Process-oriented diagnostics of tropical cyclones in global climate models

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and

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Motivations

- Early **global climate model (GCM)** simulations have been able to produce **tropical cyclone (TC)**-like vortices (e.g., Manabe et al. 1970; Bengtsson et al. 1982; Haarsma et al. 1993; see Camargo and Wing 2016 for review).

- Continuing advances in computational power and numerical methods made it feasible to run GCMs at 0.25 degree or lower.

- Recently, many studies have examined TCs in high-resolution GCM simulations with Δx = 0.25-0.5 degree.

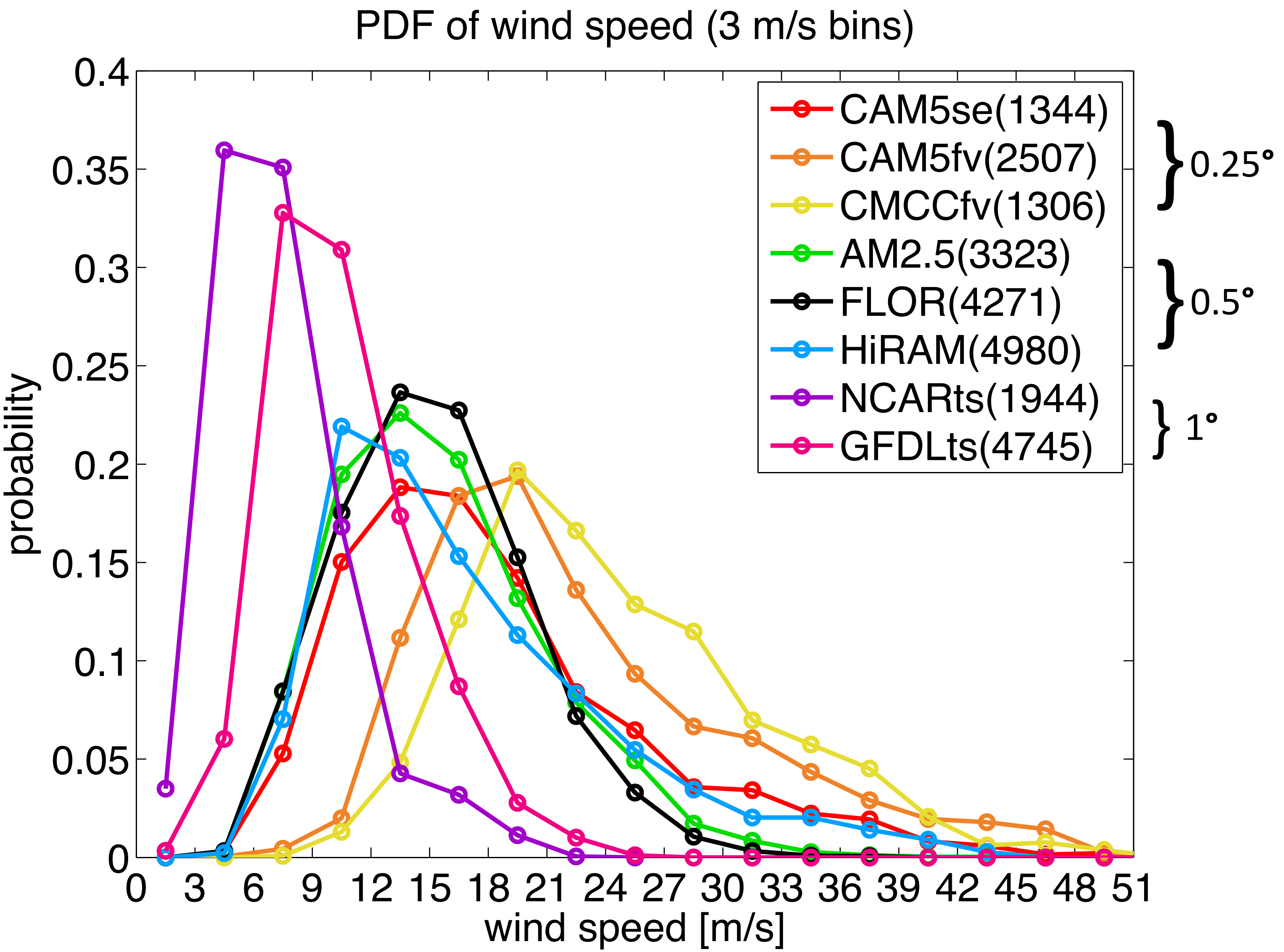
- Using smaller horizontal grid spacing tends to improve simulations of TCs, but models show a wide spectrum in their ability to reproduce the observed TC climatology, such as genesis, track, and intensity.

- The goal of this study is to
  (1) examine storm structures that are simulated differently by different GCMs.
  (2) and see if these structural differences could explain inter-model differences in simulated TC activity.

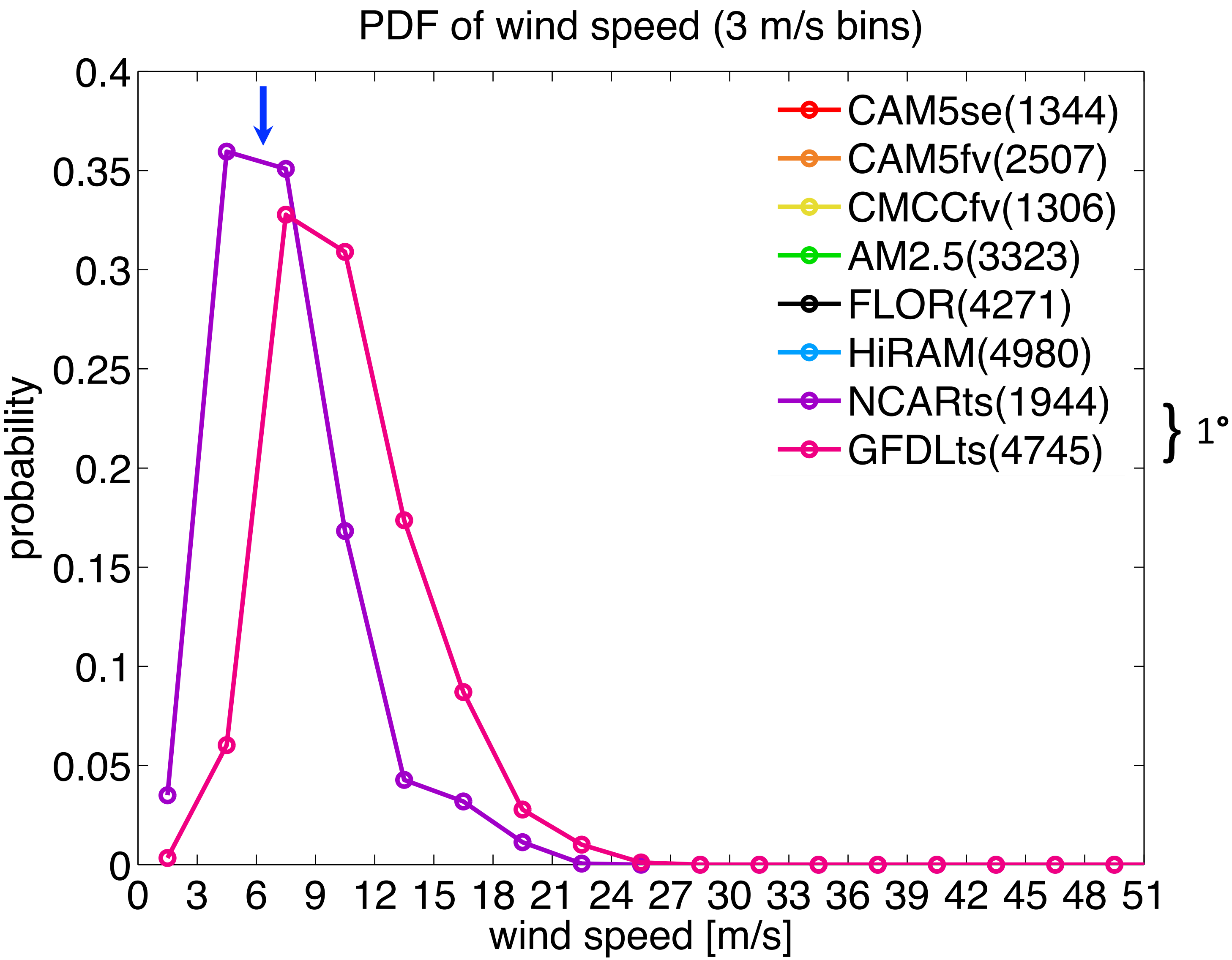
Simulation data

		Δx	levels	Years	Coupled?
	NCAR CAM5se	28 km	30	1992-1999	No
0.25°	NCAR CAM5fv	30 km	30	1996-1997	No
	CMCC CM2	30 km	30	1958-1959	Yes
	GFDL AM2.5	62 km	32	1984-1985	No
0.5°	GFDL FLOR	62 km	32	1984-1985	Yes
	GFDL HiRAM	62 km	32	1984-1985	No
1°	MDTF NCAR CAM5	121 km	30	1990-1994	No
	MDTF GFDL AM4	125 km	32	2008-2012	No

- The analysis uses 6-hourly data to create storm composites at similar intensity (3 m/s bins)
- Only TCs located within +/- 25 degrees are considered (i.e., no sub-tropical storms or extratropical transitions)
- NCAR CAM5se has the 0.25° resolution only over the North Atlantic.



- Maximum of azimuthally averaged surface wind speed is used to measure TC intensity.
- Stronger TCs are more frequent in higher-resolution GCM experiments.



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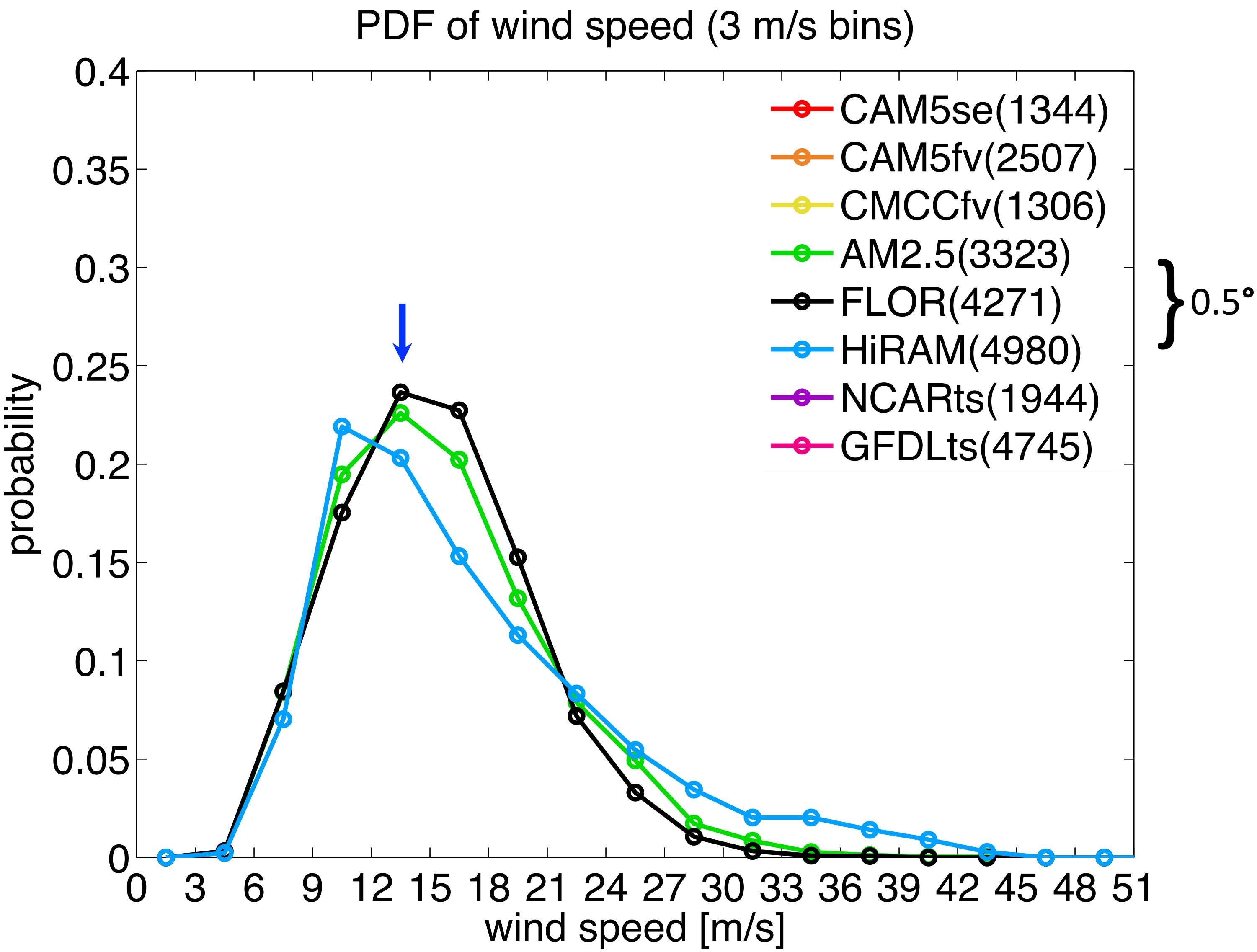

