Journal of Geophysical Research: Oceans

Supporting Information for

Air-Sea Fluxes for Hurricane Patricia (2015): Comparison with Supertyphoon Haiyan (2013) and under Different ENSO Conditions

Hsiao-Ching Huang[1], Julien Boucharel[2], I-I. Lin[1], Fei-Fei Jin[2, 3], Chun-Chi Lien[1], Iam-Fei Pun[1]

[1]Department of Atmospheric Sciences, National Taiwan University, Taipei, Taiwan; [2]Department of Atmospheric Sciences, SOEST, University of Hawaii at Manoa, Honolulu, Hawaii; [3]Laboratory for Climate Studies, Beijing Climate Center, Chinese Meteorological Agency, Beijing, China

Corresponding author: I-I Lin (iilin@as.ntu.edu.tw)

Contents of this file

Introduction

This supporting information provides 1 text, 14 figures and 2 tables:

Text S1 provides the descriptions of 3DPWP model and the simulation information in this study.

Figure S1 shows the anomalies ocean conditions for Patricia and Haiyan. Figures S2-S5 and S7-S8 are TC's intensification process of SHF and LHF. Figure S6 is SST cooling effect under a slower translation speed between different latitude. Figures S9-S12 show the comparison of three strong EP El Niño conditions. Figures S13-S14 show the TC wind profile and the implementation of TC forcing in the 3DPWP model.

Table S1 provides TC data of Patricia and Haiyan. Table S2 is corresponding to Figures S9-S12, show the comparison of three strong EP El Niño conditions.

Text S1. Description of **t**hree dimensional Price-Weller-Pinkel (3DPWP) mixed layer model

The 3DPWP model is a numerical ocean model proposed by Price et al. [1994]. It simulates the changes of upper ocean current, temperature, and salinity fields induced by a hurricane. The 3DPWP model essentially embraces the 1D version of PWP model [*Price et al.*, 1986] that is hydrostatic with primitive equations. This model is designed to handle the vertical mixing process, vertical and horizontal advections, as well as air-sea exchanges. In this model, the surface mixed layer evolves due to entrainment mixing and air-sea exchanges. The surface heat flux is computed by assuming the air temperature (T_a = 26 °C) and the dewpoint temperature (T_d = 25 °C) are constant. The bulk transfer coefficient for sensible and latent heat flux is 1.3×10^{-3}. The momentum flux (or surface wind stress) is calculated from bulk transfer formula. The drag coefficient (C_d) in this study is based on Powell et al. [2003].

It has been noted in Price [1981] that entrainment mixing is the primary mechanism for reducing the SST beneath a moving hurricane (or tropical cyclone (TC)), while air-sea heat exchange plays only a minor role. According to Price [1981], the entrainment mixing accounted for ~85% of the TC-induced SST cooling, and air-sea heat exchange for remained ~15%. It solves the wind-driven, baroclinic ocean response, including a treatment of turbulent vertical mixing in the upper ocean. The important process of vertical mixing in the 3DPWP model is implemented through the mixing parameterization, inducing density (modified by temperature and salinity) and velocity shears (driven by TC wind). The upper ocean will be adjusted until three stability criteria are satisfied, which are static stability:

$$\frac{\partial \rho}{\partial z} \geq 0,$$

mixed-layer shear flow stability (bulk Richardson number R_b):

$$R_b = \frac{g \delta \rho h}{\rho_0 (\delta V)^2} \geq 0.65,$$

and stratified shear flow stability (gradient Richardson number R_g):

$$R_g = \frac{g\, \partial \rho / \partial z}{\rho_0 (\partial V / \partial z)^2} \geq 0.25$$

where z is positive downward depth with z = 0 begin the sea surface, ρ_0 is density of sea water taken as 1024 kg/m^3, ρ is the density of sea water at each depth, h is the mixed layer depth, V is the horizontal current, g is the acceleration due to gravity, and δ represents the vertical difference across the base of the mixed layer. The model runs with time steps Δt = 360 s.

The size of this model domain is 450 km (in the cross-track direction) by 460 km (in the along-track direction) with a 5 km horizontal resolution. The vertical resolution is 5 m for the upper 100 m, 10 m for the depth between 100-200 m, and 50 m for the depth between 200-1000 m. Each model grid point is homogeneously initialized with the same temperature and salinity vertical profiles, and thus the ocean initial condition is horizontally homogeneous over the whole domain. Simulations were performed for the periods of TC's intensification, from tropical storm (TS, ≧35 knots) stage to peak strength. The initial ocean temperature and salinity profiles in this study were obtained from two datasets, a) GODAS reanalysis monthly means data averaged from TS to peak and b) the nearest pre-TC (within 3-5 days prior to TC's passing) Argo in-situ floats observation data along TC tracks.

Furthermore, the TC-induced SST in 3DPWP model is not only affected by pre-TC ocean conditions and atmospheric factors as mentioned above, but also associated with TC intensity (wind speed) and TC transit time, which controlled by TC size (*D*) and TC translation speed (U_h) [*Lin et al.*, 2008]:

$$TC_{transit-time} = \frac{D}{U_h}.$$

In this study, the TC is assumed moving with a constant translation speed (U_h), and its intensity and structure will not change over time. A maximum wind speed, radius of maximum wind (*rmw*), and U_h are required to characterize the TC in the model. The TC's latitude and U_h are mean values along the TC tracks from TS to peak and TC size (*D*) is determined by the radius of 50 knots wind at the peak strength. The TC-induced SST cooling impact region is averaged over a circle area of 2.5 times *rmw* from the TC center. All the TC characteristics (U_h, *D*, *rmw*, and storm structure) in the simulations were obtained from the best track data of NHC and JTWC. TC's radial wind profile which we used to construct the TC wind field in the model consists of rmw, the radii of 64 knots wind (r64), 50 knots wind (r50), and 34 knots wind (r34) at TC's peak (corresponds to Table S1). The wind profiles for Patricia and Haiyan are shown as Figure S13.

In addition, the implementation of TC forcing is shown as Figure S14. The TC in the model moves from bottom to top along the middle of x-axis at a constant U_h (left panel). For example, given the radius of Patricia is 83.3 km, Patricia moves from (x, y) = (0, -83.3) to (0, 83.3) at U_h = 6.2 m/s. The initial SST and the resultant TC-induced SST field are presented in the right panel of Figure S14.

Furthermore, given the current model setting we have mentioned above, 3DPWP may overestimate the SST cooling, because the TC intensity (wind speed) and structure of the TC are unchanged over time. It is one of the limitation we have to note for this uncoupled model.

