Diagnostics for an Extreme Rain Event near Shanghai during the Landfall of Typhoon Fitow (2013)

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ABSTRACT

Typhoon Fitow made landfall south of Shanghai, China, on 6 October 2013. During the following two days, precipitation in excess of 300 mm day$^{-1}$ occurred 400 km to the north of the typhoon center. The rain-producing systems included (i) outward-spiraling rainbands, which developed in the storm's north sector in favorable environmental wind shear, and (ii) frontal cloud as a result of coastal frontogenesis.

Over the rain area, in addition to enhanced ascent, there were increases in low-level moisture, convective instability, and midlevel relative vorticity. There is evidence of a preconditioning period prior to the rain when midlevel subsidence and boundary layer moistening occurred. From analysis of low-level equivalent potential temperature the following observations were made: (i) after landfall, a cold, dry airstream wrapped into Fitow’s circulation from the north, limiting the inner-core rainfall and producing a cold-air boundary, and (ii) an extended warm, moist airstream from the east converged with the cold-air intrusion over the rain area.

The heavy rain occurred as the large-scale flow reorganized. Major anticyclones developed over China and the North Pacific. At upper levels, a large-amplitude trough relocated over central China with the entrance to a southwesterly jet positioned near Shanghai. Back trajectories from the rain area indicate that four environmental interactions developed: (i) increasing midlevel injection of moist potential vorticity (PV) from Fitow’s circulation; (ii) low-level warm, moist inflow from the east; (iii) midlevel inflow from nearby Typhoon Danas; and (iv) decreasing mid-to upper-level injection of PV from the midlatitude trough. The authors propose that the resultant PV structure change provided a very favorable environment for the development of rain systems.

1. Introduction

At landfall, tropical cyclones (TCs) pose significant forecast problems because of the potential devastation to life and property from strong winds and heavy rain (Chen 2012). However, they can also provide much needed widespread precipitation, which supports industry and farming. The task of forecasting the distribution and local intensity of rainfall, particularly heavy rain, is very challenging. This difficulty became evident during the heavy rain event following the landfall of TC Fitow (2013), when most of the numerical forecast guidance was poor.

After TCs make landfall, they normally weaken and rainfall correspondingly decreases. For the case analyzed here, the TC circulation and inner-core rainfall did rapidly weaken at landfall, but the rainfall some 400 km to the north of the typhoon center rapidly and substantially increased. When there are new sources of energy available to TCs, such as baroclinic potential energy from westerly troughs or latent heat from monsoon surges, the remnant circulation can revive and even produce “rainfall reinforcement associated with landfalling tropical cyclones” (RRLTCs; Dong et al. 2010; Bosart and Lackmann 1995). There are many studies on...
the interaction between TCs and midlatitude baroclinic environments. They interestingly focus on either the extratropical transition (ET) of TCs (e.g., Klein et al. 2000; Harr and Elsberry 2000; Jones et al. 2003; Ritchie and Elsberry 2003, 2007; Anwender et al. 2008) or the antecedent rainfall well ahead of TCs (Stohl et al. 2008; Srock and Bosart 2009; Galarneau et al. 2010; Lee and Choi 2010; Baek et al. 2013; Moore et al. 2013). Fitow was not an ET event, since there is no evidence that the circulation transitioned into an extratropical cyclone. Figure 1 shows cyclone phase space (CPS) diagrams, based on Hart (2003), for Fitow. They indicate that Fitow did not undergo ET and retained its warm-core, symmetric structure until rapid dissipation occurred and

![ACCESS-G Analysis](image)

**Fig. 1.** CPS diagrams based on Hart (2003) for Typhoon Fitow from 1200 UTC 5 Oct to 0600 UTC 7 Oct 2013. CMA best track and ACCESS-G analysis data have been used for the calculations. The final analysis point is the last time that the Fitow low-level, synoptic-scale circulation could be identified.
TC tracking ceased. There is no evidence of a low-level, synoptic-scale circulation when tracking ceased (not shown). The CPS diagrams and the dissipation of the surface circulation also suggest that Fitow did not evolve into a warm seclusion (e.g., Shapiro and Keyser 1990; Schultz et al. 1998). Rainfall mostly occurred following the landfall of Fitow and so it is not an antecedent rain event to the storm, but may have been an predecessor rain event (PRE; Galarneau et al. 2010) to Danas, which was located approximately 800 km to the east of the rain event. There are also similarities to the squall lines preceding landfalling tropical cyclones described in Meng and Zhang (2012). Indeed, although the rainbands here may not have been squall lines, the environmental conditions for the Fitow event are somewhat similar to those documented in Meng and Zhang (2012). There are thus few studies on heavy rain events like that of Fitow, which are remote from the typhoon center, associated with a postlandfall TC, occur in combination with the intrusion of cold air from the north, and with another TC located well to the east. These unique aspects of the Fitow rain event are analyzed in this study. In particular, we are interested in the influence of the evolving large-scale flow and the roles of Fitow and Danas during the heavy rain.

Although most TC rainfall may be associated with the landfall of the inner circulation, extreme rain can sometimes occur at large radial distance from the center. Galarneau et al. (2010) define PREs as “coherent mesoscale regions of heavy rainfall, with rainfall rates >100 mm (24 h)$^{-1}$, that occur approximately 1000 km poleward of recurring tropical cyclones.” Cote (2007) and Bosart et al. (2012) document a number of prelandfall cases where heavy rain occurred at some distance from storm centers. According to these studies, PREs were typically located ~1000 km ahead of the parent tropical system, occur 1–2 days prior to the arrival of the TC, and last for ~12 h. A mid- and upper-level jet-entrance-region confluence zone, well downstream of an approaching TC, was a favored synoptic location for development. The orientation of midlatitude troughs and ridges lying poleward of TCs modulated whether, where, and when a PRE formed, while mesoscale surface boundaries acted as a focus for PRE heavy rainfall (Gao et al. 2009; Galarneau et al. 2010; Dong et al. 2010; Lee and Choi 2010; Schumacher et al. 2011; Baek et al. 2013; Milrad et al. 2013, Moore et al. 2013). These studies implied that the upstream TC is an important source of moisture for PREs.

