4. THE TROPICS—H. J. Diamond and C. J. Schreck, Eds.

a. Overview—H. J. Diamond and C. J. Schreck

The Tropics in 2017 were dominated by neutral El Niño–Southern Oscillation (ENSO) conditions during most of the year, with the onset of La Niña conditions occurring during boreal autumn. Although the year began ENSO-neutral, it initially featured cooler-than-average sea surface temperatures (SSTs) in the central and east-central equatorial Pacific, along with lingering La Niña impacts in the atmospheric circulation. These conditions followed the abrupt end of a weak and short-lived La Niña during 2016, which lasted from the July–September season until late December.

Equatorial Pacific SST anomalies warmed considerably during the first several months of 2017 and by late boreal spring and early summer, the anomalies were just shy of reaching El Niño thresholds for two consecutive, overlapping seasons of April–June and May–July. Thereafter, SSTs cooled through the remainder of the year and exceeded La Niña thresholds during September–November and October–December.

For the global tropics, land and ocean surfaces combined (measured between 20°S and 20°N), the 2017 annual average temperature was 0.31°C above the 1981–2010 average. This makes 2017 the third warmest year for the tropics since records began in 1880, behind only 2016 (+0.55°C) and 2015 (+0.53°C). Precipitation over land for the same latitudes was above the 1981–2010 average for three major datasets (GHCN, GPCC, GPCP), with anomalies ranging from 45 to 125 mm above average. The dataset analyzed for tropical rainfall over the oceans (GPCP; Adler et al. 2003) measured tropical precipitation 14 mm above the 1981–2010 average.

Globally, 85 named tropical storms (TS) were observed during the 2017 Northern Hemisphere storm season and the 2016/17 Southern Hemisphere storm season, as documented in the International Best Tracks Archive for Climate Stewardship (IBTrACS; Knapp et al. 2010). Overall, this number was slightly more than the 1981-2010 global average of 82 TSs. By comparison, Diamond and Schreck (2017) reported 93 named storms for 2016, although that number decreased to 85 after reanalysis. In terms of accumulated cyclone energy (ACE; Bell et al. 2000), the North Atlantic basin had an ACE of about 241% of its 1981-2010 median value and was the only basin that featured an above-normal season. For the North Atlantic, this was the fourth most active season since at least 1950 and the seventh most active season in the historical record (since 1854). The western North

Pacific, South Indian, and Australian basins were all particularly quiet, each having about half their median ACE.

Three tropical cyclones (TCs) reached the Saffir– Simpson scale category 5 intensity level—two in the North Atlantic and one in the western North Pacific basins. This number was less than half of the eight category 5 storms recorded in 2015 (Diamond and Schreck 2016), and was one fewer than the four recorded in 2016 (Diamond and Schreck 2017).

The editors of this chapter would like to insert two personal notes recognizing the passing of two giants in the field of tropical meteorology.

Charles J. Neumann passed away on 14 November 2017, at the age of 92. Upon graduation from MIT in 1946, Charlie volunteered as a weather officer in the Navy's first airborne typhoon reconnaissance unit in the Pacific. Later, as head of research and development at the National Hurricane Center, he developed techniques for statistical tropical cyclone track forecasting, error and risk analysis, and the compilation of a complete set of historical Atlantic hurricane tracks and intensities dating from the 1800s. These data were prototypes for the modern day best track datasets upon which so much of our science relies. Charlie was known for his friendliness and for his generosity in readily sharing data and his expertise, and he was the recipient of numerous national and international awards. Please visit www .hurricanecenterlive.com/charles-newman.html for more information.

Professor Tiruvalam Natarajan Krishnamurti ("Krish" to all who knew and worked with him) passed away on 7 February 2018, at the age of 86. He was Professor Emeritus and Lawton Distinguished Professor of Meteorology at Florida State University's (FSU) Department of Earth, Ocean, and Atmospheric Science. Krish, along with Bill Gray, is considered one of the fathers of modern tropical meteorology. For more than a half-century, Krish was a pioneer in tropical meteorology and numerical weather prediction, including high-resolution forecasting of hurricane tracks, landfall, and intensities; short- and long-range monsoon prediction; and interseasonal and interannual variability of the tropical atmosphere. Krish was the recipient of the highest awards given by both the American Meteorological Society and the World Meteorological Organization.

Both Charlie and Krish will be greatly missed by all who knew and worked with them, as well as for all that they accomplished to advance the science of tropical meteorology.

## ENSO and the tropical Pacific—M. L'Heureux, G. Bell, and M. S. Halpert

The El Niño–Southern Oscillation (ENSO) is a coupled ocean–atmosphere climate phenomenon over the tropical Pacific Ocean, with opposite phases called El Niño and La Niña. For historical purposes, NOAA's Climate Prediction Center (CPC) classifies and assesses the strength and duration of El Niño and La Niña using the Oceanic Niño index (ONI, shown for the last half of 2016 and all of 2017 in Fig. 4.1). The ONI is the 3-month (seasonal) running average of SST anomalies in the Niño-3.4 region ( $5^{\circ}N-5^{\circ}S$ ,  $170^{\circ}-120^{\circ}W$ ) calculated as the departure from the 1986–2015 base period. ENSO is classified as El Niño (La Niña) when the ONI is at or greater than +0.5°C (at or less than -0.5°C) for at least five consecutive, overlapping seasons.

The ONI shows 2017 was ENSO-neutral during most of the year, with the onset of La Niña conditions occurring during boreal autumn. ENSO-neutral conditions at the start of 2017 followed the abrupt end of a short-lived, weak La Niña in 2016. That event lasted from July–September (JAS) until late December 2016 (Bell et al. 2017a).

Although officially ENSO-neutral, 2017 started off cooler relative to average, as reflected by a December–February (DJF) 2016/17 ONI value of -0.3°C. Also, La Niña's atmospheric impacts lingered into 2017. However, the equatorial Pacific continued to warm, and by late boreal spring and early summer the ONI increased to +0.4°C (just shy of El Niño thresholds) for two consecutive, overlapping seasons of April–June (AMJ) and May–July (MJJ). Thereafter, the ONI decreased through the remainder of the year, exceeding thresholds for La Niña during September–



Fig. 4.1. Time series of the ONI (°C) during the last half of 2016 and all of 2017. Overlapping, 3-month seasons are labeled on the x-axis. Values less than -0.5°C are shaded blue, indicating La Niña conditions. ONI values are derived from the ERSSTv5 dataset and are based on departures from the 1986–2015 monthly means. (Huang et al. 2017).

November (SON; -0.7°C) and October–December (OND; -0.9°C).

#### I) OCEANIC CONDITIONS

Figures 4.2b,h further illustrate that 2017 was bookended by below-average SSTs in the east-central equatorial Pacific Ocean. Yet it was only in the last season (SON 2017) that La Niña appeared, as the negative SST anomalies expanded and strengthened from the international dateline to coastal South America (Figs. 4.2g,h). In contrast, the rest of the year was more clearly ENSO-neutral, with near-average SSTs evident across much of the central and eastern Pacific Ocean (and above-average SSTs persisting in the western Pacific Ocean; Figs. 4.2c-f). The primary exception to this pattern occurred near coastal South America during DJF and March-May (MAM, Fig. 4.2d) 2017, when above-average SSTs emerged and became quite intense. This warming is indicative of a so-called "coastal El Niño" (Takahashi and Martínez 2017; see Sidebar 7.2). During February-April 2017 the SST anomalies exceeded +2.5°C and were accompanied by damaging rainfall and flooding in Peru (L'Heureux 2017; Di Liberto 2017).

Consistent with the overall equatorial SST evolution, subsurface temperatures east of the dateline were generally near average most of the year (Fig. 4.3), with a broad stretch of negative anomalies becoming evident with the onset of La Niña (Fig. 4.3d). West of the dateline, the positive SST anomalies evident for much of the year were accompanied by higher subsurface temperatures and a deeper-than-average oceanic thermocline. However, these positive subsurface anomalies weakened as the year went on, and the thermocline began to shoal in the eastern Pacific in association with a developing La Niña.

2) ATMOSPHERIC CIRCULATION: TROPICS AND SUBTROPICS Consistent with the average to below-average SSTs in the east-central equatorial Pacific, atmospheric anomalies during both DJF 2016/17 and SON 2017 were La Niña-like (Figs. 4.4, 4.5). Tropical convection (as measured by outgoing longwave radiation) was enhanced over Indonesia and suppressed over the central Pacific Ocean during these two seasons (Figs. 4.4a,d; 4.5a,d), with some evidence for weak La Niña impacts lingering into MAM 2017 (Figs. 4.4b, 4.5b). Correspondingly, the low-level (850-hPa) wind anomalies over the western and central tropical Pacific were easterly in both periods, which indicated a strengthening of the trade winds (Figs. 4.4a,b,d).

The associated upper-level (200-hPa) winds over the central tropical Pacific in both hemispheres indi-



Fig. 4.2. Seasonal SST (left) and anomaly (right) for (a),(b) DJF 2016/17; (c),(d) MAM 2017; (e),(f) JJA 2017; and (g),(h) SON 2017. Contour interval for seasonal SST is 1°C. For anomalous SST, contour interval is 0.5°C for anomalies between  $\pm 1$ °C, and 1°C for anomalies >  $\pm 1$ °C. Anomalies are departures from the 1981–2010 seasonal adjusted OI climatology (Reynolds et al. 2002).



FIG. 4.3. Equatorial depth-longitude section of Pacific Ocean temperature anomalies (°C) averaged between 5°N and 5°S during (a) DJF 2016/17, (b) MAM 2017, (c) JJA 2017, and (d) SON 2017. The 20°C isotherm (thick solid line) approximates the center of the oceanic thermocline. The data are derived from an analysis system that assimilates oceanic observations into an oceanic general circulation model (Behringer et al. 1998). Anomalies are departures from the 1981–2010 monthly means.



Fig. 4.4. Anomalous 850-hPa wind vectors and speed (contour interval is 2 m s<sup>-1</sup>) and anomalous OLR (shaded, W m<sup>-2</sup>) during (a) DJF 2016/17, (b) MAM 2017, (c) JJA 2017, and (d) SON 2017. Reference wind vector is below right of color bar. Anomalies are departures from the 1981–2010 monthly means.

cated enhanced mid-Pacific troughs flanking the region of suppressed convection near the dateline (Figs. 4.5a,d). The resulting anomalous cross-equatorial flow near the dateline, flowing from the Southern Hemisphere tropics into the Northern Hemisphere, was especially prominent during DJF (Fig. 4.5a). However, the upper-level winds were anomalously westerly over the central tropical Pacific only during SON 2017, which indicates that the broader, overturning Pacific Walker circulation was enhanced only late in the year (Fig. 4.5d).

In the Northern Hemisphere, a La Niña-like anomalous 500-hPa height anomaly pattern was evident both early (DJF) and late (SON) in the year (see Online Figs. S4.1 and S4.2). In particular, both periods featured an anomalous ridge over the North Pacific Ocean in association with a retracted East Asian jet stream. Downstream of the ridge, anomalous troughing occurred over western Canada while an anomalous ridge was apparent over the southern contiguous United States. This teleconnection pattern, with three centers of action over the Pacific– North American region, is indicative of La Niña–like forcing from the tropical Pacific.

c. Tropical intraseasonal activity—S. Baxter, C. Schreck, and
G. D. Bell

In the atmosphere, tropical intraseasonal variability was prominent throughout the year, alternating between constructive and destructive interference with the background low-frequency state. Two aspects of this intraseasonal variability are the Madden–Julian Oscillation (MJO; Madden and Julian 1971, 1972, 1994; Zhang 2005), and convectively coupled equatorial waves which include equatorial Rossby waves and atmospheric Kelvin waves (Wheeler and Kiladis 1999; Kiladis et al. 2009). There were three distinct periods of MJO activity during 2017 spanning a total of eight months (Fig. 4.6). Between the first two active MJO periods, intraseasonal variability reflected



FIG. 4.5. Anomalous 200-hPa wind vectors and speed (contour interval is 4 m s<sup>-1</sup>) and anomalous OLR (shaded, W m<sup>-2</sup>) during (a) DJF 2016/17, (b) MAM 2017, (c) JJA 2017, and (d) SON 2017. Reference wind vector is below right of color bar. Anomalies are departures from the 1981–2010 period monthly means.



FIG. 4.6. Time-longitude section for 2017 of 5-day running anomalous 200-hPa velocity potential (×  $10^6 \text{ m}^2 \text{s}^{-1}$ ) averaged for  $5^\circ \text{N}-5^\circ \text{S}$ , from NCEP-NCAR reanlysis (Kalnay et al. 1996). For each day, the period mean is removed prior to plotting. Green (brown) shading highlights likely areas of anomalous divergence and rising motion (convergence and sinking motion). Red lines and labels highlight the periods when the MJO was most active; solid (dashed) lines indicate the MJO enhanced (suppressed) phase. Anomalies are departures from the 1981–2010 base period daily means.

atmospheric Kelvin waves (Fig. 4.7) and tropical cyclone activity. Between the latter two active MJO periods, intraseasonal variability largely reflected the evolution to La Niña.

The MJO is a leading intraseasonal climate mode of tropical convective variability. Its convective anomalies often have a similar spatial scale to ENSO but differ in that they exhibit a distinct eastward propagation and generally traverse the globe in 30–60 days. The MJO affects weather patterns around the globe (Zhang 2013), including monsoons (Krishnamurti and Subrahmanyam 1982; Lau and Waliser 2012), tropical cyclones (Mo 2000; Frank and Roundy 2006; Camargo et al. 2009; Schreck et al. 2012), and extratropical circulations (Knutson and Weickmann 1987; Kiladis and Weickmann 1992; Mo and Kousky



Fig. 4.7. Time-longitude section for 2017 of anomalous OLR (W m<sup>-2</sup>) averaged for 10°N-10°S (Lee 2014). Negative anomalies indicate enhanced convection and positive anomalies indicate suppressed convection. Contours identify anomalies filtered for the MJO (black), atmospheric Kelvin waves (red), and Rossby waves (blue). Red labels highlight the main MJO episodes. Contours are drawn at  $\pm 12$  W m<sup>-2</sup>, with the enhanced (suppressed) convective phase of these phenomena indicated by solid (dashed) contours. Anomalies are departures from the 1981–2010 base period.

1993; Kousky and Kayano 1994; Kayano and Kousky 1999; Cassou 2008; Lin et al. 2009; Riddle et al. 2013; Schreck et al. 2013; Baxter et al. 2014). The MJO is often episodic, with periods of moderate or strong activity sometimes followed by little or no activity. The MJO tends to be most active during ENSOneutral and weak ENSO periods. The MJO is often absent during strong El Niño events (Hendon et al. 1999; Zhang and Gottschalck 2002; Zhang 2005), though the strong El Niño winter of 2015/16 exhibited unusually strong MJO activity (Baxter et al. 2017).

Common metrics for identifying the MJO include time-longitude plots of anomalous 200-hPa velocity potential (Fig. 4.6) and anomalous outgoing longwave radiation (OLR; Fig. 4.7), as well as the Wheeler-Hendon (2004) Real-time Multivariate MJO (RMM) index (Fig. 4.8). In the time-longitude plots, the MJO exhibits eastward propagation from upper left to lower right. In the RMM, the MJO propaga-



Fig. 4.8. Wheeler-Hendon (2004) Real-time Multivariate MJO (RMM) index during 2017 for (a) Jan-Mar, (b) Apr-Jun, (c) Jul-Sep, and (d) Oct-Dec. Each point represents the MJO amplitude and location on a given day, and the connecting lines illustrate its propagation. Amplitude is indicated by distance from the origin, with points inside the circle representing weak or no MJO. The eight phases around the origin identify the region experiencing enhanced convection, and counter-clockwise movement reflects eastward propagation.

tion and intensity are seen as large, counterclockwise circles around the origin. When considered together, these diagnostics point to three main MJO episodes during 2017. MJO #1 was a strong episode that began in January and continued into March. MJO #2 was a weak but long-lived signal that began in June and lasted into early September. MJO #3 featured strong MJO activity that began in October and continued through the end of the year.

