The role of African easterly waves north of the African easterly jet on tropical cyclogenesis

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ATM 741 Project Presentation

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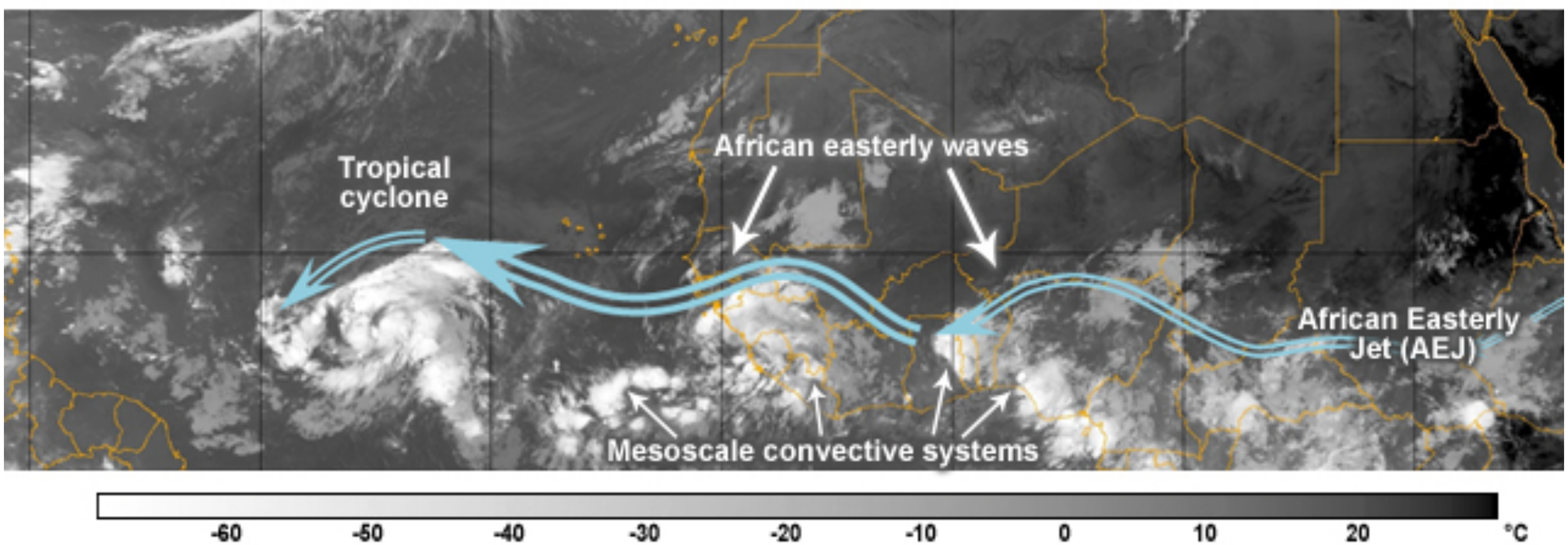
Background

❖ Most tropical cyclones (TCs) begin as African easterly waves (AEWs)

❖ **Traditional thinking:** tropical cyclogenesis originates from waves south of African easterly jet (AEJ)



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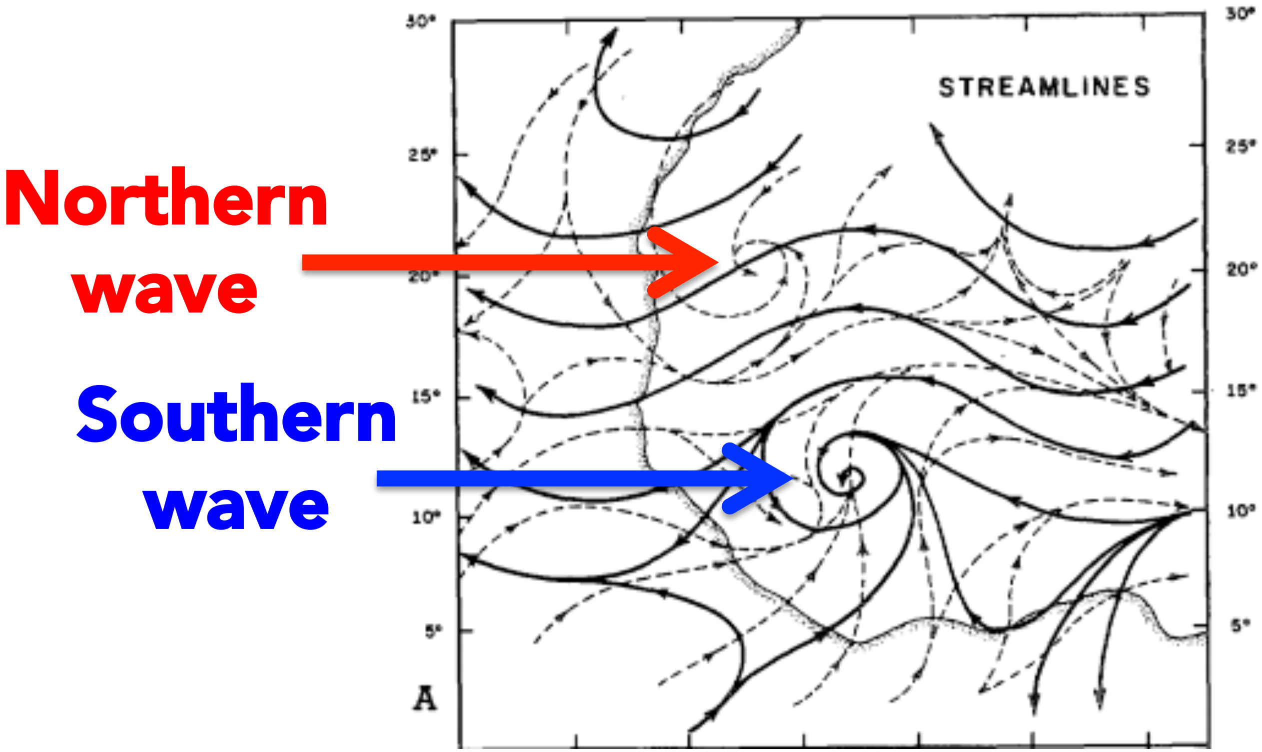
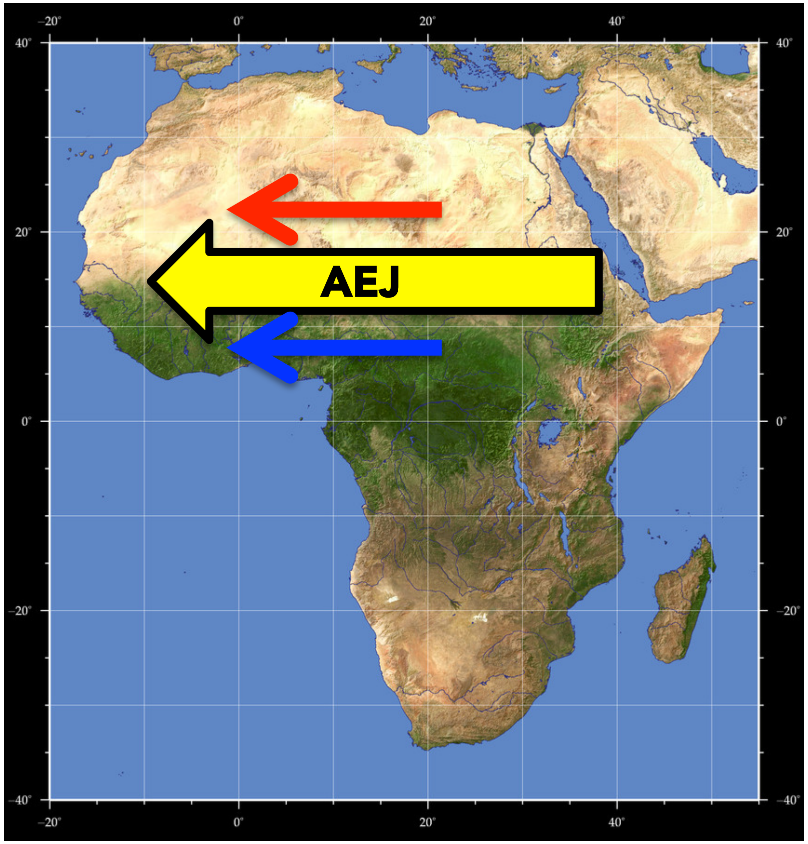
Background

- Two propagation paths discovered in the late 1960's (Carlson 1969)



Background

❖ **Two propagation paths!**



Background

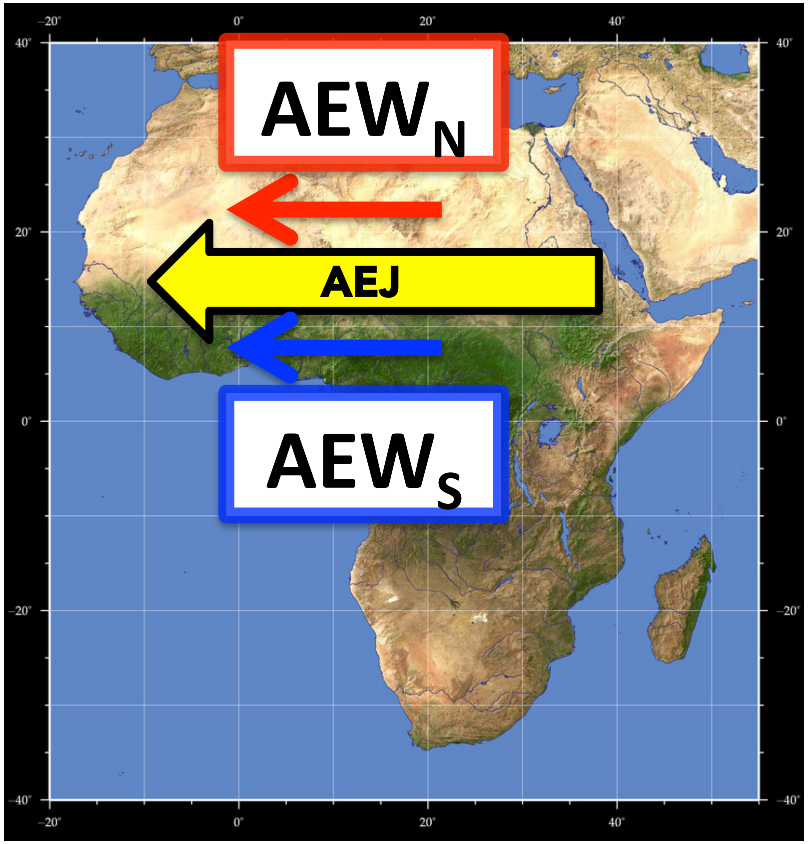
- Two propagation paths!

AEW_N

- Forms from Saharan heat low
- Maximized at low-levels (850 hPa)

AEW_S

- Forms from moist convection and jet
- Maximized at mid-levels (700 hPa)



Background

❖ Two propagation paths!

