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Planetary-Scale Low-Level Circulation and the Unique Development of Hurricane Wilma in 2005

Jinwoong Yoo, Robert V. Rohli and Jennifer Collins

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Abstract

Large-scale atmospheric and oceanic conditions in the western Atlantic basin were analyzed to understand the unique tropical cyclogenesis (TCG) and intensification mechanism of Hurricane Wilma in 2005, the most intense Atlantic basin tropical cyclone (TC) on record. An analysis of 850 hPa circulations depicted in the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data suggests that anomalous development of the 850 hPa circulation pattern triggered by Hurricane Vince (October 8–11, 2005) contributed to the development of a large-scale low-level vortex that preceded Wilma's TCG in the eastern Caribbean. In particular, weakened easterly winds in the central tropical Atlantic assisted the unique large-scale cyclonic circulation over the western Atlantic about a week before Wilma's TCG. The unprecedented rapid intensification of Wilma was investigated considering the interactions between mid-latitude troughs and large-scale low-level circulations as well as anomalously warm SST conditions. The global Weather Research and Forecasting (WRF) model run for Hurricane Wilma suggests that the role of mid-latitude systems in TC activity is more important than previously believed and that every in situ large- or meso-scale vortex and circulation component at least in the immediately neighboring region of TCG seems to have a significant influence on TCG processes.

Keywords: tropical cyclone genesis, Hurricane Wilma, vortices, WRF, low-level circulations

1. Introduction

The importance of large-scale external circulations in tropical cyclogenesis (TCG) seems irrefutable, based on the numerous persuasive previous studies [1–3]. In a composite analysis of tropical cyclones (TCs) that developed from monsoon troughs over the western North Pacific, Briegel and Frank [2] hypothesized that eastward-propagating subtropical troughs poleward of the location of TCG support TCG by providing upper-tropospheric vorticity advection, thereby forcing upper-level divergence and uplift. Briegel and Frank [2] highlighted that successfully developing TCs had 850 hPa southwesterly surges in addition to the monsoonal easterly winds approximately 48–72 hours prior to TCG, potentially triggering the low-level convergence and deep uplift necessary for TCG. Using a global numerical weather prediction model for TCG in the western North Pacific, Chan and Kwok [4] derived a similar conclusion to Briegel and Frank [2] regarding the general synoptic-scale features present before a TCG, specifically the relatively important roles of the low-level trade winds and the southwesterly low-level wind surge prior to TCG. Interestingly, however, Briegel and Frank [2] also found that nongenesis cases have upper-level troughs both to the northwest and to the northeast of the genesis region, which complicates the distinction between TCG-triggering and non-TCG-triggering synoptic settings. Data limitations precluded the specification of the source of the southwesterly surge into the genesis location, other than any preexisting TCs, which only occur in about 34% of all the genesis cases [2].

Therefore, there are still some uncertainties with regard to synoptic-scale features as predictors of TCG. The confusion partly arises from a lack of understanding of the circumstances under which the combination of synoptic-scale features optimizes TCG. Moreover, use of these synoptic-scale features as TCG predictors in the Atlantic basin can be problematic because of the differences in basin size and landmass-ocean distribution. While the monsoon trough is the breeding region of most TCs in the western North Pacific basin, there is apparently no monsoon trough region in the western Atlantic [4].

In an analysis of Tropical Storm Arlene (2005), Yoo et al. [5, 6] found that low-level vortex dynamics advected temporary low-level westerly winds from the eastern North Pacific into the western Atlantic which, when combined with orographically enhanced low-level south-easterly winds from Central America, promoted TCG in the western Atlantic basin. Yoo [7] also suggested a potential influence of low-level wind enhancement in North America on several cases of western Atlantic TCG. Yoo [7] noted that when strong positive potential vorticity (PV) anomalies in the form of mid-latitude troughs occur with strong low-level convection over a vast region in the middle-to-high latitudes of North America, occasionally an alley of a low-level wind surge develops from the mid-latitude trough southward toward the western Atlantic, enhancing the large-scale low-level vortex of the developing storm. Yoo [7] also suggested that the enhancement of this low-level wind surge alley was a harbinger of the intensification of Hurricane Cindy and Hurricane Dennis of 2005. To better understand the relationship between large-scale geophysical features and TCG mechanisms over the western Atlantic, more case studies of TCG in the western Atlantic are warranted to analyze the characteristics of interactions of such features leading to TCG.

Hurricane Wilma (October 15–25, 2005) was the most intense hurricane recorded in the Atlantic basin, with a minimum central pressure of 882 hPa and an estimated peak sustained wind speed of 160 kt. Wilma caused 23 deaths and US$20.6 billion damage to the US alone [8]. Despite its record-breaking anomaly features, with the exception of a cursory analysis in the TC report from the National Hurricane Center (NHC), no study has been conducted to understand the relative importance of the atmospheric features discussed above in Wilma's TCG. This chapter reviews the large-scale atmospheric conditions from the early development stage of Wilma. The focus of the study is on the relative and collective roles of high-latitude PV anomaly and low-level wind surges of various origins.

2. Data and methods

The "best track" data from NHC are used as guidelines of the track and intensity changes of Hurricane Wilma. Large-scale sea surface temperature (SST) patterns are described using the National Oceanic and Atmospheric Administration (NOAA) optimum interpolation (OI) ¼ degree daily SST V2 data, which include in situ SST measurements from ships and buoys, satellite observations from Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) sensor on National Aeronautics and Space Administration (NASA's) Aqua satellite and NOAA 17/NOAA 18 Advanced Very High Resolution Radiometer (AVHRR), and National Centers for Environmental Prediction (NCEP) sea ice data [9].

The NCEP/National Center for Atmospheric Research (NCAR) reanalysis (NNR) data [10] are used to show the large-scale wind pattern during the development of Hurricane Wilma until it reached its peak maximum intensity over the Caribbean Sea by 1200 UTC October 19. The period of decreased intensity after moving from the Yucatan Peninsula to Florida will not be described in this study because the large-scale conditions that created the early TCG stage of Wilma are the main interest. The NNR dataset includes pressure-level variables in 17 vertical layers on a global 2.5° × 2.5° grid. Hennon and Hobgood [11] noted that NNR data are superior to the European Centre for Medium Range Weather Forecasts (ECMWF) reanalysis dataset in the tropics. Daily and long-term mean interpolated outgoing longwave radiation (OLR) data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website at http://www.esrl.noaa.gov/psd/ are used to produce the daily OLR anomalies to represent strong surface convection [12].

The Weather Research and Forecasting (WRF) model is executed for Hurricane Wilma with a global model domain setting to reproduce hourly hemispheric-to-meso-scale circulations during its TCG and intensification period with improved spatial and temporal resolution over general circulation models (GCMs). The global WRF model domain was set with (x, y) dimensions of 721 × 361 (d01) (**Figure 1**). The global domain has a grid size of 55.58874 km in the x and y directions. The model microphysical schemes are configured following the NCAR Advanced Hurricane WRF (AHW) microphysics guidelines, including (i) Lin et al. cloud microphysics scheme [13]; (ii) the Rapid Radiative Transfer Model (RRTM) scheme for longwave radiation [14]; (iii) Dudhia scheme for shortwave radiation [15]; (iv) the Yonsei

University planetary boundary layer (PBL) parameterization; (v) the Monin-Obukhov scheme for the surface layer option; (vi) the thermal diffusion scheme for the land surface physics; and (vii) Kain-Fritsch (new Eta) scheme for the cumulus parameterization [16]. The 38 sigma (σ) level set of [17] was applied. The model "top" is defined at 50 hPa. The model run was set to update daily SST every 6 hours into the model integration. The daily "real-time global" (RTG) SST data were interpolated sequentially to produce 6 hourly input data for the WRF run.
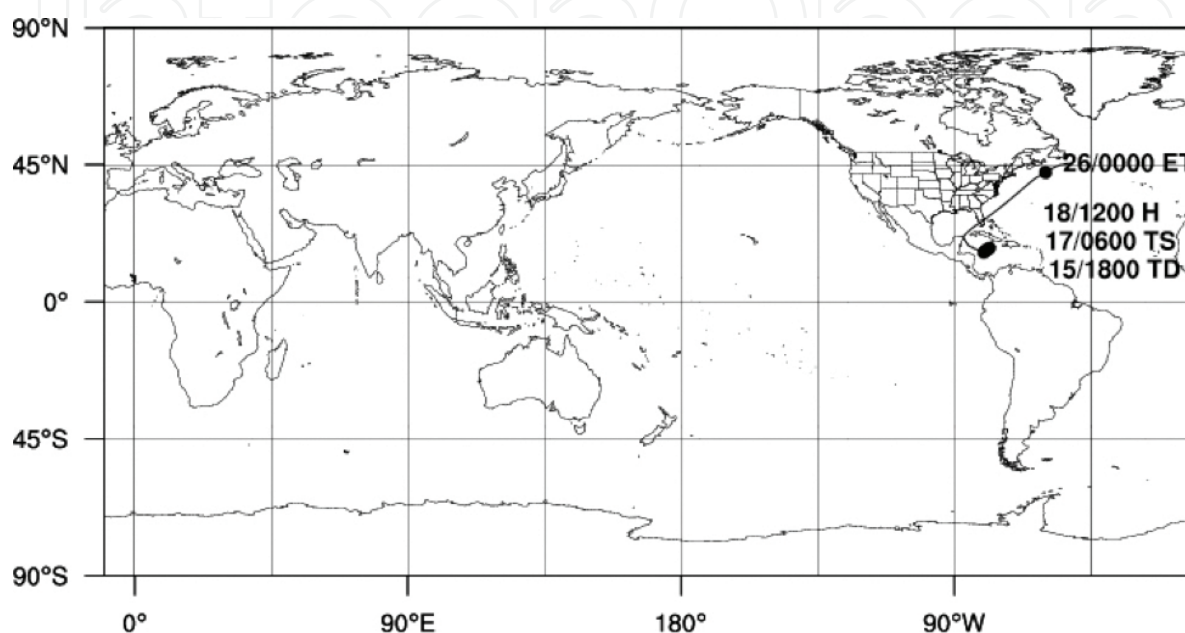
Figure 1. The model domain of global WRF for Hurricane Wilma in 2005. NHC best tracks were plotted with major intensity changes annotated.

