A Top-down Pathway to Secondary Eyewall Formation in Simulated Tropical Cyclones

Bryce Tyner
International Hurricane Research Center
Florida International University, Miami, FL

Collaborators:
Ping Zhu (FIU), Jun Zhang (HRD/AOML),
Sundararaman Gopalakrishnan (HRD/AOML), Frank Marks Jr. (HRD/AOML),
Vijay Tallapragada (EMC)

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Outline

- Introduction/Motivation
- Model Setup
- Sensitivity Studies
  - Idealized Case
  - Real-data Case Studies: Rita (2005) and Edouard (2014)
- Discussion/Conclusions

Introduction/Motivation

- Secondary eyewall formation (SEF) and ensuing eyewall replacement cycles (ERCs) have long been documented in intense tropical cyclones (TCs) (e.g., Fortner 1958).

- Because ERCs often lead to rapid changes in TC intensity and structure, timely prediction of incipient SEF is critical to forecasters.

- Despite their commonality in observations, forecasters continue to struggle with predicting SEF events.

- Numerical models struggle with SEF and ensuing ERCs.

Introduction/Motivation

Table 2-1: Names of AHW simulations screened for secondary eyewalls.

Year	Name	Maximum Saffir-Simpson category	Observed SE in nature	Number of simulations screened
2005	Emily	4		2
2005	Katrina	5	√	7
2005	Rita	5	√	7
2005	Wilma	5	√	3
2007	Dean	5	√	3
2007	Felix	5	√	7
2008	Ike	4	√	8
2009	Bill	4	√	12
2009	Fred	3		7
2009	Gustav	4	√	4
2010	Igor	4	√	3
			Total:	60

Table 2-2: AHW simulations with secondary eyewalls analyzed in subsequent chapters.

Storm		AHW version	Microphysical scheme	Initialization [day/month]	[UTC]	Output frequency [min]
Katrina 2005	K60	2.2	WSM5	27/08	00	60
Rita 2005	R60	2.2	WSM5	21/09	00	60
Katrina 2005	K10	2.1.2	WSM3	27/08	00	10
Igor 2010	R10	3.2	Thompson	11/09	00	10

Abarca (2011)

Out of 60 WRF-ARW simulations of intense TCs screened, only four displayed SEF.

Introduction/Motivation

- Why do models struggle with simulating realistic/accurate SEF/ERC?
  - A triggering mechanism for SEF formation needs to be established.

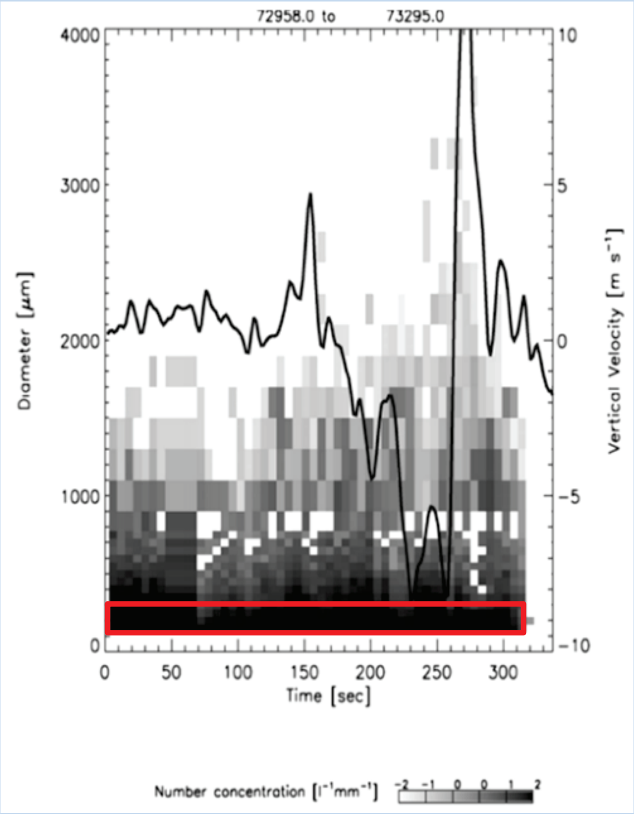
- Several recent studies have suggested the importance of boundary layer processes in triggering a “bottom-up” pathway to SEF
  - Here, we propose an alterative triggering mechanism for SEF, driven from the “top-down”.

Introduction/Motivation

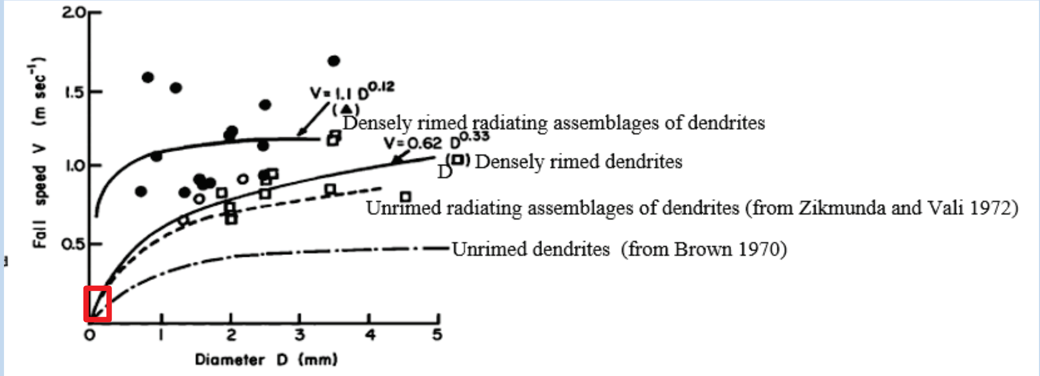
- Zhu and Zhu (2015) showed that altering the snow terminal velocity can affect the occurrence and characteristics of SEF in WRF-ARW.
  - The underlying mechanism that modulates SEF by snow terminal velocity was not fully explored .

- What do the snow terminal velocities in real TCs look like?
  - Few studies have examined this, likely due to observational limitations in TCs.

Introduction/Motivation



McFarquhar and Black (2004)



Locatelli and Hobbs (1974)

- Observed high number concentration of solid-phase condensate with fall speeds less than 0.2 ms^{-1}
- Are these smallest, lightest solid-phase hydrometeors present in simulated TCs?

Model Setup

- Use of HWRF version 3.7a operational settings

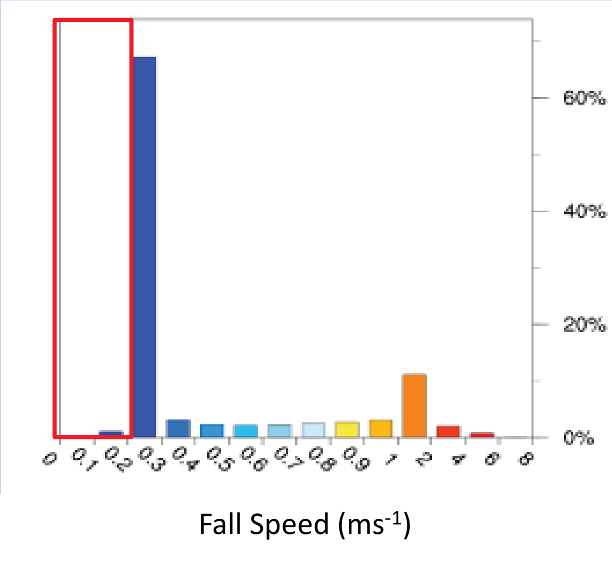
- Three cases examined: one idealized, two real-data cases

- Idealized: Setup followed Zhu and Zhu (2014)
  - Idealized simulation run for nine days

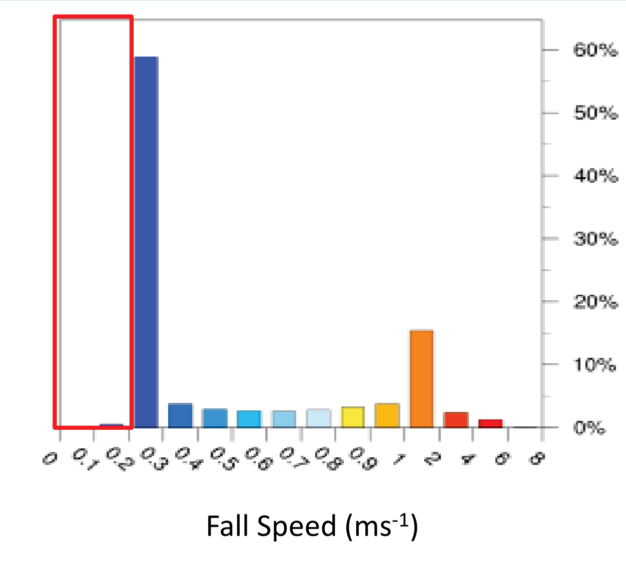
- Real-data cases:
  - 126 hour forecasts (following operational HWRF)
  - Rita (2005): Initialized at 00 UTC 20 September
  - Edouard (2014): Initialized at 00 UTC 14 September

Control Simulations: Solid-phase Fall Speed

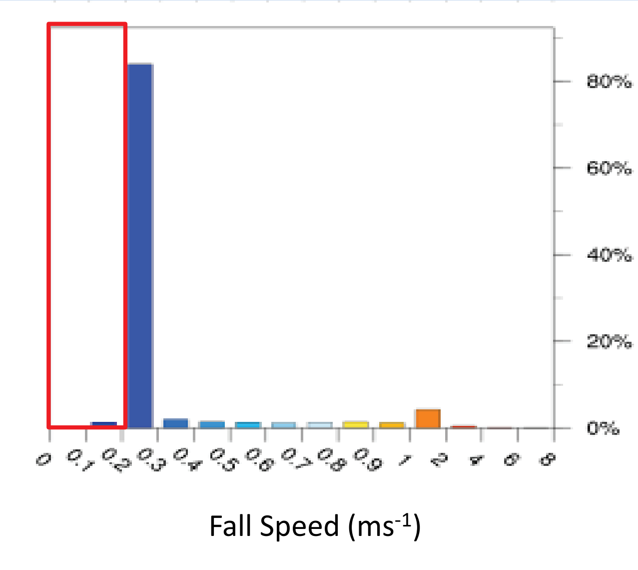
- Lack of solid-phase condensate with fall speeds less than 0.2 ms^{-1}
  - Does this have an impact on the SEF process?