AEW$_N$

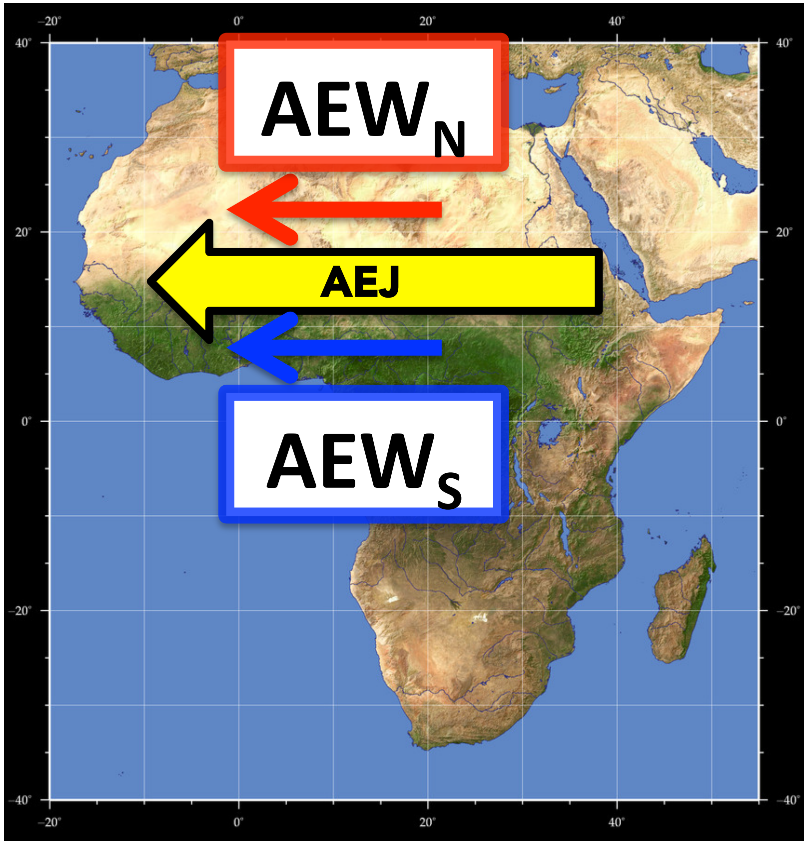
❖ Forms from Saharan heat low

❖ Maximized at low-levels (850 hPa)

AEW$_S$

❖ Forms from moist

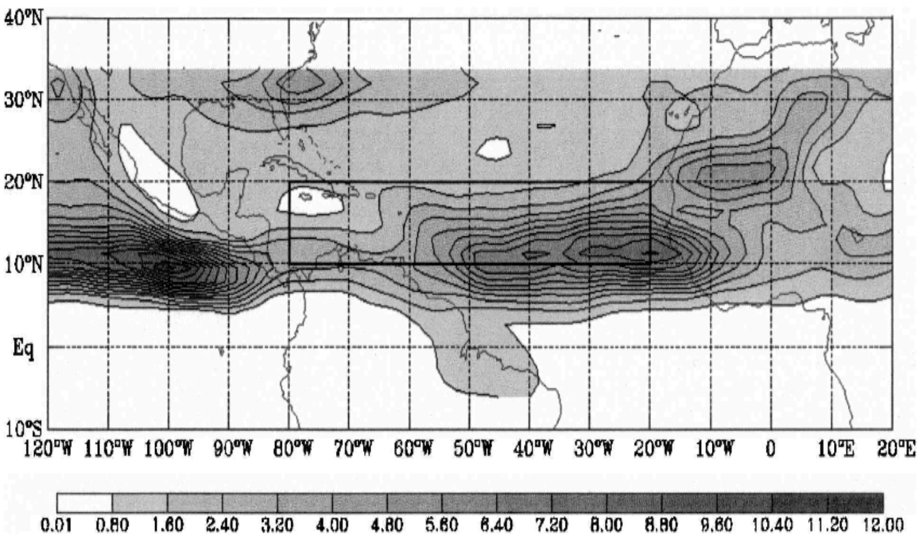
Can AEW$_N$s contribute to tropical cyclogenesis?



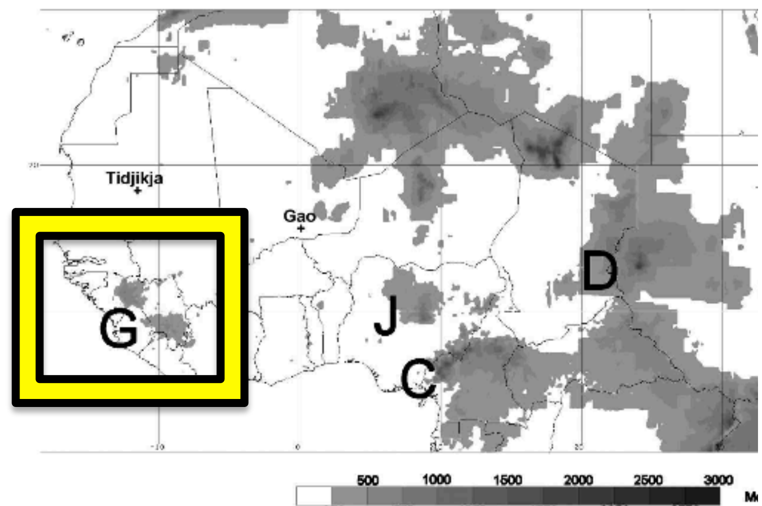
Background

Can AEW$_N$s contribute to tropical cyclogenesis?

NOT REALLY



Track density per month (Thorncroft and Hodges 2001; Hopsch et al. 2007)

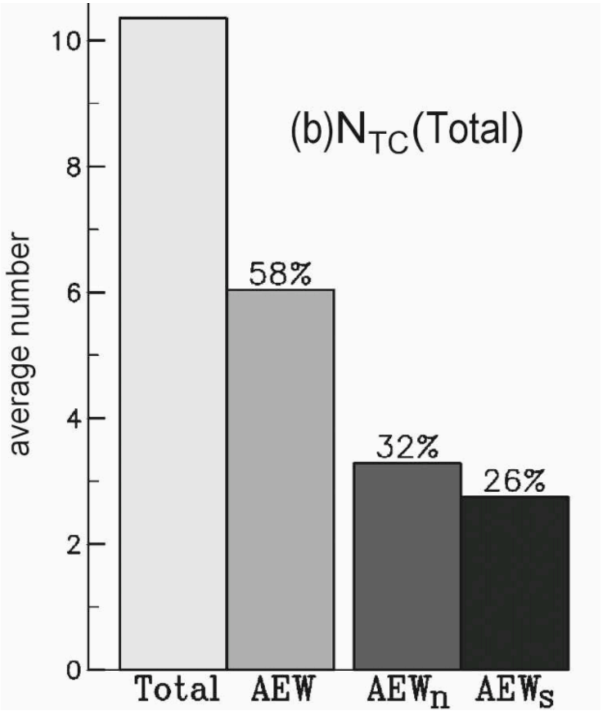


Guinea highlands enhances PV generation associated with AEW$_S$ (Thorncroft and Hodges 2001; Hopsch et al. 2007)

Background

Can AEW_Ns contribute to tropical cyclogenesis?

YES

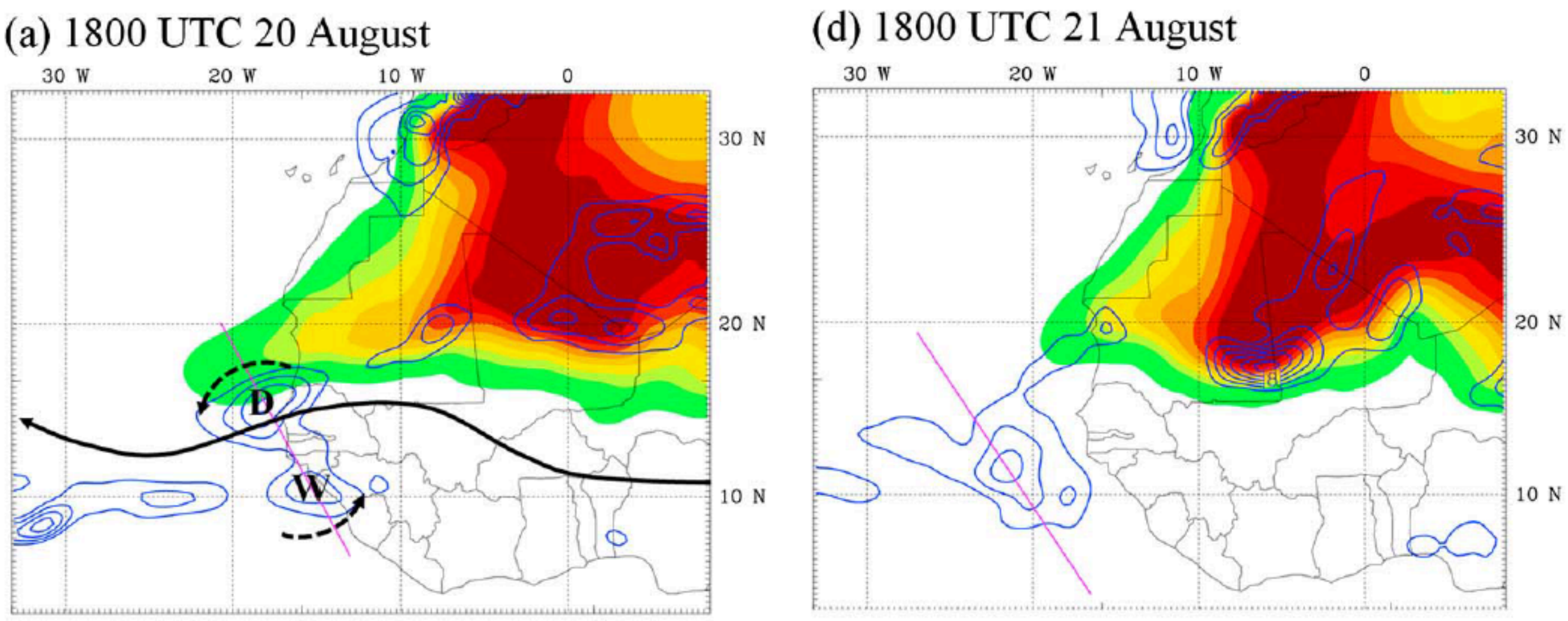


Average number of TCs, AEWs, AEW_N, and AEW_S per season (Chen et al. 2008)

Background

Can AEW$_N$s contribute to tropical cyclogenesis?

YES



Wet and Dry vortices merge and form TS Debby in 2006 (Chen and Liu 2014)

Questions

1. Can an AEW_N contribute to tropical cyclogenesis?
    - Lots of low-level cyclonic relative vorticity
    - Very dry…

Questions

1. Can an AEW_N contribute to tropical cyclogenesis?
   - Lots of low-level cyclonic relative vorticity
   - Very dry…

2. What is the relative or collective importance of AEW_Ns and AEW_Ss on tropical cyclogenesis?
   - AEW_Ss can develop ample low-level relative vorticity on its own through topographically-enhanced convection
   - Relative vorticity associated with the AEW_N may be important
   - Merging can increase the low-level vorticity

Outline

1. Can an AEW_N contribute to tropical cyclogenesis?
   - ❖ Observational data lacks high spatial and temporal resolution
     - ❖ Move to modeling framework

2. What is the relative or collective importance of AEW_Ns and AEW_Ss on tropical cyclogenesis?
   - ❖ Vorticity budget (described later)
   - ❖ Quantify the importance of merging process

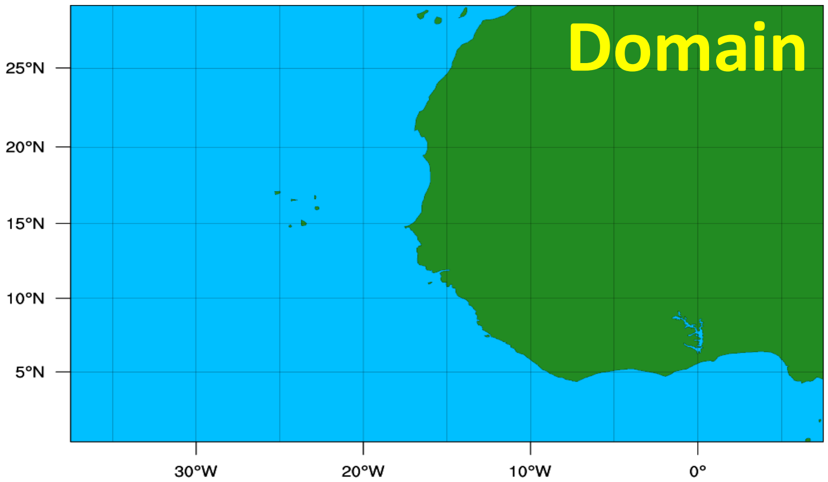
Case Study

- **Investigate the evolution of Hurricane Danielle (2004)**
- **Associated with an AEW_N and AEW_S that merged within the main development region (MDR)**

Methodology

Version 3.7.1 of the Advanced Research WRF (ARW)

- Single stagnant domain
- 27 km horizontal resolution
- 61 vertical levels
- ERA-Interim Reanalysis and NCEP Real-Time SST analysis initialization
- Output every 30 minutes



Type	Parameterization
microphysics	WRF Single-Moment 6-class
cumulus	Grell 3D
shortwave	RRTMG shortwave
longwave	RRTMG longwave
PBL	Yonsei University
land surface	Noah

Methodology

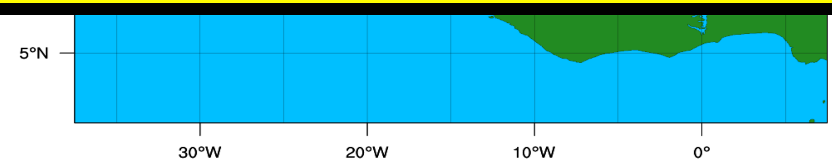
Version 3.7.1 of the Advanced Research WRF (ARW)

Two model simulations:

Control: ERA-Interim reanalysis inputted

No Vortex: AEW_N removed in the model

- ❖ 61 vertical levels
- ❖ ERA-Interim Reanalysis and NCEP Real-Time SST analysis initialization
- ❖ Output every 30 minutes