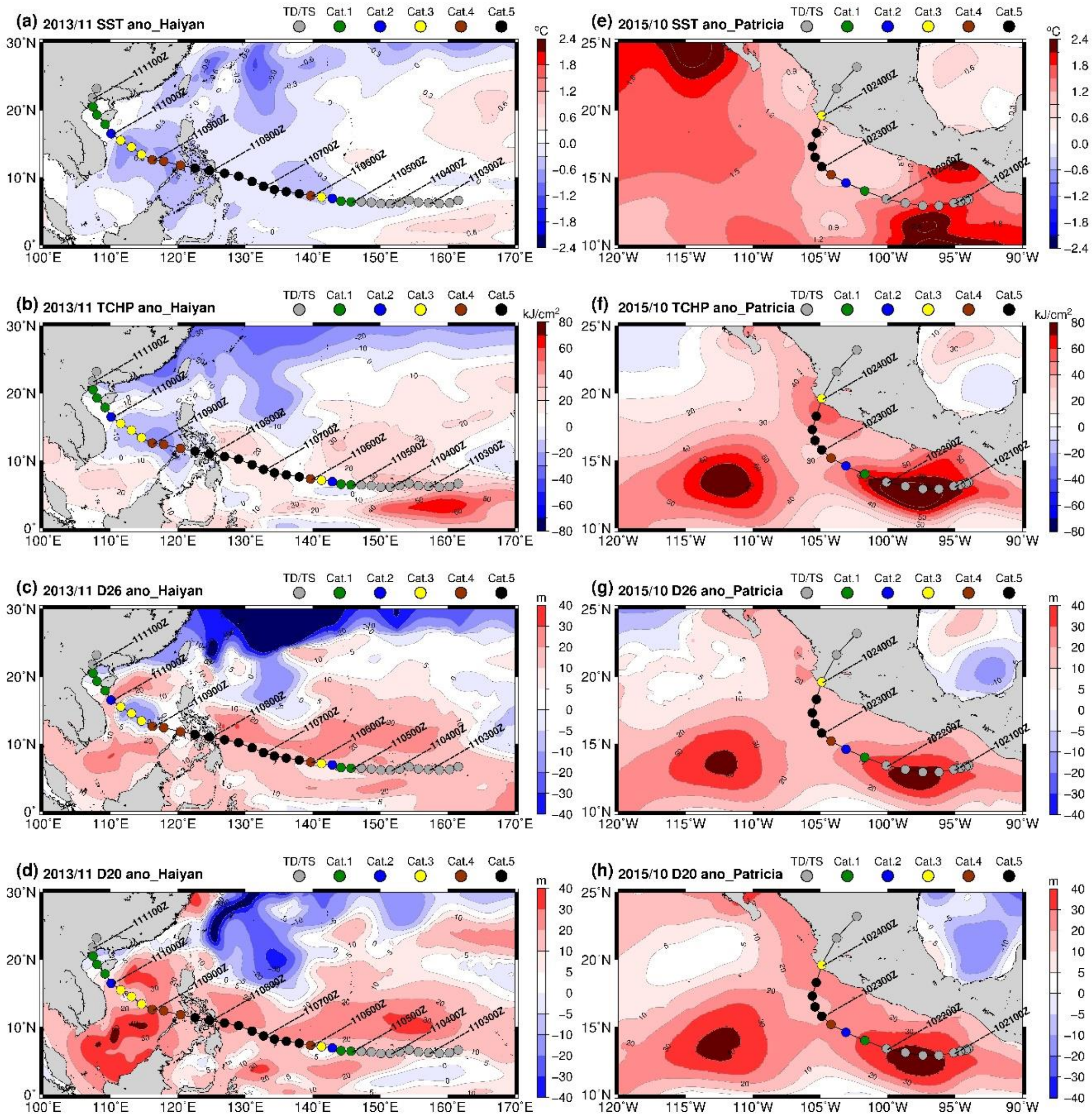

Figure S1. As in Figure 1, but for SST anomalies, TCHP anomalies, D26 anomalies, and D20 anomalies.

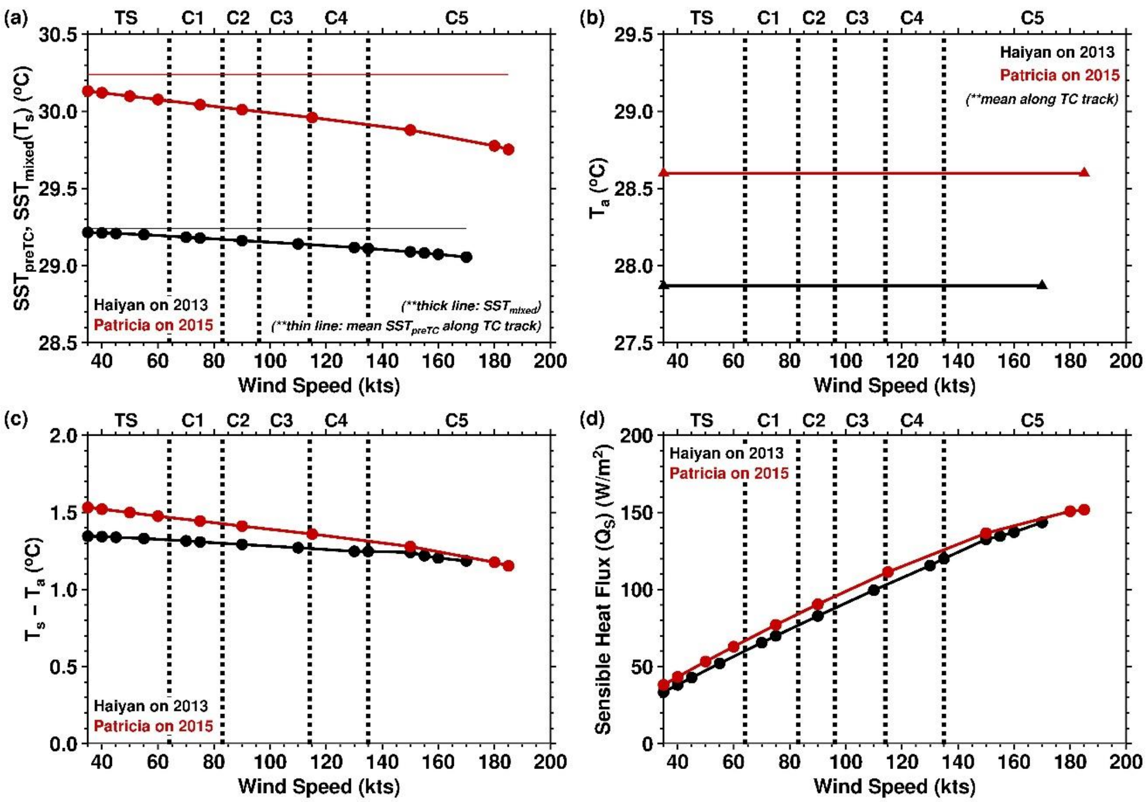

Figure S2. As in Figure 2, but for the corresponding mean pre-TC SST (SST_{preTC}) along TC track (thin line) and TC-induced SST cooling result ($SST_{mixed} = T_s$) (thick line) in **(a)**, the mean near surface air temperature (T_a) along TC track in **(b)**, during-TC air-sea temperature difference ($\Delta T = T_s - T_a$) in **(c)**, and sensible heat flux (SHF) in **(d)**.