Evidence of coastal frontogenesis as a major process with respect to enhanced precipitation was first described in Bosart et al. (1972). Knupp et al. (2006) documented the case of Hurricane Gabrielle when east-northeastly surface flow transported cool air off the west coast of Florida, toward Gabrielle’s convergent warm core, and promoted the development of shallow warm and cold fronts that were prominent during the landfall phase. This is similar to the Fitow event described here. A case study of heavy rain distant from a hurricane’s center was also presented by Srock and Bosart (2009), who demonstrated that heavy rain during the landfall of Marco was associated with cold-air damming and coastal frontogenesis. Tropical Storm Marco did not experience ET during this time period. Interestingly, two other TCs were also active in the near vicinity, which the authors claim to have had an effect on the rain event. For the rain event considered here, Fitow also did not experience ET, TC Danas was located to its east, and there is evidence presented in section 7 that Danas may have acted as a source of moisture and potential vorticity for the rain systems. The case of TC Fitow thus bears some similarities to these previous studies, but contains some important differences and additions that we will discuss. A major difference is that the extreme rainfall occurred in the vicinity of, but some 400 km away from, the center of landfalling TC Fitow, and was associated with (i) propagating outer rainbands from that storm and (ii) a cold-air intrusion from the north. These unique aspects, including the impact of Fitow on the event, are discussed in the manuscript. Galarneau et al. (2013) present evidence that the intensification of Hurricane Sandy (2012) occurred as “cold continental air encircled the warm core vortex” and “occurred in response to shallow low-level convergence below 850 hPa that was consistent with the Sawyer–Eliassen solution for the secondary circulation that accompanied the increased baroclinicity in the radial direction.” This scenario is also somewhat similar to the processes we describe for the heavy rain associated with postlandfall Fitow, even though, unlike Sandy, it remained warm-core symmetric (Fig. 1), and the rain occurred well to the north of Fitow’s center and following its dramatic weakening. Based on numerical sensitivity simulations, Niu et al. (2005) also suggested that when cold air encircled a TC making landfall in eastern China, the precipitation to the north of the TC would be enhanced via frontogenesis associated with the interaction between cold air from the north and warm air from the TC circulation, producing an inverted typhoon trough pattern. In addition, if part of the cold air wrapped into the typhoon’s inner core, the inner convection would be suppressed. Similarities between the study here and previous work include that the heavy rain event seems to have been a result of an interaction, whatever that might be, between Fitow and an evolving and favorable environmental flow, with (i) an upper-level jet entrance region very near the rain area, (ii) a tropical storm to the east of Fitow, and
(iii) coastal frontogenesis with its associated secondary circulation. In addition we will discuss the role that Fitow played in the event, even though the rain occurred well to the north of its circulation center and it was dissipating as the rain developed.

In the following sections we will expand upon these issues, introduce some additional synoptic- and mesoscale aspects, analyze some back trajectories from the rain area to evaluate the influence of environmental flow changes and neighboring weather systems (in particular TCs), and discuss the relevance of these to the production of heavy rain. The major objectives of this study are to (i) document the origin and evolution of the mesoscale systems that produced the heavy rain and (ii) provide evidence that the large-scale circulation changes influenced the efficiency of the rain systems by producing a highly favorable thermodynamic and kinematic environment. An overview of the TC Fitow event is provided in Yu et al. (2014), who describe details of the track, intensity, and rainfall.

The manuscript is organized as follows. Section 2 describes the sources of data used in the study. Section 3 documents observational aspects of the rainfall and the mesoscale rain systems that produced the heavy rain. Section 4 illustrates the evolving synoptic-scale flow during the event, including the evolution of the environmental wind shear and frontogenesis processes. Section 5 describes the use of mesoscale observations to (i) document the mesoscale characteristics of the rain systems and (ii) verify high-resolution forecasts. Section 6 illustrates the thermodynamic and kinematic changes that occurred over the local rain area, based on validated high-resolution forecasts. Section 7 shows results from back-trajectory calculations, used to illustrate possible interactions with the storm’s environment and surrounding weather systems. Section 8 offers the summary and our conclusions.

2. Data sources

In this study, extensive use is made of high-density local and international datasets for both describing observed characteristics of the rain event, and for verification of operational, high-resolution forecasts. The observational datasets include high-resolution surface and rain gauge observations over eastern China; composite radar reflectivities from the observation sites at Shanghai, Ningbo, WenZhou, and Hangzhou (see Fig. 2 for locations of Hangzhou Bay and the radar sites, relative to the region of heavy rain); Multifunctional Transport Satellite (MTSAT) infrared imagery; and Climate Prediction Center (CPC) morphing technique (CMORPH) Tropical Rainfall Measuring Mission (TRMM) rainfall estimates (Joyce et al. 2004; Huffman et al. 2007; Ebert et al. 2007). Objective analyses are obtained from the ECMWF interim reanalysis (ERA-Interim; Dee et al. 2011) at 1.5° resolution and the Australian Community Climate and Earth System Simulator–Global (ACCESS-G; Puri et al. 2013) at 0.5° resolution. Operational, high-resolution forecasts are derived from ACCESS-TC (Davidson et al. 2014).

Rainfall data from the 3-hourly, 0.25° × 0.25° CMORPH are used in this study. Comparisons of CMORPH and reanalysis datasets has been carried out by Ruane and Roads (2007), Ebert et al. (2007), and Sapiano and Arkin (2009). An evaluation of CMORPH data during tropical cyclone events can be found in Yu et al. (2009). Assessment of TRMM/TMPA data for tropical cyclone events is provided by Chen et al. (2013a,b). The above studies show that both TMPA 3B42 and CMORPH are suitable for rainfall analyses of TCs as they are highly correlated, with generally low biases when compared against observations, even though they both tend to underestimate heavy rain.

ACCESS-TC was developed for operational and research applications on tropical cyclones. For the application here, after verification, operational forecasts from the system for Fitow are used for model-based diagnostics. A detailed description of the ACCESS-TC system is contained in Davidson et al. (2014). The base system runs at a resolution of 0.11° across 50 levels. The domain is relocatable and nested in coarser-resolution ACCESS forecasts. Initialization consists of five cycles of 4DVAR assimilation over 24 h prior to the initial time and forecasts to 72 h are made. Without vortex specification, initial conditions usually contain a weak and misplaced circulation. Significant effort has been devoted to building physically based, synthetic inner-core structures, validated using historical dropsonde data and surface analyses from the Atlantic. Based on estimates of central pressure and storm size, vortex specification is used to filter the analyzed circulation from the original analysis, construct the inner core of the storm, locate it to the observed position, and merge it with the large-scale analysis at outer radii.

Using all available conventional observations and only synthetic surface pressure observations from the idealized vortex to correct the initial location and structure of the storm, the 4DVAR builds a balanced, intense 3D vortex with a well-developed boundary layer and secondary circulation. Mean track and intensity errors for the Australian region and northwest Pacific storms have been encouraging, as are results from the operational model running at the Australian National Meteorological and Oceanographic Centre. The system became fully operational in November 2011 after extensive verification (Davidson et al. 2014).
The back trajectories shown here are calculated using the HYSPLIT Lagrangian trajectory system developed at NOAA (Draxler and Hess 1998) and implemented at the Australian Bureau of Meteorology (http://www.wmo.int/pages/prog/www/DPS/WMOTDNO778/rsmc-melbourne-a.htm). The trajectories are based upon ERA-Interim analyses every 6 h.

