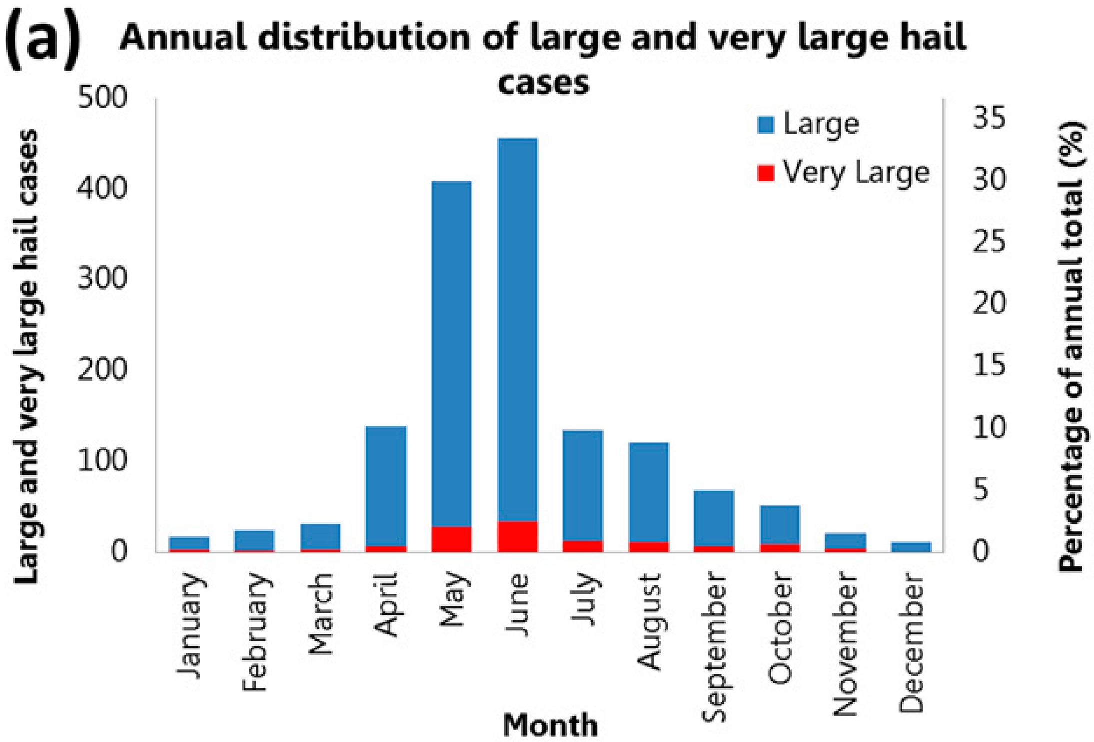
The ratio of very large hail to severe hail in Turkey (defined as 4.5 cm or larger and 1.5 cm or larger, respectively) is 0.083, comparable to 0.082 for theUnited States (with 2.00 in and 0.75 in thresholds) as suggested by Schaefer et al. (2004), and far lower than Finland's 0.36 [5 cm or larger hail cases within 2 cm or larger hail cases; Tuovinen et al. (2009)].

The largest hailstone in Turkey is not exactly known owing to the rarity of objective size information in the hail reports. However, some extreme cases have been reported. These include a hailstone in Kadirli on 3 November 1936 estimated to weigh somewhere between 300 and 1000 g, a 750-g hailstone in Iznik on 1 July 1947, and roughly a half dozen other reports of hailstones exceeding 400 g since the 1930s.

3.3.3 Annual cycle and geographical distribution

Severe hail in Turkey is most frequent in spring and summer. June is the peak month, followed by May (Fig. 3.5), with 864 events (58 % of all cases) being reported in these two months. Moreover, very large hail also is most frequent in June (34 events) and May (28 events), followed by July and August (13 and 12 events, respectively). Hailstones with diameters larger than 6 cm have the same peak months, with 6 occurrences in June and 4 in May. Severe hail is least likely in December. The peak season is comparable to other parts of southern Europe. For example, the peak season for severe hail is late May to early July for Bulgaria (Simeonov 1996), May–June for northern Greece (Sioutas et al. 2009), June for northeastern Italy (Giaiotti et al. 2003), May through September for France (Vinet 2001), and May through July for northern Spain (Sánchez et al. 1996). On the other hand, Cyprus experiences severe hailmore frequently in December, compared to other months (Michaelides et al. 2008), which is consistent with our results for the southern coasts of Turkey (discussed below).

The geographical distribution of severe hail cases is relatively uniform in Turkey when compared to tornadoes (Kahraman and Markowski 2014), and roughly follows the distribution of thunderstorm days as well as lightning fatalities and injuries (Tilev-Tanriover et al. 2015). Severe hail has been reported in all of Turkey despite considerable topographic variability (Fig. 3.6). However, regional differences in severe hail occurrences, as well as hail frequency overall (i.e., nonsevere and severe hail), are evident in monthly distributions (Fig. 3.7). For example, in the winter, when hail frequency is a minimum nationwide, hail still poses a threat along the Mediterranean (southern) and Aegean (western) coasts, where the proximity to the relatively warm water presumably provides the instability required for hail. In March, the region of higher hail frequency begins expanding into the interior regions, and by April the inlands generally have a higher hail likelihood (especially severe hail) than the coastal regions, particularly southeastern Turkey, where there is a maximum in both severe hail cases and hail days (e.g., at the Siirt observing station, hail is observed an average of 1.5 days in April). In May and June, the peak season for severe hail, severe hail is most likely in interior Turkey, although the maximum in hail days lies in northeastern Turkey, where peak frequencies approach 2 hail days per month. As hail frequencies decline in late summer and fall toward the winter minimum, hail probabilities decline most slowly in extreme northeastern Turkey.



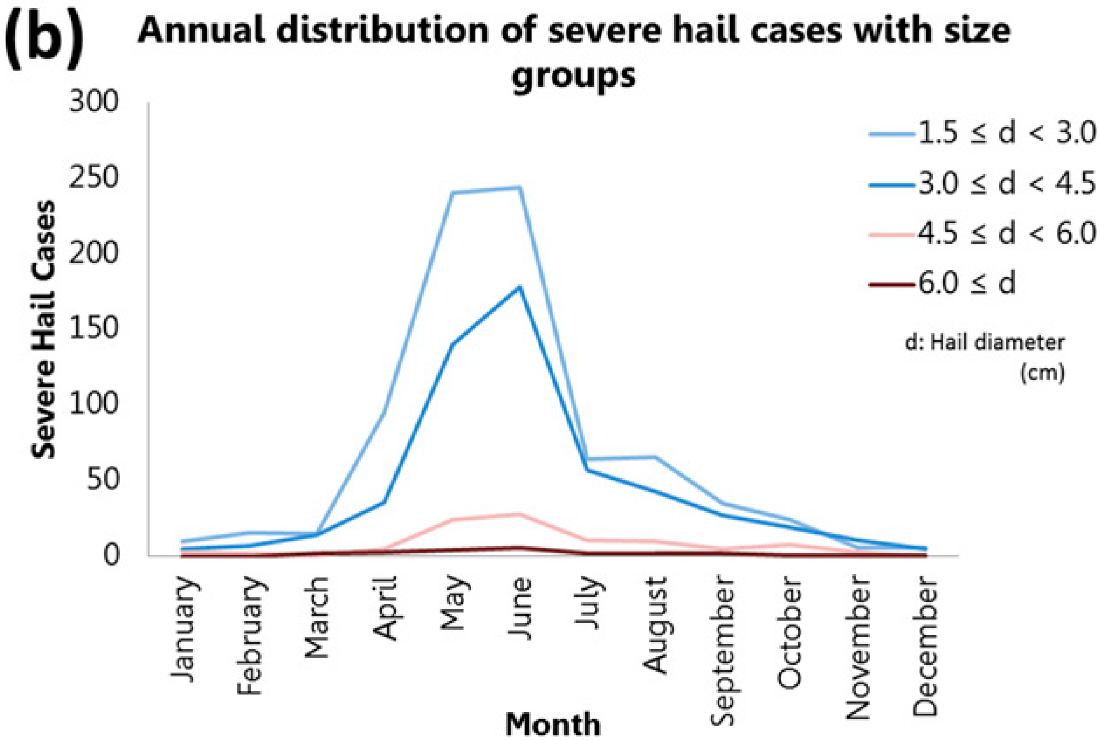


Figure 3.5 : Annual distribution of (a) large and very large hail cases and (b) size groups for severe hail cases in Turkey.

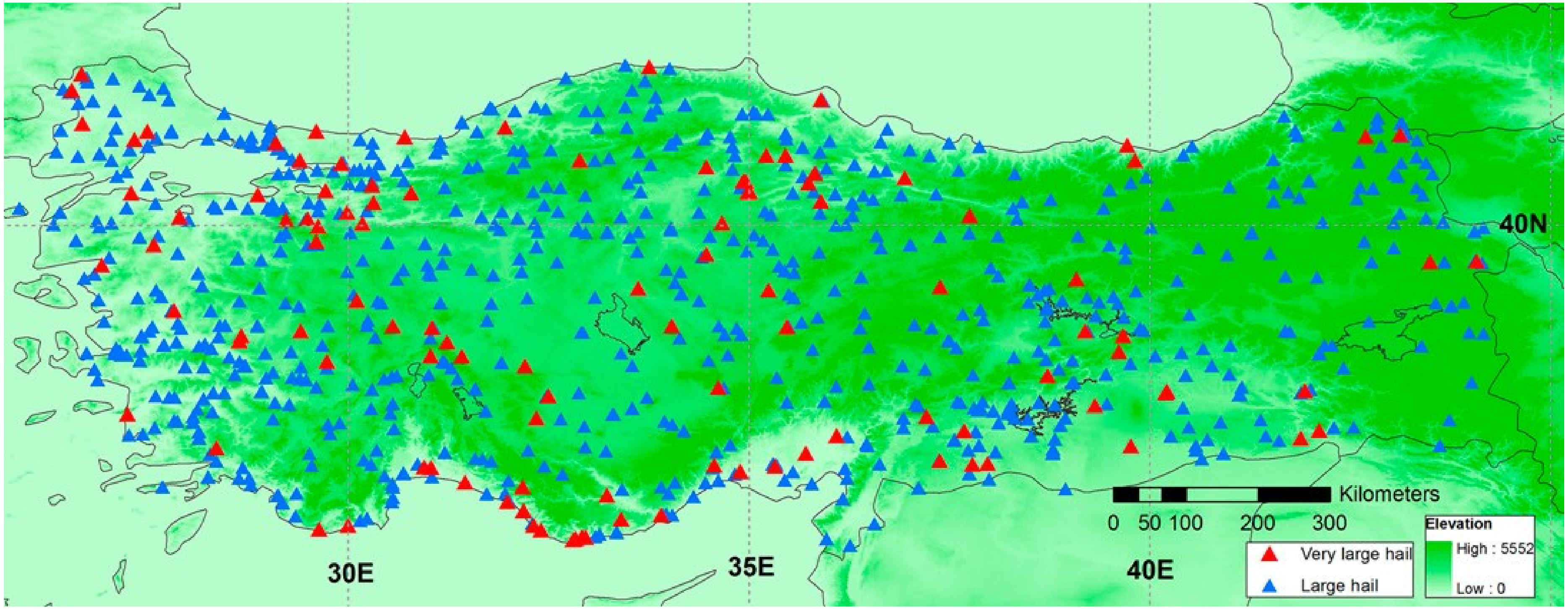


Figure 3.6 : Locations of large and very large hail cases in Turkey and topography.

