The Unusual Behavior and Precipitation Pattern Associated with Tropical Storm Ignacio (1997)

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ABSTRACT

A case study of eastern North Pacific Tropical Storm Ignacio (1997), which brought rainfall to the southwestern United States as a tropical cyclone and to the northwestern United States as an extratropical cyclone, is presented. This tropical cyclone formed from a region of disturbed weather, rather than a tropical wave, outside the typical eastern North Pacific genesis region and intensified into a tropical storm coincident with the passage of an upper-tropospheric trough. Moisture transported from Ignacio along an outflow jet associated with the trough resulted in precipitation in Mexico and the southwestern United States. As Ignacio moved north and away from the trough, this tropical cyclone weakened and eventually underwent extratropical transition over the open ocean, in contrast to climatological eastern North Pacific tropical cyclone behavior. Ignacio then strengthened as an extratropical cyclone due to favorable baroclinic conditions and the passage of another upper-tropospheric trough before making landfall on the northern coast of California, bringing rain to the northwestern United States. Ignacio's remnant moisture eventually merged into a slow-moving midlatitude low pressure system that developed after interacting with the extratropical remnant of Hurricane Guillermo.

1. Introduction

The southwestern United States is a semiarid region that receives much of its annual precipitation during the summer months, most of which is associated with the North American monsoon (NAM; Adams and Comrie 1997; Higgins et al. 1997). The states of Arizona, New Mexico, and Colorado get about half of their annual rainfall from July to September, on average, and most of this precipitation falls from thunderstorms generated by the moist, unstable atmospheric conditions associated with the NAM.

Other moisture sources contribute to precipitation during the NAM aside from moisture transport from the Gulf of Mexico. Surges of cool, moist low-level air can propagate northward up the Gulf of California and contribute to environments conducive to deep convection (Stensrud et al. 1997; Fuller and Stensrud 2000; Higgins et al. 2004). Commonly known as "gulf surges," these events can be initiated by the passage of tropical easterly waves (Stensrud et al. 1997). The intensity and impact of these gulf surges vary based on the timing of the easterly wave and its interaction with a midlatitude trough propagating east over the western United States (Stensrud et al. 1997). Gulf surges can also be triggered by a tropical cyclone (TC) passing near the mouth of the Gulf of California (Douglas and Leal 2003; Higgins and Shi 2005). In addition to these gulf surge events, subtropical upper-level lows that propagate westward along the southern periphery of the subtropical ridge (Finch and Johnson 2010) can influence upper-level dynamics and enhance convective precipitation in the NAM region (Douglas and Englehart 2007; Bieda et al. 2009). The number of subtropical upper-level troughs that occur during a single monsoon season can greatly impact overall summertime rainfall amounts in a given year (Douglas and Englehart 2007).

The frequency of the aforementioned sources are themselves influenced by intraseasonal and interannual variability associated with NAM rainfall (e.g., Higgins et al. 1999; Englehart and Douglas 2006; Douglas and Englehart 2007). Other, less regular sources of moisture during the NAM have the potential to contribute significant amounts of summer rainfall if the frequency and/or intensity of precipitation resulting from any or all...
of these more common sources decrease. The TC remnants, which can range from part of the storm that has been separated from the parent circulation to the entire cyclone itself, are occasionally advected into the southwestern United States from the eastern North Pacific and the Gulf of Mexico. These TC remnants provide an additional source of tropical moisture when synoptic conditions are favorable (e.g., Collins and Mason 2000; Ritchie et al. 2006; Corbosiero et al. 2009; Ritchie et al. 2011, hereafter R11).

Most eastern North Pacific TC remnants enter the southwestern United States due to an interaction with a midlatitude trough (R11; Corbosiero et al. 2009) or a strong subtropical ridge (R11). Though the winds associated with these TCs typically weaken after making landfall on the coastline of Mexico or, rarely, California, the tropical moisture they contain can produce large amounts of rainfall after interacting with local topography. However, many factors can influence the storm’s interaction with the midlatitude flow and thus the resulting pattern and intensity of precipitation. This poses a significant forecast problem, particularly in a region where heavy precipitation is a relatively rare occurrence.