3. Observational aspects of rainfall

Figure 2 shows radar reflectivities, composited from radars at WenZhou, Ningbo, Hangzhou, and Shanghai during Fitow’s landfall. The locations of these radar sites and other relevant place names are shown in Fig. 2 (and later in Fig. 11). The radars’ field of view covers the entire domain plotted in Fig. 2. Fitow’s landfall occurred near 1800 UTC 6 October 2013. Figure 2 illustrates the development of the rainbands (RB1, RB2, and RB3) that correspond with the outer rainbands to Fitow’s north that produced the heavy rainfall, as well as the inner-core convection. Note how RB2 intensifies as it moves to the north. RB3 was very active at landfall but then rapidly weakened within 12 h. The reflectivities also suggest the development of a frontal-like rainband, which appeared to evolve from a secondary outer
rainband (RB2; Figs. 2b–g) and was transformed into a coastal rainband (RB2; Figs. 2i–m) as the inner-core cloud (RB3) rapidly weakened. That is, this band seemed to commence as an outer rainband from the TC that transforms and develops as the environment in which it is embedded evolves. Later we will offer some physically based speculation on the reasons for the development and northward propagation of the rainbands. Figure 3 displays 3-hourly CMORPH rainfall estimates from 0600 UTC 6 October to 0300 UTC 8 October 2013. Although there may be some underestimation of rainfall from CMORPH over land, we have used these estimates mostly to assess rainfall over the ocean, where the estimates are reasonably reliable (Chen et al. 2013b). These independent data support the description of the cloud features indicated from the radar data. There appear to have been three mesoscale rain systems that affected the Hangzhou Bay area, just south of Shanghai near 30°N, 121°E. An initial outer rainband (RB1 in Fig. 2) developed and propagated northwestward across the Hangzhou Bay area during the period 0600–1500 UTC 6 October (top panels in Fig. 2). A second, more active, outer rainband (RB2) developed a few hours later to the south of the first band, propagated to the north, and intensified. It became quasi stationary near northern Zhejiang, just south of Shanghai. RB2 then appeared to rotate into a mostly north–south-orientated line of rainfall, through Shanghai by 0300 UTC 7 October. This rainband fluctuated in strength but extended southward and had a peak in the vicinity of Shanghai and northern Zhejiang around 1800 UTC 7 October. Inner-core rainfall (RB3) was very active at...
landfall but rapidly weakened and dissipated within 9 h (Figs. 2d–g).

Note that the two outer rainbands strengthened as they moved northward. They became mostly separated from the parent Fitow circulation, intensified, and seemed to take on lives of their own. So what processes maintained and enhanced the rain activity from these cloud bands? The inner-core rainfall associated with Fitow was active at landfall, but very rapidly decreased in the 9 h between 1800 UTC 6 October and 0300 UTC 7 October. RB1 appeared to have some characteristics of a warm front, while RB2 seemed to evolve into coastal frontal cloud. Similar characteristics have been described previously for transitioning storms by Harr and Elsberry (2000), Jones et al. (2003), and Kitabatake (2008). This pattern of evolution is consistent with the environmental flow changes, described in section 4, which favored a region of high rainfall near the Hangzhou Bay area (low-level moistening and large-scale ascent), the intrusion of cold, dry air from the north into Fitow’s inner core, and the establishment of a frontal boundary separating cold, dry air from the north and warm, moist air from the east. In section 5b we will discuss observed and forecast rainfall amounts at specific observing sites around Hangzhou Bay. These rainfall observations also support the categories of rain systems discussed above.

4. Synoptic-scale flow changes

a. Flow fields

The remarkable changes in the synoptic-scale flows that occurred prior to and during the heavy rain event are illustrated in Fig. 4. From top to bottom the panels in Fig. 4 show 200- and 500-hPa wind fields, and the mean sea level pressure (MSLP) analysis, at 0000 UTC 3 October (Figs. 4a–c, well prior to the heavy rain), 0000 UTC 5 October (Figs. 4d–f, just prior to the heavy rain), and at 1800 UTC 6 October 2013 (Figs. 4g–i, just at the landfall of Fitow and the start of the heavy rain). The following main points are noted:

1) There was a significant reorganization of the large-scale flow over a very broad area.
2) Between the first and third times illustrated, major surface anticyclones developed over China and the northwestern Pacific with a long, over-the-sea trajectory of low-level easterly flows flowing toward the China coast.
3) TC Danas developed during the period and was located in relatively close proximity to Fitow, just about 1500 km to its east-southeast.
4) Through the midlevels, deep easterly flow is clearly evident and eventually seems to connect the Danas and Fitow circulations. Note as well how Fitow’s midlevel circulation appears to be undergoing capture by the midlatitude trough to the north as northwest-to-westerly flows wrap around the Fitow circulation. We will illustrate that, facilitated by the evolving environment, the TC systems during this capture may have provided a source of midlevel potential vorticity and moisture for the rain system.
5) At upper levels, the large-amplitude trough, while progressive at high latitudes appeared to regress at lower latitudes from just east of China to be located over central China. There was also an intensification and westward extension of the mid- to upper-tropospheric, geopotential ridge toward the coast of China. This change repositioned the entrance to a southwesterly jet to near Hangzhou Bay.
6) The changes in the synoptic-scale flows produced a change in the vertical structure of the horizontal wind field over the rain area. A situation favorable for heavy rain of low-level easterlies overlain by upper-level southwesterlies, suggesting moist isentropic ascent (or warm air advection), had developed near Hangzhou Bay and likely played a role in helping to force ascent.