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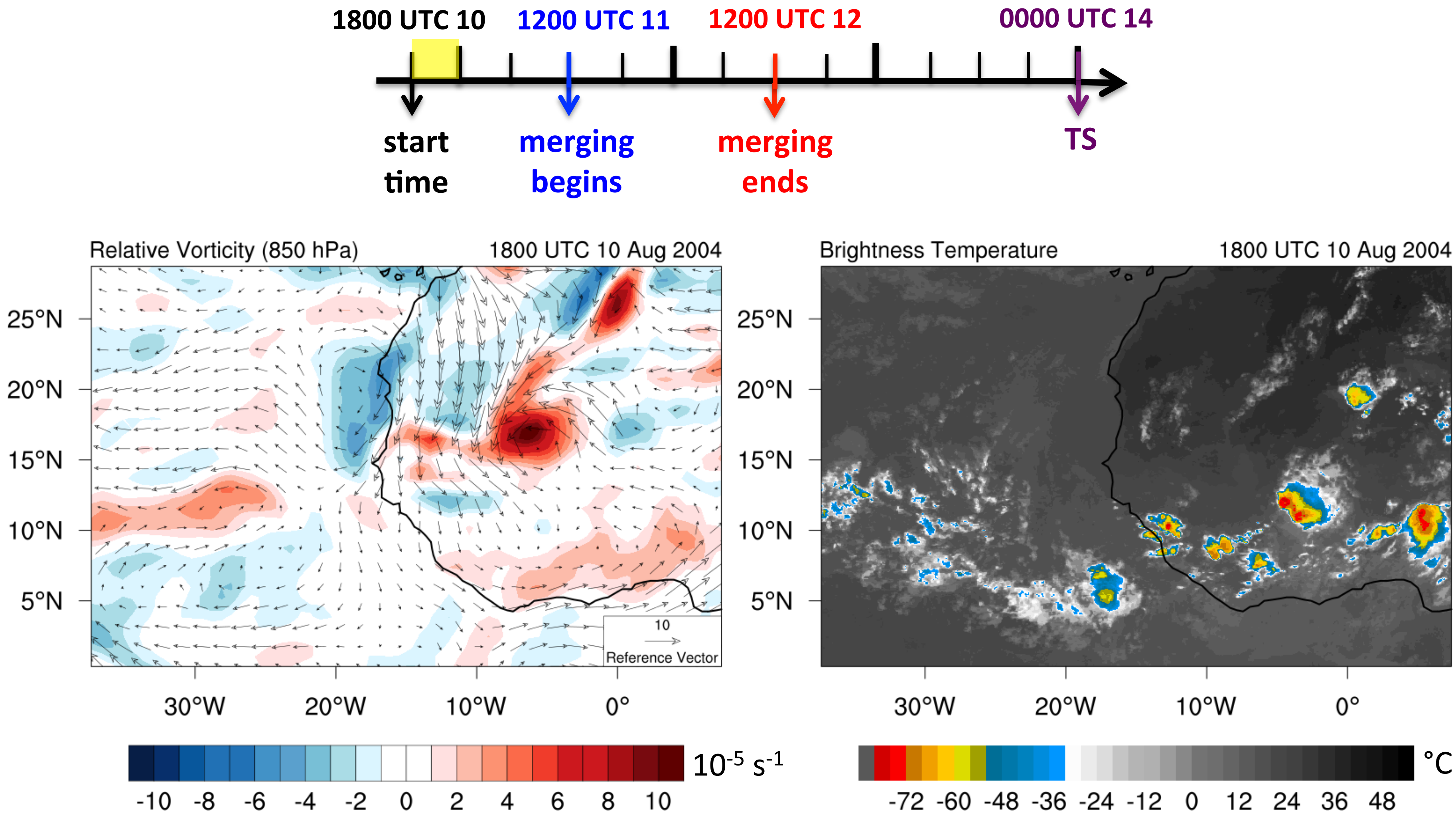

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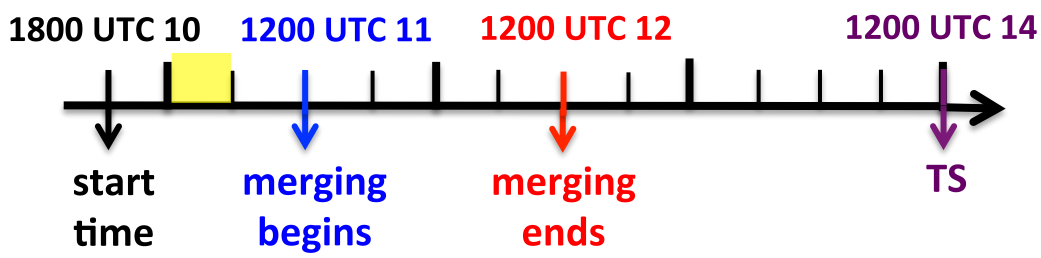

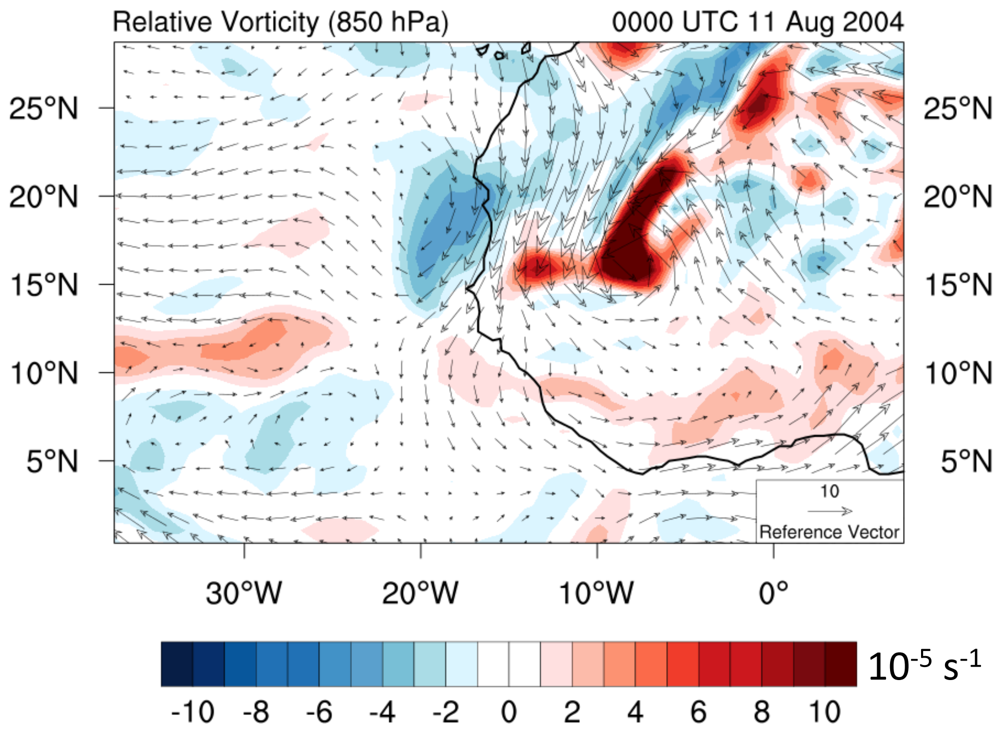

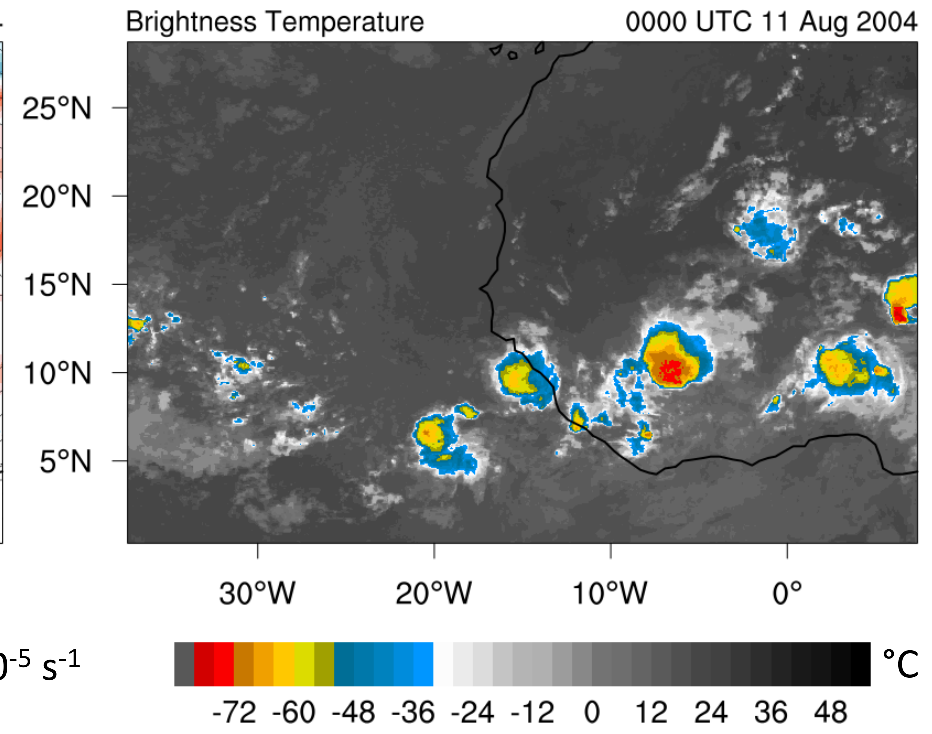

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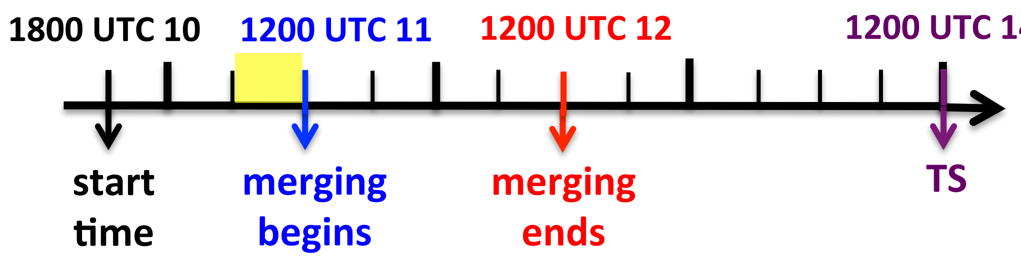

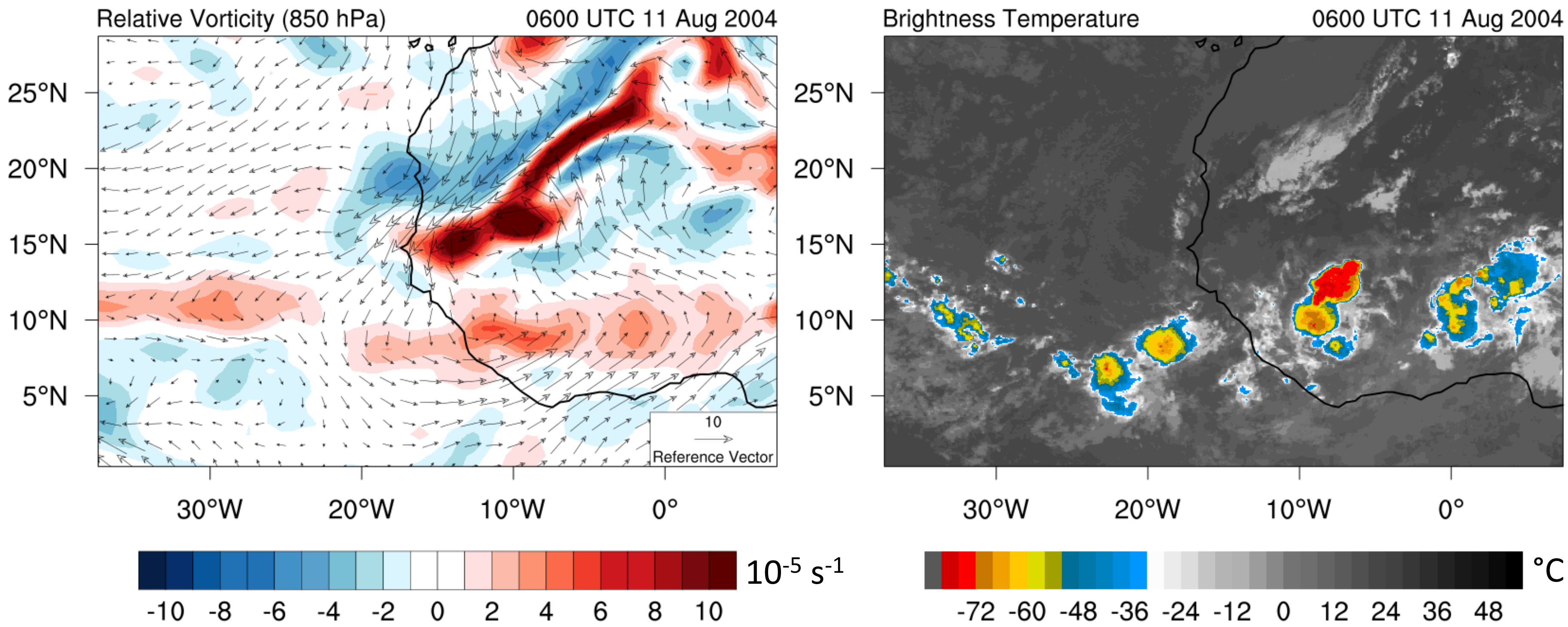

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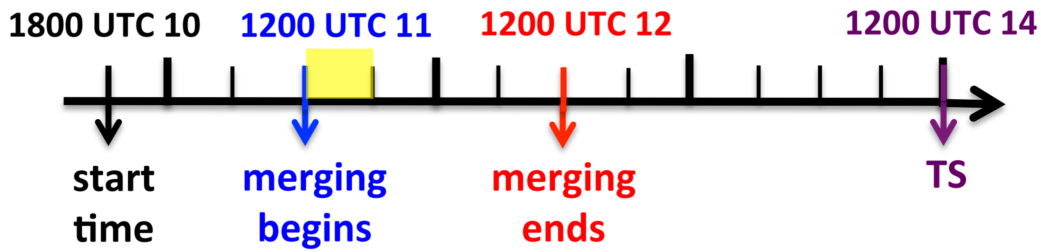

