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Rapid intensification of tropical cyclones: Vortex waves seeded by aurorally-generated atmospheric gravity waves?

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Abstract. Convective bursts have been linked to intensification of tropical cyclones [1]. We consider a possibility of convective bursts being triggered by aurorally-generated atmospheric gravity waves (AGWs) that may play a role in the intensification process of tropical cyclones [2]. A two-dimensional barotropic approximation is used to obtain asymptotic solutions representing propagation of vortex waves [3] launched in tropical cyclones by quasi-periodic convective bursts. The absorption of vortex waves by the mean flow and formation of the secondary eyewall lead to a process of an eyewall replacement cycle that is known to cause changes in tropical cyclone intensity [4]. Rapid intensification of hurricanes and typhoons from 1995-2018 is examined in the context of solar wind coupling to the magnetosphere-ionosphere-atmosphere (MIA) system. In support of recently published results [2] it is shown that rapid intensification of TCs tend to follow arrival of high-speed solar wind when the MIA coupling is strongest. The coupling generates internal gravity waves in the atmosphere that propagate from the high-latitude lower thermosphere both upward and downward. In the lower atmosphere, they can be ducted [5] and reach tropical troposphere. Despite their significantly reduced amplitude, but subject to amplification upon over-reflection in the upper troposphere, these AGWs can trigger/release moist instabilities leading to convection and latent heat release. A possibility of initiation of convective bursts by aurorally generated AGWs is investigated. Cases of rapid intensification of recent tropical cyclones provide further evidence to support the published results [2].

Convective bursts and tropical cyclone intensification

The importance of latent heat release in convective bursts (CBs) in TCs was first hypothesized [6,7] and CBs have been linked to tropical cyclone intensification [8]. The amount of energy released in a typical CB has been estimated to be capable of significant intensification [9,10,11] showed a series of CBs preceding intensifications of hurricane Opal and typhoon Paka, respectively. A global survey of CB events covering years 1999-2002 [12] showed that 80% of TCs have at least one CB episode and that CBs usually occur during or just prior the intensification phase of the storm cycle. A comparison study covering years 2011-2014 [13] of TCs with and without CBs revealed that the correlation between outflow and the TC intensification rate was higher for TCs accompanied by CBs than for those without CBs, implying that a rapid deepening of inner core convection is important for intensification of a TC's secondary circulation.

Vortex Rossby waves and formation of inner bands

Outward-propagating spiral rain bands have been known to affect the structure and intensity of tropical cyclones [14]. They can be initiated by deep convection in the eyewall and have been described as vortex Rossby waves (VRWs) [15]. The radially outward-propagating VRWs are responsible for initiation of the inner spiral rain bands, and can affect the structure and intensity of the mean vortex by wave-mean flow interaction [16,17]. The absorption of VRWs in critical layers is known to lead to formation of the secondary eyewall, and ultimately to a process of eyewall replacement cycles, which is thought to play an important role in rapid intensification of TCs.

Modeling of vortex Rossby waves

Nikitina and Campbell [18] presented asymptotic solutions for a problem representing VRW propagation in tropical cyclones and considered the interaction between the waves and the mean flow in the vortex. The stream function (right) show positive values coded in red-orange color. The orange arcs (spiral sleeves) beyond the critical radius represent the outward propagating spiral bands of the tropical cyclone. The waves are forced by perturbations on the eyewall. The wave number is selected equal to one to represent the asymmetric structure of perturbations caused by convective bursts. For the modeling, a two-dimensional barotropic approximation of the TC was used, and the mean rotation speed in TC was taken as a function decreasing with the radial distance from the centre. At a critical radius, where the speed of the wind in TC matches the phase speed of the propagating waves, energy exchange between waves and the mean flow occurs, which can cause the TC intensification. From mathematical point of view the critical radius corresponds to a singularity in the equation of wave propagation. The model demonstrates absorption of the waves by the mean flow and attenuation of the wave amplitude outside of the critical radius. The wave absorption provides energy to the cyclone intensification. The problem was solved in f-plane approximation for propagation of small-amplitude vortex waves:

$$\left(\frac{\partial}{\partial t}+\frac{\bar{v}}{r}\frac{\partial}{\partial \lambda}\right)\nabla^2\psi-\frac{1}{r}\psi_\lambda\frac{d}{dr}\left(\bar{v}'+\frac{\bar{v}}{r}\right)=0,$$

where $\psi(r,\lambda,t)$ is the wave streamfunction,

and $\bar{v}(r)/r = \Omega(r)=\Omega_0(1-\alpha r^2), \alpha>0,$ is the mean angular velocity.