Based on an analysis of the synoptic-scale flow changes, a favorable situation for very heavy rain was developing in the vicinity of Hangzhou Bay. The precise location of the rainfall and the mesoscale circulations, discussed above, that would produce the rainfall are considered in more detail in the following sections.

b. Environmental vertical wind shear

Wind shear can influence the location of convective asymmetries in TCs (Frank and Ritchie 1999; Corbosiero and Molinari 2002), as well as the organization of mesoscale convective systems (e.g., Houze 2004 and references therein). We have calculated wind shear relative to the Fitow circulation by computing the mean wind at various pressure levels over a 300–500 km annulus centered on the storm’s location. We have made these calculations based on ACCESS-G analyses and the ACCESS-TC forecast. Figure 5 shows a time–height series of mean environmental wind calculated in this way from these datasets. Note that the operational track for Fitow ended, with a central pressure of 1000 hPa, at 0600 UTC 7 October and thus this is the final time in the cross section. Wind shear can be readily inferred from Fig. 5. Comparison between observed and forecast environmental winds that were directly influencing the Fitow circulation suggests that ACCESS-TC was forecasting the near environment of the storm quite well, although the turning of the winds
with height is confined to a shallower layer in the forecast. An interesting aspect in the figures is the trend toward southwesterly wind shear just prior to and during landfall. This can be seen as upper-level southerlies overlay low-level easterlies as the storm approaches landfall along the coast of China. The shear is not large, being of the order of 10 m s\(^{-1}\), and so should not be too detrimental to the storm’s intensity (Frank and Ritchie 1999), thus indicating it should not be a major factor in Fitow’s rapid weakening after landfall. However, the shear would have had the effect of favoring convective development over the north-to-northwest sector of the storm just prior to landfall. As can be seen from Figs. 2 and 3, multiple outer rainbands were observed to develop over this sector. Some of these intensified as they propagated northward and contributed to the heavy rain as they moved into a location favorable for large-scale ascent. We thus suggest that the evolution of Fitow’s environment favored rainband development to its north and this played a major role in the rain event. The presence of Fitow in a weakly sheared environment generated the outer rainbands that were to eventually produce some of the observed heavy rain. Thus, even though heavy rainfall occurred well to the north of Fitow’s center, its presence in favorable vertical shear was critical to the development of the rainbands that were to eventually produce the heavy rain.

c. Environmental conditions over the heavy rain area

Figure 6 shows time–height series over a 1\(^\circ\) latitude–longitude box centered over the heavy rain area, of mean wind, vertical velocity, and potential vorticity.
(PV) from ACCESS-G analyses (6-h intervals) as well as from the ACCESS-TC forecast (3-h intervals). Again, the comparison between the evolution of these analyzed and forecast fields is quite consistent. There is clearly correspondence between the timing of the ascent maxima in the analyzed and forecast fields. Note that the ascent maxima coincide with the timing of the low-level winds turning to the east and the upper-level winds turning to the southwest (i.e., anticyclonic turning with height). However, there is a much deeper layer of stronger southerly winds in the forecasts. At mid- to upper levels high PV existed over the region and increased to a maximum at the time of maximum ascent. The vertical structure of the PV and ascent fields, with maxima through midlevels, suggests that neither vertical advection nor horizontal convergence were dominant processes in enhancing the midlevel vorticity. The evidence suggests that horizontal advection was playing a significant role in increasing the midlevel cyclonic vorticity over the rain area.

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FIG. 5. Time–height plot of the environmental wind (full barb is 10 m s\(^{-1}\)) from 1200 UTC 5 Oct to 0600 UTC 7 Oct 2013, which is defined by the average wind inside an annulus between 300 and 500 km from typhoon center. The filled triangle denotes the time of landfall. (a) ACCESS-G analysis data (time interval is 6 h). (b) ACCESS-TC forecast data (time interval is 3 h) from base time (1200 UTC 5 Oct 2013).
FIG. 6. Time–height series of area-averaged wind (full barb is 10 m s\(^{-1}\)), vertical velocity (≤0.05 Pa s\(^{-1}\); contour interval is 0.05 Pa s\(^{-1}\)), and PV (shading; PVU) over the heavy rainfall area (29.5\(^\circ\)–30.5\(^\circ\)N, 120.5\(^\circ\)–121.5\(^\circ\)E) from 1200 UTC 5 Oct to 1200 UTC 8 Oct 2013. (a) ACCESS-G analysis data (time interval is 6 h). (b) ACCESS-TC forecast data (time interval is 3 h) from base time (1200 UTC 5 Oct 2013).
d. Frontogenesis processes

Examination of the environmental fields suggests that frontogenesis with its associated secondary circulation was active at times during the rain event. Following Srock and Bosart (2009), we have quantified this process using the 2D frontogenesis function:

\[ F_{\text{div}} = \frac{1}{2} \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) \nabla_h \theta, \]

where \( u \) and \( v \) are zonal and meridional wind components and \( \theta \) is potential temperature. Note that the function is the product of horizontal mass convergence and the magnitude of the horizontal potential temperature gradient. From ACCESS-G, Fig. 7 shows analyzed fields of the frontogenesis function at selected times during Fitow’s landfall and the rain event. Note that large values of the function are diagnosed over the heavy rain area and not elsewhere. Notwithstanding the fact that horizontal convergence may be influenced by the presence of moist convection, the previous discussion suggests that the environmental flow changes were also playing an important role in (i) the establishment of the large potential temperature gradients and (ii) low-level convergence. Further evidence of this is provided in Fig. 8, which shows the evolution of potential temperature and wind via west–east and south–north cross sections through the rain area (~30.5°N, 121.5°E). A preexisting potential temperature gradient existed over the rain area near the time of landfall of TC Fitow. But during the following 24 h this gradient concentrated over the rain area in both the zonal and meridional directions. As pointed out by a reviewer, there was a buckling in the isentropes around 118°–120°E and this development of warm- and cold-air boundaries was a sign of the warm-air advection from the east, and cold-air advection from the north. Evidence thus indicates that frontogenesis was a contributing factor to the heavy rain, particularly for the evolution of RB2. The process is very similar to that originally documented in Bosart et al. (1972).
FIG. 8. (a)–(d) Zonal height cross sections along 30°N (121°E) of potential temperature (contour interval is 1 K) and horizontal wind (full barb is 10 m s⁻¹), from ACCESS-G analysis data. (e)–(h) As in (a)–(d), but for meridional height cross sections. The times chosen are the same as in Fig. 7 (from top to bottom): 1800 UTC 6 Oct (landfall time), 0000 and 1200 UTC 7 Oct, and 0000 UTC 8 Oct 2013. The vertical lines mark the region of heavy rain (28°–32°N, 119°–123°E; see Fig. 3).
5. Mesoscale features and verification of ACCESS-TC

In this section high-resolution observational datasets are used to further describe the mesoscale characteristics of the rain event and to verify forecasts from ACCESS-TC.

a. Verification of track and intensity forecast

Figure 9 shows observed and 72-h forecast tracks and intensities from operational ACCESS-TC for Fitow and Danas from base time 1200 UTC 5 October 2013. The forecasts clearly show very useful skill, with track errors for Fitow ranging from about 10 km at t = 0 h to around 150 km at t = 36 h. Forecasts of intensity for Fitow are also encouraging, with the observed and forecast spin-down after landfall being quite consistent, even though the forecast timing of the landfall is in error by about 4 h. For Danas the forecast is less skillful. However, we note that this system actually entered the ACCESS-TC domain through a lateral boundary and thus its location and intensity on entry can be seen to have quite large errors.

