Large-eddy simulation of idealized hurricanes at different sea surface temperatures

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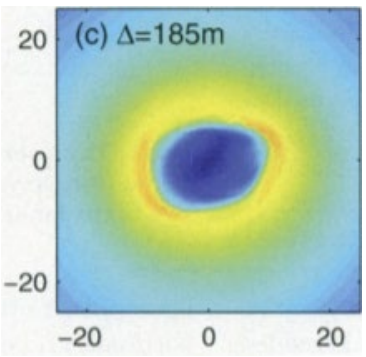
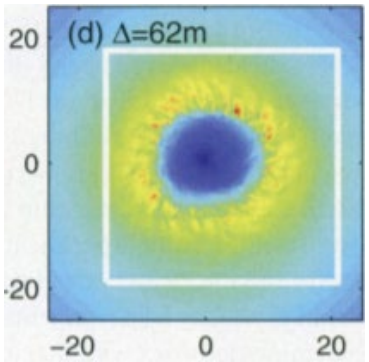
Outline

- **Simulation set-up**
- **Basic wind characteristics**
  - Maximum wind speed versus SST
- **Flow field characteristics**
  - Resolution and turbulent structures
- **Wind speed distribution**
  - Variation with SST
- **Potential damage function**
  - Integrated kinetic energy and new method
- **Conclusions**
- **Ongoing study**

Motivation



Domain d05



Domain d06

Sst-26.3°

Rotunno et al. (2009) found that a transition to randomly distributed, small-scale turbulent eddies occurs when the grid size decreases from 185 to 62 m at a sst of 26.3°.

Rotunno, R., Chen, Y., Wang, W., Davis, C., Dudhia, J. and Holland, G. J., 2009: Large-eddy simulation of an idealized tropical cyclone. Bull. Amer. Meteor. Soc., 90, 1783–1788.

In our study, we further investigate the influence of sst on hurricane intensity and turbulent structure through high resolution simulations of hurricanes at various ssts in no-shear conditions.

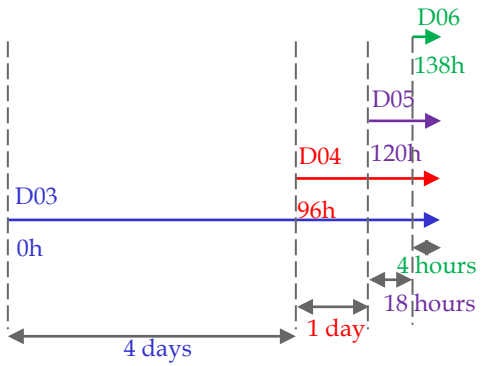
Key factor: SST

- 28° (input_sounding: default)
- 26° (input_sounding: θ-2, Qv*0.93*0.93)
- 27° (input_sounding: θ-1, Qv *0.93)
- 29° (input_sounding: θ+1, Qv *1.07)

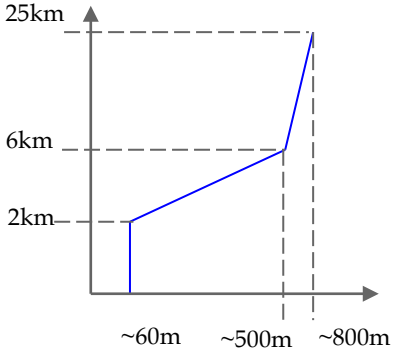
Note: assumes Qv changes 7% per degree
θ is potential temperature of 28° case
Qv is vapor mixing ratio of 28° case

Simulation settings

The simulated period	2007_09_01_00:00:00~2007_09_07_00:00:00 (UTC)					
Algorithm	WRF			WRF-LES		
Domain	1	2	3	4	5	6
Horizontal grid distance (m)	15000	5000	1666.67	555.56	185.18	61.72
Horizontal grid number	405*405	301*301	598*598	598*598	598*598	967*967
Vertical layer number	87					
Time step (s)	60	20	6.67	2.22	0.74	0.25
Start time(dd_hh)	01_00	01_00	01_00	05_00	06_00	06_18
End time(dd_hh)	07_00	07_00	07_00	07_00	07_00	06_22
wrfxtrm_d0* (time interval)	6h	3h	2h	1h	10min	1min



Start time of each domain



Vertical levels

Simulation settings

Microphysics: WSM6

No radiative scheme
Temperature nudge time constant: 12h

No cumulus scheme

Surface layer: Revised MM5 Monin-Obukhov

YSU pbl scheme: domains 1, 2, 3
1.5 order TKE closure (3D): domains 4, 5, 6

Surface exchange coefficients: Donelan Cd + Const z0q

Vertical-velocity damping is adopted

```
!-----------------------------------------------------------------------
!               USER SETTINGS

!  Parameters for analytic vortex:
!  Reference:  Rotunno and Emanuel, 1987, JAS, p. 549

   r0     =   412500.0     ! outer radius (m)
   rmax   =    82500.0     ! approximate radius of max winds (m)
   vmax   =       15.0     ! approximate value of max wind speed (m/s)
   zdd    =    20000.0     ! depth of vortex (m)


! other settings:

   fcor   =  5.0e-5        ! Coriolis parameter (1/s)
   sst    =  28.0          ! sea-surface temperature (Celsius)
```

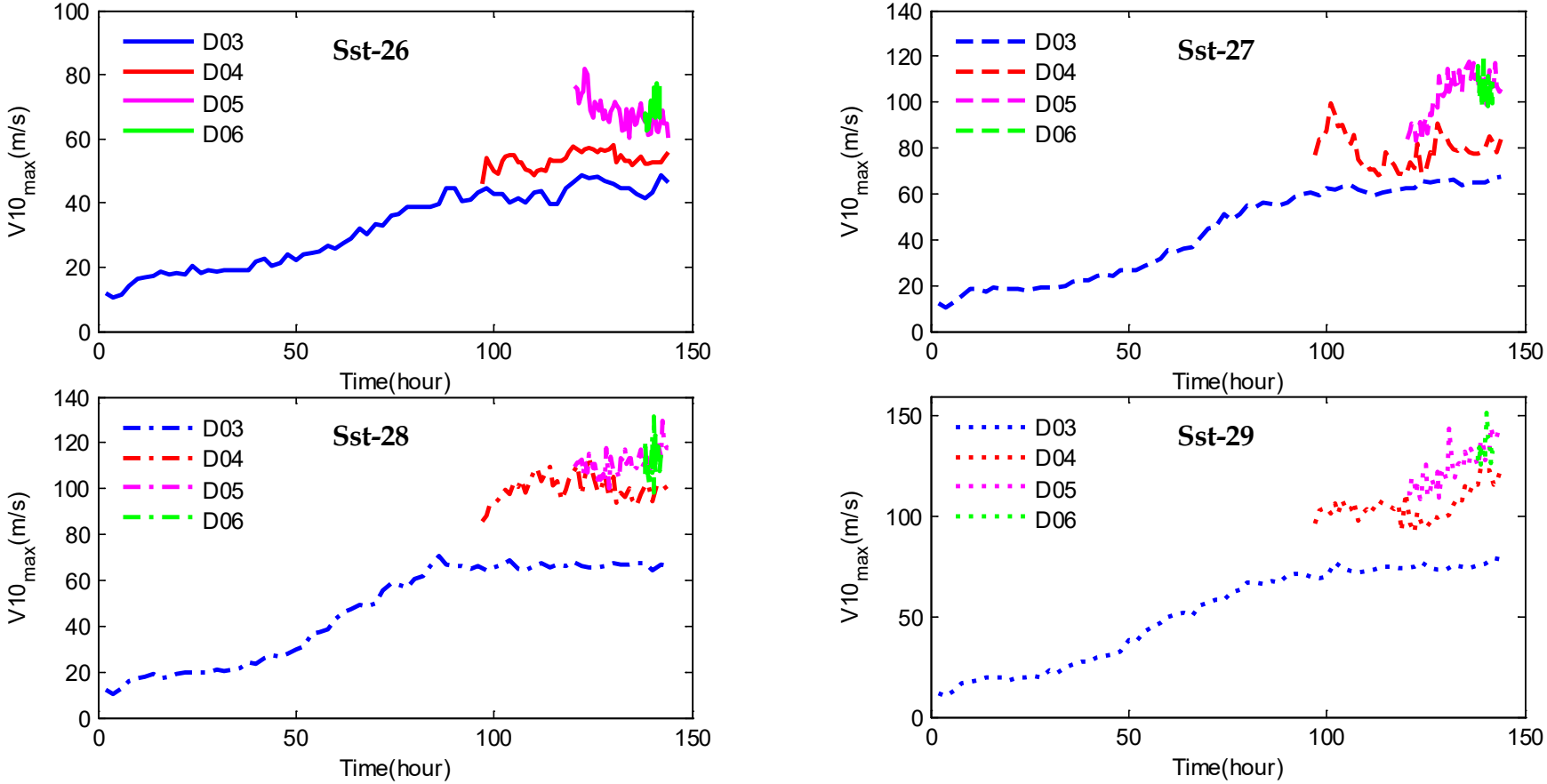
Output files:

3D:
wrfout_d0*, d03, 4, 5, 6--- 2h, 1h, 30min, 10min
wrf_trad_fields_d0* , d03, 4, 5, 6--- 2h, 1h, 30min, 10min