R11 investigated the impact of 43 cases of eastern North Pacific TC remnants on the southwestern U.S. region from 1992 to 2005. These TC remnants were
sorted into five groups based on large-scale spatial patterns (e.g., Fig. 5 from R11). Tropical Storm Ignacio, from the 1997 eastern North Pacific hurricane season, fell into the fifth group, reserved for cases that could not be clearly defined by any one of the first four groups. Instead, Ignacio appeared to share characteristics with TCs from groups 1 and 3 as described by R11 (Fig. 1).

Group 1 comprises TCs that recurve in the midlatitudes in conjunction with a midlatitude upper-level trough (Fig. 1a), some of which actually undergo and complete extratropical transition (ET). Extratropical transition is the process by which a TC's energy source shifts from latent heat release in a warm core to baroclinic processes with a cold core as it moves poleward into the midlatitude flow (e.g., Jones et al. 2003). Tropical Storm Ignacio contributed rainfall to the southwestern and central United States much like a group 1 case, yet it did not exhibit a northwest-to-northeast recurvature (Fig. 2). Group 3 includes storms with largely north and/or northwest motion bringing rainfall to the west coast of the United States (Fig. 1b). These TCs move northwest parallel to the Mexican coastline and occasionally turn northward near the U.S.–Mexico border, producing rainfall along this track. Ignacio took a northwest-to-north track (Fig. 2a) much like a group 3 case (Fig. 1b) and contributed coherent rainfall along the western coast of the United States, yet it also contributed rainfall to northern Mexico and the southwestern and central United States, atypical behavior for a group 3 case.

Ignacio was unusual in several other ways. First, it formed northwest of the typical genesis region (Fig. 2a) and maintained minimal tropical storm strength of 35 kt for only 18 h (Fig. 2b). During this time, it produced cloudiness and precipitation over northern Mexico and the southwestern and central United States (Fig. 2a). Second, despite its short time at tropical storm intensity (Fig. 2b), the system retained its circulation while moving northward over cooler sea surface temperatures (SSTs; Fig. 2a), and underwent ET near 30°N. During the 1989–2009 period, only 6.7% of all eastern North Pacific TCs in the National Hurricane Center (NHC) best track dataset (HURDAT; Davis et al. 1984) reached 30°N, including Tropical Storm Ignacio, and most of these storms were near the end of their lifetimes at that latitude. Finally, subsequent to ET, Ignacio strengthened, moved northward, and brought measurable precipitation to the northwestern United States (Fig. 2a). This behavior pattern, in contrast with eastern North Pacific climatology, demonstrates that Ignacio is worthy of further study.

In this study we investigate the life cycle of this unusual TC. First, we explore Ignacio’s early life and impact on the southwestern United States. Next, we examine the factors behind Ignacio’s cohesive structure, northward motion, extratropical transition, northern region of precipitation, and extended lifetime. Section 2 describes the data and methods employed in this study; section 3 discusses the genesis and lifetime of Ignacio as a TC, including large-scale features and resultant precipitation; section 4 explores the ET and extratropical lifetime of Ignacio, including large-scale features and resultant precipitation; section 5 compares Ignacio to published climatology; and section 6 summarizes the results.

2. Data and methods

Sea level pressure, maximum wind speed, and storm center location every 6 h were provided by HURDAT. Rainfall data for Tropical Storm Ignacio were extracted from the daily 1° Climate Prediction Center (CPC) unified U.S.–Mexico precipitation dataset (available online at http://www.cgd.ucar.edu/cas/catalog/surface/precip/us-mex.html). The 3-hourly Geostationary Operational
Environmental Satellite (GOES) infrared (IR) and water vapor (WV) images used to track Ignacio’s central circulation and outflow moisture were obtained through the Global International Satellite Cloud Climatology Project (ISCCP) B1 Browse System (GIBBS; available online at http://www.ncdc.noaa.gov/gibbs/).