Although the forecasts of Fitow’s track and intensity are encouraging, this does not guarantee that its evolving structure and rainfall have also been forecast well (e.g., Davidson and Ma 2012). We demonstrate below that the rainfall prediction from this forecast also verifies quite well and so we are confident that the forecast can be used to obtain detailed diagnostics to document and understand the kinematic and thermodynamic processes over the rain area.

b. Verification against rain gauge observations

Figures 10a–c show analyzed, accumulated rainfall from the dense rain gauge network over eastern China. Figures 10d–f show the corresponding forecast rainfall from the 1200 UTC 5 October ACCESS-TC forecast. Although there are clearly errors in the forecast, particularly at the mesoscale, the forecasts show encouraging skill in rainfall prediction for these time scales. Comparison of the 2-day observed and forecast accumulations, which of course eliminates some of the timing errors in the forecast rainfall, is particularly encouraging. There is perhaps some indication of the mesoscale rain features described earlier even in these diagrams. The inner-core rainfall (RB3 in Fig. 2), the first rainband (RB1 in Fig. 2), the second rainband (RB2), and the later coastal rainfall (southern part of RB2 in Fig. 2) are indicated in these forecast accumulations by the large values initially around Hangzhou Bay and the development of large values along the coast at a slightly later time.

We additionally note that observed or forecast heavy rainfall was located on the windward slope of the terrain (Figs. 10c,f,i) in the low-level northeast and easterly flow (Fig. 7). Also evident is the developing frontal boundary along the coast with convergence between northerlies over land and easterlies over the ocean. The coastal front and surface convergence are collocated with the region of heaviest rainfall (RB2). It is quite possible that up slope flow in the developing and persistent onshore easterly winds acted to release convective instability to maintain the intense rainfall. Effects of the underlying terrain on rainfall maintenance and even reinforcement associated with the circulation of landfalling tropical cyclones can be found in Niu et al. (2005) and Dong et al. (2010). It is difficult to separate the effects of orographic uplift and environmental influences on the rainfall. The analysis conducted here suggests a modulation of the rainfall by the topography in an evolving environment highly conducive to heavy rainfall. It may be of interest to conduct some experiments on the sensitivity to model topography.

Detailed verification of the timing and intensity of rainfall is illustrated in Fig. 11, which shows 3-hourly observed and forecast accumulated rainfall amounts for six surface observing stations. The top panel in Fig. 11 shows the locations of cities used for the verification. Of course, this point comparison represents a very difficult form of verification, but the forecast does quite well. The first heavy rain episode occurred between about 1200 UTC 6 October and 0300 UTC 7 October and was quite well predicted by the model (cf. black and gray banners). We suggest that this rain corresponded with the northward-propagating rainbands described earlier. The impact of these rainbands is evident mostly at Wenlin, Ningbo, Yuyao, and Hangzhou, which are all located farther south than Jiaxing and Shanghai. As can be seen in Figs. 2 and 3, these stations were in the direct path of the outer rainbands as they propagated northwest and intensified. Rainfall from these rain systems at locations just slightly farther north was much less, but not insignificant. A separate, local heavy rain event appears to occur between about 1800 UTC 7 October and 0300 UTC 8 October, 1 day after landfall. This rain was associated with the north–south-orientated, coastal rainband that developed a little later (as shown by RB2 as it shifted from a northwest–southeast orientation to a north–south direction). Based on the evidence presented in section 4d of the presence of active frontogenetic processes, we suggest that coastal frontogenesis (e.g., Bosart et al. 1972) played an important role in this rainfall. The rain feature is very distinct from other previously documented rainfall
FIG. 9. Operational tracks and intensities issued by CMA (black lines) and forecasted by ACCESS-TC (red lines) for Typhoons Fitow and Danas. (a) Tracks, with filled circles (open squares) denoting Fitow’s (Danas’s) positions every 6 h from 1200 UTC 5 Oct to 1200 UTC 8 Oct 2013 (Note that Fitow’s track report ended at 0600 UTC 7 Oct 2013). (b) Comparison of Fitow’s MSLP (solid line) and maximum surface wind (dashed line). (c) As in (b), but for Danas.
types like the inverted typhoon trough discussed by Niu et al. (2005). The forecast does not predict this point rainfall at this time particularly well, but we note that the forecast had small timing and location errors, which caused poor verification based on this metric. The forecast did produce rain at this time, but it was not quite heavy enough and occurred at a place and time that were slightly different than the observed. It is of interest though that the model did still try to generate some coastal rainfall during the period (see Figs. 10c,f and 13).

c. Verification against satellite imagery and CMORPH data

Figure 12 shows a comparison between synthetic infrared satellite cloud imagery from ACCESS-TC and actual infrared imagery from MTSAT at 1500 UTC 5 October, 1800 UTC 6 October, and 0300 and 1200 UTC 7 October. Base time of the ACCESS-TC forecast is 1200 UTC 5 October 2013. This diagram illustrates large-scale aspects of the evolving observed
FIG. 11. The 3-hourly accumulated rainfall (mm) recorded by six surface stations from 1500 UTC 6 Oct to 0300 UTC 8 Oct 2013. The black (gray) banners denote 3-h observed (forecasted) rainfall by rain gauges (by ACCESS-TC). The locations of the six surface stations are shown as red triangles in the top panel. The stations are Wenlin, WL; Ningbo, NB; Yuyao, YY; Hangzhou, HZ; Jiaxing, JX; and Shanghai, SH. Hangzhou Bay separates SH to the north and NB to the south.
and forecast cloud fields in which the mesoscale rain systems were embedded. There is clearly encouraging coherence between the synthetic and actual imagery. A striking feature of the imagery is the developing extratropical interaction, best indicated here by the cloud streaming out of the storm in an extended outflow channel and in association with a southwesterly jet streak, described in section 4. Such midlatitude trough interactions and outflow channels are regularly associated with intensifying or transitioning TCs (e.g., Chen and Gray 1985; Klein et al. 2000) and may also occur with other heavy rain events, like PREs (Cote 2007; Dong et al. 2010). So why did Fitow not undergo ET? As indicated by Ritchie and Elsberry (2007) and Atallah et al. (2007), the upper trough may have been too distant from Fitow for it to influence an ET. The rapid decay of the inner-core rainfall is also evident, as is the presence and persistence of cold clouds over the rain area near 30°N, 120°E. The forecast for Danas is not particularly skillful, since the forecast is slow in moving the storm to the north. Its intensity, as suggested by the forming eye in the actual imagery, is also not well forecast.