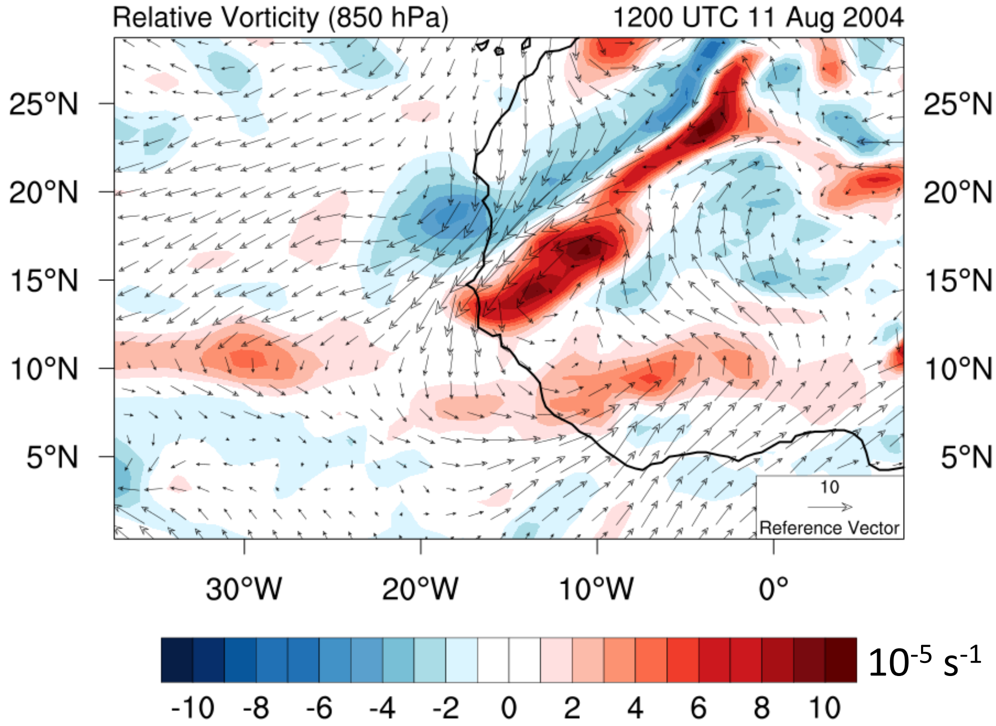

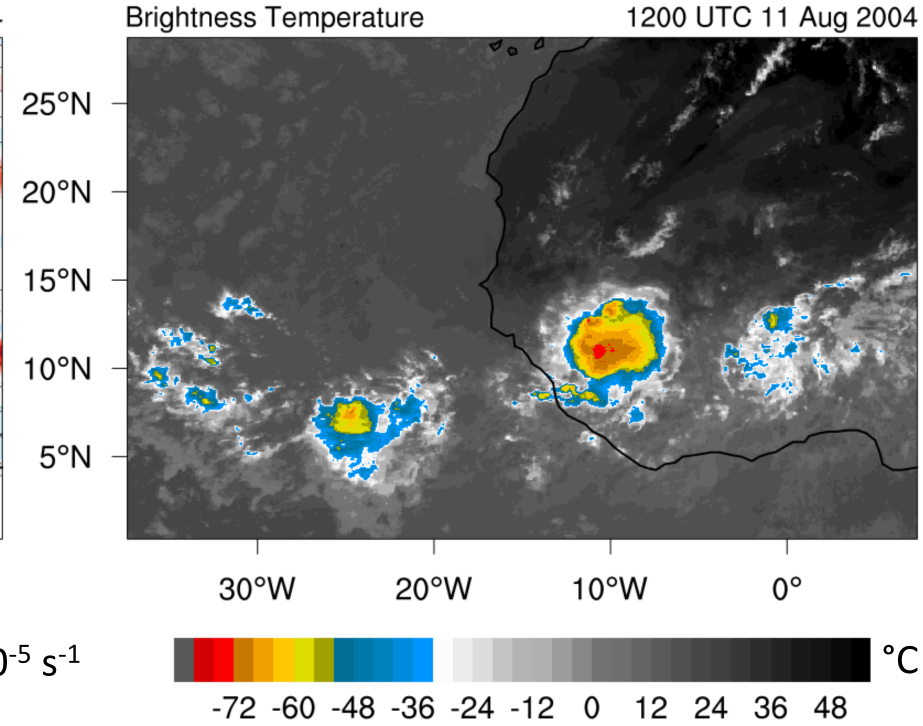

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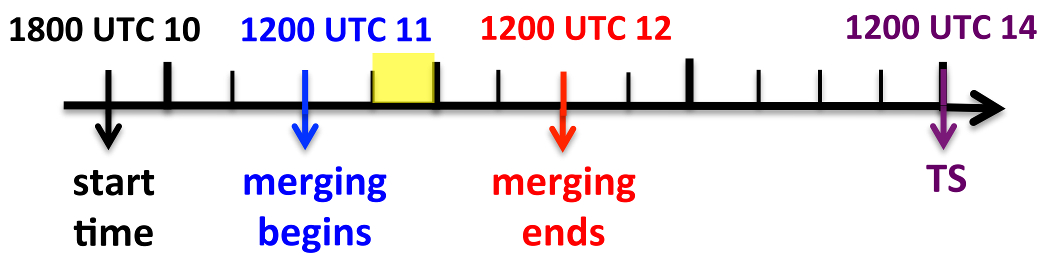