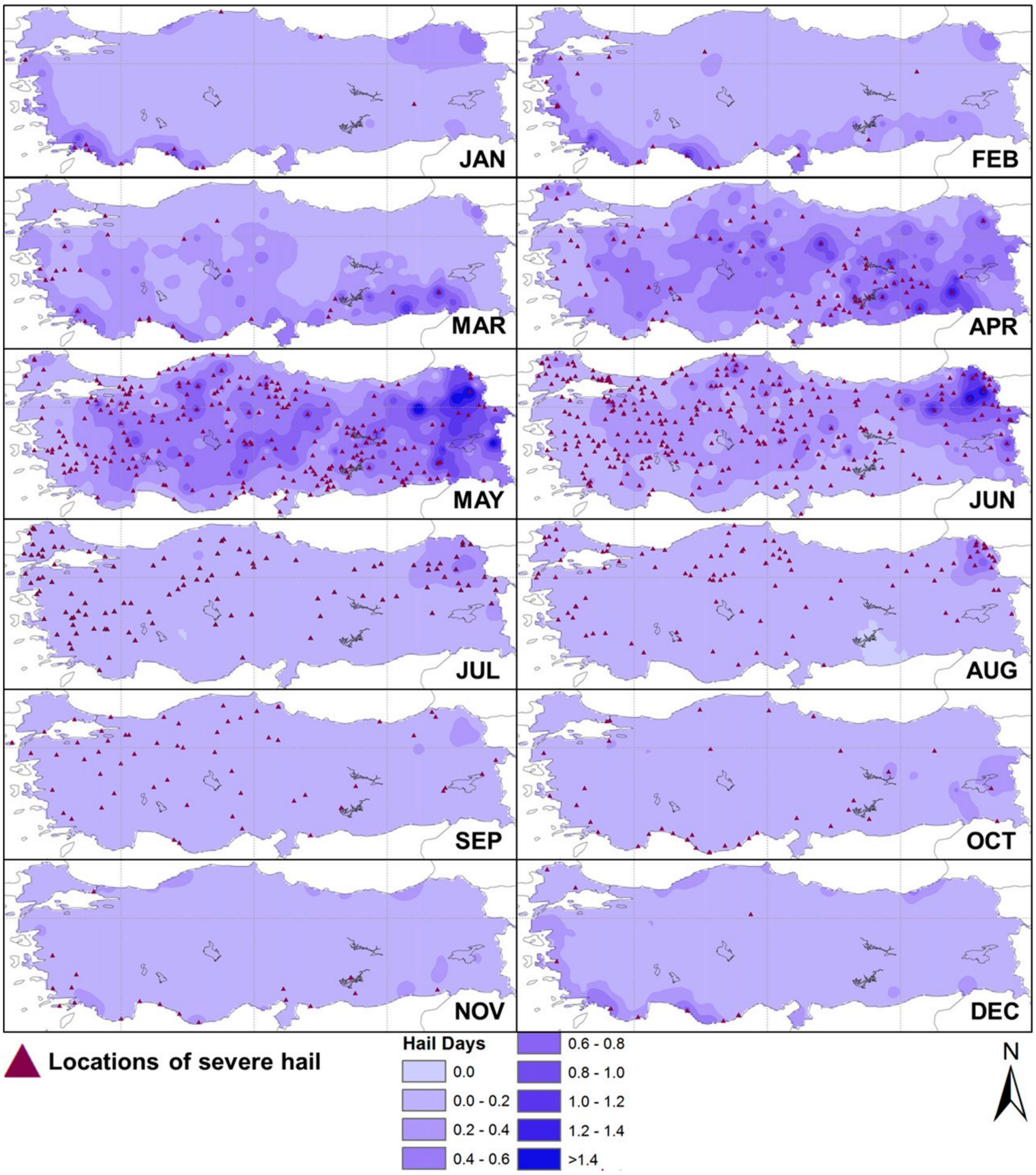


Figure 3.7 : Geographical distribution of all hail days (shaded) and locations of severe hail (red triangles) per month. All hail days data are from 277 stations of TSMS, 1960–2013. Data are bilinearly interpolated with an inverse distance weighting method (variable radius, second power), on a grid of 263 x 100 points.

3.3.4 Diurnal cycle

Severe hail is most frequently observed during 1200–1459 UTC (1400–1659 LST), with 230 cases, followed by 0900–1159 UTC (1100–1359 LST), with 150 cases (Fig. 3.8). The peak is similar for very large hail; 19 of 45 very large hail events occur between 1200 and 1459UTC. Severe hail with a diameter of 3.0–4.4cm more frequently occurs than 1.5–2.9-cm-diameter hail in evening hours (between 1500–1759 and 1800–2059 UTC). Of the cases with diameter of 6.0cm or larger, the peak time interval is 1500–1759 UTC. However, severe hail cases have a nighttime minimum, presumably owing to a combination of less-frequent nighttime thunderstorms (Fig. 3.9) and underreporting.

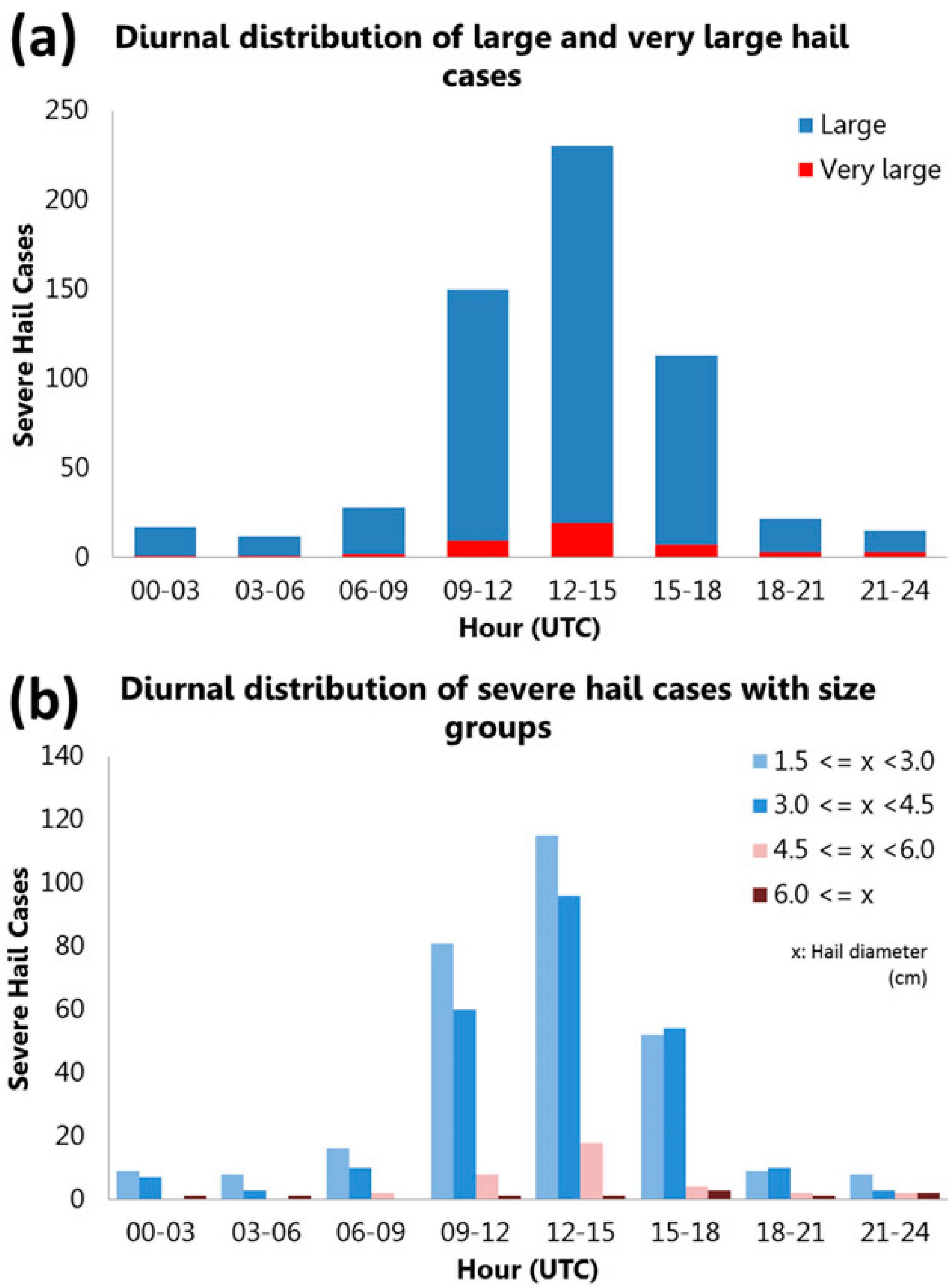


Figure 3.8 : Diurnal distribution of (a) large and very large hail cases and (b) size groups for severe hail cases in Turkey