MJO #1 featured a zonal wave-1 pattern of strong convective anomalies with a periodicity of 30–35 days (Figs. 4.6, 4.8a), which is on the fast end of phase speeds for MJO events. The plot of anomalous velocity potential (Fig. 4.6) shows that the MJO circumnavigated the globe almost twice during this period, and the RMM index (Fig. 4.8a) indicates that the event was strongest in February. The episode ended in March when the convective anomalies became dominated by westward-moving Rossby waves (Fig. 4.7, blue contours). This period was followed during April and May by a series of fast propagating atmospheric Kelvin waves (Fig. 4.7, red contours).

Impacts from MJO #1 included distinct periods with westerly and easterly zonal wind anomalies over the western Pacific, including a significant westerly wind burst (labeled WWB) and a significant easterly trade wind surge (labeled TWS) event (Fig. 4.9a). These conditions produced alternating downwelling and upwelling equatorial oceanic Kelvin waves, the last of which was a downwelling wave whose anomalous warming reached the west coast of South America in early June (Fig. 4.9b).

In the extratropics, MJO #1 may have had impacts over the North Pacific and North America. The 500hPa height anomalies (not shown) featured an extratropical wave train that terminated in an anomalous

ridge over the contiguous United States, a pattern associated with the MJO as it traverses the Maritime Continent (Schreck et al. 2013; Baxter et al. 2014). In the second half of February and early March, however, there was little evidence of an MJO extratropical response over North America.

MJO #2 occurred during June–August, and its wave-1 signal circumnavigated the globe about 1.5 times (Fig. 4.6). The MJO's periodicity during this episode was about 60 days, which is on the slower side of the MJO phase speed envelope. This episode terminated when the anomalous convective pattern became more dominated by tropical cyclone activity and two high-amplitude atmospheric Kelvin waves (Fig. 4.7). The RMM index indicates that MJO #2 was quite weak (Fig. 4.8c). Consequently, its impacts were also weak and limited, with no associated equatorial oceanic Kelvin wave activity and only weak linkages



Fig. 4.9. (a) Time-longitude section for 2017 of anomalous 850-hPa zonal wind (m s<sup>-1</sup>) averaged over 10°N-10°S from CFSR (Saha et al. 2014). Black contours identify anomalies filtered for the MJO. Red labels highlight the main MJO episodes. Significant westerly wind bursts and trade wind surges (TWS) that resulted in notable downwelling and upwelling oceanic Kelvin waves are labeled. (b) Time-longitude section of the anomalous equatorial Pacific Ocean heat content for 2017, calculated as the mean GODAS temperature anomaly at 0-300-m depth (Behringer et al. 1998). Yellow/red (blue) shading indicates above- (below-) average heat content. The relative warming (dashed lines) and cooling (dotted lines) due to downwelling and upwelling equatorial oceanic Kelvin waves are indicated. Anomalies are departures from the 1981-2010 base period pentad means.

to Northern Hemisphere TC activity. This MJO may have played a role in enhancing the eastern North Pacific TC activity during July and in suppressing that basin's TC activity during August (see Section 4f3).

MJO #3 was a period of strong MJO activity that began during October and persisted through the end of the year, making nearly two passes around the globe. The average periodicity was about 45 days, but the propagation slowed with time: the first MJO circumnavigation of the globe took about 30 days, while the second took almost twice that (Fig. 4.6).

This episode had several notable impacts. First, it was in phases 5–7 during most of October (Fig. 4.8d), which are generally less favorable phases for Atlantic hurricane activity. Therefore, it may have played a role in the October activity being closer to climatology after a record-breaking September, despite La Niña conditions which typically favor late-season Atlantic hurricane activity (Klotzbach et al. 2017). Second, the MJO's strong WWB west of the dateline in December (Fig. 4.9a) triggered a downwelling equatorial oceanic Kelvin wave that led to warming of the upper ocean by late December (Fig. 4.9b). Third, this MJO likely played a role in modulating the relative strength and position of anomalous upper-level ridging over the North Pacific and, in turn, supporting cold air outbreaks over east-central North America during late December 2017 and early January 2018 (L'Heureux 2018).

Within the equatorial Pacific Ocean itself, two key aspects of intraseasonal variability during 2017 were likely not related to the MJO. The first was the rapid development during August, and the subsequent persistence, of negative upper-ocean heat content anomalies across the eastern half of the Pacific basin. This evolution reflected the developing La Niña. The second was additional strengthening of those negative anomalies from mid-September to

mid-November in response to an upwelling equatorial oceanic Kelvin wave. This upwelling wave was associated with a trade wind surge event in September over the far western Pacific (Fig. 4.9a).

#### d. Intertropical convergence zones

#### I) PACIFIC—A. B. Mullan

Tropical Pacific rainfall patterns are dominated by two convergence zones, the intertropical convergence zone (ITCZ) and the South Pacific convergence zone (SPCZ), both of which are strongly influenced by ENSO and longer time-scale variations (Schneider et al. 2014; Vincent 1994; Folland et al. 2002). Figure 4.10 summarizes the convergence zone behavior for 2017 using rainfall patterns rather than cloudiness, and it allows comparison of the 2017 seasonal variation against the longer-term 1998-2016 climatology. Rainfall transects over 20°N to 30°S are presented for each quarter of the year, averaged across successive 30-degree longitude bands, starting in the western Pacific at 150°E-180°. The rainfall is estimated from satellite microwave and infrared data using NOAA's CPC morphing technique (CMORPH; Joyce et al. 2004) and is available at 0.25° resolution.



FIG. 4.10. Rainfall rate (mm day<sup>-1</sup>) from CMORPH analysis during 2017 for (a) Jan–Mar, (b) Apr–Jun, (c) Jul–Sep, and (d) Oct–Dec. The separate panels for 3-month periods show the 2017 rainfall cross-section between 20°N and 30°S (solid line) and the 1998–2016 climatology (dotted line), separately for four 30° sectors from 150°E–180° to 120°–90°W.

The ITCZ lies between 5° and 10°N and is most active during August-December, when it lies at its northernmost position and displays more of an eastnortheasterly tilt. The SPCZ extends diagonally from around the Solomon Islands (10°S, 160°E) to near 30°S, 140°W, and is most active during November-April. As described in Section 4b, 2016 ended with the demise of a weak La Niña and neutral conditions prevailed for most of 2017, with the eventual emergence of another weak La Niña in October. In the first quarter of 2017 (Fig. 4.10a), both the ITCZ and the SPCZ were poleward of their normal positions, likely due to persistence of the weak La Niña conditions of the previous year (Mullan 2017). Thus, island groups close to the equator (e.g., Kiribati and Tokelau) experienced continued dry conditions (www.niwa .co.nz/climate/icu). Conversely, many islands within the Federated States of Micronesia were far enough north of the equator to experience wetter conditions due to the displaced ITCZ (www.weather.gov/peac /update). Please refer to Section 7h2 for more details.

Figure 4.10a also shows that, except west of the dateline, the ITCZ was much weaker than normal across the North Pacific. Figure 4.11 gives an alternative view of the much drier-than-normal conditions that prevailed across most of the tropical Pacific during January–March. The other unusual feature of the convergence zones in this quarter, apparent in

Fig. 4.10a, is what is commonly referred to as the double ITCZ in the far eastern tropical Pacific. The southern branch of the ITCZ is seen during February through April but only in ENSO-neutral or La Niña years. The southern ITCZ was prominent during these months in 2017 (Fig. 4.11) and was one of the strongest since the beginning of the Tropical Rainfall Measuring Mission (TRMM) satellite era [equivalent to 2009, not shown; TRMM has since been replaced by the Global Precipitation Measurement (GPM) satellite in 2014 (Hou et al. 2014)].

The tropical Pacific remained in a neutral ENSO state through April–June and July–September, often with weak but conflicting ENSO

signals in the atmosphere and ocean. For example, conditions at the end of June indicated a negative Southern Oscillation index (i.e., leaning towards El Niño), but large-scale rainfall and convection anomalies showed more intense-than-normal convection and rainfall over large parts of Indonesia, indicative of a La Niña pattern. In general, the ITCZ and SPCZ were near their climatological positions and intensities during this 6-month period, although the SPCZ was somewhat more active than usual at about 10°S during April–June (Fig. 4.10b). Associated with this enhanced convection, SSTs were 0.5°–1.0°C above normal throughout the central and western subtropical South Pacific (see Fig. 4.2d).

In September, the tropical Pacific edged closer to La Niña conditions, with anomalous cooling in the



FIG. 4.11. CMORPH rainfall anomalies over the tropical Pacific for Jan-Mar 2017, as a percentage of the 1998–2016 average. The white areas indicate anomalies within 25% of normal.



FIG. 4.12. CMORPH rainfall rate (mm day<sup>-1</sup>) for Oct-Dec, for each year 1998 to 2017, averaged over the longitude sector  $180^{\circ}$ -150°W. The cross-sections are color-coded according to NOAA's ONI, except for 2017 (a La Niña period) shown in black.

eastern and central tropical Pacific, an increase in the Southern Oscillation index, and more enhanced easterly trade winds in the central and western equatorial Pacific. During the last quarter of 2017, La Niña conditions became more consistent across both atmospheric and oceanic features. The ITCZ and SPCZ remained at their climatological locations west of the dateline; on average, however, both were displaced poleward of their normal positions to the east of the dateline (Fig. 4.10d).

In the central north Pacific (180°-120°W), rainfall was well below normal from the equator to the latitude where the ITCZ rainfall peaked (about 8°-9°N as depicted in Fig. 4.10d). In the 180°-150°W sector, the latitude of peak rainfall matched well with previous La Niña events, but the intensity was the lowest since the beginning of the TRMM satellite record. Figure 4.12 shows the south-north rainfall transect of Fig. 4.10d, except that every year from 1998 is shown, color-coded according to NOAA's Oceanic Niño index. October-December 2017, classified as a La Niña quarter, is highlighted separately in black. Although rainfall north of the equator was unusually weak for a La Niña, conditions along the equator and southwards followed the expected La Niña behavior. Islands near the equator (e.g., Nauru and all the Kiribati groups) thus continued the dry conditions they had experienced since the weak La Niña at the end of 2016. In the Southern Hemisphere during October-December, the SPCZ matched well with past La Niña periods with respect to both intensity and latitudinal location (Fig. 4.12).

#### 2) ATLANTIC-A. B. Pezza and C. A. S. Coelho

The Atlantic ITCZ is a well-organized convective band that oscillates approximately between 5°–12°N during July–November and 5°N–5°S during January– May (Waliser and Gautier 1993; Nobre and Shukla

1996). Equatorial atmospheric Kelvin waves can modulate the ITCZ intraseasonal variability (Guo et al. 2014). ENSO and the southern annular mode (SAM) also influence the ITCZ on the interannual time scale (Münnich and Neelin 2005). The SAM is typically positive during La Niña events, and it was generally so in 2017 (from April onwards) when the equatorial Pacific started to anomalously cool from ENSO neutral (Fig. 4.13a) to a La Niña state (Fig. 4.13b). The SAM is the primary pattern of climate variability in the Southern Hemisphere (Marshall 2003; Thompson et al. 2011), influencing latitudinal rainfall distribution and temperatures from the subtropics to Antarctica. The station-based index of the SAM is based on the zonal pressure difference between the latitudes of 40°S and 65°S. As such, the SAM index measures a "see-saw" of atmospheric mass between the middle and high latitudes of the Southern Hemisphere (Marshall 2003). A positive SAM value can be indicative of a number of things; for instance, a positive SAM coupled with La Niña conditions may lead to increased extratropical cyclone transition of tropical cyclones across or toward New Zealand (Diamond and Renwick 2015).



Fig. 4.13. Spatial distribution global SST anomalies (°C; Reynolds et al. 2002) for (a) Jan-Apr and (b) Sep-Dec 2017.

While in principle this reversal toward the cool ENSO phase would tend to favor the Atlantic ITCZ moving south, in reality the change occurred too late in the ITCZ's southern migration season in order to have a positive effect on the rainy season in northeastern Brazil, even though overall the ITCZ was very active over the ocean. For the most part an enhanced South Atlantic anticyclone, increased trade winds, and relatively warmer waters north of the equator prevailed. This was accompanied by a mostly negative South American sector (SA) index, although not so pronounced as in some previous years (Fig. 4.14a). The SA index, as defined in Fig. 4.14, is given by the



Fig. 4.14. (a) Monthly OISST (Smith et al. 2008) anomaly time series averaged over the South American sector (SA region, 5°S-5°N, 10°-50°W) minus the SST anomaly time series averaged over the North Atlantic sector (NA region, 5°-25°N, 20°-50°W) for 2013–17, forming the Atlantic index. Positive phase of the index indicates favorable conditions for enhanced Atlantic ITCZ activity. (b) Atlantic ITCZ position inferred from OLR (Liebmann and Smith 1996) during May 2017. Colored thin lines indicate the approximate position for the six pentads of the month. Black thick line indicates the Atlantic ITCZ climatological position for May. The SST anomalies (°C) for May 2017 based on the 1982-2016 climatology are shaded. The two boxes indicate the areas used for the calculation of the Atlantic index in (a).



FIG. 4.15. Observed 2017 precipitation anomalies (mm day<sup>-1</sup>) for tropical and subtropical South America during (a) Jan-May and (b) Jun-Dec. Anomalies calculated based on the 1998-2016 climatology derived from CMORPH (Joyce et al. 2004).

SST south of the equator minus the SST north of the equator over key areas of ITCZ influence. The ITCZ tends to shift toward the warmer side of this gradient. Indeed, it was generally north of its climatological position for most of 2017, especially in May when it is typically at its southernmost location (Fig. 4.14b).

As discussed above, the overall convection was active over the ocean, and although northeastern Brazil remained dry, the eastern Amazon region (Para state) had above-normal precipitation during the wet season (Fig. 4.15a). The ITCZ remained active for the remainder of the year, mostly over the ocean, as La Niña developed (Fig. 4.15b).

#### e. Global monsoon summary—B. Wang

The global monsoon (GM) is the dominant mode of annual variations of tropical–subtropical precipitation and circulation (Wang and Ding 2008) and thus a defining feature of seasonality and a major mode of variability of Earth's climate system. Figure 4.16 summarizes the monsoon rainfall anomalies for both the SH summer monsoon (SHSM) from November 2016 to April 2017 and the NH summer monsoon (NHSM) from May to October 2017.

Global land monsoon precipitation is strongly influenced by the status of ENSO, especially the land areas of Asia, Australia, northern Africa, and Central



Fig. 4.16. Precipitation anomalies (mm day<sup>-1</sup>) averaged for (a) northern winter season: Nov 2016–Apr 2017 and (b) northern summer: May–Oct 2017. The red lines outline the global monsoon precipitation domain defined by (a) annual range (local summer minus winter) precipitation exceeding 300 mm and (b) summer mean precipitation >55% of the total annual precipitation amount (Wang and Ding 2008). Here the local summer denotes May–Sep for the NH and Nov–Mar for the SH. Precipitation indices for each regional monsoon are defined by the areal mean precipitation in the corresponding rectangular regions (dashed blue boxes), which are highly correlated with the precipitation averaged over the corresponding real regional monsoon domains (see Table 4.1). Rainfall data were taken from the Global Precipitation Climatology Project (GPCP; Huffman et al. 2009). Note that the threshold of 300 mm excludes a small latitudinal band of the monsoon in the Sahel.

America (Wang et al. 2012). As documented in Fig. 4.1 for this year, the equatorial Pacific SSTs evolved from a weak La Niña from NDJ to a neutral state, then toward another weak La Niña during SON. Figure 4.16 indicates that the monsoon precipitation anomalies are generally in normal states with a few individual regions slightly positive, consistent with the near-neutral ENSO SST anomalies. Figure 4.17 shows the time series of the monsoon precipitation and low-level circulation indices for each regional monsoon. Note that the precipitation indices represent the total amount of precipitation over both land and ocean. The definitions of circulation indices for each monsoon region are shown in Table 4.1. The precipitation and circulation indices together represent the strength of each regional monsoon system.

During the SH summer (November 2016–April 2017), global precipitation exhibited a pattern consistent with the decay of a weak La Niña (averaged ONI = -0.2): suppressed



Fig. 4.17. Normalized summer mean precipitation (green) and circulation (red) indices in each of eight regional monsoon regions (see Table 4.1). Indices are normalized by their corresponding std. dev. Numbers shown in the corner of each panel denote the correlation coefficient between seasonal mean precipitation and circulation indices. Dashed lines indicate std. dev. of  $\pm 0.5$ . Here the summer denotes May-Oct for the NH and Nov-Apr for the SH. [Source: GPCP for precipitation; Upper air indices as described in Yim et al. (2014).]