The majority of the atmospheric fields analyzed in this study were obtained from the global 6-hourly, T255 (nominally 0.7°) resolution European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim) dataset (Dee et al. 2011), hosted by the Research Data Archive (RDA), which is maintained by the Computational and Information Systems Laboratory (CISL) at the National Center for Atmospheric Research (NCAR). The 6-hourly, 2.5° National Centers for Environmental Prediction (NCEP)–NCAR 40-yr reanalysis (Kalnay et al. 1996) and the 3-hourly, 32-km North American Regional Reanalysis (NARR; Mesinger et al. 2006) datasets supplied additional fields not available from the ERA-Interim dataset, including integrated column moisture fluxes, outgoing longwave radiation (OLR), and related anomalies (Liebmann and Smith 1996). SST fields were explored using daily, 0.25° National Oceanic and Atmospheric Administration (NOAA) optimum interpolation (OI) data (Reynolds et al. 2007) and monthly, 1° NOAA OI data (Reynolds et al. 2002).

**FIG. 4.** Magnitude (m s\(^{-1}\); solid) and direction (°; dotted) of (a) ERA-Interim 200–850-hPa steering flow and (b) ERA-Interim 200–850-hPa wind shear. Lighter shaded box indicates tropical life cycle; darker shaded box indicates extratropical life cycle.

**FIG. 5.** ERA-Interim 200-hPa divergence (10\(^{-6}\) s\(^{-1}\); positive values shaded, negative values dashed contours) and 200-hPa winds (m s\(^{-1}\)) for (a) 0000 UTC 17 Aug, (b) 1200 UTC 17 Aug, and (c) 0000 UTC 18 Aug. The overlaid dashed line indicates the analyzed position of the 200-hPa trough axis, and the TC symbol indicates the position of Ignacio at that time.
ERA-Interim fields, including geopotential heights, relative vorticity, vertical velocity, divergence, and winds were plotted at multiple levels and times to examine the progression of the storm over its lifetime. Relative humidity (RH) and OLR fields were plotted using the NCEP–NCAR dataset. SST and SST anomaly plots were examined for anomalous patterns that might help explain the behavior of the TC.

Additional fields were computed from ERA-Interim data, including potential temperature, temperature advection, \( \mathbf{Q} \) vectors, and \( \mathbf{Q} \)-vector divergence [see Bluestein 1992, his Eq. (5.7.55)]. The \( \mathbf{Q} \) vectors were used to diagnose quasigeostrophic (QG) vertical motion. For a given value of static stability at a particular pressure level, \( \mathbf{Q} \) vectors are proportional to the horizontal temperature gradients and the horizontal shear of geostrophic wind. Given the \( \mathbf{Q} \)-vector form of the omega equation [e.g., Eq. (5.7.54) from Bluestein 1992], forcing for vertical motion can be represented by \( \mathbf{Q} \)-vector fields, where \( \mathbf{Q} \)-vector convergence forces ascent and \( \mathbf{Q} \)-vector divergence forces descent. Eddy momentum fluxes were also calculated in order to ascertain the degree to which the environment influenced the TC [e.g., Molinari and Vollaro 1989, their Eq. (6)]. Inward transport of cyclonic angular momentum, represented by a positive angular momentum flux, is indicative of the nearby passage of an upper-level trough. Positive angular momentum flux produces enhanced outflow at 200 hPa near the eddy flux maximum (Molinari and Vollaro 1989), which can assist TC intensification.

Deep-layer (200–400 hPa) vector wind shear was calculated from ERA-Interim wind data by subtracting the 850-hPa wind from the 200-hPa wind and averaging that field over a 300–600-km annulus centered on the storm. Steering flow for Ignacio was averaged over a 600-km radius using eight different pressure levels. This method assumed that the storm winds were symmetric about the center. Tests showed that the size of the radius used to compute the averages for these two parameters did not greatly impact the results. The resulting averages were plotted as a time series to examine trends in the steering flow and average shear.

![Fig. 6. Eddy momentum flux (10^{17} \text{ kg m}^2 \text{ s}^{-2}) computed at four different radii during Ignacio's lifetime. The layer 200–400 hPa was used at 50-hPa resolution as provided by the ERA-Interim dataset. Lighter shaded box indicates tropical life cycle; darker shaded box indicates extratropical life cycle.](image)

