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Recent progress in the fundamental understanding of tropical cyclone motion

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ABSTRACT

While the fundamental understanding of the movement of a tropical cyclone (TC) is fairly mature, there are still notable advancements being made. This paper summarizes new concepts and updates on existing fundamental theories on TC movement obtained from simplified barotropic models, full-physics models, and data analysis particularly since 2014. It includes the recent works on the interaction of the TC with its environment and the fundamental aspects of predictability related to TC movement. The conventional concepts of the steering flow, β-gyre, and diabatic heating remain important. Yet, a more complete understanding of mechanisms governing TC movement serves as an important basis toward the further improvement of track forecasts.
1. Introduction

Amongst all the elements of tropical cyclone (TC) forecasting, the position (commonly referred to as “track”) forecast is considered by many forecasters to be the most important metric, because the forecasts of intensity, rainfall, and storm surge become less meaningful if the track forecast is wrong. The movement of a TC is largely controlled by the synoptic-scale flow, but it is also modified by the β-gyre effect and the diabatic heating. Because of the importance of the TC track, the effects of topography, land-sea contrast and the interaction with other systems on the TC motion have also been intensively studied for a long time.

However, there has recently been considerable progress in understanding the movement of the TC. With the errors in track forecasts decreasing over several decades, consideration of the physical processes that were previously thought of as "minor" have become more important. It is also important to highlight the updated understanding of well-known mechanisms, and the fundamental aspects of predictability related to TC movement.

Therefore, this paper reviews on the very recent fundamental findings that would serve as an important basis toward the further improvement of track forecast. We do not repeat detailed discussions on the concepts mentioned earlier in the excellent reviews by
Elsberry (1995), Chan (2010, 2017) and in the report on the TC track in 8th International Workshop on Tropical Cyclones (IWTC-8) by Elliot and Yamaguchi (2014). To do so, the focus is placed particularly on the fundamental and theoretical progress since 2014. Although the recent advances in the forecasting skill of operational centers and the new techniques are out of our main focus, Heming et al. (conditionally accepted in TCRR) reviews the recent progress in TC track forecasting and expression of uncertainties, and Magnusson et al. (2019) reviews the recent advances in understanding difficult cases of track forecasts for more details.

The paper is organized as follows. In Section 2, the conventional concept of steering is revisited. In Section 3, updated understandings obtained from a non-divergent barotropic model are introduced. Sections 4–7 describe the new findings and updates on the recurvature, influence of terrain, air-sea interaction, and large-scale features, respectively. Section 8 shows recent studies on the dynamics of large forecast errors. In Section 9, our conclusions are summarized.

2. Revisit to the concept of steering flow

Previous studies agree that TC motion is primarily driven by the environmental steering flow (e.g., Chan and Gray 1982). The environment steering wind is driven by
synoptic-scale features in the vicinity of the TC and the definition can be broadened to include the effect of mesoscale features and subsynoptic-scale asymmetric circulations such as $\beta$-gyres generated by the interaction between the TC circulation and planetary vorticity gradient. An optimal environmental steering flow, which varies the vertical extent of the steering layer and the radius, has successfully accounted for the TC track in many cases (e.g., Velden and Leslie, 1991; Galarneau and Davis, 2013).

Recently, Wu and Chen (2016) conducted the potential vorticity tendency (PVT) diagnosis for the sub-kilometer high-resolution simulation of Typhoon Matsa (2005) to address the question why the steering flow is important in TC motion. They found that the conventional deep-layer-mean steering, which is optimally determined over a certain radius from the TC center (defined as the geometric center of the circle on which the azimuthal-mean tangential wind reaches a maximum), plays a dominant role in TC motion because the contributions from other processes are largely canceled out due to the coherent structure of the TC circulation. The conventional steering approximately accounts for the combined effect of the contribution of the advection of the symmetric potential vorticity by the asymmetric flow and the contribution from the advection of the wave-number-one potential vorticity component by the symmetric flow except the
short-time fluctuations (Fig. 1). Therefore, the conventional steering represents the TC
motion by averaging over a reasonable time period.