TABLE 4.1. (Modified from Yim et al. 2013). Definition of the regional summer monsoon circulation indices and their correlation coefficients (CCs) with the corresponding regional summer monsoon precipitation indices for the period 1979–2015. All circulation indices are defined by meridional shear of zonal winds at 850 hPa which measures the intensity (relative vorticity) of the monsoon troughs at 850 hPa except the northern African (NAF) and East Asian (EA). The NAF monsoon circulation index is defined by the westerly monsoon strength: U850 (0°–15°N, 60°–10°W) and the EASM circulation index is defined by the meridional wind strength: V850 (20°–40°N, 120°–140°E) which reflects the east–west thermal contrast between the Asian continent and western North Pacific. The precipitation indices are defined by the areal mean precipitation over the blue box regions shown in Fig. 4.18. The correlation coefficients were computed using monthly time series (148 summer months) [Jun–Sep (JJAS) in NH (1979–2015) and Dec–Mar (DJFM) in SH (1979/80–2015/16]. The bolded numbers represent significance at 99% confidence level.

Region	Circulation Index Definition	сс
Indian (ISM)	U850 (5°–15°N, 40°–80°E) minus U850 (25°–35°N, 70°–90°E)	0.71
Western North Pacific (WNPSM)	U850 (5°–15°N, 100°–130°E) minus U850 (20°–35°N, 110°–140°E)	0.78
East Asian (EASM)	V850 (20°–40°N, I20°–I40°E)	0.73
North American (NASM)	U850 (5°–15°N, 130°–100°W) minus U850 (20°–30°N, 110°–80°W)	0.84
Northern African (NAFSM)	U850 (0–15°N, 60°–10°W)	0.72
South American (SASM)	U850 (5°–20°S, 70°–40°W) minus U850 (20°–35°S, 70°–40°W)	0.77
Southern African (SAFSM)	U850 (0°–15°S, 10°–40°E) minus U850 (10°–25°S, 40°–70°E)	0.55
Australian (AUSSM)	U850 (0°–15°S, 90°–130°E) minus U850 (20°–30°S, 100°–140°E)	0.89

precipitation over the Pacific ITCZ and southern Indian Ocean convergence zone, and increased precipitation over the Maritime Continent and adjacent regions (Fig. 4.16a). As a result, the Australian summer monsoon region received slightly more precipitation than normal, and the strength of the corresponding circulation was also above normal (Fig. 4.17h). The southern African summer monsoon precipitation and circulation were near normal (Fig. 4.17f), while the South American monsoon shows slightly belowaverage intensity in both precipitation and circulation (Fig. 4.17g). Overall, the SH summer monsoon during November 2016 to April 2017 was normal.

During the NH summer (May–October) of 2017, ENSO was neutral (average ONI = 0.0) and global precipitation also tended to be near normal, as did overall NH summer monsoon precipitation (Fig. 4.16b). On regional scales, the summer precipitation over India, East Asia, and western North Pacific were all near normal (Figs. 4.17a–c), while precipitation was above normal over the North American monsoon region and slightly above normal over the northern African monsoon region (Figs. 4.17d,e).

## f. Tropical Cyclones

I) OVERVIEW-H. J. Diamond and C. J. Schreck

The IBTrACS dataset comprises historical TC best-track data from numerous sources around the globe, including all of the WMO Regional Specialized Meteorological Centers (RSMC; Knapp et al. 2010). IBTrACS represents the most complete compilation of global TC data. From these data, Schreck et al. (2014) compiled climatological values of TC activity for each basin for 1981–2010 using both the WMO RSMCs and the Joint Typhoon Warning Center (JTWC). These values are referenced in each subsection.

The tallying of the global TC numbers is challenging and involves more than simply adding up basin totals, because some storms cross TC basin boundaries, some TC basins overlap, and multiple agencies are involved in tracking and categorizing TCs. Compiling the activity using preliminary IBTrACS data over all seven TC basins (Fig. 4.18), the 2017 season (2016/17 in the Southern Hemisphere) had 85 named storms (wind speeds  $\geq$  34 kt or 17 m s<sup>-1</sup>). This number matches the post-analysis 2016 total (Diamond and Schreck 2017) and is slightly above the 1981–2010



Fig. 4.18. Global summary of TC tracks overlaid on the associated OISST anomalies (°C) for the 2017 season relative to 1982-2010.

average of 82 (Schreck et al. 2014). The 2017 season also featured 41 hurricanes/typhoons/cyclones (HTC; wind speeds  $\geq$  64 kt or 33 m s<sup>-1</sup>), which is below the 1981–2010 average of 46 HTCs (Schreck et al. 2014). Twenty storms reached major HTC status during the 2017 season (wind speeds  $\geq$  96 kt or 49 m s<sup>-1</sup>), which is near the long-term average of 21 and is six fewer than the post-analysis 26 HTCs recorded in 2016 (Diamond and Schreck 2017).

In Sections 4f2–4f8, the 2017 seasonal activity is described and compared to the historical record for each of the seven WMO-defined hurricane basins. For simplicity, all counts are broken down by the United States' Saffir–Simpson scale. The overall picture of global TCs during 2017 is shown in Fig. 4.18 and actual counts by category are documented in Table 4.2. The North Atlantic hurricane season was above normal in both storm numbers and intensity (Section 4f2). In fact, it was the only basin globally that featured above-normal accumulated cyclone energy (ACE). The central and eastern North Pacific hurricane season was well below normal for number of storms (Section 4f3). The western North Pacific had less than half of its normal annual ACE, and the Southern Hemisphere had one of its quietest TC seasons on record, particularly with respect to ACE (Sections 4f6–8).

Globally, only three storms during the year reached Saffir-Simpson category 5

strength (wind speeds  $\geq$  137 kt or 70.5 m s<sup>-1</sup>), which is one less than in 2016 and five fewer than in 2015. The three 2017 storms were Hurricanes Irma and Maria in the North Atlantic and Super Typhoon Noru in the western North Pacific. Sidebars 4.1 and 4.3 detail the records set and devastating local impacts of Irma and Maria, respectively.

Several other Saffir–Simpson category 3 and 4 intensity level systems during 2017 also had major impacts, including: (1) Hurricane Harvey in the North Atlantic, (2) Typhoons Tembin and Hato in the western North Pacific, and (3) Tropical Cyclone Debbie in the Australian basin. Also noteworthy was the development of Tropical Cyclone Donna in the southwest Pacific basin in early May 2017, a date which is outside of the formal TC season for that basin. Donna became the most intense TC recorded in that basin during the month of May.

TABLE 4.2. Global tropical cyclone counts by basin in 2017.								
Basin	TDs	TSs	HTCs	Major HTCs	SS Cat 5	ACE (× 10 <sup>4</sup> kt <sup>2</sup> )		
North Atlantic	18	17	10	6	2	225		
Eastern North Pacific	20	18	9	4	0	97		
Western North Pacific	35	26	12	4	I	150		
North Indian	4	4	2	I	0	15		
South Indian	5	5	2	I	0	28		
Australian Region	8	8	3	3	0	30		
Southwest Pacific	7	7	3	I	0	35		
Totals	98	85	41	20	3	580		

- 2) ATLANTIC BASIN—G. D. Bell, E. S. Blake, C. W. Landsea, S. B. Goldenberg, and R. J. Pasch
- (i) 2017 Seasonal activity

The 2017 Atlantic hurricane season produced 17 named storms, of which 10 became hurricanes and 6 of those became major hurricanes (Fig. 4.19a). The HURDAT2 30-year (1981–2010) seasonal averages are 11.8 tropical (named) storms, 6.4 hurricanes, and 2.7 major hurricanes (Landsea and Franklin 2013).

The 2017 seasonal ACE value (Bell et al. 2000) was about 241% of the 1981–2010 median (92.4  $\times$  10<sup>4</sup> kt<sup>2</sup>; Fig. 4.19b). This value is well above NOAA's thresholds for an above-normal season (120%) and an extremely active season (165%), www.cpc.ncep .noaa.gov/products/outlooks/background \_information.shtml.

This ACE value makes 2017 the most active season since 2005, and the first extremely active season since 2010. It also makes 2017 the fourth most activeseason



FIG. 4.19. Seasonal Atlantic hurricane activity during 1950-2017 based on HURDAT2 (Landsea and Franklin 2013). (a) Number of named storms (green), hurricanes (red), and major hurricanes (blue), with 1981-2010 seasonal means shown by solid colored lines. (b) ACE index expressed as percent of the 1981-2010 median value. ACE is calculated by summing the squares of the 6-hourly maximum sustained surface wind speed (knots) for all periods while the storm is at least tropical storm strength. Red, yellow, and blue shadings correspond to NOAA's classifications for above-, near-, and below-normal seasons, respectively (www .cpc.ncep.noaa.gov/products/outlooks/background information.shtml). The thick red horizontal line at 165% ACE value denotes the threshold for an extremely active season. Vertical brown lines separate high- and low-activity eras.

since at least 1950 and the seventh most active season in the historical record (since 1854). However, it should be noted that reliable basin-wide records for exact season-to-season comparisons with ACE began in the mid-1970s with the advent of the geostationary satellite era (Landsea et al. 2006).

The occurrence of above-normal and extremely active seasons shows a strong multidecadal signal. The 2017 season is the 15th above-normal season and the 9th extremely active season since the current high-activity era for Atlantic hurricanes began in 1995. The previous Atlantic high-activity era (1950–70) also featured numerous above-normal and extremely active seasons. In stark contrast, the intervening low-activity era of 1971–94 featured only two above-normal seasons, and none were extremely active (Goldenberg et al. 2001).

#### (ii) Storm formation regions, tracks, and landfalls

A main delineator between above-normal and below-normal Atlantic hurricane seasons is the number of hurricanes and major hurricanes that develop from storms that are named while in the main development region (MDR, green boxed region in Fig. 4.21a) spanning the tropical Atlantic Ocean and Caribbean Sea between 9.5° and 21.5°N (Goldenberg and Shapiro 1996; Goldenberg et al. 2001; Bell and Chelliah 2006). When activity is high in the MDR, overall seasonal TC activity and ACE are also high. The vast majority of storms which form within the MDR do so during the peak months (August-October, ASO) of the season. This peaked climatology is why seasonal hurricane predictions are essentially based on predictions for ASO of the atmospheric and oceanic conditions within the MDR (Goldenberg and Shapiro 1996; Klotzbach et al. 2017).

During 2017, seven of the ten Atlantic hurricanes and five of the six major hurricanes first became named storms during ASO in the MDR. For the season as a whole, MDR-originating storms produced an ACE of 212% of the 1981–2010 median and accounted for 86% of the total season's ACE. The strongest and longest-lived MDR storm of the season was Major Hurricane Irma, which developed in late August and by itself produced an ACE value of 77.5% of the 1981–2010 median. Only one storm in the satellite record since 1966 (Major Hurricane Ivan in 2004) produced a larger ACE.

Extremely active seasons have a higher frequency of landfalling tropical storms, hurricanes, and major hurricanes. During 2017, there were 13 separate storm landfalls for the basin as a whole. This count reflects ten distinct named storms, of which six formed in the MDR. These six MDR storms include all three landfalling major hurricanes and two of the three (excluding Nate which formed in the extratropics) landfalling non-major hurricanes.

Six named storms struck the United States during 2017, including three catastrophic major hurricanes (Harvey in Texas, Irma in Florida, and Maria in Puerto Rico and the U.S. Virgin Islands), one nonmajor hurricane (Nate in Louisiana/ Mississippi), and two tropical storms (Cindy in Texas and Emily in Florida). Harvey was the first continental U.S. landfalling major hurricane since Wilma struck Florida in October 2005.

From a historical perspective, 86% (12 of 14 seasons) of extremely active seasons during 1950-2017 featured at least two continental U.S. landfalling hurricanes (Fig. 4.20a). This rate far exceeds the 50% rate (7 of 14 seasons) for above-normal seasons that were not extremely active and is almost triple the rate (30%, 6 of 20 seasons) for near-normal seasons. Only 5% (1 of 20 seasons) of the below-normal seasons since 1950 produced multiple continental U.S. landfalling hurricanes. Similarly, 71% (10 of 14 seasons) of extremely active seasons since 1950 featured at least one major hurricane landfall in the continental U.S (Fig. 4.20b). This is more than double the 31% rate (17 of 54 seasons) of landfalling major hurricanes for all other seasons combined. Interestingly, about 20% of below-normal seasons have had a continental U.S. landfalling major hurricane.



Fig. 4.20. Continental U.S. landfalling hurricane frequencies during 1950–2017 for each of NOAA's season types. (a) Percent of specified season type with at least two U.S. hurricane landfalls, and (b) percent of specified season type with one or more U.S. major hurricane landfall. Above-normal seasons include those labeled "Extremely Active" and "Above Normal Not Extremely Active." Season classifications are shown in www.cpc.ncep.noaa.gov/products/outlooks /background\_information.shtml. Landfall data is based on HURDAT2 (Landsea and Franklin 2013).

The entire region around the Caribbean Sea also typically sees an increased number of hurricane landfalls during extremely active seasons. During 2017, eight named storms struck the region. These included two catastrophic major hurricanes (Irma and Maria), two non-major hurricanes (Franklin and Katia in eastern Mexico), and four tropical storms (Bret in Trinidad and Venezuela; Harvey in Barbados and St. Vincent; Nate in Central America; and Philippe in Cuba).

# (iii) Atlantic sea surface temperatures

SSTs were above average during ASO 2017 across the MDR, the Gulf of Mexico, and much of the extratropical North Atlantic (Fig. 4.21a). The areaaveraged SST anomaly within the MDR was +0.54°C (Fig. 4.21b). The area-averaged SST anomaly within the Caribbean Sea, a subregion of the MDR, was



Fig. 4.21. (a) ASO 2017 SST anomalies (°C). (b),(c) Time series of ASO area-averaged SST anomalies (°C) in (b) the MDR [green box in (a)] and (c) the Caribbean Sea [red box in (a) spanning 60°–87.5°W and 10°–21.5°N]. Red lines in (b) and (c) show a 5-pt. running mean of each time series. Data source is ERSSTv4 (Huang et al. 2015). Anomalies are departures from the 1981–2010 monthly means.

+0.60°C. This departure for the Caribbean Sea was the second highest since 1950 and followed the record warmth of ASO 2016 (Fig. 4.21c).

Historically, when assessing links between Atlantic SSTs and hurricane season strength, it is important to consider their common relationships to largerscale climate patterns. Two key climate patterns are the Atlantic multidecadal oscillation (AMO; Enfield and Mestas-Nuñez 1999; Goldenberg et al. 2001; Bell and Chelliah 2006; Bell et al. 2011, 2012) and ENSO (Gray 1984; Tang and Neelin 2004; Bell and Chelliah 2006). These SST-based phenomena strongly control large-scale atmospheric conditions (such as vertical wind shear, trade winds, moisture, atmospheric stability, etc.) across the MDR, thereby influencing the strength of the hurricane season.

The AMO predisposes the ocean-atmosphere system to be either more or less conducive to Atlantic hurricane activity for periods of 25–40 years at a time. One measure of the AMO is the standardized time series of the detrended Kaplan AMO index (www .esrl.noaa.gov/psd/data/correlation/amon.us .long.data). For ASO 2017, that index was +1.51 standard deviation (std. dev.), indicating the positive (i.e., warm) phase of the AMO. The standardized 7-year running mean (using ASO seasons only) of the detrended Kaplan AMO index for ASO 2017 was +1.75 std. dev. (Fig. 4.22a). Historically, the warm AMO is associated with the Atlantic high activity eras of 1950–70 and 1995–present. Conversely, the Atlantic



FIG. 4.22. SST time series for 1900–2017 based on ERSSTv4 (Huang et al. 2015). (a) Standardized (std. dev.) 7-yr running mean of the detrended Kaplan AMO index based on the ASO season only. (b) Standardized (std. dev.) 7-yr running mean of the difference between ASO area-averaged SST anomalies in the MDR and those for the entire global tropics (20°N–20°S).

low activity eras of 1900–20 and 1971–94 were associated with the negative (i.e., cool) phase of the AMO.