Idealized



Rita (2005)



Edouard (2014)

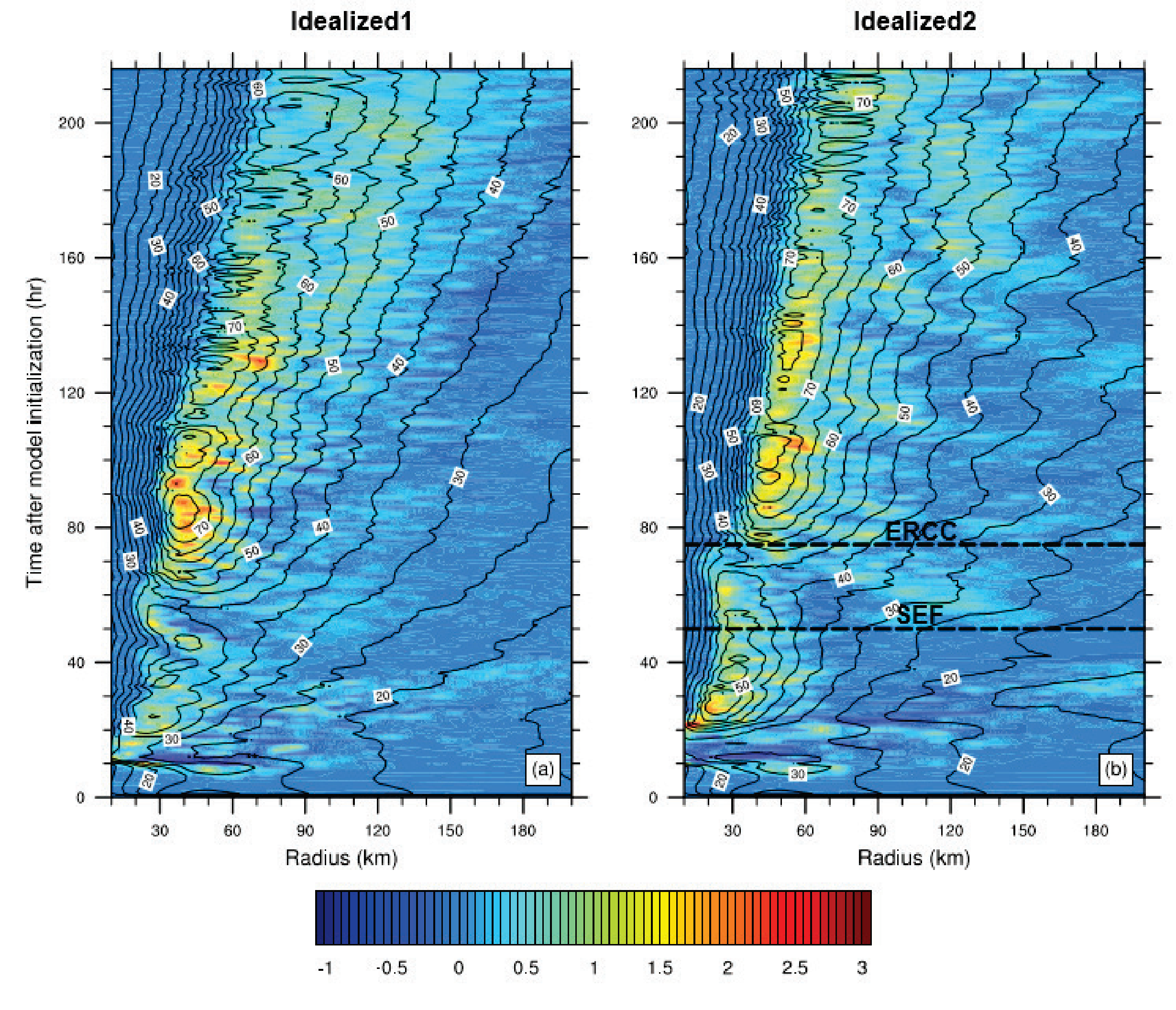
Model Setup

- Conducted additional sensitivity experiments where we reduced the solid-phase condensate fall speed to a factor of ¼ of the operational value
  - Simplest way to get readily-present smallest, lightest solid-phase condensate
  - Not meant to be interpreted as tuning of microphysics

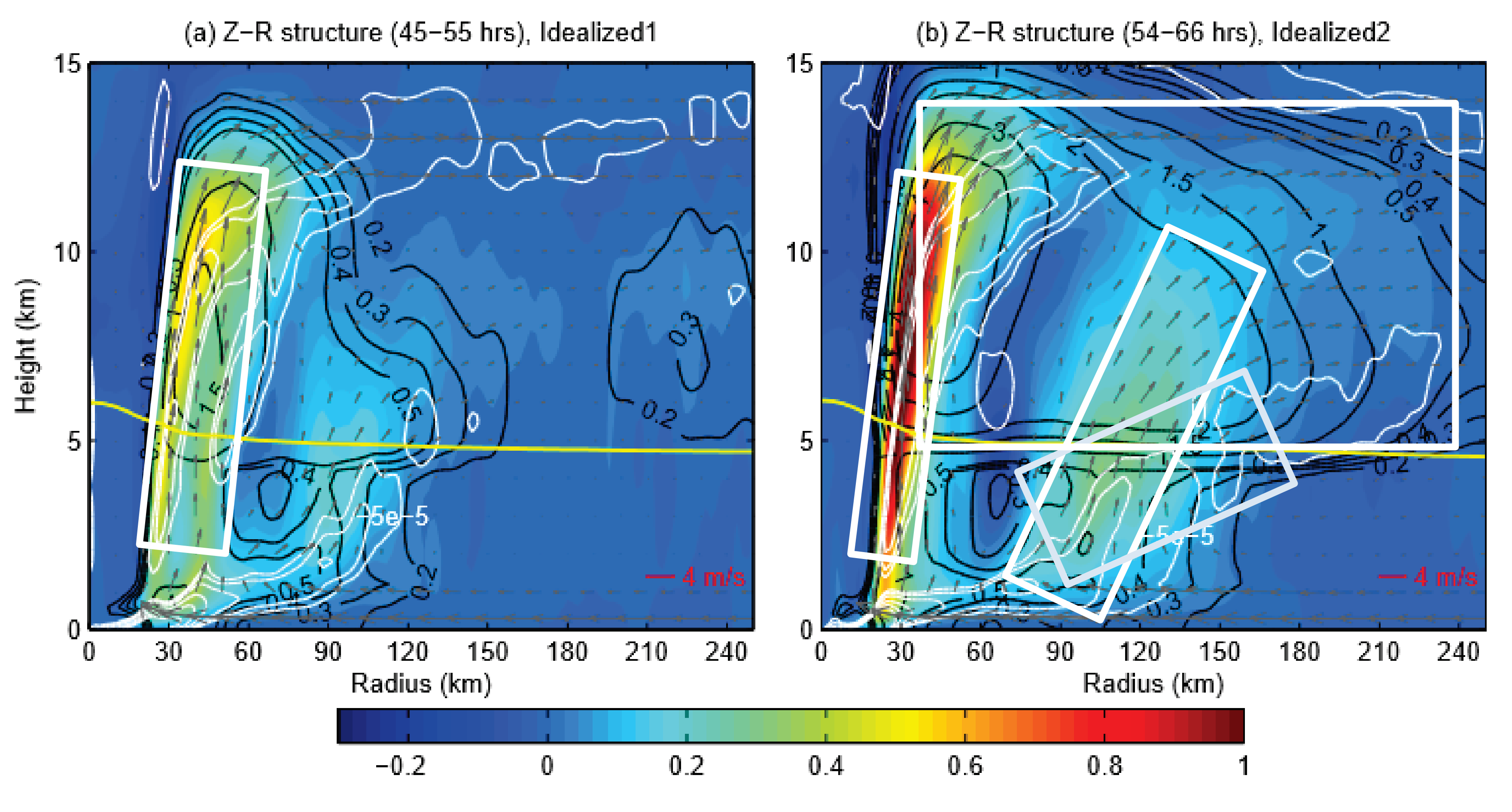
Experiment Name	Initialization Time	Description
Idealized1	00 UTC 01 Jan. 1111	Operational Settings
Idealized2	00 UTC 01 Jan. 1111	$V_s \cdot$ ¼
Rita1	00 UTC 20 September 2005	Operational Settings
Rita2	00 UTC 20 September 2005	$V_s \cdot$ ¼
Edouard1	00 UTC 14 September 2014	Operational Settings
Edouard2	00 UTC 14 September 2014	$V_s \cdot$ ¼

Idealized Case

- Much cleaner SEF and ERC in Idealized2 than Idealized1
- Weak SEF-like event occurring around t=40–60 hr for Idealized1



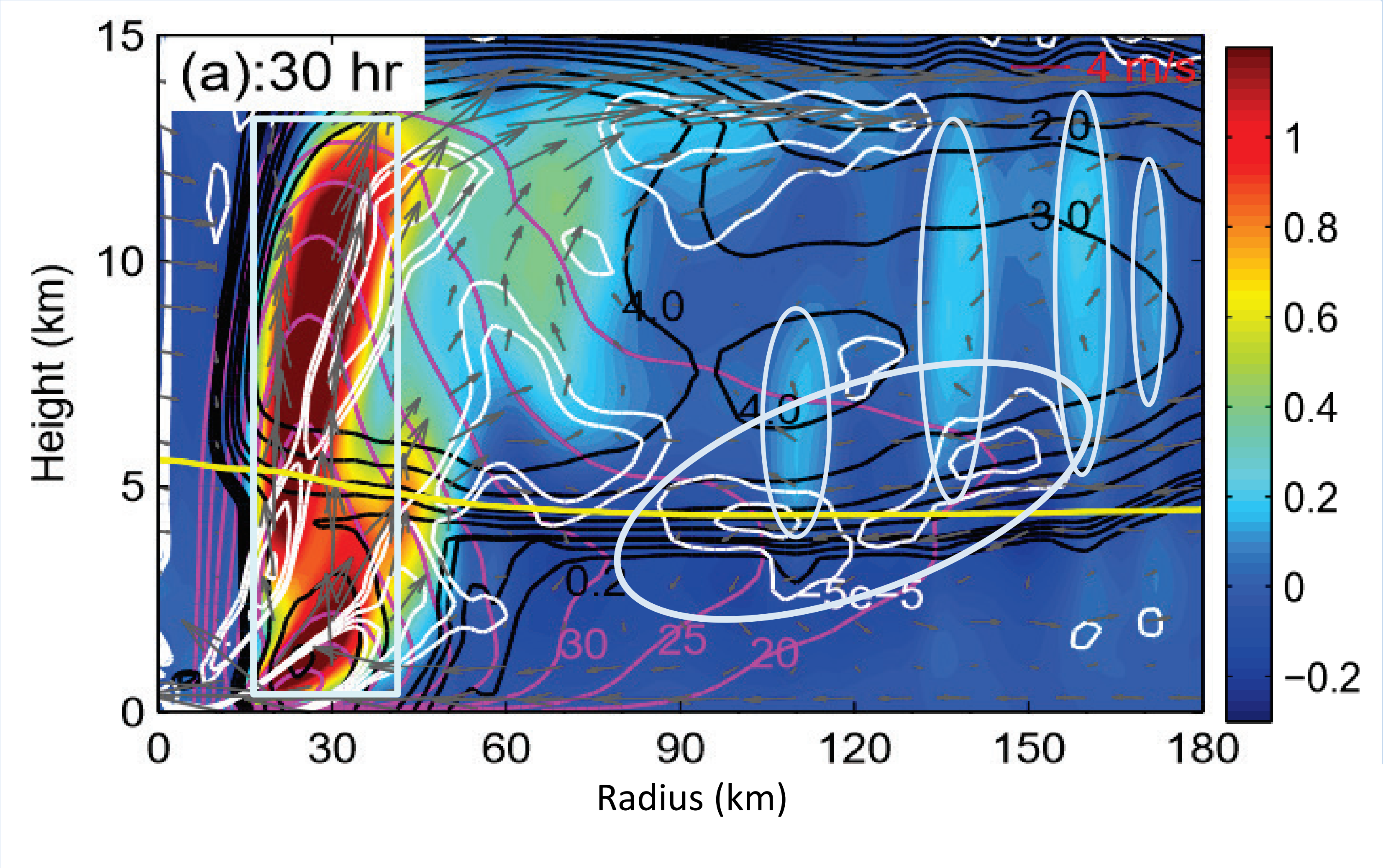
Idealized Case



Vertical velocity (shading, ms^{-1})
Transverse circulation (vectors, ms^{-1})

