Genesis of tropical cyclone Agni: Physical Mechanisms

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1. Introduction

Mesoscale convective complex plays an important role in the development of tropical disturbances. The pathway by which these mesoscale cumulus complexes organize to form a large-scale tropical cyclone vortex is one of the great unsolved problems in dynamical and tropical meteorology. The factors interacting on various spatial scales, and playing an important role in the genesis of tropical deep convections are described by Gray, 1968; Cheung, 2004. Besides SST and vertical wind shear (850 – 200 hPa), the other atmospheric parameters which can contribute to the genesis of the tropical cyclones include conditional instability and cyclonic absolute vorticity in lower troposphere; Relative Humidity (RH) in middle troposphere (500 – 700 hPa); meridional wind shear; anti-cyclonic relative vorticity in upper troposphere; 200 hPa divergence and sensible heat. The conceptual model of cooperative intensification of organized moist convection and cyclone vortex through destabilization of tropical atmosphere resulting from radiative heating, surface forcing etc. was well known for last few decades (Ooyama, 1964; Charney and Eliassen, 1964). In this mechanism the convection is described as the selective release of CAPE in regions where the large scale circulation happens to converge replacing it elsewhere. This model describes well the spin-up of the vortex in response to the convective heating and mass flux occurs however the control of convection by vortex scale flow/ cumulus parametrization is not well understood.

In atmosphere, the observed rate of change of CAPE in the maritime tropical atmosphere is much smaller than what would occur if de-stabilization of the atmosphere by large scale process were unopposed by convection (Arakawa and Schubert, 1974). Thus the temperature (mass distribution) of tropical atmosphere is determined by conditions that convection is in statistical equilibrium with large scale and not by selective release or stored CAPE. The required thermodynamic dis-equilibrium has to be provided by large reservoir of energy with the mechanism of releasing energy through the wind dependent rate of transfer of enthalpy. This mechanism termed as wind-evaporation feedback mechanism (Neelin et al., 1987) and wind-induced surface heat exchange (WISH) by Yano and Emanuel, 1991. In this mechanism the amount of relizable energy in marine tropics can be represented by thermodynamic disequilibrium between tropical ocean and atmosphere (Emanuel, 1987). This mechanism can be explained based on exchange of sensible heat and latent heat. In this mechanism total increase in heat contains is proportional to lag increase in water vapor contain and decrease in pressure ans is known as heat input by isothermal expansion. However the major unsolved problem of tropical cyclogenesis is now to understand how a weak amplitude tropical disturbance transformed into a surface vortex of sufficient strength that can amplified by WISHE process.

Recent studies by Bister and Emanuel, 1997; Ritchie & Holland, 1997 suggested that mesoscale convective vortices which form in stratiform precipitation region at mid-levels of the troposphere in disturbed weather regions are precursore to tropical cyclo-genesis. Both these studies suggested that mid-level mesoscale convective vortices are necessary for building a surface vortex. Bister and Emanuel hypothesized downward advection of vertical velocity via mesoscale subsidence in association with stratiform precipitation. Ritchie & Holland hypothesized downward development by succession of mid-level merger between mesoscale vortices that form in stratiform precipitation region following deep convective episode.

Montgomery and Farrell, 1993; Montegomery & Enagonio, 1998 and Hendricks et al., 2004, suggested all together different mechanism for development of surface vortices. Hot towers are in general termed as a positive influence to genesis via subsidence warming around them and the attaindant surface pressure fall (Simpson et al., 1998). The low-level vortex merger and anti-symmetrization of small scale diadiabatically generated cyclonic potential vorticity anomalies (convective bursts) could intensify a large scale vortex on realistic time scale Tangential momentum spin-up can be explained through the organizational mechanism process and potential merger or diadiabatic vortex merger pre-conditioned atmosphere. In this work we have simulated the pregeneis period of the cyclone using a mesoscale model Advanced Research WRF version 2.1.1 (ARW) to understand the role of mesoscale features and to identify associated physical processes in the genesis of tropical cyclone Agni.