They also argue the short-time fluctuations that cause the deviation of the
conventional steering from the instantaneous TC motion. It is reasonably explained by
the trochoidal motion, which is reproduced in their high-resolution simulation as an
oscillation of the TC motion speed with respect to the 9 h running mean. Although the
displacement from the 9 h running mean track is usually less than 6 km, the fluctuation
cannot be accounted for by the conventional deep-layer-mean steering flow.

3. Barotropic framework

Recently, Gonzalez et al. (2015) have examined the linear \( \beta \)-gyres as a stream
function dipole with a uniform southeasterly ventilation flow across the vortex obtained
from a barotropic non-divergent model\(^1\). The \( \beta \)-gyre effect can be interpreted in terms of
a wave number-1 vortex Rossby wave. Based on Cotto et al. (2015), the frequencies of
vortex Rossby waves in cylindrical coordinates are confined to a “passband” between
zero frequency and theoretical limit as exemplified in Fig. 2. Because the positive mean
radial gradient of the vorticity in the outer region constitutes an outer waveguide that

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\(^1\) In this paper, a TC primary circulation is anticlockwise unless noted otherwise.
supports very-low-frequency vortex Rossby waves, the reproduced structure of $\beta$-gyre clearly depends on the radial profile of the basic vorticity field. In other words, the TC translation speed associated with $\beta$-gyre depends on the profile of outer basic vorticity. They also show that although the simulated storm with the linear model accelerates to unrealistically fast speed (8.5 m/s), the introduction of non-linearity yields the forced wavenumber-1 gyres that have opposite phase of the linear gyres. In their simulation, the ventilation flow counteracts the advection by the linear gyres to limit the overall vortex speed up to approximately 3 m/s.

Scheck et al. (2014) investigated the structure and evolution of singular values (SVs) for a stable TC-like vortex in background flows with horizontal shear using a non-divergent barotropic model (Fig. 3). In anti-cyclonic shear with westerly wind to the north, the leading initial SV for a stable TC-like vortex is aligned with streamlines connected to stagnation points. The singular value for the leading SV for anticyclonic shear is larger than that for the cyclonic shear. The evolved SV indicated a southwest-northeast displacement of the vortex. This is associated with the efficient advection by the outer perturbation. Their work suggests the importance of decreasing errors around the stagnation points for improving track forecasts of TCs in anti-cyclonic shear with westerly wind to the north.
4. Recurvature

The recurvature is basically explained by the change of the environmental flow that steers the TC. Recent works have shown that the occurrence and location of the recurvature are sensitive to the sea surface temperature (SST) field and the size of TC, as discussed in Sections 5 and 6. Notably, it has been found that a TC initiated at a higher latitude can recurve by itself even in the absence of background flow (Chan and Chan, 2016; Fig. 4). Differential horizontal advection of the planetary vorticity by the TC circulation at different vertical levels leads to the development of vertical wind shear (known as the β-shear), upper tropospheric anticyclone, and asymmetric distribution of convection. The flow associated with the upper tropospheric anticyclone on the equatorward side of the TC and the diabatic heating associated with the asymmetric convection combine to cause the TC to recurve as the intrinsic property. Given that a TC located at a higher latitude has a slower development (Li et al., 2012), the anticyclonic outflow of a higher-latitude TC therefore advects the upper tropospheric anticyclone less outward (see Fig. 3 of Chan and Chan (2016)). As a result, the upper tropospheric anticyclone of the TC at the higher latitude is located closer to the vortex and thus has a greater influence on the TC movement. It subsequently leads
to the convection and diabatic heating asymmetries to cause the intrinsic recurvature at higher latitudes. This mechanism is thought to play some role in the movement of the TC at a higher latitude, when, in particular, the environmental steering flow is weak.