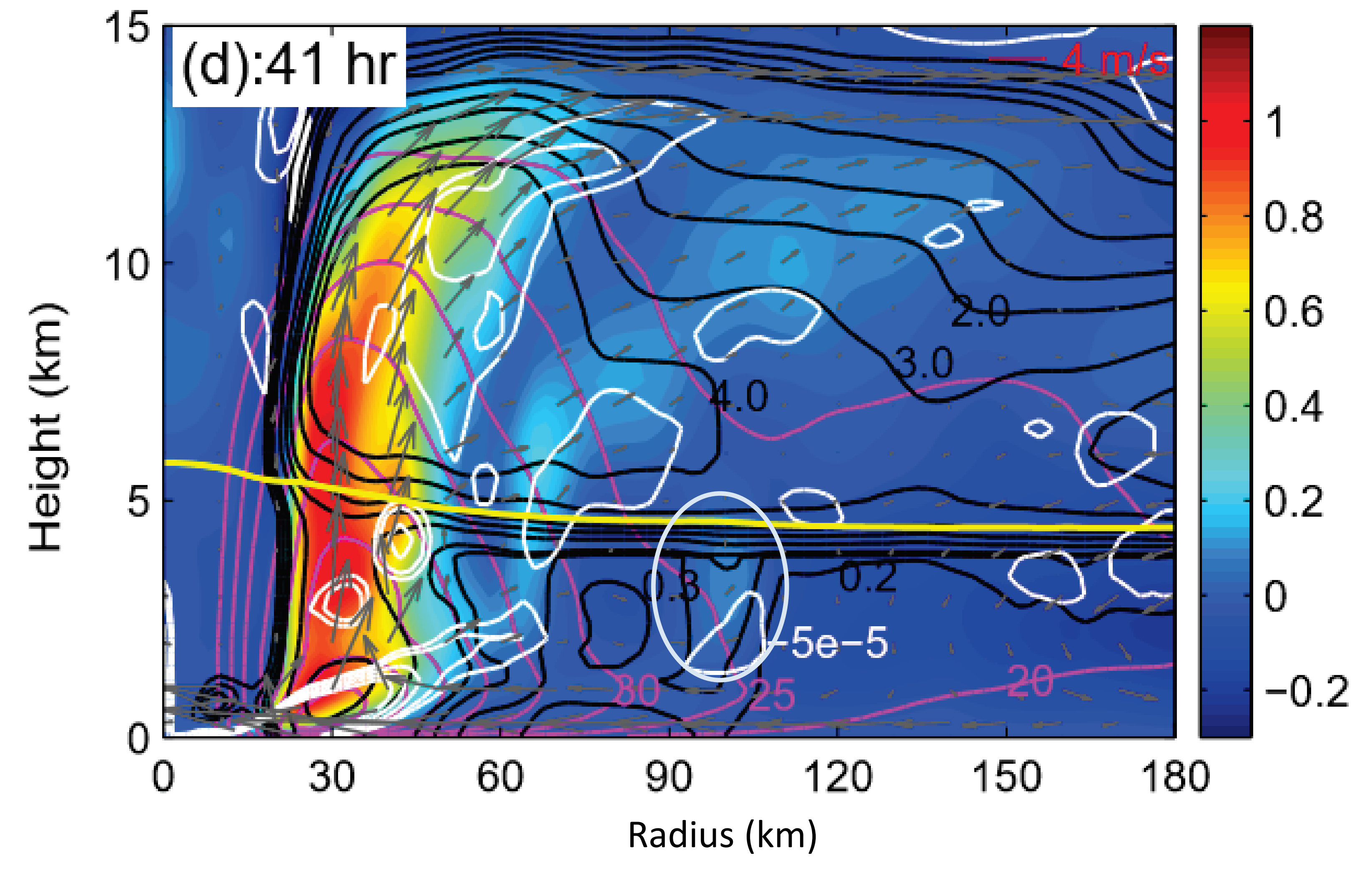
Total condensate (black contours, gkg^{-1})
Radial flow convergence (white contours, s^{-1})

Idealized2



Vertical velocity (shading, ms^{-1})
Transverse circulation (vectors, ms^{-1})
Tangential winds (purple contours, ms^{-1})
Total condensate (black contours, gkg^{-1})
Radial flow convergence (white contours, s^{-1})

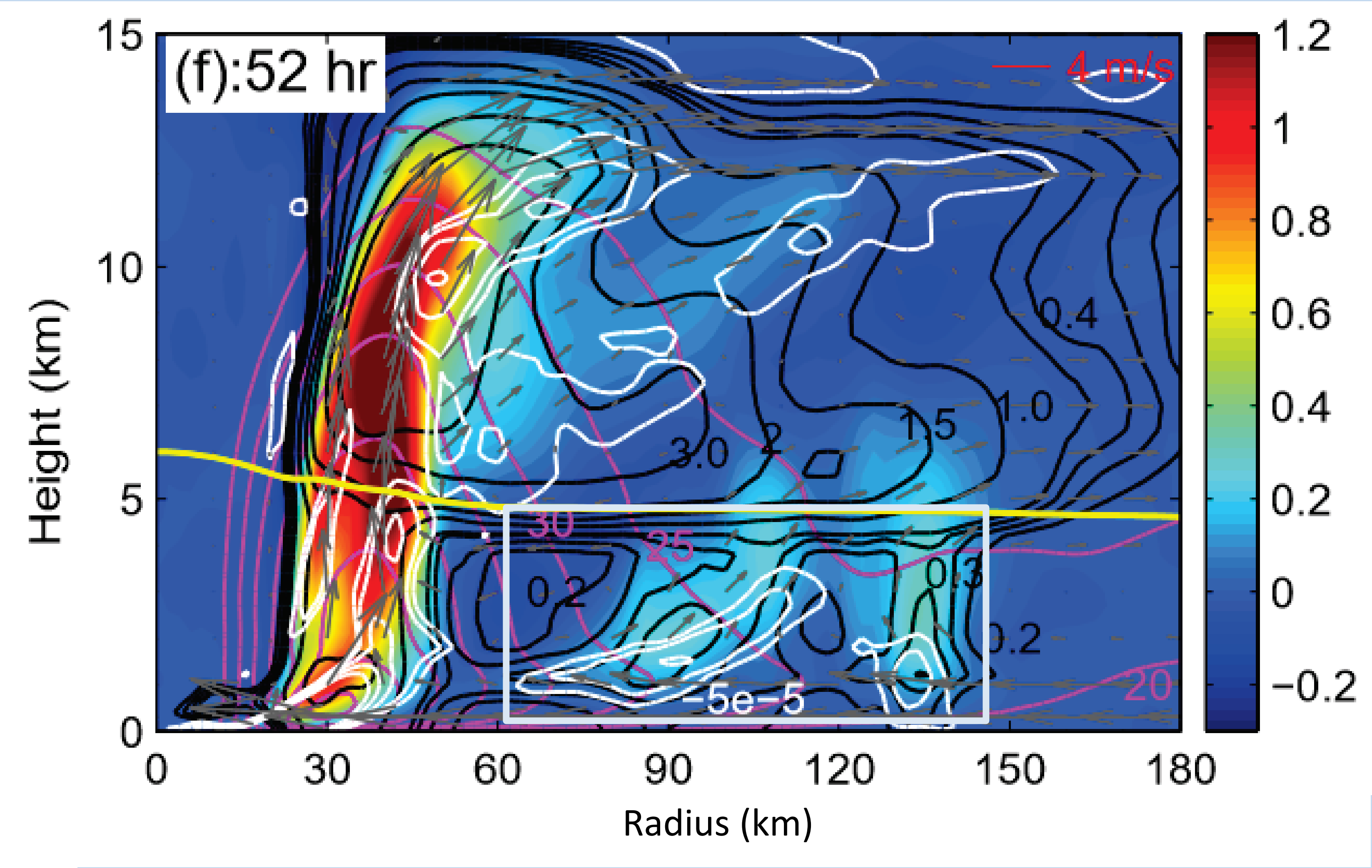
Idealized2



Vertical velocity (shading, ms^{-1})
Transverse circulation (vectors, ms^{-1})
Tangential winds (purple contours, ms^{-1})

Total condensate (black contours, gkg^{-1})
Radial flow convergence (white contours, s^{-1})

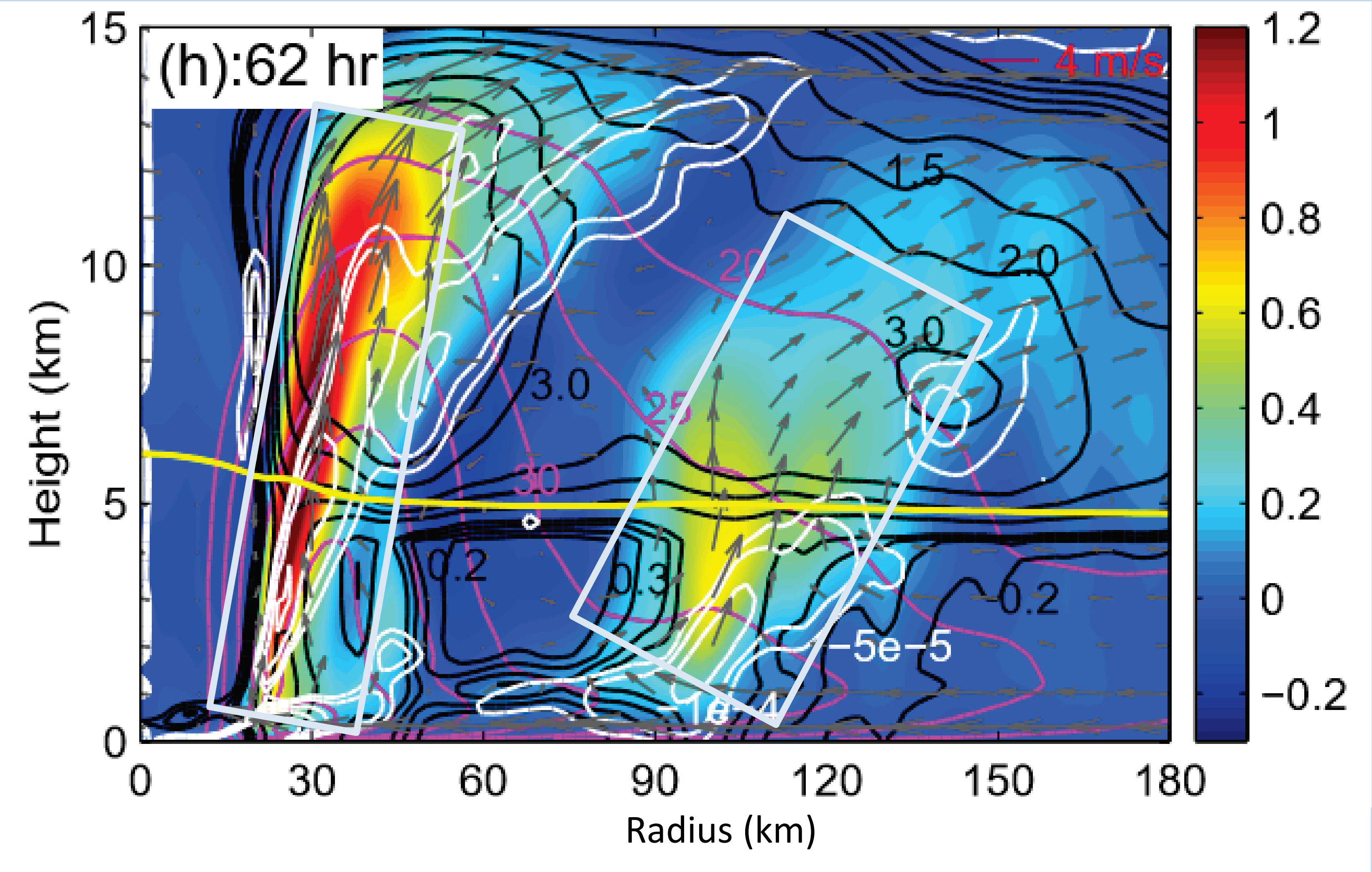
Idealized2



Vertical velocity (shading, ms^{-1})
Transverse circulation (vectors, ms^{-1})
Tangential winds (purple contours, ms^{-1})