![Fig. 7. NARR moisture flux from 700 hPa to top of atmosphere (kg m\(^{-1}\) s\(^{-1}\); shaded, arrows), 500-hPa geopotential heights (m; solid contours), and 500-hPa \( \mathbf{Q} \)-vector convergence (1 × 10^{-9} \text{ Pa m}^2 \text{ s}^{-1}; \text{dashed contours}) for (a) 1800 UTC 17 Aug and (b) 0000 UTC 18 Aug. Overlaid dashed line indicates analyzed position of 500-hPa trough axis.](image)
3. Tropical lifetime of Ignacio

a. Large-scale circulation pattern and features

Examination of 500-hPa geopotential heights over Ignacio’s lifetime reveals two atmospheric features of interest (Fig. 3). The first feature, highlighted by a plot of the mean 17–21 August 1997 NCEP–NCAR reanalysis 500-hPa geopotential height anomalies (Fig. 3a), is a stronger than usual ridge in place over the southwestern United States and northern Mexico. Much of the flow over the Pacific Ocean west of Mexico was influenced by this strong ridge, which provided a weak southeasterly steering flow early in Ignacio’s lifetime (Fig. 4). Once the storm moved around the ridge, its motion became almost directly northward (Fig. 2). The second feature in Fig. 3a is a distinct region of below-normal geopotential height values reminiscent of a closed low over the Pacific Ocean off the coasts of Washington, Oregon, and northern California. The low pressure system responsible for these negative anomalies formed after the tropical depression remnant of Hurricane Guillermo, one of the strongest eastern North Pacific hurricanes on record (Lawrence 1999), interacted with the midlatitude flow and underwent ET west of 160°W in the central Pacific (Fig. 3b). The resulting low moved slowly around the deep subtropical high in place over the northern Pacific (Fig. 3b) and lingered near 140°W to the west of Ignacio’s track.

Despite the rapid onset of a strong El Niño event prior to the start of the 1997 eastern North Pacific hurricane season (McPhaden 1999), SSTs within 1° of the center
of the developing TC were normal (not shown) and marginal for TC development (26°–27°C).

b. **Genesis and intensity change of Ignacio**

A summary of the 1997 eastern North Pacific hurricane season states that 13 of the 17 named storms underwent cyclogenesis in association with the passage or presence of an African easterly wave (Lawrence 1999). An exception to the typical pattern of formation in 1997, Tropical Storm Ignacio underwent genesis near 18.7°N, 117.9°W in a large area of disturbed weather that existed west of Mexico during 14–16 August (Lawrence 1999). The mesoscale convective system (MCS) that may have produced this region of disturbed weather moved over the Pacific from the Sierra Madre Occidental around 1200 UTC 13 August. As MCSs have been shown to initiate cyclogenesis in the eastern North Pacific (Zehnder and Gall 1991), it is possible that this MCS contributed to Ignacio’s development. Ignacio also formed unusually far north and west, as the climatological region is near 100°W and south of 15°N (Pasch and Mayfield 1996). The box in Fig. 2a indicates the region in which about 75% of the TCs formed during the period 1989–2009 according to the NHC best track database.

On 17 August, an upper-tropospheric trough passed to the north of Ignacio as it intensified to tropical storm strength (Fig. 5). This trough may have contributed to Ignacio’s intensification as the upper-level divergence to the north of the system increased (Figs. 5a,b). Ignacio’s interaction with this trough resembles a favorable distant interaction as found for Atlantic storms by Hanley et al. (2001). Although the storm’s total pressure change never reached that study’s criterion of a 10-hPa pressure fall, a time series of eddy momentum flux (Fig. 6) shows increased eddy momentum flux into the TC circulation at 780 and 1015 km in association with the trough’s passage. Ignacio strengthened to its peak tropical intensity of 35 kt during this period. Just as the trough assisted Ignacio’s initial development, it also contributed to its subsequent weakening. As the trough moved east of the TC on 18 August (e.g., Fig. 5c), the indirect divergence aloft that had led to Ignacio’s strengthening decreased, as did the eddy momentum flux provided by the trough (Fig. 6). This lack of upper-level support, combined with cool SSTs of about 24°C near Ignacio (Fig. 2a), likely prevented further intensification and ultimately led to Ignacio weakening back to a tropical depression (Fig. 2b).