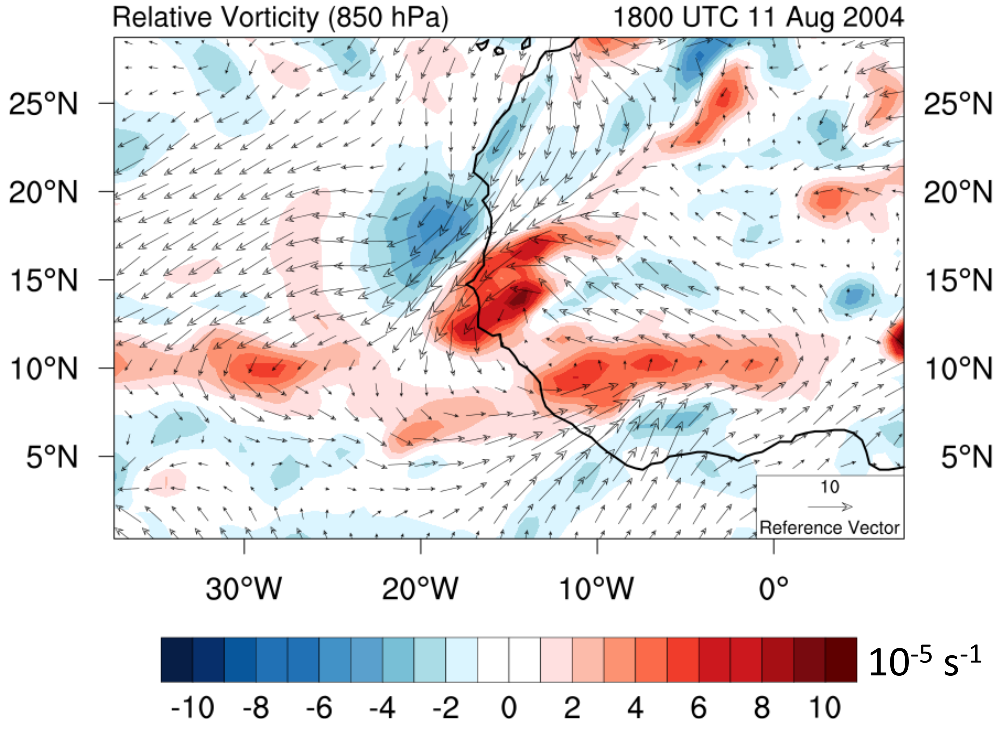

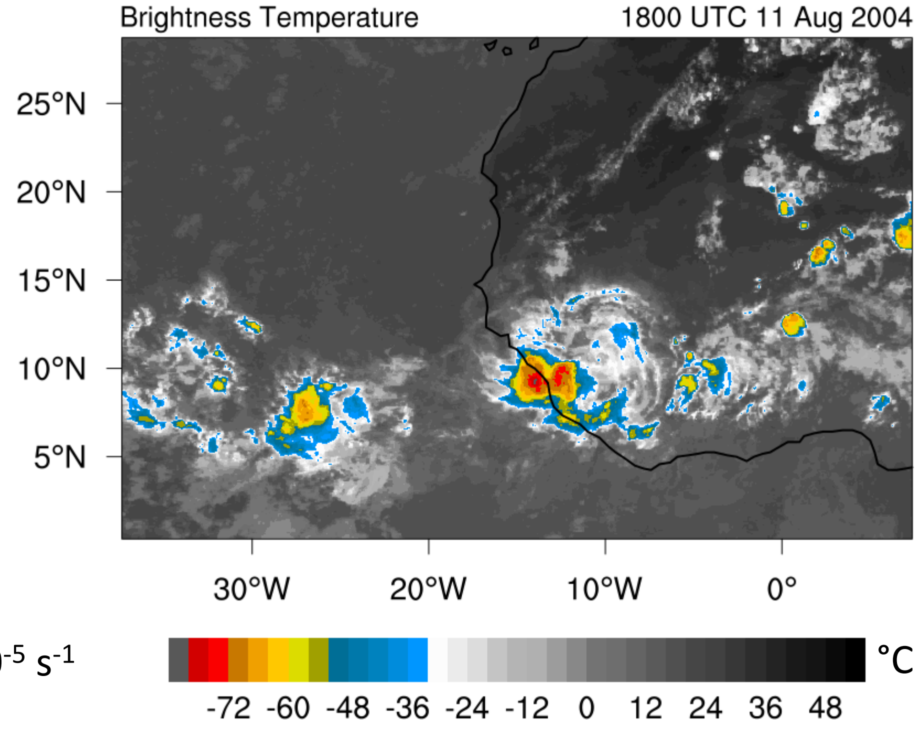

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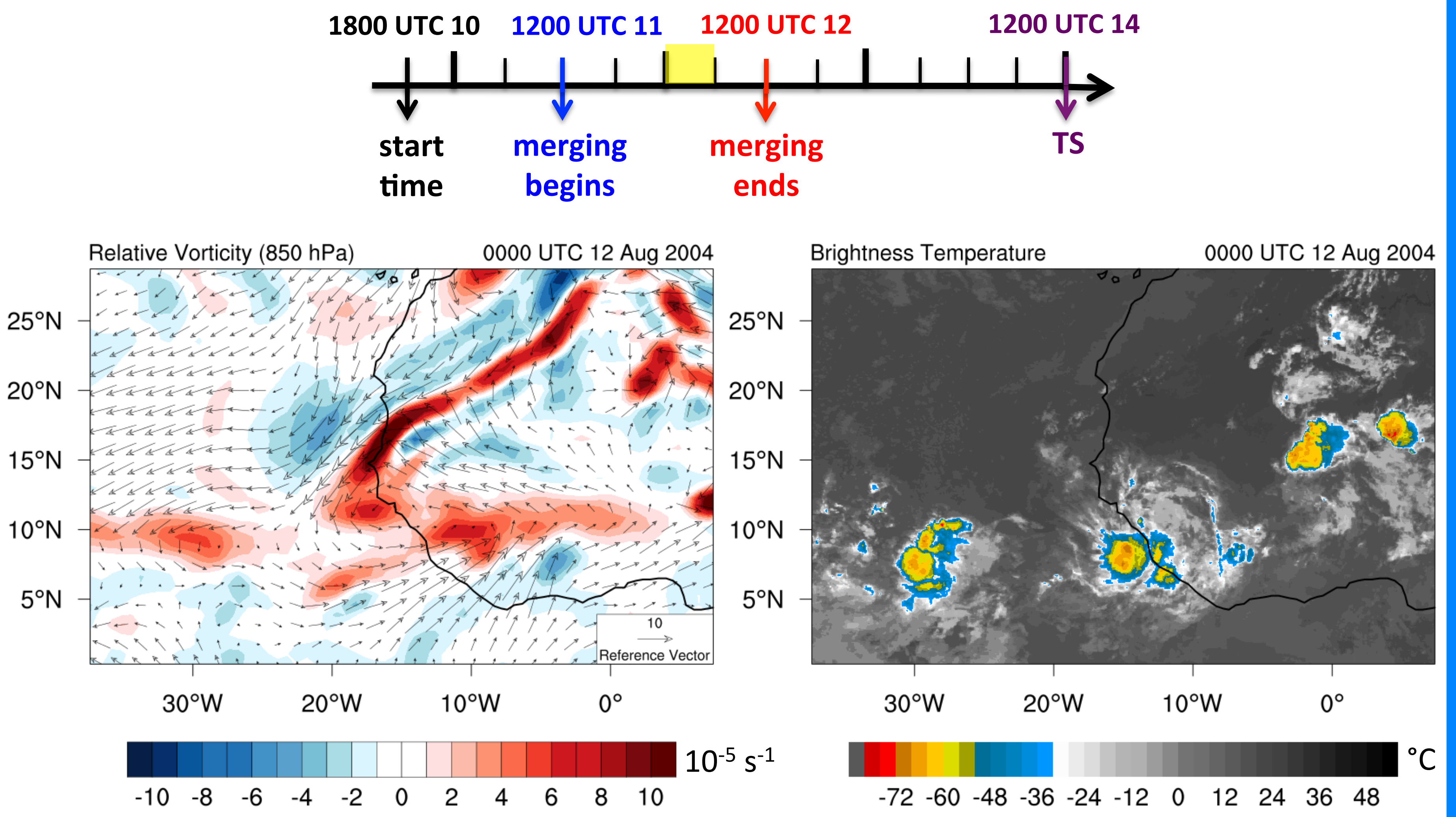

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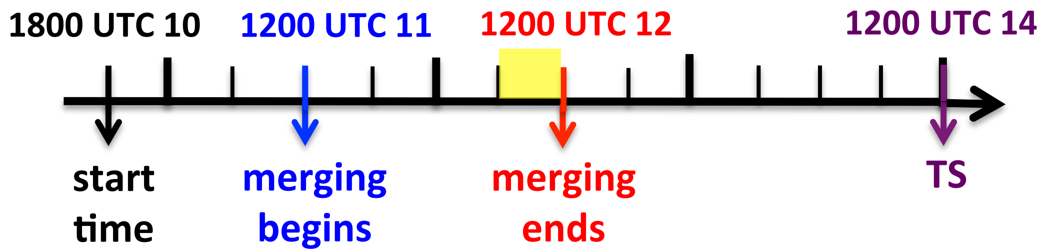

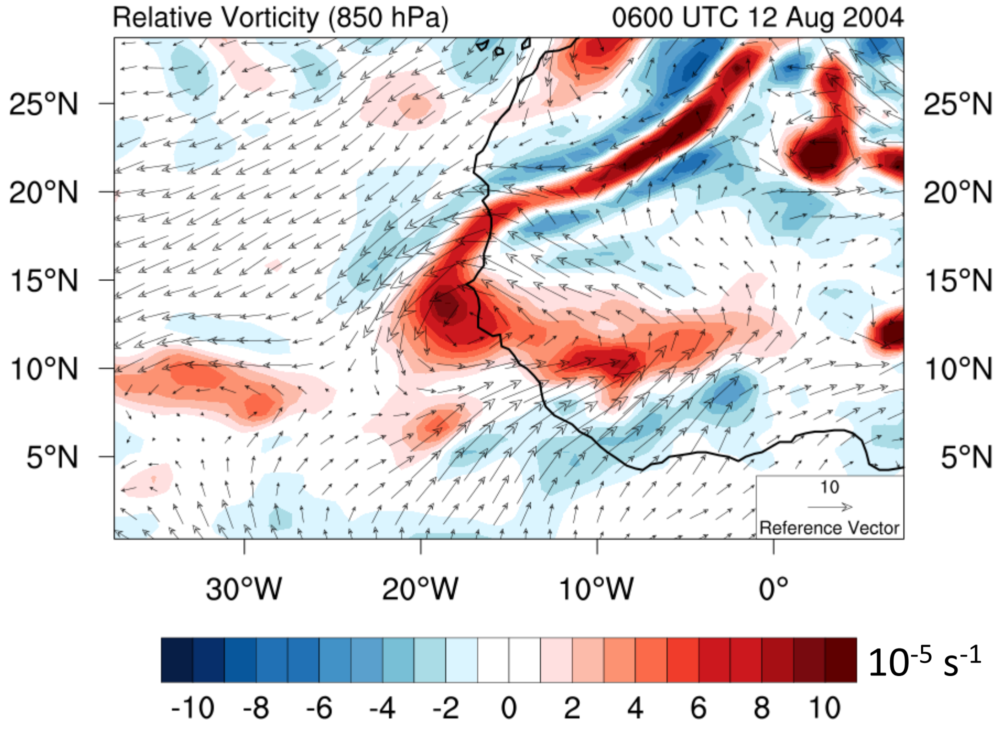

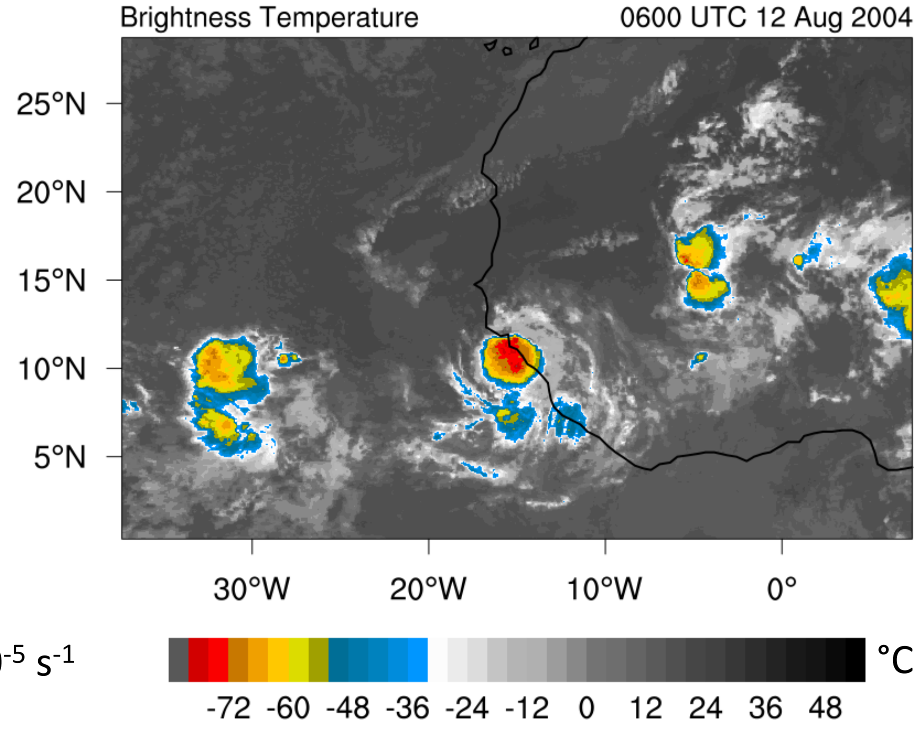

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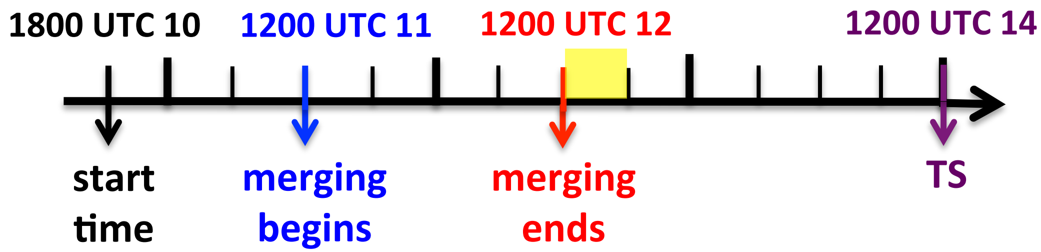

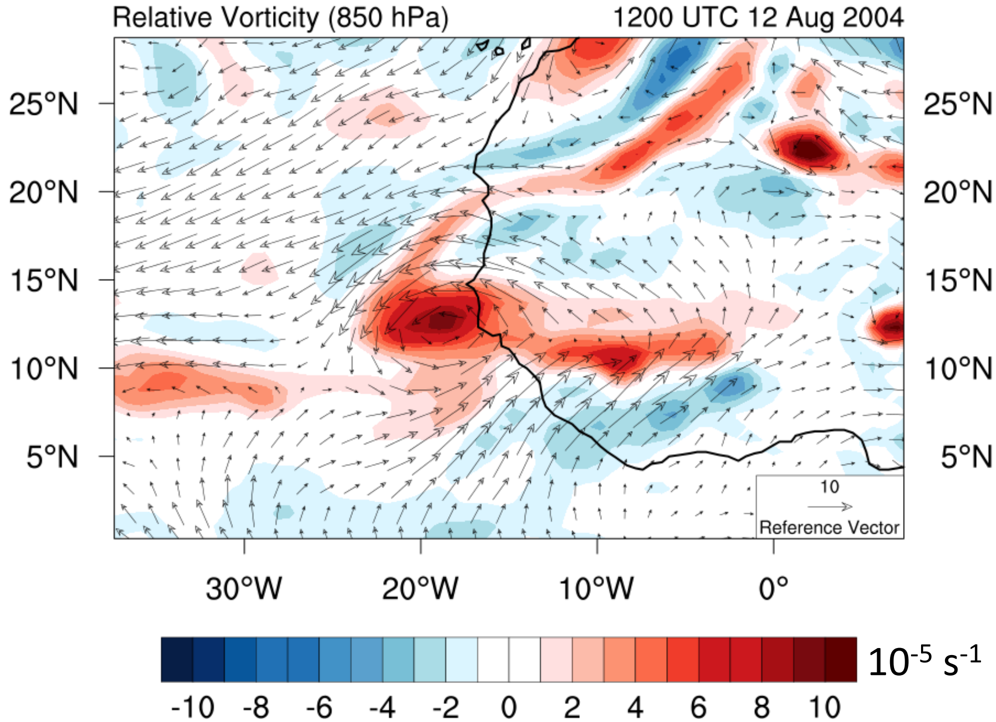

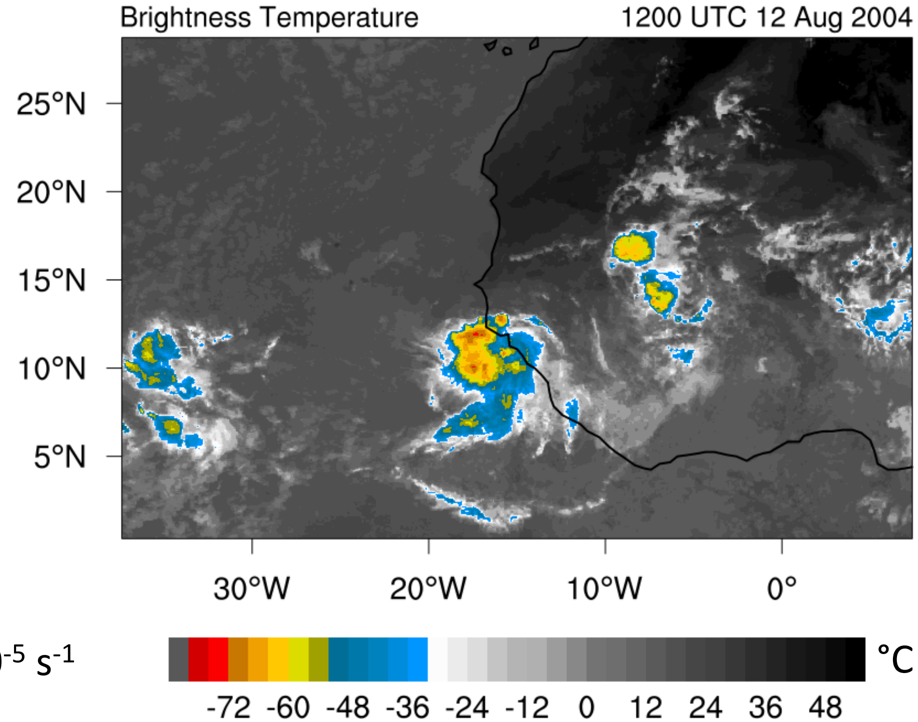

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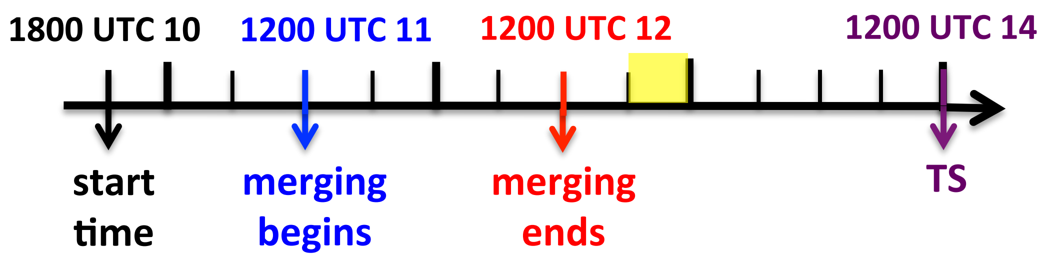