5. Influence of topography

The interaction between terrain, basic flow and the TC is non-linear. Recent studies have made efforts in further understanding of the mechanisms leading to TC track deflection (Lin et al., 2016). The following mechanisms have been proposed to explain the upstream track deflection: (1) Advection by orographically blocking basic flow, (2) Channeling effect, (3) Asymmetric latent heating, (4) Asymmetric steering flow in middle levels, (5) Terrain induced gyres, (6) Approach angles and landing location.

Tang and Chan (2014) analyzed the terrain effect in Taiwan and the Philippines. The terrain induced gyres are found over both Central Mountain Range of Taiwan and the mountains of Luzon. A pair of terrain-induced gyres rotate cyclonically around the TC, and the flow associated with the gyres starts to push the TC northward (Fig. 5). As the TC is about to make landfall, the anticyclonic gyre is located north and the cyclonic gyre south of the TC. Furthermore, the height of the terrain controls the strength of the terrain-induced gyre, with weaker gyre in the Philippines terrain simulation. The PVT
diagnosis showed that while horizontal advection played a major role, and the importance of diabatic heating became comparable during the landfall period.

Jian and Wu (2008) and Huang et al. (2011) suggested that the low-level channeling effect is the main contribution to the track deflection for a TC that is very close to the land. In other words, a low-level northerly jet can form in the channel in the western quadrant of the approaching westward-moving storm, where the inner-core circulation is constrained by the presence of the terrain. Wu et al. (2015) investigated a different mechanism related to the effect of sudden track changes of TCs approaching to Taiwan. An important finding in the study is that the robust flow characteristic identified during the southward turn of a TC is the azimuthally asymmetric tangential wind at middle levels, instead of low levels. The azimuthal change in the wind speed is connected to the azimuthal change in vertical velocity. Sensitivity experiments with respect to different parameters demonstrated that the southward track deflection is a common phenomenon prior to landfall. The results also suggest that when the terrain is higher, a TC approaches the northern part of the terrain, or when the translation speed is lower, the track deflection of the TC would be prominent. Other parameters such as the width and length of the mountain, and the radius of maximum wind (RMW) have relatively limited effects on the track of the TC.
Lin et al. (2016) used the vorticity tendency (VT) diagnostic to examine the southward deflection of TC. When the TC was upstream the mountain, the easterly basic flow became sub-geostrophic as a result of orographic blocking. The TC decelerated and was deflected to the south, with the VT primarily dominated by the horizontal advection (see Fig. 1 of Lin et al. (2016)). After that, the TC passed over the mountain clockwise, steered by the orographically generated high-pressure. During this time period, the VT was mainly contributed by the horizontal advection and stretching terms. The diabatic heating was linked with the northwestward movement over the lee-ward slope. The enhanced advection of eyewall convective clouds associated with diabatic heating contributed to the abrupt turning of the TC to the northwest.

Both the channeling effect and the asymmetries in the mid-levels, contribute to the southward track deflection of a TC. Huang and Wu (2018) investigated the motion of a TC that is deflected southward while moving westward toward idealized terrain similar to that found in Taiwan. The analyses of both the flow asymmetries and PVT demonstrate that horizontal advection contributes to the southward movement of the TC [see Fig. 9 of Huang and Wu (2018)]. The track deflection is examined in two separate time periods, with different mechanisms leading to the southward movement. The changes in the background flow induced by the terrain first cause the large-scale
steering current to push the TC southward, even though the TC is still far from the
terrain. As the TC approaches the idealized topography, the role of the inner-core
dynamics becomes important. Figure 6 shows that the TC-terrain-induced channeling
effect results in further southward deflection of the track at the integration time of \( t = \)
40-50 h. The asymmetries in the mid-level flow also develop during this period (Fig. 6),
in part associated with the effect of vertical momentum transport. The combination of
the large-scale environmental flow, low-level channeling effect and the asymmetries in
the mid-level flow all contribute to the southward deflection of the TC track.