High-speed solar wind streams

from coronal holes generate compression regions, called co-rotating interaction regions (CIRs), as the fast stream overtakes slow solar wind. Time series of hourly averages of solar wind plasma parameters, including the velocity V, the interplanetary magnetic field (IMF) magnitude B, the standard deviation σ_{Bz} of the IMF B_z and proton density n_p, are used in the **superposed-epoch (SPE) analysis keyed to times of rapid intensification of tropical cyclones [3].**

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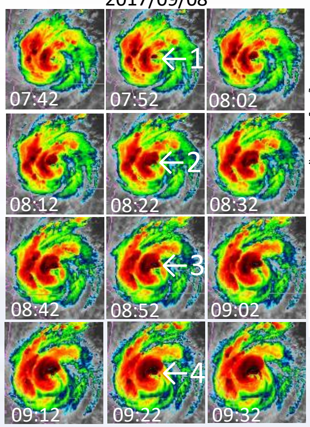
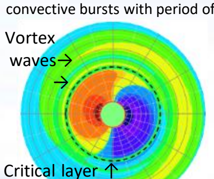


Hurricane Katia (2017)

Images extracted from the animation using the GOES-16 Clean Window (10.3 μm) Channel show a series of four convective bursts with period of ~30 min.

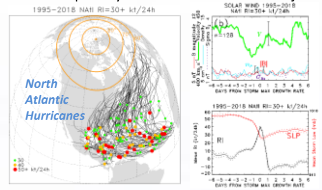


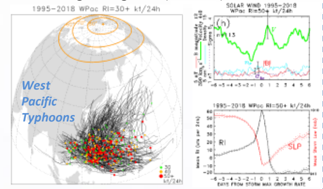
Modeling vortex waves

in a tropical cyclone. The waves are forced by oscillation at the eye-wall (red circle in the center). Waves are absorbed at the critical layer (radius) with the phase shift and decreasing of the amplitude. The stream function positive values are coded in red-orange color. The orange arcs (spiral sleeves) beyond the critical radius represent the outward propagating spiral bands of the hurricane [18].

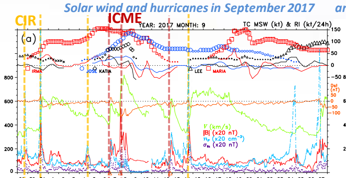
Rapid intensification (RI) of tropical cyclones

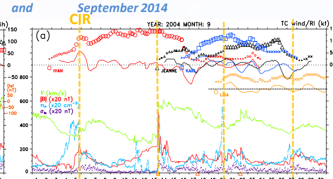
is defined as the maximum sustained wind (MSW) increase of at least 30 kt (15.4 m/s) in a 24-h period. The results of the SPE analysis of solar wind plasma parameters keyed to a given maximum RI are shown. The maps show the "best tracks" of tropical cyclones and the altitude-adjusted corrected geomagnetic (AACGM) latitudes. [3]

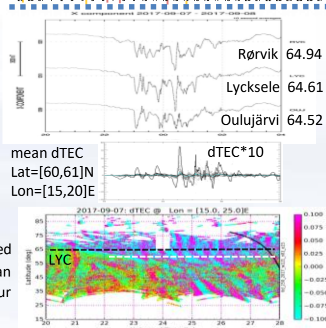


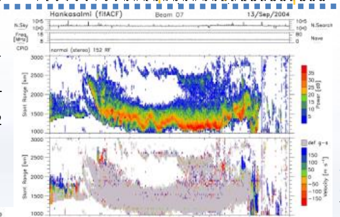


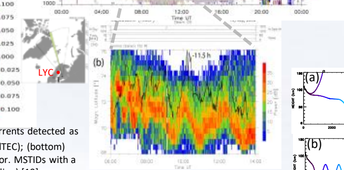
Solar wind and hurricanes in September 2017 and September 2014