2D:
wrfxtrm_d0*, d03, 4, 5, 6---2h, 1h, 10min, 1min

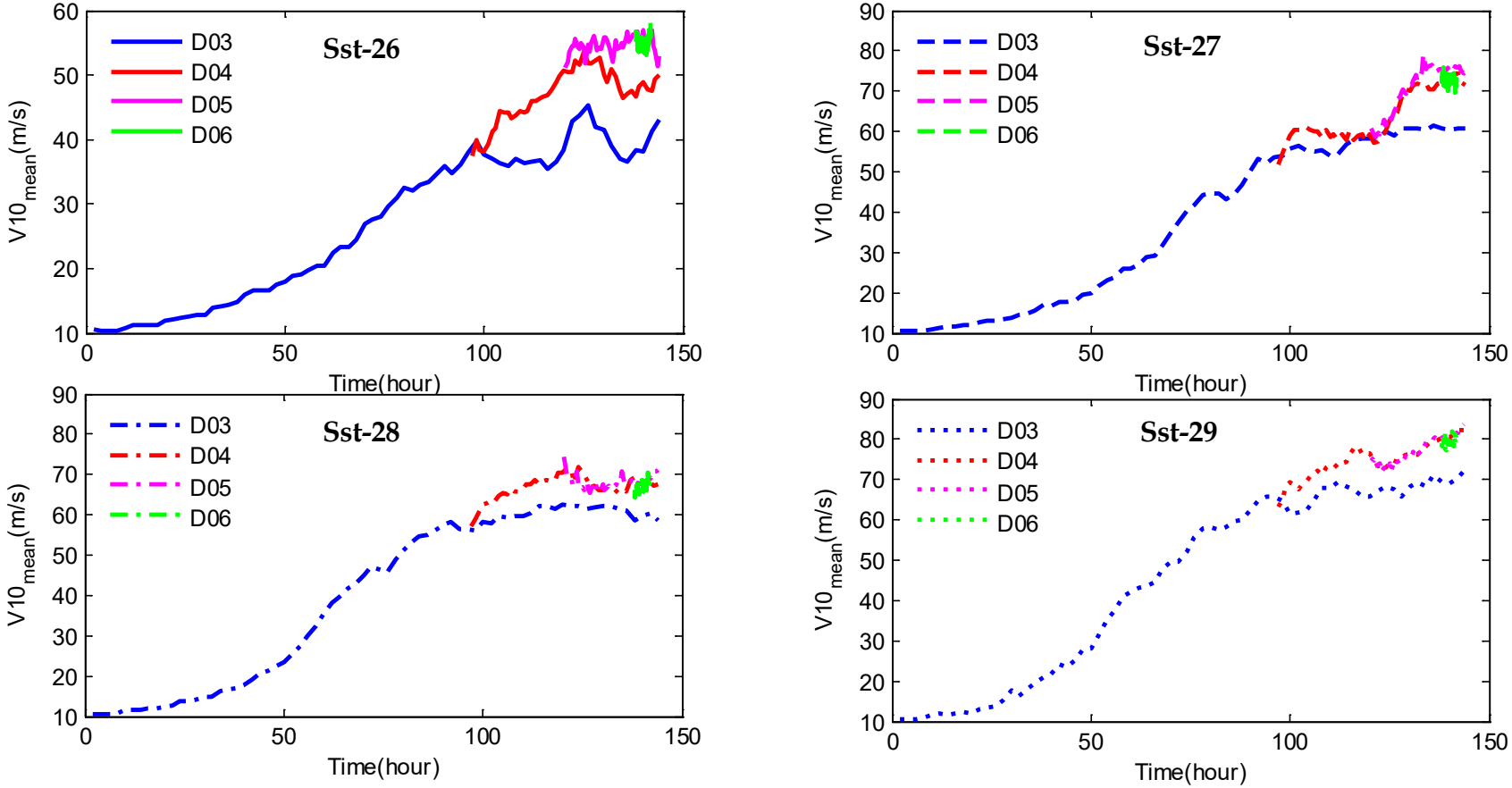
Part 1. basic wind characteristics

Max of instantaneous wind speed at 10m height



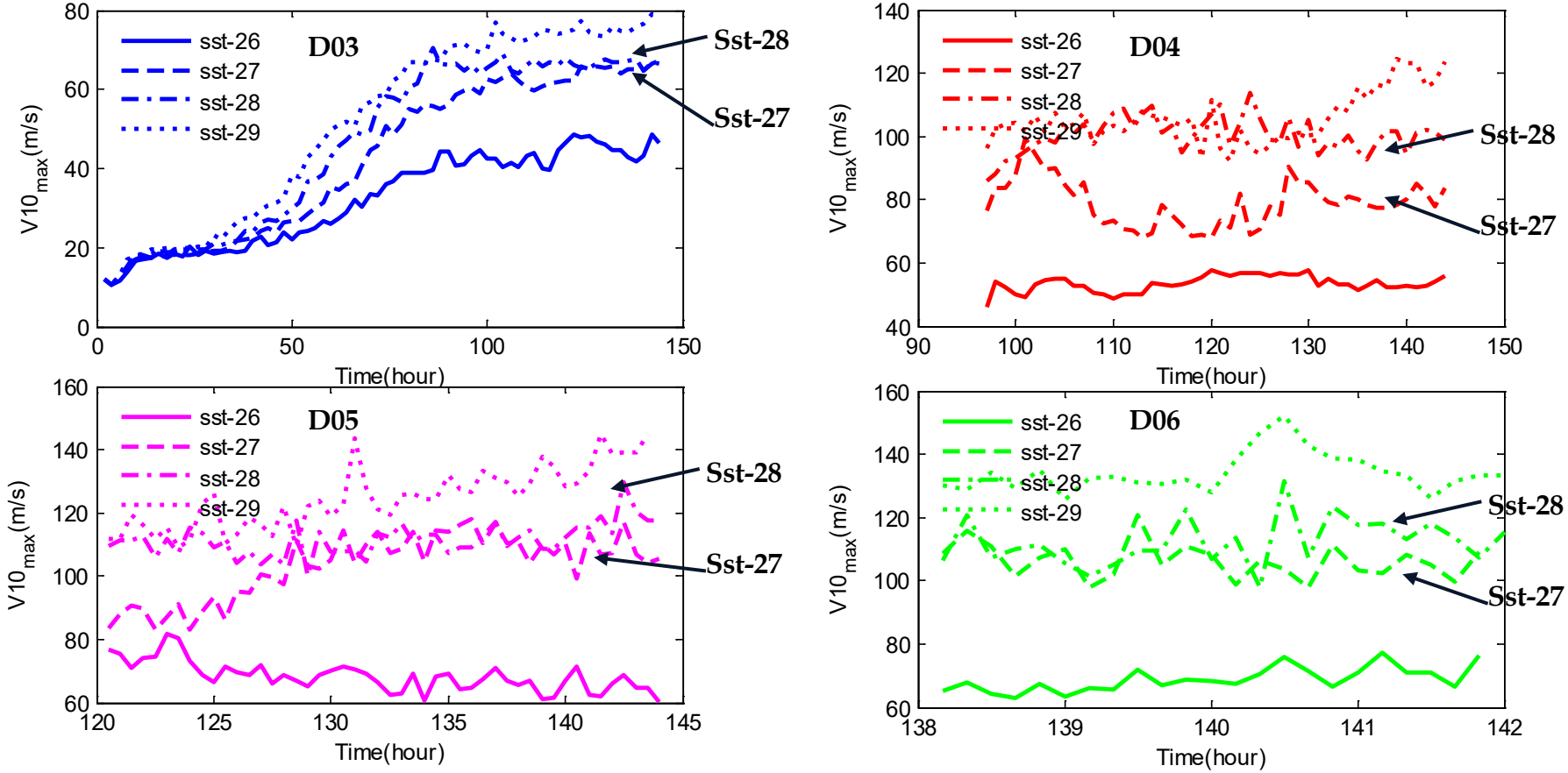
Max of instantaneous wind speed of domain 6 convergences to domain 5.