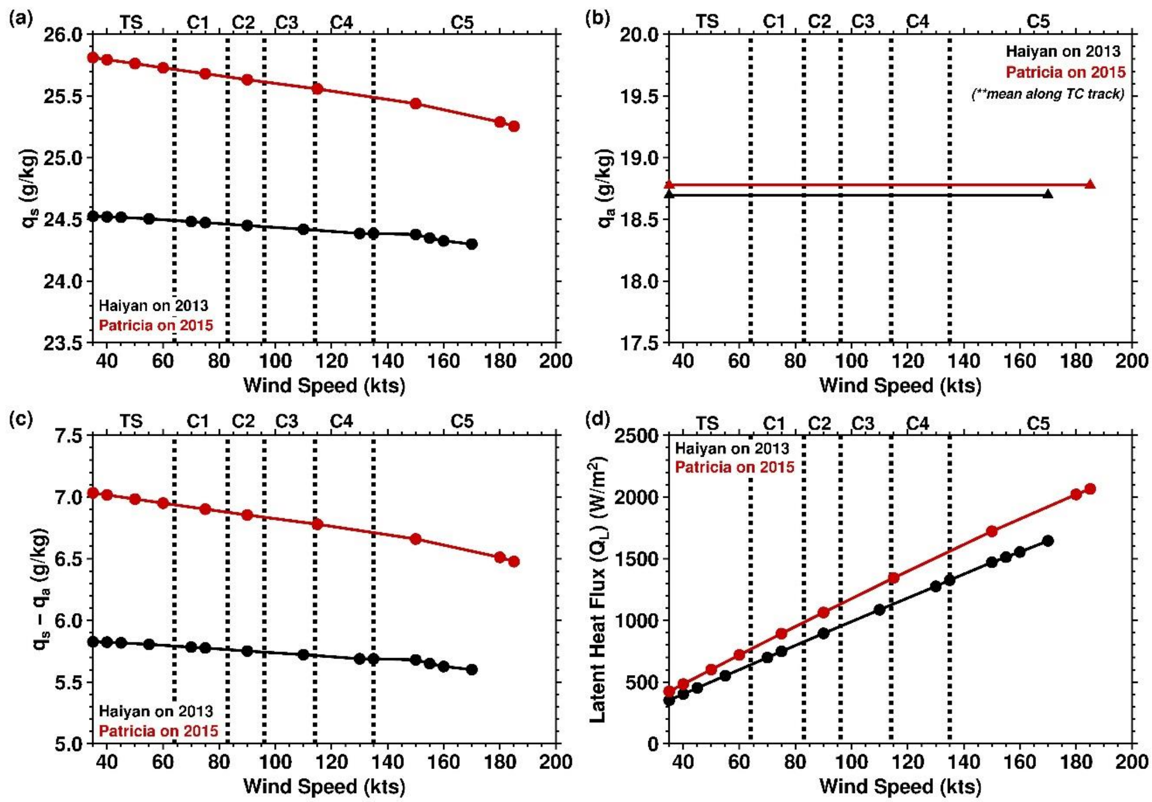

Figure S3. As in Figure 2, but for the corresponding surface specific humidity of pre-TC SST (q_s) in **(a)**, mean near-surface air humidity (q_a) along TC track in **(b)**, air-sea humidity difference ($\Delta q = q_s - q_a$) in **(c)**, and latent heat flux (LHF) in **(d)**.

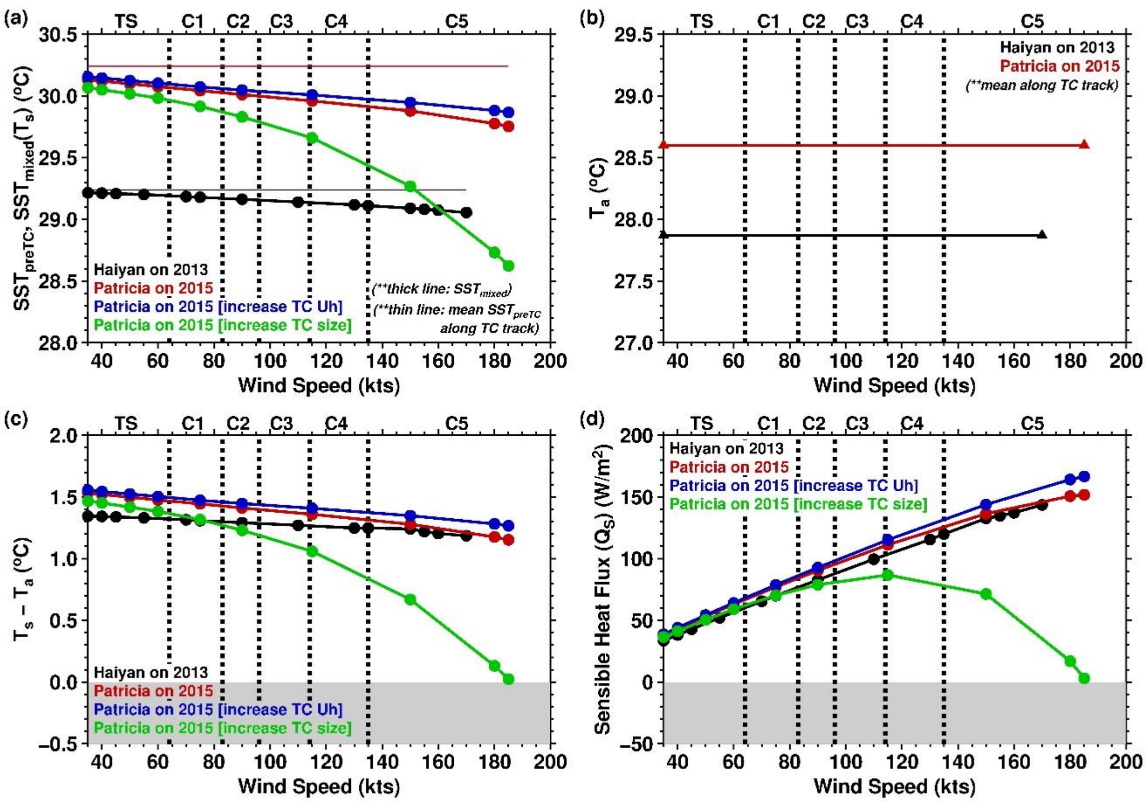

Figure S4. As in Figure 3, but for the corresponding mean pre-TC SST (SST_{preTC}) along TC track (thin line) and TC-induced SST cooling result ($SST_{mixed} = T_s$) (thick line) in **(a)**, the mean near surface air temperature (T_a) along TC track in **(b)**, during-TC air-sea temperature difference ($\Delta T = T_s - T_a$) in **(c)**, and sensible heat flux (SHF) in **(d)**.