6. The role of atmosphere-ocean interaction

Recent research suggest that the initial SST can affect TC tracks. Katsube and
Inatsu (2016) and Sun et al. (2017) have shown that warmer SSTs tend to promote
earlier northward recurvature of the TCs in some cases in the western North Pacific
(WNP). Sun et al. (2017) ascribed this result to the retreat of the subtropical high in the
experiment in which the higher SST was used (Fig. 7). With a simplified linear
baroclinic model, Katsube and Inatsu (2016) interpreted this track change as the
well-known subtropical thermal response documented by Hoskins and Karoly (1981)
(Fig. 8).
While the persistent SST forcing can affect TC tracks, the direct impact of the
storm-induced oceanic feedback on the TC track is less obvious. Model studies do not
show a strong impact of atmosphere-ocean coupling on the track of TCs. There have
been a range of investigations: idealized TC studies with and without ocean coupling
(e.g. Zhu et al, 2004, Duan et al., 2013), the role of adding wave coupling (Liu et al.
2011), and individual case studies in the Atlantic (e.g. Winterbottom et al., 2012). To
obtain more reliable results, Ito et al. (2015) conducted 34 TC cases (281 simulations)
near Japan and found a minor effect of the atmosphere-ocean coupling on TC track.
They report that the atmosphere-ocean coupling slightly deflects the TC position to the
left (by roughly 20 km) during the forecast time of 36 hours presumably because
significant sea surface cooling on the right-hand side is not favorable to convective
activities leading the genesis of potential vorticity (Fig. 9).

However, secondary and indirect influences of ocean coupling on the track via
changes in intensity may be possible for some cases. In the case of TC Fanapi (2010),
the storm-induced cooling weakened the vertical coherence of the TC. A weakening and
shallower cyclone may be more sensitive to lower level flow so that the effective
steering flow may change as the coupling reduces the intensity (Lin et al., 2018).
Coupling with the ocean could indirectly change the cyclone upper level anticyclone
through intensity (diabatic heating) changes and the symmetry of the convection. In this way the track may respond differently to the flow. Srinivas et al. (2016) showed that the use of the coupled model and AMSR-E-based initial condition for six TCs in the Bay of Bengal yielded some improvement by 14% in the 3-day track forecast with respect to the fixed National Oceanic and Atmospheric Administration SST.

It is important to distinguish among the role of storm-induced cooling in short-term time-scale, and seasonal or climate time-scale. There is no doubt that coupling with the ocean can modify the large-scale SST patterns and hence the winds of the steering flow on longer time scales (e.g. Ogata et al. 2016; Sun et al. 2017). The seasonal forecast and climate projections of track densities is expected to be sensitive to atmosphere-ocean coupling. However, a recent climatological study of the entire Indian Ocean shows no significant impact of employing a coupled model on track density (Lengaigne et al. 2018).

7. Large scale features

A monsoon gyre (MG) is identified as a low-frequency cyclonic (or anticyclonic) circulation in the lower (or upper) troposphere with a diameter of about 2000-2500 km (e.g., Lander 1994). Sudden poleward track changes often occur when a TC is located to
the east of a MG. Previous model studies show that a binary interaction of the MG and
the TC in which the TC is advected cyclonically around and moves into the center of
the MG. Then, a β-induced dispersion in the southeast yields the northward steering
(Carr and Elsberry, 1995). Recently, Liang and Wu (2015) investigated three types of
tracks (sudden northward, northward without a sharp turn, and westward) when a TC is
initially located in the eastern semicircle of an MG (Fig. 10). TCs that take westward
tracks and northward tracks without a sharp turn do not experience a coalescence
process, which is seen in northward tracks with a sharp turn. Westward-turning TCs
move faster than MGs, while northward-turning TCs without a sharp turn move more
slowly than MGs. They also showed that a type is also sensitive to the initial position
and the structure of TCs and MGs. Ge et al. (2018) indicated that the sharp northward
turn can also be influenced by the vertical structure and the intensity of an MG. In their
idealized simulation with a deeper and stronger MG, the total VT of TC’s
wavenumber-1 component has become almost absent due to the vorticity advection of
the MG. It means that the westward steering flow vanishes when the centers of the TC
and the MG have almost collocated with each other. After the speed of the TC slows
down, the TC has exhibited a sharp northward turn by the β-effect as consistent with a
barotropic model simulation (Fig. 11). In contrast, a TC experiences a nearly constant
northwestward track with a shallower MG. They also showed that the differences in the radial gradient of the relative vorticity also yield the similar track differences in a simple barotropic model. Bi et al. (2015) showed that the sharp northward turn of Typhoon Megi (2010) was induced by the strength of the TC in the initial field, as no sharp turn was observed when the initial TC was weakened. These works suggest that the TC track depends on both of low-frequency flows associated with the MG and the TC vortex itself.