Max of time averaged wind speed at 10m height



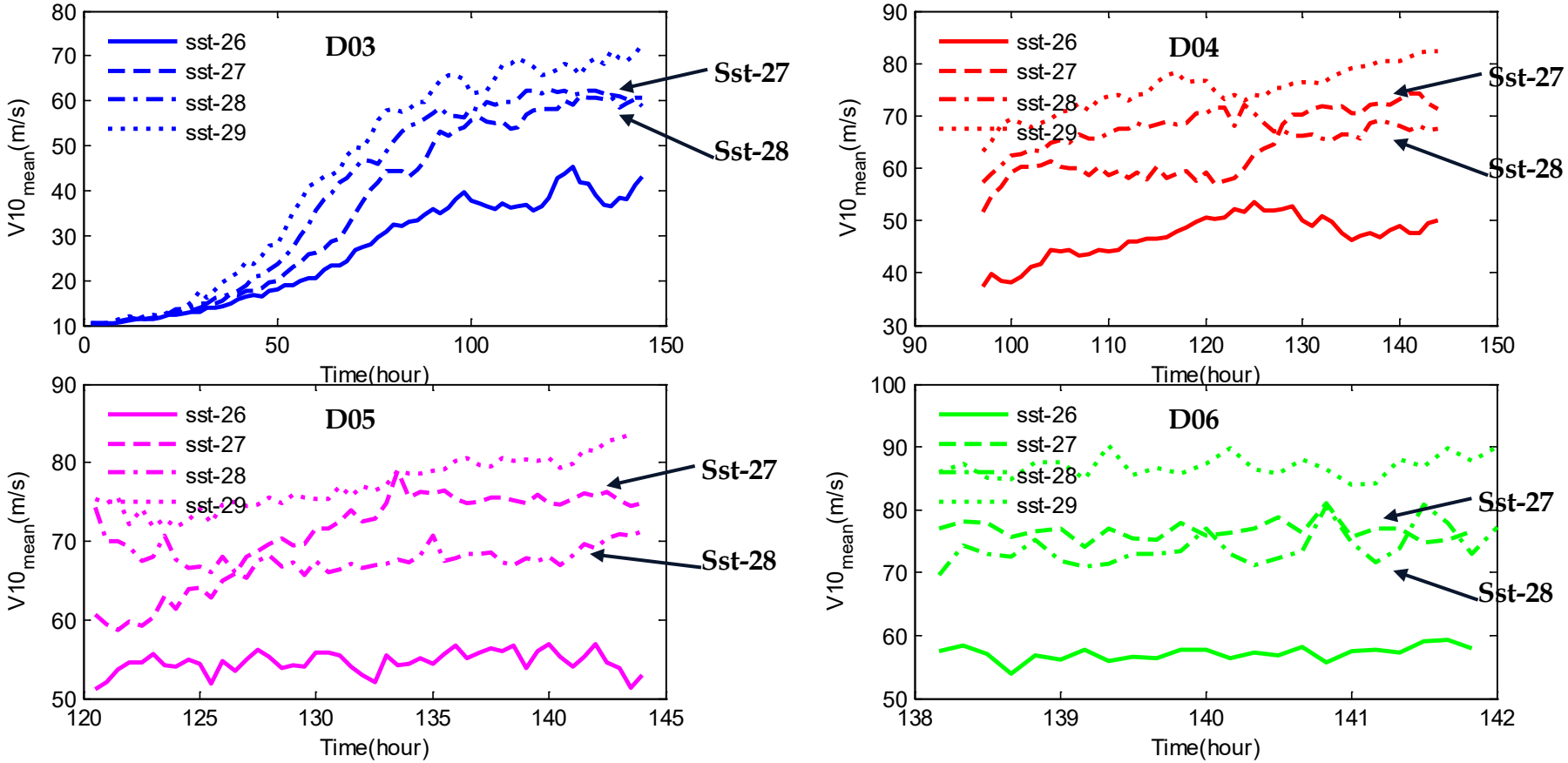
Also, max of time averaged wind speed of domain 6 convergences to domain 5. For sst-28 and 29, domain 4 also conergences to domains 5 and 6.

Max of instantaneous wind speed at 10m height



Interesting phenomenon:
Maximum of instantaneous wind speed lines cross for sst-27 and sst-28 cases.

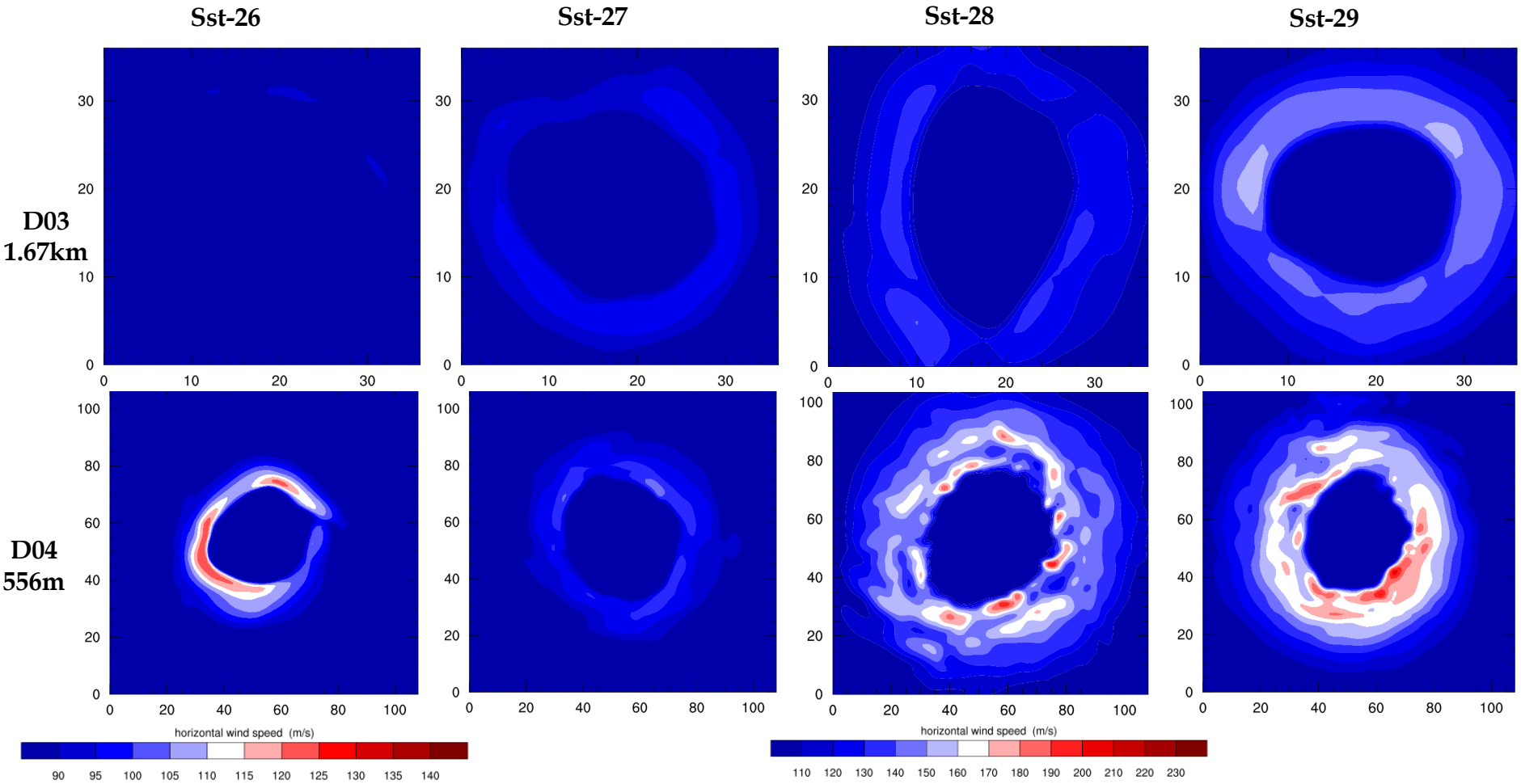
Max of time averaged wind speed at 10m height



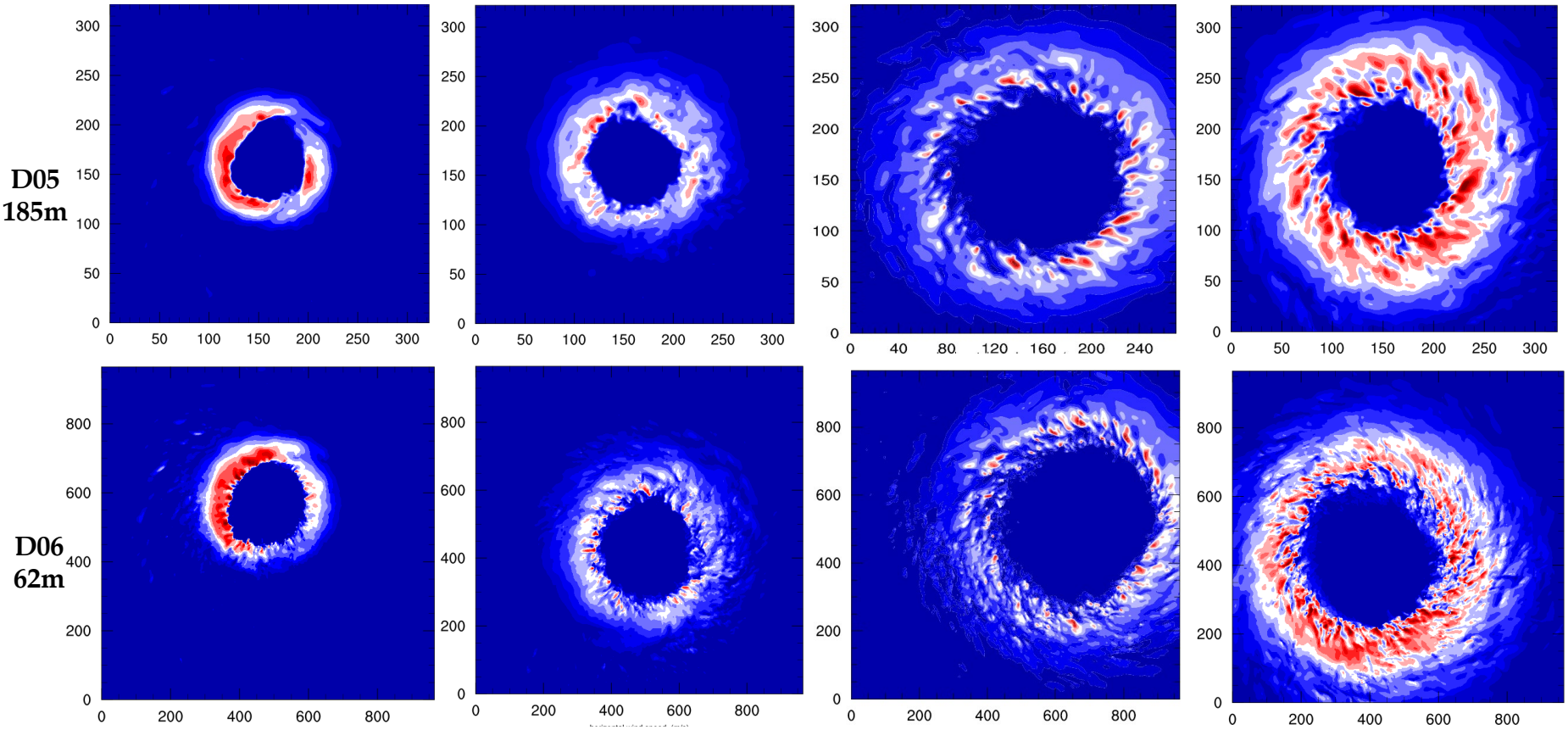
More obviously, maximum of time averaged wind speed lines cross for sst-27 and sst-28 cases.