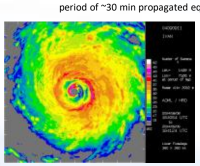






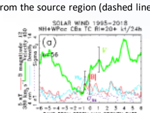


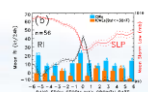
AGWs/TIDs: (top) Source region of AGWs/TIDs: Ionospheric currents detected as fluictuations of the X-comp magnetic field. (middle) Mean differential TEC (dTEC); (bottom) Keogram of dTEC showing meridional propagation of TIDs for European sector. MSTIDs with a period of ~30 min propagated equatorward from the source region (dashed line) [19].



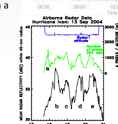
Hurricane Ivan (2004):

NOAA/HRD WP-3D lower-fuselage radar reflectivity single sweep showing a convective burst and secondary eyewall on Sept. 9, 2004. (http://www.aoml.noaa.gov/hrd/Storm_pages/ivan2004/radar.html).

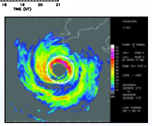




Convective bursts and RI of TCs The SPE analysis of (a) solar wind plasma parameters and (b) SLP and RI keyed to the maximum intensification (RI = 20+ kt) of tropical cyclones associated with CBs. The occurrence distributions of major HSSs/CIRs (light blue) and ICMEs (orange) are shown [3].

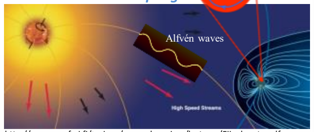


Airborne radar reflectivity (black line) averaged within the white circle that included CBs in the hurricane Ivan eyewall.



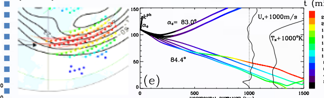
NOAA/HRD WP-3D lower-fuselage radar reflectivity obtained on September 13. One of a series of convective bursts (CBs) in the eyewall of hurricane Ivan is shown.

Solar wind – MIA coupling



http://www.ava.fmi.fi/~minna/researchseminar/lectures/Eijanluento.pdf

Solar wind coupling to the magnetosphere-ionosphere-atmosphere (MIA) system generates **atmospheric gravity waves** (AGWs) that impact troposphere and may provide a lift of unstable air to release instabilities in the troposphere and to initiate/trigger convection to form cloud and precipitation bands [20,21,22].

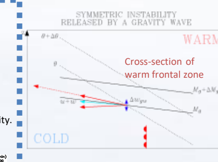


Gravity waves initiate convection

The symmetric instability is an interplay of buoyancy and Coriolis restoring forces: The slopes of isolines of potential temperature θ and geostrophic momentum Mg in the x-z plane are such that ∂θ/∂z > 0 and ∂Mg/∂x > 0, meaning that atmosphere is stable to purely vertical and horizontal displacements but **unstable to slantwise displacements.**

←Traveling ionospheric disturbances

The SuperDARN Hankasalmi radar backscatter power and line-of-sight (LoS) velocity. Grey: Groundscatter



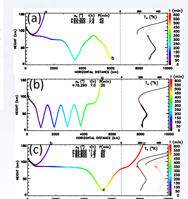
Solar wind Alfvén waves or pressure pulses modulate ionospheric convection, which is a source of gravity waves.

Ray tracing of gravity wave energy using dispersion relation by Hines (1960) [23]

$$(\omega^2-\omega_a^2)\,\omega^2/C^2-\omega^2(k_x^2+k_z^2)+\omega_b^2k_x^2=0$$

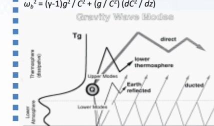
$\omega_a=\gamma g/2C$ is the acoustic cutoff frequency,
γ, C, g are the ratio of specific heats, speed of sound, and acceleration due to gravity,
k_x and k_z are the components of the wave vector $\mathbf{k}$.