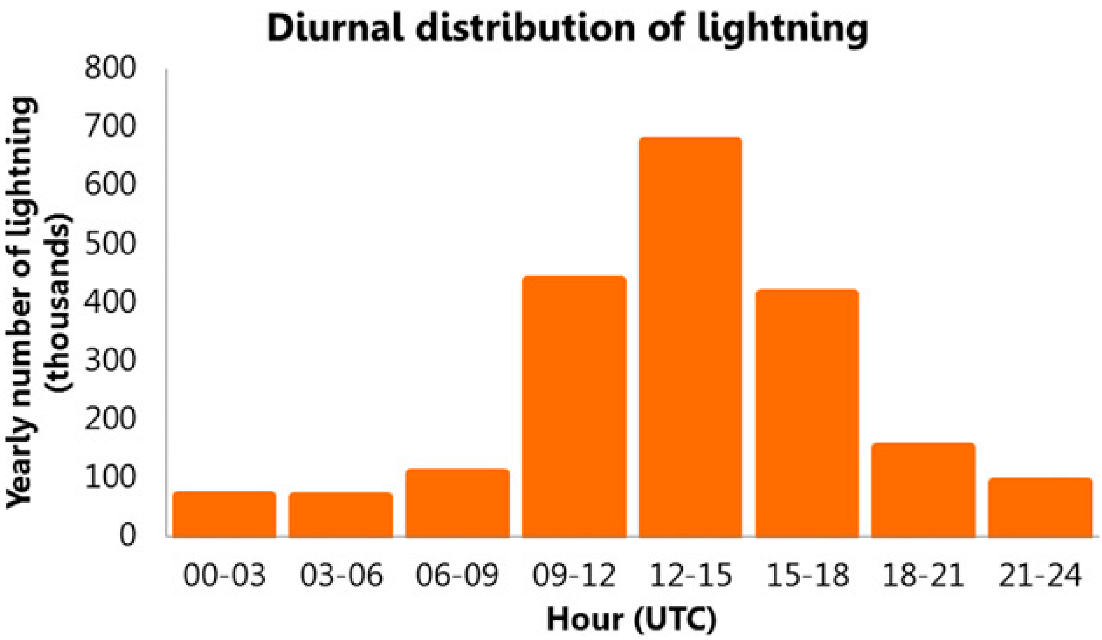


Figure 3.9 : Diurnal distribution of lightning in Turkey (yearly average with 1 Oct 2011–30 Sep 2013; data from Vaisala).

4. SEVERE CONVECTIVE STORM ENVIRONMENTS IN TURKEY[5]

4.1 Introduction

Skillful forecasting of convective storms and their attendant hazards, such as tornadoes or large hail, requires knowledge of the characteristics of the environments in which the phenomena tend to occur. Existing studies of environmental conditions supportive of severe convective storms cover mainly the United States (U.S.) and parts of Europe. Rasmussen and Blanchard (1998) analyzed U.S. National Weather Service soundings from 1992 and focused on discriminating between environments associated with supercells that produced tornadoes of F2 intensity and stronger (deemed "significant" tornadoes), supercells without significant tornadoes, and nonsupercell thunderstorms. A subsequent study by Thompson et al. (2003) utilized soundings from 40-km Rapid Update Cycle (RUC)-2 analyses to investigate environments of "significantly tornadic" supercells, "weakly tornadic" supercells, nontornadic supercells, and discrete nonsupercell storms between April 1999 and June 2001. Furthermore, Johnson and Sugden (2014) used RUC analyses to study U.S. large hail environments, though the RUC analyses had a higher resolution (20-km and 13-km grid intervals between 2003–2011). Investigations in more localized regions also have been performed for parts of North America using gridded model analyses and observed soundings. For example, Lombardo and Colle (2011) investigated the relationship between the structure of the convection ("cellular," "linear," and "nonlinear" cases were identified) and the characteristics of the environment in severe convective weather events in the northeastern U.S. for the warm seasons between 2002–2007, using North American Regional Reanalysis data (32-km grid spacing). Dupilka and Reuter (2011) examined the environments of F2+ tornadoes, F0–F1 tornadoes, and

[5] This chapter is based on the paper Abdullah Kahraman, Mikdat Kadıoğlu, Paul M. Markowski (2017). Severe Convective Storm Environments in Turkey. Monthly Weather Review, Vol:145. DOI: 10.1175/MWR-D-16-0338.1 .

nontornadic storms with >= 3 cm hail within central Alberta, Canada, between 1967–2000, using observed soundings.

Studies of convective storm environments covering the entire continent of Europe are generally lacking, in large part because of the inhomogeneity of storm data reports across Europe from one country to another. Thus, investigations that rely on storm reports tend to be limited to small regions or individual countries. In a study covering most of Europe, Kaltenböck et al. (2009) used soundings obtained from European Centre for Medium-Range Weather Forecasts (ECMWF) gridded analyses for April–September, 2006–2007, to investigate the environments of F2–F3 tornadoes, F0–F1 tornadoes, severe hail events, severe wind events, heavy precipitation events, thunderstorms, and null cases. As an example for studies covering smaller regions, Groenemeijer and van Delden (2007) used observed soundings obtained within and in close proximity to the Netherlands between 1975–2003 to investigate the environments of F1+ tornadoes, F0 tornadoes, waterspouts, hail >=3 cm, hail < 3 cm, thunder, and no severe weather in the country. Further studies have been performed for Poland, Finland, coastal Croatia, and parts of Spain for some severe weather types. Taszarek and Kolendowicz (2013) studied a total of 97 tornado cases with radiosonde observations in and around Poland between 1977–2012. Tuovinen et al. (2015) studied 23 significant hail day soundings and 93 null thunderstorm soundings in Finland between 1972–2011. Renko et al. (2016) studied the environments of 62 waterspouts in the eastern Adriatic Sea (Croatian coasts) using radiosonde observations between 2001–2013. Merino et al. (2013) compared 100 days between 2001–2010 with and without hail in northeastern Spain, using soundings obtained from WRF simulations with 9-km horizontal grid spacing. Finally, for a broader area in central Europe, Pucik et al. (2015) investigated the characteristics of 16 421 radiosondes associated with thunderstorms (of which 3866 were associated with at least one severe weather occurrence) between 2007–2013.

Additional studies have compared the characteristics of convective storm environments in North America and Europe. Brooks (2009) studied 159 significant tornado soundings and 1031 significant nontornadic soundings in the U.S. between 1997–1999, and 152 “significant tornadic” soundings and 61 “significant nontornadic” soundings in Europe between 1958–1999 using National Center for Atmospheric Research (NCAR)/National Center for Environmental Prediction (NCEP) reanalysis data. Grünwald and Brooks (2011) subsequently used the same reanalysis dataset to compare the environments associated with 303 tornadoes in Europe between 1958–1999, and 4510 tornadoes in the U.S. between 1991–1999.

The findings obtained from the aforementioned prior studies targeting a variety of geographical regions suggest that although there are some ingredients of convective storm environments common to all regions [e.g., no matter what the region, convective storms require convective available potential energy (CAPE)], there are also considerable regional differences in the magnitudes of some of the most popular parameters used in convective storm forecasting owing to contrasting climatological and perhaps topographical characteristics.

This study is motivated by the fact that no prior studies, even those that have covered most of Europe, have investigated convective storm environments in Turkey. There is no environmental conditions studied for Middle East as well as most of the Mediterranean countries as well. The data and methods used in the study are described in section 4.2. The distributions of environmental parameters calculated for observed tornado, waterspout, and severe hail cases are presented in section 4.3. Due to the lack of a severe windstorm database in Turkey, severe wind environments are not included in the study (an effort on building a severe wind database is still going on). Finally, some conclusions appear in section 4.4.

4.2 Data and methods

A severe weather database for Turkey has been built in recent years using official and unofficial records from a wide variety of sources. Tornado (including waterspouts) and severe hail (hail with a diameter of at least 1.5 cm) records from the database are used as severe weather observations in this study [see Kahraman and Markowski (2014), and Kahraman et al. (2016), for details of the tornado and severe hail dataset, as well as climatologies for Turkey; see Tilev-Tanriover et al. (2015) for a thunderstorm climatology of the country. The group is also working on collecting severe wind data for use in future studies.]. The geographical distribution of tornado and severe hail cases in Turkey indicates different characteristics in terms of regionality and intensity contrasts (Figure 4.1).