Part 2. flow field characteristics

Small-scale turbulent eddy

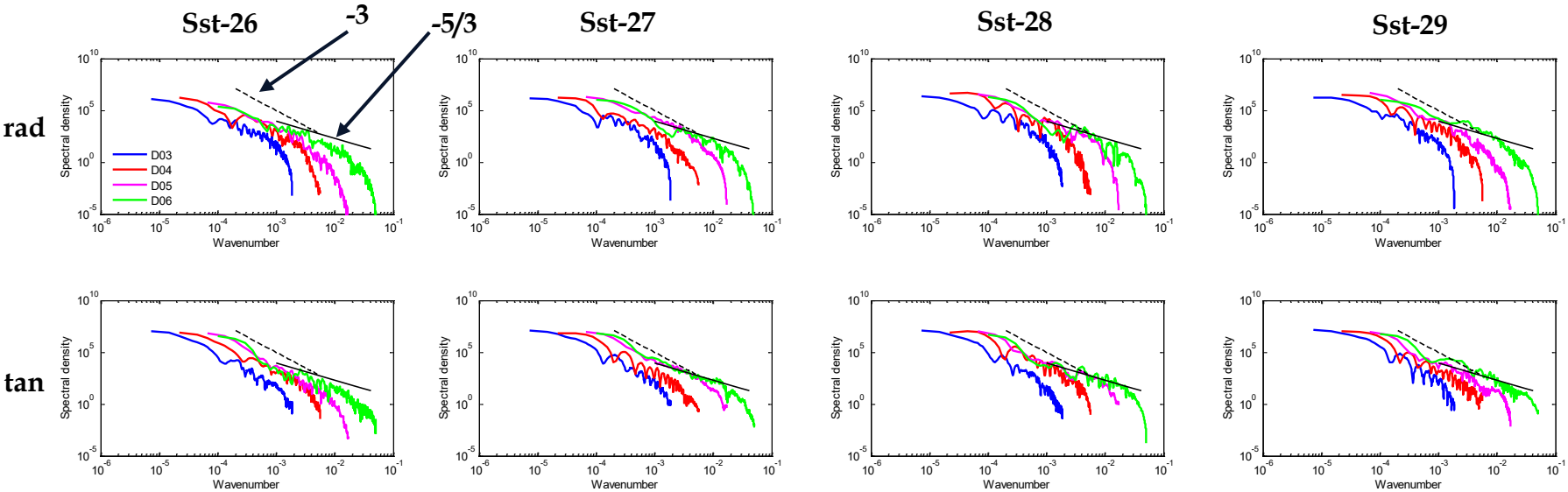


Small-scale turbulent eddy

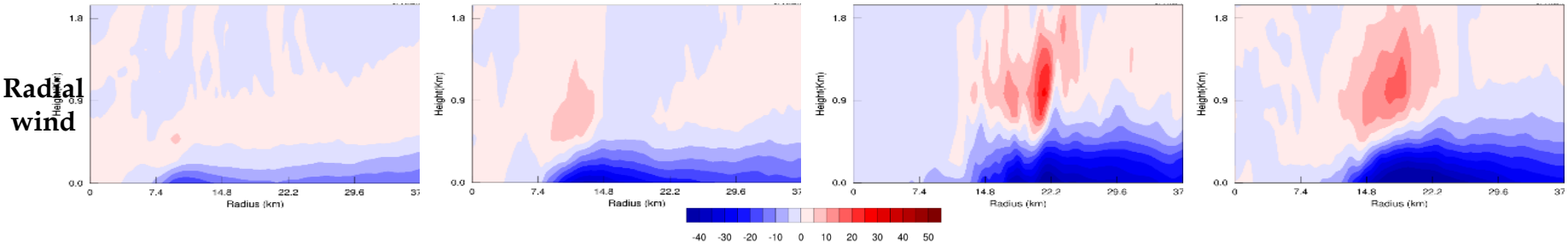


Sst-26, domain 5 does not have small-scale turbulent structures, other three cases have. For sst-28 and 29, domain 4 also has some small-scale structures.

Small-scale turbulent eddy



For larger sst, the needed horizontal grid size that transition to small-scale turbulent eddies is coarse. This may be relate to the radial inflow depth.