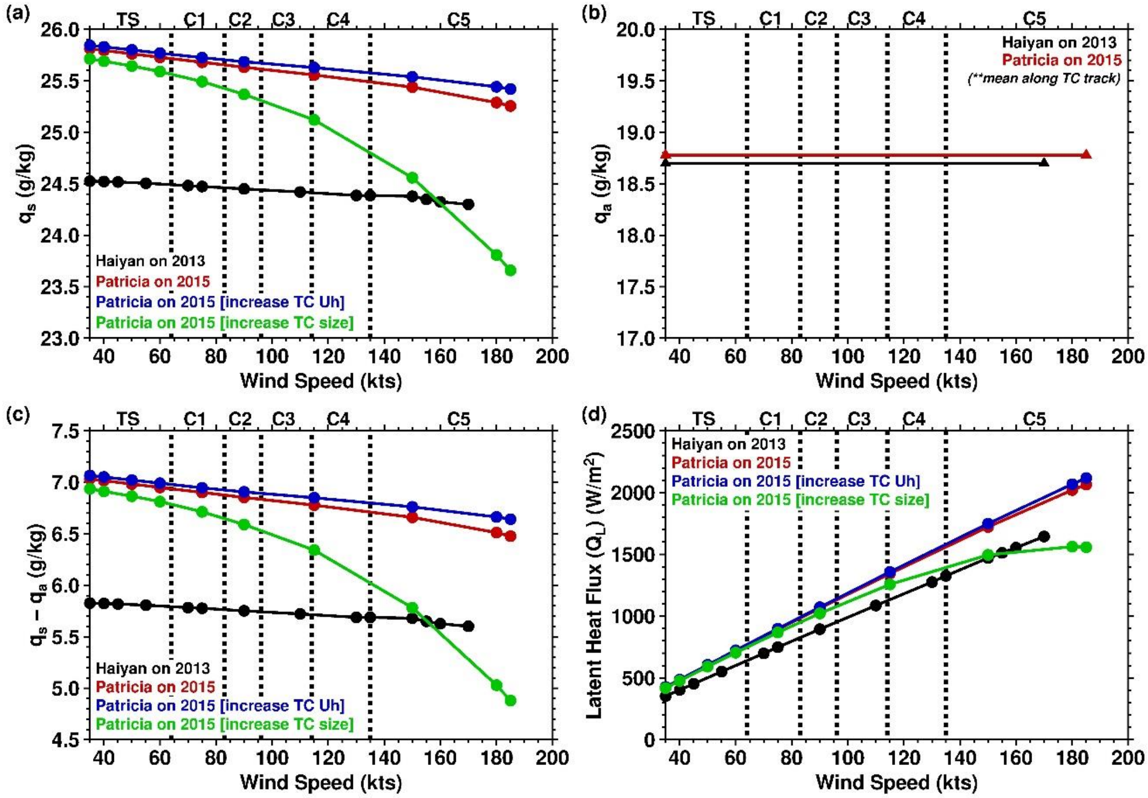

Figure S5. As in Figure 3, but for the corresponding the surface specific humidity of pre-TC SST (q_s) in **(a)**, the mean near-surface air humidity (q_a) along TC track in **(b)**, air-sea humidity difference ($\Delta q = q_s - q_a$) in **(c)**, and latent heat flux (LHF) in **(d)**.

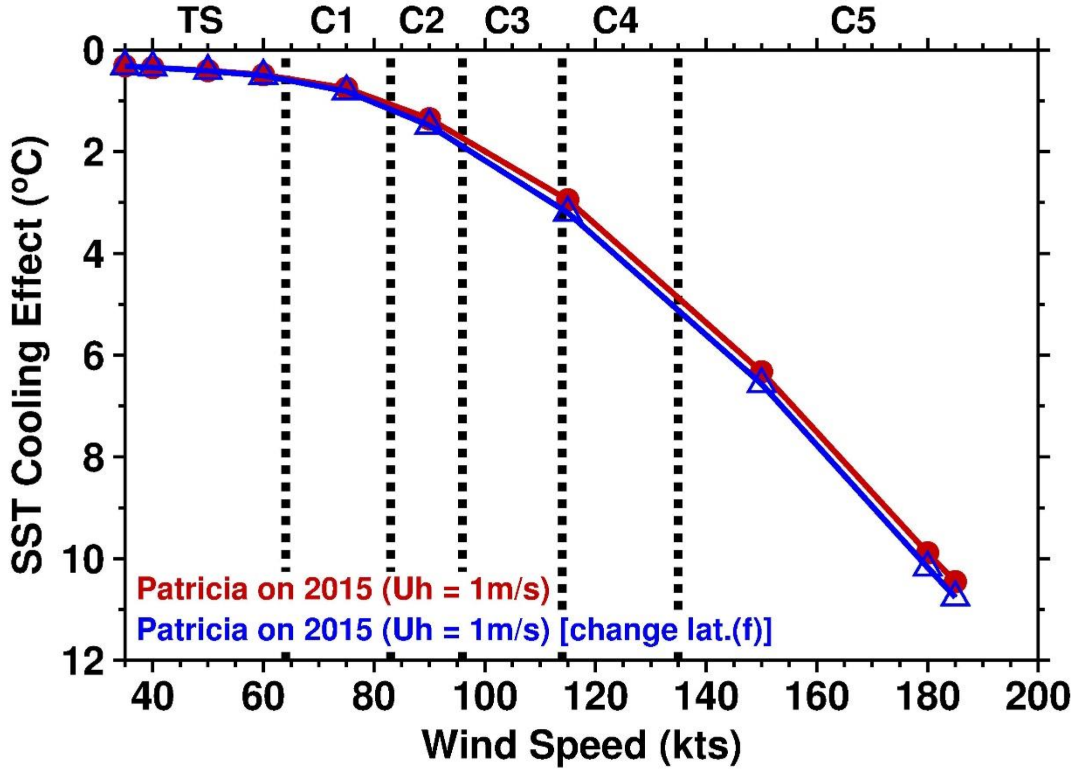

Figure S6. As in Figure 4(b), but for under a slower translation speed, U_h = 1 m/s.