c. **Precipitation in the southwestern United States**

Plots of NARR moisture flux (Fig. 7) integrated from 700 hPa to the top of the atmosphere in order to capture moisture advected above the mountainous terrain show a plume of moisture extending from Ignacio into Mexico and the southwestern United States. Although it is difficult to separate the large-scale drivers of the moisture fluxes, it seems likely that a combination of the subtropical ridge to the east of Ignacio and the upper-level trough to the north assisted in transporting moisture from the storm to the southwestern United States. Transient upper-level divergence (Fig. 5c) and midlevel QG forcing (Fig. 7) associated with the upper-level trough contributed to enhanced midlevel upward vertical motion over Arizona and western New Mexico (Fig. 7b). Water vapor images (e.g., Figs. 8b and 9) indicate that these conditions resulted in the development of summertime thunderstorms and rainfall over eastern Arizona and western New Mexico on 18 August and then farther east in eastern New Mexico and western Texas on 19 August (Figs. 8b,c and 9). This precipitation in the southwestern United States exhibited similar, if weaker, characteristics to predecessor rain events (Galarneau et al. 2010).

Note that, although moisture from Ignacio was advected into the southwestern United States over an approximately 48-h period, the period of rainfall was brief and coincided with the brief period of ascent associated with the trough passage. Surface temperatures in the region also decreased in association with the cloud cover produced by these storms (not shown). These effects over land occurred despite the strong ridge steering Ignacio’s central circulation away from the coast.

4. **Extratropical life cycle of Ignacio**

a. **Extratropical transition**

The dominant large-scale feature during Ignacio’s lifetime aside from the ridge was a deep, slow-moving extratropical low pressure system associated with the remnants of Hurricane Guillermo (Fig. 3). This large
midlatitude low, located to the northwest of Ignacio, contributed to an increasing southerly flow over the TC beginning as early as 18 August (Fig. 4a), causing Ignacio’s extratropical circulation to move directly northward for more than 60 h (Fig. 2a).

Around 0600 UTC 18 August, Ignacio’s cloud signature began to appear increasingly asymmetric (e.g., Fig. 8b), and it began to resemble the satellite presentation of the second step from the ET conceptual model in Klein et al. (2000). At this time, the NHC declared that the TC had weakened to tropical depression strength. Six hours later, WV imagery indicated that Ignacio had entrained more dry air from the south (not shown) as the environmental vertical wind shear began to increase (Fig. 4b). By 0000 UTC 19 August, 12 h before NHC ET time, the TC exhibited a distinct comma-like shape, with cirrus clouds extending from the northeast quadrant off the coast of California to hundreds of kilometers inland (Fig. 8c). At this time Ignacio’s structure began to look like the third step from the Klein et al. (2000) ET conceptual model.

A shortwave trough propagated around the large, quasi-stationary low pressure system that had once been Hurricane Guillermo by 0000 UTC 19 August (Fig. 10a). This 500-hPa trough strengthened and moved farther southeast, approaching Ignacio from the west, and by 1200 UTC the trough had moved over the northwestern quadrant of the storm (Fig. 10b). This movement of the trough contributed to a deep (200–850 hPa) southerly steering flow over Ignacio. This flow, also influenced by the strong ridge over northern Mexico (Fig. 4a), began to accelerate the cyclone more rapidly northward (Fig. 2a) and contributed to the environmental vertical wind shear reaching values over 14 m s\(^{-1}\) (Fig. 4b).

The NARR grid resolution is too low (3 h, 32 km) to properly resolve the intensity of the TC and generally provides lower values than those given by the NHC best track. This is reflected in the approximately 9 m s\(^{-1}\) difference between the best track and the maximum NARR 10-m wind speed through 1500 UTC 19 August shown in Fig. 11. Thus, the sharp increase in maximum NARR 10-m winds from 1500 UTC 19 August to 0000 UTC 20 August reflects storm intensification and wind field expansion analyzed by the NARR during ET, with a closed circulation evident by 0000 UTC 20 August at 850 hPa (Fig. 11b). Along with the increasing wind speed, a corresponding decrease occurred in NARR sea level pressure (Fig. 11a). Additionally, \(Q\)-vector convergence developed at 500 hPa nearIgnacio as a shortwave trough approached the storm, resulting in upward motion (e.g., Figs. 10 and 12). Moderate 200–850-hPa environmental vertical wind shear was also present as the TC moved northward (Fig. 4b).
Cyclone phase space plots were calculated from the ERA-Interim reanalysis for 17–20 August following the methodology described in Hart (2003). This analysis demonstrates a storm’s changing symmetry and vertical structure as it transitions from a tropical to an extratropical cyclone. Figure 13 compares the thermal wind in the 900–600-hPa layer to the difference in the TC’s geopotential thickness on either side of a line bisecting the system along its direction of motion in order to evaluate the storm’s structure. Only the lower-level thermal wind is shown due to the shallow nature of the tropical cyclone during its lifetime. Ignacio only retained its symmetric structure until 1200 UTC 18 August, after which the symmetry parameter $B$ exceeded 10 m (Fig. 13). The storm remained asymmetric for the rest of its lifetime.