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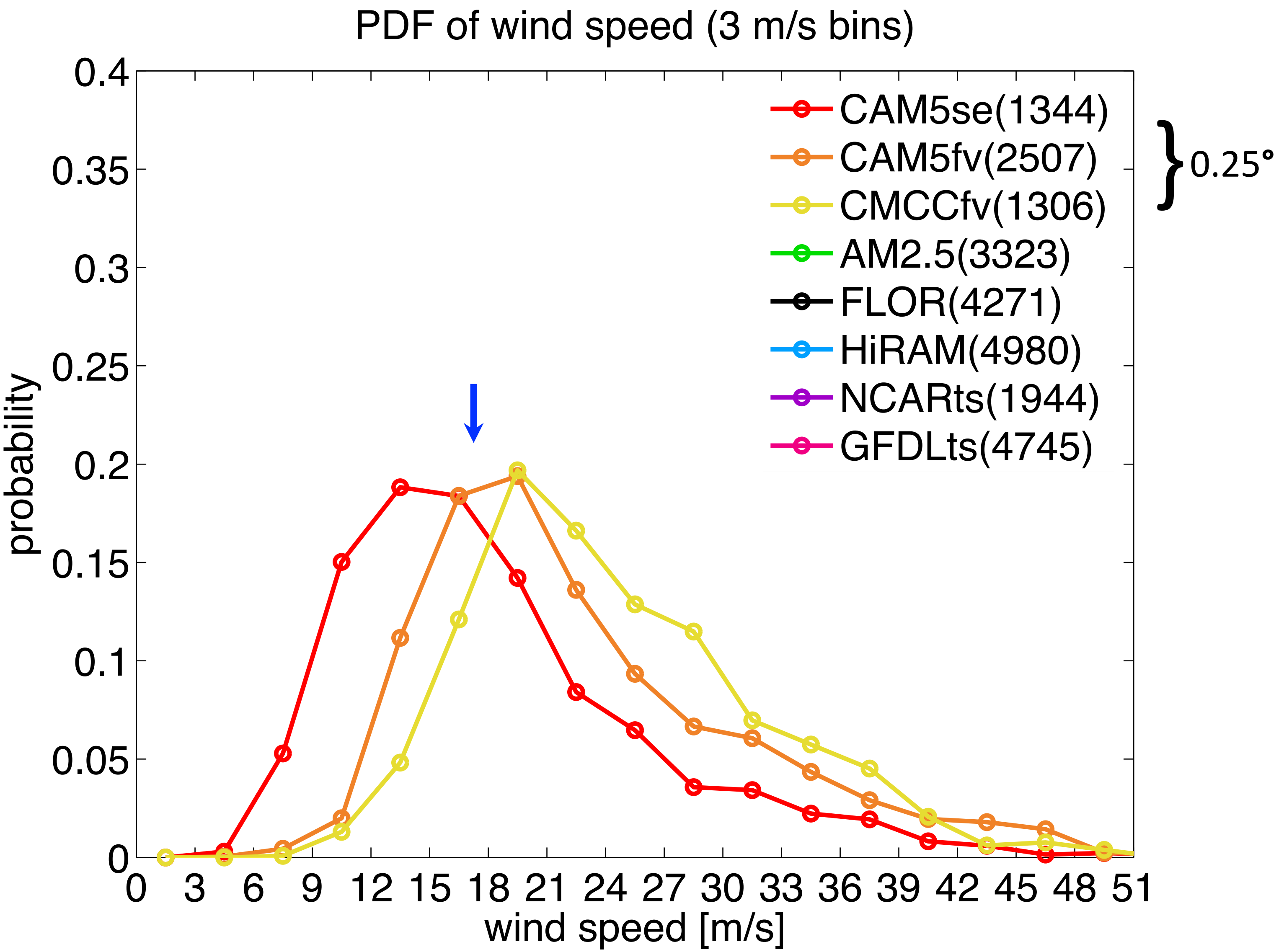

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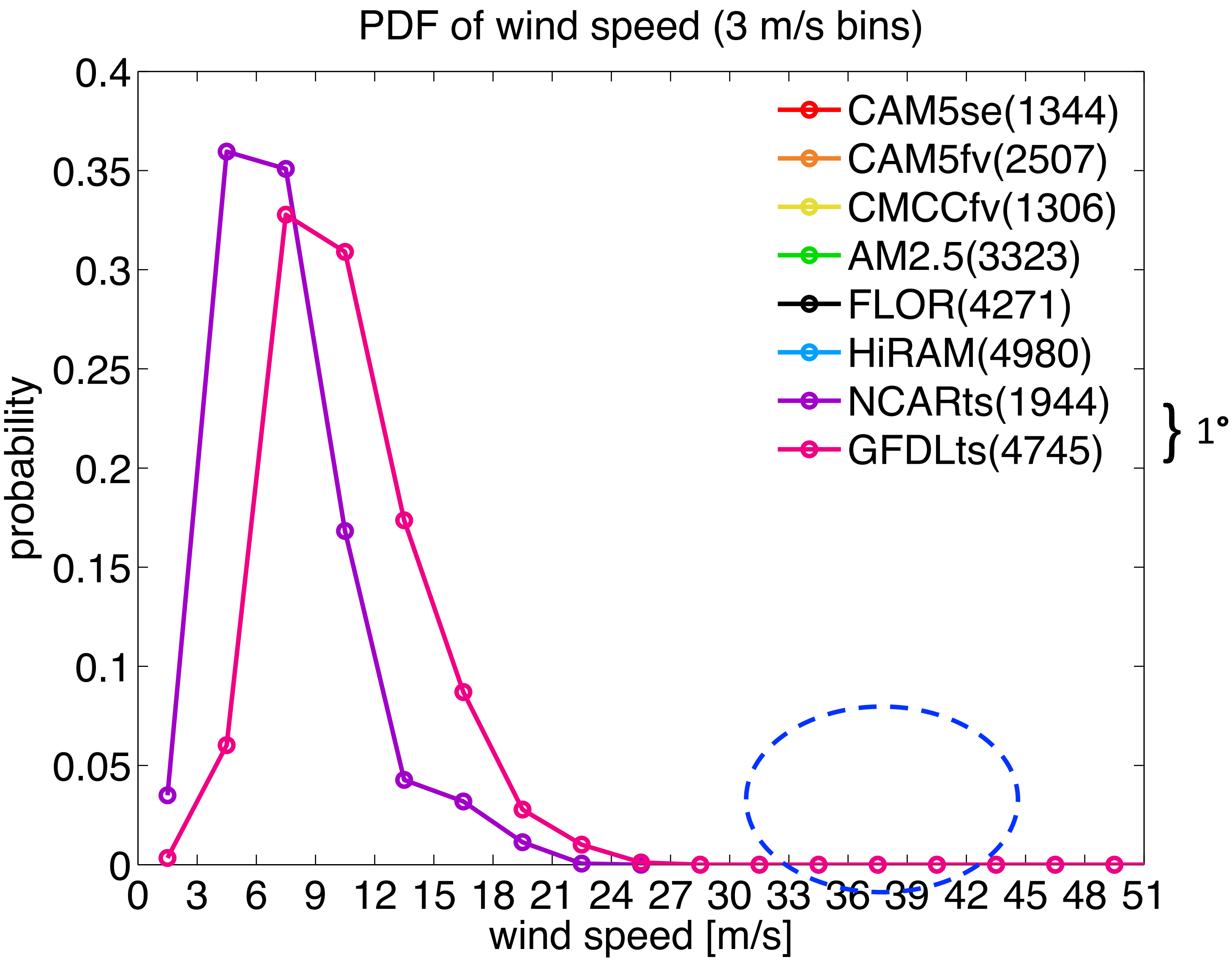

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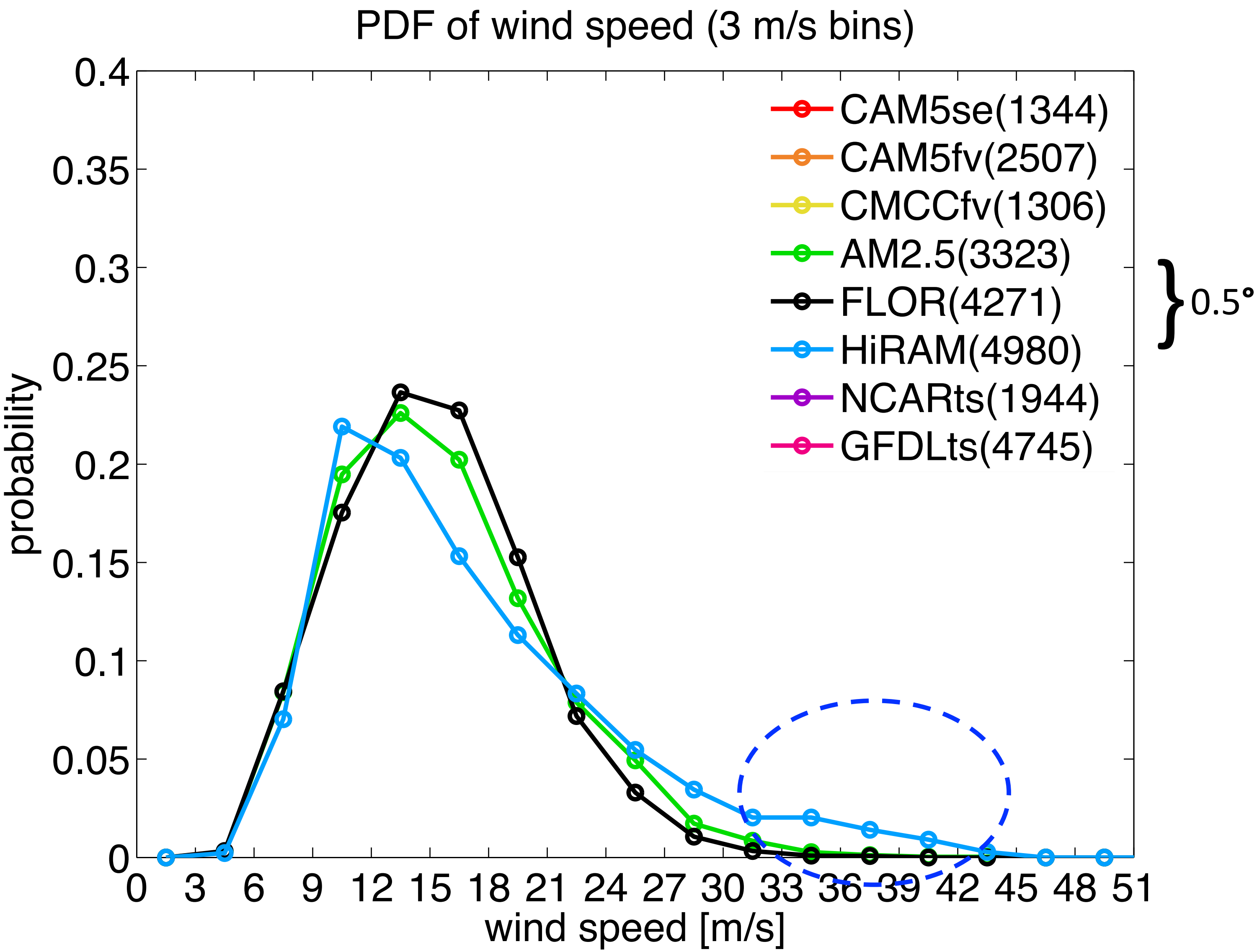

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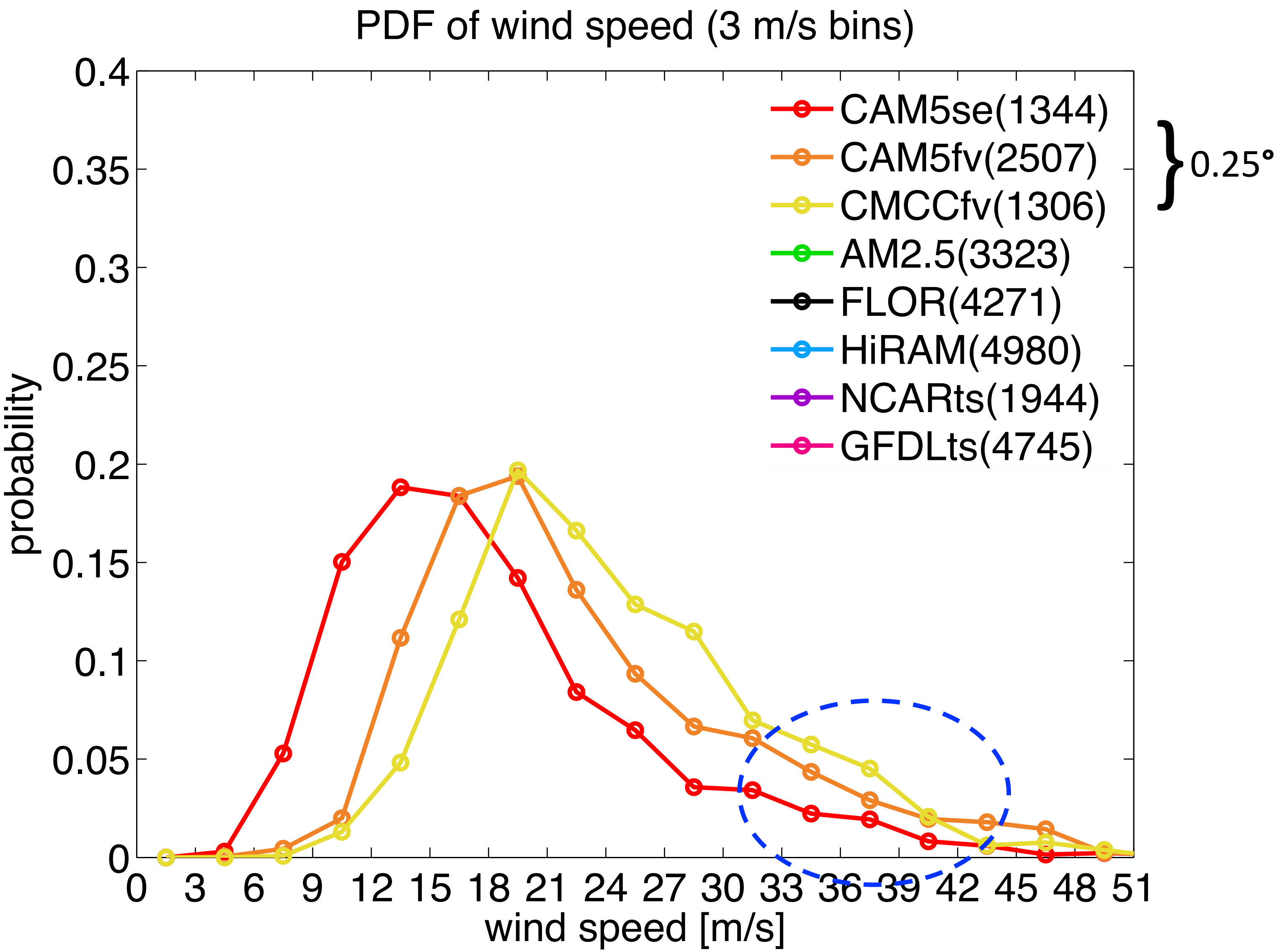