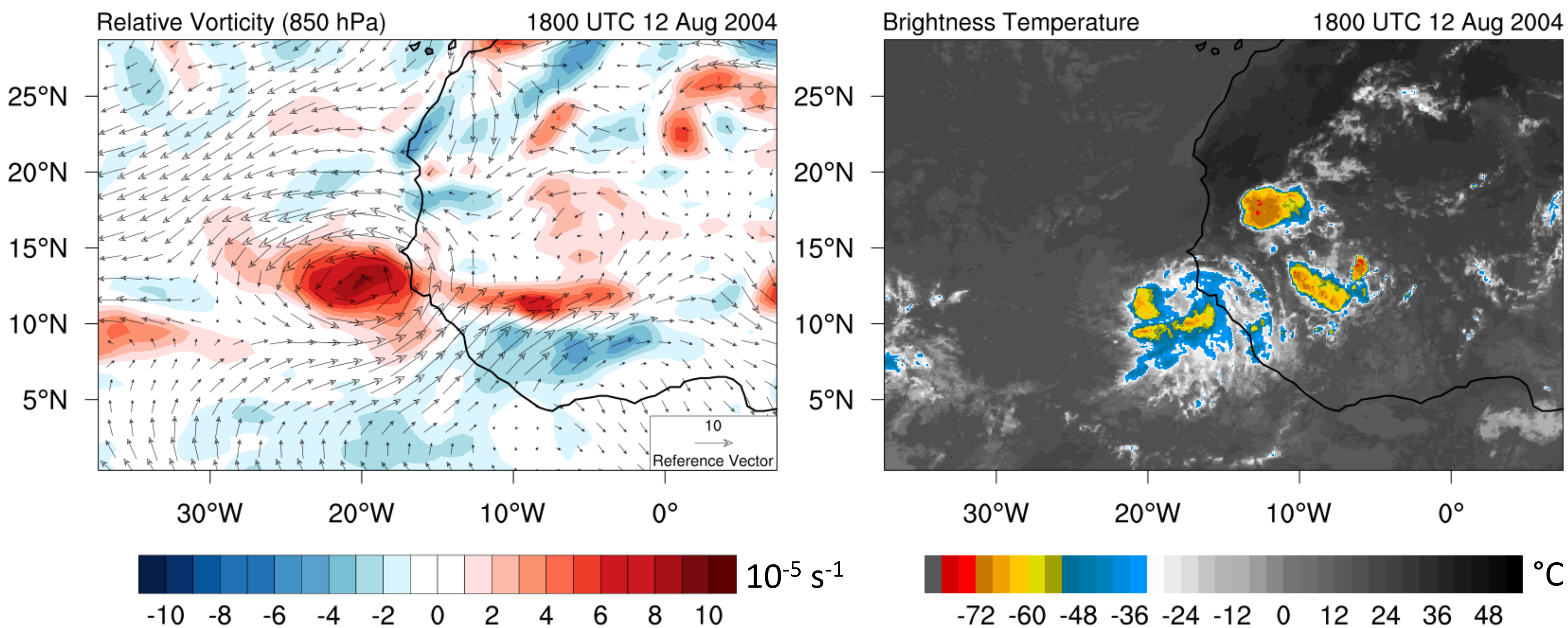

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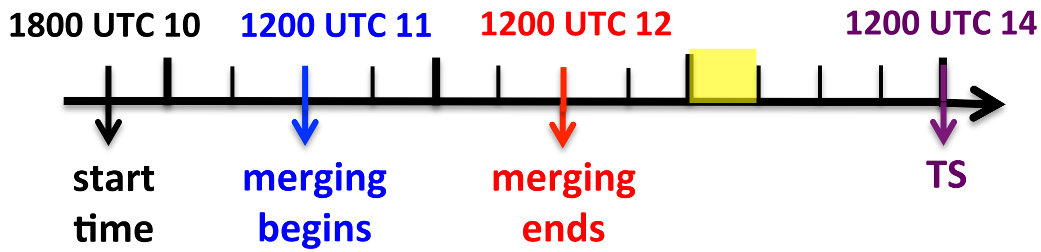

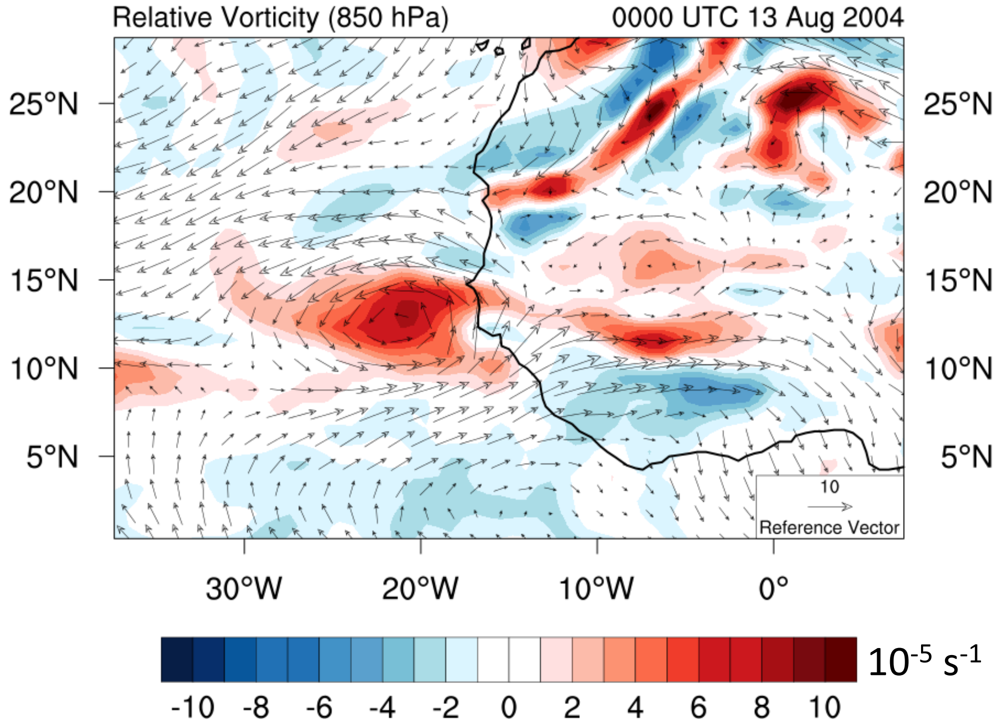

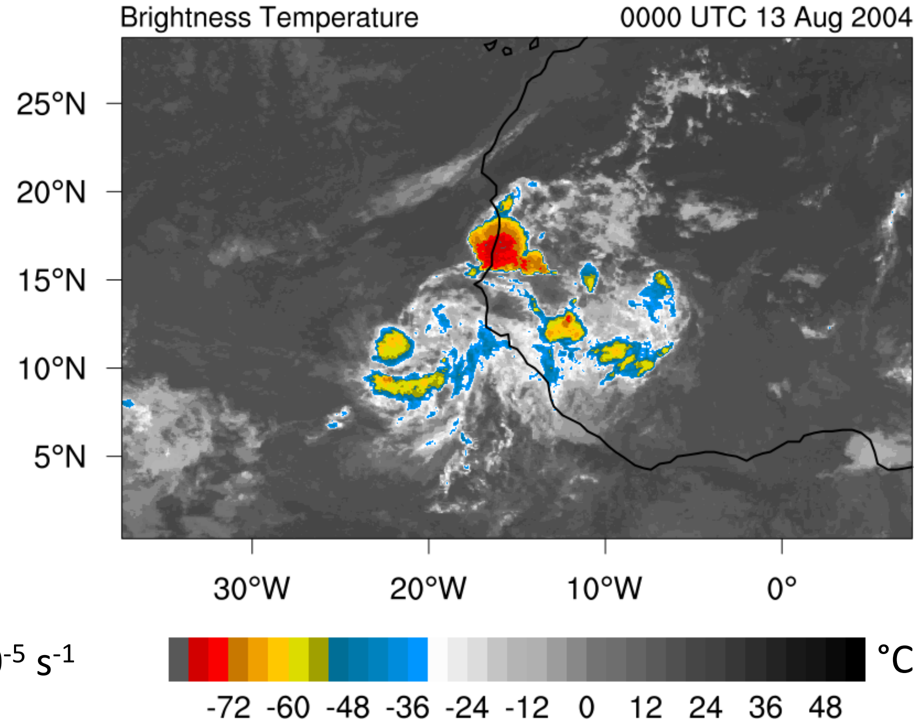

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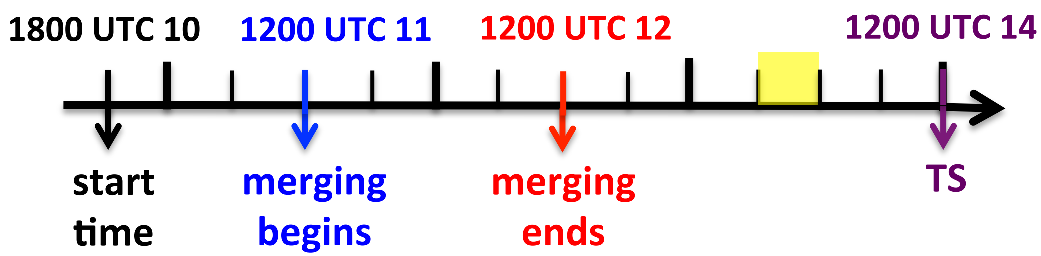