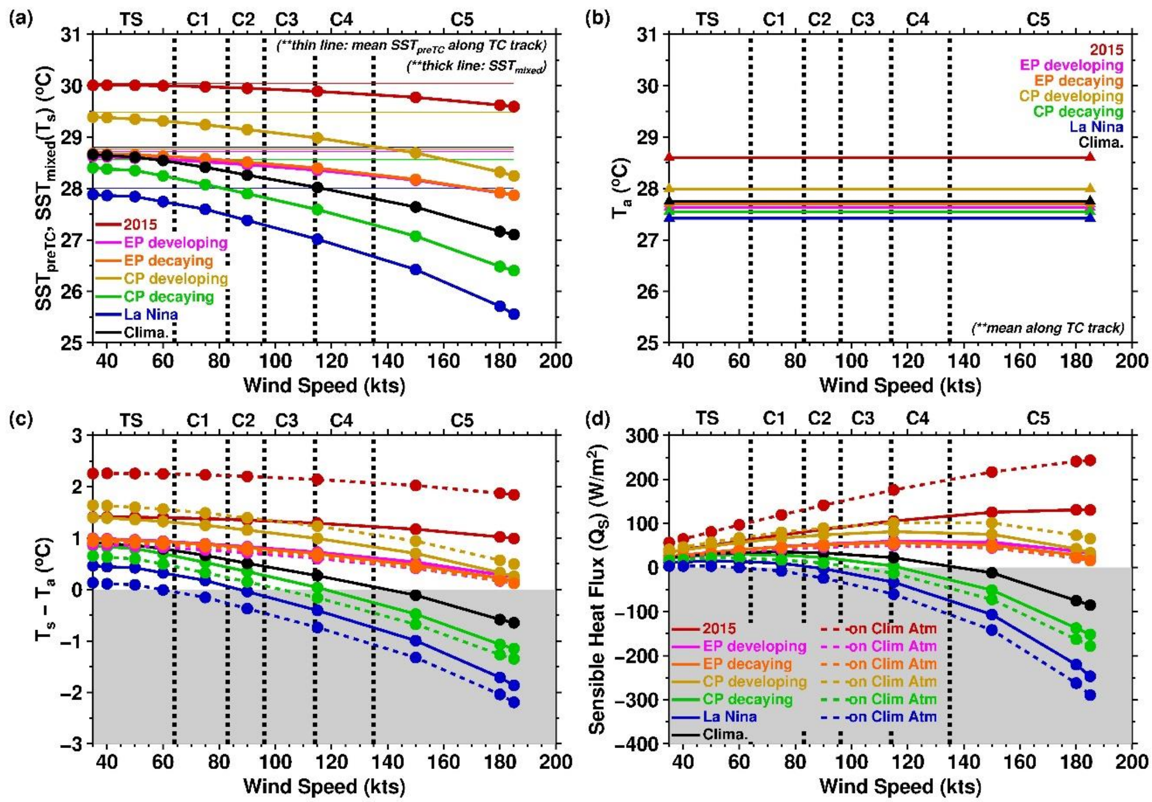

Figure S7. As in Figure 6, but for the corresponding mean pre-TC SST (SST_{preTC}) along TC track (thin line) and TC-induced SST cooling result ($SST_{mixed} = T_s$) (thick line) in **(a)**, the mean near surface air temperature (T_a) along TC track in **(b)**, during-TC air-sea temperature difference ($\Delta T = T_s - T_a$) in **(c)**, and sensible heat flux (SHF) in **(d)**.

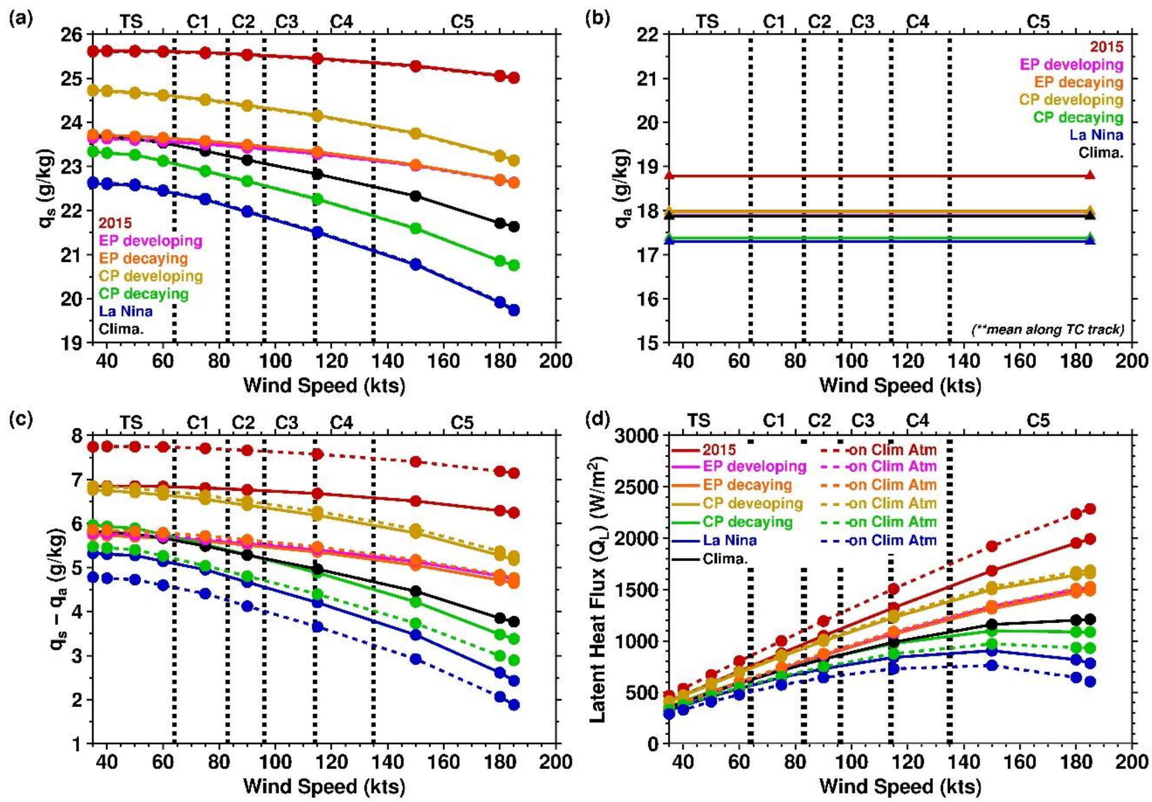

Figure S8. As in Figure 6, but for the corresponding the surface specific humidity of pre-TC SST (q_s) in **(a)**, the mean near-surface air humidity (q_a) along TC track in **(b)**, air-sea humidity difference ($\Delta q = q_s - q_a$) in **(c)**, and latent heat flux (LHF) in **(d)**.