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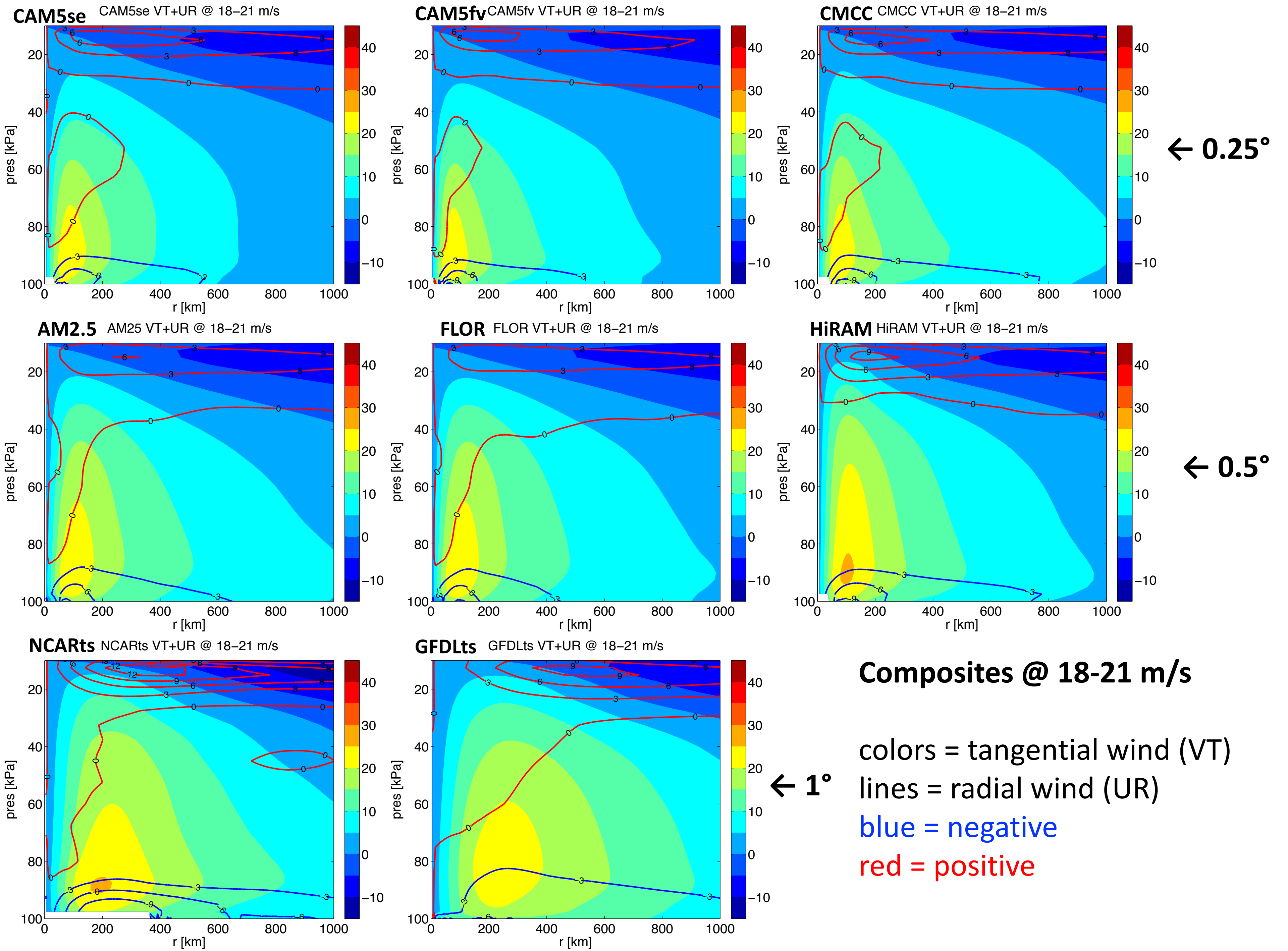

CAM5se
CAM5se VT+UR @ 18–21 m/s
CAM5fv
CAM5fv VT+UR @ 18–21 m/s
CMCC
CMCC VT+UR @ 18–21 m/s
← 0.25°
AM2.5
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FLOR
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HiRAM
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← 0.5°
NCARts
NCARts VT+UR @ 18–21 m/s
GFDLts
GFDLts VT+UR @ 18–21 m/s
← 1°
pres [kPa]
r [km]
Composites @ 18-21 m/s
colors = tangential wind (VT)
lines = radial wind (UR)
blue = negative
red = positive

From: UCAR EOL

A 10-second review of TC wind field

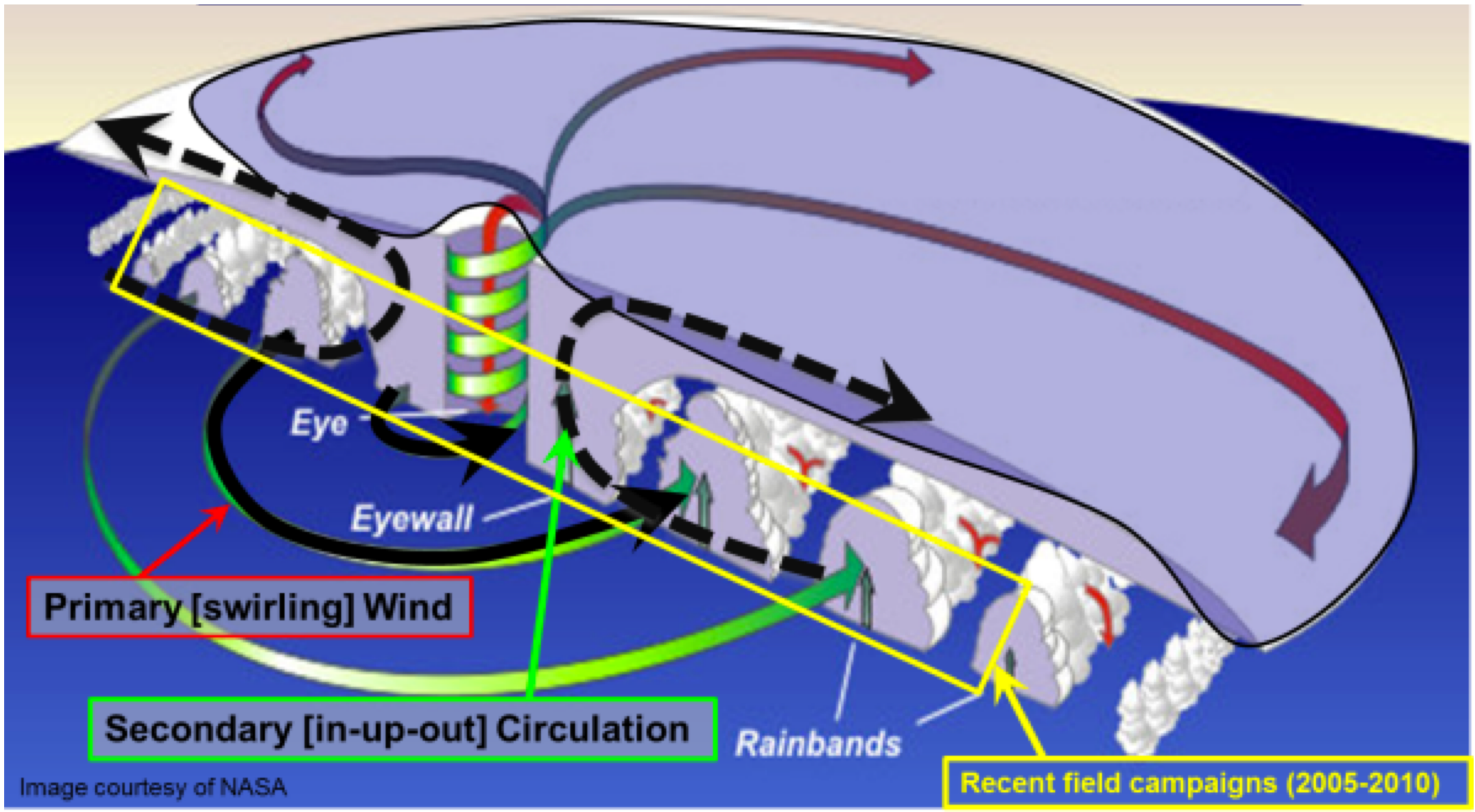
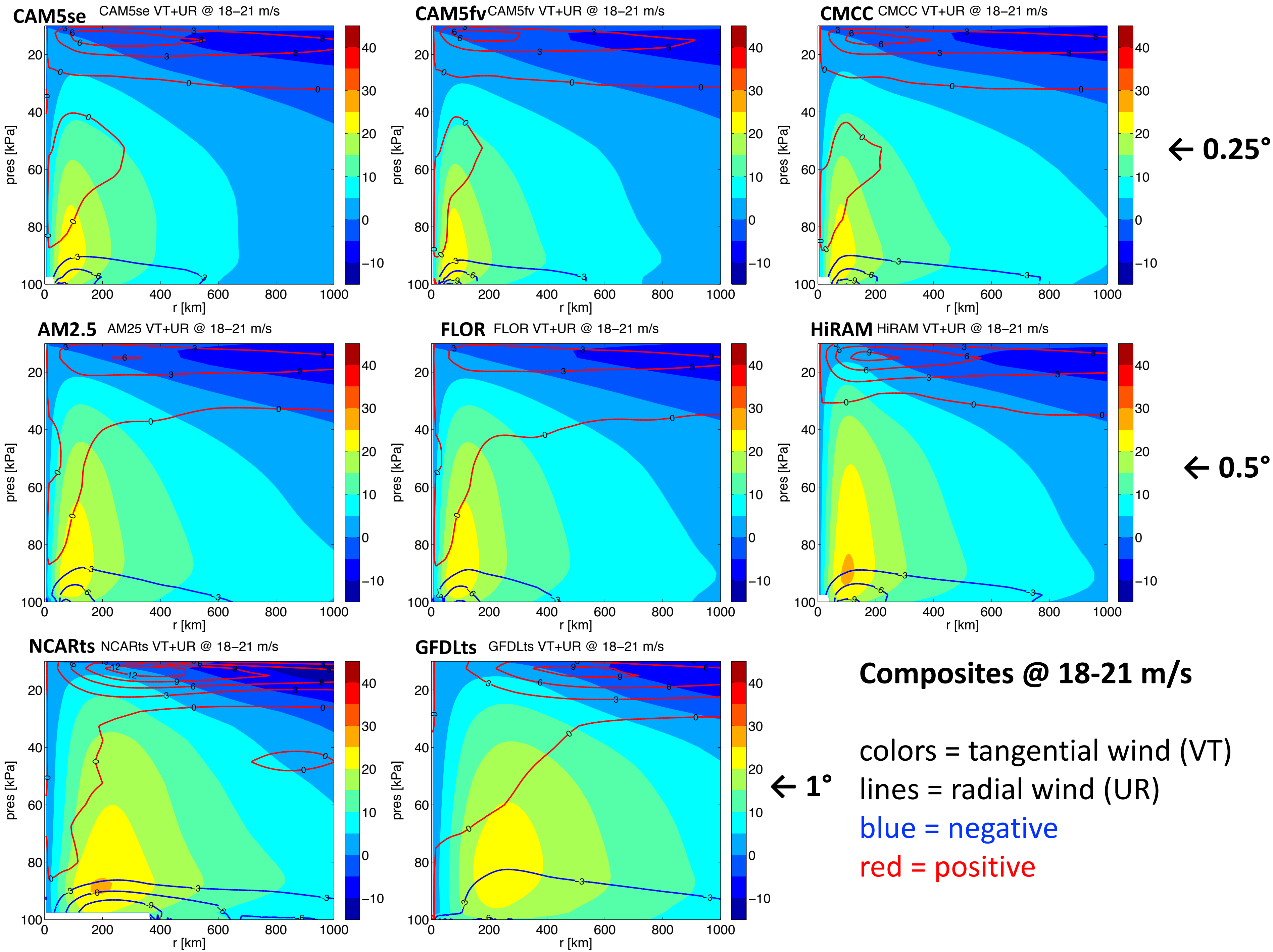


Figure valid for NH only (sorry SH friends..)