In the global WRF model simulation, two different runtimes were executed. The first set of simulations runs from 0000 UTC October 7 to 0000 UTC October 21, to include the anomalous circulation that Hurricane Vince introduced in the North Atlantic about 1 week prior to Wilma's TCG—a duration of 336 hours. The second set of the simulations runs from 0000 UTC October 14 to 0000 21 October UTC, which only includes the pregenesis condition, TCG, and the development of Wilma—a duration of 168 hours. Both simulations end on 0000 UTC October 21, though Wilma continued to maintain hurricane intensity until 1800 UTC October 25. The latter half of the first model simulation result is compared to the result of the second run to evaluate the accuracy of the global WRF model.

To run the WRF model, 6 hourly NCEP Global Forecast System (GFS) final (FNL) operational global analysis data (1° × 1°) and daily RTG SST data are used for three-dimensional input data and for SST update (available from National Weather Service at ftp://ftp.polar.ncep.noaa.gov/pub/history/sst/), respectively. The model run is set to update SST every 6 hours into the model integration. The FNL data for this study are obtained from the Research Data Archive (RDA), which is maintained by the Computational and Information Systems Laboratory (CISL) at NCAR. The original data are available from the RDA (http://dss.ucar.edu) in dataset number ds083.2.

3. Hurricane Wilma in 2005 overview

3.1. Large-scale low-level dynamics

After Tropical Storm Tammy (October 5–6, 2005) diminished over Florida, a large-scale, low-level wind surge (>10 m s^{-1}) developed off the Atlantic coast of North America (**Figure 2a**). This surge was associated with a mid-latitude Rossby wave trough over the northern North
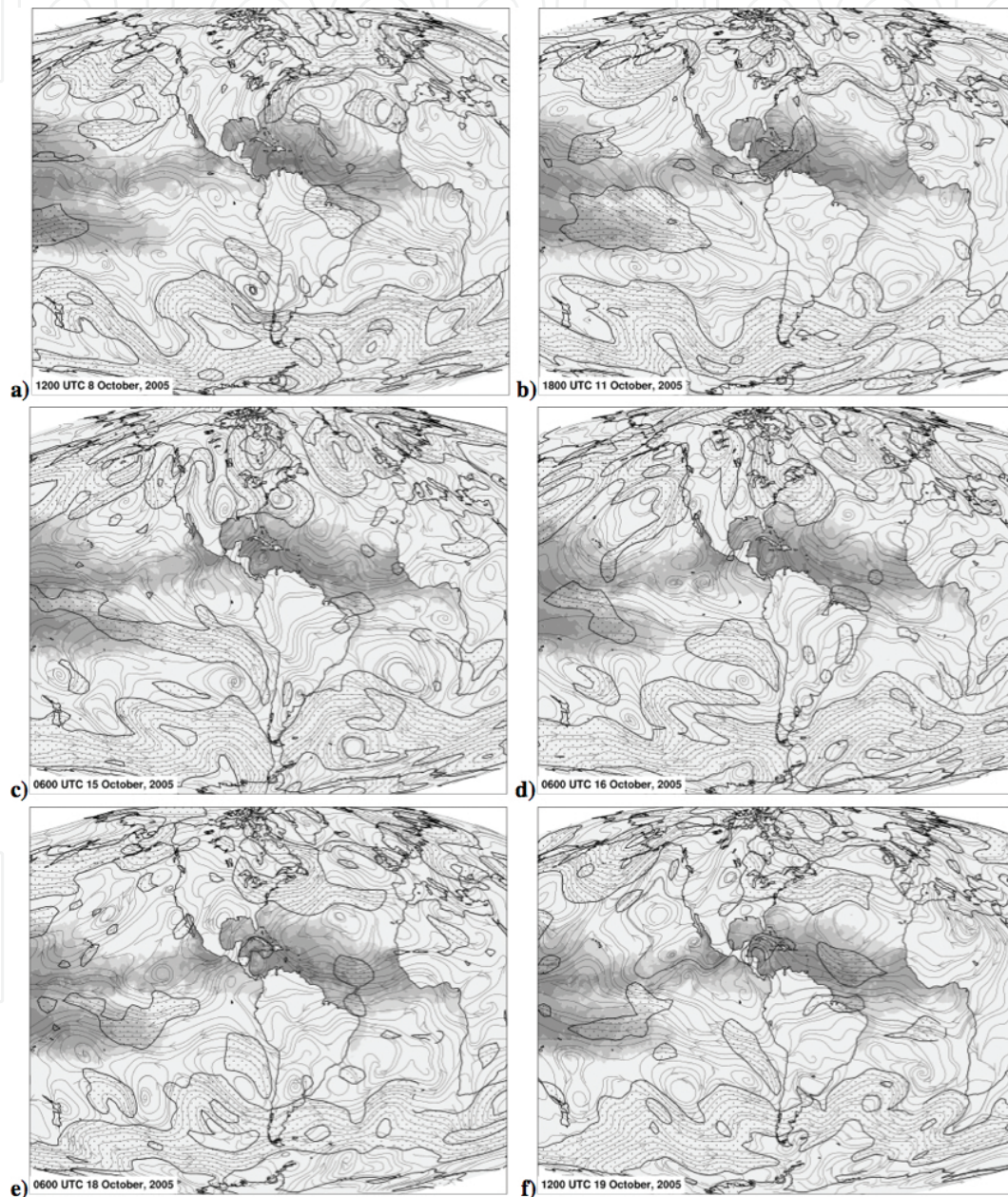
Figure 2. Wind stream analysis (850 hPa) of NCEP/NCAR reanalysis data and NOAA optimum interpolation (OI) ¼ degree daily sea surface temperature (SST) V2 data superimposed by low-level wind surge at (a) 1200 UTC October 8, (b) 1800 UTC October 11, (c) 0600 UTC October 15, (d) 0600 UTC October 16, (e) 0600 UTC October 18, and (f) 1200 UTC October 19, 2005. Areas of low-level wind surges exceeding 10 m s^{-1} are enclosed by dots within the thick solid contour lines, for which the interval is 15 m s^{-1}. SSTs exceeding 26°C are contoured with dark shades at a 1°C interval.

Atlantic and a subtropical anticyclone to the east of North America (also known as the Bermuda-Azores high). The mid-latitude trough seems to have assisted the formation of the subtropical high to the east of North America and a frontal low in the eastern North Atlantic, the latter of which later became Hurricane Vince (October 8–11, 2005) off the coast of western Africa (**Figure 2a**). Interactions between the subtropical high and the frontal low (Hurricane Vince) to its east deformed the shape of the subtropical high in its southern flank in the North Atlantic.

The abnormally strong frontal low also contributed to weakening of tropical easterly winds from western Africa. Due to the weakened easterly winds over the Caribbean Sea and the Gulf of Mexico during this period, the warm SST could avoid heat loss due to advection, accumulating more thermal energy in the low-level atmosphere and at the sea surface over the vast region. Meanwhile, vigorous southeasterly winds emanating from the South Atlantic subtropical high produced strong low-level wind surges over a vast area northeast of Brazil (**Figure 2a**).