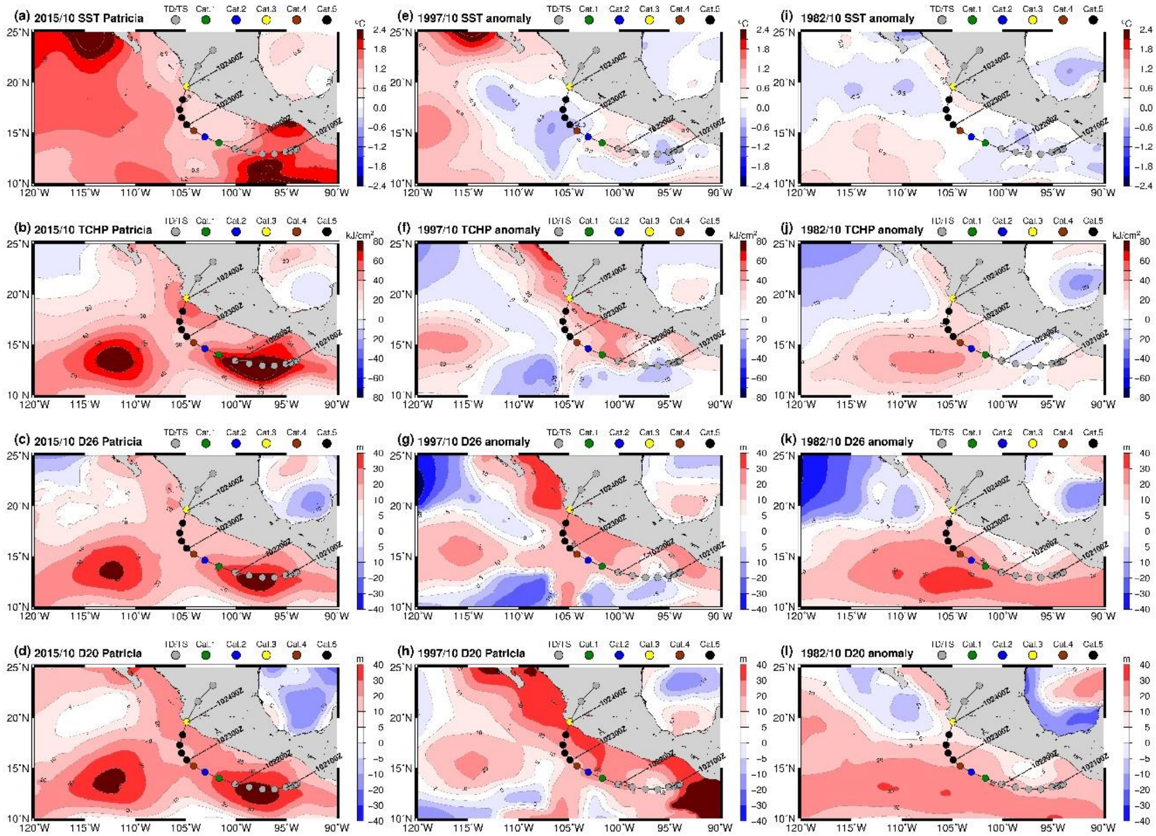

Figure S9. The pre-existing ocean conditions of different strong EP developing year, 1982 (right panels), 1997 (middle panels), and 2015 (left panels). **(a)-(d)** are respectively monthly sea surface temperature (SST), tropical cyclone heat potential (TCHP), depth of 26 °C isotherms (D26), and depth of 20 °C isotherms (D20) anomalies in October 2015 with the trajectories and intensity of hurricane Patricia superimposed. **(e)-(h)** and **(i)-(l)** are the same but in 1997 and 1982.

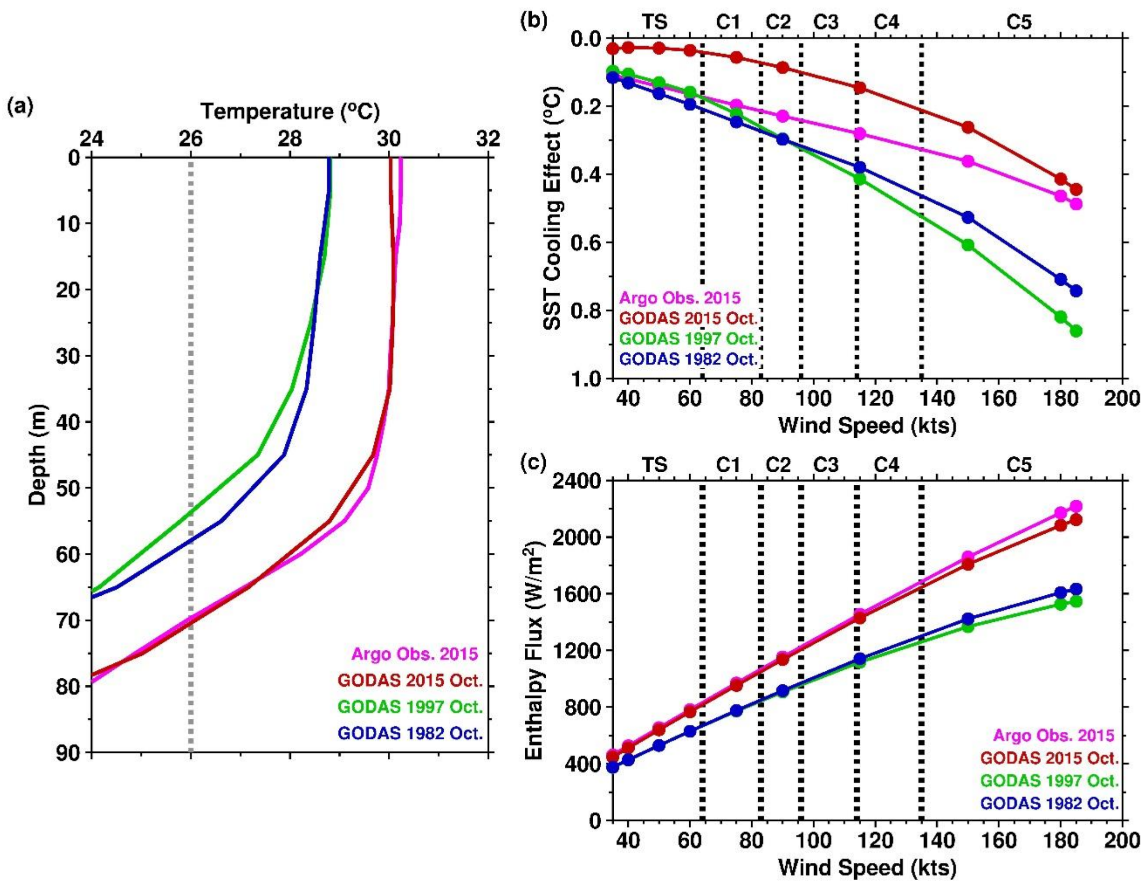

Figure S10. The intensification process from TS to peak of Patricia in 2015 and different strong EP developing year, 1982 and 1997. **(a)** shows the pre-existing sea surface temperature anomalies from GODAS reanalysis data in October 2015 with the trajectory and intensity of hurricane Patricia and the available Argo floats locations (magenta triangle marks in Figure 1e) superimposed. **(b)** shows the pre-TC oceanic vertical thermal structure of GODAS reanalysis monthly mean data along Patricia track in 2015 (red), 1997 (green), 1982 (blue), and the average of 2015 Argo profiles (magenta). The respective corresponding TC-induced SST cooling effect and inferred enthalpy fluxes estimated from different wind speed (categories) are shown in **(c, d)**.