- The TC wind field is made of
  1. **Primary**, cyclonic tangential wind that circles around the storm center
  2. **Secondary**, overturning circulation that is made of low-level radial inflow and upper-level radial outflow, with rising motions in the eyewall (e.g., in-up-out circulation)



Composites @ 18-21 m/s

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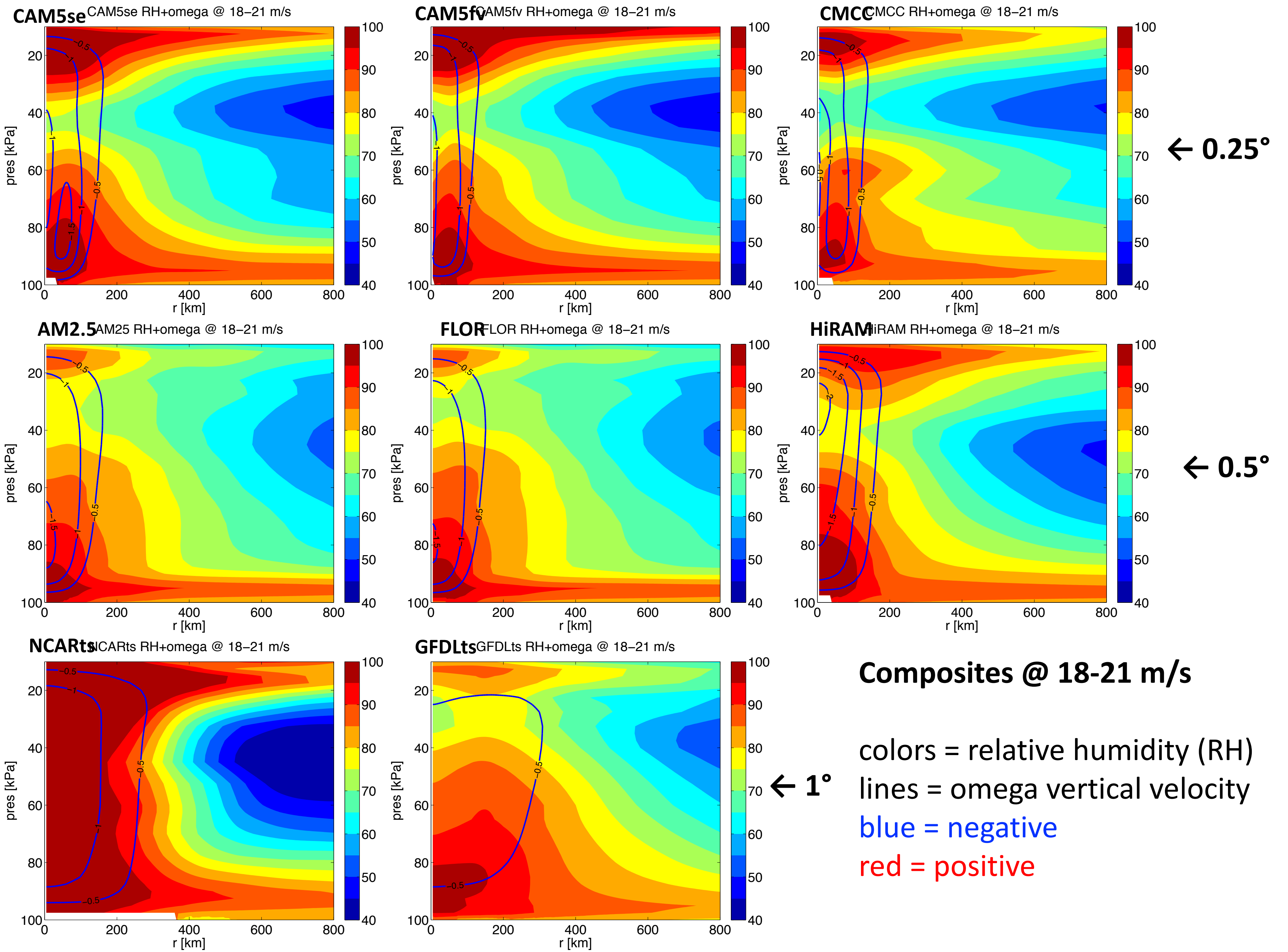

CAM5se CAM5se RH+omega @ 18–21 m/s
CAM5fv CAM5fv RH+omega @ 18–21 m/s
CMCC CMCC RH+omega @ 18–21 m/s
← 0.25°
AM2.5 AM25 RH+omega @ 18–21 m/s
FLOR FLOR RH+omega @ 18–21 m/s
HiRAM HiRAM RH+omega @ 18–21 m/s
← 0.5°
NCARts NCARts RH+omega @ 18–21 m/s
GFDLts GFDLts RH+omega @ 18–21 m/s
← 1°
pres [kPa]
r [km]
Composites @ 18-21 m/s
colors = relative humidity (RH)
lines = omega vertical velocity
blue = negative
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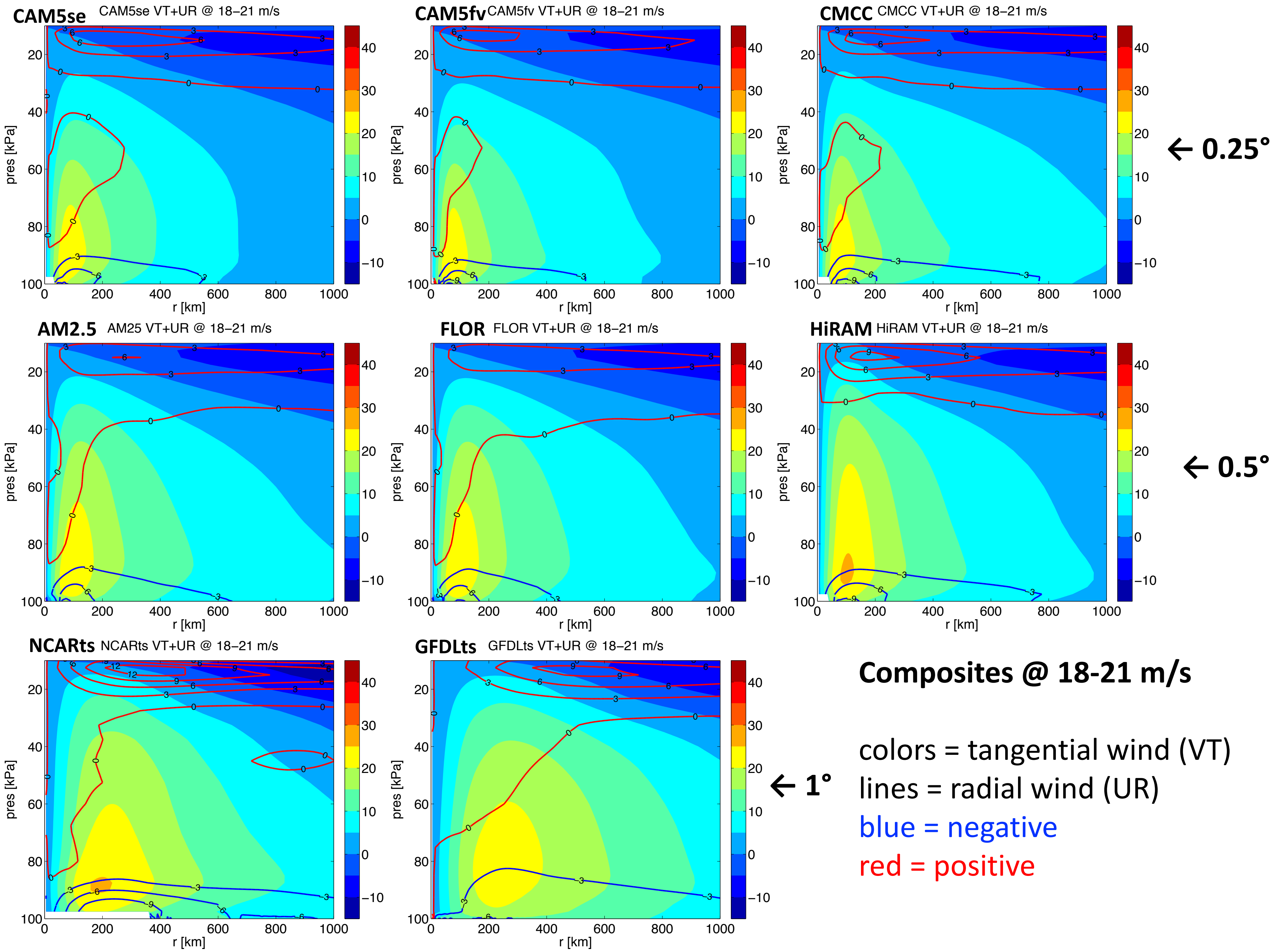
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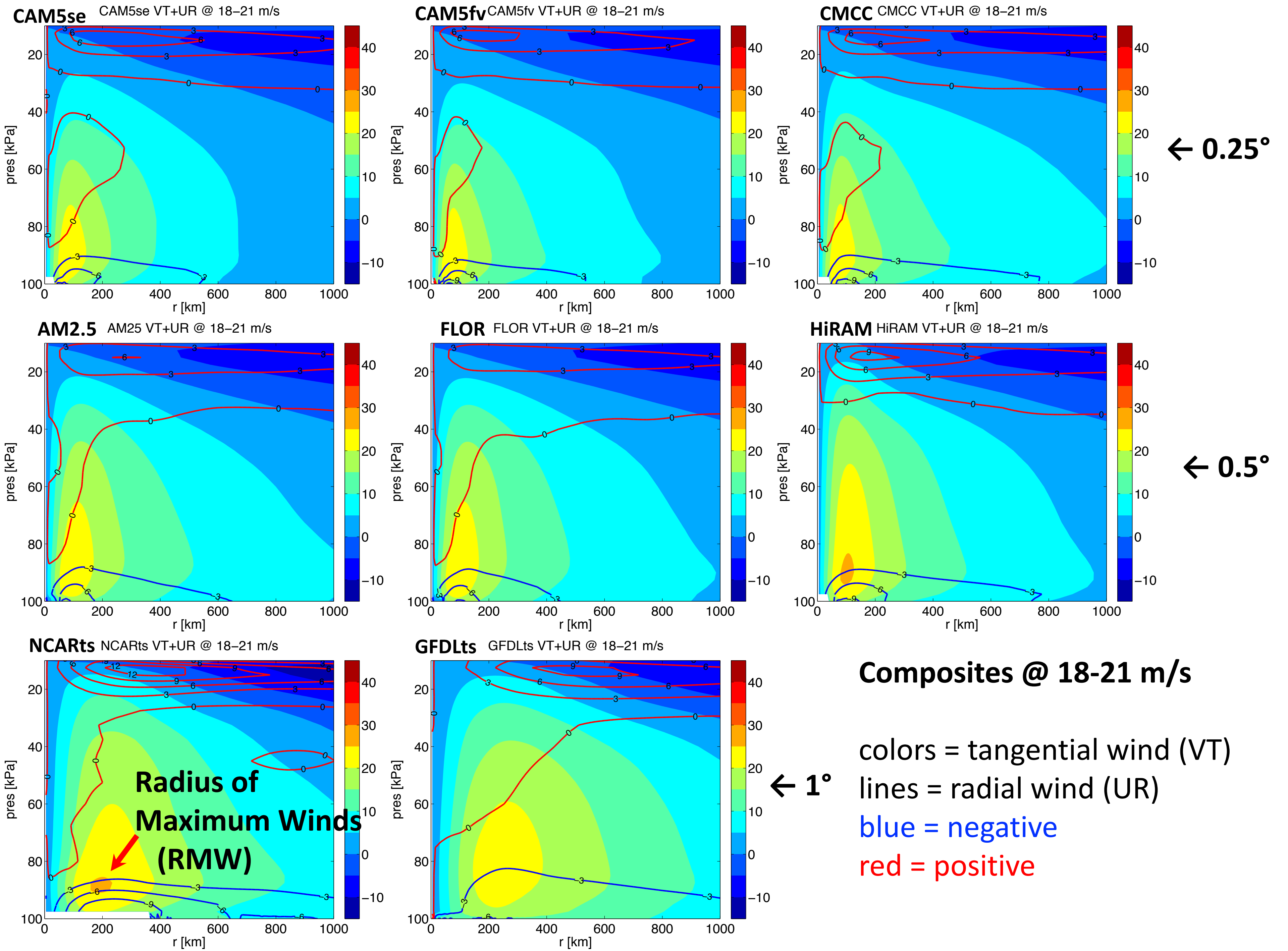

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HiRAM VT+UR @ 18–21 m/s
← 0.5°
NCARts
NCARts VT+UR @ 18–21 m/s
Radius of Maximum Winds (RMW)
GFDLts
GFDLts VT+UR @ 18–21 m/s
← 1°
pres [kPa]
r [km]
Composites @ 18-21 m/s
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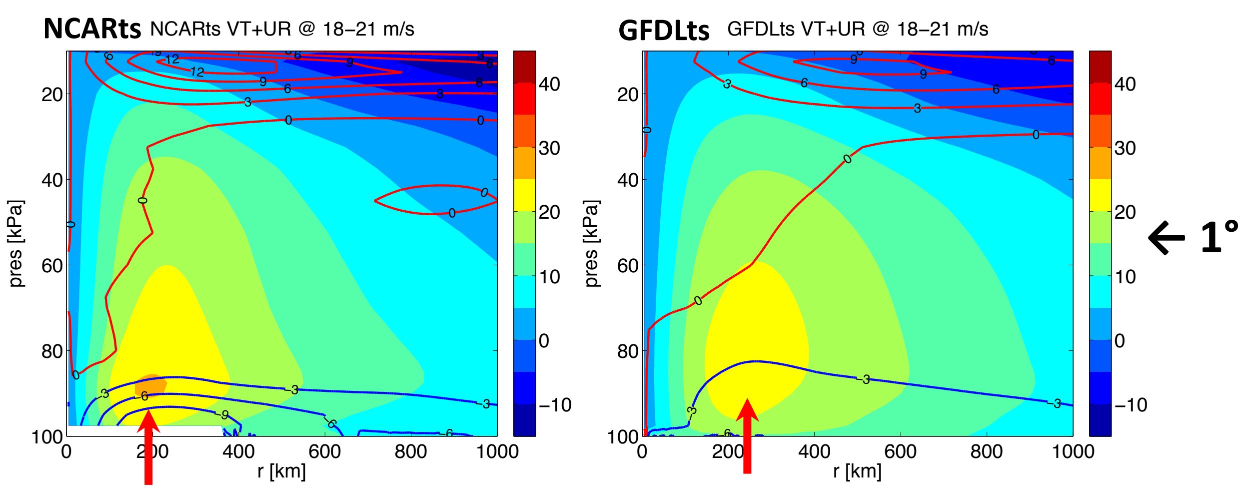

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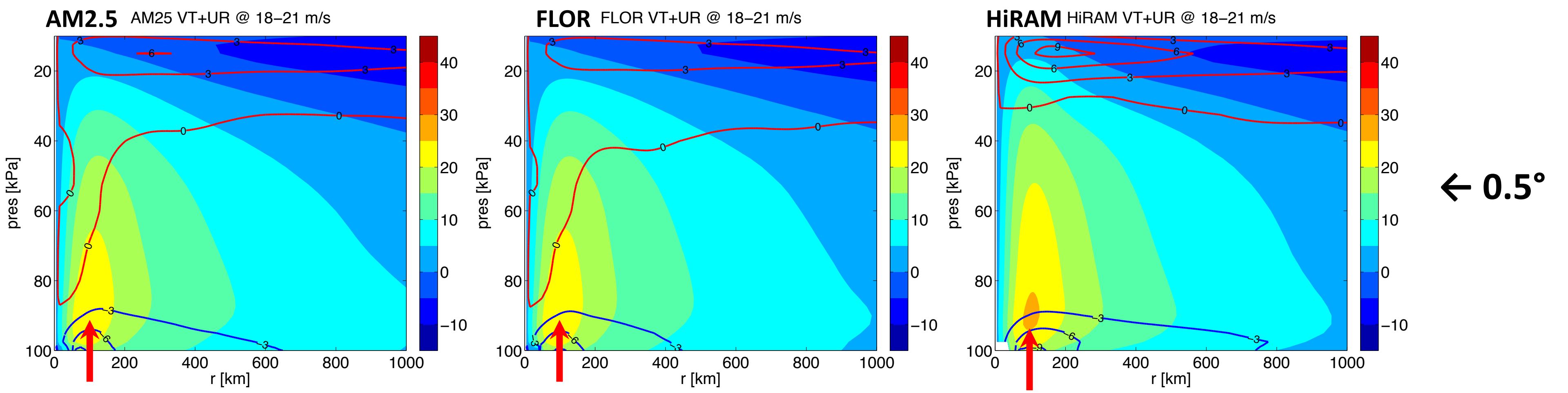