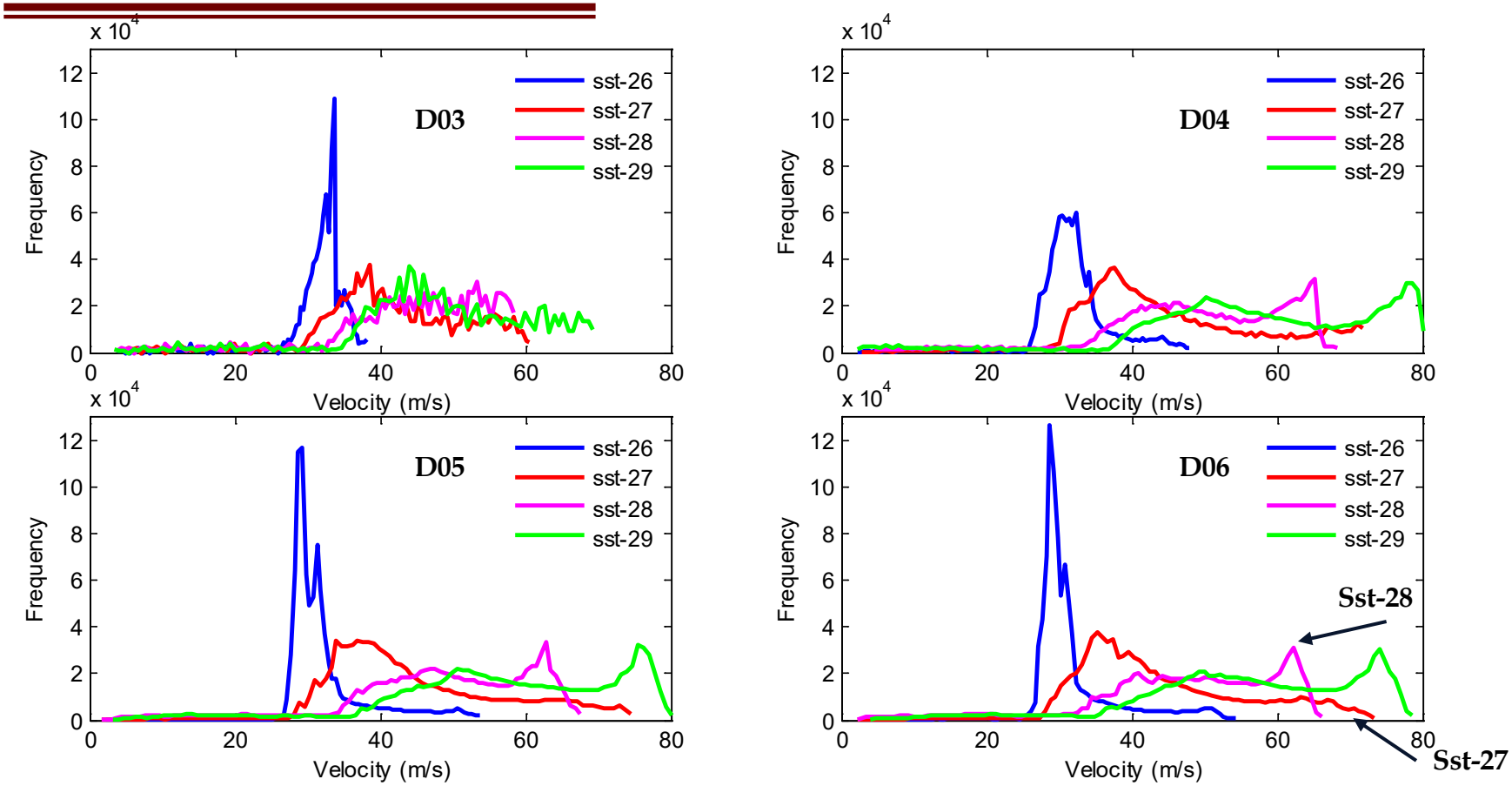


Part 3. wind speed distribution

- **Motivated by the maximum wind crossing for sst-27 and sst-28**

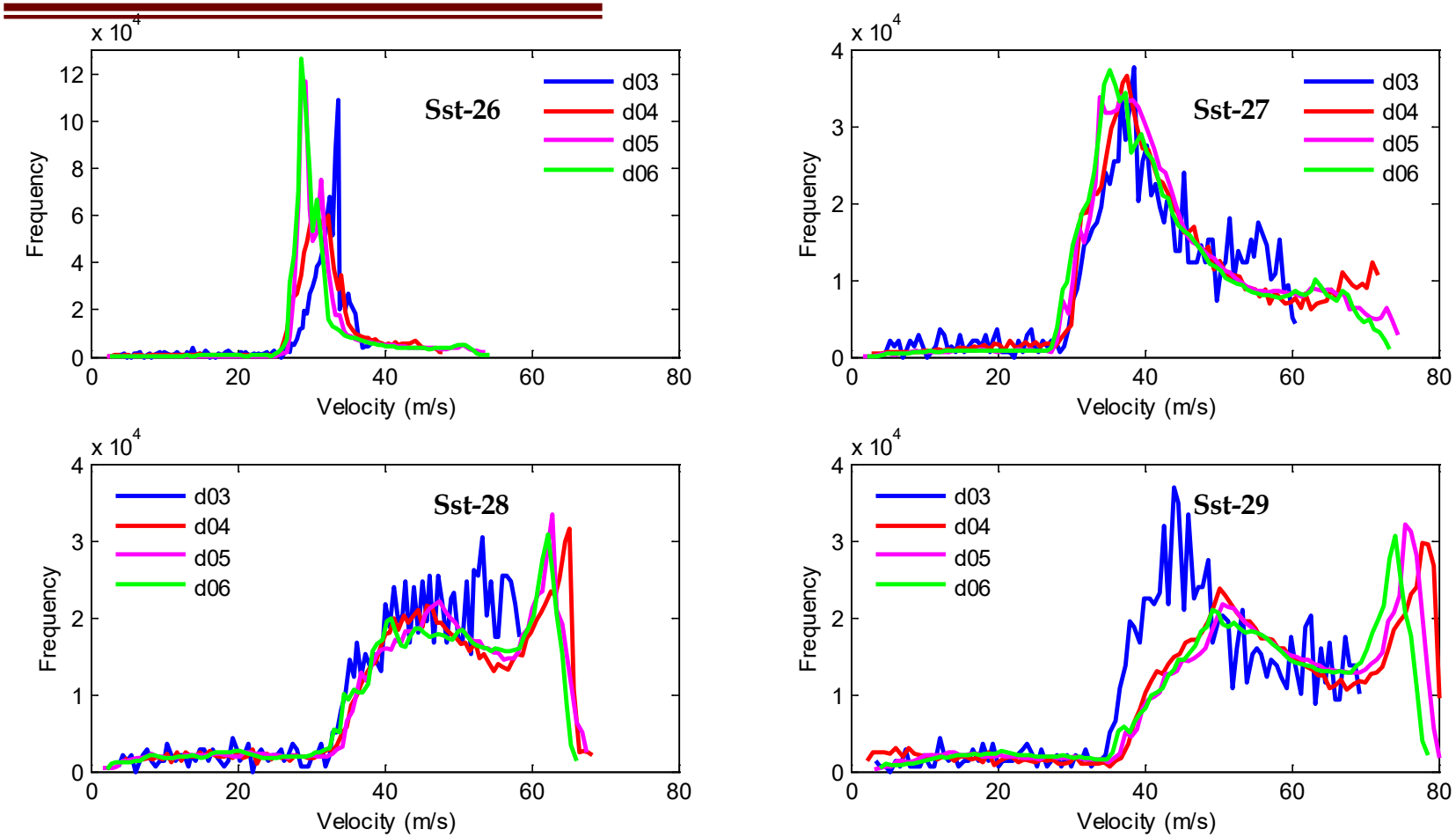
By analyzing the histogram of frequency for the domain D6 area

Histogram of time averaged wind speed



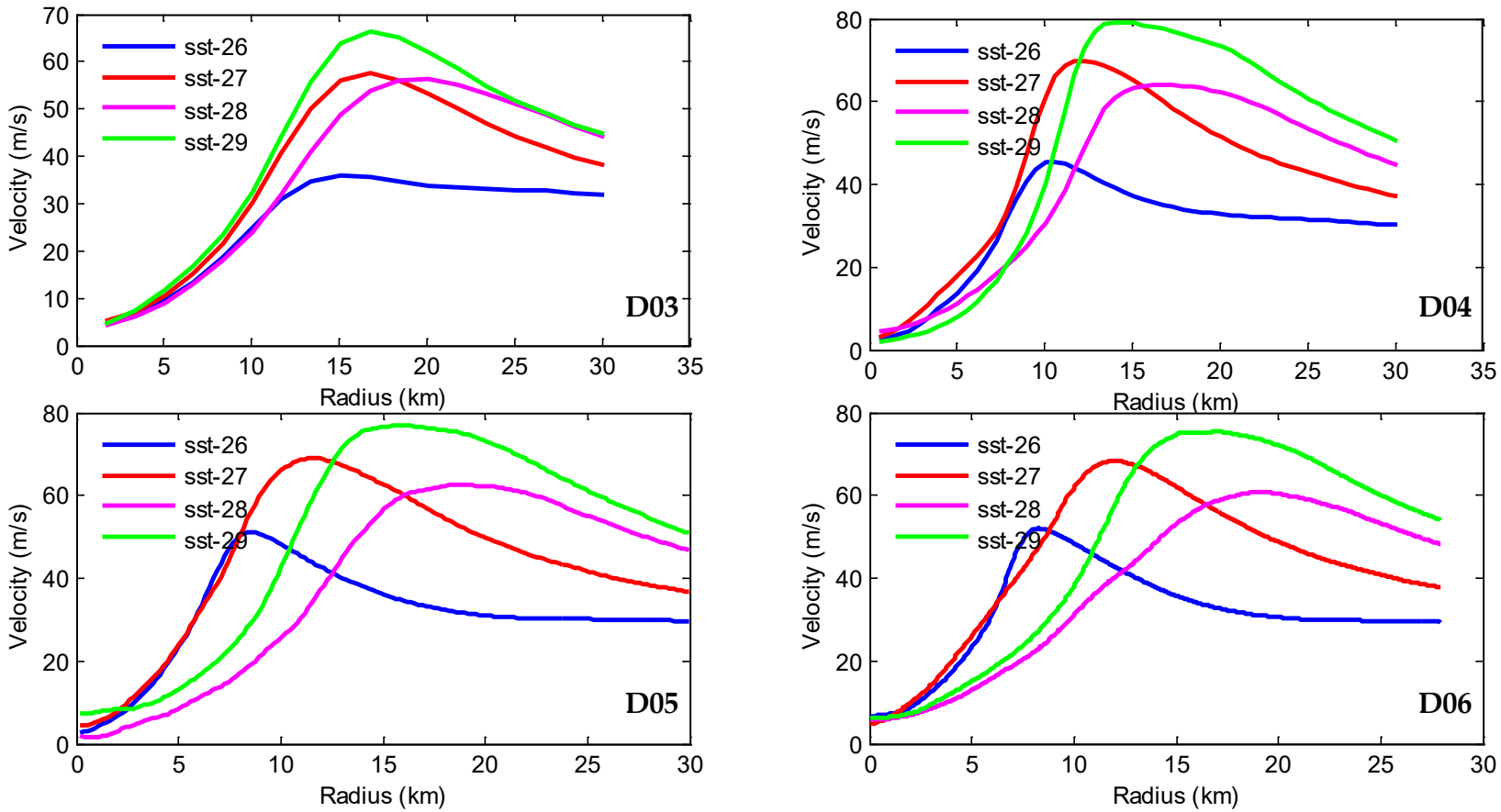
Even though sst-27 has the largest value, while sst-28 has a larger area of high speed (~60 m/s), the second peak. The second peak (even domain D4) only occurs at sst-28 and sst-29, that means, from sst-27 to sst-28, the distribution changes to bimodal.