Wei et al. (2016) statistically investigated the relationship between the upper tropospheric cold low (UTCL) and the TC tracks over the WNP during 2000-2012. They found that for all the TCs and the UCTLs within a 15-degree interaction distance, there is little impact of the UTCL on the average directional change of the TC track, unlike the results obtained by the previous case studies. Albeit with the lower frequency, most of the left-turning TCs within a 5-degree distance experienced abrupt left-turning as much as 50 degrees in 12 hours (Fig. 12). The TCs tended to be slowed down when undergoing abrupt directional changes.

Sun et al. (2015) investigated the interaction between a TC and a subtropical high over the WNP, focusing on the initial size of the TC for the cases of TCs Songda (2004) and Megi (2010). With the increase of initial storm size, the main body of subtropical
high tends to withdraw, and the TCs, which are initially located on the south western
dge of the subtropical high, tend to turn northwards earlier (Fig. 13). The increase in
the mass flux with the larger vortex decreases the geopotential height of the middle
troposphere in the outer region of the TC and thus it leads to a break of the subtropical
high on the WNP.

8. Dynamics of large forecast errors in TC tracks

Track forecast errors have generally decreased owing to increased observations and
many improvements in numerical weather prediction systems. Recently, Landsea and
Cangialosi (2018) posted an interesting discussion topic on the limits of TC track
predictability that we have reached. However, there are still forecast busts in which
track forecast errors are very large (Yamaguchi et al. 2017; Magnusson et al. 2019). The
investigation of such cases remains one of the major issues for TC researchers and
operational centers.

The theoretical reasons behind such large track errors were explored by Torn et al.
ensemble sensitivity analysis, the authors concluded that the foremost factor in creating
large ensemble spread was a steering flow pattern with a saddle point of strong
deformation (Fig. 14) downstream of the current location of the TC. In this pattern,
small perturbations to the initial state have drastic consequences for the track prediction 2-4 days later.

Yamada et al. (2016) investigated a large northward bias seen in Japan Meteorological Agency Global Spectral Model (JMA-GSM) for the case of TC Fensheng (2008), in which the track was successfully simulated using the Nonhydrostatic Icosahedral Atmospheric Model (NICAM) with finer grid spacing. Their diagnosis using vorticity budget showed that the large bias can be attributed to the marked asymmetry of rainfall concentrating in the downshear side (Fig. 15). Although both models could reproduce the asymmetric structure due to the vertical wind shear, large differences were found in the vertical structure and magnitude of stretching term. The results suggest that the storm-scale heating profile as a response to the persistent vertical shear can induce the large track forecast errors in some cases.

Saunders et al. (2019) showed significant sensitivity of the notable hurricane track of hurricane Joaquin (2015) to the choice of cumulus convection. Their diagnosis suggested that the structure of the hurricane core region including the vertical extent of diabatic heating, vertical velocity and relative humidity, could also play an important role in addition to changes in large scale flow. Specifically, the asymmetry and local
absolute vorticity tendency over the inner-core region and its vicinity has a strong implication for Joaquin’s hairpin turn.