Total condensate (black contours, gkg^{-1})
Radial flow convergence (white contours, s^{-1})

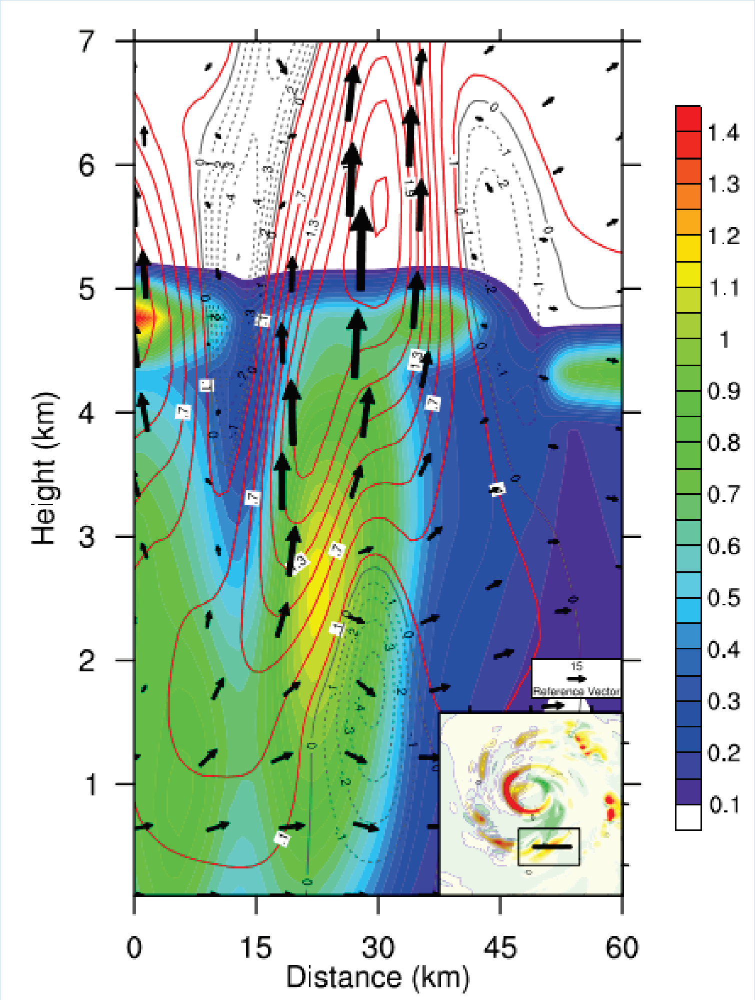
Idealized2



Vertical velocity (shading, ms^{-1})
Transverse circulation (vectors, ms^{-1})
Tangential winds (purple contours, ms $^{-1}$)

Total condensate (black contours, gkg^{-1})
Radial flow convergence (white contours, s^{-1})

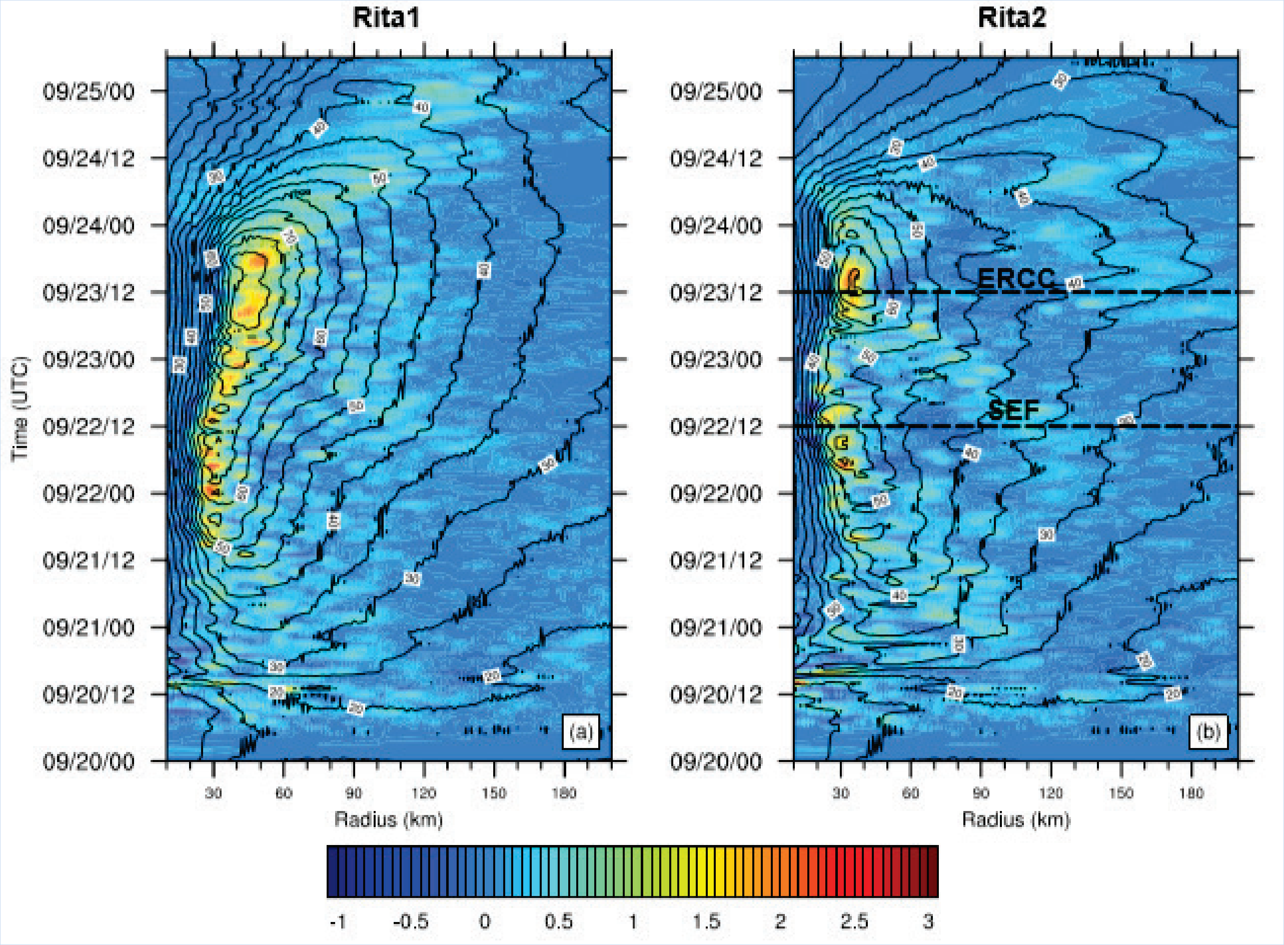
Idealized2



Rain water mixing ratio (shading, gkg^{-1})
Wind speed (vectors, ms^{-1})
Updrafts (red contours, ms^{-1})
Downdrafts (black contours, ms^{-1})

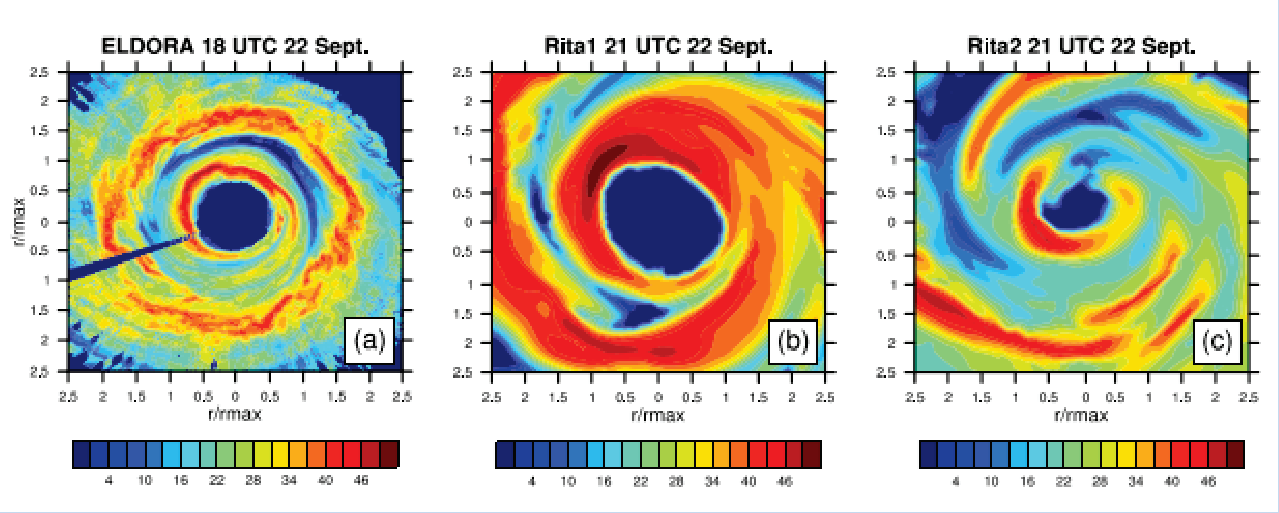
Rita (2005)

- Primary eyewall much weaker in Rita2 than Rita1 (in contrast to idealized case)
- In Rita2, a secondary maximum in vertical velocity associated with outer rainband convection developed , moved radially inward, and eventually became the secondary eyewall.