Another complementary measure of the AMO is the standardized 5-year running mean of the difference between the area-averaged SST departure in the MDR and that of the global tropics (Fig. 4.22b, based on Vecchi and Soden 2007). The warm AMO during ASO 2017 featured an anomalously warm MDR compared to the remainder of the global tropics (0.36°C higher), a relationship seen throughout the historical record for active seasons. These observations, combined with the seasonal ACE time series (Fig. 4.19b), suggest that continuation during 2017 of the current Atlantic high-activity era was associated with the ongoing warm phase of the AMO.

Another ocean-atmosphere related factor for the 2017 Atlantic hurricane season was the development of La Niña in October (see Section 4b). La Niña is conducive to a more active Atlantic hurricane season because it reduces the vertical wind shear and decreases the atmospheric stability in the western MDR (Gray 1984; Tang and Neelin 2004). Cool neutral ENSO conditions prevailed during the other two peak months of the season (August and September).

#### (iv) Atmospheric conditions

The atmospheric conditions within the MDR during ASO 2017 reflected an inter-related set of anomalies which are typical of other extremely active seasons (Landsea et al. 1998; Bell et al. 1999, 2000, 2004, 2006, 2009, 2011, 2012, 2014, 2015, 2016; Goldenberg et al. 2001; Bell and Chelliah 2006; Kossin and Vimont 2007). Historically, the combination of a warm AMO and La Niña yields the most spatially extensive set of atmospheric conditions that are conducive for Atlantic hurricane activity, while the combination of El Niño and the cool AMO yields the least conducive conditions (Bell and Chelliah 2006).

In the lower atmosphere, the conducive conditions during ASO 2017 included below-average heights/ sea-level pressure (blue shading, Fig. 4.23a) across the MDR, along with weaker trade winds (i.e., westerly anomalies) extending from the eastern tropical North Pacific across the southern MDR to Africa. These westerly anomalies extended up to 700-hPa, the approximate level of the African easterly jet (AEJ), and were associated with a deep layer of anomalous cyclonic relative vorticity across the entire MDR (Fig. 4.23b). As noted by Bell et al. (2011), the increased cyclonic shear along the equatorward flank of the AEJ helps the easterly waves within the MDR to be better maintained and also provides an inherent cyclonic rotation to their embedded convective cells.



FIG. 4.23. ASO 2017: (a) anomalous 1000-hPa heights (shaded; m); (b) anomalous 700-hPa cyclonic relative vorticity (shaded; × 10<sup>6</sup> s<sup>-1</sup>); (c) 200-hPa total streamfunction (contours, interval:  $5 \times 10^6$  m<sup>2</sup> s<sup>-1</sup>) and anomalies (shaded), from NCEP–NCAR reanalysis (Kalnay et al. 1996). The corresponding anomalous wind vectors (m s<sup>-1</sup>) are shown in each panel. In (b), the thick solid line indicates the axis of the mean African easterly jet which was hand-drawn based on total seasonal wind speeds (not shown). In (c) the upper-level ridge and TUTT discussed in the text are labeled and denoted by thick black lines. Vector scales are below right of color bar. Green box denotes the MDR. Anomalies are departures from the 1981–2010 means.

In the upper atmosphere at 200-hPa, the circulation during ASO 2017 featured an extensive and persistent ridge of high pressure across the western half of the MDR and the western North Atlantic (Fig. 4.23c). This pattern was accompanied by an eastward displacement of the tropical upper tropospheric trough (TUTT) from the western MDR to the central MDR and central North Atlantic. Consistent with this pattern, the upper-level westerly winds were weaker than average (indicated by easterly anomalies)



Fig. 4.24. ASO 2017: 200-850 hPa vertical wind shear magnitude (shaded;  $m s^{-1}$ ) (a) total and (b) anomalies. Overlaid in (a) are the total 200-hPa streamfunction field (contours, interval:  $5 \times 10^6 \text{ m}^2 \text{ s}^{-1}$ ) and the 200-850 hPa layer mean wind vectors (m s<sup>-1</sup>) representing the steering current. The upper-level ridge and TUTT discussed in the text are labeled and denoted by thick black lines. Vector scale is below right of color bar. Green box denotes the MDR. Data is from NCEP-NCAR reanalysis (Kalnay et al. 1996). Anomalies are departures from the 1981-2010 means on total seasonal wind speeds (not shown). In (c) the upper-level ridge and TUTT discussed in the text are labeled and denoted by thick black lines. Vector scales are below right of color bar. Green box denotes the MDR. Anomalies are departures from the 1981-2010 means.

in the western MDR along the southern flank of the anomalous ridge. The resulting vertical wind shear (Fig. 4.24a) was also weaker than average across the central and western MDR as well as in the vicinity of the Bahamas (Fig. 4.24b).

As a result, weak vertical wind shear (<  $10 \text{ m s}^{-1}$ ) extended across the entire MDR from Africa to Central America, as well as northward over the western North Atlantic (Fig. 4.24a). Also, the associated steering current (Fig. 4.24a, vectors) allowed African easterly waves and named storms to track farther westward into the region of anomalously weak vertical wind shear and exceptionally warm SSTs. These conditions greatly increased the number and strength of the TCs within the MDR, as well as the number of landfalling hurricanes.

The exceptionally strong and persistent ridge over the western Atlantic was a crucial aspect of the 2017 Atlantic hurricane season. Although La Niña technically developed in October, a La Niña–like pattern of tropical convection was already present in September. The rapid response in the upper-level atmospheric circulation to the developing La Niña likely helped maintain that ridge during October–November [a period when two hurricanes (including Major Hurricane Ophelia) and two tropical storms formed] and may have contributed to the September conditions as well.

A pronounced ridge such as this was last seen in association with the record strong 2005 Atlantic hurricane season (Bell et al. 2006). Therefore, while the warm AMO and La Niña set the stage for an extremely active 2017 Atlantic hurricane season, these combined climate factors alone do not likely account for the combined magnitude and duration of the western Atlantic ridge, which is seen less frequently.

# 3) EASTERN NORTH PACIFIC AND CENTRAL NORTH PACIFIC BASINS—M. C. Kruk and C. J. Schreck

#### (i) Seasonal activity

The eastern North Pacific (ENP) basin is officially split into two separate regions for the issuance of warnings and advisories by NOAA's National Weather Service. NOAA's National Hurricane Center in Miami, Florida, is responsible for issuing warnings in the eastern part of the basin (ENP) that extends from the Pacific Coast of North America to 140°W, while NOAA's Central Pacific Hurricane Center in Honolulu, Hawaii, is responsible for issuing warnings in the central North Pacific (CNP) region between 140°W and the dateline. This section summarizes the TC activity in both warning areas using combined statistics, along with information specifically addressing the observed activity and impacts in the CNP region.

The ENP/CNP hurricane season officially spans from 15 May to 30 November. Hurricane and tropical storm activity in the eastern area of the basin typically peaks in September, while in the CNP TC activity normally reaches its seasonal peak in August (Blake et al. 2009). During the 2017 season, a total of 18 named storms formed in the combined ENP/CNP basin (Fig. 4.25a). This total includes 9 hurricanes, 4 of which were major hurricanes. The 1981–2010 IB-TrACS seasonal averages for the basin are 16.5 named storms, 8.5 hurricanes, and 4.0 major hurricanes (Schreck et al. 2014).

The 2017 seasonal ACE index was  $98.5 \times 10^4$  kt<sup>2</sup> (Fig. 4.25b), which is below the 1981–2010 mean of 132.0 × 10<sup>4</sup> kt<sup>2</sup> (Bell et al. 2000; Bell and Chelliah 2006; Schreck et al. 2014). The CNP basin only had



Fig. 4.25. Seasonal TC statistics for the full ENP/CNP basin over the period 1970–2017: (a) number of named storms, hurricanes, and major hurricanes and (b) the ACE index (×  $10^4$  kt<sup>2</sup>) with the 2017 seasonal total high-lighted in red. Horizontal lines denote the corresponding 1981–2010 base period means for each parameter.

one storm in 2017: The remnants of Major Hurricane Fernanda moved from the ENP to the CNP as a weak tropical storm before dissipating around 146°W. The long-term 1981–2010 IBTrACS mean in the CNP basin is 4.7 storms making the 2017 season much below average.

#### (ii) Environmental influences on the 2017 season

Figure 4.26 shows the mean environmental conditions that the ENP and CNP TCs experienced in 2017. The borderline weak La Niña is indicated by the cool SST anomalies along the equatorial eastern Pacific and warm anomalies to the north (Fig. 4.26a). Much of the TC activity was concentrated along the Mexican coast, which is not unusual during La Niña years (Collins and Mason 2000; Fu et al. 2017). The SST anomalies were slightly above normal in that region. Mixing from the storms themselves may have played a role in tempering those anomalies (Hart et al. 2007), but the OLR anomalies (Fig. 4.26b) were also near-normal and suggest weaker-than-normal



FIG. 4.26. May–Nov 2017 anomaly maps of (a) SST (°C; Banzon and Reynolds 2013), (b) OLR (W m<sup>-2</sup>; Lee 2014), (c) 200–850-hPa vertical wind shear (m s<sup>-1</sup>; vectors) and scalar (shading) anomalies, and (d) 850-hPa winds (m s<sup>-1</sup>; vectors) and zonal wind (shading) anomalies. Anomalies are relative to the annual cycle from 1981–2010, except for SST which is relative to 1982–2010 due to data availability. Hurricane symbols with letters denote where each ENP TC attained tropical storm intensity. Wind data obtained from CFSR (Saha et al. 2014).

convection in the region. Weak easterly vertical shear anomalies, on the other hand, did favor the TC activity (Fig. 4.26c). Similarly, a narrow swath of 850-hPa westerly anomalies along 10°–15°N would have provided enhanced cyclonic vorticity, wave accumulation, and/or barotropic energy conversion (Maloney and Hartmann 2001; Aiyyer and Molinari 2008; Rydbeck and Maloney 2014).

ENP TC activity is strongly influenced by the MJO (Maloney and Hartmann 2001; Aiyyer and Molinari 2008; Slade and Maloney 2013), and recent studies have found a greater role for convectively coupled Kelvin waves in modulating tropical cyclogenesis (Schreck and Molinari 2011; Ventrice et al. 2012a,b; Schreck 2015, 2016). Figure 4.27 uses OLR to examine the intraseasonal evolution of convection during the 2017 ENP hurricane season. Following Kiladis et al. (2005, 2009), the black contours identify the MJOfiltered anomalies and the blue contours identify the Kelvin waves. Easterly waves are also apparent in the unfiltered anomalies (shading) as westward moving features, such as those leading up to Tropical Storms Jova and Selma.



FIG. 4.27. Longitude-time Hovmöller of OLR (W m<sup>-2</sup>; Lee 2014) averaged 5°-15°N. Unfiltered anomalies from a daily climatology are shaded. Negative anomalies (green) indicate enhanced convection. Anomalies filtered for Kelvin waves are contoured in blue at -10 W m<sup>-2</sup> and MJO-filtered anomalies in black at ±10 W m<sup>-2</sup>. Hurricane symbols and letters indicate genesis of ENP TCs.

A weak MJO event in early July likely contributed to an active month that included five named storms, including Major Hurricanes Eugene and Fernanda. The subsequent dry phase of the MJO provided the longest break (21 days) between named storm formations from June through September. MJO activity appeared to play less of a role in the remainder of the season. However, Kelvin waves probably enhanced conditions for at least three tropical storms: Lidia, Ramon, and Selma.

### (iii) TC impacts

During the 2017 season, five named storms made landfall along the western coast of Mexico or Baja California, while the one storm in the CNP region did not make landfall in Hawaii. The long-term annual average number of landfalling storms on the western coast of Mexico is 1.8 (Raga et al. 2013); thus this year was exceptional, in part due to the number of storms forming so close to the coast (Fig. 4.26).

Tropical Storm Beatriz (31 May–2 June) was the first storm to make landfall in 2017 along the Mexican coast, followed closely by Tropical Storm Calvin (11–13 June). Both storms brought torrential rainfall and landslides to the Oaxaca and Guerraro areas of coastal Mexico. Beatriz produced localized rainfall of up to 380 mm, and five people were killed when mudslides washed away their homes and vehicles. Additional rainfall from Calvin, while not as extreme as Beatriz, exacerbated relief efforts and compounded the already saturated soils leading to further landslides and mudslides.

Tropical Storm Lidia (31 August-03 September) tracked northwest along the entire Baja Peninsula. While maximum sustained winds were 55 kt (29 m s<sup>-1</sup>), the storm weakened dramatically as it crossed over the mountainous terrain of the Baja Peninsula. The biggest impact from Lidia was heavy rainfall, up to 300 mm in San Jose Del Cabo, resulting in numerous flooded streets and the cancellation of several dozen flights from Mexico City International Airport. In the city of Cuautitlán Izcalli, located in the central state of Mexico, roughly 300 people were evacuated after the nearby El Ángulo dam collapsed, and in Ecatepec de Morelos a nearby canal overflowed, filling many homes with sewage. The wind field from Lidia made a close approach to southern California in the United States, where gusty winds were reported along area beaches.

Hurricane Max (13–15 September) made landfall in areas of the Mexican coastline already plagued by tropical storms earlier in the season. Max briefly intensified to hurricane strength about 12 hours prior to landfall, with maximum sustained winds of 75 kt (39 m s<sup>-1</sup>). The city of Guerraro, flooded by Beatriz and Calvin, was also affected by torrential rains from Max. Two people died as rapidly rising rivers swept away their residence. Meanwhile over the ocean, large waves and swell, with peak wave heights of 3–5 m, sunk six boats before they could return to port.

Tropical Storm Selma (27–28 October) was the final storm of the 2017 season, and the first storm on record to make landfall in El Salvador. When combined with a cold front moving through Honduras, rainfall was widespread across the region, resulting in the overtopping of at least a dozen local rivers.

# 4) WESTERN NORTH PACIFIC BASIN—S. J. Camargo (i) Introduction

The TC season in the western North Pacific (WNP) was below normal by most measures of TC

activity considered. According to the JTWC<sup>1</sup>, the 2017 season had 26 named storms (which is the median). These included 12 typhoons (bottom quartile is  $\leq 14$ ) two of which reached super-typhoon (130 kt, 65 m s<sup>-1</sup>) status (bottom quartile is  $\leq 2$ ). In Fig. 4.28a, the number of each category per season is shown for the period 1945–2017. While the number of tropical storms matched the climatological median, the number of typhoons and supertyphoons was below normal. Only 46% of tropical storms became typhoons (bottom quartile is  $\leq 57\%$ ). Further, the percentage of typhoons reaching supertyphoon intensity (17%) was below normal (median is 24%).

The JMA total for 2017 was 27 named storms (above the median of 26; Fig. 4.28b). Guchol was considered a tropical storm by JMA but only a tropical depression by JTWC. Saola was considered a severe tropical storm by JMA and a typhoon by JTWC<sup>2</sup>. The Philippine Atmospheric, Geophysical, and Astronomical Services Administration named all 22 TCs that entered its area of responsibility, including Tropical Depression Bising (February) which was considered a tropical depression by JMA but was not tracked by JTWC. Only 41% of the storms reached typhoon intensity (bottom quartile is  $\leq$  50%).

#### (ii) Seasonal activity

The season had a slow start, with the first named tropical storm not developing until April (Muifa). No TCs formed in May and only one tropical storm (Merbok) formed in June. In contrast, July was an active month with 8 TCs (top quartile is 5) forming: Tropical Storms Nanmandol, Talas, Sonca, Kulap, Roke, and Haitang; Typhoon Nesat; and Supertyphoon Noru. The two typhoons for July 2017 ranked among the bottom quartile. Four TCs were simultaneously active in the WNP during 21–23 July, 3 with TS strength on

<sup>&</sup>lt;sup>1</sup> The TC data used here are from the Joint Typhoon Warning Center (JTWC) western North Pacific best-track dataset for the 1945–2017 period and from the JTWC preliminary operational data for 2017. Climatology is defined using the period 1981–2010, with exception of landfall statistics, where 1951–2010 was used. The best-track data from the RSMC-Tokyo, Japan Meteorological Agency was used in Fig. 4.28b. All other figures and statistics were obtained using JTWC TC data. All statistics are based on the climatological distribution (CLD), unless specifically stated that is based on the historical record.