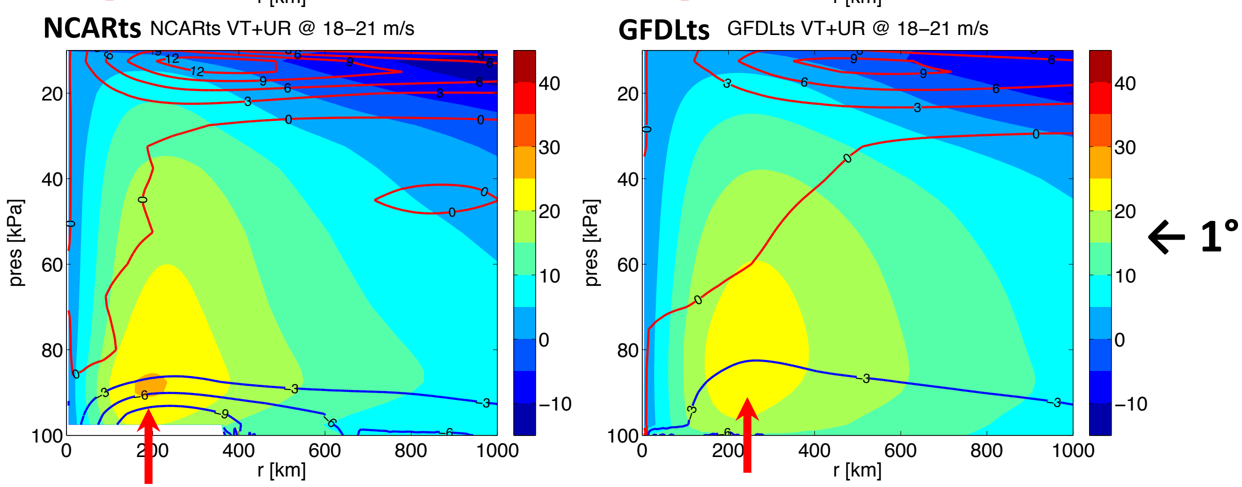

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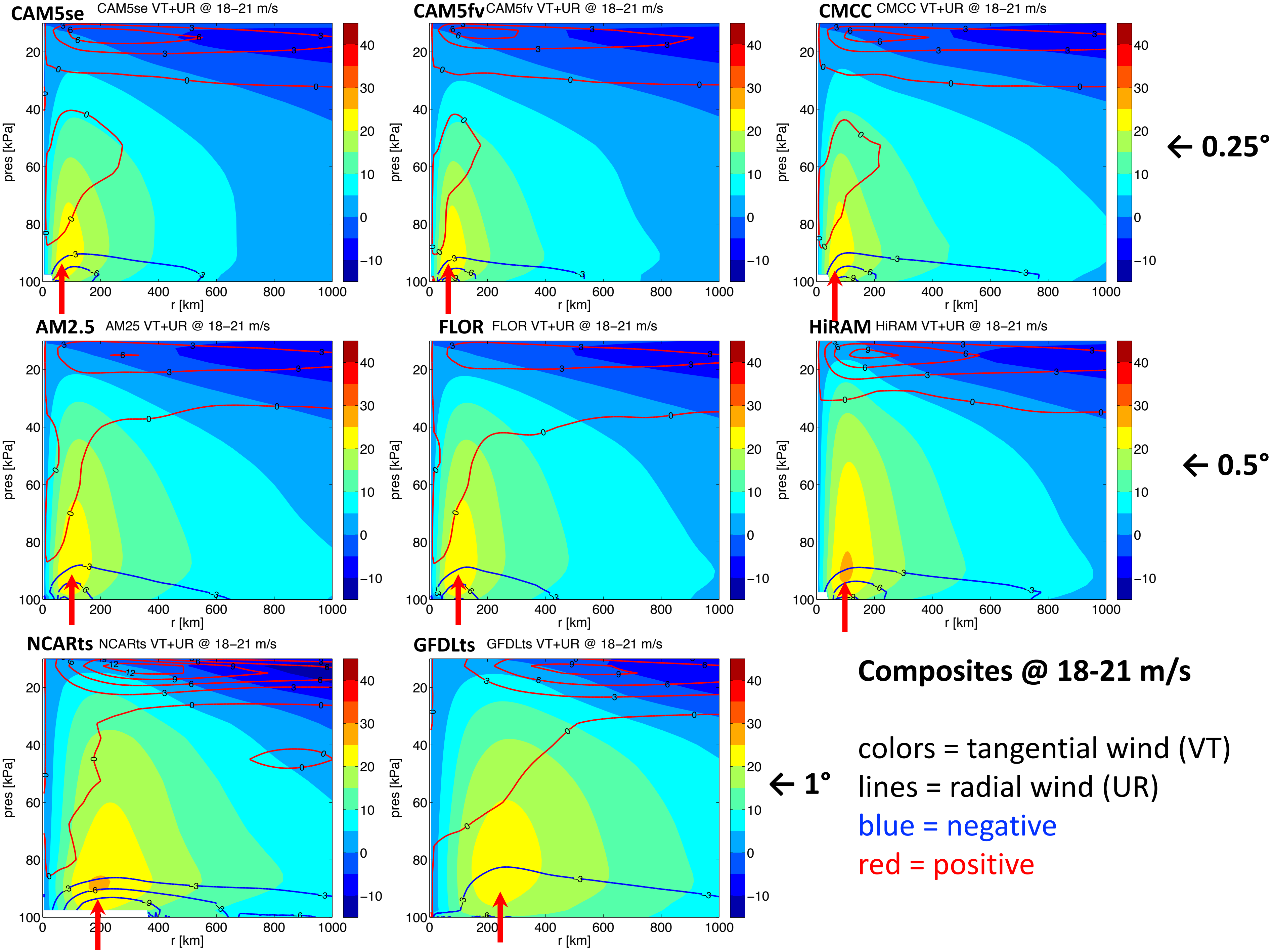

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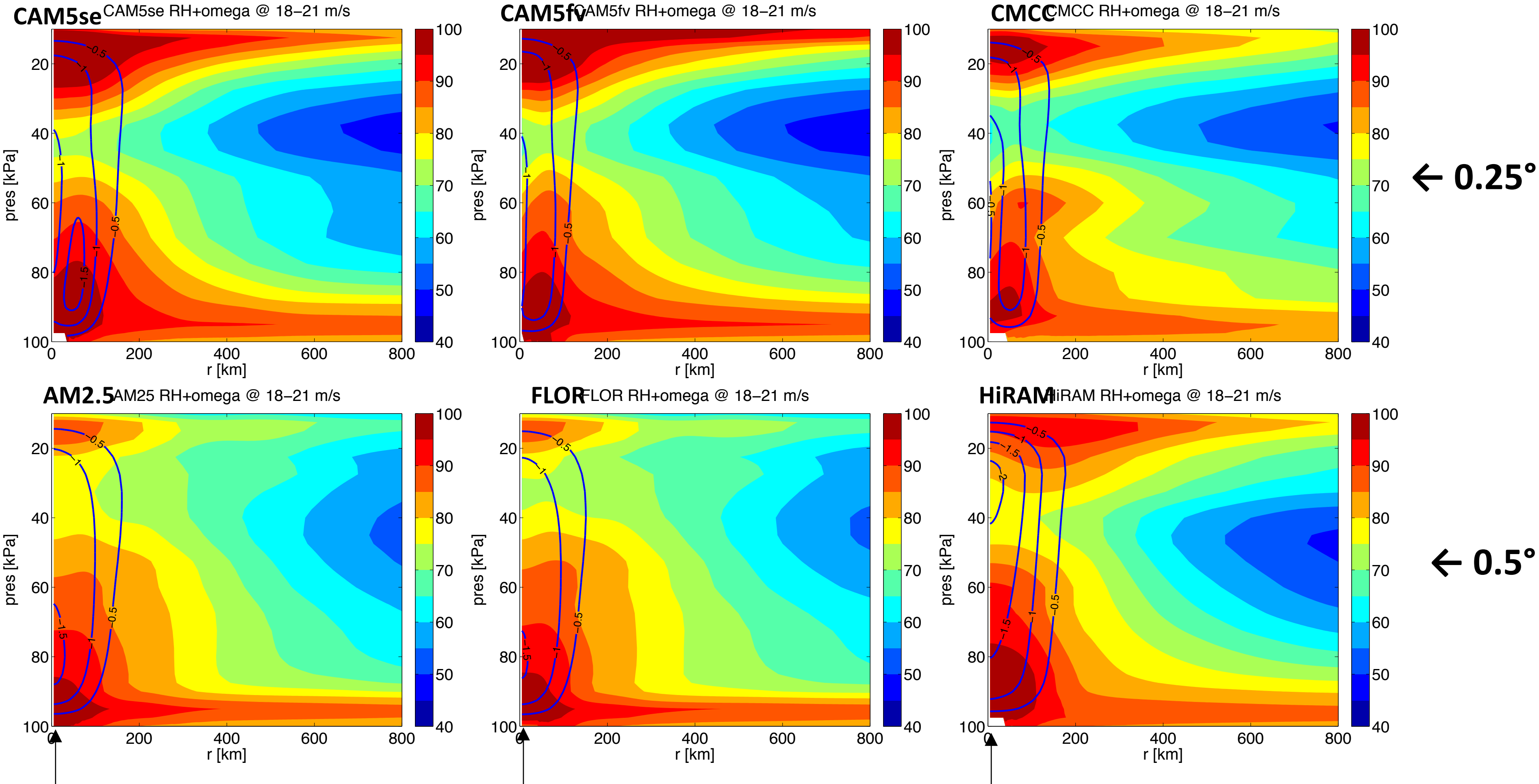
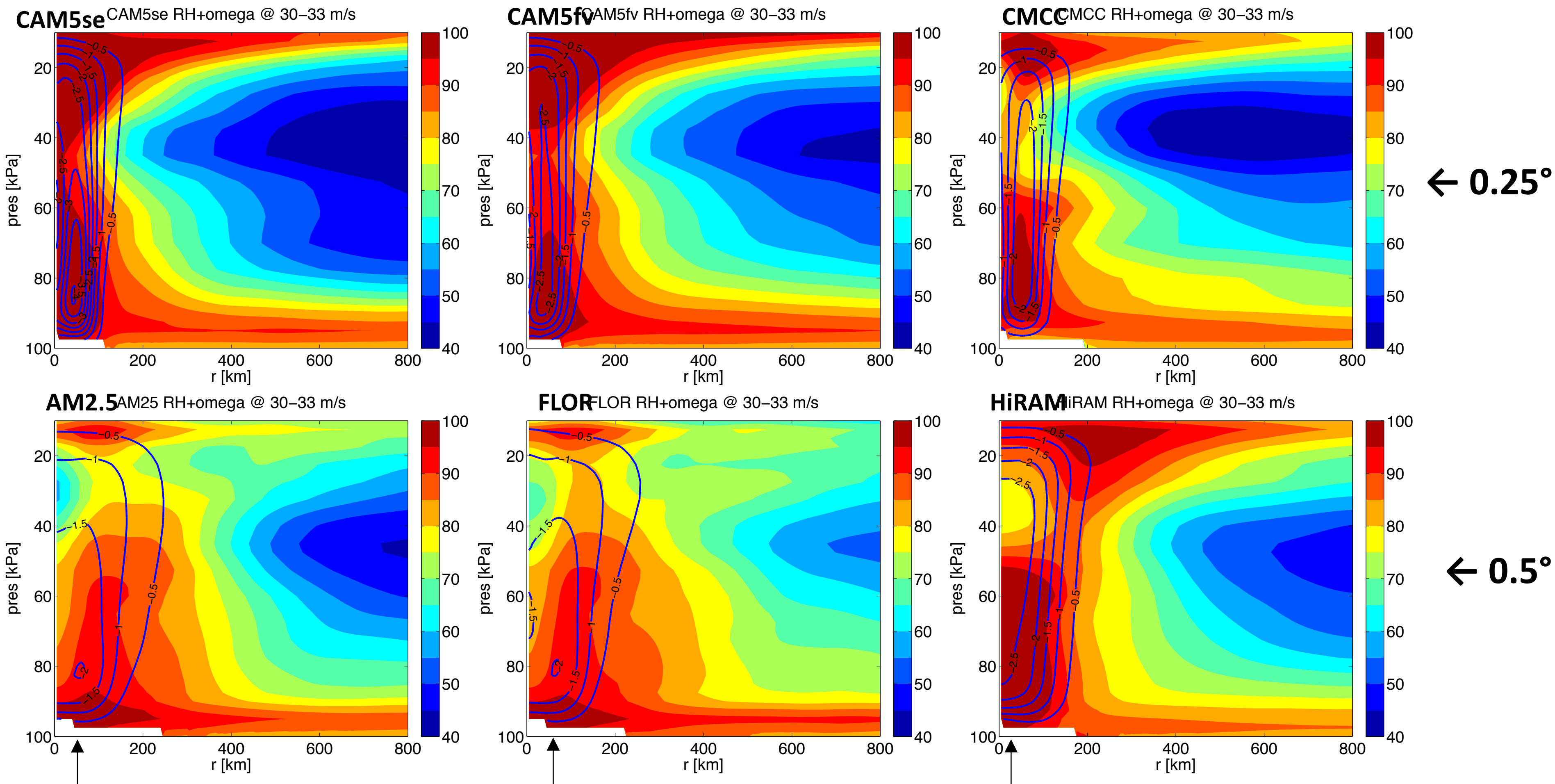