Regarding the development of Hurricane Wilma, low-level westerly winds from the eastern North Pacific should not be disregarded. The evolution of synoptic-scale low-level vortices in the eastern North Pacific is driven by the interplay between subtropical high pressure systems in the eastern South Pacific and in the eastern North Pacific, at least in the case of Arlene four months earlier [6]. Since early in October, synoptic-scale low-level conditions in the Pacific had supported the development of a low-level anticyclonic vortex in the eastern North Pacific. In particular, anomalously strong southeasterly winds from the southeastern Pacific subtropical high advected momentum effectively to the anticyclone in the eastern North Pacific, culminating in low-level westerly winds in the region (**Figure 2b**). Although the intensities of the low-level wind surges changed slightly, the general setting of the large-scale low-level vortices distribution around Central America was maintained for an extended period of time during early October.

Particularly, the western flank of the southeastern protrusion of the elongated North Atlantic subtropical anticyclone, which was northeast of the Caribbean Sea or Puerto Rico, became a seed zone for the development of an unusually intense 850 hPa cyclonic vortex at the subsynoptic scale by October 8 (**Figure 2a** and **b**). This vortex was able to develop as the easterly wind in the central tropical Atlantic weakened, allowing the cross-equatorial southeasterly wind east of the Caribbean Sea to approach 25°N (**Figure 2a**). By October 9, the abnormally large-scale low-level cyclone with its center hovering over the eastern Caribbean maintained its extended shape, from the southwestern Caribbean to the northeast.

Meanwhile, the westerly winds from the eastern North Pacific were sufficiently strong to traverse the western Caribbean around October 11, and they converged with the southeasterly and easterly winds in the eastern Caribbean (**Figure 2b**). This convergence reinforced the preexisting subsynoptic-scale low-level cyclonic flow over the Caribbean Sea, which continued on 0000 UTC October 13 despite weakened westerly winds upon the disappearance of the eastern North Pacific low-level circulation.

Beginning around 0000 UTC October 14, a meso-scale high and a mid-latitude trough were developing over Texas and inland central Canada, respectively. This anticyclone over Texas grew quickly while the subsynoptic-scale low-level cyclonic flow over the Caribbean Sea had split into two cyclonic circulations over the Caribbean and adjacent to the US Atlantic coast—one on the northern and the other on the southern edge of the cyclonic zone (**Figure 2c**). The northern cyclonic circulation near the US Atlantic coast became an extratropical cyclone, and the southern cyclone over the Caribbean Sea strengthened near Jamaica by October 14, becoming a tropical depression by 1800 UTC October 15. Pasch et al. [8] suggested that tropical waves "traversing the Caribbean" might have been associated with the formation of the tropical depression. However, no apparent tropical wave "traversing" the Caribbean during that time might have affected the TCG. Instead, the 850 hPa streamline analysis shows clearly that the large-scale low-level wind was traversing the Caribbean from north to south (**Figure 2c**). By 1200 UTC October 15, the mid-latitude trough merged with the extratropical cyclone, strengthening the extratropical cyclone further (**Figure 2d**). The enhanced extratropical cyclone impeded low-level easterly winds from the central tropical Atlantic from entering into the Caribbean Sea by deflecting the easterlies in the central tropical Atlantic northward to the east of the Caribbean Sea. This circulation allowed for the sustenance of the low-level circulation in the Caribbean Sea without significant interference by the normally zonally propagating tropical waves, allowing the warm SST to accumulate more thermal energy at the sea surface and adjacent low-level atmosphere over the Caribbean Sea (**Figure 2d**).

Meanwhile, the tropical depression over the Caribbean Sea maintained its subsynoptic-scale vortex between the northerly winds associated with the trough in the northeastern US and the southeasterly winds from the South Atlantic (**Figure 2d**). Neither of the two 850 hPa circulations were strong enough to support a wind surge around the intensifying tropical depression, but these two moderate drive trains caused the "weak and ill-defined steering" [8] of the storm for the first few days of the storm that was to become Wilma. In this environment of only weak background and adjacent circulations, the depression slowly strengthened over October 16 and became a tropical storm at 0600 UTC October 17.

Over October 17–18, the North Atlantic subtropical high strengthened and began to produce more vigorous low-level easterly winds in the central tropical Atlantic toward the Caribbean Sea (**Figure 2e**). At the same time, the mid-latitude trough continued to advect the momentum of the low-level atmosphere to the anticyclone centered over Texas. This anticyclone continued to produce 850 hPa northerly winds from the southeastern US toward the Yucatan peninsula, to the west of Wilma in the Caribbean Sea, thereby enhancing cyclonic vorticity of Wilma (**Figure 2e**). During that time, Wilma drifted toward the west-northwest and strengthened into a hurricane by 1200 UTC October 18. An explosive deepening occurred during the night of the 18th/19th, and Wilma's maximum sustained wind speed had increased to near 150 kt (Category 5 on the Saffir-Simpson Hurricane Scale) by 0600 UTC October 19 [8]. By 1200 UTC October 19, the peak sustained wind speed of 160 kt was recorded for Wilma with the estimated minimum central pressure of 882 hPa—the lowest pressure recorded for a hurricane in the Atlantic basin [8]. While Wilma underwent this unprecedented rapid intensification, low-level wind surges associated with the North Atlantic high were active over the northeastern US and

in the central tropical Atlantic (**Figure 2f**). Hurricane Wilma was located in the middle of the steering flow cornered by the terrain in Central America.

3.2. Sea surface temperature conditions

As shown in **Figure 3**, SSTs in the entire western Atlantic basin and central tropical Atlantic exceeded the 26°C climatological threshold for TC development (e.g. [18]) during the lifespan of Wilma, with western Atlantic SSTs peaking at over 30°C. In contrast, SSTs in the eastern North Pacific basin were barely over 26°C (**Figure 3**). The general SST condition over the western Atlantic was warmer than the average during 1971–2000, while the southern Caribbean and central tropical Atlantic had even stronger positive anomalies during the period (**Figure 4**). It is notable that SSTs were below average over the majority of the eastern North
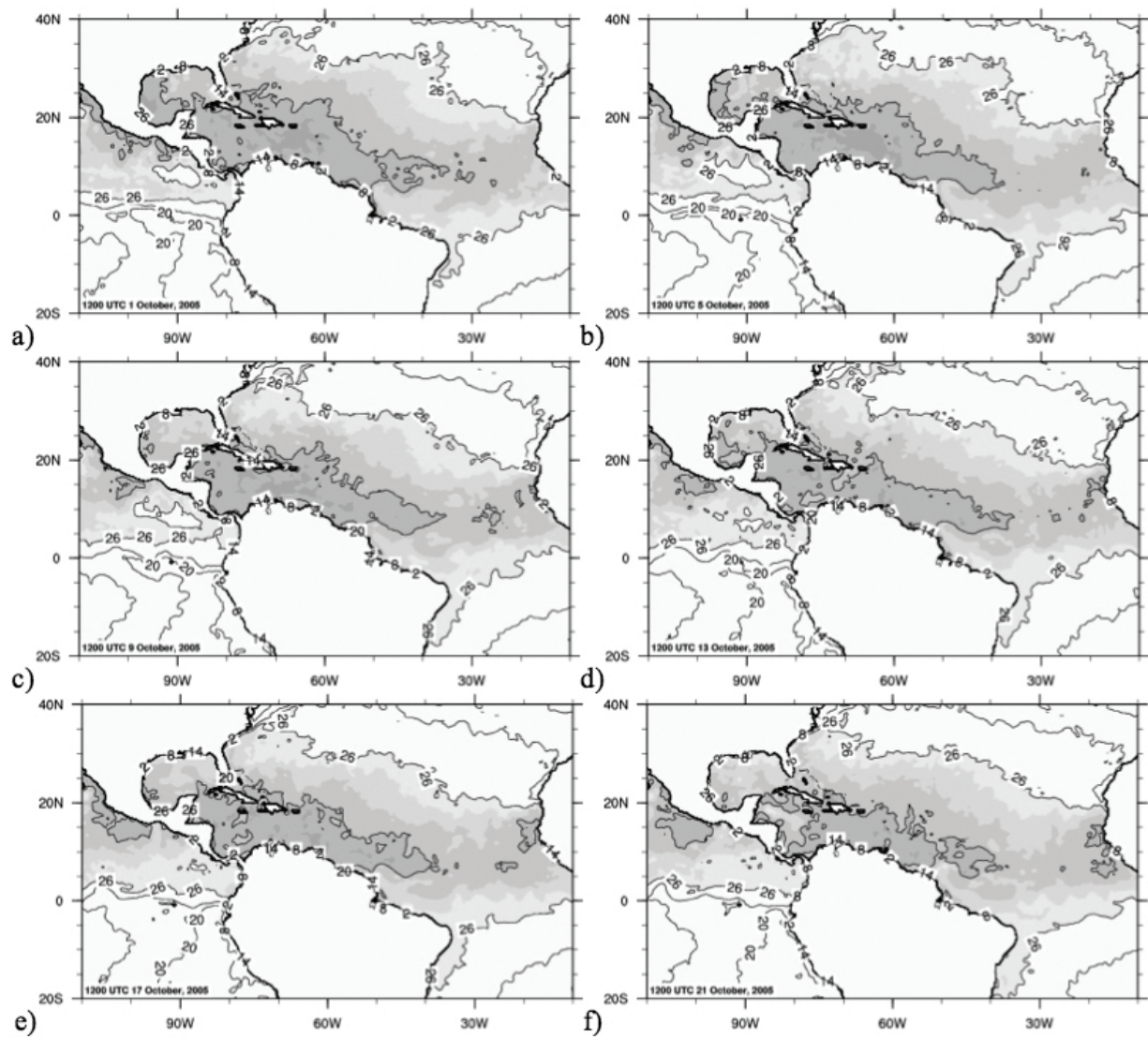
Figure 3. SSTs over the tropical and western Atlantic every 4 days during October 1–21, 2005. The thick contour lines are drawn at a 3°C interval, and SSTs exceeding 26°C are contoured with dark shades at a 1°C interval.