It is also interesting to study the evolution of the forecast rainfall at higher time resolutions. Similar to Fig. 3, which shows estimated CMORPH rainfall at 3-h intervals, Fig. 13 shows 3-hourly forecast rainfall accumulations from the ACCESS-TC forecast. Interesting aspects of the forecast, which bear many similarities to the observed rainfall described earlier, include the following points:

(i) Rainfall asymmetries develop to the north and northeast of Fitow, consistent with the diagnosed environmental southwesterly shear acting on the storm’s circulation (Figs. 13a–d).
(ii) There is development of multiple active outer rainbands in the northeast sector of the Fitow circulation that propagate north or northwestward (Figs. 13e–h).
(iii) There is a very rapid decrease in inner-core rainfall after landfall (Figs. 13e–l).
(iv) There is evidence of coastal rainfall, although not as intense as observed, along the coast of Zhejiang province, south of Hangzhou Bay (Figs. 13i–p).

The operational forecast provided useful, but far from perfect guidance on the impending heavy rain event. In subsequent sections we will use the forecast to further explore possible dynamical and
thermodynamic reasons for the heavy rain and Fitow’s rapid dissipation.

d. Verification against surface observations

Boundary layer wind and moisture are critical to the development of convection and thus we have used these variables as metrics of forecast quality. Figure 14 shows a comparison between observed winds from the surface observing network and forecast 10-m winds from ACCESS-TC at various times during the rain event. The RMS errors at each analysis time are shown in Fig. 14g. The diagram and the quantitative verification indicate that there are reasonable comparisons to be made between the observed and predicted winds and dewpoint temperatures. The mean RMS errors over the forecast for vector wind and dewpoint are about 5 m s$^{-1}$ and 1.5 K, respectively. These errors are only marginally larger than the observational measurement and scale-dependent
errors. This quite good comparison, together with other verification, suggests that the model is representing changes in the thermodynamics and kinematics of the real atmosphere over the rain area reasonably well.

6. Thermodynamic and kinematic changes over the local rain area

The verification above indicates that the ACCESS-TC forecast may be representing many observed aspects of the rain event and so we now use the forecast to analyze the possible thermodynamic and kinematic changes within the local rain area. Note that because of its relatively high time and space resolution, more realistic ascent field, and the implied dynamical balance inherent in the forecast model, we believe that use of the model output adds value to that available in global analyses. Critical to the evolution of an efficient rain system are the availability of moisture, the production and maintenance of convective instability (here monitored using the figure).

Fig. 14. (a)–(f) Observed winds from surface stations (blue wind barb; full barb is 10 m s\(^{-1}\)) and dewpoint temperature (blue; K), and ACCESS-TC-forecasted 10-m wind (red wind barb) and surface dewpoint temperature (red value) every 6 h from 1200 UTC 6 Oct to 1800 UTC 7 Oct 2013. (g) The RMSE of surface wind and RMSE of dewpoint temperature are indicated by solid (dashed) lines from 1500 UTC 5 Oct to 1200 UTC 8 Oct 2013. The maximum, minimum, and mean errors are given at the bottom.
the vertical gradient in equivalent potential temperature, vertical wind shear, the presence of conditions favorable for large-scale ascent, and possibly inertial stability (vorticity) (since this may influence the ease with which horizontal flows can transport moisture to the rain area). An ingredients-approach based on lift, moisture, and instability is discussed in, for example, Doswell et al. (1996). Changes in some of these parameters have been discussed earlier in this article. Figure 15 shows forecasts every 6 h leading up to the heavy rain event of equivalent potential temperature and wind at 975 hPa obtained from the ACCESS-TC forecast from base time 1200 UTC 5 October 2013. As discussed above, the 3-hourly accumulated rainfall shows many of the observed features of the rainfall. These features include the model's representation of (i) the inner-core rainfall and (ii) the active, northward-propagating rainbands during landfall. There are some indications of the frontal rainband (Fig. 15e), but the model has underforecast the rainfall associated with this feature. High theta-e air begins to enter Hangzhou Bay and surrounding areas around 1200 UTC 6 October as southeast-to-northeast winds (Fig. 4) enter the region and start to converge. From this time, the outer rainbands begin to form. Low theta-e air, initially located to the west of Shanghai and TC Fitow, begins to wrap into the

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**Figure 15.** (a)–(i) ACCESS-TC 975-hPa equivalent potential temperature (color shading) and winds (full barb is 10 m s\(^{-1}\)), and 3-hourly accumulated rainfall (green; contour interval is 20 mm) every 6 h from 0600 UTC 6 Oct to 0600 UTC 8 Oct 2013.
circulation at landfall and the inner-core rainfall and circulation rapidly spin down as this occurs. At the same time, a boundary between low and high theta-e air is established near the coast, with high theta-e air in the easterly flow over the ocean and low theta-e air in the wraparound flow from the north. These conditions are associated with a combination of warm (cold) and moist (dry) advection from the east (north) and are very suggestive of frontogenetic processes.

These characteristics bear similarities to classical ET of TCs (e.g., Klein et al. 2000). However, for TC Fitow and based on Fig. 15, there is no evidence that the circulation transitioned into an extratropical cyclone. To examine the structural changes over the heavy rain area, Fig. 16 shows time–height series, over a $2^\circ \times 2^\circ$ box centered on the rain area, of vertical motion ($\omega$), equivalent potential temperature, relative vorticity, and relative humidity from the ACCESS-TC forecast, base times 1200 UTC 4 and 5 October 2013 (Figs. 16a–c and Figs. 16d–f, respectively). These base times are chosen because although they show many common characteristics, the earlier forecast did not predict the heavy rain as well as the later forecast, and it is of interest to try and find the differences in the two forecasts as a means of isolating some critical aspects of the heavy rain event. The following main points are noted:

1) Both forecasts predict ascent at approximately the right time, although the later forecast has stronger and more enduring ascent.

2) Low-level moistening occurs prior to the heavy rain and this coincides with diagnosed large-scale upper- to midlevel subsidence. We suggest that this is an important preconditioning phase that temporarily inhibits the development of deep convection, while allowing the boundary layer to moisten for the later heavy rain.

3) Large increases in low-level theta-e occur prior to the heavy rain, in association with the moistening. As a consequence, the convective instability increases substantially (decreasing theta-e with height) prior to the rain and is maintained through most of the event.

4) Low-level convergence (not shown) and ascent begin to increase prior to the heavy rain and seem also to be aspects of the preconditioning. This continues during and even after the rain event. The unique aspect of the convergence field is the deepening in this parameter during the heavy rain. It remains unclear if this is related to the presence of rain clouds and their heating profiles or some other effect like environmental flow changes.

5) Low-level moistening begins prior to the onset of heavy rain. Relative humidity reaches values of greater than 90%. The rapid moistening in the lead up to the event indicates the presence of large convective instability.