Brunt-Väisälä (buoyancy) frequency ω_b is defined as $\omega_b^2=(\gamma-1)g^2/C^2+(g/C^2)(dC^2/dz)$

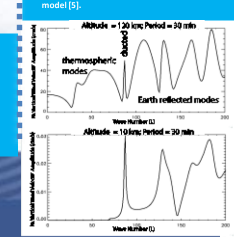


Ray tracing of AGWs:

Ray paths for gravity waves with period (a) 40 min (b) 20 min and (c) 60 min in the MSIS90 model atmosphere. The neutral temperature T_N height profiles for each ray are superposed. T_N for the first down leg path is shown in red dotted line. [3]



Thermospheric gravity waves: Observations and interpretation using the transfer function model [5].



Conclusions

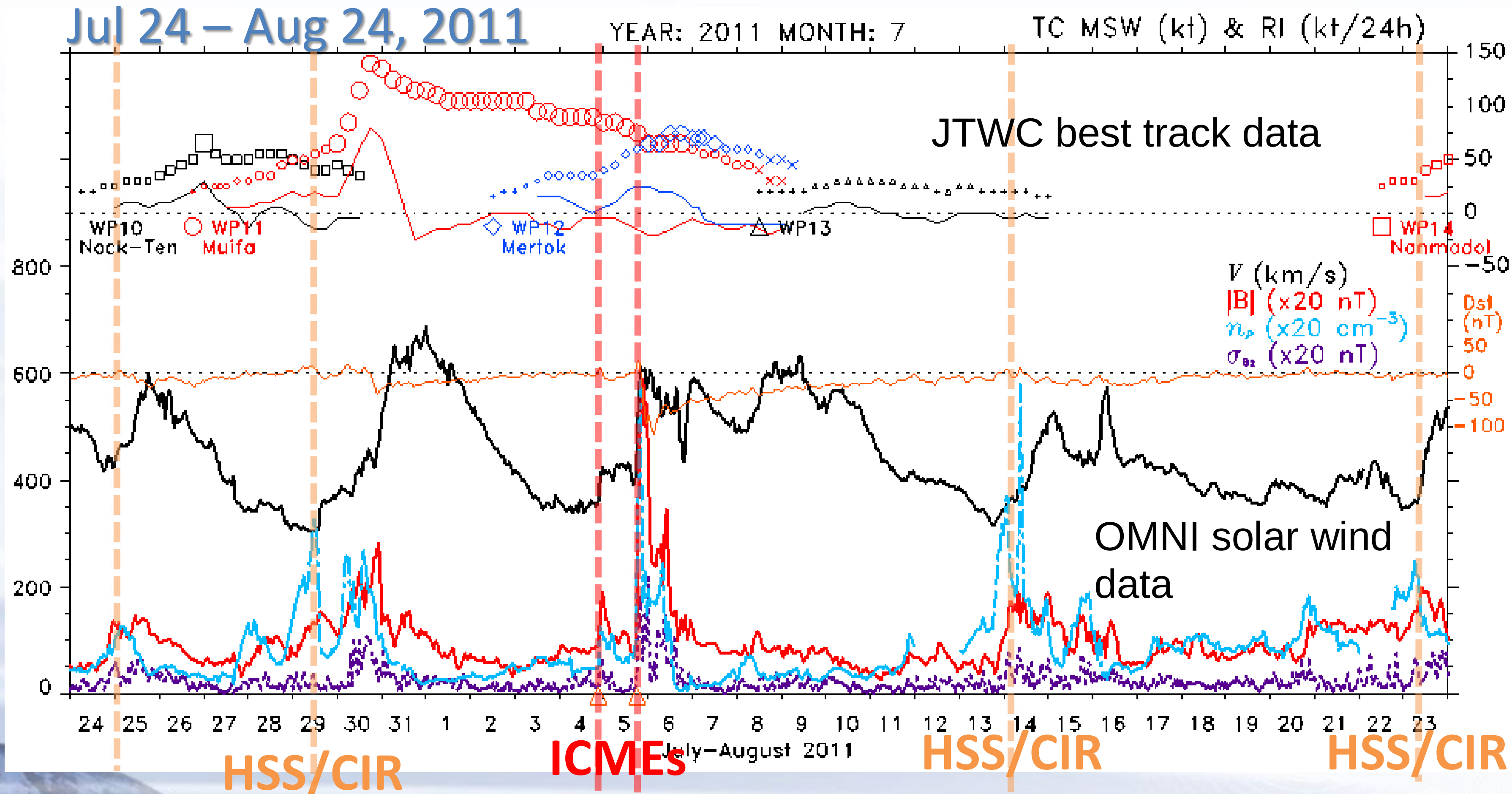
Rapid intensifications of tropical cyclones tend to follow arrivals of high-speed solar wind from coronal holes or coronal mass ejections. Solar wind coupling to the magnetosphere-ionosphere-atmosphere generates atmospheric gravity waves in the lower thermosphere at high latitudes that can reach troposphere. It is suggested that they can trigger/release instabilities, moist symmetric instability in particular, and initiate convection bursts leading to outward-propagating spiral rain bands that have been described as vortex Rossby waves and play a role in the intensification of tropical cyclones.

