Future Increase in Super-typhoon Intensity Associated with Climate Change

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Introduction

- Tropical cyclones, including hurricanes and typhoons, are undoubtedly the most vigorous and devastating weather systems.
- A Super-typhoon, the most intense tropical cyclone category in the western North Pacific, occurs less frequently, but its landfall causes catastrophic disaster. The typhoon Haiyan is a typical example of super-typhoon.
- Great concern regarding future change in typhoon intensity in the western North Pacific is raised.
- A very high-resolution dynamical model with no convective parameterizations is necessary for quantitative prediction of the most intense category of tropical cyclone such as super-typhoons.
- In the present study, we addressed the problem to what extent super-typhoons will become intense in the global warming climate of the late twenty-first century by using a very high-resolution (2-km) cloud-resolving model.
Characteristics of the CReSS model

- **Basic equations:** a three-dimensional, non-hydrostatic and compressible equation model.
- **Coordinate system:** a terrain-following in a two or three dimensional domain.
- **Spatial representation:** finite difference scheme (Arakawa C grid in horizontal, Lorenz grid in vertical).
- **Time integration:** mode-splitting scheme (acoustic terms implicit in vertical)
- **Ground model:** $n$-layer 1-dim. thermal conductivity model.
- **Ocean model:** $n$-layer 1-dim. diffusion model.
- **Surface process:** bulk scheme (Louis scheme).
- **Map projections:** Lambert, Polar stereo, Mercator, Lat-lon.
- **Parallel processing:** inter-node: the Message Passing Interface (MPI), intra-node: OpenMP.
- The CReSS model is optimized for parallel computers (parallel and serial versions).
Downscale simulation of the most intense typhoons simulated in the MRI JMA AGCM (GSM) 20 km resolution experiments

Downscale simulations were performed using the cloud-resolving model (CReSS) for the AGCM simulated typhoons which fit the following conditions for the present and future climate conditions.

1. The life-time minimum sea level pressure is below 970hPa in the AGCM simulation.
2. The position of the life-time maximum intensity is located in the area of 120—150 E and 20—45 N.
   (Green square in the figure)

Present climate: 30 typhoons
Future climate: 30 typhoons
Setting of the downscale simulations using the CReSS model

- **Domain**: 2000~2500 × 2000~2500 km
- **Horizontal resolution**: 2 km
- **Grid number in vertical**: 67
- **Grid spacing in vertical**: 200 ~450 m
- **Computation period**: From 3 days before maximum intensity in AGCM to 1 or 2 days after the maximum
- **Topography and SST**: real topography and GCM SST
- **Initial and boundary conditions**: MRI GSM 20km
- **Cloud physics**: bulk cold rain parameterization
- **Radiation**: MSTRNX
- **Ocean model**: one-dim model (60 layers, 30m)
- **Land model**: one-dim model (60 layers, 9m)
Scatter diagram minimum slp of cloud-resolving model and AGCM

Minimum slp in CReSS (hPa)

在未来气候（红色钻石）和当前气候（绿色方块）中，气压低值的分布显示了一个正相关的趋势。
Minimum slp and maximum wind of the present climate typhoons

- **s**: downscale simulations
- △ : observation (JMA best track)
- Dashed line: Atkinson & Holliday (1977)

Life-time minimum sea level pressure (hPa)

\[ v_m = 0.373(1000 - p_c) + 34 \]  
\( r^2 = 0.96 \)

\[ v_m = 0.389(1000 - p_c) + 31 \]  
\( r^2 = 0.89 \)

Atkinson & Holliday (1977)

\[ v_m = 3.45(1010 - p_c)^{0.644} \]

Observed minimum slp in 1951-2012

\[ v_m = 0.389(1000 - p_c) + 31 \]  
\( r^2 = 0.89 \)
Minimum slp and maximum wind of the future climate typhoons

Dashed line: Atkinson & Holliday (1977)

\[ v_m = 0.378(1000 - p_c) + 31 \quad (r^2 = 0.95) \]

\[ v_m = 3.45(1010 - p_c)^{0.644} \]

Life-time minimum sea level pressure (hPa)
Life-time minimum slp and MPI pressure of the present climate typhoon

Life-time minimum sea level pressure (hPa)
Life-time minimum slp and MPI pressure of the future climate typhoon

Life-time minimum sea level pressure (hPa)
Super-typhoon tracks in the future climate simulations