2. Synoptic History of Agni

Two deep convective mesoscale disturbances were observed in the Equatorial Indian ocean on 19 November 2004 and at 18UTC 26 November 2004. The first disturbance was located at about 800 km southeast of Colombo, Sri-Lanka and the second at about 160 Km north of equator. The second disturbance originated from the remnants of the first disturbance as low-level circulation, with the maximum wind speed of around 11 m s^{-1} (20 Knots). From 00 UTC 27 November 2004 to 03 UTC 28 November 2004 the second disturbance organized itself to form Tropical Cyclone Agni. The deep convection associated with it organized with maximum surface wind speed of around 15 m s^{-1} (30 knots) surrounding the center. During the organization, it was observed that the centers of the intensification moved about half degree south of the equator without losing its counter clockwise rotation. This erratic behavior questioned the necessary condition of required large Coriolis parameter either side of equator for the genesis of tropical cyclone. After surviving its excursion south of equator, at 06 UTC 28 November 2004 this tropical disturbance strengthened to tropical storm and was located around 75 Km north of equator. Then, cyclone Agni followed northwestward track for most of its life span and intensified as tropical cyclone on 12 UTC 29 November, 2004. After 06 UTC 30 November 2004 the cyclone passed through the region of heavy wind shear. This lead to its dissipation from tropical cyclone to tropical storm on 18 UTC 30 November 2004. Further its movement towards Somalia coast made it to dissipate on 18 UTC 3 December 2004.

3. Model Configuration

To understand the physical processes involved in genesis of this rare category tropical cyclone, a high resolution (10 Km) downscaling is carried out using WRF version 2.1.1. A domain of 444 X 222 X 31 computational grid points ranging from 45^0 E to 85^0 E in longitude and 5^0 S to 15^0 N in latitudes is used for this study. WRF model is initialized by using Final Analysis Data for the period of 26 November - 4 December 2004 and integrated using time step of 60 sec. For this study, the micro-physical sub-grid processes are represented by the scheme described by Lin et al., 1983. The Kain-Fritsch scheme (KF-Eta; Kain, 2004) is used to represent cumulus parameterization. Yonsei University PBL parameterization scheme (Hong and Dudhia, 2003, Hong etal., 2006) is used for this simulation. Rapid Radiative Transfer Model (RRTM) long-wave radiation parameterization (Mlawer et al., 1997) and short wave radiation parametrization used in this model is given by Dudhia, 1989 are used to represent radiation processes in the atmosphere.

4. Features associated with Genesis of Agni

The trends in the maximum SST over the Indo-Pacific belt follow the seasonal march of the Sun across the equator. These resemble the positional changes of Equatorial trough over the same region. The meridional positional changes of the trough depend on the rate of ocean surface heating. In addition, the Equatorial winds over the Indo-Pacific region reduce the evaporational cooling of sea surface and the oceanic mixed layer depth in winter season (October-December). This keeps the sea warm despite the opposite trend of the Sun during winter months. Due to this, SST attains a secondary maximum in this region. SST over the region of genesis of Agni, during the period 00 UTC 26 November 2004 to 06 UTC 28 November 2004 were ranging between $28.6^0 – 29.4^0$ C as observed from NCAR- NCEP Final Analysis Dataset (FNL). These values are above the minimum temperature required for cyclogenesis. This is the prime factor responsible for increase in the thermodynamic capacity of atmosphere, which favors the development of deep convection. The favorable position of the Equatorial trough over the regions of higher values of SST and necessary thermal energy and surface heat flux from warm ocean favor the formation of deep convection and tropical cyclones. The simulated surface heat flux shows large spatial and temporal variability with values typically ranging between 10 – 80 W m^{-2} on either side of the equator during pre-genesis period of Agni. The associated circulation features show the presence of equatorial trough over the Arabian sea with embedded low level circulations with the maximum surrounding wind speed of around 15 m s^{-1}. The south – north migration of low level cyclonic circulation across the equator is also observed in the simulated outputs.