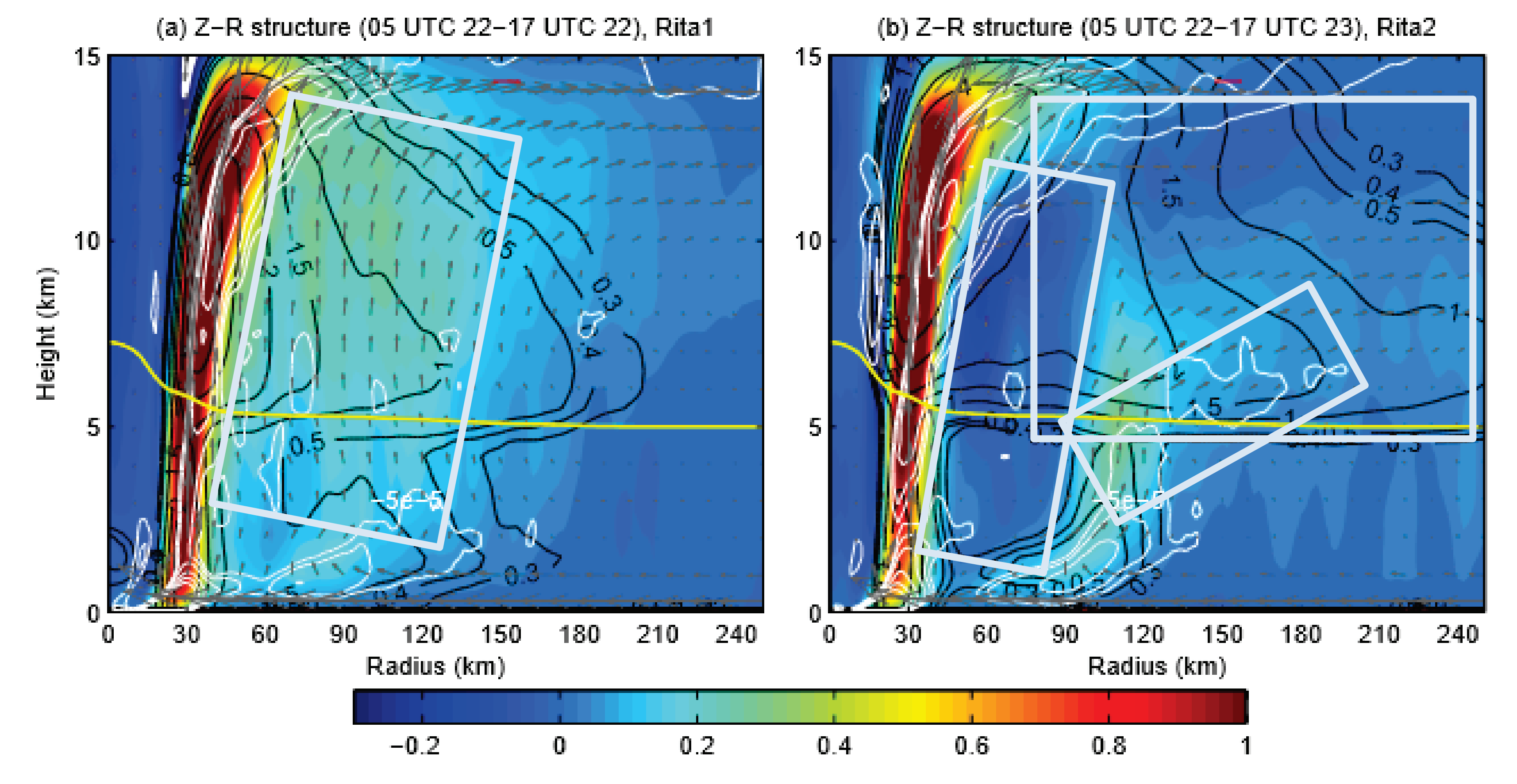


Rita (2005)

- Eyewall structure in Rita2 much closer to observed double eyewall structure
  - Similar sizes, strengths and radial separation of eyewalls for Rita2 and observations
  - Well-defined moat downdraft region separating the eyewalls
  - Primary eyewall much stronger, eye much larger in Rita1 compared to observations
  - SEF was slightly delayed in Rita2 compared to observations



Rita (2005)

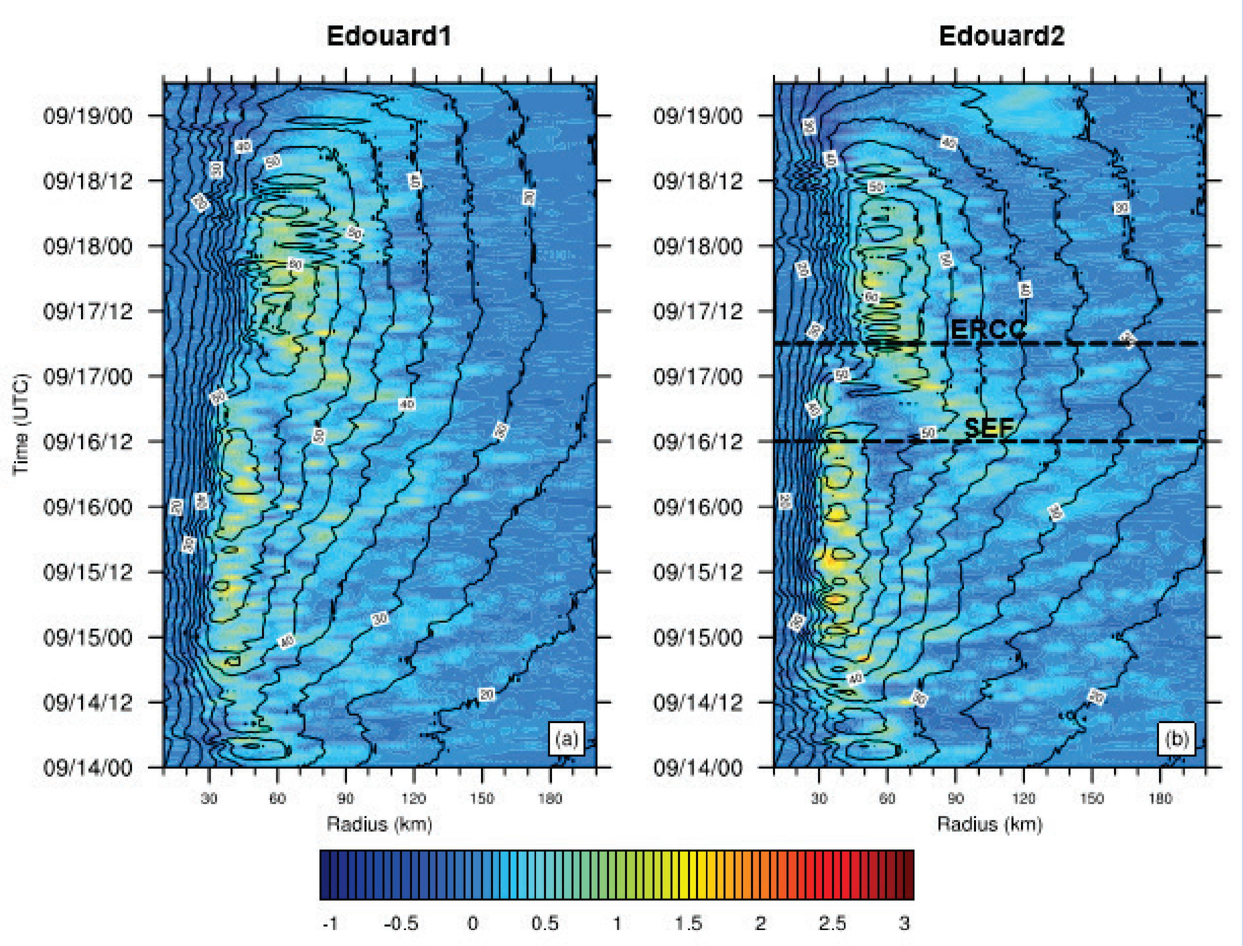


Vertical velocity (shading, ms^{-1})
Transverse circulation (vectors, ms^{-1})

Total condensate (black contours, gkg^{-1})
Radial flow convergence (white contours, s^{-1})

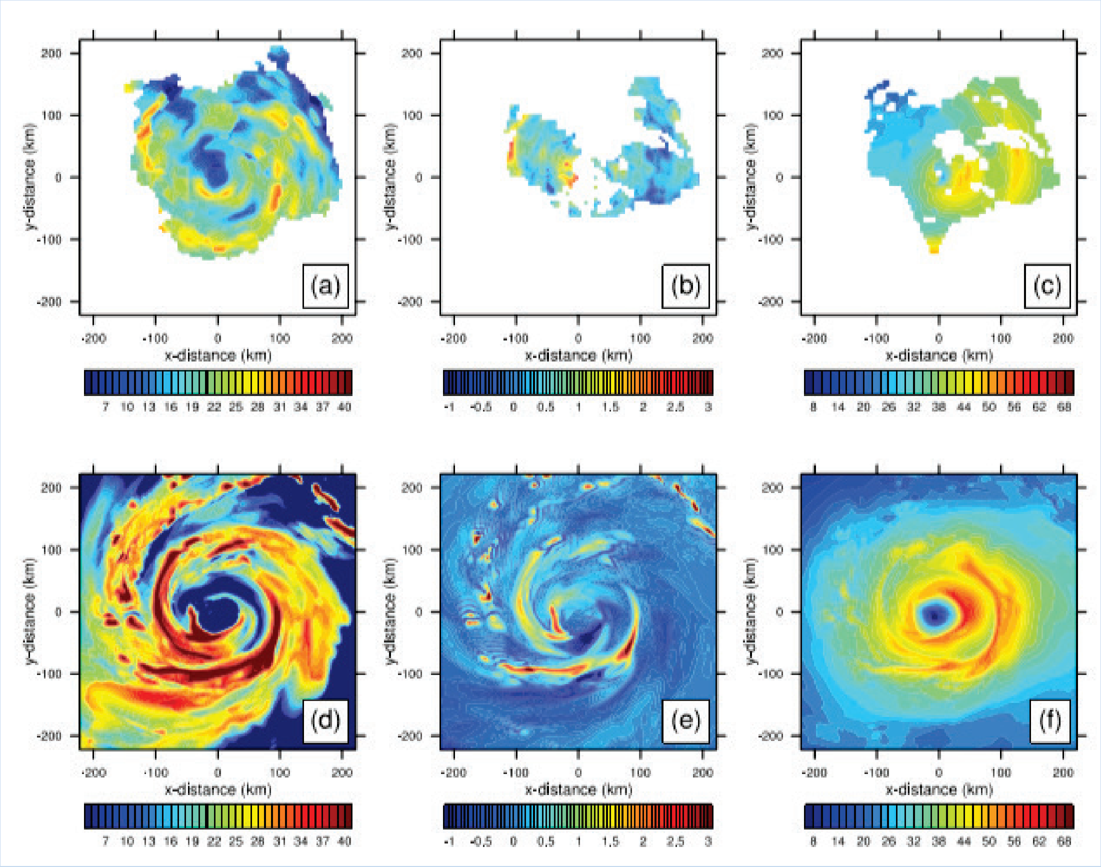
Edouard (2014)

- Some indication of SEF from 18 UTC 16 Sept. - 09 UTC 17 Sept. in Edouard1, but it was not clearly separated from the primary eyewall (to be discussed later).
- For Edouard2, a concentrated area of convection developed at 00 UTC 16 Sept., intensified, moved radially inward, and developed into the secondary eyewall.