Histogram of time averaged wind speed



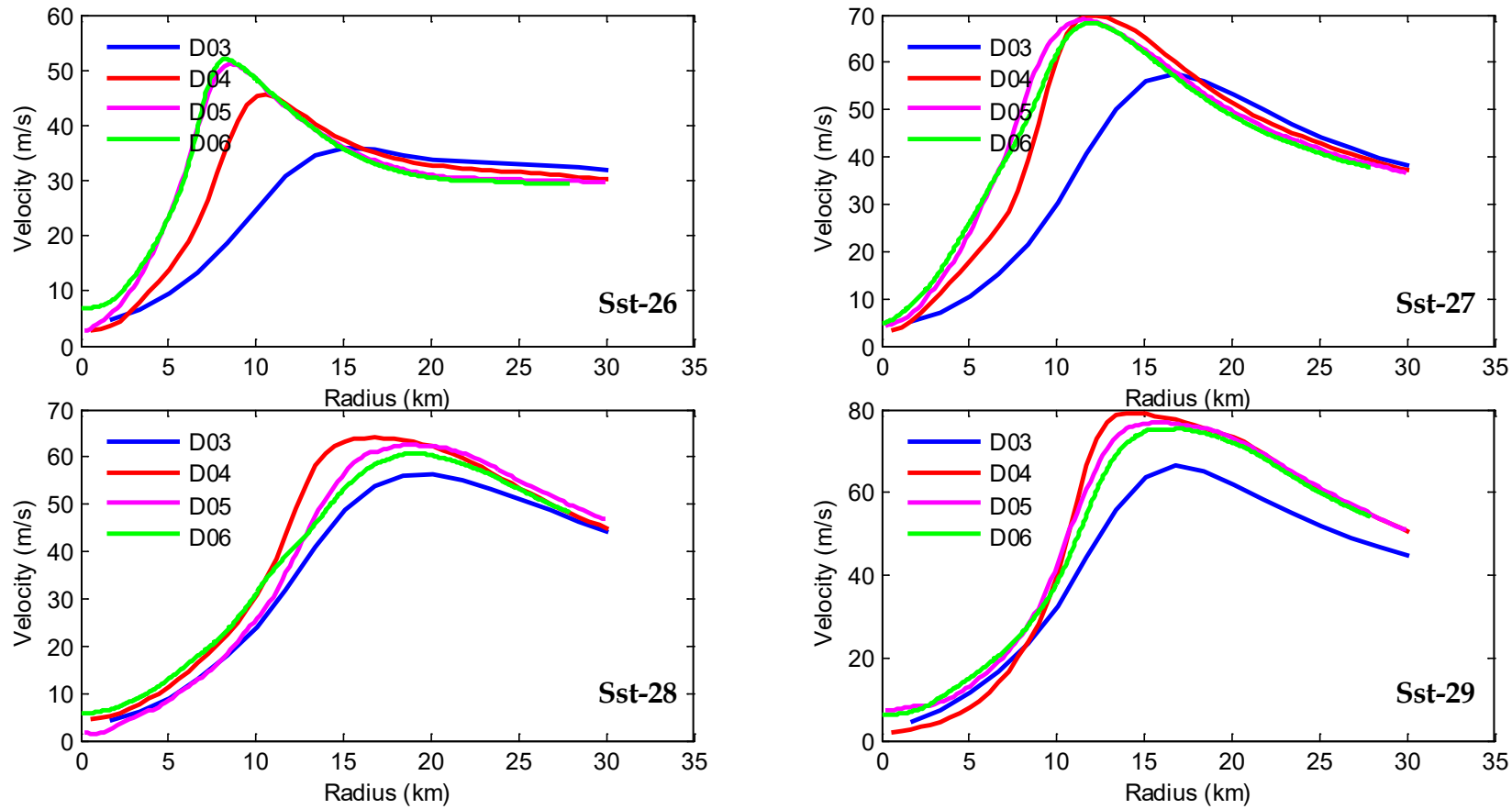
The wind speed distribution of domain 6 convergences to domain 5. Also double peak convergences.

The radial distribution of time averaged wind speed



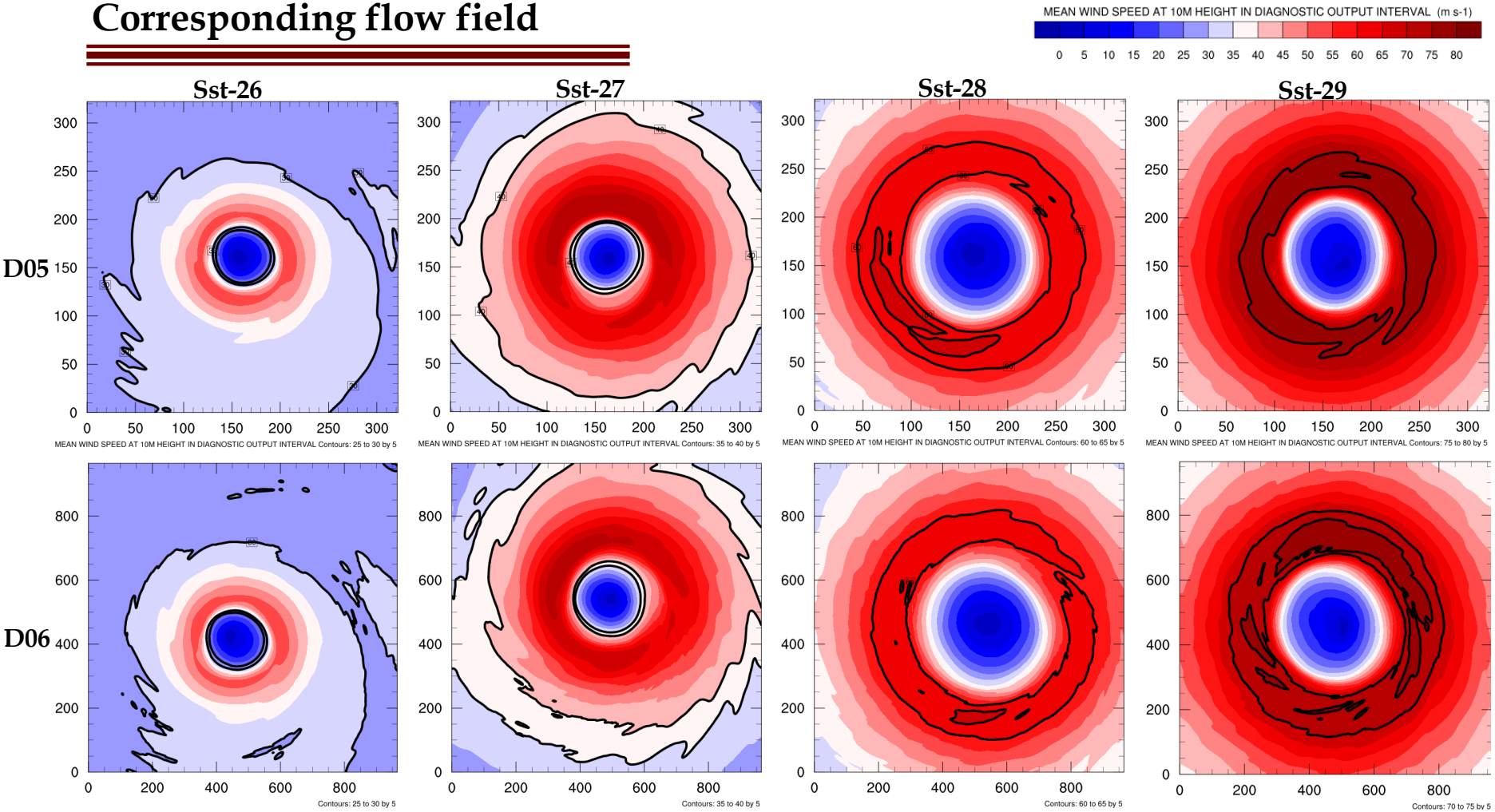
The radial distribution of wind speed is flatter for sst-28 and sst-29 which may explain the second peak of histogram.

The radial distribution of time averaged wind speed



The radial distribution of wind speed at domain 6 convergences to domain 5.

Corresponding flow field



Sst-28 and 29 could be more similar to annular hurricane which means that some fundamental aspect of the hurricane structure changes as sea surface temperature increases.

Part 4. a new potential damage indicator

- **The maximum wind alone may be insufficient for the damage potential**

  Based on previous slides, we will look more area integrated quantities.

The integrated kinetic energy (IKE)

Powell, M. D., and Reinhold T. A., 2007: Tropical cyclone destructive potential by integrated kinetic energy. Bull. Amer. Meteor. Soc., 88, 513–526.

$$IKE = \int_V 1/2\, \rho U^2 dV$$

where the wind speeds are taken from each grid cell of each domain and integrated nominally 1 m in the vertical (centered at the 10 m level).

The integrated kinetic energy (TJ)

	Sst-26	Sst-27	Sst-28	Sst-29
D03	21.4473	26.9941	32.0593	39.1604
D04	19.2459	25.1936	30.0641	38.2024
D05	19.3476	24.9583	30.0451	38.0359
D06	19.3220	24.8361	30.1485	37.7903

And, a damage-weighted sum as a damage indicator

$$IKE_{sum} = IKE_{25-40} + 6IKE_{41-54} + 30IKE_{55}$$

Wind destructive potential thresholds are defined that include light (25 to < 41 m/s, IKE_{25-40}), moderate (41 to < 55 m/s, IKE_{41-54}), and severe (>=55 m/s, IKE_{55})

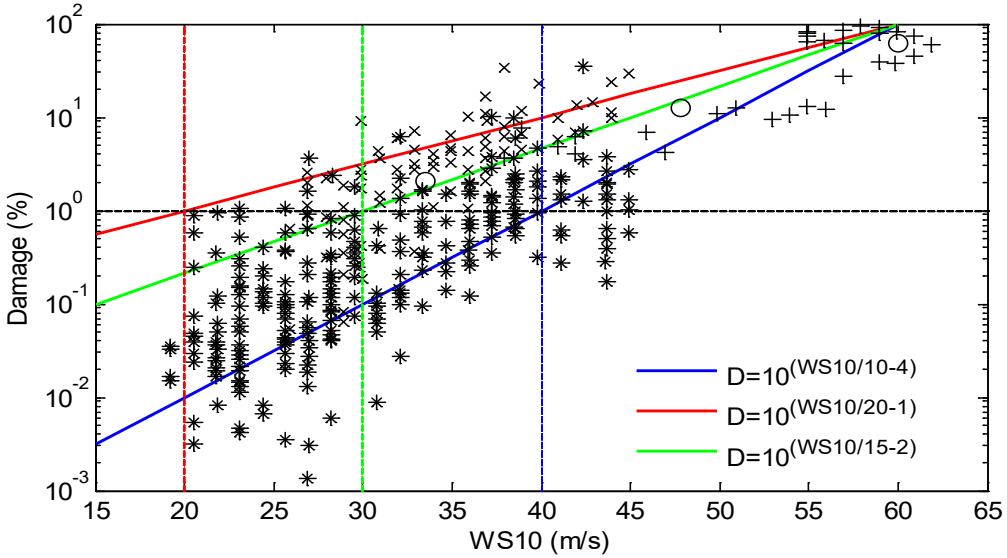
This will be used for comparison with our new indicator.

$$W_{DP} < 4 = 0.67 + 0.017(\mathrm{IKE}_{25-40} + 6\ \mathrm{IKE}_{41-54}) - 5.4 \times 10^{-5}[(\mathrm{IKE}_{25-40} + 6\ \mathrm{IKE}_{41-54}) - 109.6]^2; \quad (2)$$

$$W_{DP} > 4 = 3.28 + 1.007 \times \mathrm{Log}_{10}(30\ \mathrm{IKE}_{55}) + 0.271 \times [\mathrm{Log}_{10}(30\ \mathrm{IKE}_{55}) - 1.629]^2. \quad (3)$$

Too complicated and also cannot resolve the small size but intense hurricane in Powell & Reinhold (2007), so in our study, we use the same data to find a simplified potential wind damage indicator.