<sup>&</sup>lt;sup>2</sup> It is well known that there are systematic differences between the JMA and the JTWC datasets, which have been extensively documented in the literature (e.g., Wu et al. 2006; Nakazawa and Hoshino 2009; Song et al. 2010; Ying et al. 2011; Yu et al. 2012; Knapp et al. 2013; Schreck et al. 2014).



Fig. 4.28. (a) Number of tropical storms (TS), typhoons (TY), and supertyphoons (STY) per year in the western North Pacific (WNP) for the period 1945–2017 based on the JTWC best-track dataset. (b) Number of tropical cyclones (TC; all storms which reach TS intensity or higher) from 1951 to 1976; number of TSs, severe tropical storms (STS) and TY from 1977 to 2017 based on the JMA best-track dataset. Panels (c) and (e) show the cumulative number of tropical cyclones with TS intensity or higher (named storms) and number of TYs, per month in the WNP in 2017 (black line), and climatology (1981–2010) as box plots [interquartile range: box; median: red line; mean: blue asterisk; values in the top or bottom quartile: blue crosses; high (low) records in the 1945–2016 period: red diamonds (circles)]. Panels (d) and (f) show the number of NSs and TYs respectively, per month in 2017 (black line) and the climatological mean (blue line), the blue plus signs denote the maximum and minimum monthly historical records and the red error bars show the climatological interquartile range for each month (in the case of no error bars, the upper and/or lower percentiles coincide with the median. [Sources: 1945–2017 JTWC best-track dataset, 2017 JTWC preliminary operational track data for panels (a) and (c)–(f). 1951–2017 RSMCenter-Tokyo, JMA best-track dataset for panel (b).]

22 and 23 July. August was also an active month with 6 named storms (top quartile is  $\geq$  6): 3 tropical storms (Nalgae, Pakhar, and Mawar) and 3 typhoons (Banyan, Hato, Sanvu), each matching the median for that month. Only 4 TCs (bottom quartile is  $\leq$  4) formed in September: Tropical Depressions Guchol, 22W, and Typhoons Talim and Doksuri, with only two storms reaching tropical storm or typhoon intensity, which is in the bottom quartile for both distributions ( $\leq 4$ and  $\leq$  2.5, respectively). The TC activity increased somewhat in October, with three typhoons (Khanun, Lan, and Saola), in the bottom quartile for named storms ( $\leq$  3) but matching the median for typhoons. Lan was the second storm of the season to reach supertyphoon intensity in the season. In November there were 2 tropical storms (Haiku and Kirogi) and 1 typhoon (Damrey), which ranked in the top quartile for named storms ( $\geq$  3) but in the bottom quartile for typhoons ( $\leq$  1). The 2017 typhoon season concluded with two December TCs: Tropical Storm Kai-Tak and Typhoon Tembin, each in the top quartile for their respective categories.

The early season (January–June) totals (2 tropical storms and no typhoons) were in the bottom quartile of all storm counts ( $\leq$  3 and  $\leq$  1, respectively). In contrast, the peak season (July–October) had 19 named storms (median is 17) and 10 typhoons (median is 12). The late season (November and December) total of 5 named storms and 2 typhoons was in the top quartile for named storms ( $\geq$  4) and equal to the median for typhoons. The overall character of the season was a normal number of TCs, but a low number attaining typhoon intensity, with the greatest TC activity concentrated from July to August.

#### (iii) Environmental conditions

During the peak and latter part of the season, the tropical Pacific SST transitioned from neutral to weak La Niña conditions. The mean genesis location in 2017 was at latitude 15.8°N, longitude 129.9°E, which was a shift northwestward from the climatological mean of latitude 13.2°N, longitude 141.6°E (standard deviation 1.9° latitude and 5.6° longitude. This northwestward shift is typical during La Niña years (e.g., Chia and Ropelewski 2002; Camargo et al. 2007). The mean track position of 19.5°N, 133.7°E was also northwestward relative to the WNP climatological mean of 17.3°N, 136.6°E (standard deviations of 1.4° latitude and 4.7° longitude). Therefore, these shifts were consistent with a La Niña event.

Also consistent with a weak La Niña, the total ACE in 2017 was below normal (Camargo and Sobel 2005), in the bottom quartile, and the eighth lowest

value of seasonal ACE in the historical record (Fig. 4.29a). The only months when ACE was not below the median were April and July; January–March, May, June, September, and November all had ACE values in their respective bottom quartiles. The bulk of the seasonal ACE occurred in July and August (Fig. 4.29b), with those months contributing 25% and 26% of the total ACE respectively, followed by October (21%). The ACE values in September and November were the 9th and 11th lowest for those months in the historical record.

Only 3 typhoons in 2017 were in the top quartile for ACE per storm: Supertyphoons Noru and Lan, and Typhoon Talim, contributing 26.6%, 13.4%, and 10.8% of the seasonal ACE, respectively. Combined, they accounted for just over half of the seasonal ACE. The only storm in the top decile was Supertyphoon Noru. It should be noted that Noru contributed to the



FIG. 4.29. (a) ACE index per year in the western North Pacific for 1945–2017. The solid green line indicates the median for the climatology (1981–2010), and the dashed lines show the climatological 25th and 75th percentiles. (b) ACE index per month in 2017 (black line) and the median during 1981–2010 (blue line), the red error bars indicate the 25th and 75th percentiles. In case of no error bars, the upper and/or lower percentiles coincide with the median. The blue "+" signs denote the maximum and minimum values during the 1945–2016. (Source 1945–2016 JTWC best-track dataset, 2017 JTWC preliminary operational track data.)



FIG. 4.30. (a) SST anomalies (°C) for Jul-Oct (JASO) 2017. (b) Pl anomalies (kt) in JASO 2017. (c) Relative humidity 600-hPa relative humidity anomalies (%) in JASO 2017. (d) GPI anomalies in JASO 2017. First positions of storms in JASO 2017 are marked with an asterisk. (e) Zonal winds in JASO 2017 (positive contours are shown in solid lines, negative contours in dash dotted lines and the zero contour in a dotted line) [Source: atmospheric variables: NCEP/NCAR Reanalysis data (Kalnay et al. 1996); SST (Smith et al. 2008).]

ACE values for both July and August, as it was active from 20 July to 9 August.

There were 85 days with named storms. From these active days, 36 had typhoons and 6 had major typhoons (categories 3–5), all in the bottom quartiles. The percentage of days during the season with typhoons and major typhoons were 28.6% and 4.8%, respectively in the bottom quartile of their distributions ( $\leq$  33% and  $\leq$  10%, respectively). The percentage of major typhoons days is the sixth lowest in the historical record (two of those happened in 1945 and 1948, when the data reliability was much lower). The median lifetime of the 2017 season for named storms and typhoons was 4.5 and 5.6 days, respectively, both in the bottom quartile ( $\leq 6.3$  and  $\leq 7.8$  days). The longest living storm was Supertyphoon Noru, which lasted 19.5 days (20 July–9 August), which places it in the 98th percentile for all WNP named storms since 1945. Tropical Storm Kai-Tak (10.8 days) was the only other WNP named storm in 2017 in the top quartile ( $\geq 10.5$  days). All other storms in 2017 had lifetimes at or below the median. The occurrence of

short-lived storms this season is typical of La Niña years (Camargo and Sobel 2015) and related to the northwest shift of TC activity.

Including tropical depressions, 26 storms made landfall<sup>3</sup> in 2017, ranking in the 95th percentile compared with the 1951–2010 climatology. Of these, 11 made landfall as tropical depressions (second highest in the historical record), 7 as tropical storms (median is 6), 8 as typhoons (top quartile is  $\geq$  7), and none as major typhoons (bottom quartile is  $\leq$  1). Vietnam was hit by 9 storms this season, including Typhoon Damrey, which was the strongest typhoon to make landfall in south-central Vietnam in 16 years, and Typhoon Doksuri which affected the northern and central Vietnam provinces. The median number of landfalls in Vietnam per year is 4.5; 9 landfalls (at any intensity) is in the 90th percentile of the climatological distribution of landfalls there.

Figure 4.30 shows the environmental conditions associated with the typhoon activity in 2017. The main feature is the borderline weak La Niña with below-normal SST anomalies in the eastern and central Pacific during July-October (JASO; Fig. 4.30a) and slightly above normal SST in the WNP. This SST pattern is reflected in other environmental fields, as can be seen in potential intensity (PI; Emanuel 1988; Fig. 4.30b), 600-hPa relative humidity (Fig. 4.30c), and genesis potential index (GPI; Emanuel and Nolan 2004; Camargo et al. 2007; Fig. 4.30d) anomalies, which were positive in the western part of the basin and negative in the eastern part, typical of La Niña years. The GPI anomalies had a maximum near and east of the Philippines, in the region of high occurrence of TC formation. The maximum extent of the monsoon trough, as defined by the zonal wind (Fig. 4.30e) maximum extension, was confined to the area west of 130°E, consistent with the westward shift of the genesis location in 2017.

#### (iv) TC impacts

Many storms had significant social and economic impacts in 2017. Typhoon Tembin, known as Vinta in the Philippines, struck the Philippine province of Mindanao in late December, causing 200 deaths with 172 missing, making it the deadliest WNP TC of 2017. Tembin hit the Philippines less than one week after Tropical Storm Kai-Tak (named Urduja in the Philippines) made landfall causing 160 deaths and leaving 163 missing<sup>4</sup>. The costliest typhoon in the season was Typhoon Hato, with damages totaling almost \$7 billion U.S. dollars, impacting Macau and Hong Kong, as well as several provinces along the Pearl River, where storm surge caused major flooding in various provinces of mainland China. Hato was the strongest typhoon to hit Macau and Hong Kong in 50 years.

# 5) North Indian Ocean basin—M. C. Kruk

The North Indian Ocean (NIO) TC season typically extends from April to December, with two peaks in activity: during May–June and again in November, when the monsoon trough is positioned over tropical waters in the basin. TCs in the NIO basin normally develop over the Arabian Sea and Bay of Bengal between 8° and 15°N. These systems are usually short-lived, relatively weak, and often quickly move into the Indian subcontinent (Gray 1968; Schreck et al. 2014).

According to the JTWC, the 2017 TC season produced three tropical storms, one cyclone, and no major cyclones (Fig. 4.31a). The 1981–2010 IBTrACS seasonal averages for the basin are 3.9 tropical storms, 1.4 cyclones, and 0.6 major cyclones (Schreck et al. 2014). The seasonal ACE index was  $15.8 \times 10^4$  kt<sup>2</sup>, which is near the 1981–2010 mean of  $16.3 \times 10^4$  kt<sup>2</sup> (Fig. 4.31b). Typically, there is enhanced TC activity, especially in the Bay of Bengal, during the cool phase of ENSO (Singh et al. 2000). While this season was not yet a fully-developed La Niña, two storms developed in the Bay of Bengal and only one system, Tropical Storm Four (9 December), developed in the Arabian Sea.

The second named storm of the season was Cyclone Mora (27-30 May), which had maximum sustained winds of 65 kt (33 m s<sup>-1</sup>) and a minimum central pressure of 978 hPa. The cyclone caused dramatic impacts across Sri Lanka, the Andaman Islands, and Bangladesh due to widespread flooding rains and significant storm surge. At landfall, the storm surge was a stunning 3 m above astronomical high tide, resulting in an inland penetration of saltwater nearly 20 km. The government of Bangladesh estimated 52 000 homes were destroyed by the storm which displaced an estimated 260 000 people. In Sri Lanka, Cyclone Mora exacerbated ongoing flooding from an active period of the southwest monsoon, resulting in numerous floods and landslides, killing more than 200 people and displacing 630 000 more.

<sup>&</sup>lt;sup>3</sup> Landfall is defined when the storm track is over land and the previous location was over ocean. In order not to miss landfall over small islands, first the tracks were interpolated from 6-hourly to 15 minute intervals before determining if the storm track was over land or ocean using a high-resolution land mask.

<sup>&</sup>lt;sup>4</sup> Casualty statistics are from the ReliefWeb site; for Tembin see https://reliefweb.int/disaster/tc-2017-000182-phl and for Kai-Tak, see https://reliefweb.int/disaster/tc-2017-000180-phl.



FIG. 4.31. Annual TC statistics for the NIO for 1970–2017: (a) number of tropical storms, cyclones, and major cyclones and (b) estimated annual ACE index (in  $kt^2 \times 10^4$ ) for all TCs at least tropical storm strength or greater intensity (Bell et al. 2000). The 1981–2010 means (horizontal lines) are included in both (a) and (b).

The most intense storm in the basin was Cyclone Ockhi late in the season, from 29 November to 6 December, with maximum sustained winds of 90 kt (45 m s<sup>-1</sup>) and a minimum central pressure of 976 hPa. The storm originated over Sri Lanka and moved west-northwest into the Arabian Sea and then turned northeast where it was affected by a cold continental airmass which led to its quick demise west of the Gujarat coastline. However, the storm again plagued areas of Sri Lanka with additional rainfall and galeforce winds. The strong winds forced the diversion of flights to Mattala and closed schools. Farther west across the Maldives, two cargo boats were capsized by the cyclone, with more than a dozen other boating incidents reported during the height of the storm. As the storm turned northeast back toward India, it generated large ocean swells which led to substantial erosion along the west-facing Mumbai beaches. In addition, the cyclone-generated waves deposited over 80000 kg of trash and debris on the Mumbai beaches following 125 mm of rainfall.

6) SOUTH INDIAN OCEAN BASIN—M. C. Kruk and C. Schreck

The South Indian Ocean (SIO) basin extends south of the equator from the African coastline to 90°E, with most cyclones developing south of 10°S. The SIO TC season extends from July to June encompassing equal portions of two calendar years (the 2017 season includes storms from July to December 2016 and from January to June 2017). Peak activity typically occurs during December-April when the ITCZ is located in the Southern Hemisphere and migrating toward the equator. Historically, the vast majority of landfalling cyclones in the SIO affect Madagascar, Mozambique, and the Mascarene Islands, including Mauritius and Réunion Island. The Regional Specialized Meteorological Centre (RSMC) on La Réunion serves as the official monitoring agency for TC activity within the basin.

The 2016/17 SIO storm season was below average with five named storms, of which two were cyclones and one was a major cyclone (Fig. 4.32a). The



Fig. 4.32. Annual TC statistics for the SIO for 1980– 2017: (a) number of tropical storms, cyclones, and major cyclones and (b) estimated annual ACE index (in  $kt^2 \times 10^4$ ) for all TCs at least tropical storm strength or greater intensity (Bell et al. 2000). The 1981–2010 means (horizontal lines) are included in both (a) and (b). Note that ACE is estimated due to lack of consistent 6-h sustained winds for each storm.

1981–2010 IBTrACS seasonal median averages are eight tropical storms, four cyclones, and one major cyclone (Schreck et al. 2014). The 2016/17 seasonal ACE index was  $30.8 \times 10^4$  kt<sup>2</sup>, which is about onethird of the 1981–2010 average of  $91.5 \times 10^4$  kt<sup>2</sup> (Fig. 4.32b), and the lowest since the 2010/11 season. SSTs and 850-hPa winds were both near normal in 2016/17 (Figs. 4.33a,d). The quiet season likely relates more to changes in the upper-level circulation. Positive OLR anomalies across the eastern portion of the basin



FIG. 4.33. Jul 2016–Jun 2017 anomaly maps of (a) SST (°C; Banzon and Reynolds 2013), (b) OLR (W m<sup>-2</sup>; Lee 2014), (c) 200–850-hPa zonal wind shear (m s<sup>-1</sup>; vectors) and scalar (shading) anomalies, and (d) 850-hPa winds (m s<sup>-1</sup>; vectors) and zonal wind (shading) anomalies. Anomalies are relative to the annual cycle from 1981– 2010, except for SST which is relative to 1982–2010 due to data availability. Letter symbols denote where each SIO TC first attained tropical storm intensity. Wind data obtained from CFSR (Saha et al. 2014).

suggested a broad area of unfavorable subsidence (Fig. 4.33b). The western half of the basin, on the other hand, experienced westerly vertical shear anomalies in excess of 4.5 m s<sup>-1</sup>, which would have precluded significant activity there.