References

[1] Kaplan J., et al., Wea. Forecasting, 25, 220–241, 2010.
[2] Wang Y., Wu C.-C., Meteor. Atmos. Phys., 87, 257–278, 2004.
[3] Prikryl P., et al., J. Atmos. Sol.-Terr. Phys., 183, 36-60, 2019.
[4] Mayr H.G., et al., J. Geophys. Res., 89, 10929–10959, 1984.
[5] Mayr H.G., et al., Space Sci. Rev. 54, 297–375, 1990.
[6] Malkus J. S., Riehl H., Tellus, 12, 1–20, 1960.
[7] Riehl H., Malkus J., Tellus, 13, 181–213, 1961.
[8] Steranka J., et al., Mon. Wea. Rev., 114, 1539–1546, 1986.
[9] Kelley O. A., Halverson J. B., J. Geophys. Res., 116, D20118, 2011.
[10] Rodgers E.B., Olson W.S., Mon. Wea. Rev., 126(5): 1229–1247, 1998.
[11] Rodgers E.B., et al., J. Appl. Meteorol., 39, 1983–2006, 2000.
[12] Hennon, P.A., Ph.D. dissertation, Ohio State Univ., 2006.
[13] Oyama S., et al., J. Meteor. Soc. Japan, 96B, 2018.
[14] Wang Y., J. Atmos. Sci., 66, 1250–1273. 2009.
[15] Montgomery M.T., Kallenbach R.J., Quart. J. Roy. Meteor. Soc., 123, 435–465 1997.
[16] Montgomery M.T., Brunet G., Dyn. Atmos. Oceans 35: 179–204, 2002.
[17] Brunet G., Montgomery M.T., Dyn. Atmos. Oceans 35: 153–177.2002.
[18] Nikitina L.V., Campbell L.J., Stud. Appl. Math., 135, 377–446, 2015.
[19] Zhang S.-R., et al., Space Weather, 17(12), 1748-1764, 2019.
[20] Prikryl P., et al., Ann. Geophys., 27, 31-57, 2009.
[21] Prikryl P., et al., J. Atmos. Sol.-Terr. Phys. 149, 219-231, 2016.
[22] Prikryl P., et al., J. Atmos. Sol.-Terr. Phys., 171, 94–110, 2018.
[23] Hines, C. O., Can. J. Phys., 38, 1441–1481, 1960.