Wind damage (D): a new potential damage indicator



Formula 1 (blue):
- 100% @60 m/s
- 1% @40 m/s

Formula 2 (red):
- 100% @60 m/s
- 1% @20 m/s

Formula 3 (green):
- 100% @60 m/s
- 1% @30 m/s

From Figure 3 in the Powell & Reinhold (2007), we can define potential damage (%) as

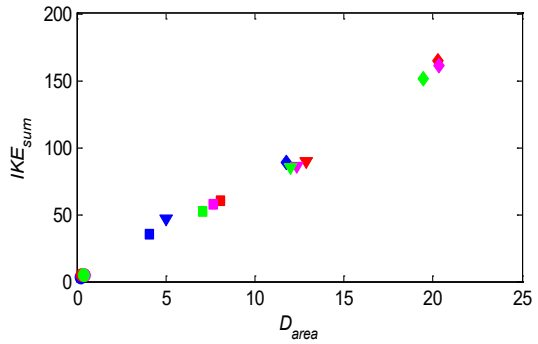
$$\log_{10} D = WS10/10 - 4$$ **(Formula-1) as lower bound,**

$$\log_{10} D = WS10/20 - 1$$ **(Formula-2) as upper bound,**

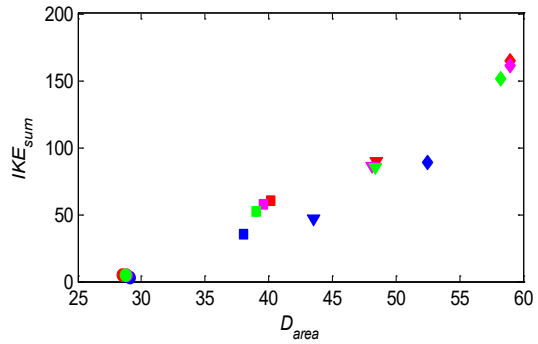
$$\log_{10} D = WS10/15 - 2$$ **(Formula-3) as median value.**

These three formulas may be suitable to different regions where offshore or coastal structures have different wind resistance levels according to age and building codes.

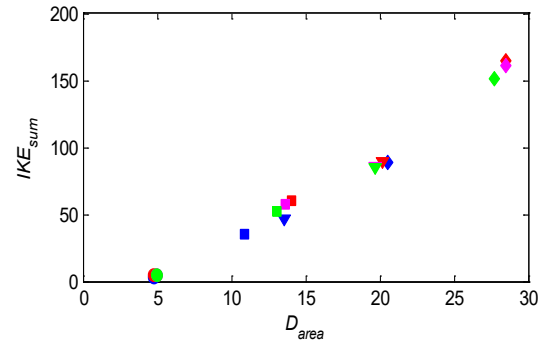
Wind damage (D): area integral vs IKE



Formula-1



Formula-2



Formula-3

Green dots represent domain D6

The linear relationship for Darea and IKE.

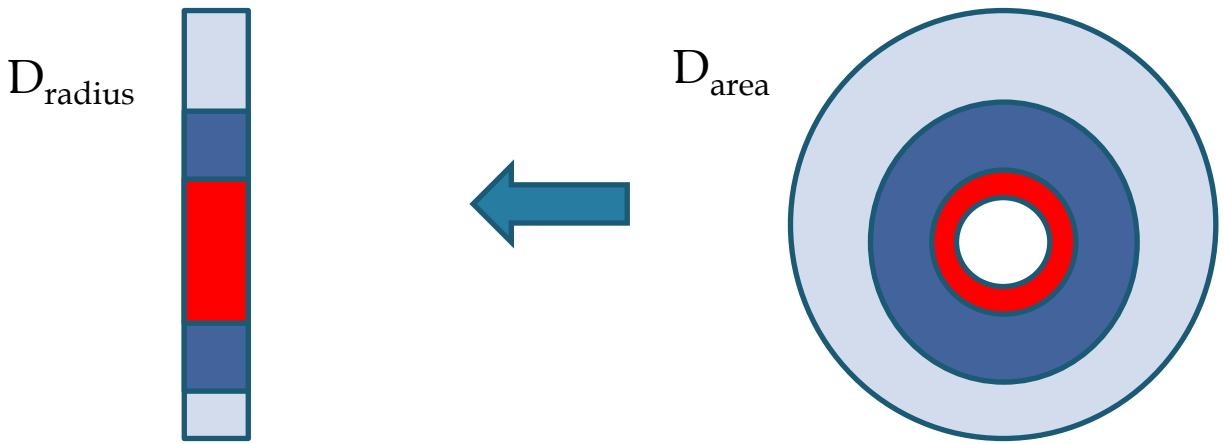
Note that for different formulas of wind damage, the small speed part has a different weight, so the value of wind damage changes a lot because smaller velocities occupy larger areas.

Darea, (unit, 10^{10} % m^2 or 10^4 % km^2): is equivalent to 100% damage in a 10 km square or 1% damage in a 100 km square.

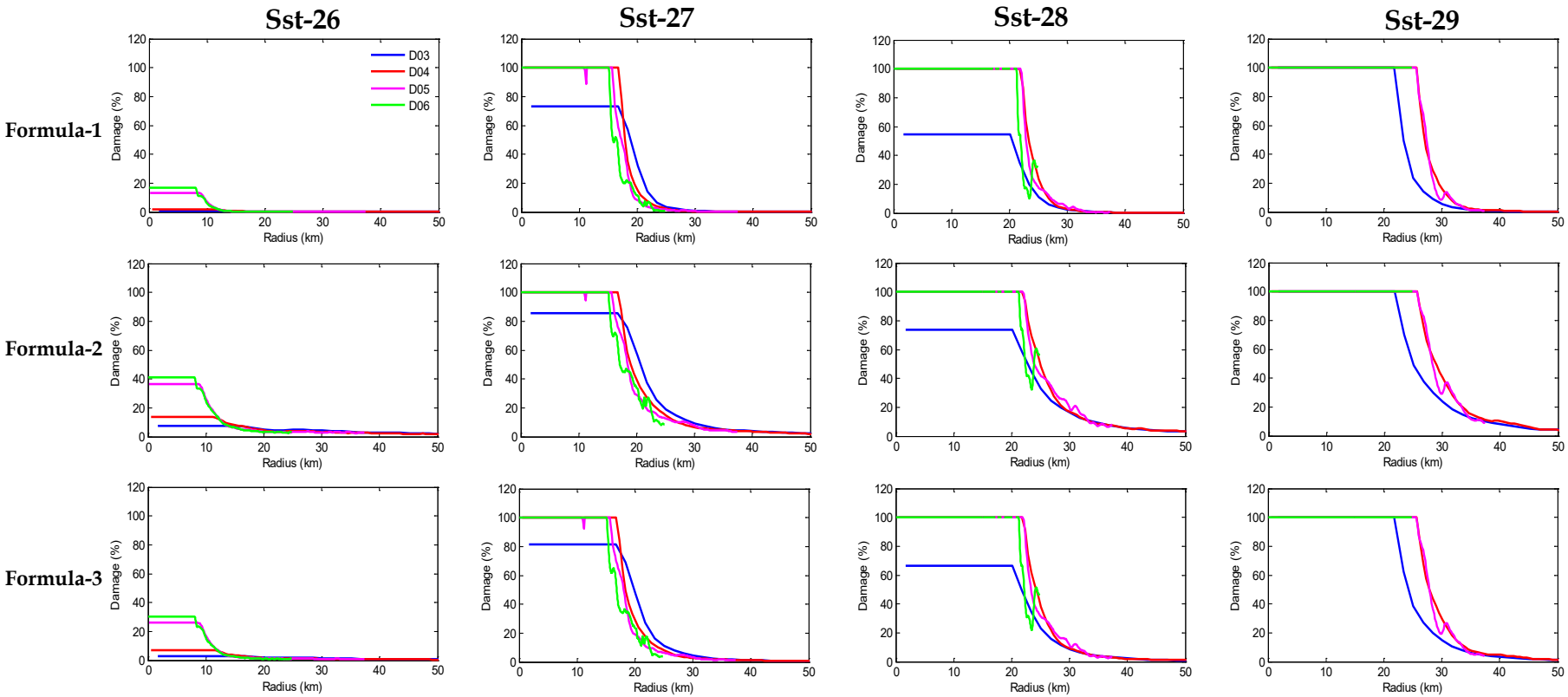
IKE, (unit, TJ).

D_{radius}

- However, the area integral may not be the best measure because it underestimates the relative area affected by the strongest winds in a moving hurricane.
- So we will modify wind damage to be integrated by radius applying the eyewall wind damage within that radius.
- This represents the damage along a coast for example or as a function of track width.