During the 2016/17 season, the strongest storm was Cyclone Enawo (3-10 March), which reached category 4 equivalent with peak sustained winds of 125 kt (64 m s<sup>-1</sup>) and an estimated minimum central pressure of 932 hPa. The storm was the strongest to strike Madagascar since Gafilo in 2004. Enawo initially developed near the center of the basin out of the monsoon trough and gradually strengthened as it headed southwest towards Madagascar. The intense cyclone attained its maximum intensity just prior to landfall on 7 March before impacting the towns of Sambava and Antalaha. According to advisories from the RSMC La Réunion, storm surge was estimated to be 3-4 m across these areas, which ultimately led to swamped rice fields, displaced residents, and an estimated 81 fatalities due to the storm.

#### 7) AUSTRALIAN BASIN—B. C. Trewin (i) Seasonal activity

The 2016/17 TC season was near normal in the broader Australian basin (areas south of the equator and between 90° and 160°E<sup>5</sup>, which includes the Australian, Papua New Guinean, and Indonesian areas of responsibility), despite a late start, with only one cyclone before mid-February. The season produced nine TCs (Fig. 4.34), near the 1983/84–2010/11 average<sup>6</sup> of 10.8, and consistent with neutral to cool ENSO conditions. The 1981–2010 IBTrACS seasonal averages for the basin are 9.9 named storms, 7.5 TCs, and 4.0 major TCs. All references to TC category in this section use the Australian Bureau of Meteorology TC intensity scale.

There were six TCs in the western sector<sup>7</sup> of the Australian region during 2016/17, three in the northern sector, and one in the eastern sector<sup>8</sup>. Three systems made landfall in Australia as tropical cyclones, two in Western Australia and one in Queensland,

<sup>&</sup>lt;sup>5</sup> The Australian Bureau of Meteorology's warning area overlaps both the southern Indian Ocean and southwest Pacific.

<sup>&</sup>lt;sup>6</sup> Averages are taken from 1983/84 onwards as that is the start of consistent satellite coverage of the region.

<sup>&</sup>lt;sup>7</sup> The western sector covers areas between 90° and 125°E. The eastern sector covers areas east of the eastern Australian coast to 160°E, as well as the eastern half of the Gulf of Carpentaria. The northern sector covers areas from 125°E east to the western half of the Gulf of Carpentaria.

<sup>&</sup>lt;sup>8</sup> Frances passed through both the western and northern sectors.



Fig. 4.34. Annual TC statistics for the Australian basin for 1980–2017: (a) number of tropical storms, cyclones, and major cyclones and (b) estimated annual ACE index (in  $kt^2 \times 10^4$ ) for all TCs at least tropical storm strength or greater intensity (Bell et al. 2000). The 1981–2010 means (horizontal lines) are included in both (a) and (b). Note that ACE is estimated due to lack of consistent 6-h sustained winds for each storm.

while two others made landfall after weakening below tropical cyclone intensity. The first landfall of the season did not occur until 6 March, the latest first landfall since comprehensive satellite records began in 1970.

#### (ii) Landfalling and other significant TCs

The most significant cyclone of the season was Debbie, which affected eastern Australia in late March. Debbie formed as a tropical disturbance south of Papua New Guinea and initially moved south, reaching cyclone intensity on 24 March near 17°S, 152°E, before turning southwest and intensifying. It reached its peak intensity of category 4 while just off the Queensland coast at 0000 UTC on 28 March, with maximum 10-minute sustained winds of 95 kt (49 m s<sup>-1</sup>). It later made landfall at 0240 UTC (1240 local time) just north of Airlie Beach, by which time it had weakened slightly to a category 3 storm with maximum sustained winds of 80 kt (41 m s<sup>-1</sup>). Deb-

bie then moved southwest into inland Queensland, weakening below cyclone intensity by 1600 UTC. The remnant low then took a south to southeast track through Queensland, passing back out to sea near Brisbane late on 30 March. A wind gust of 142 kt  $(73 \text{ m s}^{-1})$ , the strongest measured gust on record in Queensland, was observed at the elevated Hamilton Island Airport site on 28 March, and 89 kt (46 m s<sup>-1</sup>) at Proserpine. There was extremely heavy rainfall near landfall, as well as from the remnant low; totals near landfall included 635 mm in 24 hours at Mount Jukes and 986 mm in 48 hours at Clarke Range on 28-29 March, while near the Queensland-New South Wales border, 24-hour totals on 31 March included 602 mm at Upper Springbrook, 507 mm at Chillingham, and 478 mm at Boat Harbour. A 2.6-m storm surge (0.9 m above highest astronomical tide) was observed at Laguna Quays, north of Mackay.

Debbie caused extensive wind damage in the Whitsunday region on the mainland and on offshore islands, including Airlie Beach, Proserpine, Bowen, Hamilton, and Daydream Islands, and inland to Collinsville. There was also severe flooding both in the region near landfall, including the fifth highest height on record for the Fitzroy River at Rockhampton and in the Logan, Albert, and Tweed catchments near the Queensland-New South Wales border. Moisture from the remnant low also contributed to major flooding in parts of the North Island of New Zealand on 4-5 April, including the inundation of large parts of the town of Edgecumbe where a stopbank of the Rangitaiki River was breached on 6 April. In total, three direct deaths and several indirect deaths were attributed to Debbie, while insured losses for Debbie in Australia, according to the Insurance Council of Australia, were assessed at \$1.565 billion AUS dollars (\$1.207 billion U.S. dollars), the second-largest (inflation-adjusted) insurance loss on record for an Australian tropical cyclone (after Cyclone Tracy in 1974). An additional \$91.5 million NZ dollars (\$66.7 million U.S. dollars) of insured damages happened in New Zealand from Debbie's extratropical remnants.

Blanche formed as a tropical low within a trough over the Arafura Sea on 2 March. It began to strengthen on the 3rd and moved southwest on the 4th while strengthening, crossing over the Tiwi Islands (northwest of Darwin) early on 5 March. Continuing to move southwest over the Timor Sea, it reached tropical cyclone intensity at 1200 UTC on the 5th, when approximately 200 km west of Darwin. It strengthened further to category 2 while moving southwest, with peak 10-minute sustained wind speeds of 55 kt (28 m s<sup>-1</sup>), before making landfall at that intensity at 0300 UTC on 6 March, on the northeast Kimberley coast of Western Australia between Kalumburu and Wyndham. Point Fawcett, on the Tiwi Islands, received 384 mm of rain in the 24 hours prior to 0900 local time on 5 March, its wettest day on record, while in the Kimberley, the highest recorded 48-hour rainfall was 207 mm at Me No Savvy, between Fitzroy Crossing and Halls Creek. Tropical cyclone warnings were issued for Darwin but no major impacts occurred there.

The third landfall of the season occurred on 23 March, at 0500 UTC just west of Port Hedland. The original low formed on 19 March north of the Kimberley coast, before moving west and then southwest and intensifying shortly before landfall. The cyclone was not named operationally but was analyzed as a category 2 system based on post-analysis [maximum sustained winds 50 kt (26 m s<sup>-1</sup>)] on the basis of observed surface winds, including a gust of 61 kt (32 m s<sup>-1</sup>) at a beacon offshore from Port Hedland. There was minor wind damage in the Port Hedland area and significant river rises in the Pilbara coastal rivers, De Grey River, and Fortescue River. Minor to major flooding occurred at some locations in the De Grey catchment. Port Hedland received 268 mm of rain during 22-24 March.

Yvette, in late December, and Alfred, in mid-February, were both cyclones that weakened below cyclone intensity before making landfall near Broome in Western Australia and the Northern Territory/ Queensland border, respectively. Alfred peaked offshore as a category 2 and Yvette as a category 1. Moisture from Yvette combined with a separate tropical low to bring heavy rains through a large area of central and southern Australia in the final days of December. Walungurru, near the Northern Territory/Western Australia border, received 287 mm of rain during 25-26 December, while Adelaide (61.2 mm on 28th) had its third wettest December day on record. There was significant flash flooding in parts of metropolitan Melbourne. Record high dewpoints and precipitable water levels were observed at numerous sites in South Australia and Victoria. Alfred brought some flooding and minor wind damage, and 862 mm of rain was recorded from 18 to 22 February at Sweers Island.

The most intense Australian tropical cyclone of the season was Ernie. This storm formed as a tropical low on 4 April near 10°S, 115°E, well north of Western Australia. Ernie reached tropical cyclone intensity late on 6 April near 14°S, 111°E, and then intensified exceptionally rapidly, reaching category 5 intensity within 24 hours. It reached its peak intensity (maximum sustained winds 115 kt ( $62 \text{ m s}^{-1}$ ) at 1200 UTC on 7 April near 16°S, 111°E, before turning west-southwest and weakening, dropping below tropical cyclone intensity on 10 April. The other major cyclone of the season was Frances, which reached category 3 intensity on 28–29 April, with maximum sustained winds of 70 kt ( $36 \text{ m s}^{-1}$ ), as it tracked westsouthwest through the Timor Sea between Timor and the Australian mainland. Neither Ernie nor Frances approached any land areas, although heavy rain associated with Frances did affect the Tiwi Islands.

- SOUTHWEST PACIFIC BASIN—P. R. Pearce, A. M. Lorrey, and H. J. Diamond
- (i) Seasonal activity

The 2016/17 season in the southwest Pacific officially began in November 2016, but the first named storm did not occur until February 2017, despite numerous tropical depressions during the early part of the season. Storm track data for November 2016-April 2017 was gathered from the Fiji Meteorological Service, Australian Bureau of Meteorology, and New Zealand MetService, Ltd. The southwest Pacific basin as defined by Diamond et al. (2012) (135°E-120°W) had six tropical cyclones, including three major tropical cyclones (based on the Australian TC intensity scale). As noted in Section 4f1, Fig. 4.35 shows the standardized TC distribution based on the basin spanning the area from 160°E-120°W to avoid overlaps with the Australian basin that could result in double counting of storms. However, it is important to use the definition of the southwest Pacific basin of Diamond et al. (2012) as that is how annual TC outlooks are produced and disseminated. All references to TC category in this section use the Australian TC intensity scale.

The 1981-2010 Southwest Pacific Enhanced Archive of Tropical Cyclones (SPEArTC) indicates a seasonal average of 10.4 named tropical cyclones and 4.3 major tropical cyclones. Therefore, the 2016/17 TC season had less-than-normal activity. The first storm (Tropical Cyclone Alfred) developed as a tropical disturbance in the Gulf of Carpentaria in mid-February. The season concluded in mid-May with Tropical Cyclone Ella affecting Wallis and Futuna and Samoa. The ratio of major TCs relative to the total number of named TCs in 2016/17 was 50%, down from 63% during the previous season. Tropical Cyclone Donna, which caused significant damage in northern Vanuatu and the Solomon Islands in May, was the strongest TC to form outside the official southwest Pacific TC season (which ended on 30 April 2017) on record per the SPEArTC dataset (Diamond et al 2012).



Fig. 4.35. Annual TC statistics for the southwest Pacific for 1980–2017: (a) number of tropical storms, cyclones, and major cyclones and (b) estimated annual ACE index (in  $kt^2 \times 10^4$ ; Bell et al. 2000). The 1981–2010 means (horizontal lines) are included in both (a) and (b). Note that ACE is estimated due to lack of consistent 6-h sustained winds for each storm.

#### (ii) Landfalling and other significant TCs

Tropical Cyclone Alfred developed as a tropical low on 16 February in the southern Gulf of Carpentaria. The low gradually intensified into a category 1 TC on 20 February and remained at TC strength before weakening approximately 24 hours later. Alfred was the first tropical cyclone to make landfall in Australia's Northern Territory since 2015. Alfred's peak 10-minute wind speed was 46 kt (24 m s<sup>-1</sup>) and its lowest central pressure was 994 hPa.

Tropical Cyclone Bart was a short-lived cyclone which lasted from 19 to 22 February, forming south of Samoa and traveling southeast to the south of the southern Cook Islands. Bart reached category 1 status, where peak 10-minute sustained wind speeds were 40 kt ( $21 \text{ m s}^{-1}$ ) and minimum central pressures reached 994 hPa.

Tropical Cyclone Cook was named on 8 April after forming northeast of Vanuatu. Some trees were felled and power was cut to some residents in Port Vila, Vanuatu. Cook brought heavy rain and destructive winds to parts of New Caledonia, where one fatality was reported. Cook also caused wind damage to trees and infrastructure in parts of New Zealand's North Island, one week after ex-Tropical Cyclone Debbie caused major flooding in the same area. Cook achieved category 3 status with 10-minute sustained winds of 84 kt (43 m s<sup>-1</sup>) and a minimum central pressure of 961 hPa.

Tropical Cyclone Donna formed to the north of Vanuatu on 1 May, which is just past the traditional end of the season (30 April). It achieved named storm status on 3 May, and late on 4 May it began to show a clear eye and was upgraded to a category 3 tropical cyclone. On 6 May, Donna was upgraded to category 4 status. It weakened to a category 3 storm later on 6 May but then strengthened again to category 4 status the next day before being upgraded to category 5 status on 8 May. Donna's peak 10-minute sustained wind speed reached 111 kt (57 m s<sup>-1</sup>) and its lowest minimum central pressure was 935 hPa. As a result, Donna became the strongest out-of-season TC on record for May in the southwest Pacific. Donna degraded quickly to tropical low strength on 10 May. The storm caused significant damage in Vanuatu. Entire villages across the Torres Islands in Torba Province were forced to seek shelter from the storm in caves. Throughout the province, many buildings were destroyed or severely damaged. On the island of Efate, heavy rainfall led to flooding of low-lying areas. Structures collapsed in Port Vila because they were undermined during flash floods. Across the northern half of Vanuatu, crops sustained significant damage and communications were severed with the rest of the country. In the Temotu Province of the Solomon Islands, Donna caused two fatalities. In New Zealand, Donna's remnants produced heavy rain over much of the North Island and the west coast of the South Island on 11-12 May.

The season concluded with Tropical Cyclone Ella, which formed southwest of American Samoa on 9 May. Just three hours later, the system intensified into a category 1 TC, and it reached category 2 status on 10 May. Its peak 10-minute sustained wind speed was 59 kt ( $31 \text{ m s}^{-1}$ ) with a minimum central pressure of 977 hPa.

# g. Tropical cyclone heat potential—G. J. Goni, J. A. Knaff, I.-I. Lin, and R. Domingues

This section summarizes the changes in upper ocean thermal conditions within the seven tropical cyclone (TC) basins (see Table 4.1), using tropical cyclone heat potential (TCHP; Goni and Trinanes 2003) as the main parameter. The assessment presented here focuses on the vertically-integrated upper ocean temperature conditions during the TC season of each ocean basin with respect to the long-term mean and to values observed during the previous year. TCHP is defined as the excess heat content contained in the water column between the sea surface and the depth of the 26°C isotherm. This parameter has been linked to TC intensity changes (Shay et al. 2000; Mainelli et al 2008; Lin et al. 2014) with TCHP values above 50 kJ cm<sup>-2</sup> providing the necessary ocean conditions for Atlantic hurricane intensification when favorable atmospheric conditions are present. The magnitude of the TCHP has been identified as modulating the effective SST under a TC during air-sea coupling due to latent and sensible heat fluxes (Mainelli et al. 2008; Lin et al. 2013). In addition, improved temporal and spatial sampling of the ocean has been shown to lead to the correct representation of the upper ocean density field (Domingues et al. 2015), which in turn led to reducing the error in hurricane intensification forecasts within operational numerical models (Dong et al. 2017). Fields of TCHP show high spatial and temporal variability associated mainly with oceanic mesoscale features, year-to-year variability (e.g., ENSO), or long-term decadal variability. The assessment of this variability on various timescales can be accomplished using a combination of satellite altimetry and in situ observations (Goni et al. 1996; Lin et al. 2008; Goni and Knaff 2009; Pun et al. 2013).

To assess year-to-year variations in TCHP, two fields are presented. First, Fig. 4.36 presents TCHP anomalies (departures from the 1993–2016 mean values) for the primary months of TC activity in each hemisphere: June–November in the Northern Hemisphere, and November 2016–April 2017 in the Southern Hemisphere. TCHP anomalies generally show large variability within and among the TC basins. Figure 4.37 shows the differences of TCHP between this season (2017) and last year (2016).