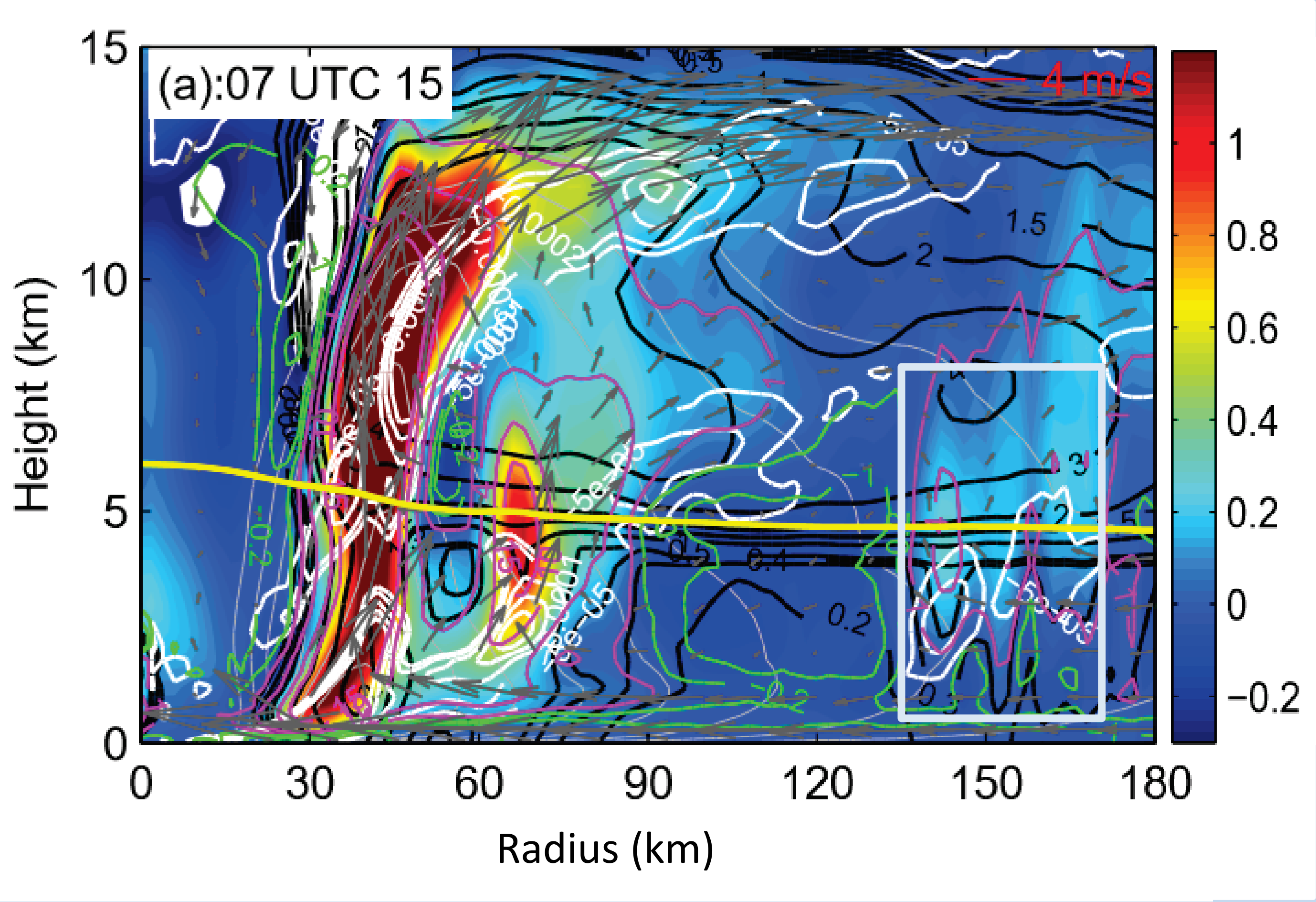


Edouard2

- Two distinct maxima of observed radar reflectivity, vertical velocity, and 3-km wind speed associated with the primary and secondary eyewalls, separated by distinct moat region

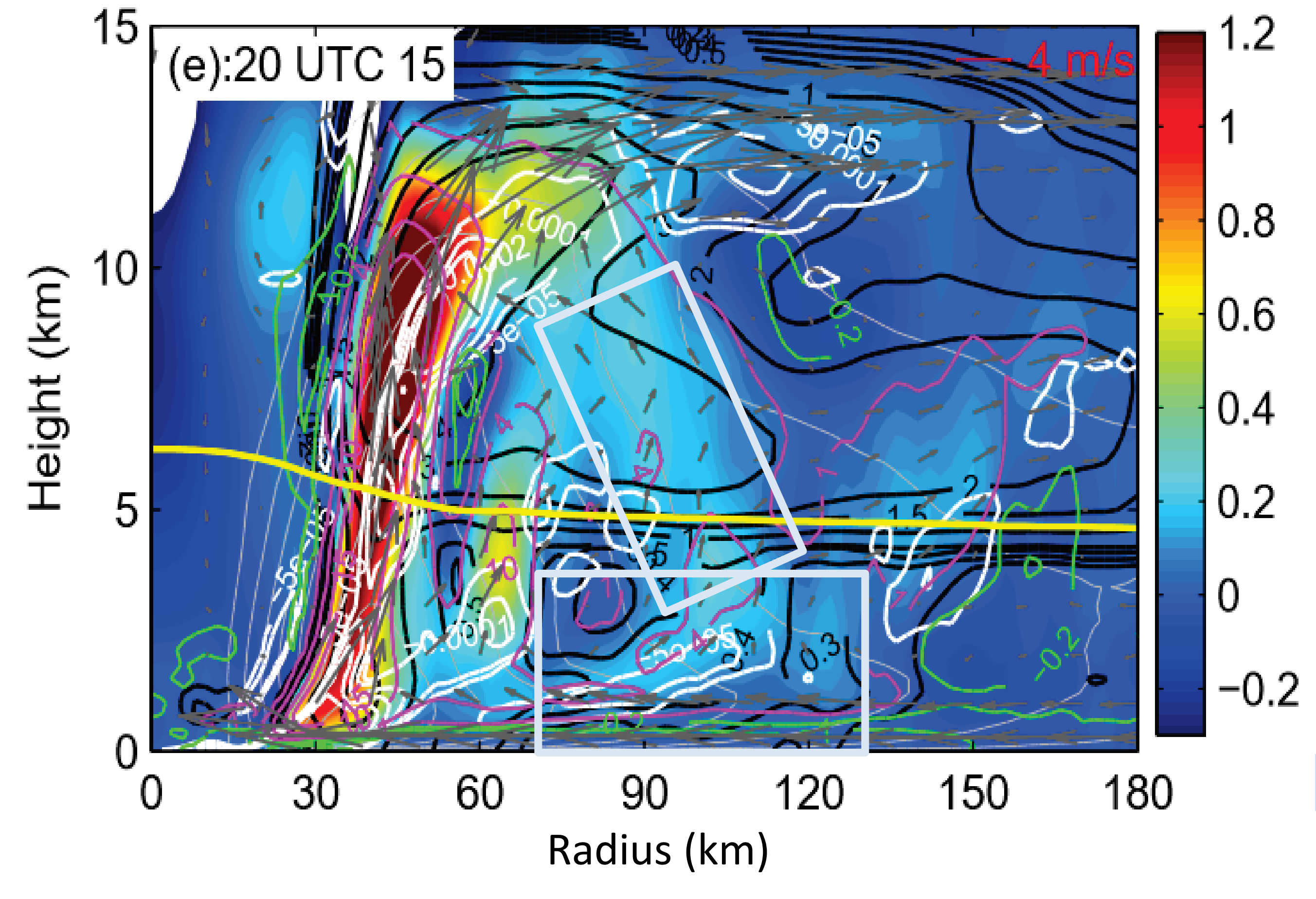


Edouard2



(a):07 UTC 15
4 m/s
Height (km)
Radius (km)
0
30
60
90
120
150
180
15
10
5
1
0.8
0.6
0.4
0.2
−0.2

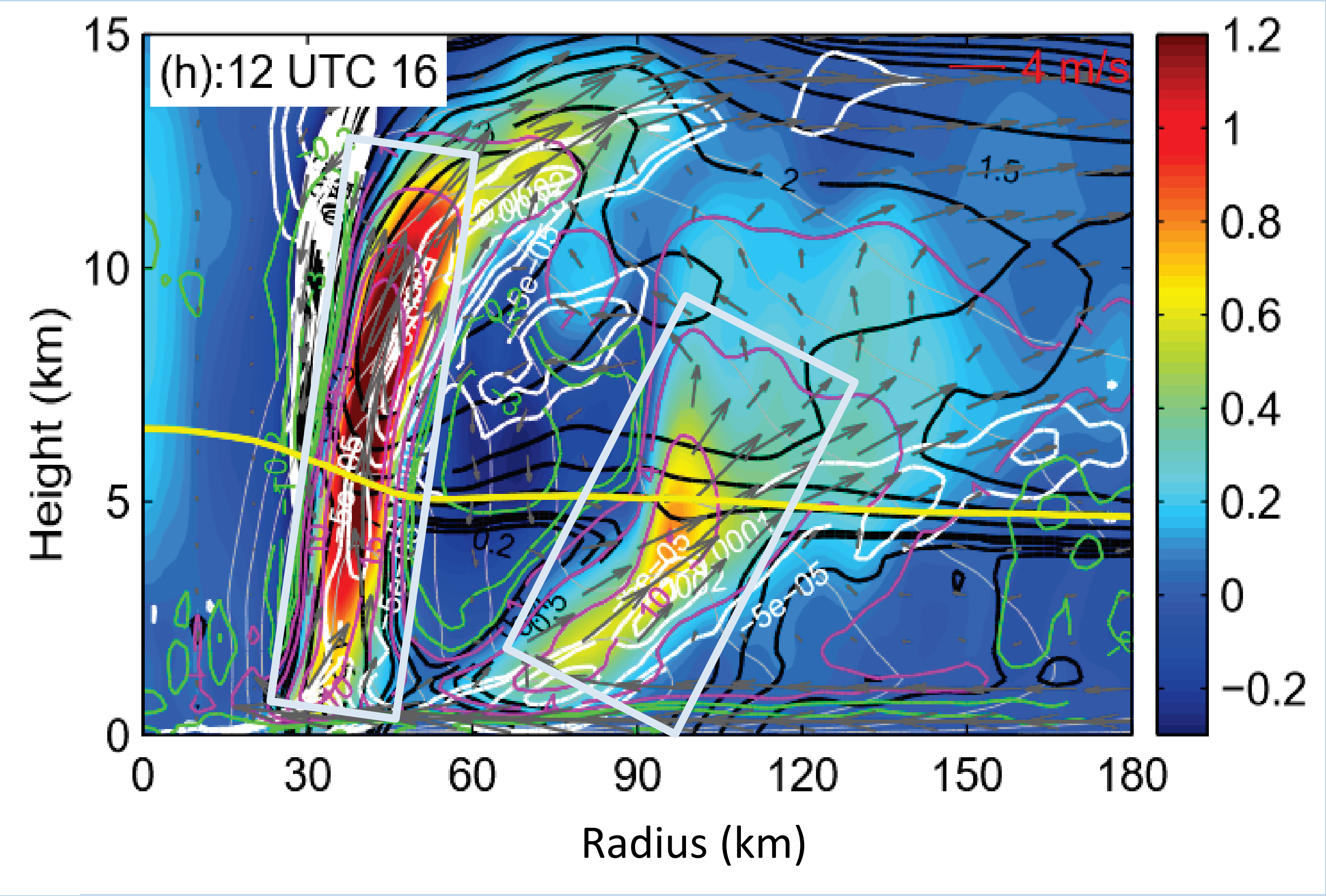
Edouard2



Vertical velocity (shading, ms^{-1})
Transverse circulation (vectors, ms^{-1})
Diabatic heating (purple contours, Khr $^{-1}$)