Composites @ 18-21 m/s

- 0.5° TCs **@ 18-21 m/s** have vertical velocity peaks at the storm center

colors = relative humidity (RH)
lines = omega vertical velocity
blue = negative
red = positive



Composites @ 30-33 m/s

colors = relative humidity (RH)
lines = omega vertical velocity
blue = negative
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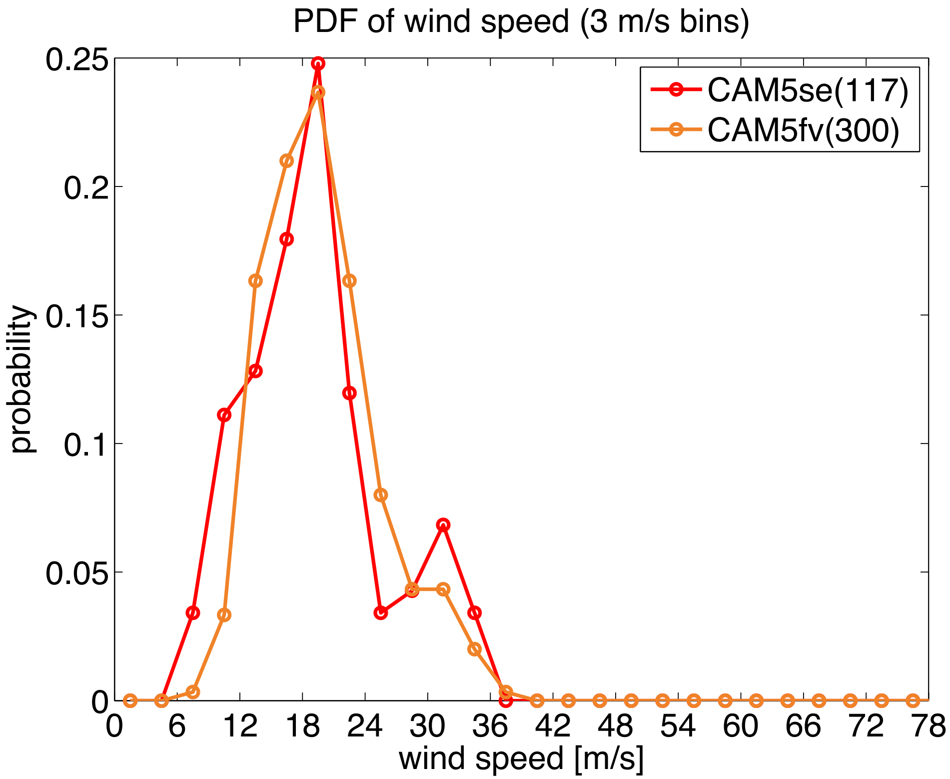
- 0.5° TCs **@ 30-33 m/s** have vertical velocity peaks at the storm center
- But, still there are rising motion at the center

	Δx	levels	Years	Coupled?
0.25° { **NCAR CAM5se**	28 km	30	1992-1999	No
NCAR CAM5fv	30 km	30	1996-1997	No



PDF of wind speed

1996-1997
North Atlantic hurricanes

- **CAM5se** and **CAM5fv** have similar parameterization physics but different dynamical cores (e.g., spectral element vs. finite volume)
- CAM5se TCs reach higher intensity more frequently than CAM5fv TCs (e.g., Reed et al. 2015 GRL) – **how?**

NCAR CAM5se
NCAR CAM5fv

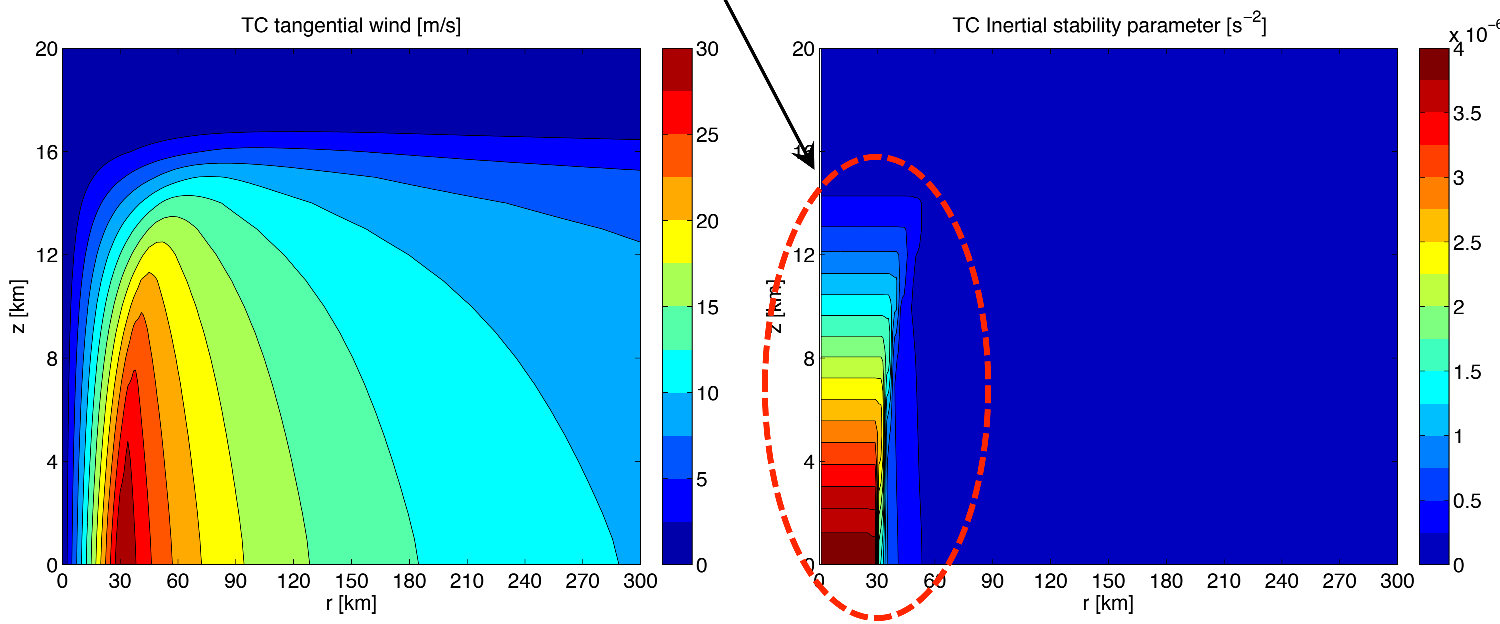
- Previous studies found that a greater amount of **diabatic heating (i.e., rainfall) in the TC inner-core region** would provide favorable conditions for TC intensification (e.g., Schubert Hack 1982; Shapiro and Willoughby 1982; Hack and Schubert 1986; Nolan et al. 2007).

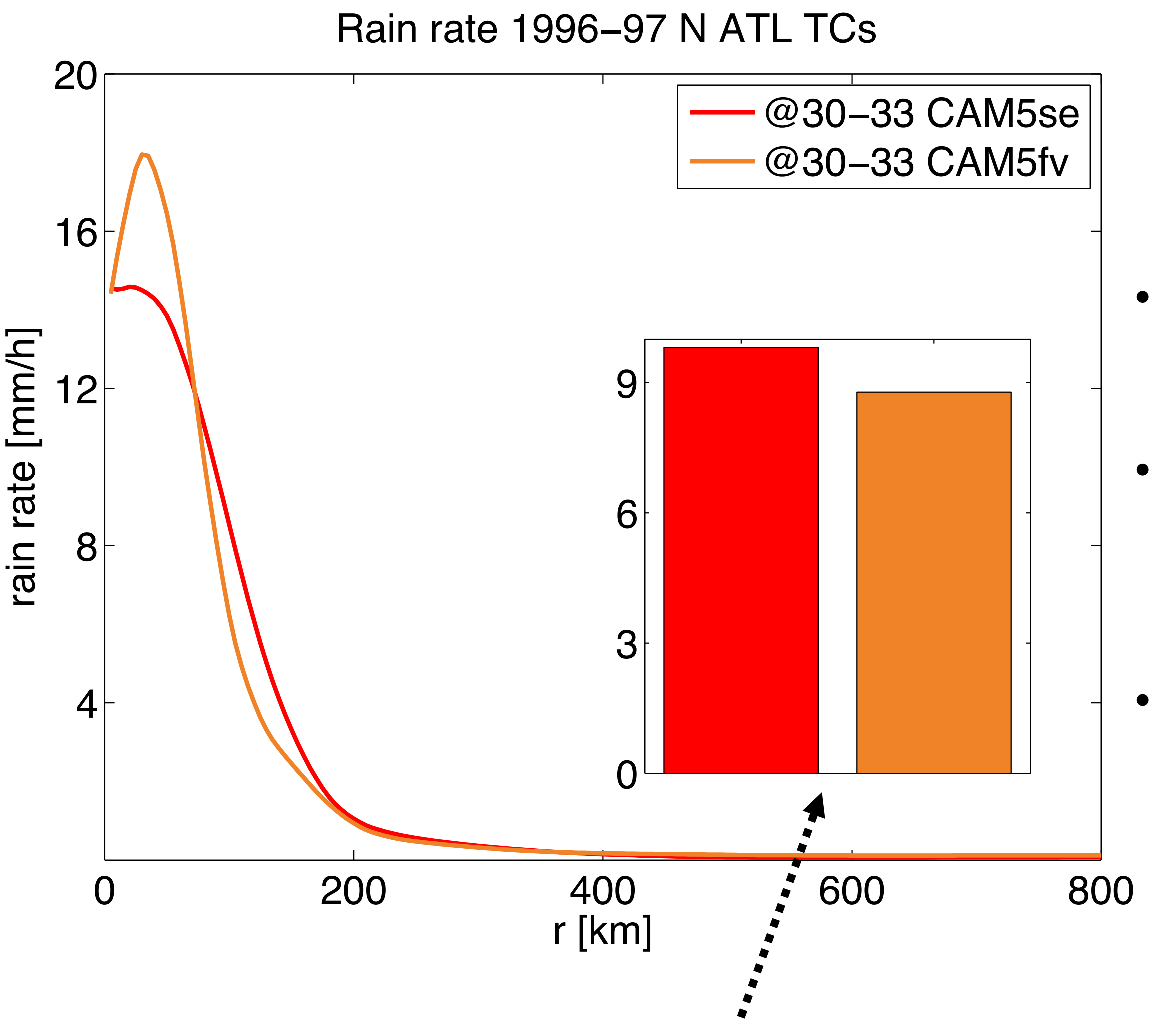
- The efficiency of converting the injected heat energy to the kinetic energy of the TC swirling circulation is proportional to inertial stability parameter (C)

- Inertial stability is higher in the TC inner-core region.

$$C = \left(f + \frac{2v}{r}\right)\left(f + \frac{\partial(rv)}{r\partial r}\right)$$

Typical TC wind field



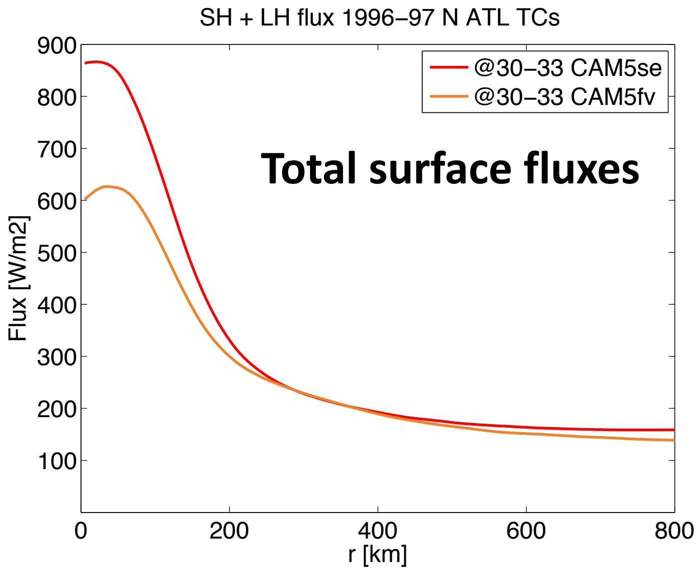


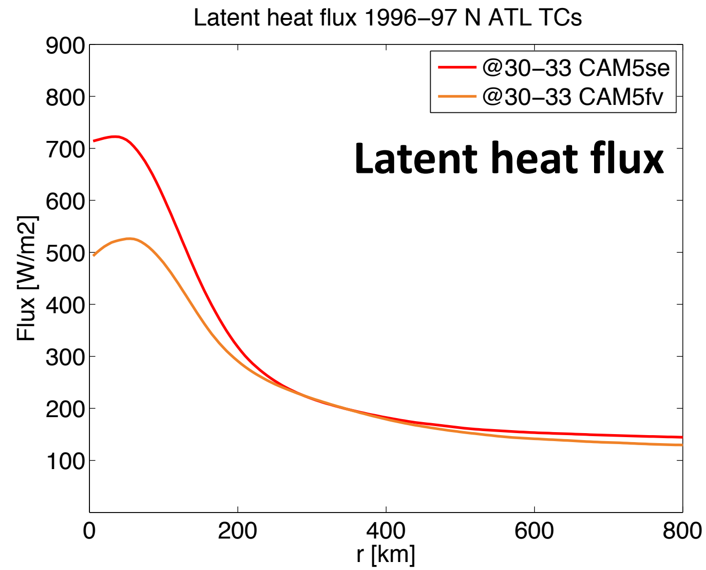
average rainfall rate
inside 2 x 850 hPa RMW
[mm/h]

Rain rate composites
@ 30-33 m/s

- CAM5fv TCs have a higher rain rate peak than CAM5se TCs.
- But CAM5se TCs have the greater inner-core (i.e., 2 x 850 hPa RMW) rainfall than CAM5fv TCs.
- More rainfall (i.e., diabatic heating) in the inner-core regions of CAM5se TCs leads to greater intensification → **How?**