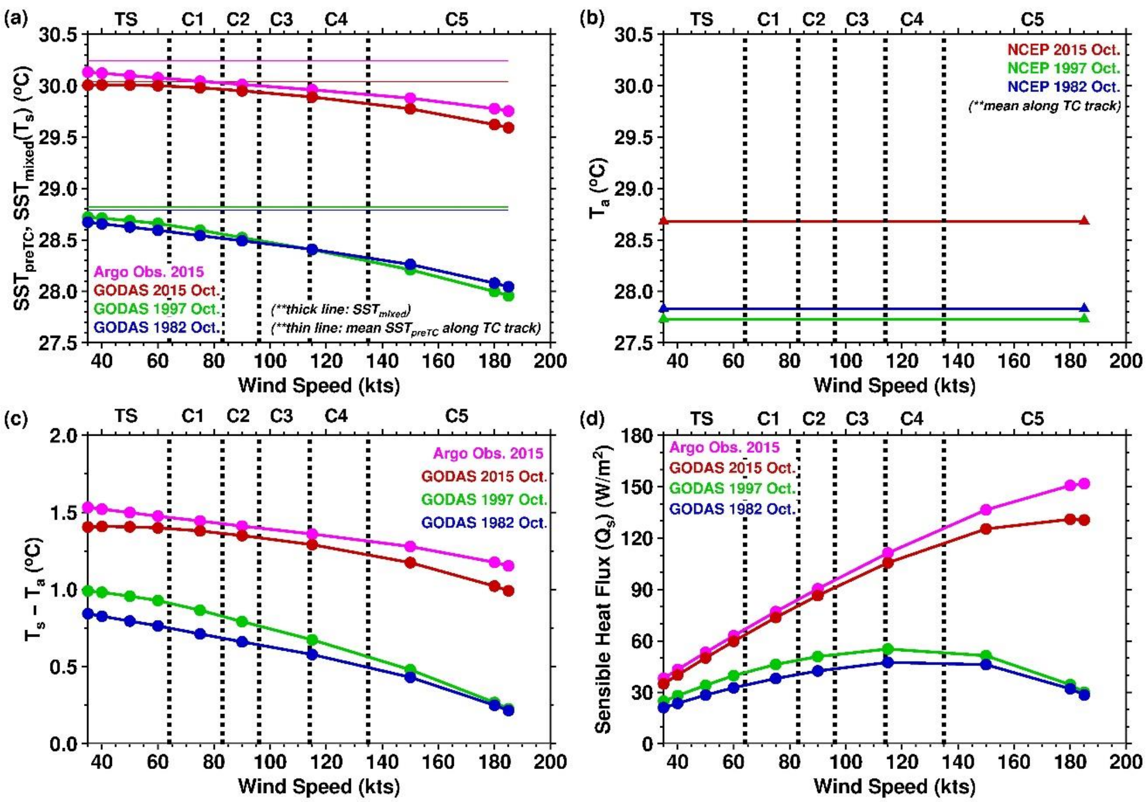

Figure S11. As in Figure S10, but for the corresponding mean pre-TC SST (SST_{preTC}) along TC track (thin line) and TC-induced SST cooling result ($SST_{mixed} = T_s$) (thick line) in **(a)**, the mean near surface air temperature (T_a) along TC track in **(b)**, during-TC air-sea temperature difference ($\Delta T = T_s - T_a$) in **(c)**, and sensible heat flux (SHF) in **(d)**.

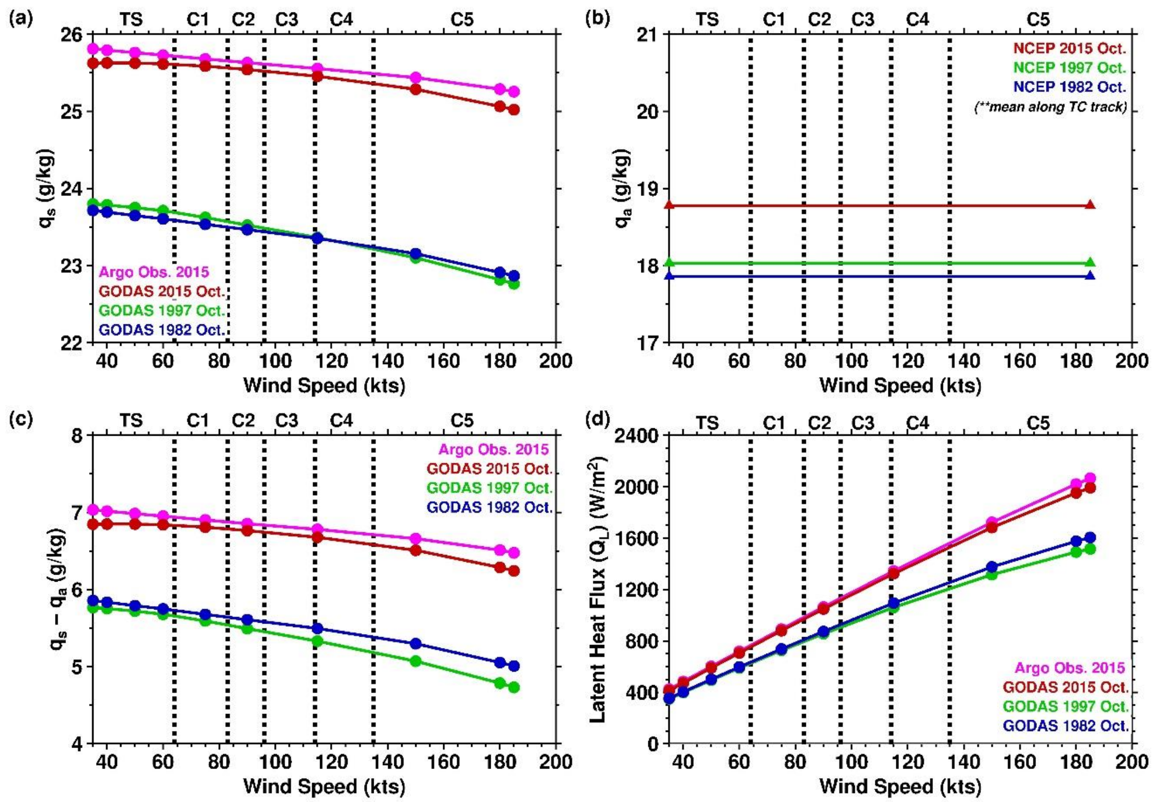

Figure S12. As in Figure S10, but for the corresponding the surface specific humidity of pre-TC SST (q_s) in **(a)**, the mean near-surface air humidity (q_a) along TC track in **(b)**, air-sea humidity difference ($\Delta q = q_s - q_a$) in **(c)**, and latent heat flux (LHF) in **(d)**.

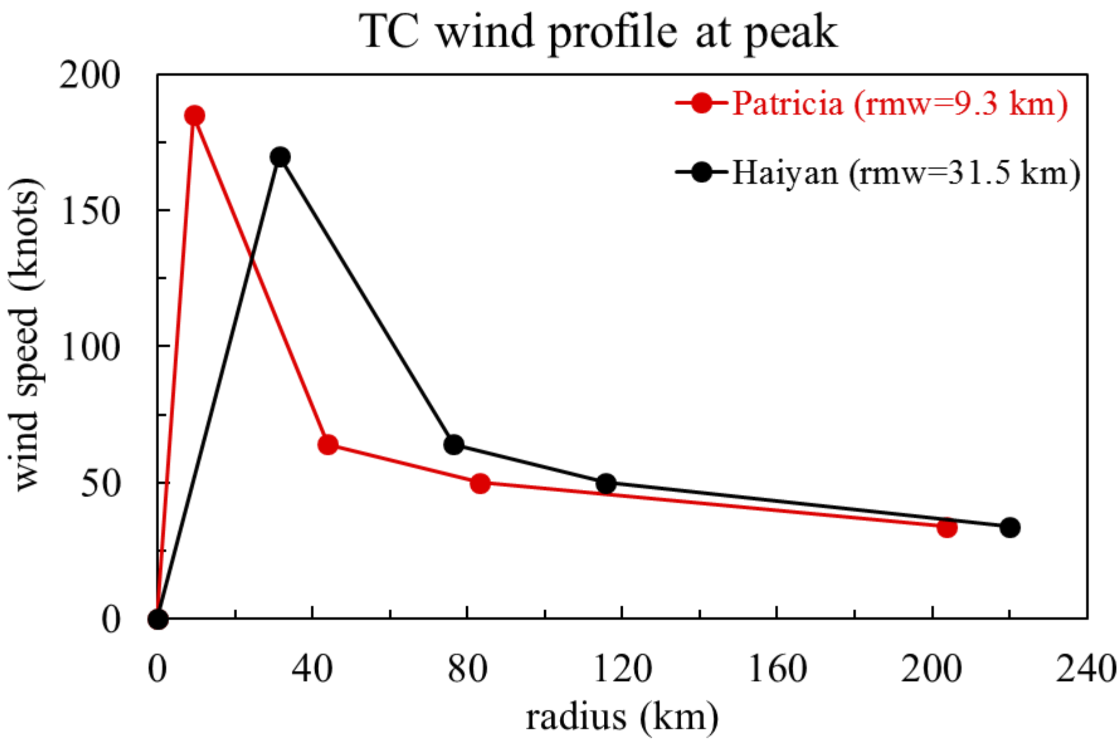

Figure S13. The wind profiles for Patricia (red) and Haiyan (black). TC's radial wind profile which we used to construct the TC wind field in the model consists of *rmw*, the radii of 64 knots wind (*r64*), 50 knots wind (*r50*), and 34 knots wind (*r34*) at TC's peak (corresponds to Table S1).