Most basins exhibited positive TCHP anomalies in 2017 (Fig. 4.36), except for a small region just east of 60°E in the southwest Indian basin. Above-average TCHP in most basins provided anomalously favorable ocean conditions for the intensification of TCs. In the tropical Atlantic basin, TCHP values observed in 2017 were approximately 10% larger than the longterm mean, consistent with the above-normal activity there. Meanwhile, the western North Pacific (WNP) basin had below-normal activity despite TCHP values being over 30% larger than the mean conditions. This is explained because the number of TCs in the WNP during a season is more closely related to atmospheric dynamics (Lin and Chan 2015) than to upper ocean conditions.

In the Gulf of Mexico, TCHP anomalies ranged between –10 and 20 kJ cm<sup>-2</sup> with the spatial distribution largely determined by the mesoscale field, such as the extension of the Loop Current, and cold cyclonic features. In the eastern Gulf of Mexico, prominent intrusion of the Loop Current caused TCHP values in 2017 to be 50% larger than the mean; a noticeable change with respect to conditions in 2016, which was characterized by a small intrusion of the Loop Current. The TCHP in the western Gulf of Mexico once again exhibited positive anomalies, with values approximately 30% larger than the long-term mean. Compared to 2016, TC activity increased in the Gulf of Mexico in 2017 with a total of five TCs including the rapidly intensifying category 4 Hurricane Harvey.

In the eastern North Pacific (ENP) basin, TCHP values were 10–20 kJ cm<sup>-2</sup> above the long-term mean associated with a continued positive phase of the Pacific decadal oscillation (Zhang et al. 1997). Anomalies observed in 2017, however, were not so large as the values observed in 2016. This change is largely due to the ENSO conditions described in Section 4b. As a consequence, average TC activity was observed in the ENP, with nine hurricanes in 2017 (Fig. 4.36).

The TCHP in the WNP basin is also closely modulated by ENSO variability (Lin et al. 2014; Zheng et



FIG. 4.36. Global anomalies of TCHP (kJ cm<sup>-2</sup>) corresponding to 2017 computed as described in the text. Boxes indicate the seven regions where TCs occur: from left to right, southwest Indian, north Indian, west North Pacific, southeast Indian, South Pacific, East Pacific, and North Atlantic (shown as Gulf of Mexico and tropical Atlantic separately). Green lines indicate the trajectories of all tropical cyclones reaching at least Saffir–Simpson category I during Nov 2016–Apr 2017 in the SH and Jun–Nov 2017 in the NH. The numbers above each box correspond to the number of category I and above cyclones that traveled within each box. Gulf of Mexico conditions during Jun–Nov 2017 are shown in the inset in the lower right corner.



Fig. 4.37. TCHP differences (kJ cm<sup>-2</sup>) between 2017 and 2016.

al. 2015). For example, from the 1990s to 2013 the WNP experienced a long-term decadal surface and subsurface warming associated with more prevalent La Niña-like conditions (Pun et al. 2013; England et al. 2014; Lin and Chan 2015). With the ENSO conditions during 2014/15, however, this warming trend stopped, but it recovered again in 2016. In 2017, further warming of the WNP basin and TCHP anomalies as large as 40 kJ cm<sup>-2</sup> were observed, which is approximately 30% larger than the long-term mean for the region. However, the overall TC activity over the WNP basin was not so active as in 2016 due to less favorable atmospheric dynamic conditions (Lin and Chan 2015; Section 4f4).

For each basin, the differences in the TCHP values between this season and 2016 (Fig. 4.37) indicate that three of the seven active TC basins exhibited a decrease in TCHP values, namely the: (1) South Indian Ocean, (2) eastern North Pacific Ocean, and (3) North Atlantic Ocean basins. It is likely that lower TCHP values in the south Indian Ocean played a role in suppressing TC activity in 2016/17, which observed only one major TC during the season. However, despite showing a moderate decrease in TCHP with respect to 2016, above-normal TC activity in terms of category 4 and 5 storms was observed in the tropical Atlantic and Gulf of Mexico, with the development of six major Atlantic hurricanes. Intense hurricane activity in the Atlantic during the last season likely benefited from above-normal TCHP in the tropical Atlantic and Gulf of Mexico (Fig. 4.36) combined with favorable atmospheric conditions associated with a cool neutral ENSO state, which is known for decreasing vertical wind shear and trade wind intensity, supporting TC development and intensification (Gray 1984). In addition, atmospheric conditions in the tropical Atlantic, as described in Section 4f2, favored the development of intense TC activity (Bell et al. 2017b). Hurricanes Irma and Maria, for example, had sustained winds that reached 160 kt (67 m s<sup>-1</sup>) and 150 kt (72 m s<sup>-1</sup>), respectively. Both storms were well observed by reconnaissance aircraft equipped with stepped frequency microwave radiometers that provide accurate estimates of surface wind speeds (Uhlhorn and Black 2003).

An increase in TCHP values with respect to the previous season was recorded in the North Indian Ocean (Arabian Sea), southeast Indian Ocean, southwest Pacific, and WNP ocean basins. The largest changes with respect to the previous season were observed in the south Indian Ocean basin, and in the WNP north of 10°N, with differences above -20 and  $20 \text{ kJ cm}^{-2}$  respectively. Super Typhoon Noru was the fifth named storm to develop during the season and experienced rapid intensification from tropical storm into a category 5 TC as it moved from an area of low TCHP (~40 kJ cm<sup>-2</sup>) into an area with TCHP values of ~80 kJ cm<sup>-2</sup>.

Ocean conditions of four of the six major hurricanes (Harvey, Irma, Jose, and Maria) of the Atlantic basin are described here. Data from the ocean observing system, including observations from underwater gliders that were deployed to collect data in support of operational hurricane intensity forecasts, are presented here (Fig. 4.38). These observations were collected because a better representation of the upper ocean temperature and salinity conditions has been shown to reduce the error in Atlantic hurricane intensity forecasts within the NOAA experimental HYCOM-HWRF operational model (Dong et al. 2017). Ocean conditions before, during, and after the passage of these hurricanes were continuously monitored by some of these gliders.

Hurricane Harvey traveled through the Caribbean Sea south of Puerto Rico on 20 August, where the upper ocean exhibited TCHP values higher than 80 kJ cm<sup>-2</sup>. In this area, underwater glider data showed that a relatively shallow mixed layer favored cooling of the upper ocean, which together with the moderate wind shear contributed to its lack of intensification in that region. Once it reached the Gulf of Mexico, Hurricane Harvey intensified from a tropical depression into a category 4 hurricane with 115 kt (51 m s<sup>-1</sup>) winds in a period of less than 48 hours as it traveled over positive TCHP anomalies in the western Gulf of Mexico. Harvey produced the largest amount of rain on record in the continental United States, which caused extensive flooding in the Houston, Texas, metropolitan area (see Sidebar 4.3 for detailed information about the precipitation associated with Harvey).



Fig. 4.38. Tracks of major Atlantic hurricanes that traveled over the Caribbean Sea and tropical North Atlantic Ocean during the 2017 hurricane season. Blue lines indicate the location of some of the underwater gliders, which were parked in fixed locations (green stars) during the passage of the major hurricanes. Background colors show values of TCHP averaged for Aug 2017, with thin contours every 10 kJ cm<sup>-2</sup>, and thick contours indicate 50 kJ cm<sup>-2</sup> and 80 kJ cm<sup>-2</sup>, respectively.

Hurricane Irma, the strongest TC globally in 2017, reached its maximum intensity of 160 kt (82 m s<sup>-1</sup>) on 6 September while traveling over waters north of Puerto Rico and Hispaniola that had TCHP values higher than 70 kJ cm<sup>-2</sup>. Underwater glider data showed that the upper ocean conditions exhibited low salinity values at the surface, partially suppressing upper ocean mixing with colder underlying waters, similar to what happened with Hurricane Gonzalo in 2014 (Domingues et al. 2015; Dong et al. 2017), but opposite to the conditions experienced during Hurricane Harvey. Glider observations also revealed that the upper 50 m of the ocean cooled by approximately 1°C (Fig. 4.39a) as a result of storm-induced mixing.

Hurricane Jose was the third strongest Atlantic hurricane in 2017 and was the seventh longest-lived Atlantic named storm in the satellite era (since 1966). While Jose was off Puerto Rico,  $2^{\circ}$ - $3^{\circ}$  latitude to the north of where Irma traveled, its trajectory coincided at a time with the cold wake left behind by the passage of Hurricane Irma. Therefore, Jose experienced a relatively cooler and well mixed upper ocean as observed by underwater glider data (Fig. 4.39b). These cooler ocean conditions may have partly contributed to its



FIG. 4.39. (a), (b) Temperature (°C) and (c) salinity profiles sampled by underwater gliders before and after the passage of three major North Atlantic hurricanes (Irma, Jose, and Maria) in 2017.

weakening from a category 4 hurricane to category 3 during this time.

Hurricane Maria traveled through the eastern Caribbean Sea and later through the same approximate area as Irma transited the tropical North Atlantic, On 20 September, after entering the Caribbean Sea following a landfall in Dominica, Maria peaked in intensity with maximum sustained winds of 150 kt (77 m s<sup>-1</sup>) and a minimum pressure of 908 hPa, making Maria the tenth-most intense Atlantic hurricane on record. When Maria's path was close to the gliders in the Caribbean Sea, these ocean observations revealed the existence of a very stable barrier layer of approximately 30-m depth (Fig. 4.39c) providing ocean conditions conducive for intensification. Maria made landfall in Puerto Rico on 20 September as an intense category 4 hurricane. Interaction with land further weakened the hurricane, though it regained some strength as it traveled over waters with TCHP values of ~70 kJ cm<sup>-2</sup> north of Hispaniola (Fig. 4.38). As it traveled farther to the north it encountered lower TCHP which helped to contribute to Maria's weakening to a tropical storm on 28 September.

In summary, 2017 was characterized by higherthan-normal values of TCHP by 10%–30% over most TC basins. Overall, TCHP anomalies observed in 2017 were not so large as anomalies observed in 2016, which likely contributed to both fewer overall TCs as well as fewer category 5 TCs globally. Ocean observations during 2017 indicated that upper ocean conditions may have favored the intensification of major TCs, but atmospheric conditions (especially in the western North Pacific) were likely not as conducive for strong TCs.

#### h. Indian Ocean dipole—J.-J. Luo

The Indian Ocean dipole (IOD), referring to the anomalous SST gradient between the western and eastern equatorial Indian Ocean, is a major internal climate mode in the tropical Indian Ocean (IO). It often starts to grow during boreal summer, peaks in September–November, and ends rapidly in December in association with the reversal of monsoonal winds along the west coast of Sumatra (Saji et al. 1999). The IOD displays a strong asymmetry with the magnitude of the positive IOD being much larger than that of the negative IOD (e.g., Hong et al. 2008). Correspondingly, air–sea coupling strength and predictability of the positive IOD are usually strong and high, respectively, compared to those of the negative IOD (Luo et al. 2007).

Following a negative IOD event in 2016 (Luo 2017), a positive IOD event developed during April–August 2017, despite the occurrence of neutral ENSO conditions during this time (Fig. 4.40). This positive IOD event was quite weak and uncoupled. The positive west-minus-east zonal SST gradient did not bring anomalous easterlies along the equatorial IO during April–August (Fig. 4.40b). Moreover, while the cold SST anomalies in the eastern IO and warm anomalies in the western IO formed a positive dipole SST pattern during April–August, local rainfall anomalies did not follow the SST anomalies. Instead, positive rainfall anomalies occurred in the eastern IO, while drier conditions occurred in the western IO (Fig. 4.40a).

Following the strong El Niño event of 2015/16, back-to-back La Niña events occurred in late 2016 and late 2017 (Figs. 4.1, 4.40c). In addition, a negative IOD started in May 2016 and persisted until January 2017 (Fig. 4.40b). Correspondingly, during December 2016–February 2017, basin-wide cold SST



Fig. 4.40. (a) Monthly anomalies of SST (°C; solid lines) and precipitation (mm day-1; dashed lines) in the eastern pole (IODE; 10°S-0°, 90°-110°E; blue lines) and the western pole (IODW; 10°S-10°N, 50°-70°E; red lines) of the IOD. (b) As in (a), but for the IOD index (measured by the SST difference between IODW and IODE, green line) and surface zonal wind anomaly (m s<sup>-1</sup>) in the central equatorial IO (Ucio; 5°S-5°N, 70°-90°E; black line). (c) As in (a), but for the SST anomalies in the Niño-3.4 region (5°S-5°N, 190°-240°E; black line) and the tropical IO (IOB; 20°S-10°N, 40°-120°E; red line). Anomalies are relative to the 1982-2017 base period. [Sources: NOAA OISST (Reynolds et al. 2002); monthly GPCP precipitation analysis (available at http://precip.gsfc.nasa.gov/); and JRA-55 atmospheric reanalysis (Ebita et al. 2011).]



Fig. 4.41. SST (°C; colors) and precipitation (contoured at: 0,  $\pm 0.5$ ,  $\pm 1$ ,  $\pm 2$ ,  $\pm 3$ ,  $\pm 4$ , and  $\pm 5$  mm day<sup>-1</sup>). Solid/ dashed lines denote positive/negative values, and thick solid lines indicate the zero contour) anomalies during (a) Dec 2016–Feb 2017, (b) Mar–May 2017, (c) Jun–Aug 2017, and (d) Sep–Nov 2017. Anomalies were calculated relative to 1982–2017. [Sources: NOAA OISST (Reynolds et al. 2002) and monthly GPCP precipitation analysis (available at http://precip.gsfc.nasa.gov/).]

anomalies appeared in the tropical IO, and warm SST anomalies were observed around Indonesia (Fig. 4.41a). Consistently dry conditions occurred in the western-central IO with wet conditions in the eastern IO to the Maritime Continent. Westerly anomalies were present in the central-eastern equatorial IO that helped deepen the thermocline in the east and generate warm upper ocean temperature in that region (Figs. 4.41a, 4.42a). Cyclonic wind anomalies in the southeastern IO, which often happen following La Niña and/or a negative IOD (Behera et al. 2006; Luo et al. 2010), tend to upwell the local thermocline and drive westward-propagating cold Rossby waves. During December 2016-February 2017, cold upper-300-m mean temperature anomalies occurred along 10°S and in the western IO, reminiscent of the Rossby wave activities (Fig. 4.42a). Meanwhile, the



FIG. 4.41. SST (°C; colors) and precipitation (contoured at: 0,  $\pm 0.5$ ,  $\pm 1$ ,  $\pm 2$ ,  $\pm 3$ ,  $\pm 4$ , and  $\pm 5$  mm day<sup>-1</sup>). Solid/ dashed lines denote positive/negative values, and thick solid lines indicate the zero contour) anomalies during (a) Dec 2016–Feb 2017, (b) Mar–May 2017, (c) Jun–Aug 2017, and (d) Sep–Nov 2017. Anomalies were calculated relative to 1982–2017. [Sources: NOAA OISST (Reynolds et al. 2002) and monthly GPCP precipitation analysis (available at http://precip.gsfc.nasa.gov/).]

cold Rossby waves and anomalous southerlies in the southeastern IO favor the occurrence of cold SST anomalies there (Figs. 4.41a,b).

During January-July, La Niña dissipated rapidly and warm anomalies appeared in the central-eastern equatorial Pacific (Fig. 4.40c). However, the wet condition continued in the eastern IO-Maritime Continent while the western IO remained dry (Fig. 4.41b). The persistent wet condition around Indonesia is consistent with a strong increasing SST trend there. Moreover, the corresponding westerly anomalies in the central-eastern equatorial IO did not generate warm upper ocean temperature anomalies in the east, probably owing to the arrival of eastward-propagating equatorial cold Kelvin waves. The cold subsurface anomalies helped generate cold SST anomalies along the west coast of Sumatra (Fig. 4.41b), which may have prevented the development of a negative IOD. Meanwhile, SSTs in the western IO increased during



Fig. 4.42. Upper 300-m mean ocean temperature (°C; colored scale) and surface wind (m s<sup>-1</sup>) anomalies during (a) Dec 2016–Feb 2017, (b) Mar–May 2017, (c) Jun–Aug 2017, and (d) Sep–Nov 2017. [Sources: NCEP ocean reanalysis (available at www.cpc.ncep.noaa.gov /products/GODAS/) and JRA-55 atmospheric reanalysis (Ebita et al. 2011).]