NCAR CAM5se
NCAR CAM5fv

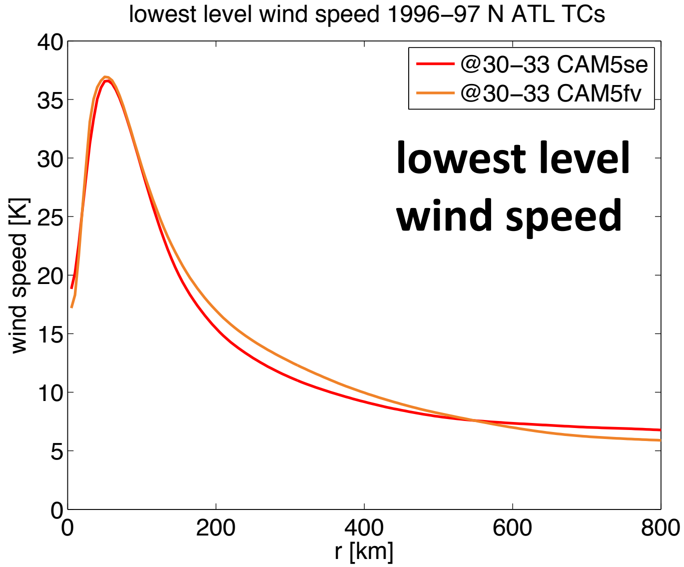


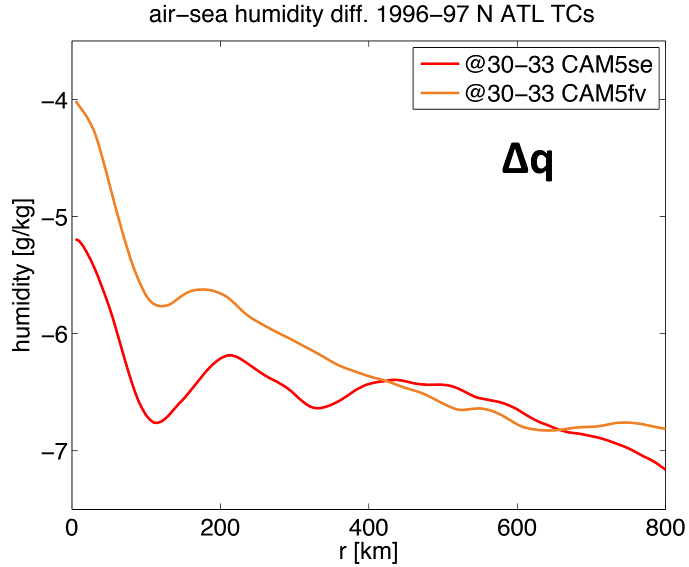


Composites @ 30-33 m/s

- The main differences between CAM5se and CAM5fv TCs are found in the surface fluxes.
- CAM5se TCs have greater surface fluxes than CAM5fv TCs, especially around the TC center.
- Most of the surface flux differences are explained by the latent heat fluxes.

➔ This is likely due to greater air-sea disequilibrium.





NCAR CAM5se
NCAR CAM5fv

GFDL AM2.5	62 km	32	1984-1985	No
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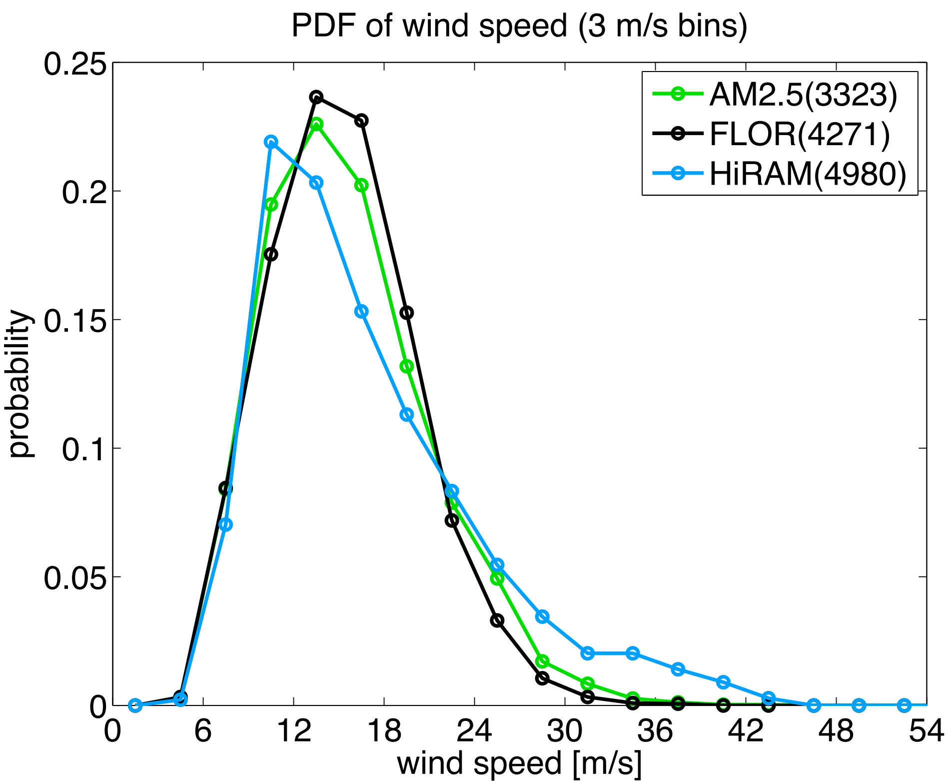
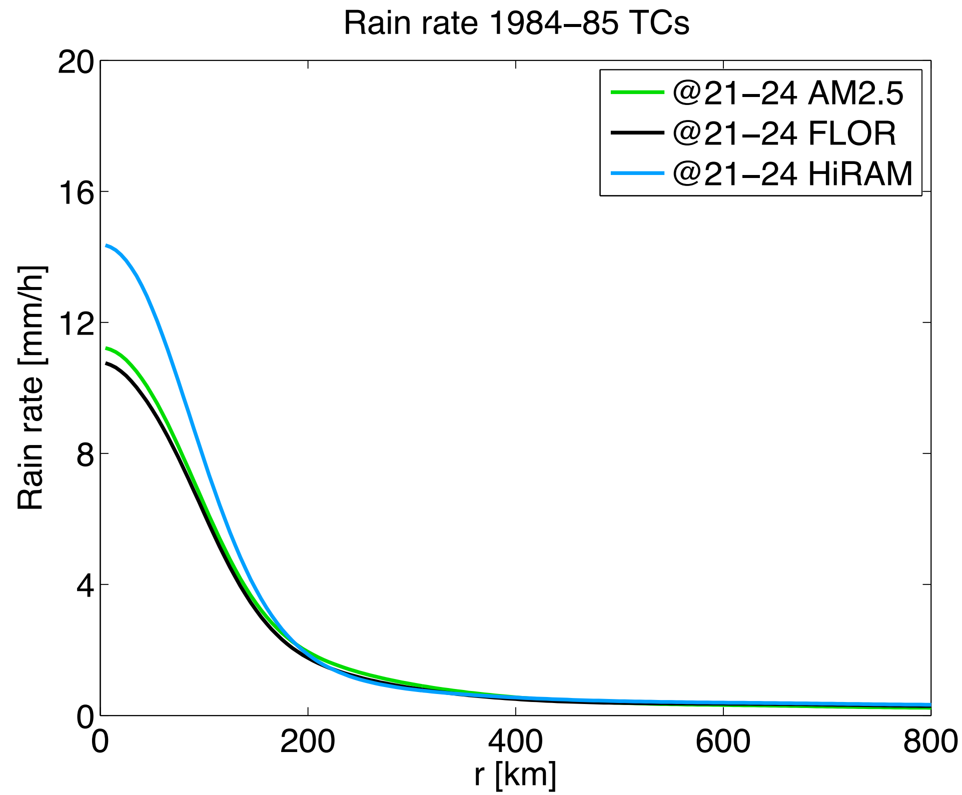


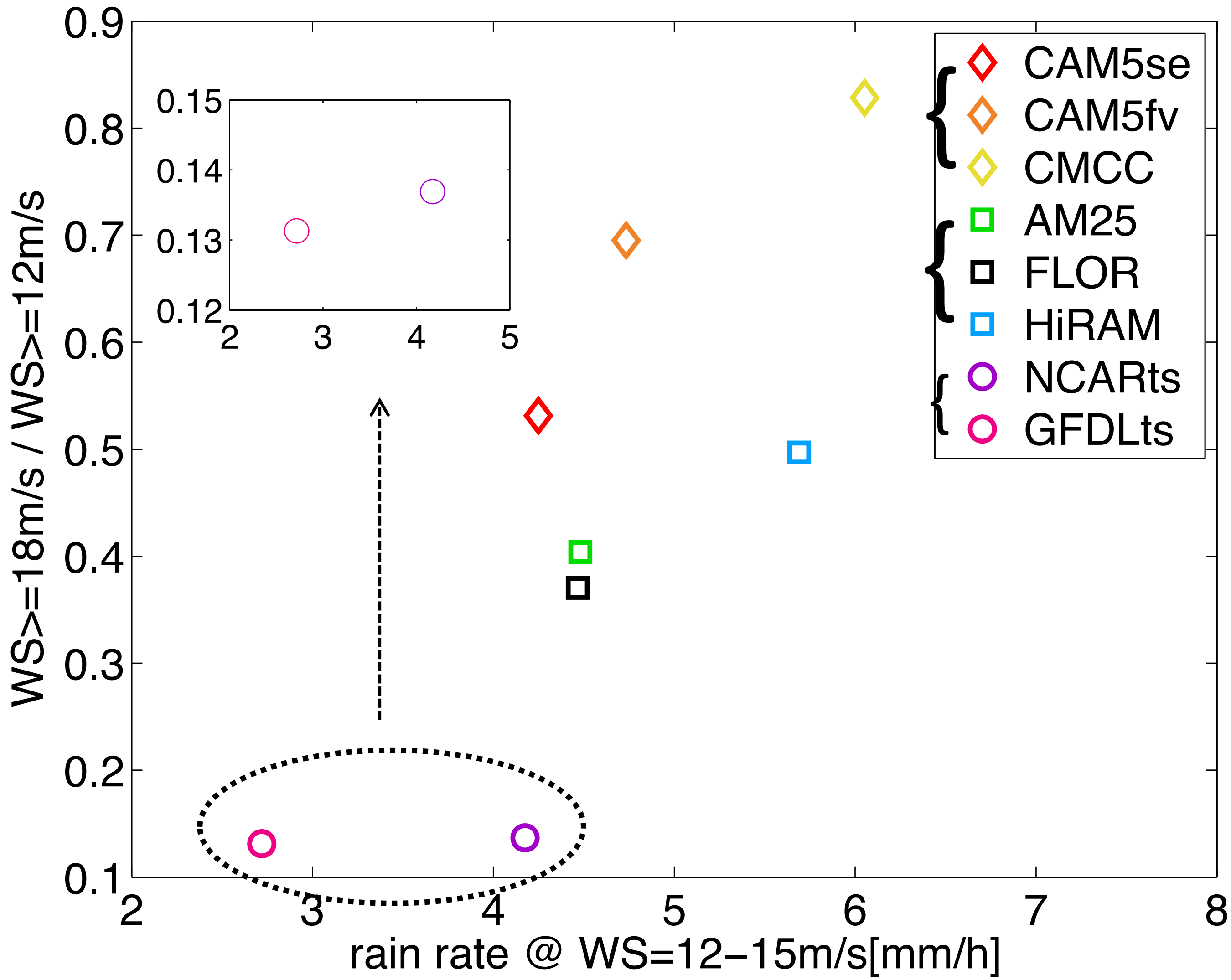


- HiRAM TCs were stronger than AM2.5 and FLOR TCs because they produced a greater amount of rainfall in the inner-core regions of TCs (see Kim et al. 2018, Journal of Climate)

- The main difference between them is the parameterization physics.

Inner-core rain rate vs. likelihood of intensification

The Y-axis: the proportions of TCs at 12 m/s intensifying to 18 m/s



The X-axis: the average rain rate in the inner-core region for TCs at 12-15 m/s

Inner-core rain rate vs. likelihood of intensification

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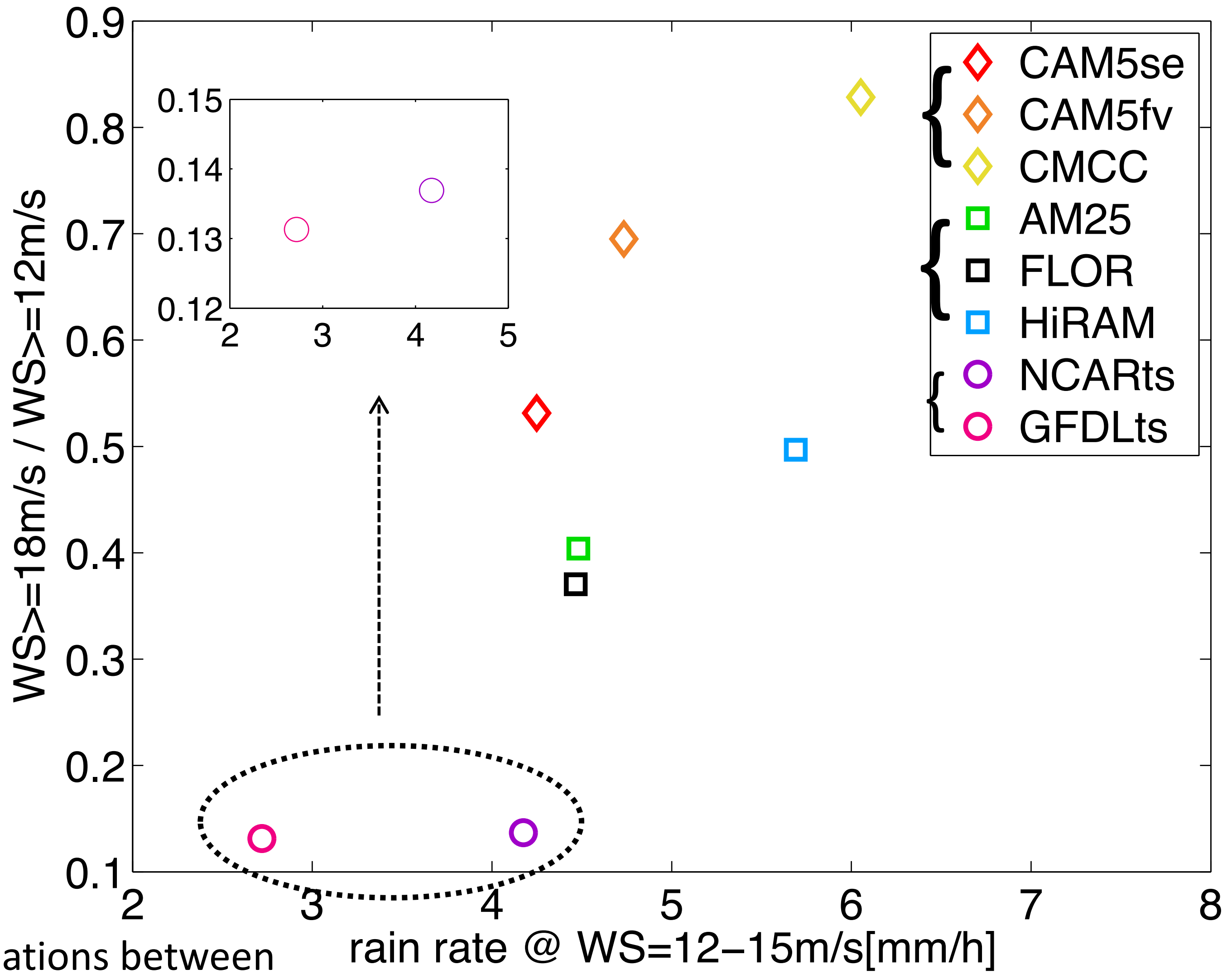


The X-axis: the average rain rate in the inner-core region for TCs at 12-15 m/s

- There are positive correlations between the inner-core rain rates and intensification probability at similar horizontal resolution.
- TCs at given intensity with greater amount of rainfall in the inner-core region are more likely to intensify to stronger TCs.