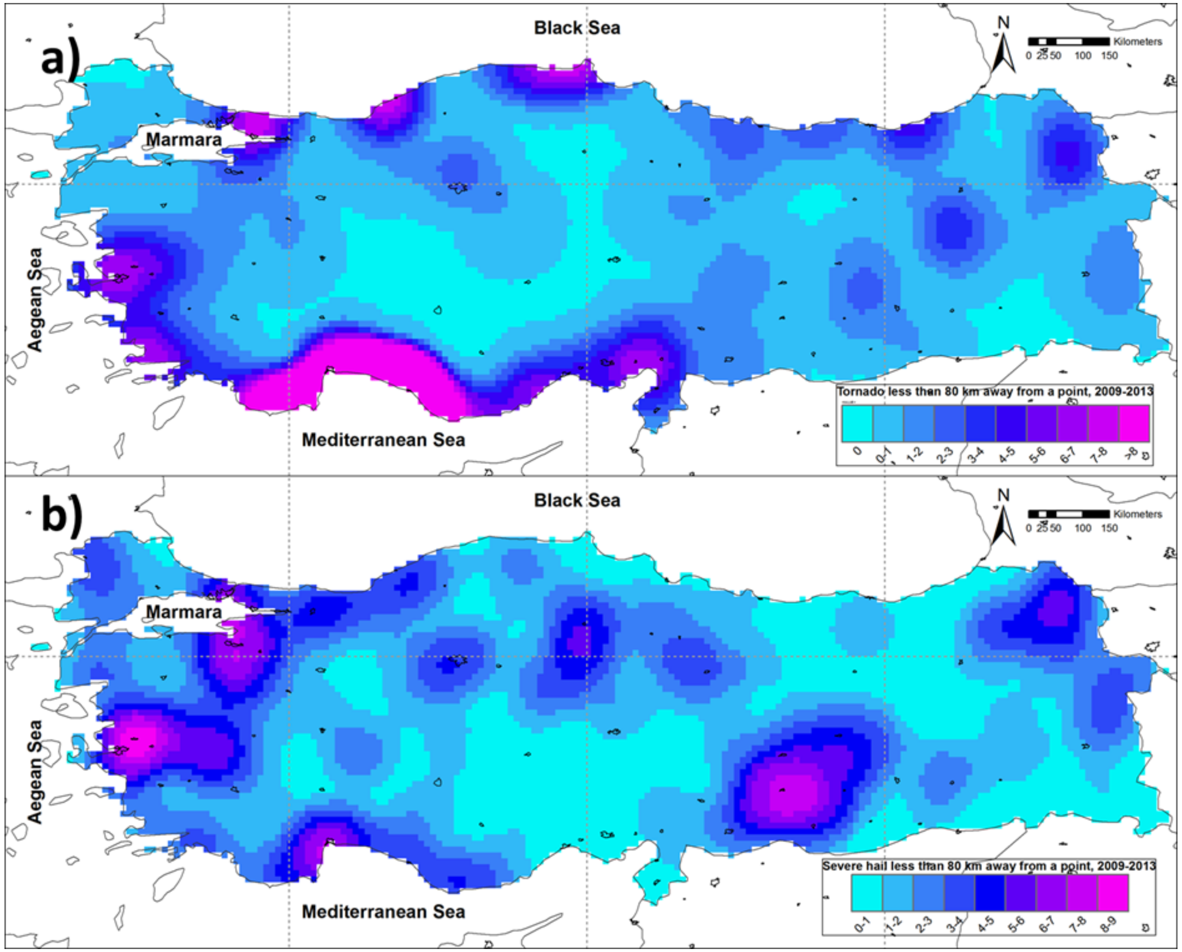


Figure 4.1: Number of a) tornado cases and b) severe hail cases less than ~60 km from a given point, between 2009-2013. Kernel density estimation with a search radius of 1.0° and output cell size of 0.1°, over 192 x 63 grids is used for mapping the distributions (The search radius was varied between 0.5° and 1.5°, and this doesn't change the pattern dramatically). Urban areas are surrounded with black contours.

Tornadoes are more common in coastal regions, partially owing to a high number of waterspouts, especially around Antalya. On the other hand, severe hail is common in the west and parts of the interior. The relative maxima in the metropolitan areas (e.g., Istanbul, Ankara, Izmir) strongly suggest a population bias and an underreporting of events in the more sparsely populated areas. (In spite of the likely underreporting in general, high severe hail and tornado frequencies have been diagnosed in some rural areas in southeastern and eastern Turkey, respectively.) Although the database contains records go back as far as the early 19th century, data from recent years are assumed to be more representative given the greater availability of reports and active efforts of documenting actual weather events, which is used in Figure 1.

Turkey has eight active stations collecting radiosonde observations twice each day, with an average spacing of approximately 500 km. There are almost always representativeness questions when using observed soundings to characterize the environments of convective storms (Davies-Jones 1993; Brooks et al. 1994; Grünwald and Brooks 2011), and the complex topography of Turkey, the proximity of much of Turkey to large bodies of water, and highly variable low-level mesoscale and microscale wind fields present additional challenges. The limited number of severe weather occurrences in proximity to the radiosonde stations in space and time, in addition to the representativeness issues, motivate our use of soundings obtained from a reanalysis dataset rather than observed soundings. Soundings obtained from reanalysis data are not free of issues, however. One well-known shortcoming is the poor representation of capping inversions, which stems from the relatively coarse vertical resolution (Brooks et al. 2003, Grünwald and Brooks 2011).

The proximity soundings used in this study were obtained from the European Centre for Medium-Range Weather Forecasts reanalysis dataset (ERA-Interim), which goes back to 1979 (Dee et al. 2011). Analyses are available every 12 h, and forecasts with 3-h intervals. The horizontal grid spacing is 0.75°, there are 28 vertical levels, consisting of one surface level and 27 pressure levels from 1000 hPa to 100 hPa. The data used in this study cover the 35-year period from 1 January 1979 –31 December 2013. NCL is used for calculations of parameters from the reanalysis data (NCL 2014).

Table 1 shows the groups of soundings analysed, and number of cases for each category (1979-2013). "Likely mesocyclonic", "likely nonmesocyclonic", and "unknown" tornado classifications are described by Kahraman and Markowski (2014), aiming at distinguishing supercellular tornadoes from others when possible (for cases without enough confidence, the “unknown” category is introduced). For a few cases, Doppler radar imagery was used for a velocity couplet and/or reflectivity patterns like hook echoes, or bounded weak echo region for discrete storms. For some others, severe weather reports (e.g. very large hail) from tornadic storms were useful. Furthermore, satellite images, and photographs/videos indicating mesocyclonic structure or nonmesocyclonic feature (e.g. a number of stationary and peaceful waterspouts depicting a line parallel to a coast) were used to determine the category if possible. Severe hail cases are classified as either “large hail” cases (diameters between 1.5–4.5 cm) or “very large hail” cases (diameters >4.5 cm).

Table 4.1: Severe weather categories used for the analysis.

Category	Definition	# of samples
TOR-sup	“Likely mesocyclonic” tornado cases (i.e. associated with supercells)	33
TOR-non	“Likely nonmesocyclonic” tornado cases (i.e. mostly waterspouts)	68
TOR-unk	“Unknown” tornado cases (tornadoes without enough confidence to fit in one of TOR-sup/TOR-non categories)	132
TOR-F2+	“Significant” tornado cases (i.e. F2 or stronger, regardless of mesocyclonic, nonmesocyclonic or unknown nature)	28
HAIL-lar	“Large” hail cases (1.5~4.5 cm of diameter in the longest direction), i.e. hazelnut size or bigger, smaller than egg size	282
HAIL-vlg	“Very large” hail cases (equal to or larger than ~4.5 cm diameter), i.e. egg size or bigger	37
SUP	Supercells without tornadoes	33

The supercell category comprises very large hail cases without any tornado reports. Soundings with most unstable CAPE (MUCAPE) less than 50 J kg-1 are excluded from the study, and in the supercell, mesocyclonic tornado, and F2+ tornado categories, soundings with negative SRH were excluded. Such soundings are assumed to be unrepresentative of the storm environment, based on our understanding that convective storms require buoyancy, cyclonically rotating updrafts require positive storm-relative helicity (SRH), and strong tornadoes are almost always associated with mesocyclones. Overall, calculations of environmental parameters are performed for 233 tornado and 319 severe hail cases within the 35-year period.

4.3 Analysis of parameters derived from ERA-Interim reanalysis

4.3.1 Measures of instability

Deep moist convection requires conditionally unstable lapse rates (at least, on average, through a large depth of the troposphere), enough moisture for a parcel to have a level of free convection (LFC), and a lifting mechanism for the parcel to reach its LFC (Doswell et al. 1996). CAPE is the result of the first two ingredients. CAPE can be computed by lifting an air parcel from the surface, some altitude above the surface, or by lifting an air parcel possessing the mean thermodynamic characteristics of a layer.

A comparison of lifting condensation levels (LCL) of surface parcels and parcels characterized by the mean properties of the lowest 100 hPa (approximately 1000 m) suggests that the latter is more representative of observed convective cloud bases (Craven et al. 2002), at least for the U.S. Great Plains. For this study, in addition to the surface level (and MUCAPE), mean layers of 200 m, 500 m and 1000 m depth are used for calculation of environmental parameters such as CAPE and LCL (only SBCAPE and MLCAPE for 200 and 1000 m are discussed).

Turkish severe storm environments are found to be associated with CAPE of up to 2000 J kg-1 for surface based parcels, with CAPE decreasing as the depth of the layer used to characterize the lifted parcel increases, as expected (Figure 2). Tornado environments in Turkey have CAPE distributions similar to the tornado environments documented in Poland having surface temperatures exceeding 18°C (Taszarek and Kolendowicz 2013), the F2+ tornado environments documented in central Europe (Pucik et al. 2015), the waterspouts environments in the eastern Adriatic Sea (Renko et al. 2016), and the tornado environments documented in the Kaltenböck et al. (2009) study that covered most of Europe CAPE in Turkish tornado environments is larger than tornado environments in Poland characterized by surface temperatures less than