Rapid intensification of typhoons

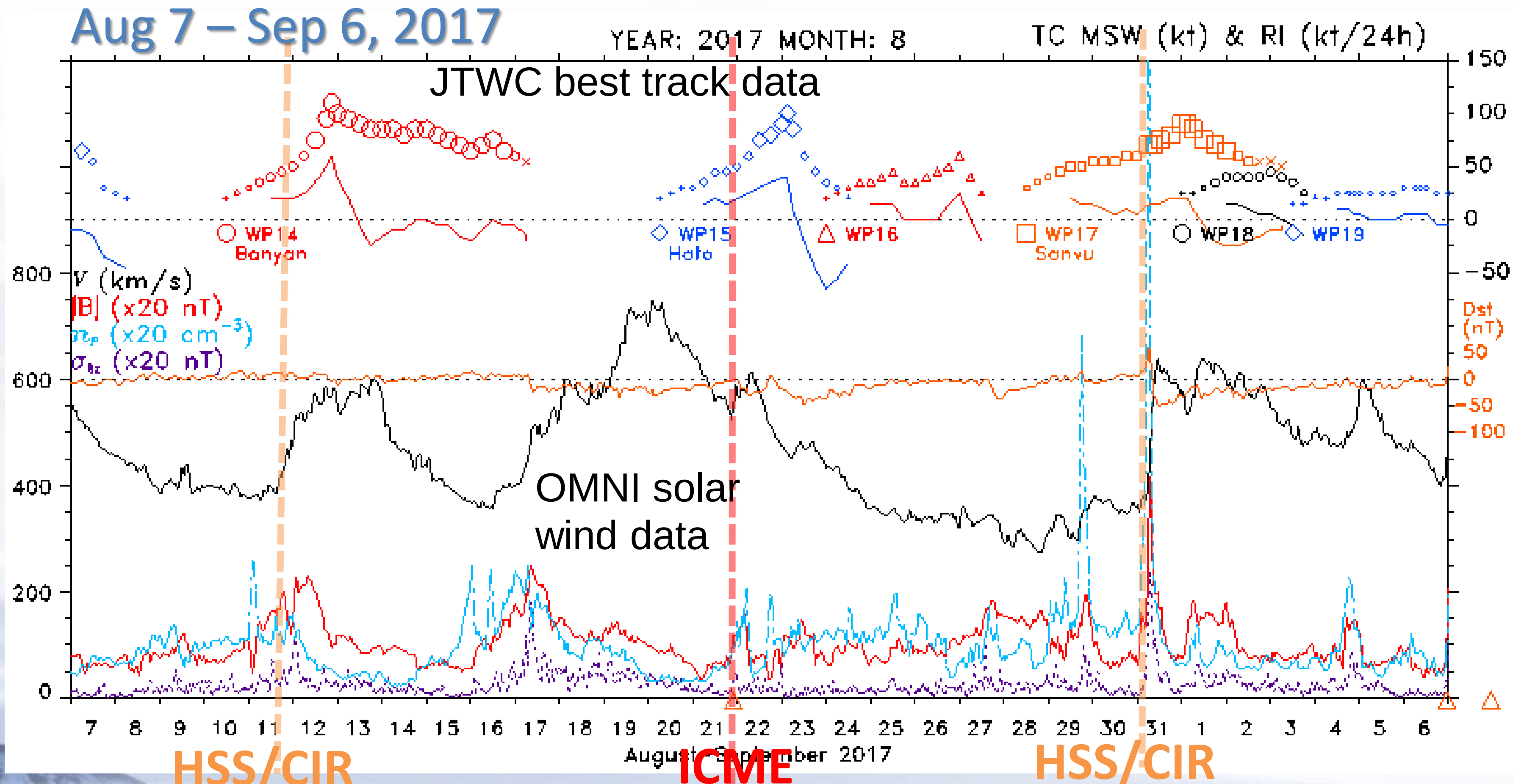
Nock-Ten, Muifa*, Mertok



*D2991 | EGU2020-1436 [Characteristics of the Concentric Eyewall Structure of Super Typhoon Muifa during Its Formation and Replacement Processes]

Rapid intensification of typhoons

Banyan, Hato*, Sanvu



*D2996 | EGU2020-3788 **Sensitivity of precipitation and structure of Typhoon Hato to bulk and explicit spectral bin microphysics schemes**