Summary

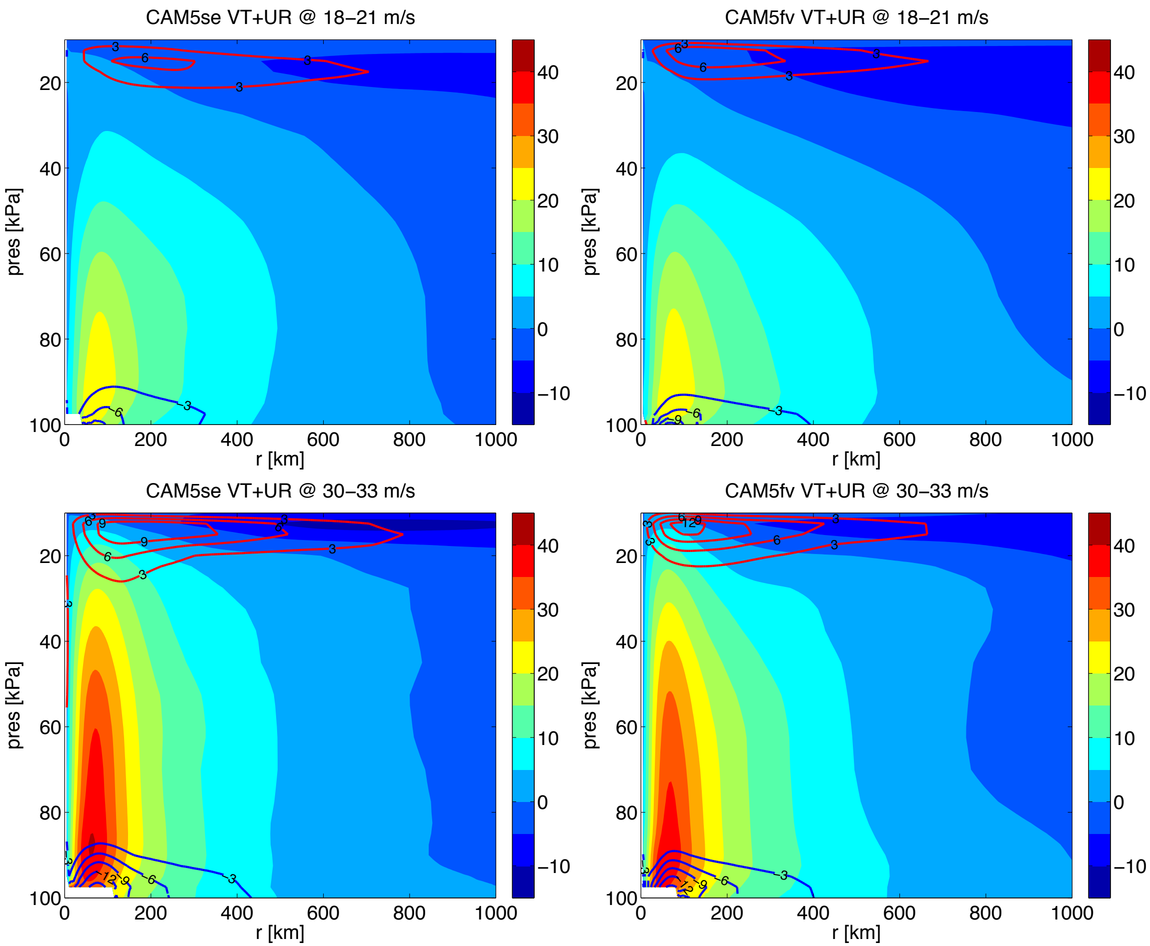
- Simulated TCs in the GCM simulations have the typical cyclonic tangential winds with overturning secondary circulations made of low-level radial inflow and upper-level radial outflow with rising motions between them.

- As Δx decreases, the RMW moves radially inward.
  - The RMWs are typically 2-4 times Δx.

- Rising motions occur off the TC center as Δx decreases and as TC intensity increases.
  - But, there are still upward motions on average at the TC center.

- At comparable resolution, TCs are stronger in some GCM simulations than others, because the simulations produce a greater amount of rainfall (i.e., diabatic heating) in the inner-core regions of TCs.

- Why some model TCs produce more rainfall in the inner-core region is currently being studied.



Composites @ 18-21 m/s

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blue = negative
red = positive

Composites @ 30-33 m/s

colors = tangential wind (VT)
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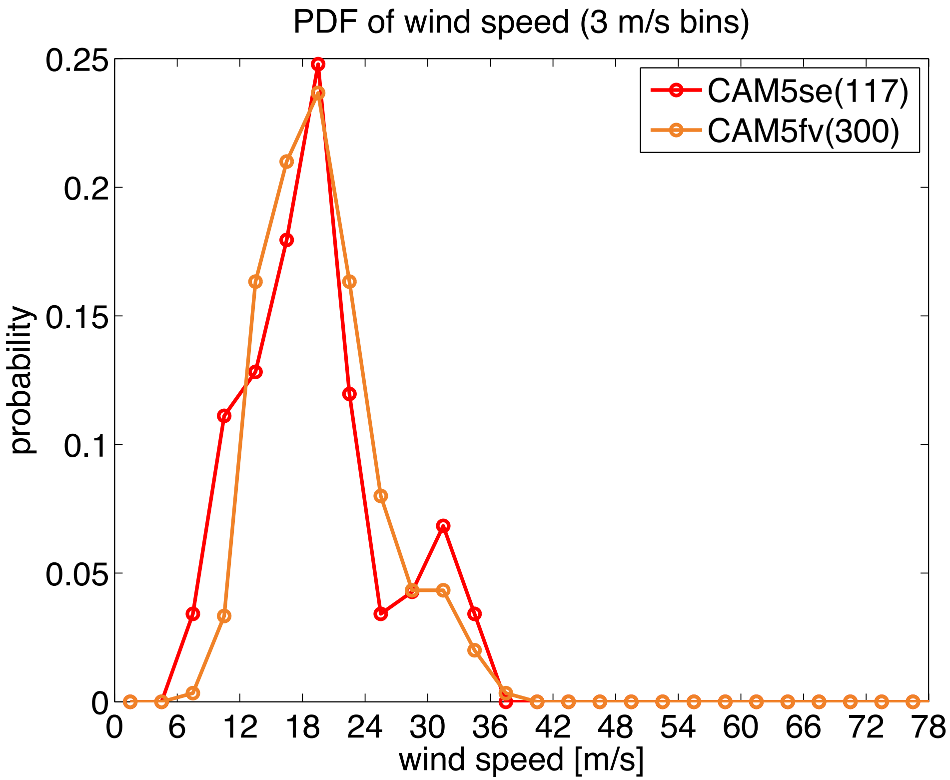
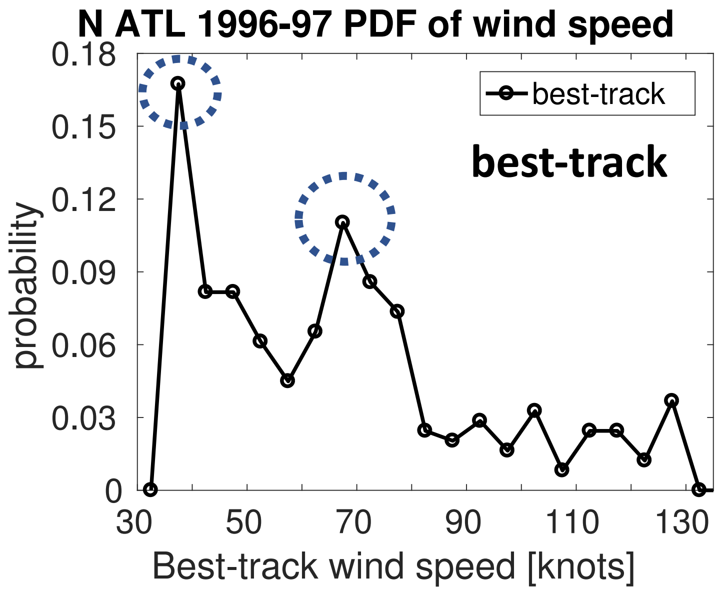
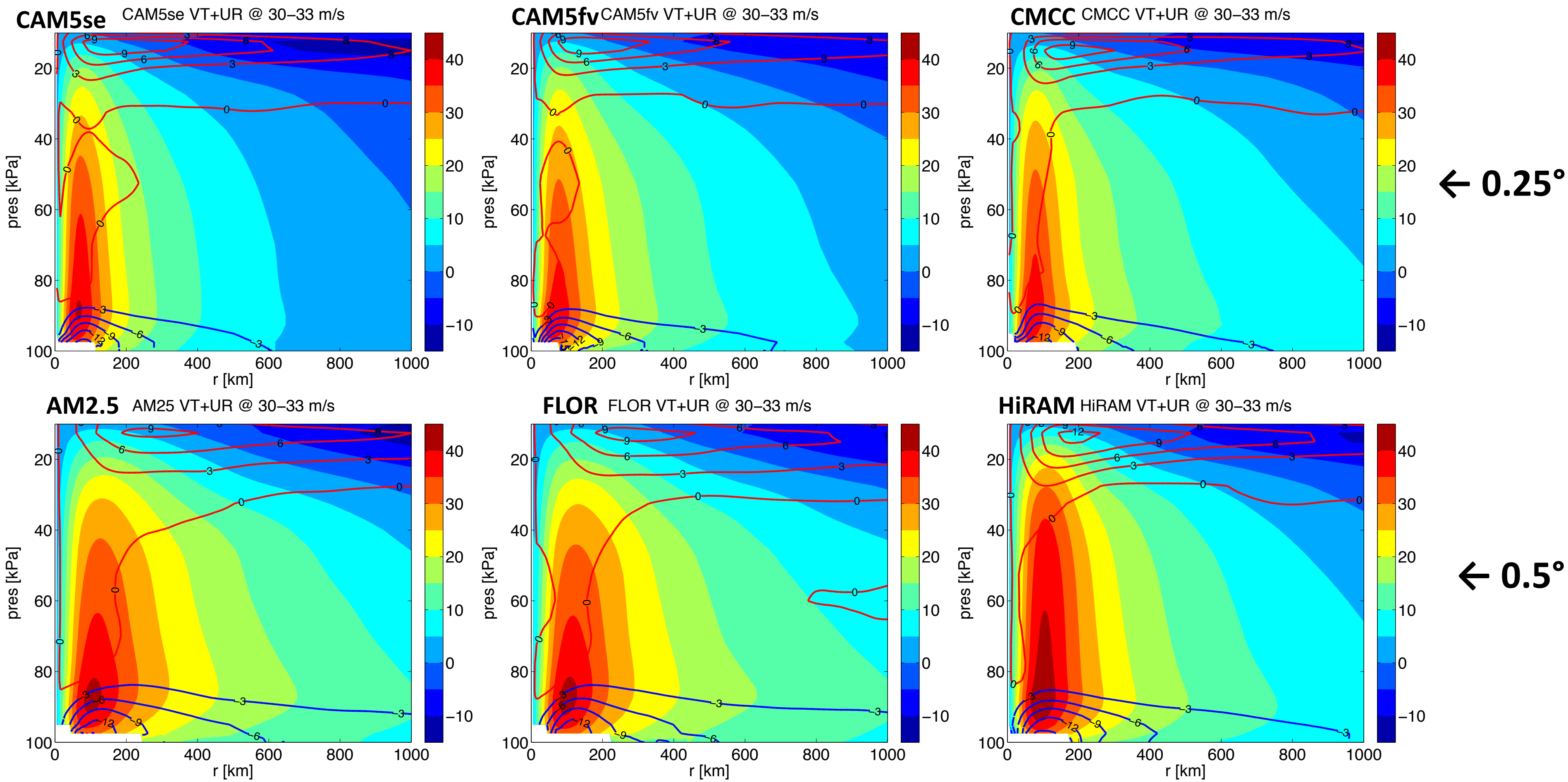
- CAM5se and CAM5fv TC horizontal wind fields look qualitatively similar


PDF of wind speed (3 m/s bins)
CAM5se(117)
CAM5fv(300)
probability
wind speed [m/s]
0.25
0.2
0.15
0.1
0.05
0
0
6
12
18
24
30
36
42
48
54
60
66
72
78


N ATL 1996-97 PDF of wind speed
best-track
best-track
probability
Best-track wind speed [knots]
0.18
0.15
0.12
0.09
0.06
0.03
0
30
50
70
90
110
130



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