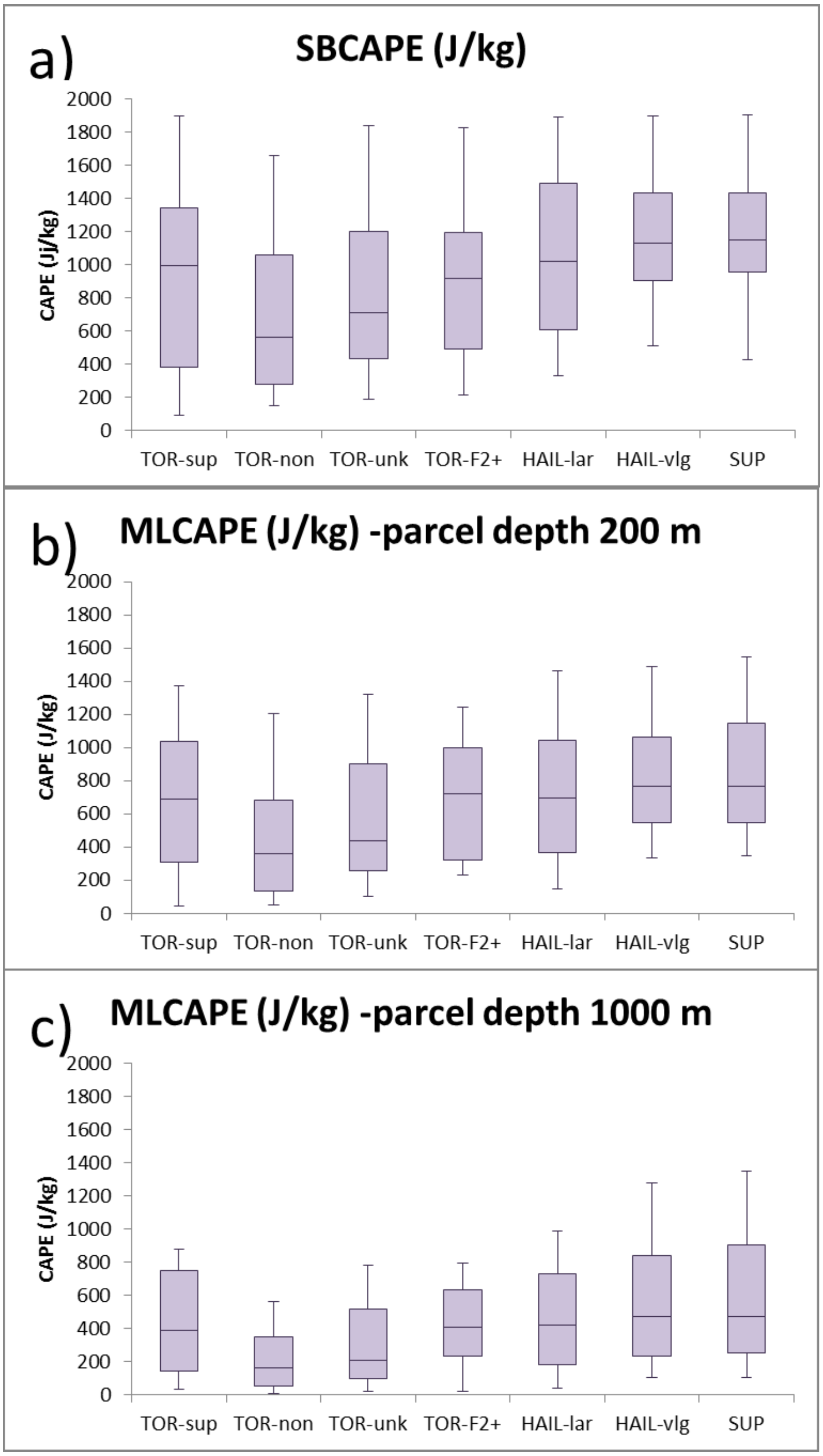


Figure 4.2 : Convective available potential energy of a) surface parcel, b) mixed layer parcel of 200 m depth, c) mixed layer parcel of 1000 m depth, for mesocyclonic tornadoes (TOR-sup), nonmesocyclonic tornadoes (TOR-non), tornadoes of unknown nature (TOR-unk), significant tornadoes (TOR-F2+), large hail (HAIL-lar, hail with a diameter of ~1.5 to ~4.5 cm), very large hail (HAIL-vlg, hail diameter ~4.5 cm or larger), and supercells without tornadoes (SUP). The boxes extend to the 25th and 75th percentiles, while the whiskers to the 10th and 90th percentiles. Median values are shown within the boxes.

18°C (Taszarek and Kolendowicz 2013), F2+ tornado environments in Poland (Taszarek and Kolendowicz 2013), Dutch tornado and waterspout environments (Groenemeijer and Van Delden 2007), and weak tornadic storm environments in central Europe (Pucik et al. 2015). However, CAPE is considerably less, on average, than in the U.S. Great Plains tornadic storm environments (e.g., Rasmussen and Blanchard 1998; Thompson et al. 2003). The differences with European countries might partially be attributed to lower latitude of Turkey as well as surrounding warmer seas, as higher temperature and moisture content more frequently exist in low levels in Turkey, despite higher elevation in most parts of the country. An average sea surface temperature (SST) of 21.22 C is observed in Eastern Mediterranean (Levantine) between 1982-2012, which is the highest among other sections of the Mediterranean Sea (Shaltout and Omstedt 2014). Black Sea's and Aegean Sea's average SST are 17.97 C and 19.05 C, respectively (Shaltout and Omstedt 2014). However, the low-level moisture supplied by the bodies of water in Turkey's proximity is less than that provided to the U.S. Great Plains region by the Gulf of Mexico owing to the warmer water temperatures of the Gulf of Mexico. (An average SST of 26.5 C is observed in the gulf between 1985-2016, according to Physical Oceanography Division, Atlantic Oceanographic and Meteorological Laboratory, NOAA)

Nonmesocyclonic tornadoes in Turkey (TOR-non), which are mostly waterspouts along the coasts, tend to form in lower CAPE environments compared to mesocyclonic tornadoes (TOR-sup in Figure 2). Tornadoes without enough confidence to be classified as mesocyclonic or nonmesocyclonic (TOR-unk) are associated with intermediate CAPE values. Also, waterspouts do not always require high CAPE values, as they may occur with shallow cloud depths even without thunder. Although these findings are meaningful, CAPE cannot be used as a discriminator between mesocyclonic and nonmesocyclonic convection, because of large overlap between categories.

For large hail occurrences, CAPE (both SBCAPE and MLCAPE) is usually higher than that of other storm environments (Figure 2). Although CAPE is not a good discriminator itself for a severe storm environment, severe hail being associated with high CAPE (together with high shear) is consistent with the literature. The large hail, very large hail, and supercell CAPE are comparable to those in Finland (Tuovinen et al. 2015), southwest Europe (Merino et al. 2013), central Europe (Pucik et al. 2015), Netherlands (Groenemeijer and van Delden 2007), much of Europe (Kaltenböck et al. 2009); but again, these are lower than U.S. values (Rasmussen and Blanchard 1998; Thompson et al. 2003; Johnson and Sugden 2014).

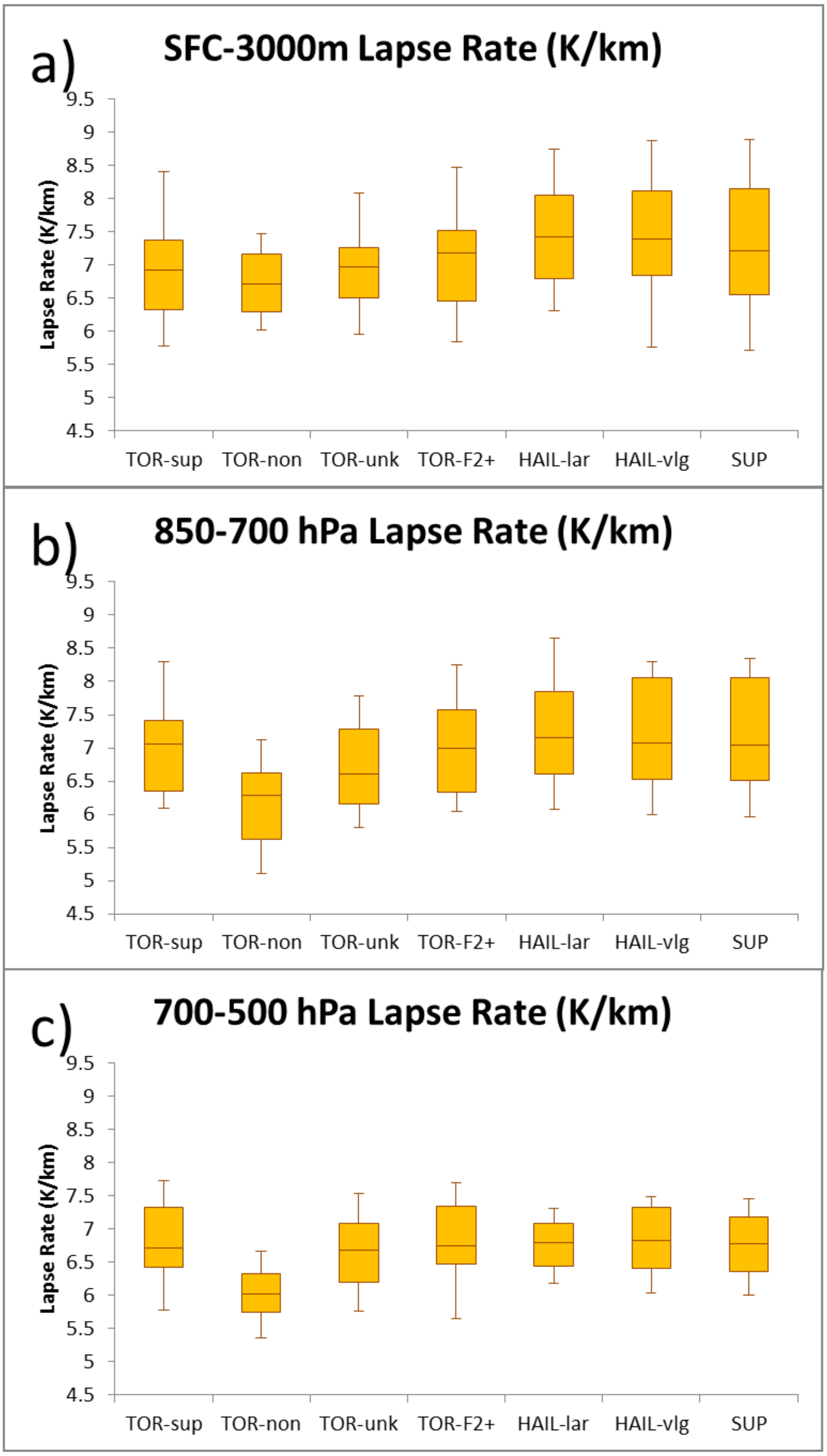


Figure 4.3 : Same as Fig. 4.2, except for lapse rate of a) surface to 3000 m above ground level, b) 850-700 hPa layer, c) 700-500 hPa layer..

Low-level lapse rates (from the surface to 3000 m AGL) are similar across all tornado environments (i.e., TOR-non, TOR-sup, TOR-unk, and TOR-F2+; Figure 3a). However, 850–700 hPa and 700–500 hPa layers are substantially less unstable in nonmesocyclonic tornado (TOR-non) environments, compared to other tornado categories (Figure 3b, 3c). This difference also explains the aforementioned lower CAPE. There is not a strong signal in lapse rates for significant tornadoes (TOR-F2+), as they range within similar ranges with mesocyclonic (TOR-sup) and "unknown" (TOR-unk) tornadoes. However, large and very large hail cases as well as supercell environments have slightly higher values than other storm categories. Again, this contributes to slightly higher CAPE for severe hail environments, compared to other environments. The differences between large and very large categories is negligible.