The availability of moisture in the mid troposphere plays an important role in the development of deep convection. A high value of RH in lower troposphere is favorable for tropical cyclone formation. As convection initialized in a mesoscale convective system, precipitation will cause downdraft within the system. If the lower troposphere is too dry, evaporation will increase cooling and then further enhance downdraft, thus inhibiting sustainable convective development. Further a dry lower troposphere simply inhibits convection due to entrainment of dry air by ascending parcel. The analysis of the mid tropospheric relative humidity during pregenesis period of Agni in the region of genesis from WRF outputs shows the values above 80 %. The migration of region of mid tropospheric relative humidity with values grater than 90% is also observed from WRF outputs. Thus wet mid tropospheric region lead to enhance the mechanism of heat input by isothermal expansion (Emanuel, 1993).

Behavior of upper tropospheric divergence, relative vorticity and vertical wind shear during the pre-genesis period of Agni for the selected periods are shown in Fig. 1 (d1-d8), Fig. 1 (v1 – v8) and Fig. 1 (s1-s8) respectively. These time periods are selected based on the prominent changes observed in the behavior of relative vorticity. As observed from Fig. 1 (v1-v3) the range of relative vorticity was between 100-150 X 10^{-5} s^{-1}, at 0600 Z of 26th with subsequent increase to 200-250 X 10^{-5} s^{-1} and 350 - 450 X 10^{-5} s^{-1}, at 17:50 Z and 21:30 Z of 26th respectively. Further intensification during pre-geneis period of Agni show the formation of vortical hot towers (the meso-regions with relative vorticity > 400 X 10^{-5} s^{-1}), their rearrangement (Fig. 1 v4-v5) around the centre of rotation and subsequently the merging of meso vortices (Fig. 1 v6-v8).

Upper Tropospheric Divergence (UTD) plays an important role in development of tropical cyclones. The strong UTD always associated with higher values of convergence at lower level. Amount of divergence as large as or larger than 10^{-4} s^{-1} can only be found in sub-synoptic or large scale rotating systems such as tropical storm during the period of their rapid development. To know the vertical extent of the deep convection in the region of genesis of Agni and the upper tropospheric feedback to the lower tropospheric convection we analyzed the UTD. As observed from the figures the regions of higher values of UTD show similar behavior but the meso regions with high values of UTD are on south-west side of the vortical hot towers (Fig 1. v2-v8). This may be attributed to the south-westward tilting of these meso vortices.

The vertical wind shear, a key inhibitor of tropical cyclone intensification, originates from the lateral forcing of the surrounding atmosphere. Shear controlled deep convections organize themselves into the locations of weak wind shear. A strong vertical wind shear advects the heat released from condensation at upper tropospheric levels and thus increases the ventilation. The increase in ventilation is responsible for the tilt of upper and lower level Potential Vorticity (PV), which in turn is responsible for the mid level warming near vortex center. This is found to inhibit convection and storm development. In addition when facing down shear, both upward motion and convection are enhanced in the region of down shear left of tropical cyclone center, and suppress in the region of up-shear right. This leads to asymmetry in distribution of convection. Vertical wind shear tends to offset the vertical tilt through a fast adjustment between asymmetric flow and asymmetric diabatic heating. Thus, it modifies vertical coherence structure of tropical cyclones and adds complexity in adiabatic dynamics of tropical vortex. As seen from the Fig 1 (v1-v8) and (s1-s8) vertical wind shear plays an important role in genesis of tropical cyclone. The meso-vortices are seen aligned along low shear regions and merged in the same region. The south-westward tilting of meso-vortices may be attributed to the effect of wind shear. Further, the north-south- north migration of low level circulation across the equator was seen under the influences of strong vertical wind shear induced by tread winds.

Conclusions

In this paper we have studied some of the physical mechanisms responsible for genesis of Agni. It is seen that wind induced surface heat exchange between ocean and atmosphere responsible for building the thermodynamic capacity of atmosphere necessary for development of small eddies over equatorial region of less wind shear. The "heat input due to isothermal expansion" mechanism caused the development of deep convection due to wet mid-tropospheric region. During the pre-genesis of Agni, reorganization clustering, and merging of meso-regions with high relative vorticity along with their migration to south and north of the equator of is also seen. Merging of meso-regions can be attributed to the influence of the low level convergence and high atmospheric wind shear. However, further analysis is required to understand the forces involved in development and merging of meso-regions.