Pacific during the same period except for some positive anomaly hot spots along the equator (**Figure 4c–f**).
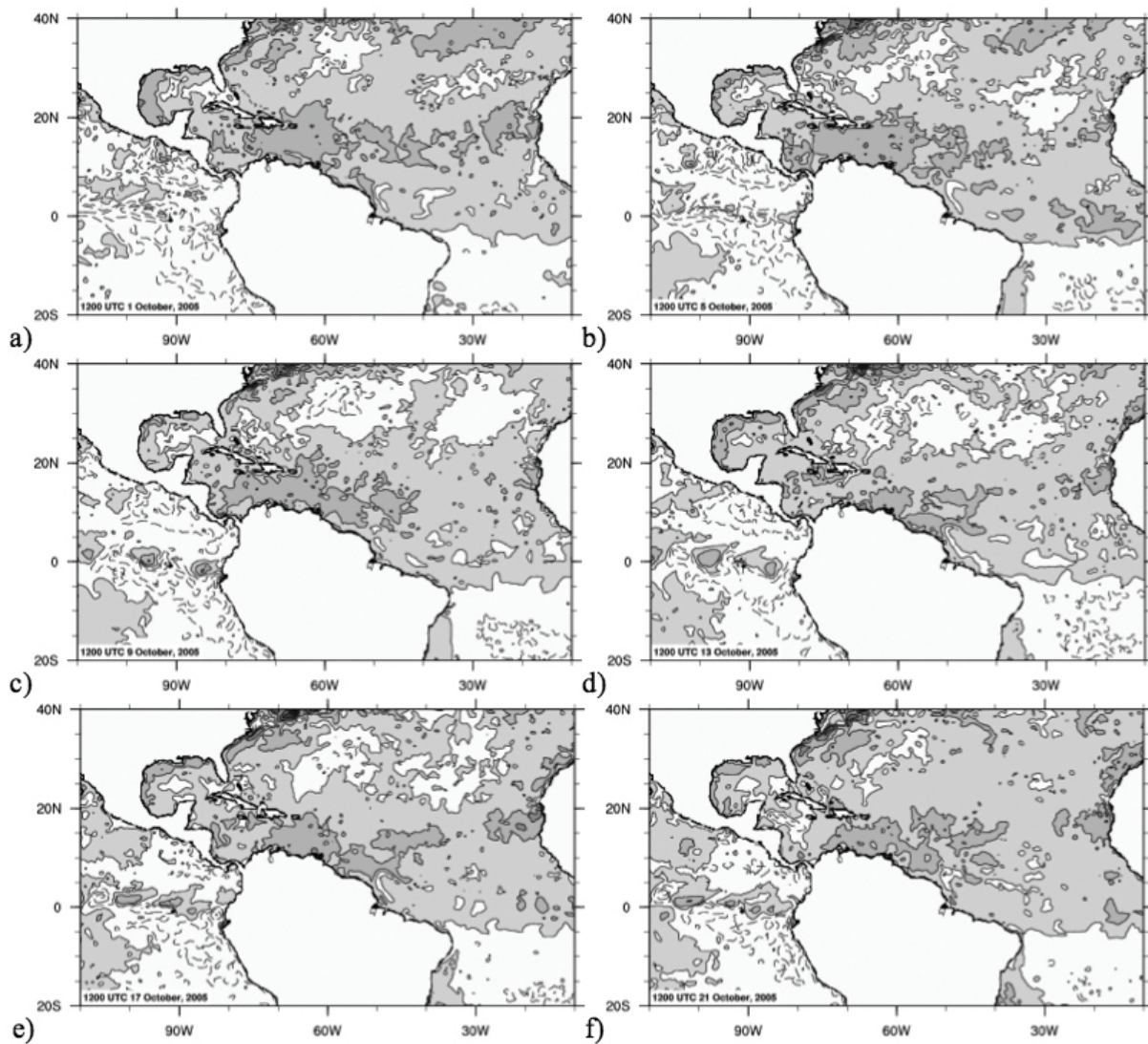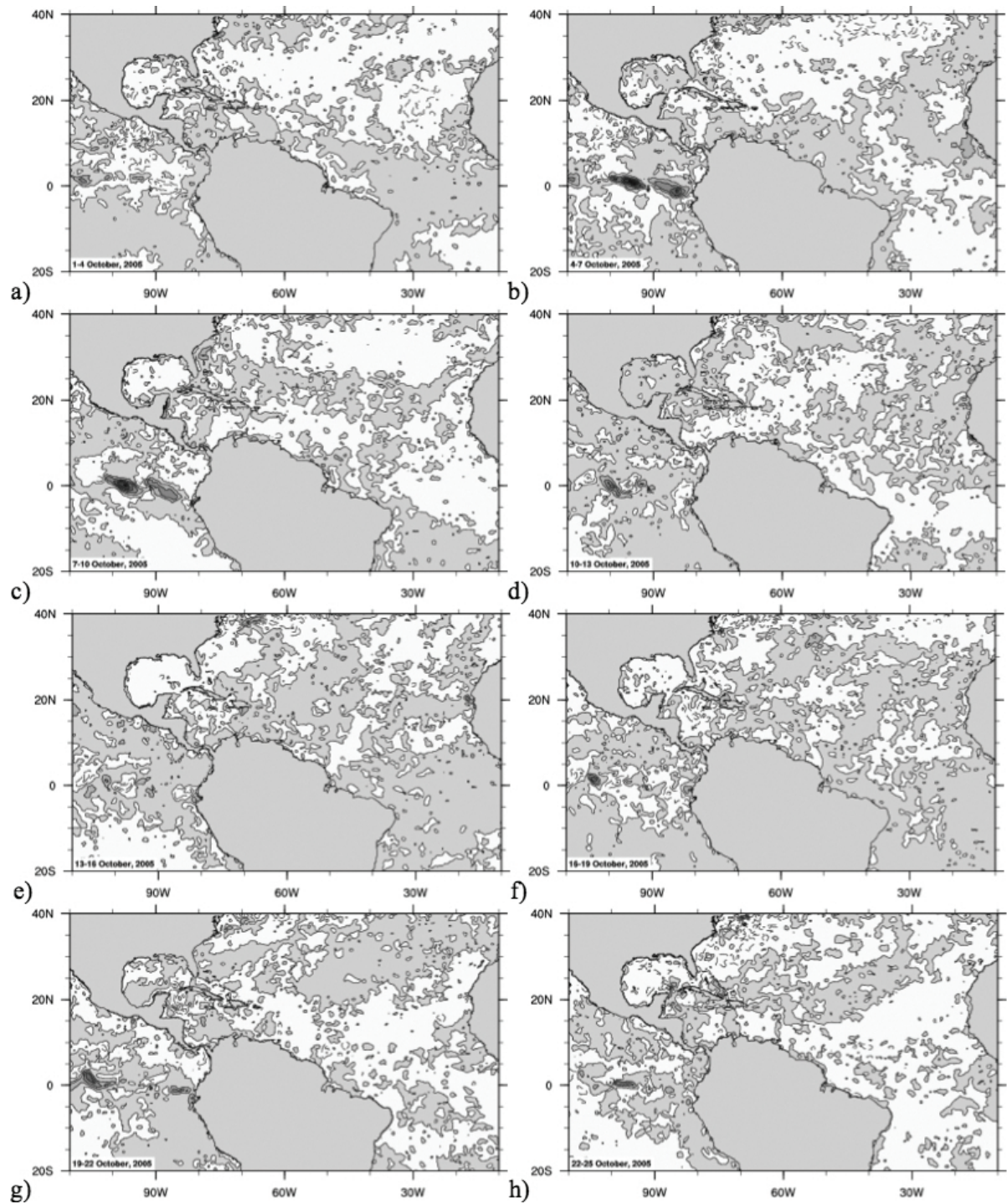

Figure 4. SST anomalies over the tropical and western Atlantic every 4 days during October 1–21, 2005. Contour lines are drawn at a 1°C interval. Positive anomalies are contoured with dark shades at a 1°C interval, and negative anomalies are drawn with dashed line contours.