4.3.2 Parameters related to vertical wind shear

Deep moist convection tends to become increasingly organized as the vertical wind shear increased (Markowski and Richardson 2010). The magnitude of the vector wind difference between the near-surface wind (typically 10 m AGL) and the 6-km AGL wind, hereafter the 0–6-km shear, has been a popular bulk measure of the vertical wind shear within the forecasting community (e.g., Bunkers 2002; Houston et al. 2008). Disorganized convection (sometimes called single-cell convection) is typical of environments having 0–6 km shear less than 10 m s-1. For 0–6-km shear of roughly 10–20 m s-1, multicellular convection can occur (e.g., squall lines and other convective systems). For 0–6-km shear exceeding roughly 15 m s-1, supercells are possible, at least in the case of relatively isolated convective storms (severe squall lines also can occur in the presence of strong shear). The strong vertical shear in supercell environments is the source of horizontal vorticity, which, upon tilting into the vertical, gives rise to the mid-tropospheric mesocyclones of supercell storms.

In the Rasmussen and Blanchard (1998) study, proximity soundings obtained near observed U.S. tornadic and nontornadic supercells had median 0–6-km shear values of 19.1 and 18.4 s-1, respectively. In another U.S. study, one that relied on RUC soundings, slightly higher 0–6 km shear values were found, with median values of 24.5 m s-1 for significant tornadoes, 22.5 m s-1 for weak tornadoes, and 22.1 m s-1 for nontornadic supercells (Thompson et al. 2003). Lesser deep-layer shear values have been found, however, in prior studies of European supercell environments, as shown for central Europe (Pucik et al. 2015), with 22 m s-1 median for significant tornadoes; the Netherlands, with 17.0, 15.3, and 27.0 m s-1 medians for F0, F1, and F2 tornadoes, respectively (Groenemeijer and Van Delden 2007); and Poland, with unrated, F0/F1, and F2/F3 tornadoes having median shears of 15.8 m s-1, 18.9 m s-1, and 25.2 m s-1, respectively (Taszarek and Kolendowicz 2013).

In Turkey, 0–6 km shear in environments associated with mesocyclonic tornadoes (TOR-sup) is (21.9 m s-1 median value, with 26.2 m s-1 75th, and 14.0 m s-1 25th percentiles) higher than the shear that has been found in prior studies of European supercell environments (Figure 4.4a). The significant tornadoes (TOR-F2+, 21.6 m s-1 median value) and tornadoes of unknown nature (TOR-unk, 18.6 m s-1 median value) categories are not distinguishable from mesocyclonic tornadoes in terms of 0–6-km shear. As expected, nonmesocyclonic tornadoes (TOR-non) occur in environments having much less 0–6-km shear compared to the environments of other storms (12.1 m s-1 median value).

In Fig. 4.4a, a slight difference of deep-layer shear between large and very large hail (as well as supercell) categories exists (14.0, 17.2 and 17.2 m s-1 median values), with very large hail (and supercells) showing higher values, closer to those of mesocyclonic tornado environments. This result is consistent with the idea that very large hail (egg size or larger) occurs mainly with supercells, which require large deep-layer shear.

Low-level shear is crucial for mesocyclonic tornadoes, and 10 m s-1 bulk shear for 0–1 km layer is a rough lower bound for favorable environments for significant tornadoes. Thompson et al. (2003) found that weak tornadoes in U.S. occur with 0–1 km shear of 8.1 m s-1 (median value), with an interquartile range of 5.7–11.3 m s-1; for significant tornadoes the median 0–1-km shear is 9.8 m s-1, with an interquartile range of 7.8–13.6 m s-1. In the Netherlands, this parameter is a good discriminator for significant tornadoes (an incredible 20.3 m s-1 median value, with a 13.2-22.1 m s-1 interquartile range for F2 tornadoes vs. 9.0 m s-1 median value, with a 7.3-12.1 m s-1 interquartile range for F1 tornadoes), and also the intensity of tornadoes (Groenemeijer and Van Delden 2007). However, for Poland, low-level shear values in the environments of tornadic storms are less than in Dutch tornadic storm environments (Taszarek and Kolendowicz 2013). Lesser low-level shear values is also the case for central Europe as a whole, as shown by Pucik et al. (2015), 25th–75th percentiles of 0–1 km shear values range between ~3 and ~9 m s-1 for both nontornadic storms and F0–F1 tornadoes, while F2+ tornadoes occur in environments with slightly higher low-level shear (~6 to ~12 m s-1 of 0–1 km shear -25th and 75th percentiles).

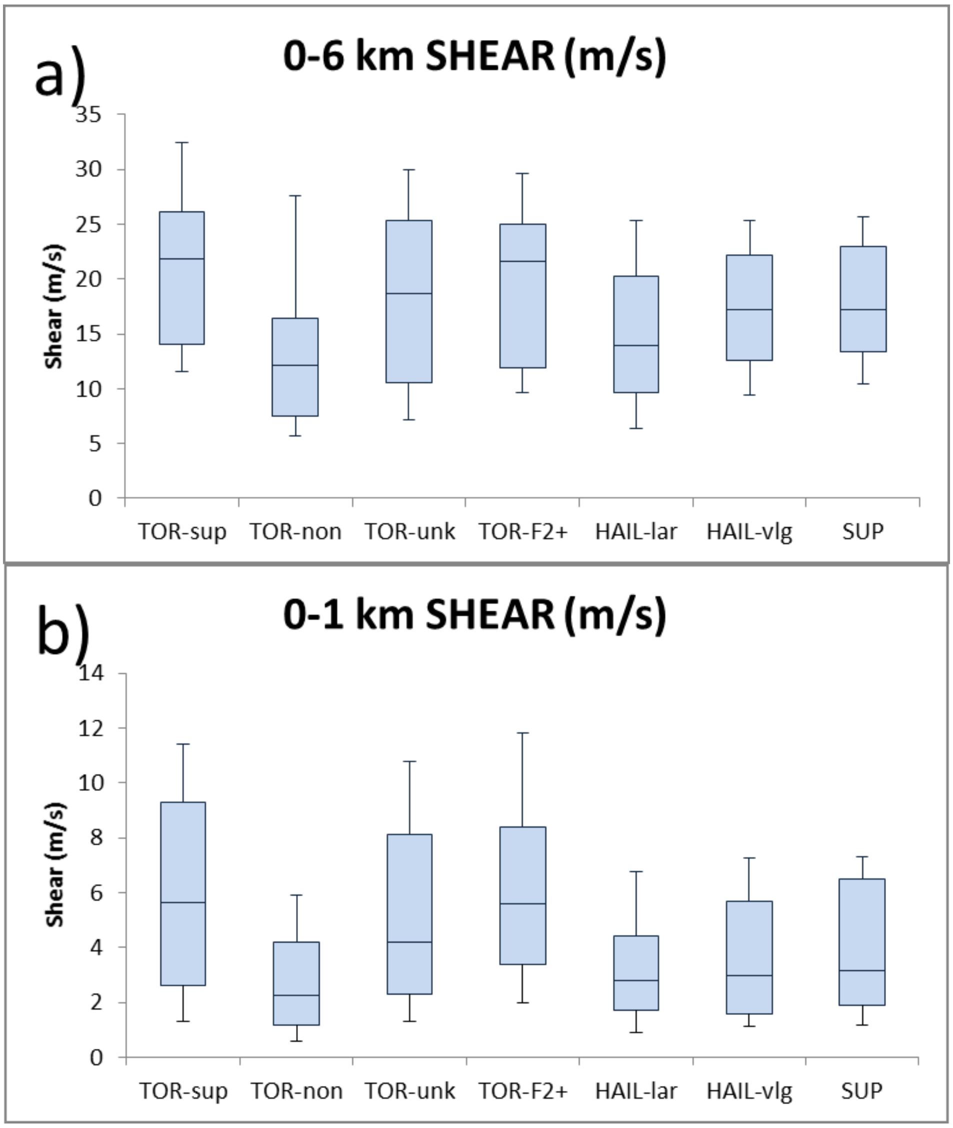


Figure 4.4 : Same as Fig. 4.2, except for bulk shear for a) layer between surface and 6 km above ground level, b) layer between surface and 1 km above ground level.

In Turkey, based on the proximity soundings obtained from the ERA-Interim data, 0–1 km shear for all environments is relatively weak, similar to the aforementioned studies for Poland and Central Europe (Figure 4.4b). F2+ tornadoes occur in low-level shear environments not distinguishable from mesocyclonic or unknown tornadoes, though the median value and lower percentiles appear to be slightly higher than other storm categories. These are below the observed low-level shear environments of tornadic supercells in the U.S., and can at least partially be attributed to the questionable representativeness of the low-level winds in reanalysis data around the very complex terrain of Turkey. Nevertheless, compared with each other, mesocyclonic tornadoes, "unknown" tornadoes, and F2+ tornadoes have stronger low-level shear environments than those of nonmesocyclonic tornadoes, large hail, and very large hail.