Total condensate (black contours, gkg^{-1})
Radial flow convergence (white contours, s^{-1})
Diabatic cooling (green contours, Khr^{-1})

Edouard2



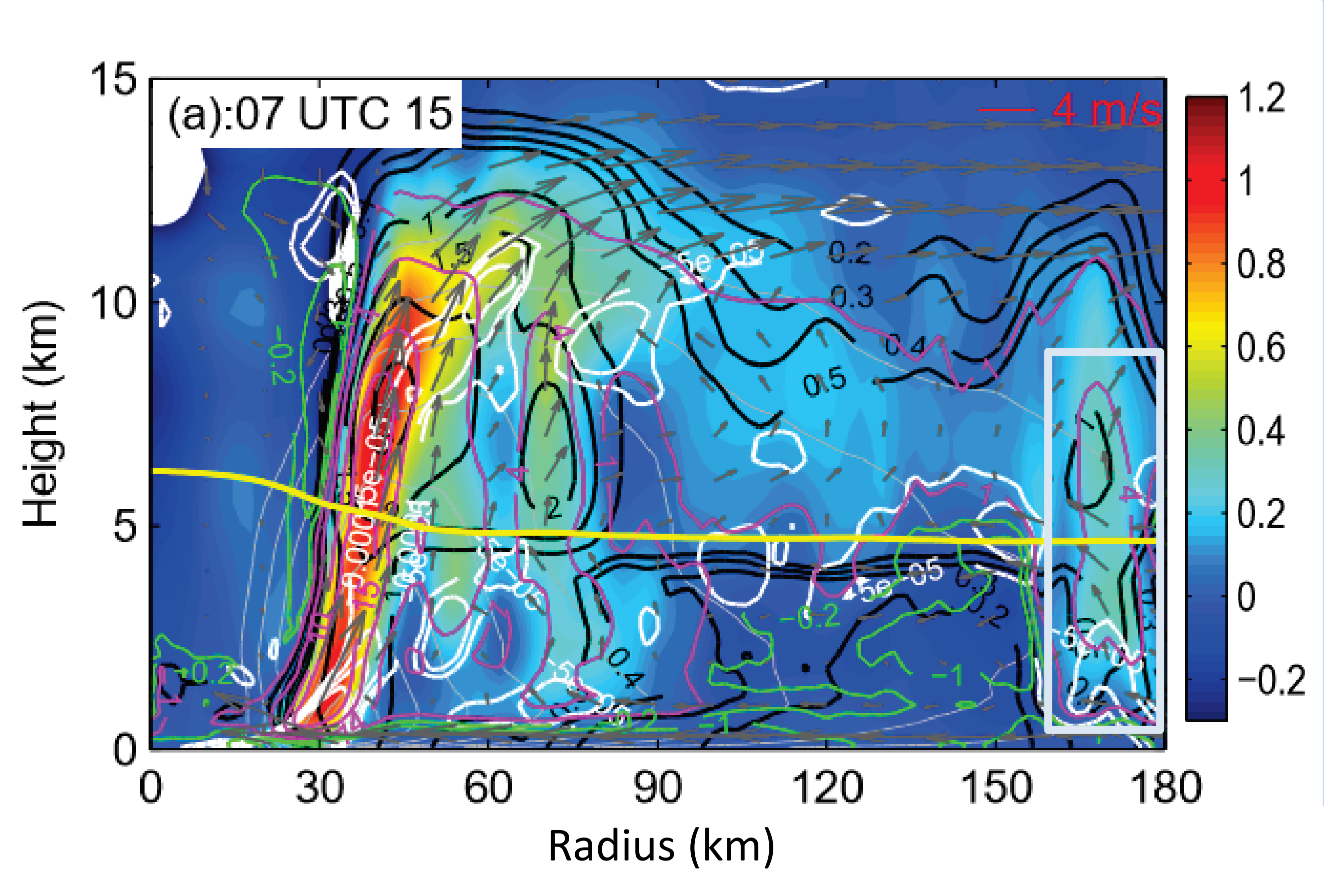
Vertical velocity (shading, ms^{-1})
Transverse circulation (vectors, ms^{-1})
Diabatic heating (purple contours, Khr $^{-1}$)

Total condensate (black contours, gkg^{-1})
Radial flow convergence (white contours, s^{-1})
Diabatic cooling (green contours, Khr^{-1})

Edouard1

- Previously mentioned that Edouard1 underwent what on the first glance appeared to be a similar SEF to Edouard2, although the former was much less clean.
- Did the two events result from the same physical processes?

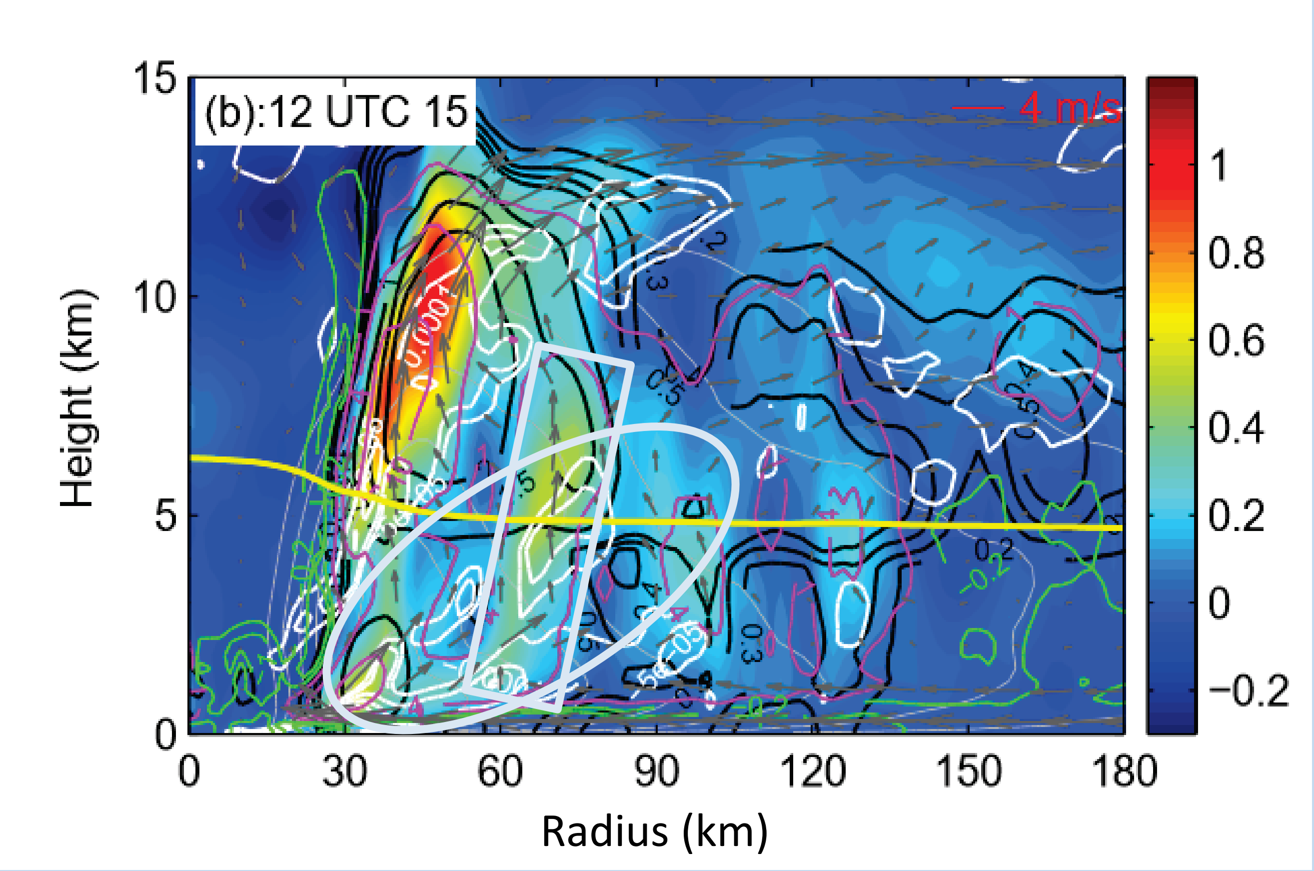
Edouard1



Vertical velocity (shading, ms^{-1})
Transverse circulation (vectors, ms^{-1})
Diabatic heating (purple contours, Khr^{-1})

Total condensate (black contours, gkg^{-1})
Radial flow convergence (white contours, s^{-1})
Diabatic cooling (green contours, Khr^{-1})

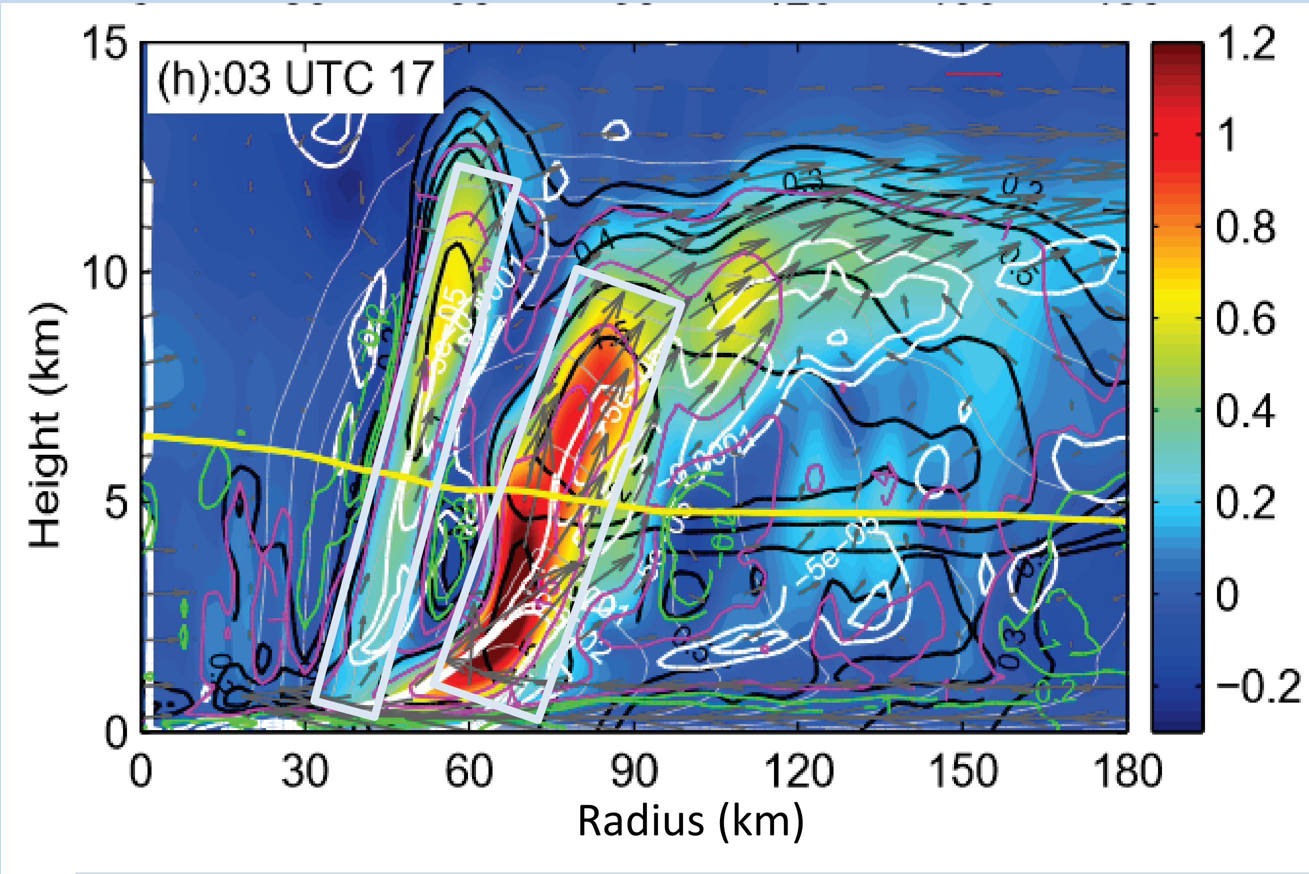
Edouard1



Vertical velocity (shading, ms^{-1})
Transverse circulation (vectors, ms^{-1})
Diabatic heating (purple contours, Khr^{-1})