SST changes over 3 and 6 days are depicted in **Figures 5** and **6**, respectively. Generally, SSTs over the Atlantic remained constant or increased slightly. Interestingly, 6-day SST change maps clearly show significant SST decreases in the Atlantic during October. SST decrease during October 1–7 (**Figure 6a**) over a broad area in the northern North Atlantic seems to be related to the passage of a mid-latitude trough that was associated with Tropical Storm Tammy (October 5–6; see **Figure 2a**). The decreasing SST in the Caribbean during October 7–13 (**Figure 6b**) represents the evaporation from the ocean, while the tropical depression (Wilma) was developing. The SST change map for October 13–19, 2005 (**Figure 6c**) suggests sea surface energy consumption by Hurricane Wilma during its early explosive intensification in the

northwestern Caribbean Sea. Finally, the SST decrease in the central tropical Atlantic (**Figure 6d**) provides evidence of the vigorous low-level southeasterly and easterly wind surges during October 19–25, 2005 (see **Figure 2f**).

Figure 5. SSTs change over 3-day intervals over the tropical and western Atlantic during October 1–25, 2005. Contour lines are drawn at a 1°C interval. SST increases are contoured with dark shades at a 1°C interval, and SST decreases are drawn with dashed line contours.
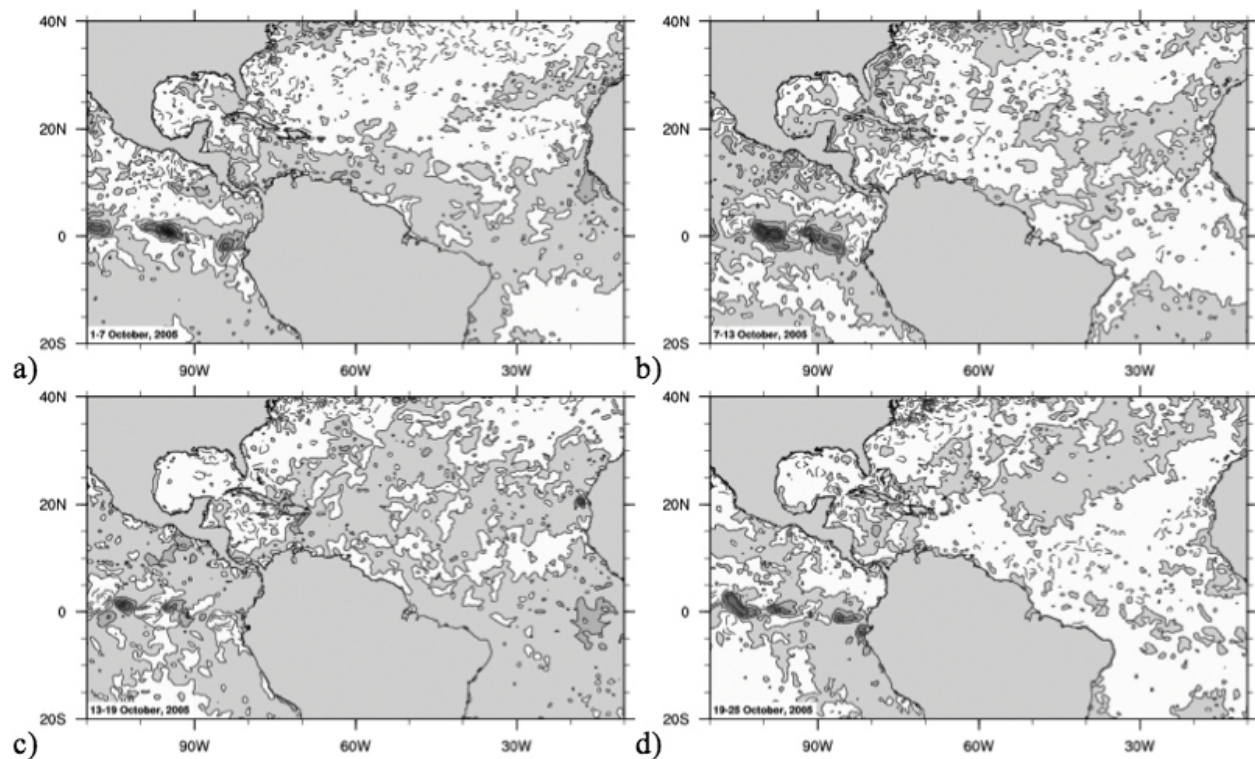
Figure 6. As in **Figure 5**, except for 6-day changes.

3.3. Potential vorticity in the upper-level atmosphere and outgoing longwave radiation

In general, mid-latitude troughs are associated with lower-level instability downwind of the trough as they provide momentum from the high latitudes and incorporate moisture from the lower latitudes. In the mid-latitudes, upper-tropospheric troughs in the Rossby waves have positive PV by nature, and positive PV anomaly regions correspond well to the locations of the 850 hPa wind surges which seem to be associated with convection as shown by OLR anomalies (**Figures 7** and **8**). However, those relationships do not apply to the lower-latitude region. Generally, upper-level PV is significantly weaker in the lower latitudes than in the mid-latitudes. Nevertheless, strong convection can occur there even with mild wind speeds, mainly because SST conditions tend to be much more favorable for strong convection in the lower latitudes than in the mid-latitudes (**Figure 3**). **Figure 8** clearly shows the cyclonic circulation development of Wilma with strong OLR anomalies over the Caribbean.

The mid-latitude trough that merged with an extratropical cyclone around the TCG period of Hurricane Wilma on October 15 (**Figure 2c** and **d**) was accompanied by the anomalously latitudinally stretched Rossby waves in the Northern Hemisphere during the period. This peculiar formation of Rossby waves resulted in a rather unusual synoptic-scale low-level wind flow with a sharp meridional circulation pattern as well as an abnormal 200 hPa PV distribution over North America (**Figure 7**). The unusual deformation of Rossby waves is likely to have increased atmospheric momentum and turbulence in the tropical latitudes by advecting vorticity during Wilma's TCG.
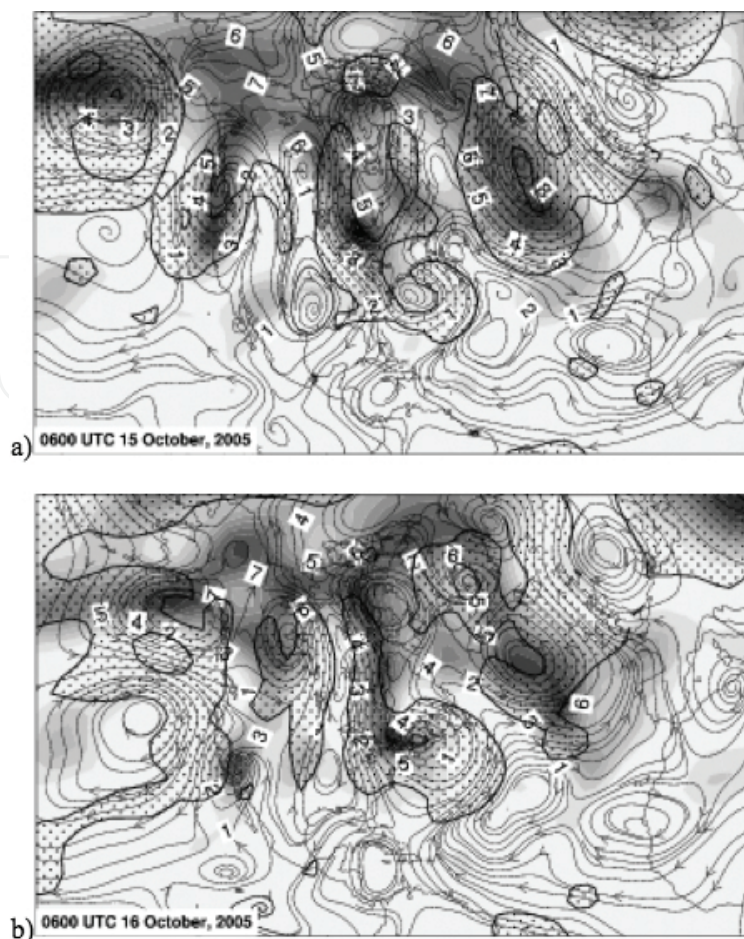
Figure 7. Abnormal distribution of 200 hPa potential vorticity (PV, shaded, 10^{-6} K m^2 kg^{-1} s^{-1}) during the early TCG period of Wilma (October 15–16, 2005). Streamline analysis (850 hPa) is superimposed on the low-level wind surge. Areas of 850 hPa wind surges exceeding 10 m s^{-1} are enclosed by dots within the thick solid contour lines, for which the interval is 15 m s^{-1}.