The sequence of Ignacio’s transformation differs from the typical progression of ET in the Atlantic Ocean as shown by cyclone phase space (Hart 2003) in that Ignacio became a cold core system while still symmetric, whereas Atlantic TCs usually become asymmetric while still warm core and then become cold core cyclones (Hart and Evans 2001).

b. Extratropical behavior and precipitation in the northwestern United States

After ET, the storm’s signature in WV imagery (Fig. 8d) and moisture flux fields (Fig. 10) showed moisture streaming over the western United States from the system. The low-level wind circulation intensified (Fig. 11) in response to upper-level QG forcing from the midlatitude trough (Fig. 12), and the storm began to appear more symmetrically cohesive in IR imagery (Fig. 14). The difference between the center of circulation as seen in the ERA-Interim and NARR 850-hPa wind fields and the position given in HURDAT for the same time is likely due to the asymmetric appearance of the storm in satellite imagery, the tilt of the storm center with height, the additional information used to compute the reanalysis fields, and the fact that the HURDAT center is located at the surface.

A rapid increase in forward motion is commonly associated with ET. This can be seen in Ignacio’s track in Fig. 2 in the increased 6-hourly spacing of the central circulation’s location. This increased spacing reflects an acceleration of the forward speed from approximately 17 kt to nearly 45 kt over a 12-h period. This movement finally brought Ignacio over land near San Francisco, California, around 0800 UTC 20 August, after which point it became increasingly disorganized (e.g., Fig. 14). Ignacio’s low-level circulation dissipated near the California coast (Fig. 11a) while the remnant circulation aloft continued carrying moisture and precipitation northward. Late on 20 August, this circulation became difficult to distinguish from the midlatitude system to its west, which eventually captured Ignacio’s remnant moisture and advected it to the northeast (not shown).

Northwestward-to-northward flow at upper levels from a convectively active region in the intertropical convergence zone (ITCZ) existed at 0000 UTC 19 August and up to 18 h earlier at the 600- and 500-hPa levels (not shown). This flow wrapped around a mid- to upper-level anticyclone before being pulled into the upper-level trough that aided the extratropical transition of Ignacio. The corresponding moisture transport was visible in WV satellite imagery (Figs. 8c,d) and moisture flux integrated from 700 hPa to the top of the atmosphere (Fig. 10). The combination of increased moisture, strong vertical wind shear, and a low-level baroclinic environment allowed Ignacio to
strengthen in the NARR fields prior to landfall and bring measurable rainfall to California, Oregon, and Washington.

The post-ET strengthening previously discussed provided the energy necessary for Ignacio to retain its upper-level structure and remain coherent over land for some time despite the lower-level circulation dissipating near San Francisco. Most of the precipitation in the northwestern United States fell to the left of the track from 0000 UTC 20 August to 0000 UTC 21 August (Fig. 2), typical for extratropical cyclones in the Northern Hemisphere (Jones et al. 2003; Atallah et al. 2007). Also contributing to the rainfall distribution was the approximately east-northeastward shear vector over most of the storm (Fig. 4b), which likely produced a forced wavenumber-1 vertical motion asymmetry in the storm circulation with preferred upward motion in the downshear left quadrant (Frank and Ritchie 2001; Ritchie and Elsberry 2001) typical of ET. In addition, 500-hPa Q-vector convergence provided QG forcing for upward motion that contributed to precipitation over the Pacific Northwest (Fig. 12).