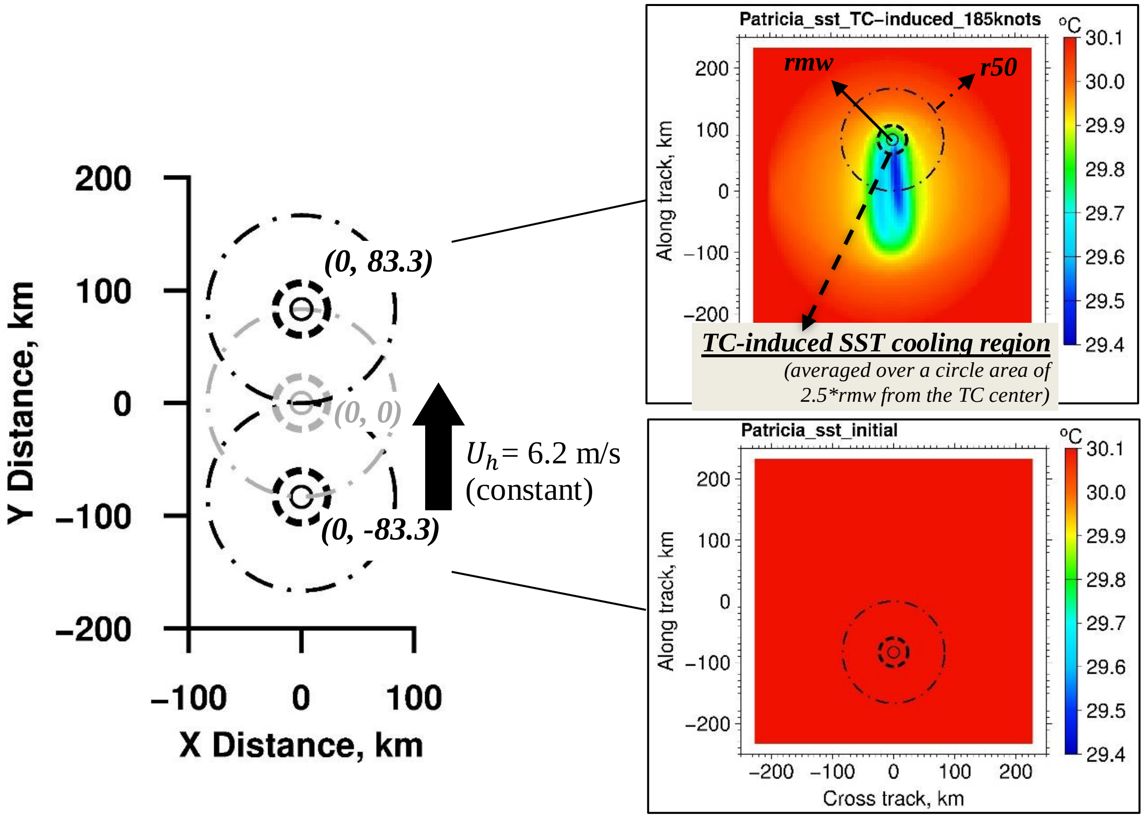

Figure S14. The implementation of TC forcing. The TC in the model moves from bottom to top along the middle of x-axis at a constant U_h (left panel). For example, given the radius of Patricia is 83.3 km, Patricia moves from (x, y) = (0, -83.3) to (0, 83.3) at U_h = 6.2 m/s. The initial SST and the resultant TC-induced SST field are presented in the right panel.

TC characteristics	TC size at peak					Translation speed, Uh_mean (m/s)
	radius of max wind, rmw (km)	radius of 64knts wind, r64 (km)	radius of 50knts wind, r50 (km)	radius of 34knts wind, r34 (km)	impact size, r = 2.5*rmw (km)	
Haiyan in Nov. 2013	31.5	76.4	115.8	219.9	78.8	8.4
Patricia in Oct. 2015	9.3	44	83.3	203.7	23.3	6.2

Table S1. Corresponding to Figures 3 and S4, S5, TC size (radius of max wind, 64 knots wind, 50 knots wind, and 34 knots wind), and cooling impact size (averaged over a circle area of 2.5 times radius of maximum wind) at the lifetime peak and average translation speed from Tropical Storm (TS) to Peak of Haiyan and Patricia.

(a) Ocean pre-conditions					
Patricia in different EP developing years	**SST_{preTC} (°C)**	**$T100_{preTC}$ (°C)**	**$TCHP_{preTC}$ (kJ/cm^2)**	**$D26_{preTC}$ (m)**	**$D20_{preTC}$ (m)**
2015 Argo	30.2	27.2	104	70	96
2015	30.0	27.0	101	70	92
1997	28.8	25.1	48	54	85
1982	28.8	24.8	54	58	79

(b) Atmospheric environment				
Patricia in different EP developing years	**T_a (°C)**	**T_d (°C)**	**q_a (g/kg)**	**VWS (m/s)**
2015 Argo	28.6	24.7	18.8	2.2
2015	28.6	24.7	18.8	2.2
1997	27.7	24.8	18.0	4.0
1982	27.8	23.9	17.9	3.9

(c) Air-sea interaction at TC peak								
Patricia in different EP developing years	**SST cooling effect (°C)**	**SST_{mixed} (T_s) (°C)**	**ΔT (T_s-T_a) (°C)**	**SHF (Q_S) (W/m^2)**	**q_s (g/kg)**	**Δq (q_s-q_a) (g/kg)**	**LHF (Q_L) (W/m^2)**	**Enthalpy flux (LHF+SHF) (W/m^2)**
2015 Argo	0.5	29.8	1.2	152	25.3	6.5	2066	2218
2015	0.4	29.6	1.0	131	25.0	6.2	1992	2122
1997	0.9	28.0	0.2	30	22.8	4.7	1516	1546
1982	0.7	28.0	0.2	28	22.9	5.0	1605	1633

Table S2. Corresponding to Figures S10-S12, the pre-existing ocean conditions from Argo profiles, GODAS monthly mean reanalysis **(a)** and atmospheric environment from NCEP/NCAR R1 monthly mean reanalysis **(b)** along Patricia trajectories in October 2015 and strong EP developing years, 1997 and 1982. Panel **(c)** shows the corresponding TC-induced ocean cooling effect, SST_{mixed}, q_s, atmospheric and ocean temperature and humidity differences(ΔT, Δq), and air-sea enthalpy flux (SHF and LHF) from the cooling effect at the life-time peak of Patricia.