During Wilma's explosive deepening (from 1200 UTC October 18 to 1200 UTC October 19), strongly positive PV and a 850 hPa trough were over the northeastern coast of the US accompanied by extremely large low-level wind surge regions from the central US to the North Atlantic (**Figure 8d** and **e**). It is interesting to note how dynamic the low-level Northern Hemisphere atmosphere was overall, as evidenced by the low-level wind surges during the TCG and intensification period (**Figure 8a–e**). Bracken and Bosart [19] suggested that vorticity advection between a subtropical anticyclone and a developing storm can play an important role in accelerating TCG. Thus, the distribution of cyclones and anticyclones affects the evolution of each circulation cell through their interplay, advecting vorticities and momentum. Therefore, the synoptic-scale anticyclone over Texas and the subtropical high in the North Atlantic should have also assisted in the spin-up of Wilma over the Caribbean Sea. The clockwise low-level circulation of the Texas anticyclone to the northeast of Wilma made contact over the Gulf of Mexico, while the North Atlantic subtropical high was interacting with Wilma, mainly in the form of easterly winds. Both anticyclones seem to have contributed to Wilma's intensification at the 850 hPa level by advecting angular momentum to the outer radii of Wilma.

The tropical easterly winds associated with the North Atlantic high contributed to Wilma's intensification by supplying a substantial amount of enthalpy from the central tropical Atlantic during October 19 (see **Figure 6**).
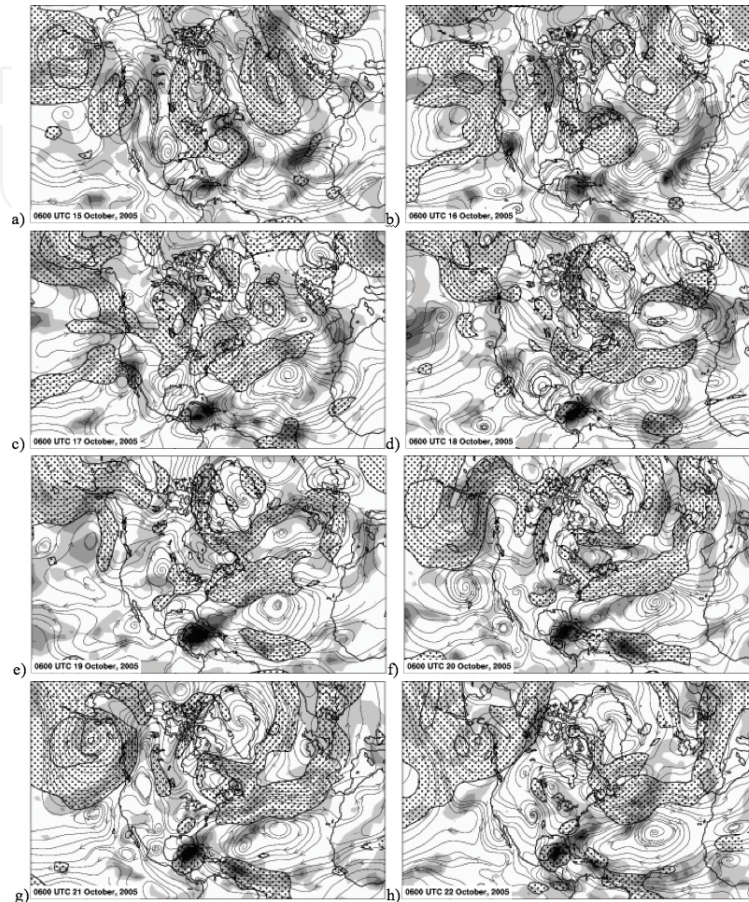

Figure 8. Evolution of the distribution of negative OLR anomalies (W m⁻², shaded) during October 15–22, 2005. Streamline analysis (850 hPa) is superimposed on the low-level wind surge. The contour interval for OLR anomalies is 30 W m⁻². Areas of 850 hPa wind surges exceeding 10 m s⁻¹ are enclosed by dots within the thick solid contour lines, for which the interval is 15 m s⁻¹.

However, as the regional anticyclone over Texas weakened, Wilma's intensity decreased on October 20 by 30 kt (still leaving her as a Category 4 hurricane) from 160 kt at 1200 UTC October 19, although at that time the tropical easterly winds from the central tropical Atlantic strengthened. These events suggest that the large-scale circulation pattern in the immediate TC environment plays an important role in TC intensity change [20]. The multidirectional sources of angular momentum advection as described here likely provided for more efficient intensification than if the angular momentum inflow had been from a sole source, such as low-level easterlies. Meanwhile, the negative OLR anomaly maps after Wilma's TCG show that Hurricane Wilma's explosive deepening (from 1200 UTC October 18 to 1200 UTC October 19) was favored by the persistent low-level inflow from the large convective region in the Caribbean Sea to the central tropical Atlantic, which is consistent with the SST change over the period (**Figures 5** and **6**).
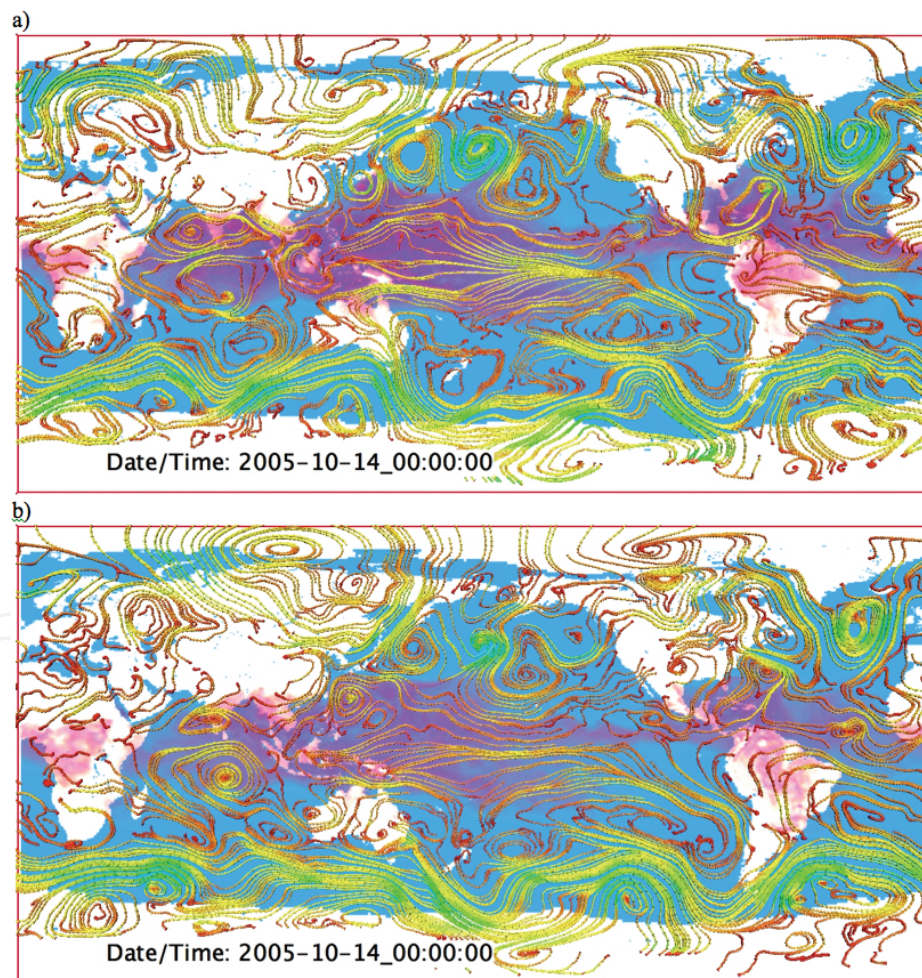
4. WRF model simulation