Total condensate (black contours, gkg^{-1})
Radial flow convergence (white contours, s^{-1})
Diabatic cooling (green contours, Khr^{-1})

Edouard1

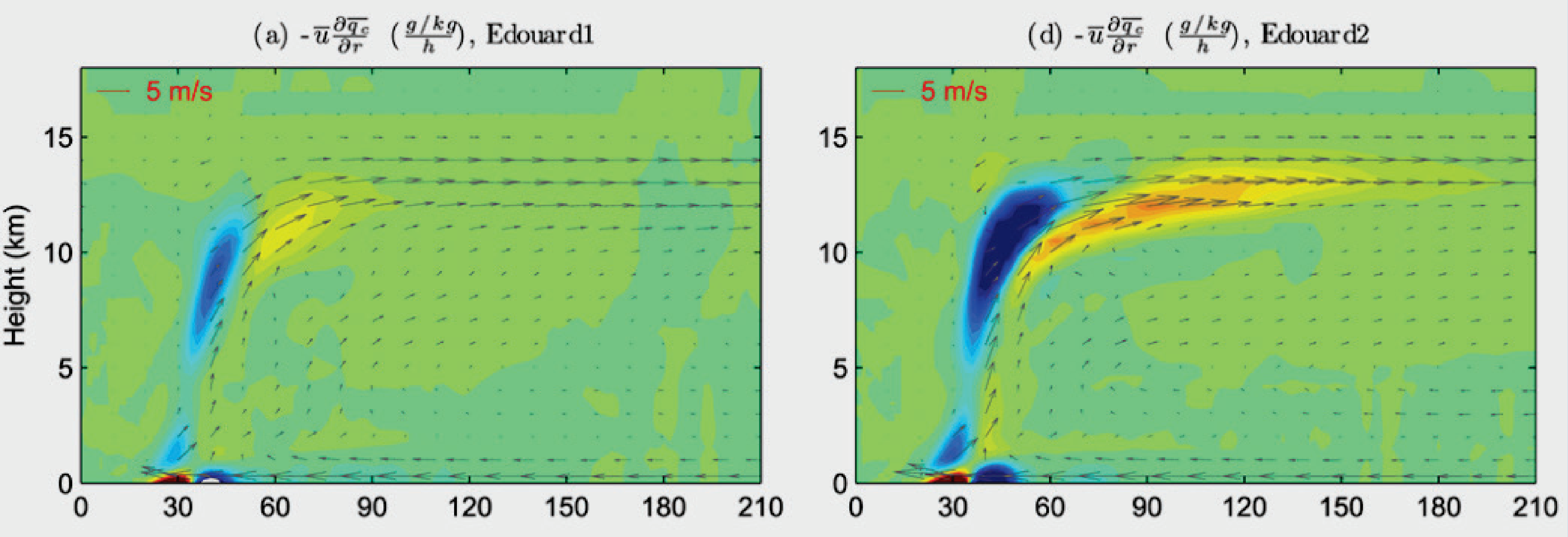


Vertical velocity (shading, ms^{-1})
Transverse circulation (vectors, ms^{-1})
Diabatic heating (purple contours, Khr $^{-1}$)

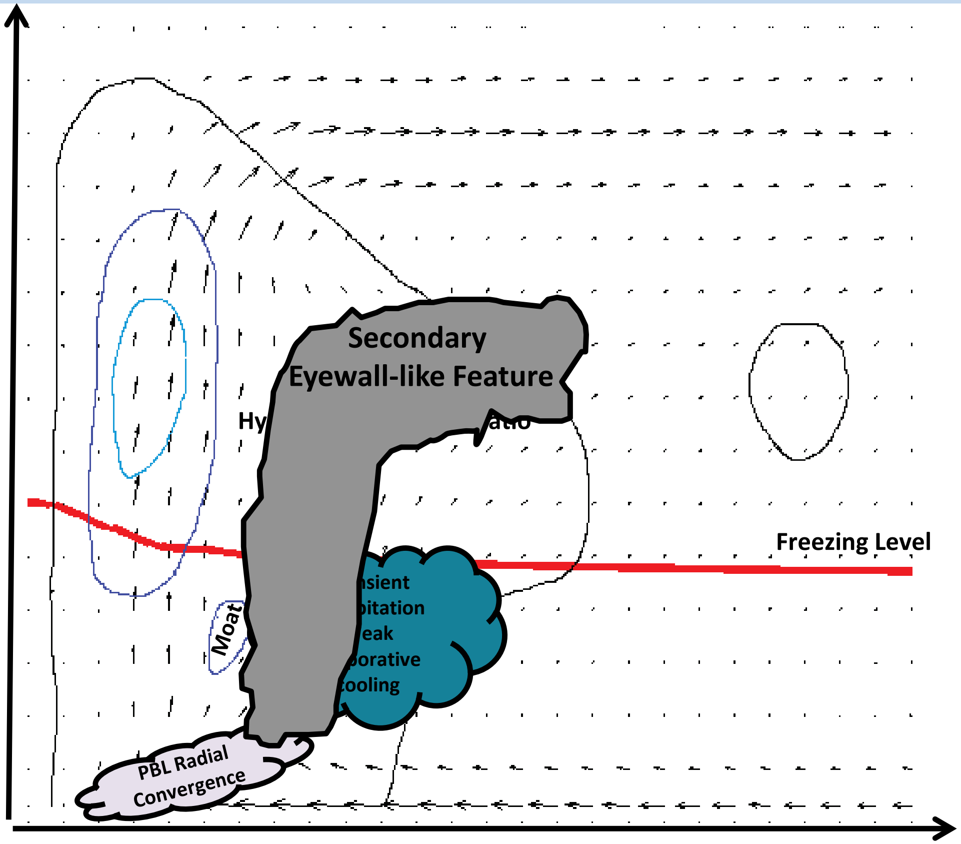
Total condensate (black contours, gkg^{-1})
Radial flow convergence (white contours, s^{-1})
Diabatic cooling (green contours, Khr^{-1})

Edouard (2014)

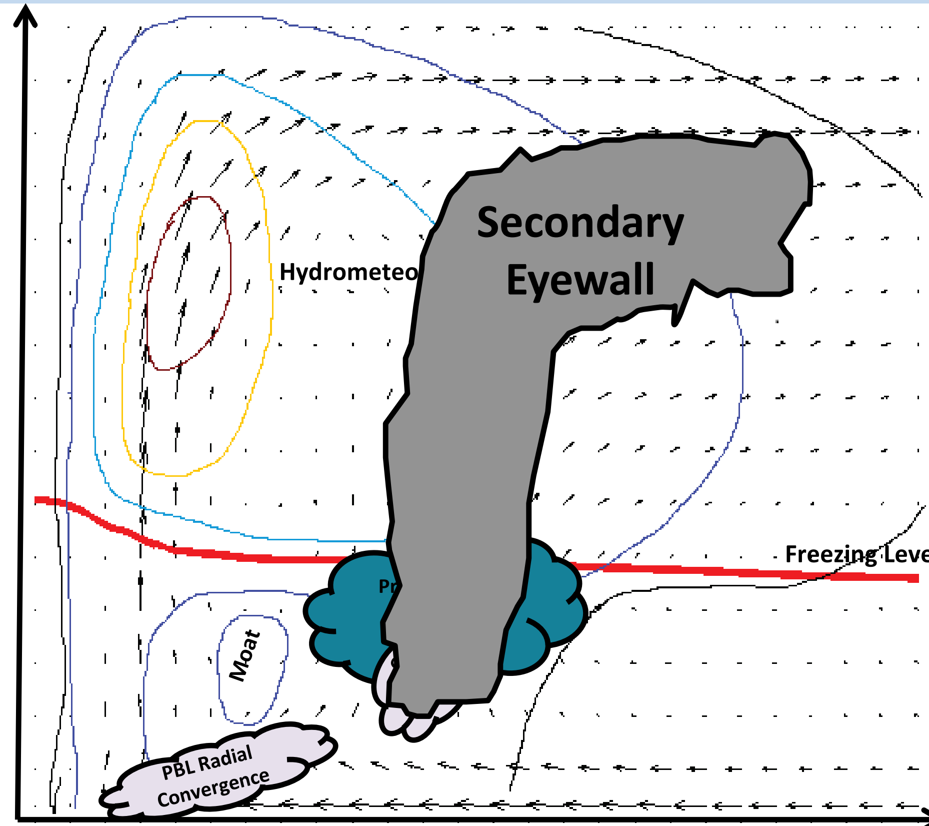
- To verify the source for the condensate at the outer radii, we conducted a budget of total-mean condensate for the two simulations.
- Reduction of particle fall velocity in Edouard2 substantially increases the radial transport of condensate by the upper-tropospheric outflow.



“SEF-LIKE” Event



“Top-down” Pathway



Discussion/Conclusions

- The default HWRF Ferrier-Aligo scheme is not producing the smallest, lightest solid-phase hydrometeors with fall speeds less than 0.2 ms^{-1}, which are likely present in observed TCs.

- By reducing particle terminal velocity to a factor of one-fourth of the operational value, clean SEF occurred in both an idealized simulation and real-case simulations of Rita (2005) and Edouard (2014), which otherwise failed to occur in simulations with the default microphysics option due to a lack of particles with fall speeds less than 0.2 ms^{-1}.

- Many of the simulated SEF characteristics for Rita2 and Edouard2 were consistent with aircraft observations, including the timing of SEF, radial location and updraft strength associated with the secondary eyewall, and a well-defined moat region void of convection separating the primary and secondary eyewalls

Discussion/Conclusions

- A “top-down” pathway to SEF is revealed in the study, initiated from the emergence of steady precipitation at the outer radii.
- This top-down pathway to SEF occurred in the sensitivity experiments with reduced particle fall velocity is in stark contrast to the SEF-like event in the control simulation of Edouard1, which was rooted in the boundary layer from the very beginning.