March–August (Fig. 4.41b,c), partly due to less cloud cover (i.e., dry condition) and strong increasing SST trend in that region. Thus, a positive dipole SST pattern formed. However, the persistent wet condition around Indonesia tends to induce westerly anomalies in the eastern IO, which prevents the occurrence of a positive air–sea feedback to intensify the positive dipole SST pattern. During September–November, in association with the development of the second La Niña event, a negative IOD signal with westerly anomalies in the central IO became apparent.

In summary, the positive IOD event in 2017 was weak and uncoupled. It did not appear to exert significant impacts on the climate in surrounding areas. Since the negative IOD in 2016 does not appear to be driven by the corresponding weak La Niña (Lim and Hendon 2017), the positive dipole SST pattern in 2017 may be largely caused by the internal mechanisms in the IO that are responsible for the biennial character of the IOD (Behera et al. 2006). Cold subsurface temperature anomalies in the southern IO, which were induced by the 2016 negative IOD, may have provided an important precursor for the occurrence of the cold SST anomalies in the eastern IO in 2017. However, the annually persistent anomalous westerlies in the IO, associated with the persistent wet condition around Indonesia, suppressed the positive air–sea interaction during the positive IOD event in 2017 and may have led to the occurrence of a weak uncoupled positive dipole SST event in April–August 2017.

# SIDEBAR 4.1: HURRICANE IRMA: REWRITING THE RECORD BOOKS—P. J. KLOTZBACH

Hurricane Irma generated the highest ACE values (Bell et al. 2000) of any Atlantic hurricane during the extremely active 2017 season. Irma developed from a tropical wave in the eastern Atlantic, reaching tropical storm status on 30 August. Over the next several days, Irma intensified into a major hurricane in an environment of anomalously weak vertical wind shear and anomalously high SSTs.

On 5 September, Irma reached category 5 intensity as it bore down on the northern Leeward Islands. Over the next several days, Irma devastated many islands in the eastern and central Caribbean, then went on to make landfall in Cuba before making two landfalls in Florida. It finally weakened to a tropical depression early on 12 September near the Georgia/Alabama border. In this sidebar, several of Hurricane Irma's most notable meteorological records are highlighted. All statistics for Irma listed in this sidebar are from the formal National Hurricane Center report on Hurricane Irma (Cangialosi et al. 2018). Historical statistics are calculated from the HURDAT2 database, which provides six-hourly estimates of historical Atlantic tropical cyclone wind speeds, pressures, and locations since 1851 (Landsea and Franklin 2013).

Irma began to set records as it approached the northern Leeward Islands. It intensified into a 155-kt (80-m s<sup>-1</sup>) category 5 hurricane late on 5 September, making it the strongest Atlantic hurricane outside of the Gulf of Mexico and Caribbean on record. Irma also shattered the old record for strongest hurricane to impact the northern Leeward Islands (defined as  $15^{\circ}-19^{\circ}N$ ,  $65^{\circ}-60^{\circ}W$ ), breaking the old record of 140 kt (72 m s<sup>-1</sup>) set by the Lake Okeechobee Hurricane of 1928 and Hurricane David (1979). Irma brought devastation to Barbuda (Fig. SB4.1), Anguilla, and portions of the U.S. and British Virgin Islands and then passed north of Puerto Rico. During its track across the Caribbean, Irma made four category 5 landfalls at: Barbuda, St. Martin, Virgin Gorda (British Virgin Islands), and Little Inagua (Bahamas).



Fig. SB4.1. GOES-16 infrared satellite image of Hurricane Irma as it made landfall over Barbuda at 0600 UTC on 6 Sep 2017.

Despite weakening slightly as it tracked across the Caribbean, Irma maintained its category 5 intensity for 2.75 consecutive days—the longest contiguous period that an Atlantic hurricane has spent at category 5 intensity in the satellite era (since 1966). It became the first category 5 hurricane to make landfall in the Bahamas since Hurricane Andrew in 1992. Irma briefly weakened to category 4 strength but then re-intensified to category 5 before making landfall in Cuba on 9 September (Fig. SB4.2). The last category 5 hurricane to hit Cuba was the Cuba Hurricane of 1924.

Land interaction with Cuba caused Irma to weaken to a category 3 hurricane, but it then re-intensified to category 4 over the warm waters of the Florida Straits before mak-

ing landfall near Cudjoe Key, Florida (Fig. SB4.2). Irma's landfall pressure in the Florida Keys of 931 hPa tied with Hurricane Carla (1961) for the tenth lowest on record for a continental U.S. landfalling hurricane. This also marked the first time on record that two category 4 hurricanes (Harvey and Irma) made landfall in the continental U.S. in the same calendar year. Irma made a second landfall near Marco Island as a category 3 hurricane. At the time of its second landfall, Irma had maximum winds of 100 kt (51 m s<sup>-1</sup>) and a central pressure of 936 hPa—the exact same maximum sustained winds and 4 hPa lower central pressure than Hurricane Wilma had when it made landfall in virtually the exact same location in 2005.



Fig. SB4.2. GOES-16 infrared satellite image of Hurricane Irma making landfall near Cudjoe Key on 1315 UTC on 10 Sep 2017.

# SIDEBAR 4.2: THE NEW GOES-R SERIES: MUCH IMPROVED "GLASSES" TO VIEW THE TROPICS—C. S. VELDEN

NOAA's Geostationary Operational Environmental Satellites (GOES) have historically been one of the principle tools utilized by tropical analysis and forecast centers to monitor hurricane activity. NOAA's National Hurricane Center (NHC), Central Pacific Hurricane Center (CPHC), and Satellite Analysis Branch (SAB), as well as the Department of Defense Joint Typhoon Warning Center (JTWC), employ GOES data and derived products for critical analysis of storm intensity and motion. Over the years, algorithms have been developed to estimate hurricane intensity from GOES imagery. The new GOES-R series (-R/S/T/U which become -16/17/18/19 when operational) includes an advanced imager with improved spatiotemporal and spectral resolution that will enable better assessment of hurricane structure and intensity. The first of this series, GOES-16, was operated in experimental mode for much of 2017 near 90°W. It was declared operational by NOAA in December 2017 and positioned at 75°W to cover the Atlantic hurricane belt.

# What are the implications of improved hurricane intensity analyses and forecasts?

The primary mission at NHC/CPHC is to save lives, mitigate property loss, and improve economic recovery efficiency by issuing the best possible watches and warnings of approaching hazardous tropical weather conditions. The 2017 Atlantic hurricane season was historic, with notable landfalling Hurricanes Harvey, Irma, and Maria. These storms were powerful examples of devastating disasters that could have been even worse if not for the accurate and timely track forecasts and warnings issued by the NHC. While hurricane track forecasts have generally improved, less progress has been made with intensity forecasts, which has prompted the NHC to elevate this issue to its top priority for the tropical meteorology research community. While gains clearly have been made, the losses due to the hurricanes in 2017 show that work remains to be done to fully address the goals set by the NHC.



Fig. SB4.3. Multispectral GOES-16 imagery: (a) infrared window (10.3  $\mu$ m) (b) and (c) water vapor (6.19  $\mu$ m, upper right, 7.34  $\mu$ m, respectively,) and (d) visible (0.64  $\mu$ m), at 2130 UTC on 5 Sep 2017 during Hurricane Irma.

In addition to operational aspects of hurricane intensity estimation, climate analyses depend heavily on the fidelity of the estimates. Trends in hurricane intensity (along with frequency, duration, and landfalls) may be linked to climate change, and these records are intrinsically dependent on satellite analyses. The GOES, along with counterparts around the world (e.g., Meteosat and Himawari), have been the backbone of the satellite-based observing system since the late 1970s.

#### How will the GOES-R series address hurricane intensity?

The most common use of satellite imagery to estimate tropical cyclone intensity is via the Dvorak technique (DT; Dvorak 1984), which employs recognizable patterns in enhanced infrared and/or visible satellite imagery to quantitatively estimate the intensity of a tropical system. Indications of continued development and/or weakening can also be found in the cloud features. Trained satellite analysts identify the cloud pattern types, and along with a series of standardized technique rules, a fairly accurate intensity analysis can be made. An objective offshoot of the DT is the advanced Dvorak technique, or ADT (Olander and Velden 2007). The ADT follows some of the same procedures and rules as the DT, but it is completely computer-based and includes many enhancements to the DT.

Both the DT and ADT will benefit from the improved attributes of the GOES-R series imager. The superior sensor performance and higher spatiotemporal resolution provide an improved ability to characterize storm cloud patterns and detect features such as emerging eyes. For example, Fig. SB4.3 shows the sharp contrast of the warm eye and cold eyewall in Hurricane Irma. This information translates into more confident DT/ADT intensity estimate analyses, which can be used in conjunction with data from the GOES-R series Geostationary Lightning Mapper (GLM) instrument. The GLM on GOES-16 is the first operational lightning mapper flown in geostationary orbit and maps total lightning (in-cloud and cloud-toground) continuously over the Americas and adjacent ocean regions. Data from GLM will inform forecasters about changes in lightning activity in the eyewall and rain bands of hurricanes, which can be used as an indicator of intensity changes, especially rapid intensification (De-Maria 2012; Xu and Wang 2018; Stevenson et al. 2018). Improved hurricane intensity analyses from the GOES-R series should result in better intensity forecasts and also benefit the fidelity of the climate record.

# SIDEBAR 4.3: HURRICANE HARVEY: THE HALLMARK STORM OF A BUSY AND WET 2017 HURRICANE SEASON FOR THE UNITED STATES—D. M. ROTH AND J. W. NIELSEN-GAMMON

The 2017 tropical cyclone season was busy for the United States, with nine Atlantic, Caribbean, and Gulf of Mexico systems affecting the nation. Harvey, originally a tropical storm over the western tropical Atlantic and eastern Caribbean Sea, traversed the Yucatán Peninsula, then redeveloped in the Bay of Campeche. It made landfall on the evening of 25 August five miles east of Rockport, as the first category 4 or stronger storm to make landfall in Texas since Carla in 1961. Its 3-m storm surge resulted in 15 000 homes destroyed and another 25 000 damaged. Remarkably, there were no deaths caused by storm surge or wind damage during landfall (Blake and Zelinsky 2018), perhaps attributable to NHC issuance of storm surge watches and warnings made operational in early 2017.

Harvey's impact, and memory of the storm, however, will be associated with its historic inland rainfall and associated flooding. It is the wettest known tropical cyclone to impact the United States, on a number of time and spatial scales.

After landfall, positioned near a col in the steering flow, Harvey's forward motion slowed to a virtual halt about 100 km inland. Harvey quickly weakened to tropical storm strength but maintained this status over land. It eventually moved southeast, moving out over the Gulf of Mexico during the morning of 28 August. Still a tropical storm, Harvey curved northeastward and made another landfall in southwest Louisiana early on 30 August. The storm then accelerated northeastward and weakened as it neared the Ohio River Valley.

At the station scale, daily rainfall totals exceeding 254 mm occurred on five successive days as the storm wandered across the area. The highest Harvey storm total precipitation presently recognized by the National Weather Service is 1538.7

mm at an automated gauge one mile southwest of Nederland, Texas. This far exceeds the previous known tropical cyclone record of 1320.8 mm. For the same gauge, the three-day total of 1338.1 mm appears to exceed any previously measured U.S. value for any type of event. Rainfall at Jack Brooks Regional Airport near Nederland shattered records for wettest day (661 mm vs. 324 mm), August (1390 mm vs. 438 mm), month (1390 mm vs. 578 mm), and summer (1814 mm vs. 804 mm). Houston Intercontinental Airport recorded its wettest 1–6 days, August, month, and year on record. Houston's monthly total doubled the previous record associated with Tropical Storm Allison in June 2001.

Area-averaged totals appear to far exceed any previously measured in the United States. The



Fig. SB4.4. GOES-16 ABI Band I (0.47  $\mu$ m) and colorcoded GLM parallax-corrected observations of lightning groups in the 5 minutes prior to the nominal time of the ABI image (red: oldest; yellow: latest), 1247 UTC on 25 Aug 2017, just prior to the rapid intensification of Hurricane Harvey.

average of 838 mm falling across Harris County—roughly two-thirds its typical annual rainfall—represents over a trillion gallons of water.

Several factors contributed to Harvey's extensive rainfall footprint and extreme volume across southeast Texas. It spent nearly 60 hours inland at tropical storm or greater intensity, the longest such duration over Texas. The cyclone moved slowly, with a continuous fetch of warm, humid Gulf air. It was large in size, based on its radius of tropical storm force winds and radius of outermost closed isobar (ROCI). During its overland time in



Fig. SB4.5. Observed rainfall totals in association with Harvey and its remnants. (Source: Weather Prediction Center, NOAA.)

Texas, it interacted with a weak frontal boundary that provided some additional focus for convection (Blake and Zelinsky 2018). Additionally, the area of heaviest rain pivoted from the storm's northeast to northwest quadrants prior to its landfall in Louisiana, generally keeping the storm's heaviest rains over southeast Texas during that time.

The magnitude of its rainfall was captured well by numerical weather prediction guidance. NOAA's Weather Prediction Center forecasts indicated 600+ mm areal average amounts by 24 August, and areal average amounts of 1000+ mm by 25 August.

The annual exceedance, or recurrence interval, for rainfall of this magnitude in southeast Texas was less than 0.1% in any given year (per the current NOAA Atlas 14), or less frequent than once in 1000 years. Harvey's rainfall totals have been included in the preliminary version of NOAA Atlas 14 Version 11 for Texas (2018, manuscript under review).

Several studies have already examined Harvey's rainfall in the context of climate change. For example, van Oldenborgh et al. (2017) found that trends in three-day rainfall totals along the north-

ern Gulf Coast accounted for an increased chance of Harveylike rainfall occurring within the region in any given year, from roughly 1 in 27000 to 1 in 9000, with similar trends found in forced climate simulations.

For portions of southeast Texas, Harvey became the flood of record. Lake Conroe exceeded its previous record maximum lake level, set in October 1994, by 18.3 cm. Major and record flooding occurred in the bayous of Houston and along rivers from the Colorado to the Sabine. The entire town of Port Arthur was submerged.

Prior to Harvey, water crossing between the basins of the Sabine/Calcasieu Rivers, the Neches/Sabine Rivers, and, more unusually, between those of the San Bernard and Colorado Rivers had been observed. However, the magnitude and duration of basin crossovers during Harvey is unique in hydrologic records.

West of Houston, two flood control reservoirs, normally dry, rapidly filled. Many residents discovered their homes were built within a reservoir footprint, though beyond the reservoir's 100-year floodplain. Reservoir operators faced a difficult challenge: flooding was unavoidable, but the release rates from the reservoirs would determine how much flooding would occur within, versus below, the reservoirs. Retaining



FIG. SB4.6. Tropical Storm Allison (2001) versus Hurricane Harvey (2017) rainfall (mm) in southeast Texas (images use the same color scale).

too much water within the reservoirs would also increase the risk of uncontrolled releases or even dam failure (Brust 2017).

The unprecedented flooding presented numerous challenges for disaster response. At Houston, familiar with localized flooding, the simultaneous inundation of watersheds throughout the metropolitan area exhausted the capacity of first responders to conduct water rescues. Public officials called on the public to help with evacuation. Hundreds responded with boats, jet skis, and even monster trucks (Sullivan 2017; Collier 2017). Rising floodwaters caused primary and backup water supply systems in Beaumont to fail. Several months later, some residents of southeast Texas were still required to boil water for drinking (Gstalter 2017). Aid for Beaumont, virtually inaccessible by land from Texas, arrived from Louisiana.

Of the 68 fatalities directly caused by Harvey, 65 were due to freshwater flooding. About 35 additional deaths are indirectly attributable to Harvey. An estimated 300 000 structures were flooded, nearly half of those in Harris County. Up to 500 000 vehicles were also flooded. Total direct damages from Harvey are estimated by NOAA at approximately \$125 billion U.S. dollars, making Harvey the second-costliest United States tropical cyclone in inflation-adjusted dollars, behind Hurricane Katrina (Blake and Zelinsky 2018).