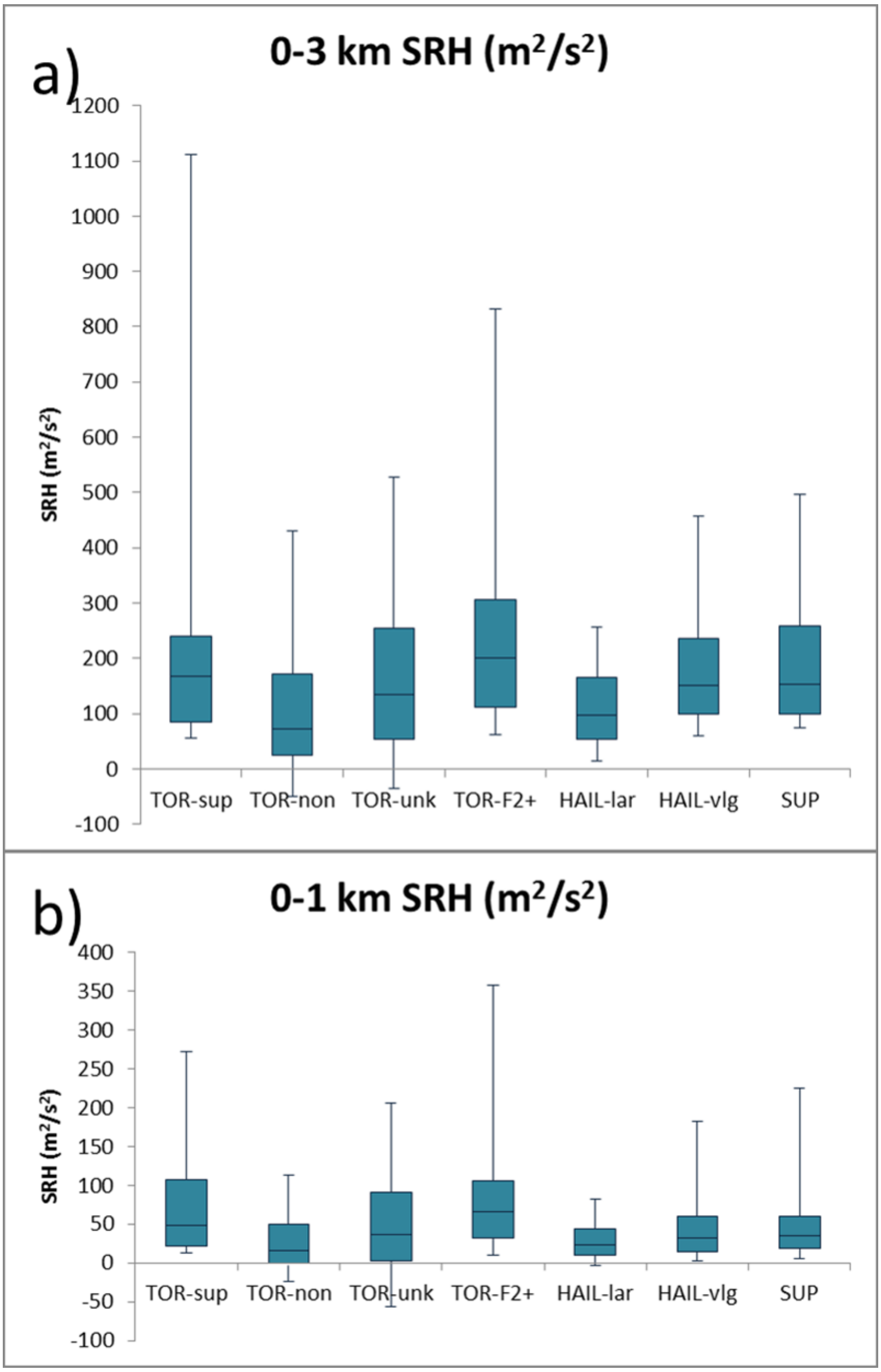


Figure 4.5 : Same as Fig. 4.2, except for storm-relative helicity calculated for right-moving supercells, for a) 0-3 km layer, b) 0-1 km layer.

SRH, for cyclonically rotating, right-moving supercells, is calculated for the 0–3 km and 0–1 km layers (Figure 4.5). In Turkey, the highest 0–3 km SRH values are associated with F2+ tornadoes, mesocyclonic tornadoes, very large hail, and supercells. The 90th percentile values exceed 1000 m2 s-2; thus, tornadic supercells in Turkey occasionally are associated with environments containing extreme SRH, as has been noted in the U.S. (Rasmussen and Blanchard 1998; Thompson et al. 2003). Such large values have not previously been documented in tornadic supercell environments elsewhere in Europe, however (Kaltenböck et al. 2009; Merino et al. 2013; Pucik et al. 2015).

SRH in the 0–1 km layer, like 0–1-km shear, is usually helpful in discriminating between environments conducive for significant tornadoes and environments supportive of only nontornadic supercells. The median 0–1-km SRH for weak tornadoes in the U.S. is 137 m2 s-2 (Thompson et al. 2003), for F0, F1, and F2 tornadoes in the Netherlands is 27 m2 s-2, 80 m2 s-2, and 196 m2 s-2, respectively (Groenemeijer and Van Delden 2007), and for F0/F1 and F2/F3 tornadoes in Poland is 87 m2 s-2 and 113 m2 s-2, respectively (Taszarek and Kolendowicz 2013). However, the median 0–1-km SRH in mesocyclonic tornado environments in Turkey is lower than most of these (48.4 m2 s-2), if not all (Figure 4.5b), which is consistent with the previously noted lesser 0–1-km shear values. The 0–1-km SRH of environments supportive of F2+ tornadoes exceeds the 0–1-km SRH of the other storm categories, however; the 90th percentile values exceed 250 m2 s-2 in the environments of both mesocyclonic tornadoes and F2+ tornadoes.

4.3.3 Lifting Condensation Level

The altitude of the lifting condensation level (LCL) has been an important discriminator between tornadic and nontornadic supercells in the U.S., given that a supercell exists and other environmental conditions are favorable (e.g. low-level shear is strong), with relatively low LCLs favoring tornadic supercells (Rasmussen and Blanchard 1998; Thompson et al. 2003). However, in other parts of the world, Turkey included, LCLs have been found to have limited utility as a tornadic versus nontornadic supercell discriminator because LCLs tend to have much less variability on severe storms days than in the U.S. (LCLs in Europe are almost always low in comparison to LCLs on the U.S. Great Plains region, especially the western Great Plains). For example, in the Netherlands, LCLs contribute practically no forecast skill for the discrimination of tornadic versus nontornadic storms (Groenemeijer and Van Delden 2007). In Poland, stronger tornadoes occurred in slightly higher LCLs than weaker tornadoes, but the median LCLs of both environments are below 1000 m (Taszarek and Kolendowicz 2013).

The distributions of LCLs, calculated by lifting surface parcels as well as parcels possessing the mean thermodynamic characteristics of the lowest 500 m, imply that convective cloud bases in Turkey are usually below 1000 m in tornadic storm environments (Figure 6). Nontornadic environments reveal higher medians and upper percentiles, but they are generally still below 1500 m. The tornadic supercell LCL distributions are narrower than the nontornadic supercell LCL distributions.

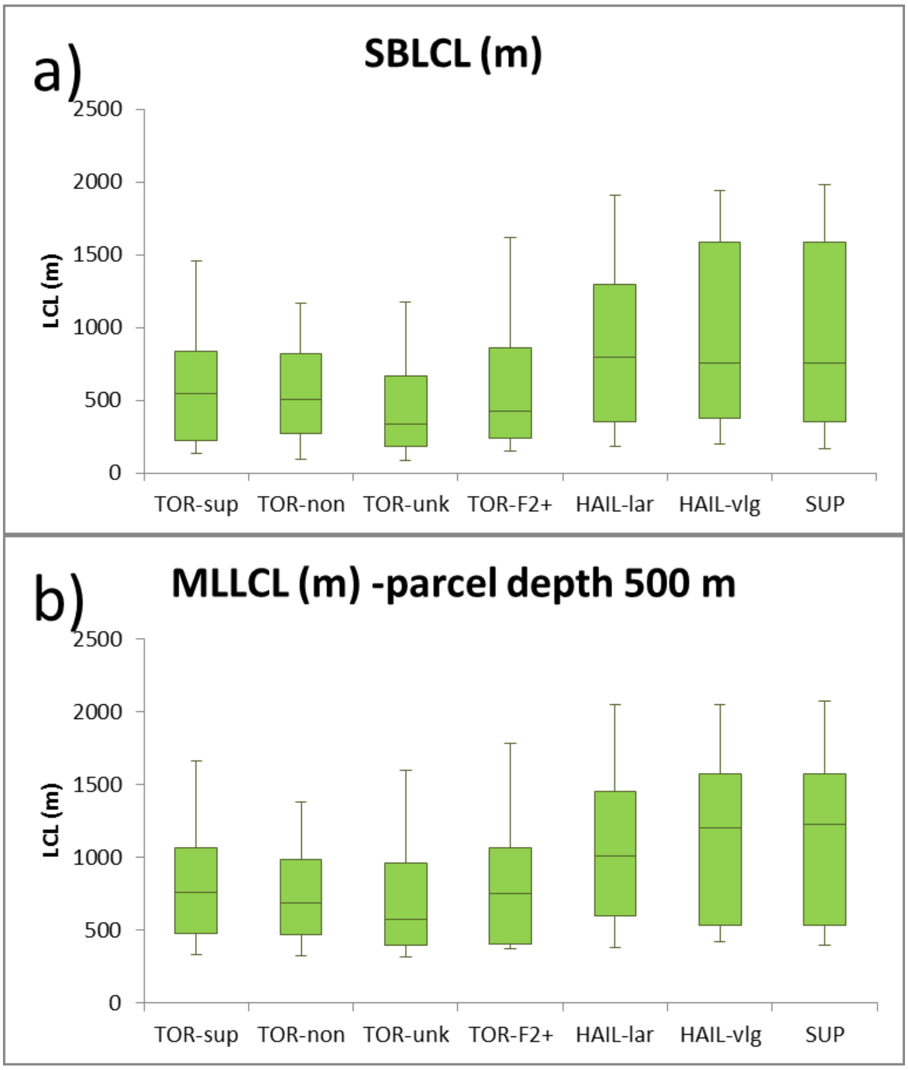


Figure 4.6 : Same as Fig. 4.2, except for lifting condensation level of a) surface-based parcel, b) mixed layer parcel of 500 m depth.

4.3.4 Composite indices

Composite indices combine multiple parameters (often a measure of instability is combined with a measure of the vertical wind shear) in an empirical way in order to help forecasters identify environments that are favorable for a certain storm type or hazard better than a single parameter might be able to. For example, neither CAPE nor shear alone indicate the potential for supercell storms, but the colocation of CAPE and strong shear is a strong indication of the possibility of supercell storms, given convective initiation.

One of the composite indices is the energy helicity index (EHI), which combines CAPE and storm-relative helicity (Hart and Korotky 1991; Davies 1993). It is formulated as

$$\boldsymbol{EHI = \frac{CAPE * SRH}{160{,}000}} \tag{4.1}$$

EHI is usually calculated using the SRH measured in the 0–3 km and 0–1 km layers. In the U.S., the median EHI obtained from the 0–3-km SRH (EHI03) for nontornadic and tornadic supercells was 0.64 and 1.48 in the Rasmussen and Blanchard (1998) study, respectively, while ordinary storm environments had a median EHI03 of just 0.14.