6) Low-level vorticity within the rain area also begins to increase prior to the heavy rain. Like convergence, it deepens during the actual rain event and then again mostly becomes confined to low levels after the rain subsides. As above, it remains unclear if this is related to the presence of rain clouds and their heating profiles or are some aspect of the environmental influence. We currently speculate that it may be at least partially influenced by the PV changes associated with environmental interactions (see section 7).

7) The major differences between the failed and successful rain forecasts are (i) understandably, the ascent field over the rain area and (ii) the much deeper and stronger vorticity tower that exists in the successful forecast between 1200 UTC 6 October and 1200 UTC 7 October. These two differences may be connected, but we speculate that the vorticity tower may be related to the injection of moist PV from Fitow (section 7), which could alter the vertical PV structure of the rain system and thus the ascent field.

An important aspect of the rain systems is that they developed as intensifying outer rainbands within the Fitow circulation. The development and northward propagation of the outer rainbands require more study and will be the subject of ongoing work. Our preliminary diagnostics suggest that they formed to the northeast of Fitow’s center in environmental southwesterly wind shear, which would favor convective development over this sector. The reasons for the outward propagation still remain unclear and will be the subject of ongoing study.

7. Back trajectories from the rain area

Changes in the vertical structure of a weather system can influence the vertical motion field associated with the circulation. Previously, we have shown that moist isentropic ascent (warm-air advection), a quasigeostrophic (OG) ascent mechanism, was prominent during the event. Another mechanism suggested by OG theory is differential vorticity advection that can be diagnostically related to the vertical motion field (Holton 1979; Hoskins et al. 1985). This could also be viewed as the weather system’s attempt to rebalance its three-dimensional circulation after the balance is disrupted by changes in its vertical structure. For the Fitow event there appeared to be interactions with the environment that influenced the evolution of the rain-producing weather system. To quantify these interactions, back trajectories from the rain area were calculated using the HYSPLIT system developed at NOAA (Draxler and
FIG. 16. (a) Time–height plot of area-averaged wind (full barb is 10 m s$^{-1}$), vertical velocity [$\omega$, with red (blue) indicating ascent (descent); Pa s$^{-1}$], and relative vorticity (positive contour interval is $10 \times 10^{-6}$ s$^{-1}$, negative contour interval is $20 \times 10^{-6}$ s$^{-1}$); (b) equivalent potential temperature (contour interval is 3 K), with the values greater than 342 K indicated by red contours; and (c) relative humidity (contour interval is 5%), with the values greater than 70% indicated by red contours. Averaging box is over the heavy rainfall area (29.5$^\circ$–31.5$^\circ$N, 120$^\circ$–122$^\circ$E) from ACCESS-TC at base time 1200 UTC 4 Oct 2013. (d)–(f) As in (a)–(c), but from ACCESS-TC at base time 1200 UTC 5 Oct 2013. Note that time increases from right to left. Filled triangle denotes landfall time (1800 UTC 6 Oct 2013).
Hess 1998) and implemented at the Australian Bureau of Meteorology (http://www.wmo.int/pages/prog/www/DPS/WMOTDNO778/rsmc-melbourne-a.htm). The trajectories are based upon ERA-Interim analyses (Dee et al. 2011) available every 6 h at 1.5° horizontal resolution.

A set of grid points (197 at each level, 0.5° apart), over an area enclosed by a radius of 4°, located within a three-dimensional volume centered on the rain system, are specified from which back trajectories are calculated. We have chosen levels at 1, 3, and 7 km to make the back trajectories. These were selected based on examination of the wind analyses at various levels (Fig. 4). The time at which the back trajectories were initially calculated is 0600 UTC 7 October: the approximate time of the start of the heavy rain and following Fitow’s landfall.

Figure 17 shows a representation of the three-dimensional back trajectories. The legend in the top right corner in Fig. 17 shows the symbols used to indicate the level value. The colors on the trajectories indicate values of PV along each trajectory. Figure 17 clearly shows four substantial environmental interactions that were influencing the circulation and its vertical structure over the rain area:

1) low-level inflow at 1 km from the east, which was warm and moist;
2) mid- to upper-level inflow from the southeast with relatively high PV, in a streamer with generally constant PV, which originated from the Fitow circulation;
3) midlevel (3 km) injection of enhanced PV from the east-southeast, which originated from the Danas circulation; and
4) mid- to upper-level injection of PV from the west, which originated from the midlatitude, high-amplitude trough.

It is clear from the previous discussion that changes in the synoptic-scale circulation produced the flows that resulted in these back trajectories. We suggest that intrusion of environmental PV and moisture into the rain area, brought about by environmental flow changes, was critical to the development of the heavy rain event. We suggest that this exchange of PV and moisture is one way to interpret the interaction between weather systems and their environments. Because of the limited domain size, we have not confirmed at this stage whether the ACCESS-TC forecasts reproduced these analyzed back trajectories. This will be part of our ongoing work and should establish if these environmental injections of PV were critical to the success or otherwise of the rain forecasts.

To illustrate how and when these environmental flow changes and interactions occurred, we have calculated back trajectories from the rain area at 7 km (the level where large interaction with the environment seemed to be occurring, as defined above) at times leading up to the rain event. Figure 18 shows back trajectories from 0000 UTC 5 October (well prior to the rain), 0000 UTC 6 October (just prior to the rain and landfall), and 0000 UTC 7 October (during the heavy rain). In addition, at each level we keep track of the area influenced by air coming from the environment (beyond 600 km from the center of the rain area, 30°N, 120.5°E) and also the percentage of PV that comes from the environment. Figures 18d and 18f show times series of “A,” the percent area of air from the environment, and “PV,” the percent PV coming from the environment. To relate the trajectories back to the wind fields, we also show wind analyses at 500 hPa, with the relative vorticity overlaid, and 700 hPa at the corresponding times.