Figure 9 shows wind conditions at 1500 m (about 850 hPa) at the time of model integration. Compared to **Figure 2**, the global WRF reproduced large-scale atmospheric circulations very closely and effectively. The color of the wind arrows represents magnitudes of wind speed; wind speed increases as the color changes from red to yellow to green to blue (0–46 m s^{-1}). Arrows in green represent winds exceeding 10 m s^{-1}. The yellow-to-purple scale in the background represents the 1500 m high water vapor in the range of 12–20 g kg^{-1}. The deformation of the low-level circulation by Hurricane Vince (October 8–11; **Figure 9a**) and the subsequent development of the anomalous low-level cyclone over and northeast of the Caribbean Sea by the westerly winds from eastern North Pacific were simulated very realistically (**Figure 9b**).
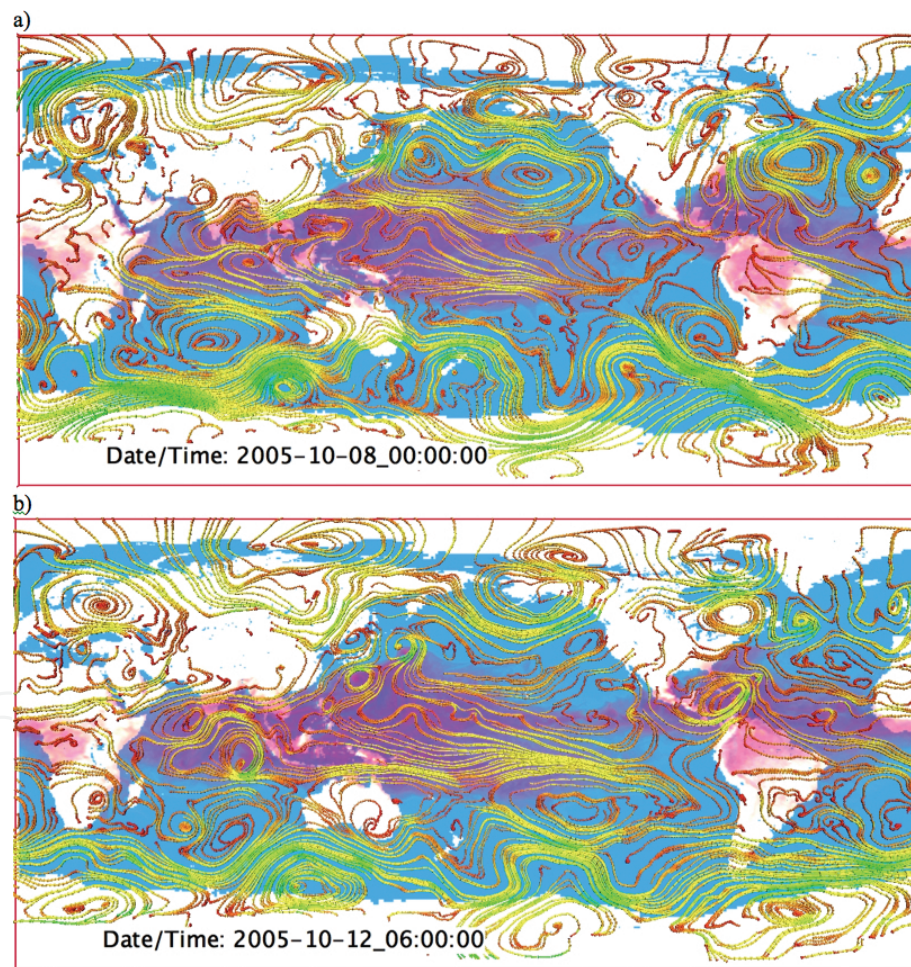

Figure 9. Samples of global WRF model simulation outputs: the anomalous circulation development of the subtropical high in the North Atlantic due to Hurricane Vince (October 8–11) (a) and the anomalous low-level cyclone over, and northeast of, the Caribbean by the westerly winds from eastern North Pacific (b). Wind conditions at 1500 m (about 850 hPa) at the time of model integration are presented with arrows. The color of the wind arrows represents wind speed: wind speed increases as the color changes from red to blue (0–46 m s^{-1}). The yellow to purple in the background represents the water vapor in the range of 12–20 g kg^{-1}.

However, the global WRF model simulation deteriorated by the seventh day after initialization (**Figure 10**), preventing the model from replicating the TCG of Wilma and its subsequent development into a hurricane over the western North Atlantic (not shown). From **Figure 10**, it seems that the major errors occurred in the high latitudes and mid-latitude systems that are directly affected by the high-latitude circulations. In fact, during the prolonged global WRF simulation, the major failure occurred in reproducing the interactions between the mid-latitude trough over the northeastern US and the subtropical low to the east of the US. As a result, the erroneous forecast in intensity and location of the mid-latitude trough over the northeastern US that was positioned to the northeast of the disturbance in the Caribbean predicted that the subtropical high would be restored in the North Atlantic, and vigorous easterly winds would resume over Central America (**Figure 11**) by October 16–20. This zonally enhanced low-level wind condition is opposite to the meridionally enhanced, low-level condition in the actual case of Wilma. In fact, the restored easterly winds over the Caribbean Sea impeded the development of a storm in the region.

Figure 10. Comparison of the large-scale low-level circulations between the global WRF model results after a 7-day continuous simulation (a) and at the model initialization (b) both at 0000 UTC October 14 using FNL and RTG SST datasets.
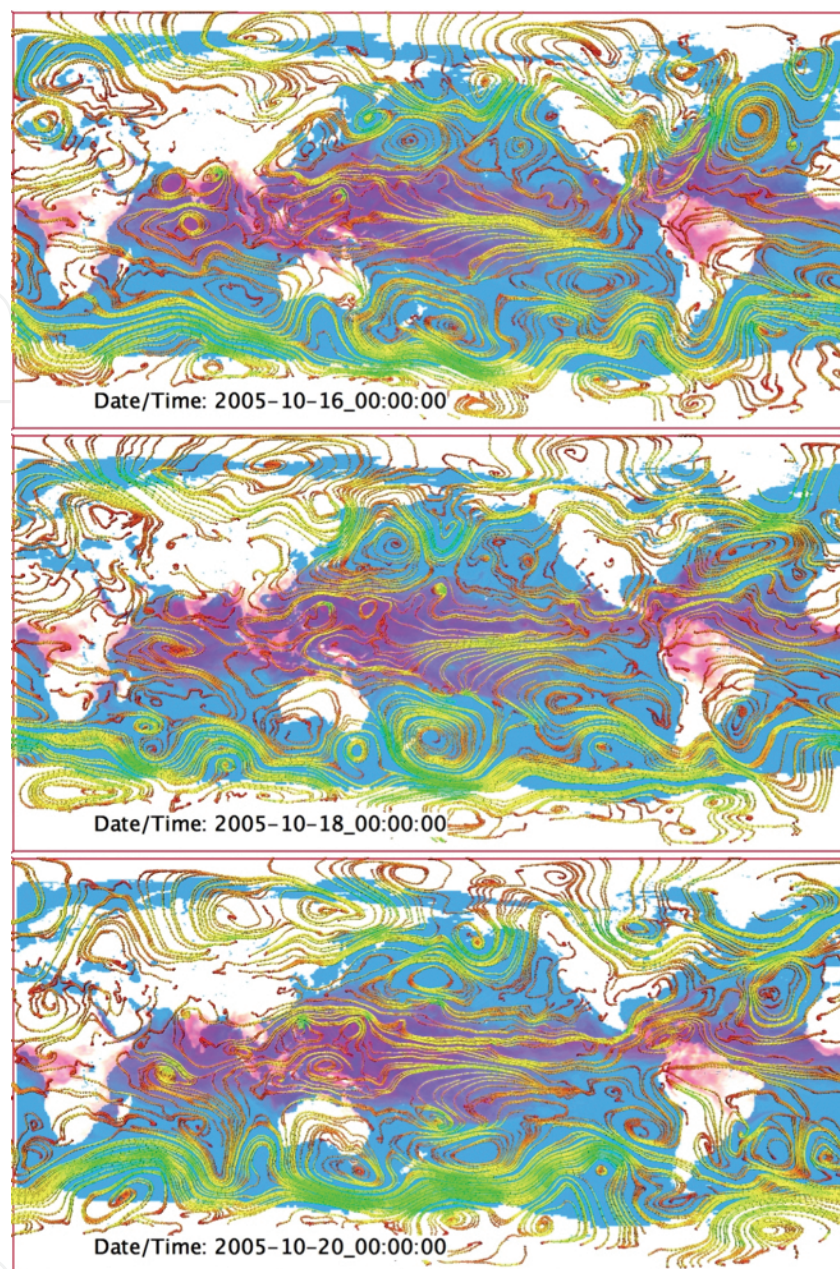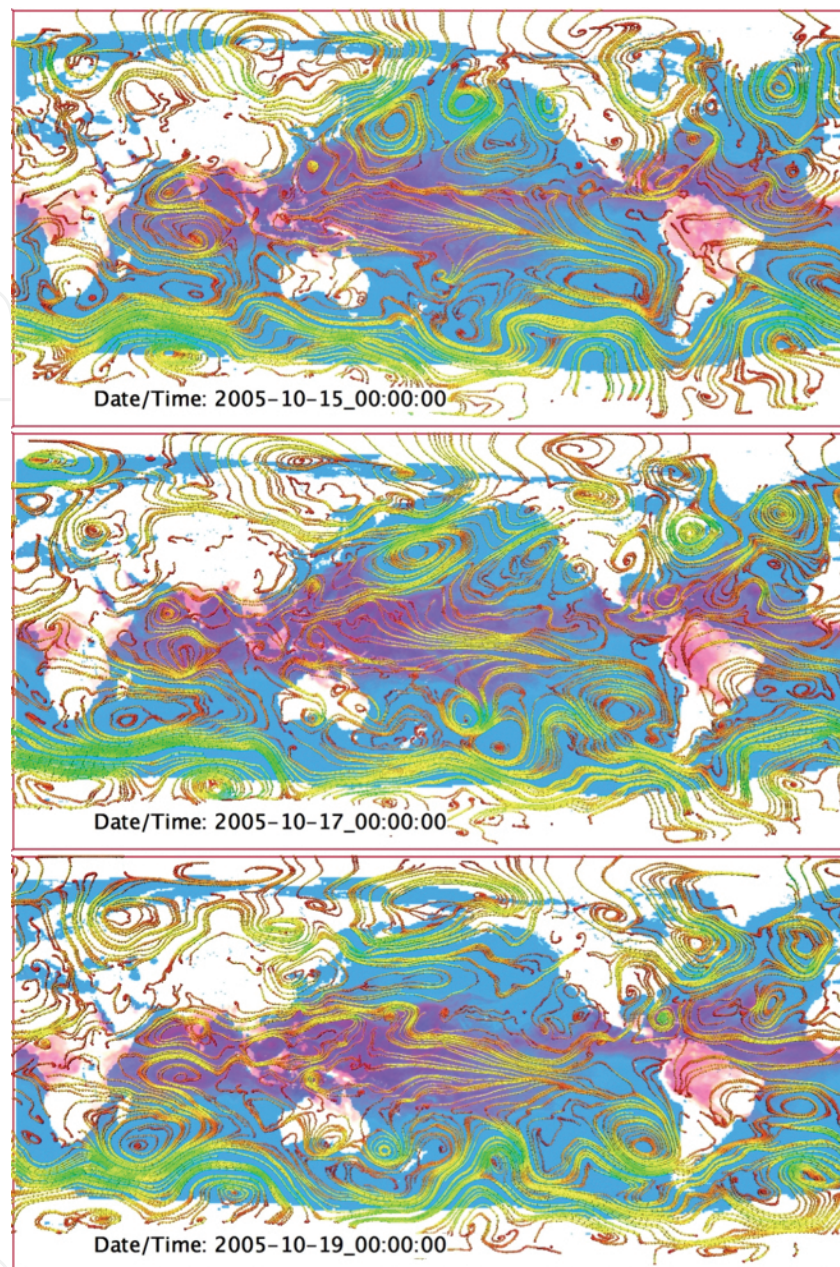
Figure 11. A failed forecast of Wilma's TCG.