9. Concluding remarks

The highly idealized models can provide an important perspective for the forecasting of the TC track. Recent works suggest that the TC track forecasting is sensitive to the radial profile of the relative vorticity in the outer region of the TC because it is related to the β-gyre and the faster developing mode. Recent idealized simulations with a full-physics model have provided deeper understanding of the existing mechanisms, as well as some previously known mechanisms: the steering flow concept, the intrinsic recurving nature, the channeling effect in the middle troposphere, the atmosphere-ocean interaction and the impact of large-scale features. It is suggested that the horizontal and vertical structure of a TC can affect its own track through the interaction with other systems or by itself. It seems that the state-of-the-art models have, to some extent, represented some of these effects. However, these findings are important for understanding the mechanism governing the change of TC tracks, particularly, when TC tracks were changed according to the use of finer meshes, new
physical schemes, or because of the topography and coastline. More accurate implementation of these components is highly desirable.

The fundamental aspects of the movement of the TC are important also because they can facilitate the design of observations and data assimilation systems. Recent works suggest that the uncertainties along streamlines connected to stagnation points for TCs in a synoptic-scale anticyclonic shear should be reduced. The recent case studies suggest that large track forecast errors can result both from the intrinsic property of the large-scale flow pattern with a saddle point yielding strong deformation and the failure of reproducing the storm-scale asymmetric heating profile.