Thompson et al.'s study found a median EHI calculated with 0–1-km SRH (EHI01) of 2.1 for significant tornadoes, whereas it was 1.4 for weak tornadoes, 0.8 for nontornadic supercells, 0.5 for marginal supercells, and 0.1 for nonsupercells. On the other hand, this index has been found not to be useful in Europe, as in almost all environments, median EHI01 values are below 0.1 (Kaltenböck et al. 2009).

In Turkey, reanalysis-derived EHI values for tornadic environments are much lower than those in the U.S., but higher than European environments (Figure 4.7a, 4.7b). The very large hail environments, F2+ tornadic storm environments, supercells, and mesocyclonic tornado environments have highest values of EHI03 and EHI01 within all categories, which are comparable to US environments except the latter. In general, low EHI in Turkey can be attributed to both CAPE and SRH to be lower than in those in the U.S. In particular, EHI01 reflects the low SRH01 (and therefore, 0–1 km shear) magnitudes. Nevertheless, F2+ tornadoes have the highest EHI01, followed by mesocyclonic tornado environments.

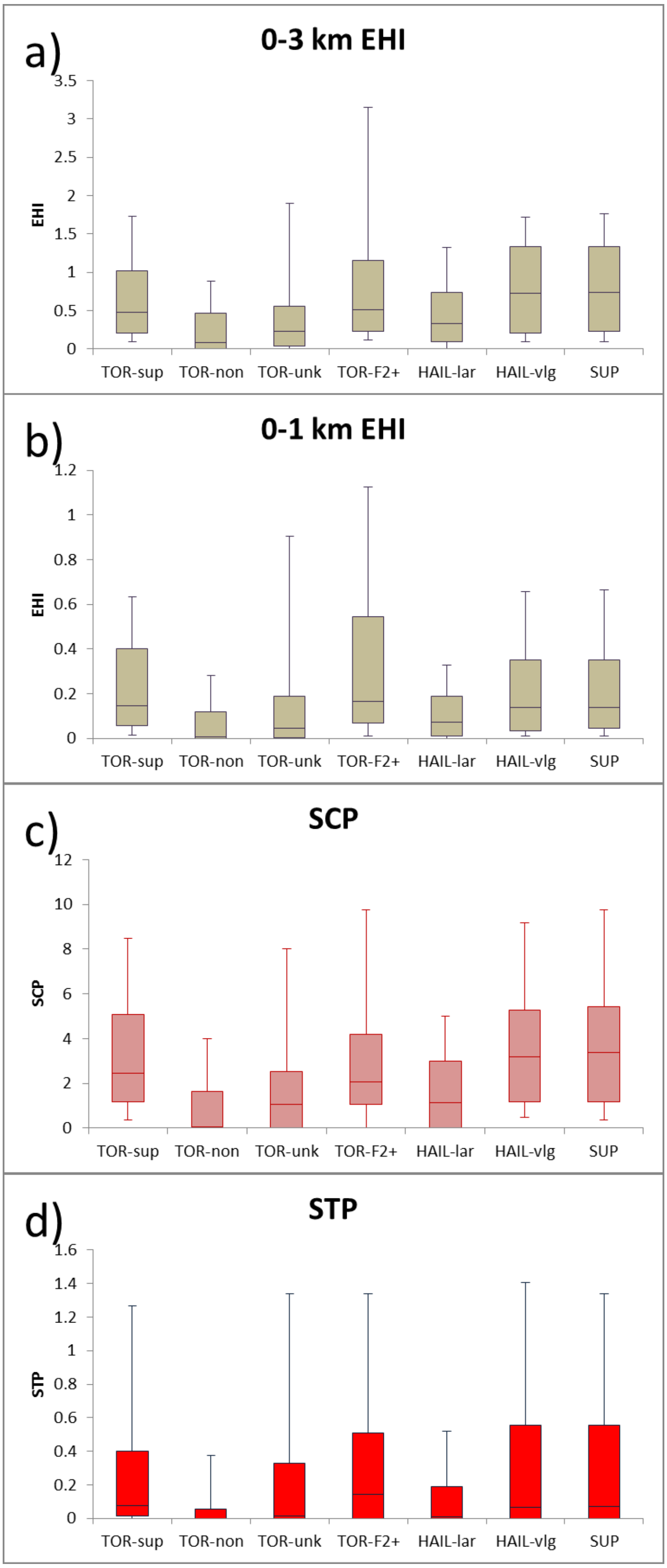


Figure 4.7 : Same as Fig. 2, except for composite parameters: a) Energy-helicity index for 0-3 km layer, b) Energy helicity index for 0-1 km layer, c) Supercell Composite Parameter, d) Significant Tornado Parameter.

Another composite index for supercell forecasting is the supercell composite parameter (SCP), which is the product of the CAPE of the most unstable lifted parcel (MUCAPE), 0–3-km SRH (SRH03), and 0–6-km shear (SH06) In this study following equation is used for SCP:

$$\boldsymbol{SCP = \frac{MUCAPE}{1000\,J/kg} * \frac{SRH03}{50\,m^2/s^2} * \frac{SH06}{20\,m/s}} \tag{4.2}$$

In Turkey, very large hail and supercell environments, followed by mesocyclonic tornado and F2+ tornado environments, have the highest SCP values. All of these environments have median values exceeding 2 (Figure 7c). Large hail environments and environments in which tornadoes of unknown intensity have occurred have median SCP values of ~1. Nonmesocyclonic tornadoes, as expected, have the lowest SCP values.

Significant tornado parameter (STP) is an index developed to identify significant tornadic storm environments (Thompson et al. 2004). It combines surface-based CAPE (SBCAPE) and deep-layer shear (ingredients for supercells), in addition to 0–1-km SRH (SRH01) and LCL (ingredients for tornadoes) in the following manner:

$$\boldsymbol{STP = \frac{SBCAPE}{1500\,J/kg} * \frac{2000-SBLCL}{1000\,m} * \frac{SRH01}{150\frac{m^2}{s^2}} * \frac{SH06}{20\,m/s}} \tag{4.3}$$

Following Thompson et al. (2002 and 2004), SBLCLs below 1000 m are limited to 1000 m, and SBLCLs above 2000 m are capped at 2000 m; 0–6-km shear is capped at 30 m s-1 and set to 0 m s-1 when less than 12.5 m s-1. STP exceeding 1 is commonly considered to be supportive of significant tornadoes in the U.S. (Thompson et al. 2004). However, owing to climatologically small 0–1-km SRH and SBCAPE in Turkey relative to the U.S., STP rarely exceeds 1 in Turkey (Figure 7d). Nevertheless, F2+ tornado environments have the highest median STP value out of all severe weather categories, and the median STP in nontornadic supercell environments is nearly zero.

5. CONCLUSIONS AND RECOMMENDATIONS

There was no publication regarding the occurrence of tornadoes, their geographical, annual, diurnal and intensity distributions in Turkey prior to this study. Also, a severe hail climatology was needed in order to go further understanding of severe convection in the country. Investigating the environmental conditions of these phenomena could be possible after building the database and climatologies.

5.1 Tornadoes in Turkey

The tornado climatology article is believed to be the most comprehensive climatology of tornadoes in Turkey to date. Tornado reports in Turkey historically have been sporadic and difficult to obtain, but reporting has improved in recent years for a number of reasons.

Nonmesocyclonic tornadoes (waterspouts) are relatively common in the fall and winter along the Turkish coastlines, especially the southern and western coastlines of the Mediterranean and Aegean Seas, respectively. In fact, the southern coastline from Antalya to Anamur is likely among the most tornado-prone regions of Europe. Tornadoes in interior Turkey are less common, or at least reported less often. However, Turkey's strongest (and deadliest, despite a relatively low-population density) tornadoes have occurred here, most often in late spring, and are associated with supercells.

The ''next step'' in studying tornadoes in Turkey is to investigate the characteristics of the environments of the tornadic storms, as well as the synoptic-scale and mesoscale processes responsible for the development of the environments.

5.2 Severe Hail in Turkey

Investigating the spatial and temporal distribution of severe hail is a prerequisite for understanding and ultimately predicting the environmental conditions that are favorable for severe hail. Turkey's severe hail climatology reveals that all parts of the country are vulnerable to severe hail ($1.5 cm), and it can occur in any season of the year. The largest hailstones exceed 5 cm in diameter and approach 1 kg in mass. Severe hail in Turkey is most likely in May and June, when severe hail is most likely in the interior of the country, especially in the east. Severe hail is least likely in the winter, though when it occurs in winter, it ismost likely along the southern and western coasts. The afternoon and early evening hours are the most favorable time of the day for severe hail. The long-term variations in Turkish severe hail events (e.g., the 1960s maximum and early 2000s minimum) are worthy of future study.

5.3 Severe storm environments in Turkey

The environments of severe convective storms in Turkey are characterized by larger CAPE on average than severe storm environments in the rest of Europe, probably at least in part because of the lower latitude and proximity to warm water. Turkish severe storm environments have less CAPE than typical U.S. severe storm environments. For deep-layer shear, again Turkish values are lower than those in U.S.. However, less low-level shear and SRH are present in Turkish tornadic supercell environments (and also other categories as well) than in tornadic supercell environments that have been studied in the Europe or the U.S. This finding could be the result of limitations of obtaining proximity soundings from reanalysis data. It can be speculated that Turkey's complex topography might modify the low level winds, creating locally more favorable severe storm environments than the environments depicted in the relatively smooth reanalysis fields, and low-level wind fields might be expected to be particularly susceptible to mischaracterization in the reanalysis datasets.

The LCL in Turkish severe storms environments is similar to the LCL documented in European environments, and LCL in both regions are lower than in U.S. severe storm environments. However, tornadic LCL distributions are narrower than nontornadic distributions. Though the composite parameters EHI and SCP are not as high on average as in the US. (i.e., commonly used U.S. thresholds for such parameters would have to be modified for use in Turkey), EHI and SCP are still useful in segregating supercell (SUP, TOR-sup, HAIL-vlg) and nonsupercell categories (e.g. TOR-non).

5.4 Practical Applications of the Study

The forecasting community as well as researchers in Turkey will benefit from the climatologies of tornadoes and severe hail in Turkey. It is suggested that this study will permit developing new techniques of forecasting severe weather with usage of useful parameters and investigation of how ingredients co-occur in some environments. Insurance sector will also have a threat map for the severe weather events, ultimately analysing the risk regionally and seasonally.

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