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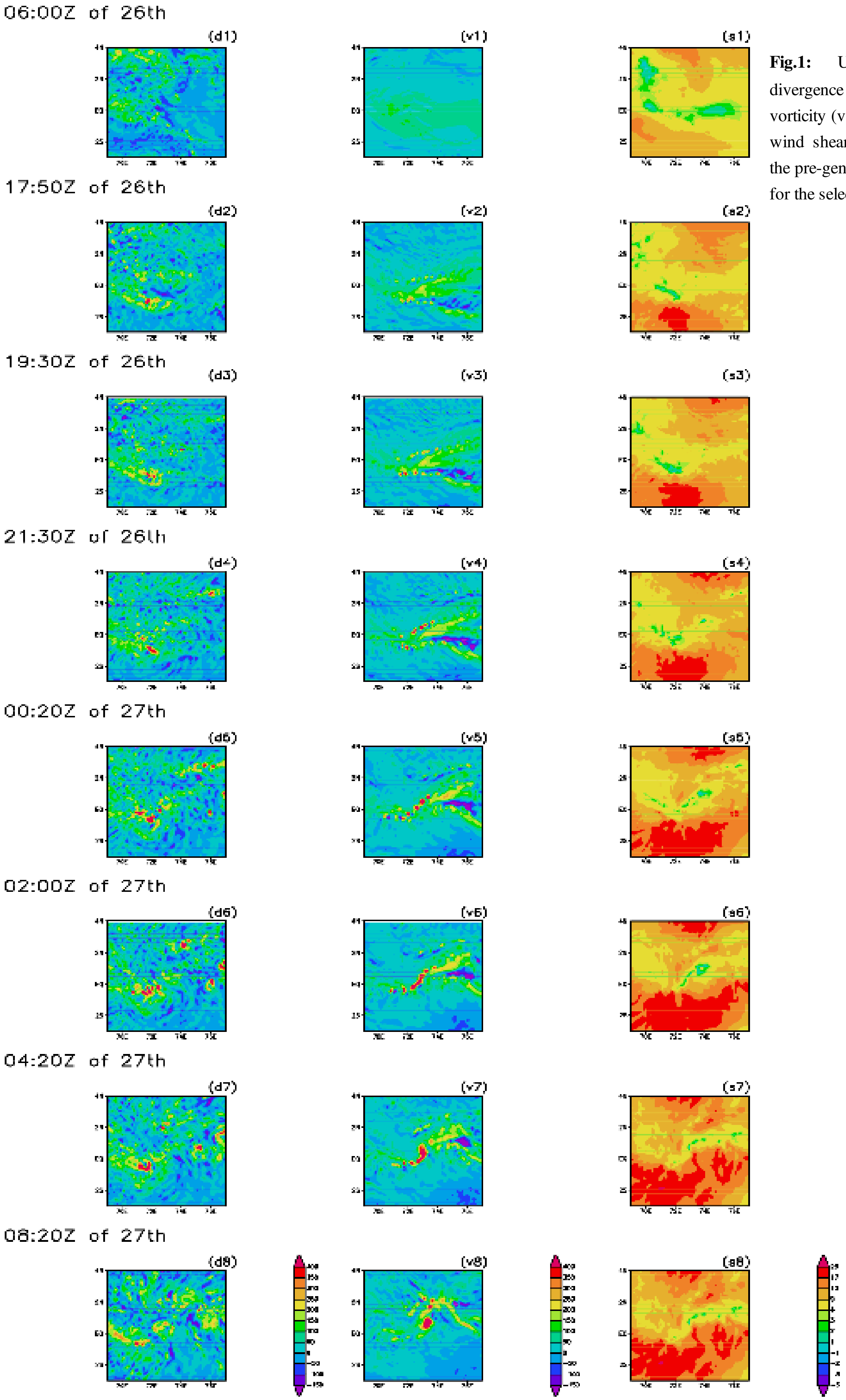

Fig.1: Upper tropospheric divergence (d1 – d8), relative vorticity (v1 – v8) and vertical wind shear (s1 – s8) during the pre-genesis period of Agni for the selected periods