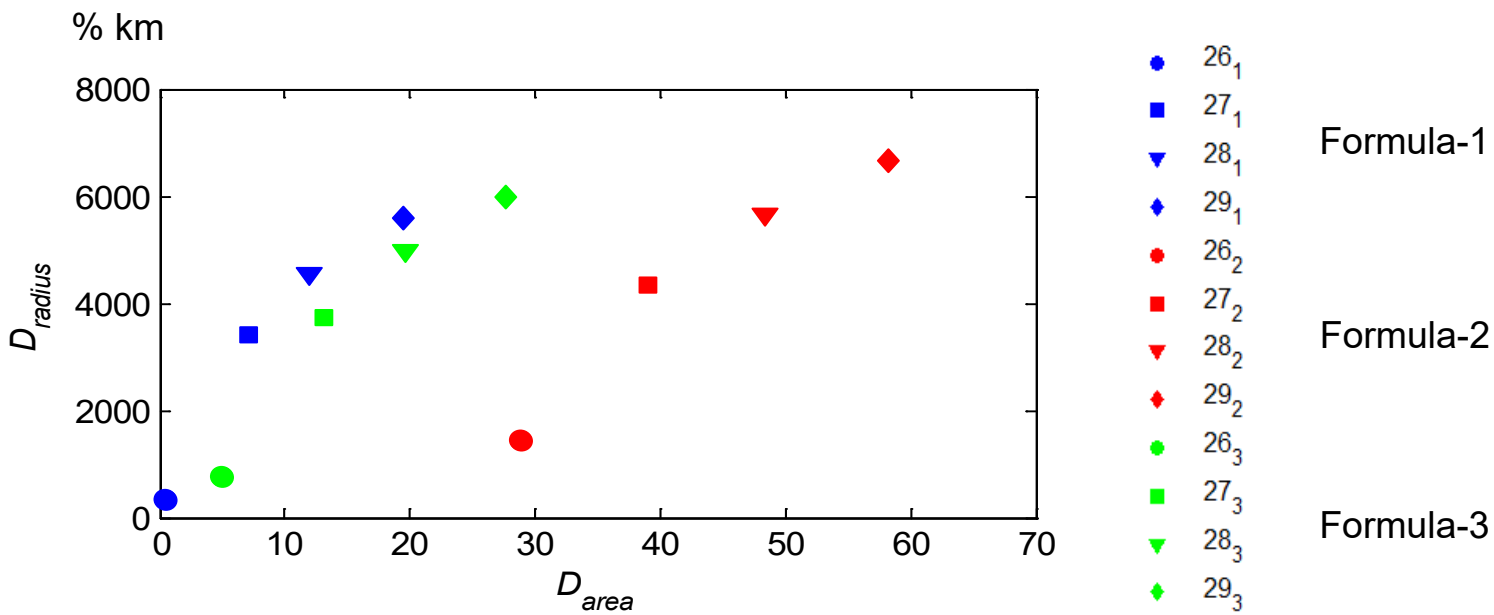


Wind damage (D): function of radius



Dradius, (unit, 10^3 % m or % km): the integral along a coast as the hurricane crosses it and a value of 1000 % km corresponds to 100% damage on a 10 km coast or 10% for 100 km.

Wind damage (D): area integral vs radius integral



Darea is more sensitive to the formulas (weak-wind tail) than Dradius. Dradius integral is more dominated by the inner hurricane region, and we know that weak wind (outer region of hurricane) contributes little to the damage, so we conclude that Dradius is a much better index to weight the relative damage between storms.

Also, formula-3 is justifiable where 1% damage corresponds to wind speeds around category-1 hurricane strength (~33 m/s), the other two formulas relative to formula-3 are for more (formula-1) or less (formula-2) resilient structures.

Practical Considerations

- For real storms full 3d wind information does not exist
- However the radius of speeds can be estimated
- This can approximate D_{radius} if we know radius of 30, 45, 60 m/s (approx., 60, 90 and 120 kt radii)

- Example major storm with max > 60 m/s (using formula 3)
  - Given that D=2 for 60+ m/s, 1 for 45 m/s and 0 for 30 m/s corresponding to 100%, 10% and 1% respectively

  - $D_{radius} = \sim 100 \times d_{60} + 30 \times (d_{45}-d_{60}) + 3 \times (d_{30}-d_{45})$

  - Where d_n is the diameter in km of windspeed contour n m/s

Other Notes

- These simulations apply to an f-plane with no mean wind and no shear, all of which would lead to more asymmetries and perhaps weaker storms for a given SST
- The simulations have constant SST, no ocean mixed-layer response that could also weaken the storms
- Here we have only addressed wind damage
- Obviously storm surge and flooding from precipitation can also cause major property damage costs that are not accounted for here

Conclusions

- **First, for the maximum of *instantaneous wind speed*, domain D6 (62m) converges to the same intensity as domain D5 (185m) showing the adequacy of 185 m grid sizes. Furthermore, for sst-28° and 29° cases, the domain D4 (556m) of *time-averaged wind speed* converges to domains D5 and D6.**

- **Second, for sea surface temperature of 26°, domain D5 does not have small-scale turbulence structures, but the other three cases all have, this is also an extension of the previous work of Rotunno et al. (2009). Furthermore, for sst-28° and 29° cases, domain D4 (556m) also shows some small structures.**

- **Third, the distribution function of speed changes between sst-27° and sst-28° cases, the latter ones having a second peak, this could be more similar to annular hurricane which means that some fundamental aspect of the hurricane structure changes as sea surface temperature increases.**

- **Finally, sst-27° and sst-28° cases show the traditional maximum wind is not sufficient for wind damage. Thus, we compare the area integrated wind damage with IKE, then we introduce the radius based method, which may be more justified in terms of track and coast lines.**

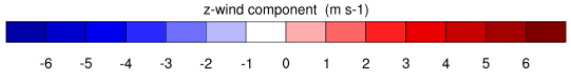
References:

Rotunno, R., Chen, Y., Wang, W., Davis, C., Dudhia, J. and Holland, G. J., 2009: Large-eddy simulation of an idealized tropical cyclone. Bull. Amer. Meteor. Soc., 90, 1783–1788.

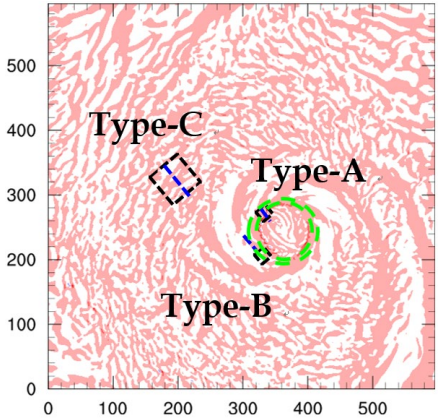
Powell, M. D., and Reinhold T. A., 2007: Tropical cyclone destructive potential by integrated kinetic energy. Bull. Amer. Meteor. Soc., 88, 513–526.

Ongoing study

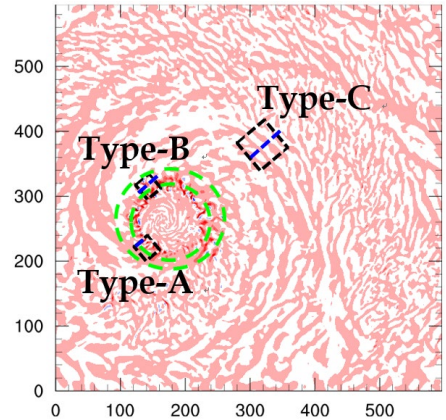
- **The mechanisms of three types of roll structure in the hurricane boundary layer**



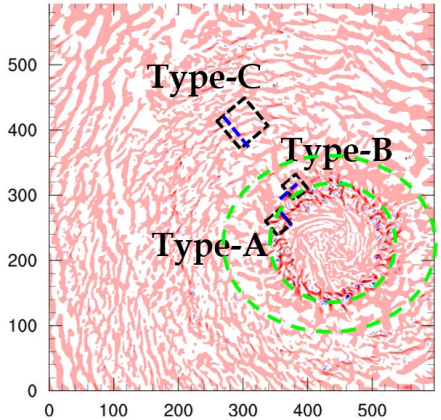
Sst-26



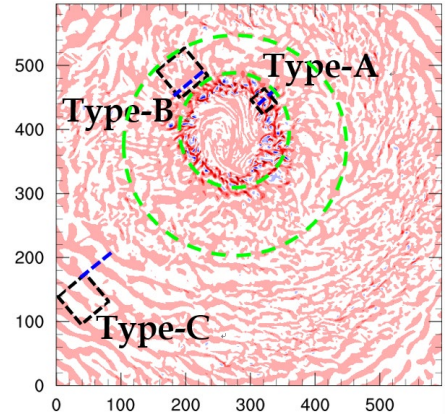
Sst-27



Sst-28



Sst-29



- **We found out that Type-A, Type-B and Type-C roll structures are caused by shear instability (0<Ri<0.25), inertia instability and inflection point instability mechanisms, respectively.**
- **This is the second study of the mechanisms of Type-A and Type-B roll structure, but is the first time to resolve the mechanisms correctly.**
- **Also we discovered two modes of Type-A roll structure that we are still investigating.**

References:

Ito, J., Oizumi, T. & Niino, H. Near-surface coherent structures explored by large eddy simulation of entire tropical cyclones. Sci. Rep. 7, 3798 (2017).