5. Comparison of Ignacio with the composite patterns from R11

As suggested in the introduction, Tropical Storm Ignacio appeared to share characteristics with both groups 1 and 3 from R11 (Fig. 15). Like group 1 cases, Ignacio interacted with a midlatitude trough around 1200 UTC 17 August that caused a shift in its direction of motion and resulted in precipitation over the southwestern
United States (Figs. 15a,d). However, Ignacio did not completely recurve from northwestward to northeastward motion like the composite group 1 TC but instead tracked almost directly northward after interacting with the trough. This deviation prevented Ignacio's subsequent behavior from being compared to group 1 TCs postinteraction.

Between the first and second trough interactions, Ignacio's behavior resembled that of a group 3 TC (Figs. 15b,e). Like group 3 cases, Ignacio's motion turned largely northward as it tracked along a break in the ridge. However, unlike the typical group 3 TC, Ignacio did not rapidly weaken as it moved over cooler SSTs but instead underwent ET as it interacted with a second midlatitude trough.

Subsequent to the second trough interaction, Ignacio again resembled a group 1 case 24 h after the composite trough interaction had occurred (Figs. 15c,f). Two key differences include the far north location of Ignacio after this second interaction as well as the strength of the midlatitude low pressure system off the west coast of the United States. The distribution of rainfall also differed due to Ignacio continuing to track northward instead of recurving to the northeast like group 1 TCs.

In summary, the evolution of Ignacio could not be described by any one of the simple forecasting paradigms presented by R11. Because of the unusual environmental conditions in place during Ignacio's lifetime as well as the unlikely occurrence of two troughs interacting with the same storm, different stages of Ignacio's
evolution can be compared to both group 1 and group 3 composite TCs.

6. Summary and conclusions

This paper presents a case study of Tropical Storm Ignacio, an eastern North Pacific TC, which exhibited unusual behavior when compared with the composite patterns of TCs described in R11. As Ignacio moved northwestward around a strong ridge in place over Mexico and the southern United States, the TC contributed moisture to the southwestern United States while still a tropical cyclone. This moisture, in combination with enhanced uplift due to the passage of an
upper-tropospheric shortwave trough, led to the development of summertime thunderstorms in the southwestern United States and subsequent precipitation. The storm’s initial intensification and the moisture outflow that intensification produced were likely enhanced at least in part by the near-passage of the upper-tropospheric trough.

Unlike most northward-moving eastern North Pacific TCs, which dissipate south of 30°N, Ignacio maintained its circulation as it was steered up to that latitude, where the TC underwent ET as another upper-tropospheric shortwave trough passed near the storm. A distinct difference between the ET of Ignacio and the “typical” ET for the region is that Ignacio developed into an extratropical cyclone rather than being absorbed by an eastward-moving midlatitude trough or dissipating over the colder ocean. This is probably the single most important factor that led to the long-lived track of Ignacio and its contribution of precipitation to the Pacific Northwest region. In addition, the process of Ignacio’s ET differed from the ET of Atlantic TCs. Ignacio became cold core while still symmetric before completing ET, whereas Atlantic TCs typically become asymmetric while remaining warm core before completing ET.

After ET, the storm reintensified due to favorable baroclinic conditions, including ample moisture and increasing southwesterly shear, with the distinction that it appears to have been stronger as an extratropical cyclone than as a TC in the NARR fields. It made landfall on the California coast, bringing clouds and precipitation to northern California, Oregon, Washington, and British Columbia. In addition to its intensification, the storm managed to travel so far north because of the large-scale environment associated with a strong, slow-moving extratropical cyclone off the coast of North America, which had originated after the remnants of Hurricane Guillermo interacted with the midlatitude flow in the central Pacific Ocean. This low pressure system eventually incorporated Ignacio’s remnant moisture. Thus, this long-lived, far-poleward-moving storm has the distinction of having contributed a coherent swath of precipitation to both the southwestern United States and the Pacific Northwest.

Comparison of Ignacio with groups 1 and 3 composites from R11 revealed that, rather than being readily classified as either type, different stages of Ignacio’s lifetime could be compared to both groups. The first and second trough interactions resembled group 1 behavior, while the period between these interactions resembled group 3 behavior.

Future work consists of expanding the climatology in R11 to find other potential cases of ET in the eastern North Pacific. Analyses will then be performed to determine if any dominant behavior patterns exist that can aid forecasters. Also, effects of topography on the distribution of rainfall resulting from Ignacio’s moisture can be explored.

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