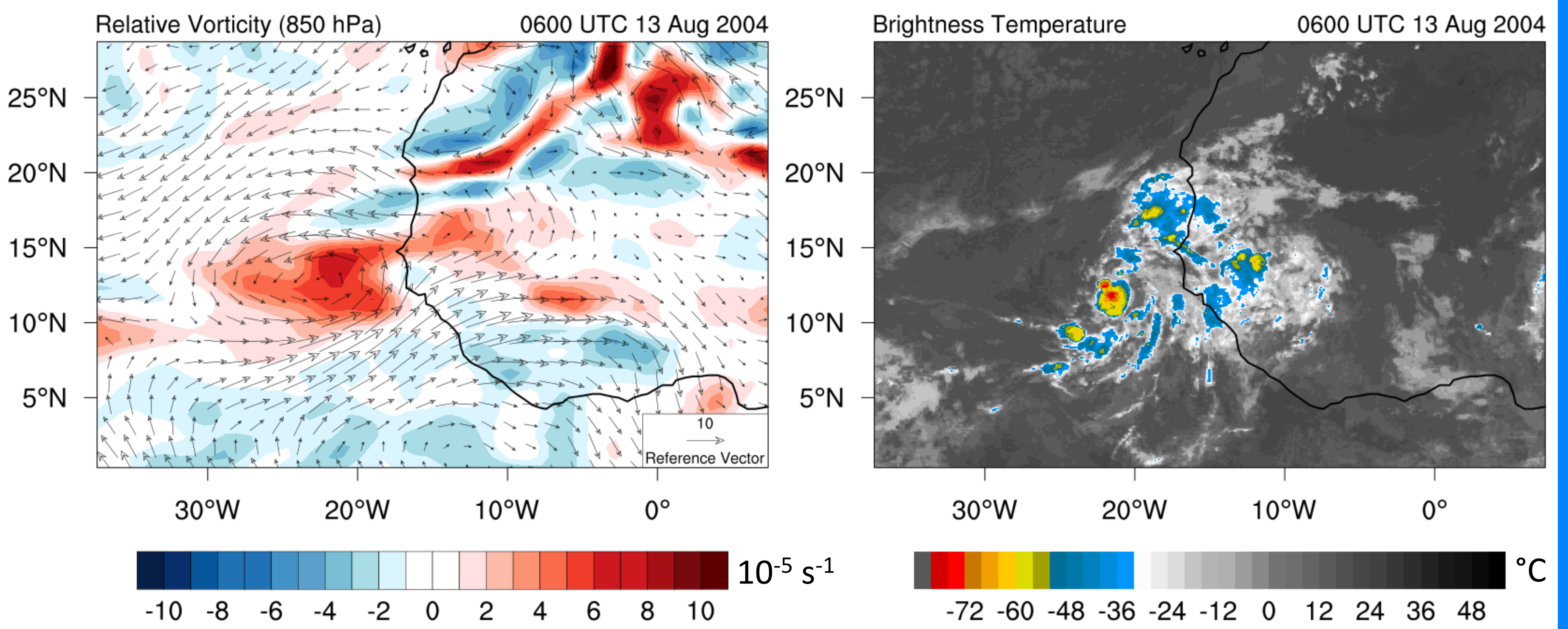

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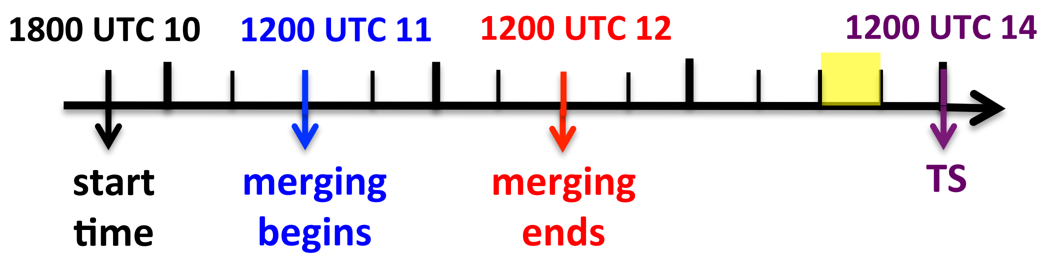

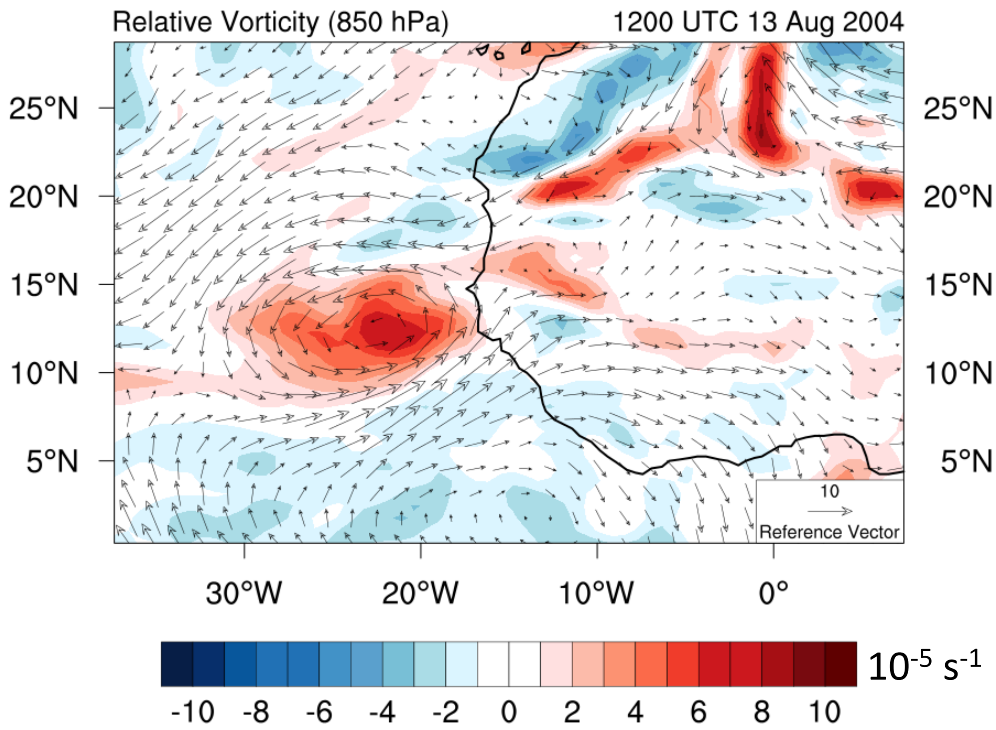

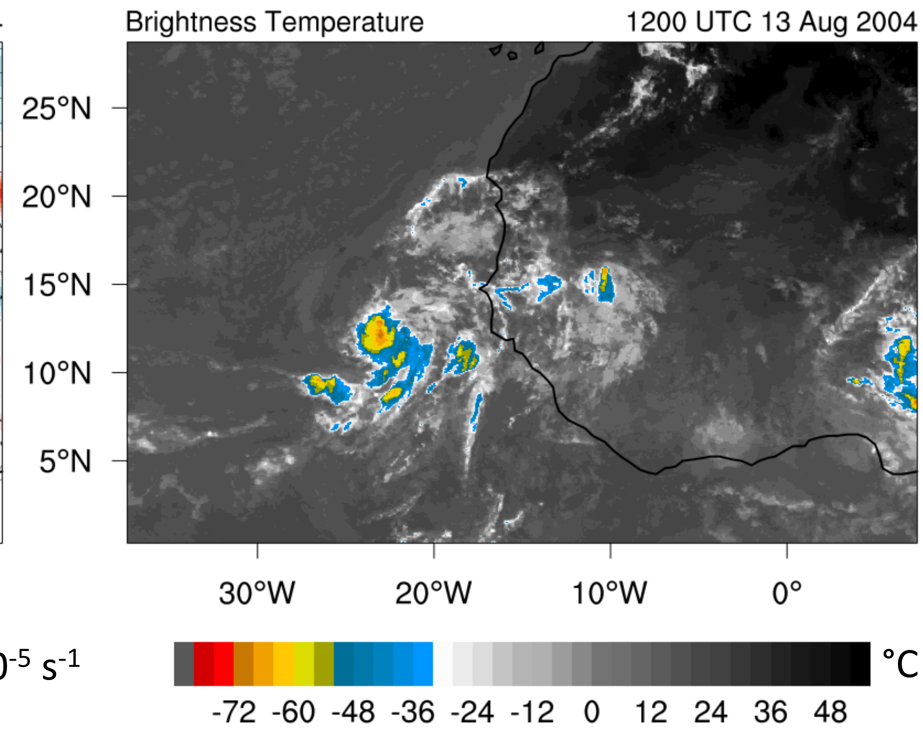

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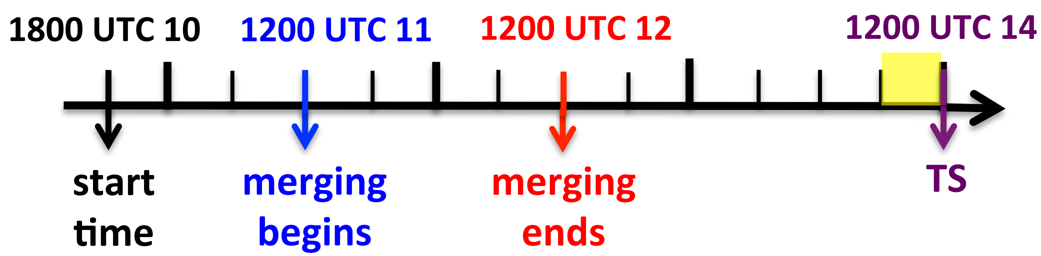

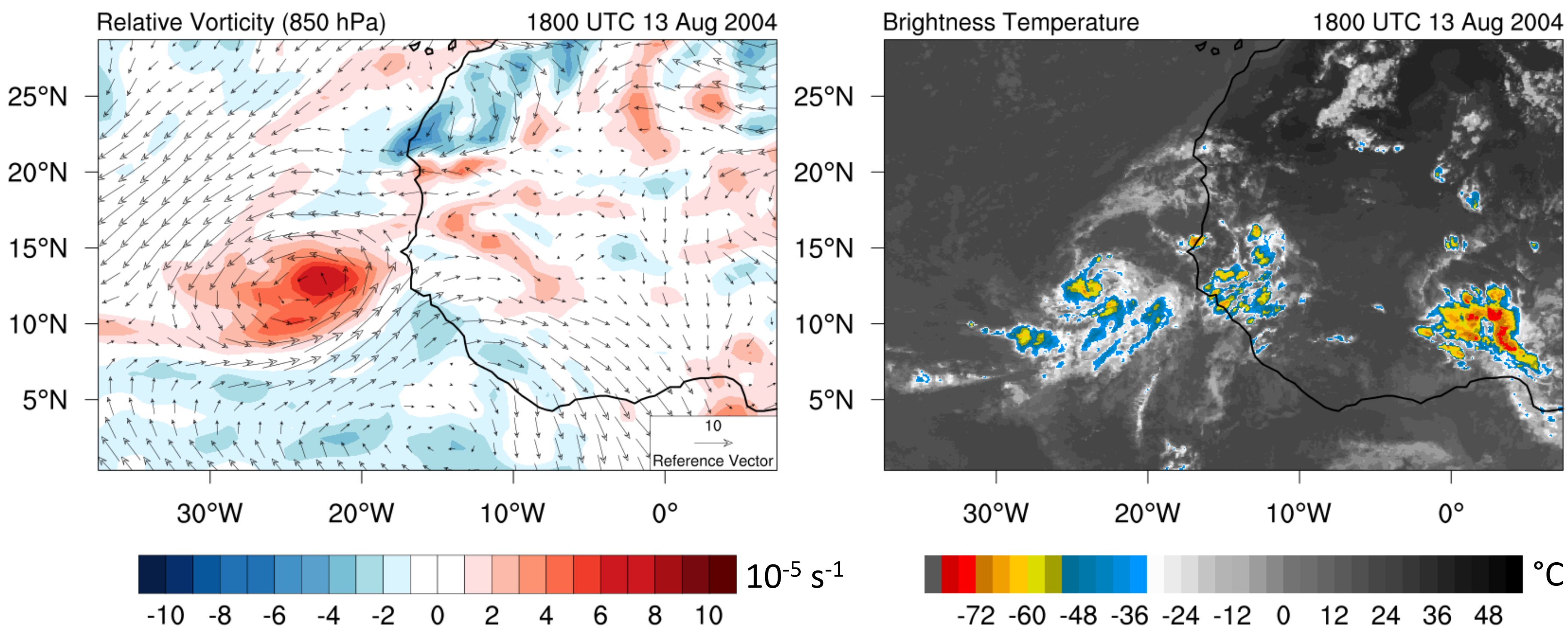

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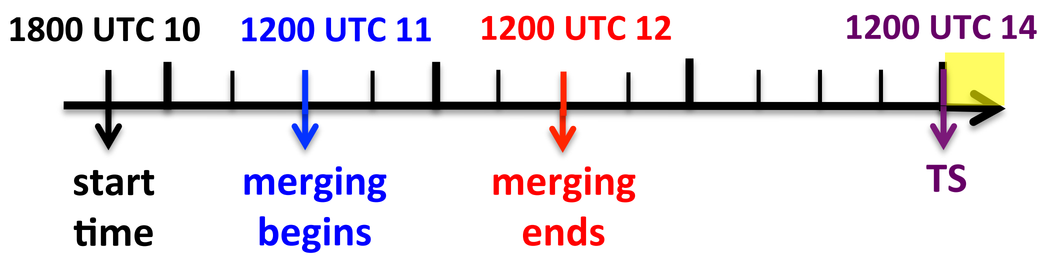