The trajectories show that well prior to the rain event, the area where rain developed was only influenced by trajectories that came from the west. This is confirmed from the corresponding wind analysis. As the event began to unfold, in addition to the trajectories from the west, a large amount of high-PV air was entering the rain area from the Fitow circulation. The wind analysis suggests that this air was exiting the storm circulation over Fitow’s north and northeast sectors and entering the rain area from the east. A lobe of cyclonic relative vorticity is seen to start exiting from the Fitow circulation from its north-northeast sector at 0000 UTC 6 October, and this lobe increases in size and strength over the next 24 h.
as it rotates toward the rain area. We suggest that the large-scale flow changes had opened up the Fitow circulation via the developing environmental trough (marked in Fig. 18), which had developed to the northwest. This “wound” then “bled” PV and moisture from Fitow into the rain area—the lobe of cyclonic vorticity in Fig. 18. An anonymous reviewer suggested that an alternative interpretation could be that increased deformation in the environment strained/elongated the Fitow vorticity into an open wave structure rather than a...
closed circulation pattern, and that there appears to be a reorganization of vorticity from a curvature-dominated flow to a shear-dominated flow. We hope to investigate this further using a form of the Okubo–Weiss parameter (Dunkerton et al. 2009; Tory et al. 2013). The deformation interaction between the trough and Fitow seems crucial to the rain event. It is quite possible that, apart from the inflow of cold, dry air, the drainage of moisture and PV from Fitow may have also contributed to its rapid demise and resulted in it being unable to transition into an extratropical cyclone. At the later time, there was also inflow coming from Danas via the developing large-scale easterly winds to the east of the rain area. We suggest that the resulting differential PV structure change over the rain area was important in the development of ascent and rainfall.

Finally, to further confirm the role of Fitow and Danas in supplying the rain system with moisture via the environmental flow, Fig. 19 shows moisture flux at 6-h intervals during the rain event obtained from

\[ Q = \nabla_h \cdot (q \nabla_h / g) , \]

where \( Q \) is the horizontal water vapor flux, \( g \) is the gravitational acceleration, \( \nabla_h \) is the horizontal wind vector, and \( q \) is the mixing ratio of water vapor. Figure 19 shows three contributions to the moisture flux affecting the rain area, similar to the back trajectories. These are from the environment to the east of the rain area, from TC Fitow, and from TC Danas. The analysis suggests that Fitow and Danas supplied both moisture and midlevel PV to the rain system. Detailed numerical experimentation and diagnostics are required to further clarify the roles of Fitow and Danas on the rain event.

8. Summary and conclusions

Late on 6 October 2013, Tropical Cyclone Fitow made landfall south of Shanghai, China, near the border of Zhejiang and Fujian Provinces. During the event, rainfall in excess of 300 mm day\(^{-1}\) was observed over a region 400 km to the north of the typhoon center. Fitow did not undergo extratropical transition, since there is no evidence of it transitioning into an extratropical cyclone. The heavy precipitation occurred in the days following landfall and so the rain was not a predecessor rain event to Fitow. With TC Danas located some 1000 km to the east, it has similarities to predecessor rain events described, for example, by Galarneau et al. (2010).

Major features of the heavy rain have been investigated using satellite data, radar reflectivity, standard meteorological observations, global analyses, and high-resolution forecasts. We have used composite radar reflectivities, CMORPH rainfall estimates, and surface observations to show that the rain was associated with (i) an initial outer rainband from Fitow, which developed and propagated northwestward across the Hangzhou Bay area (just south of Shanghai) during the period from 0600 to 1500 UTC 6 October; (ii) a second, more active outer rainband that developed a few hours later to the south of the first band, propagated to the north, and intensified; and (iii) a southwest–northeast-orientated line of frontal-like cloud, which appeared to evolve out of the second, more active rainband, which organized and fluctuated in strength as it extended southward, and which eventually produced a severe city flood in Shanghai. This latter development appears to be a different and unique feature of the Fitow event that distinguishes it from other TC cases discussed in the literature. The outer rainbands developed in the northeast sector of Fitow’s circulation, which was the favored region for convective asymmetries in the environmental southwesterly wind shear. The presence of Fitow in favorable shear was thus a very critical ingredient in the development of the rain systems that produced the heavy rain. These provided the rain-producing focus for the large-scale forcing.

We have shown that the heavy rain occurred as the large-scale flow reorganized. Major surface anticyclones developed over China and the North Pacific, resulting in the development of long, low-level, over-the-sea trajectories into the Hangzhou Bay area. At upper levels, a high-amplitude trough retrogressed over low latitudes to be located over central China with the entrance to a southwesterly jet positioned near Hangzhou Bay and Shanghai. The vertical structure of the horizontal wind field was thus upper-level southwesterlies overlaying moist, low- to midlevel easterlies. This is a very favorable structure for large-scale vertical motion associated with moist isentropic ascent or warm-air advection (e.g., Hoskins et al. 1985).

On the synoptic scale, based on back trajectories, we have demonstrated that four environmental interactions associated with the evolving large-scale flow occurred that likely influenced the development of the heavy rain. These included (i) increasing injection of midlevel moist potential vorticity (PV) from the Fitow circulation; (ii) low-level warm, moist inflow from the east; (iii) midlevel inflow from nearby Typhoon Danas; and (iv) decreasing injection of mid- to upper-level PV from the midlatitude trough. We propose that the resultant change in PV structure over the rain area was a major influence on the rain event. Analysis of the back
trajectories suggests that the environmental flow changes may have opened up the Fitow circulation through the midlevels and drained moisture and PV from the storm into the rain area. This may also have contributed to Fitow’s rapid demise and prevented it from transitioning into an extratropical cyclone.

At the mesoscale, and consistent with the trajectory calculations, there were large increases over the rain area in diagnosed ascent, low-level moisture, equivalent potential temperature, convective instability, and mid-level relative vorticity. There is evidence of a preconditioning period prior to the heavy rain during which time large-scale midlevel subsidence and boundary layer moistening occurred. Based on an analysis of low-level equivalent potential temperature, we have shown that (i) after landfall, a cold, dry airstream wrapped into the Fitow circulation from the north and west, limiting the inner-core rainfall and producing a cold-air boundary,
and (ii) a warm, moist airstream from the east converged with the cold-air intrusion over the rain area. This frontogenesis and the associated secondary circulation contributed significantly to the enhanced rainfall in the Shanghai area.

In this study we have (i) documented the mesoscale rain systems that produced the heavy rain and (ii) provided evidence of how the environmental flow changes influenced the mesoscale systems to evolve into efficient rain producers: real environmental interactions. We hope to delve more deeply into various aspects of the dynamics and thermodynamics of the event. Future studies could include addressing these questions:

(i) Why was most of the numerical guidance poor? Perhaps the models did not properly represent (i) Fitow’s horizontal and vertical structure and hence the rain-producing outer rainbands or (ii) the trajectories of air that entered the rain area.

(ii) Precisely how and why did the environmental flow changes and PV injection influence the event? The deformation interaction between the trough and Fitow through the mid- to upper levels seems crucial to the PV drainage and then the rain event.

(iii) What were the impacts of the development and propagation of the outer rainbands, which developed during the event and provided the focus of the larger-scale forcing for the heavy rain?

(iv) What are the details of the influence of frontogenesis during the event?

(v) What was the impact of diurnal variation and radiative processes on the evolution of Fitow and the rain systems (e.g., Melhauser and Zhang 2014)? These will be the subjects of ongoing investigations.

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