Thick red part: $ws > 67$ m/s
characteristic parameters of simulated typhoons and average environmental metrics

<table>
<thead>
<tr>
<th></th>
<th>super-typhoon (Present)</th>
<th>super-typhoon (Future)</th>
<th>all typhoons (Present)</th>
<th>all typhoons (Future)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>3</td>
<td>12</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Minimum $p_c$ (hPa)</td>
<td>877</td>
<td>857</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>Maximum $V_m$ (m s$^{-1}$)</td>
<td>74</td>
<td>88</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>Average $p_c$ (hPa)</td>
<td>888</td>
<td>883</td>
<td>944</td>
<td>922</td>
</tr>
<tr>
<td>Average $V_m$ (m s$^{-1}$)</td>
<td>73</td>
<td>76</td>
<td>53</td>
<td>61</td>
</tr>
<tr>
<td>Rainfall rate (mm h$^{-1}$)</td>
<td>15.9</td>
<td>15.3</td>
<td>8.9</td>
<td>11.1</td>
</tr>
<tr>
<td>Average SST ($^\circ$C)</td>
<td>28</td>
<td>30</td>
<td>28</td>
<td>30</td>
</tr>
<tr>
<td>Average CAPE (J kg$^{-1}$)</td>
<td>1390</td>
<td>1340</td>
<td>1150</td>
<td>1280</td>
</tr>
<tr>
<td>Average MPI $p_c$ (hPa)</td>
<td>899</td>
<td>893</td>
<td>900</td>
<td>894</td>
</tr>
<tr>
<td>Average MPI $V_m$ (m s$^{-1}$)</td>
<td>79</td>
<td>82</td>
<td>79</td>
<td>81</td>
</tr>
<tr>
<td>Average shear (m s$^{-1}$)</td>
<td>13.6</td>
<td>12.6</td>
<td>15.5</td>
<td>15.3</td>
</tr>
</tbody>
</table>
The most intense super-typhoon in the downscale simulations

09:00Z 08AUG2082 RR, SLP (sf008_t1809_2082aug_2km)

Contouring: 860 to 1010 interval 5 (hPa)
Contouring: 10 to 80 interval 10 (m/s)
Sensitivity of the most intense super-typhoon for initial conditions

SF008 minimum sea level pressure
Sensitivity of the most intense super-typhoon for cloud physics

Black line: single moment
Red line: double moment for ice
Sensitivity of the most intense super-typhoon for horizontal resolution

**SF008 minimum sea level pressure**

Black line: 2 km grid spacing
Red line: 1 km grid spacing
We used the Cloud Resolving Storm Simulator (CReSS) which is a non-hydrostatic and compressible model designed for parallel computers, in the present study.

The results show that number of super-typhoon increases in the future climate.

The maximum intensity of super-typhoon will increase substantially.

The life-time minimum sea level pressure of the most intense typhoon in the future climate is projected to reach 850-870 hPa.

These changes correspond to the increase of SST by 2 °C while other typhoon environmental metrics are not changed largely.
Cloud-resolving model: CReSS (Cloud Resolving Storm Simulator)

Tsuboki and Sakakibara (2002)  
HyARC, Nagoya University

Initial and boundary conditions: GPV from NPD/JMA

Wave model

Wave direction 24 grids
Frequency 36 grids

Maiami Univ. (Donelan et al., 2012)

DX = 4km
Optimized for the Earth Simulator

Ocean model: NHOES (NonHydrostatic Ocean model for ES)

Aiki and Yamagata (2004)  
Aiki et al. (2006)  
JAMSTEC

DX = 4km, DZ = 2 m for top 100 m
Initial and boundary conditions: JCOPE2 reanalysis

Ocean mixing layer model (Furuuchi et al., 2012; Nakanishi & Niino, 2009)
**CReSS Run (1D-Ocean)**

- **CReSS**
  - Momentum
  - Heat flux

- **Slab model**
  - SST

  SST is set by forcing and diffusion with no Ekman upwelling

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**Coupled Run (3D-Ocean)**

- **CReSS**
  - Momentum
  - Heat & Water flux

- **WAVE MODEL**
  - Momentum

- **NHOES**
  - Momentum

  SST is cooled by diffusion and Ekman upwelling
Upwelling after typhoon's passing

CReSS run 98 hours
CReSS run 144 hours

Coupled run 98 hours
Coupled run 144 hours

Upwelling after typhoon’s passing