Rapid intensification of typhoons
Tembin*, Balayen, Sanba

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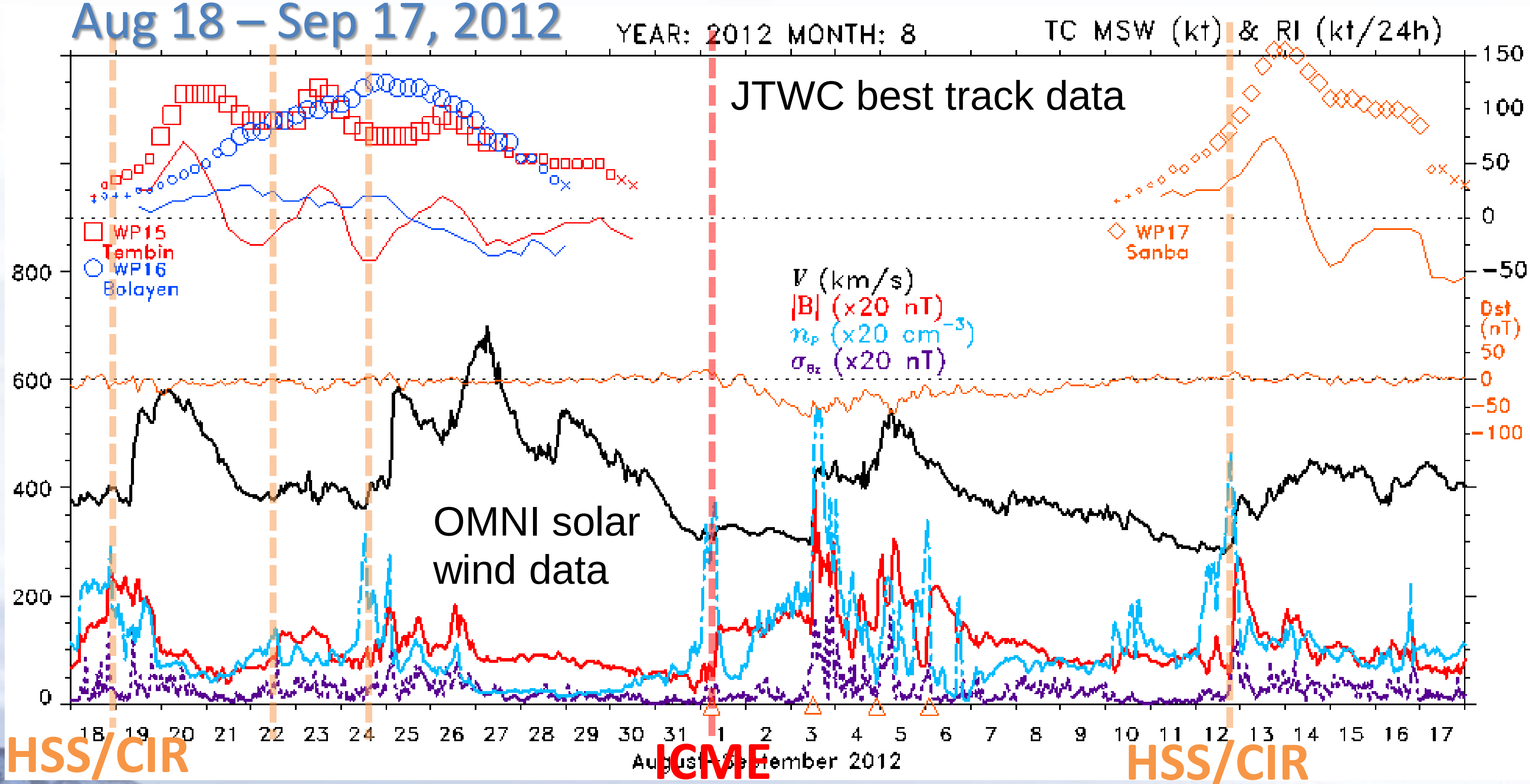
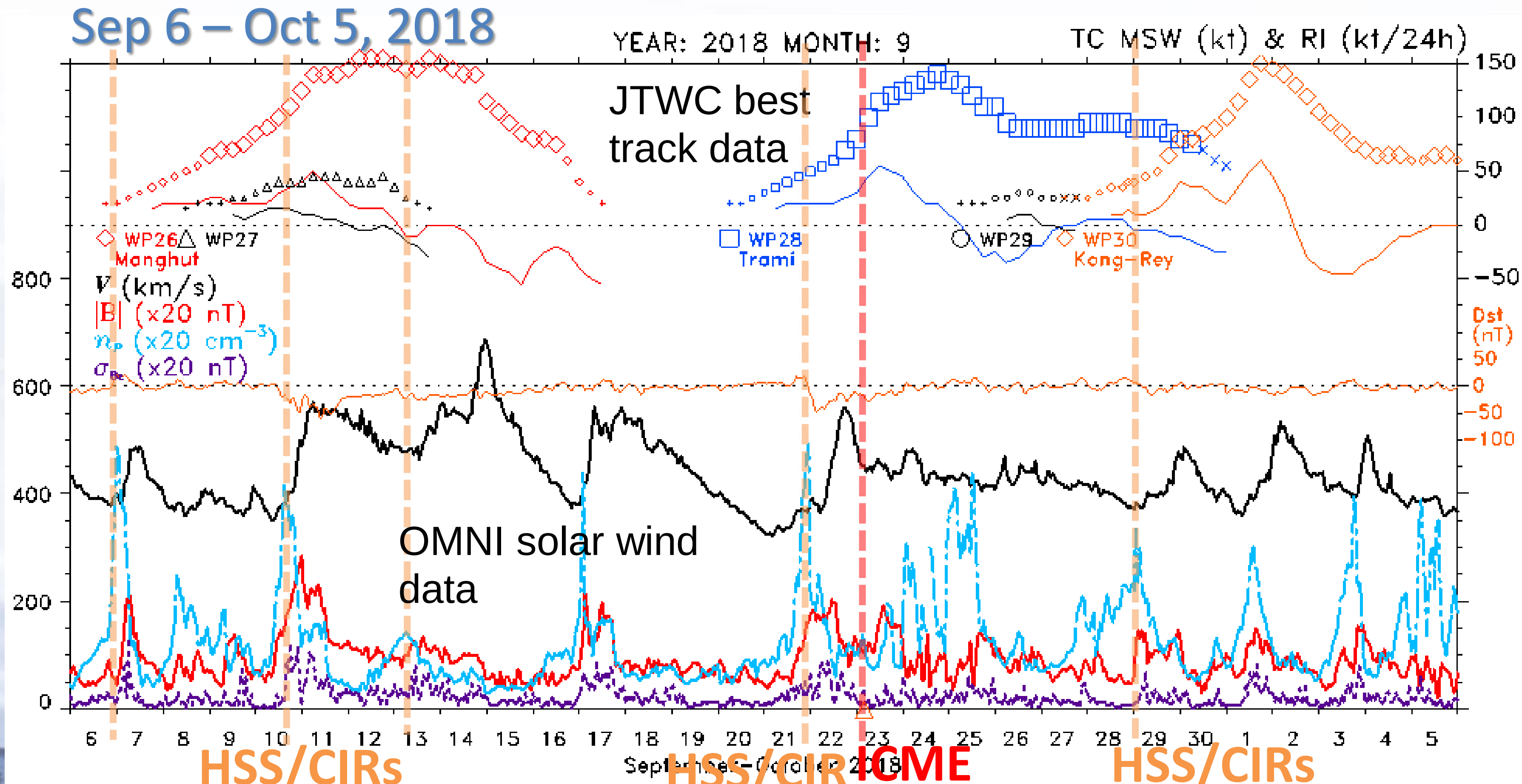


*D3003 | EGU2020-12173 **Effect of SST gradient caused by Typhoon-Generated Cold Wake on the Subsequent Typhoon Tembin in models of varying resolutions**

Rapid intensification of typhoons

Manghut*, Trami, Kong-Rey



*D3020 | EGU2020-13044 **Satellite Microwave TC Warm-core Retrieval for a 4D-Var Vortex Initialization Using a Nonhydrostatic Axisymmetric Model …** (typhoon Manghut discussed)