Thanks to the sophisticated numerical model and observations, the TC position forecast errors have decreased to less than 100 km at 24 hours and 200-300 km for 72 hour forecasts. In turn, the physical processes that were previously considered to be “minor” have become “substantial” in importance, as the required accuracy has become higher than ever. Also, the further understanding is needed for the large forecast errors and unknown processes. Although the conventional concepts of the steering flow, the $\beta$-gyre, and the diabatic heating remain important, the better understanding of various physical processes should be regarded as an important step for disentangling the complicated dynamics associated with the movement of TCs in the real world.
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Figure 1. Time series of the conventional steering (thick black) and the contributions of the horizontal advection (HA) in the PVT equation (thick purple): (a) zonal component and (b) meridional component. HA is further decomposed into the advection of the symmetric potential vorticity component by the asymmetric flow (HA1) and the advection of the wave-number-one potential vorticity component by the symmetric flow (HA2) terms. The anomaly in HA1 with respect to the conventional steering is shown in red, while HA2 is shown in blue. (after Wu and Chen, 2016)
Figure 2. Radial variation of Doppler-shifted frequency on the periphery of the vortex from Wood and White (2011) for different very low values of the rotation frequency with respect to the ground $\omega$. The outer waveguide lies between zero Doppler-shifted frequency and $\Omega_{1D}$, the frequency of a one-dimensional Rossby wave with the same tangential wavenumber and rotation frequency. (after Gonzalez et al. 2015)
Figure 3. Vorticity distribution of the initial (a),(b) and the evolved (c),(d) SVs for a single stable vortex: an optimization time interval of 2 days and background (left) cyclonic shears and (right) anticyclonic shears. The thin black contours are streamlines. In the anticyclonic shear case, the thick lines are the streamlines connected to the stagnation points (small circles) north and south of the vortex. The singular value is shown by sigma at the upper left in each panel. (after Scheck et al., 2014)
Figure 4: Six-day TC tracks a symmetric spun-up vortex initially at 25°N, 30°N, and 35°N with no background flow. The time interval between markers of each track is 6 hrs. The tracks are drawn based on the central minimum sea level pressure of the vortex (after Chan and Chan, 2016).
Figure 5. Three-hour averaged asymmetric flow difference between the landfall and control cases within eta levels 0.860–0.620. Thin lines with arrows represent the streamlines of the difference between the cases and shadings show the wind-speed difference in m s\(^{-1}\). The solid straight line represents the overall direction of the TC in the TW case within this time period and the dotted line that in the NTW case for 62–64 h. (adopted and modified after Tang and Chan, 2014).
Figure 6: Asymmetric horizontal flow (m s\(^{-1}\)) at different levels and times. Each vector indicates the zonal and meridional components calculated within 100 km of the vortex. The x-axis shows the integration time (h), and y-axis is the vertical levels in terms of atmospheric pressure (hPa) (after Huang and Wu 2018).
Figure 7. Storm track at 6 h intervals simulated in the sensitivity experiments with various underlying SST and the observed best TC track for (a) Songda (2004) and (b) Megi (2010). (after Sun et al. 2017).
Figure 8. Steering flow as calculated from the stationary linear response to diabatic heating at the cyclone center at 1200 UTC 3 Sep 2005 obtained from the warm run of the Nabi experiment. The basic-state zonal wind at 500 hPa is superimposed (m s$^{-1}$; contours with an interval of 4 m s$^{-1}$ and with negative contours dashed). Diabatic heating is imposed at the shaded region. (adopted and modified after Katsube and Inatsu 2016).
Figure 9. TC center position at T+36 h for each experiment with the non-hydrostatic atmospheric (red) and coupled (blue) models relative to the Regional Specialized Meteorological Center Tokyo best track. Vertical axis is the along-track distance in the direction of the modeled TC motion from T+30 to T+36 h, while the horizontal axis is the cross-track distance. Triangles indicate the mean positional bias in the same color (adopted and modified after Ito et al., 2015).
Figure 10. Schematic diagrams of three track types in the MG. The blue and red circles with arrows denote the MG and the TC circulation, respectively. (after Liang and Wu, 2015)
Figure 11. Simulated 3-hourly TC tracks with a deep intense MG (SG04) and a shallow weak MG (SG05). (after Ge et al. 2018)
Figure 12. The frequency (columns) and mean directional change (lines with small circles; unit: $8^\circ$) of TCs in 12 h as a function of the distance from the composite UTCL center for the selected right-turning (brown) and left turning (blue) cases. The distance is measured by $r = \sqrt{(\Delta lon)^2 + (\Delta lat)^2}$ in degree, in which $\Delta lon$ and $\Delta lat$ are the differences of latitude and longitude of two locations respectively. Filled circles show significant differences at the 95% confidence level from the corresponding WNP climatology indicated by dashed lines. The quantity with a plus in parentheses shows a significant increase in the mean directional change of the TCs in the shaded distance range over the corresponding WNP climatology. (after Wei et al. 2016)
Figure 13. The geopotential height at 500 hPa from NCEP reanalysis data and from simulations at 0000 UTC 3 September 2004 and 0000 UTC 18 October 2010, corresponding to the cases of (a–c) Songda (2004) and (d–f) Megi (2010) respectively. The contour of 5900m in Songda case and the contour of 5880m in Megi case are highlighted in red. (after Sun et al. 2015)
Figure 14. European Centre for Medium-Range Weather Forecasts ensemble forecasts of hurricane Joaquin initialized at 0000 UTC 30 September 2015. The dots indicate the location of each ensemble member at 24-h intervals, while the colored circles show a bivariate normal fit to the positions each 24 h. Purple denotes 24-h locations, cyan denotes 48-h locations, green denotes 72-h locations, red denotes 96-h locations, and magenta denotes 120-h locations. The thick black line denotes the National Hurricane Center best track positions, while the stars indicate the corresponding best track position each 24 h. The direction of the 48-h major axis is denoted by the green vector. (after Torn et al. 2018)
Figure 15. Horizontal distributions at 0000 UTC 20 June simulated by NICAM (top) and JMA-GSM (bottom). The left panels show the rain rate (shade) and surface wind vectors. The right panels show the horizontal divergence (shade) and the relative vorticity (contour) at 1.6 km MSL or 850 hPa. Broken circles indicate 200- and 400-km ranges from the surface vortex center. A blue (red) arrow indicates the TC motion and vertical shear. The 6-hourly positions of the center at surface (300hPa) are shown by circles with solid lines (rectangles with dotted lines). (after Yamada et al. 2016)