By contrast, the second simulation that was initialized at 0000 UTC October 14 successfully simulated the TCG of Wilma and its subsequent development (**Figure 12**). The WRF global model reproduced every major vortex and circulation at 850 hPa level not only over the North Atlantic but also over the neighboring basins, including the eastern Pacific, South Atlantic, and subpolar regions. But the forecasted track of Wilma shifted to the east from the actual best track when Wilma was in its hurricane stage. This error seems to be attributed to the use of a relatively large grid size for the model simulation (about 56 km) to represent the meso-scale features accurately, while the inner-core dynamics of the storm actually might have played a more important role in steering its path and determining its intensity.

Figure 12. A successful forecast of Wilma's TCG.

The successful forecast of the merger of the subtropical cyclone with the mid-latitude trough off the east coast of the US around October 16 seems to be the key point that led the subsequent successful forecasts in the unique low-level, large-scale circulation development in the case of Wilma (see **Figures 3–6** and **12**). This result suggests that the role of mid-latitude systems in TC activity is not negligible; a result that is incongruent with the current TCG forecasting emphasis solely on tropical atmospheric conditions. The comparison of the unsuccessful and successful forecasts of the TCG and development of Wilma suggests that every major vortex and circulation component at least in the immediately neighboring storm development area is important for TCG progression.

Although the calculation errors in the WRF global model simulation grew significantly after seven days of model integration, it seems that the global WRF can be used for the purpose of operational short-range TCG forecasting. This result is encouraging, considering the fact that the global WRF model was initialized 42 hours before the simulated TCG and subsequent development of a TC, and yet the forecast will be fairly accurate in one continuous simulation for the 7-day period. It should be also noted that the 7-day global WRF model simulation required less than six hours in a Linux cluster computer with 96 cores.

5. Summary and conclusion

Planetary-scale atmospheric and oceanic conditions of the western Atlantic basin were analyzed to understand the unique TCG and intensification mechanism of Hurricane Wilma in 2005, using NCEP/NCAR reanalysis data, NOAA optimum interpolation (OI) ¼ degree daily SST V2 data, NOAA/OAR/ESRL PSD interpolated OLR data, and global WRF model simulation. An anomalous development of the 850 hPa circulation pattern in the North Atlantic was triggered by Hurricane Vince (October 8–11, 2005) in the eastern North Atlantic. Circulation around the southeastern fringe of the North Atlantic subtropical anticyclone during the period had been interrupted by the presence of Vince, causing a perturbation in the downstream flow around the entire southern edge of the North Atlantic subtropical high. On the southwestern flank of the subtropical high, the perturbation contributed to the development of a large-scale 850 hPa vortex, which would eventually allow for Wilma's TCG in the eastern Caribbean Sea. Due to the change in the low-level circulation by the deformed subtropical anticyclone, weakened low-level easterly winds allowed southeasterly winds from the Southern Hemisphere and westerly winds from eastern North Pacific to become relatively important, generating an anomalously prominent low-level cyclone over the western Atlantic about a week before TCG.

The anomalously large low-level cyclone over the western Atlantic matured over the warm ocean before it was separated into two cyclones in a north-south alignment (a northern cyclone and a southern cyclone). The separation was caused by the advance of northerly winds from a mid-latitude trough over central Canada one day before TCG. By 1200 UTC October 15, the high-latitude trough merged with the northern cyclone, resulting in a strengthened northern subtropical low. The enhanced subtropical low eventually played a role in sustaining the low-level circulation in the Caribbean Sea by preventing a significant interference from the zonally propagating tropical waves (**Figure 2c** and **d**). The southern cyclone became more concentrated in the Caribbean Sea, near Jamaica by October 14, growing into a tropical depression by 1800 UTC October 15.

The unusual but persistent meridionally oriented circulation conditions allowed the tropical depression over the Caribbean Sea to strengthen slowly between the northerly winds associated with the trough in the northeastern US and the southeasterly winds from the South Atlantic (**Figure 2c** and **d**). Wilma became a tropical storm at 0600 UTC October 17. Over October 17–18, as the North Atlantic subtropical high strengthened to produce more vigorous

low-level easterly winds in the central tropical Atlantic toward the Caribbean Sea (**Figure 2e**), Wilma drifted toward the west-northwest and strengthened into a hurricane at 1200 UTC October 18.

The unprecedented rapid intensification of Hurricane Wilma during the next night took place under anomalously warm SST conditions when Wilma was trapped between the northerly winds from the mid-latitude trough and synoptic-scale southeasterly winds. During Wilma's explosive deepening, a synoptic-scale anticyclone over Texas and the North Atlantic subtropical high seems to have caused Wilma to intensify between them by advecting angular momentum to the outer radii of Wilma.

The global WRF reproduced planetary-scale atmospheric circulations at 1500 m (about 850 hPa) very closely and effectively, including the deformation of the low-level circulation by Hurricane Vince (October 8–11) and the subsequent development of the anomalous low-level cyclone over and northeast of the Caribbean. However, the error growth after seven days from the model initialization changed the steering circulations, resulting in a failed forecast of Wilma's TCG and its subsequent development into a hurricane over the western North Atlantic. It seems that the major error resulted from misrepresentation of the interactions between mid-/high-latitude systems and tropical circulations.

In contrast, the second simulation that was initialized at 0000 UTC October 14 successfully simulated Wilma's TCG and subsequent development (**Figure 12**). The WRF global model reproduced every major vortex and circulation at the 850 hPa level, not only over the North Atlantic but also at least over the neighboring ocean basins. With the successful simulation of the merger of the subtropical cyclone with the mid-latitude trough off the east coast of the US around October 16, the subsequent forecast of the global WRF model was maintained successfully, reproducing the unique low-level, large-scale circulation development in the case of Wilma (see **Figures 2c–f** and **12**). The result of the global WRF model suggests that the role of mid-latitude systems in TC activity is more important than previously considered, and that every large-scale vortex and circulation component at least in the immediately neighboring region of the storm developing area is important for TCG forecasting. More in-depth analyses are warranted to better understand the unusual development of Hurricane Wilma.

Author details

Jinwoong Yoo[1*], Robert V. Rohli[2] and Jennifer Collins[3]

*Address all correspondence to: jinwoong.yoo@gmail.com

1 The Purdue Climate Change Research Center, Purdue University, West Lafayette, IN, USA

2 Department of Geography and Anthropology, Louisiana State University, Baton Rouge, LA, USA

3 School of Geosciences, University of South Florida, Tampa, FL, USA

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