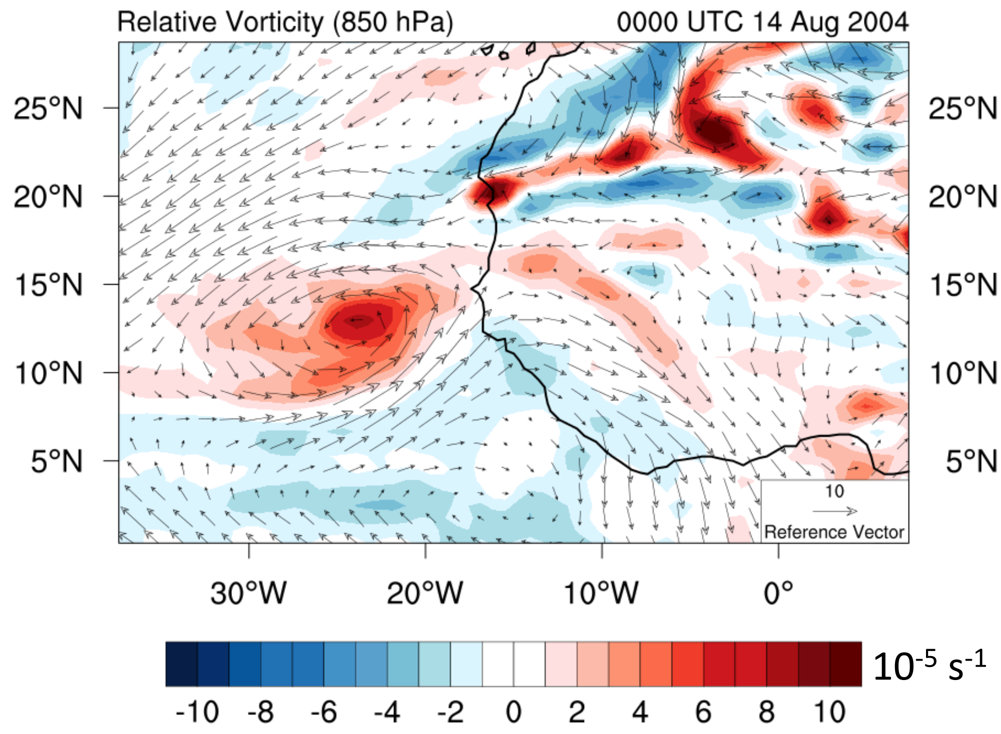

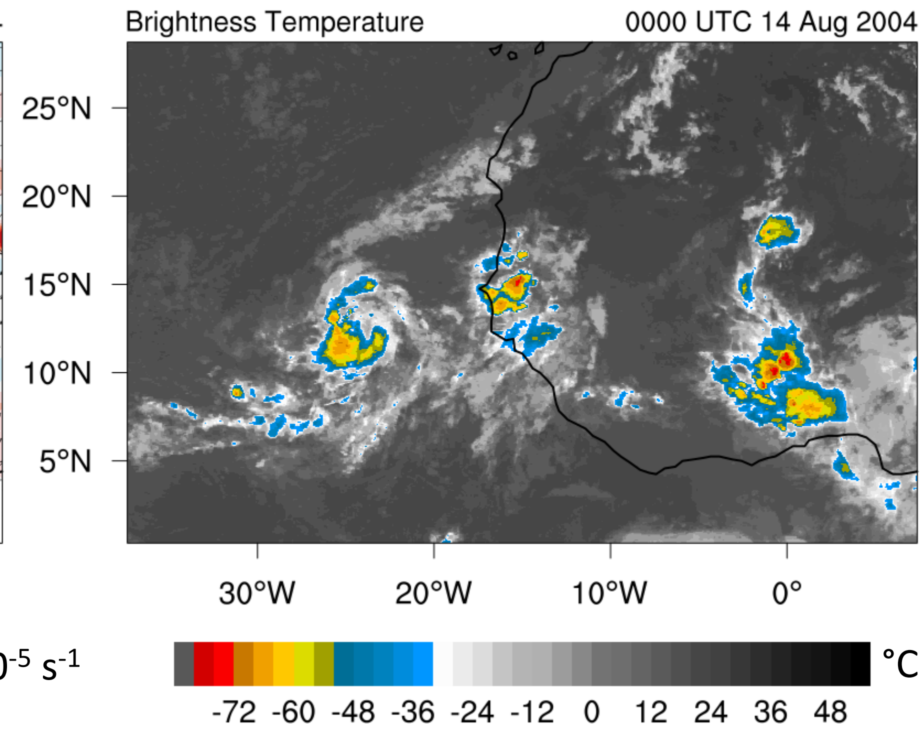

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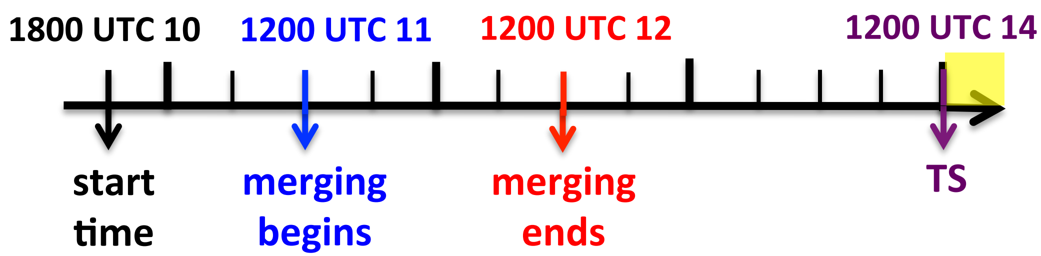

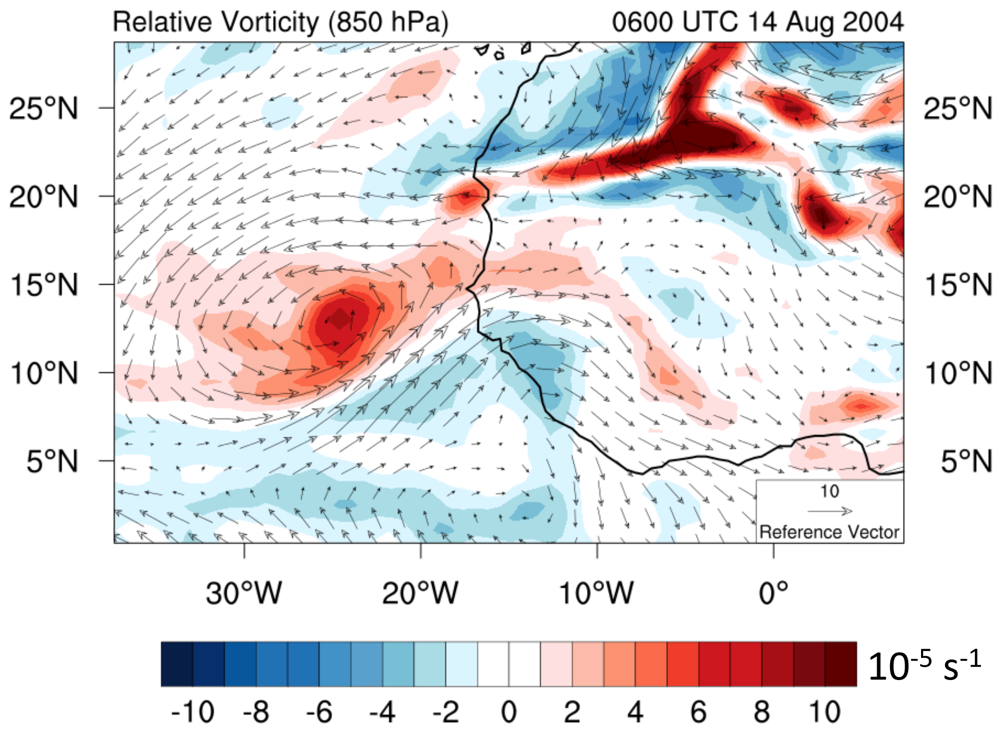

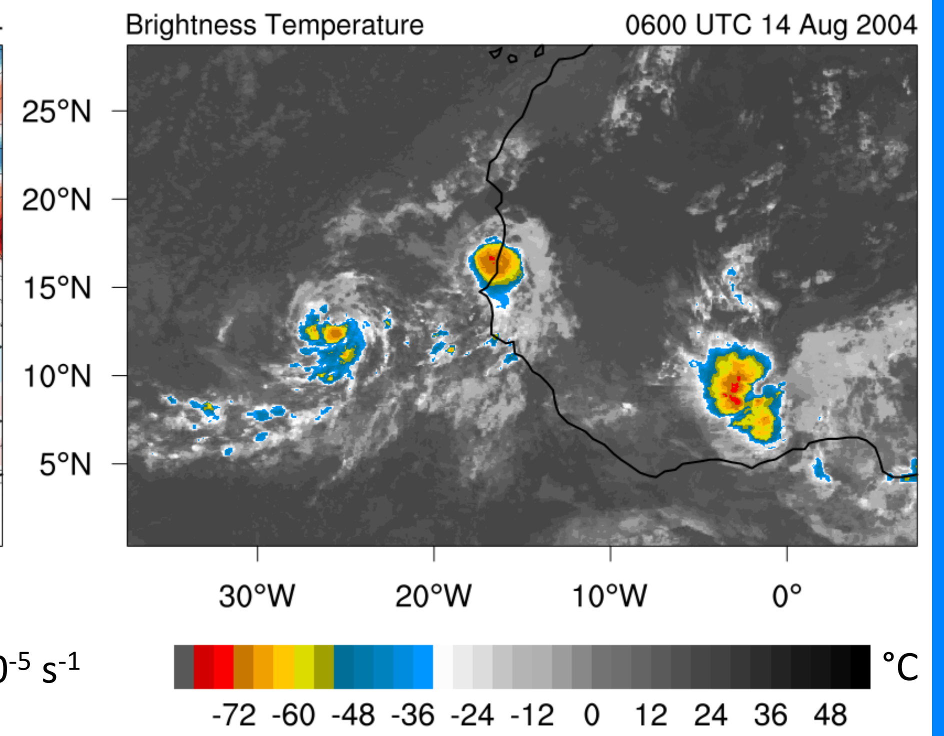

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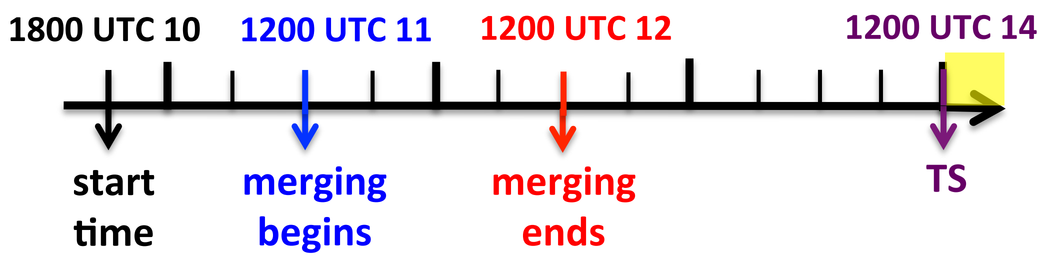

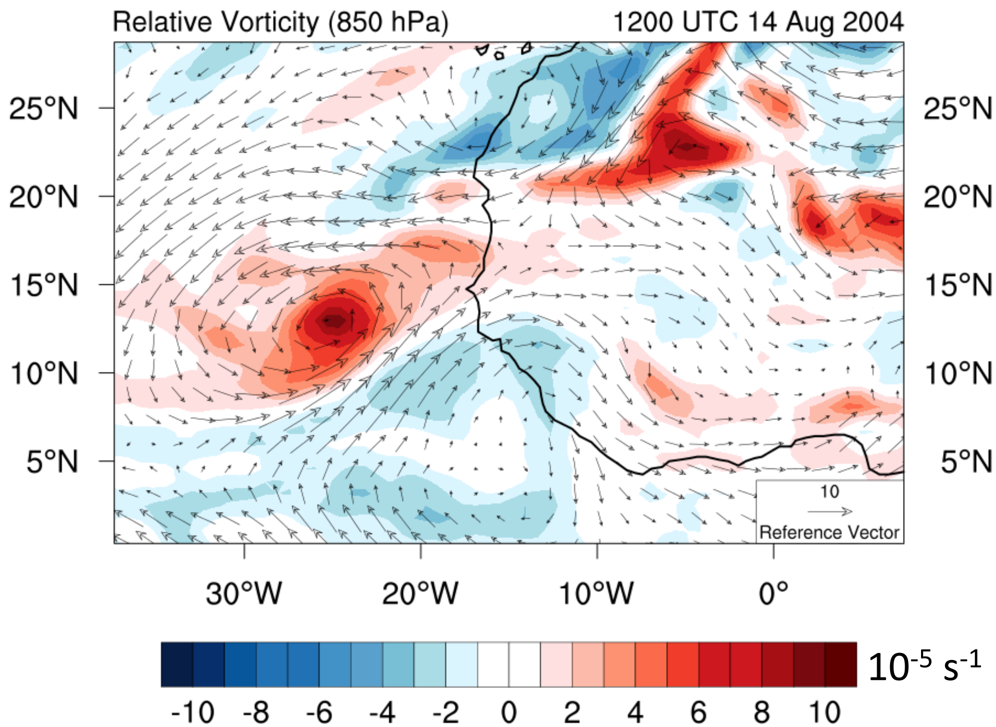

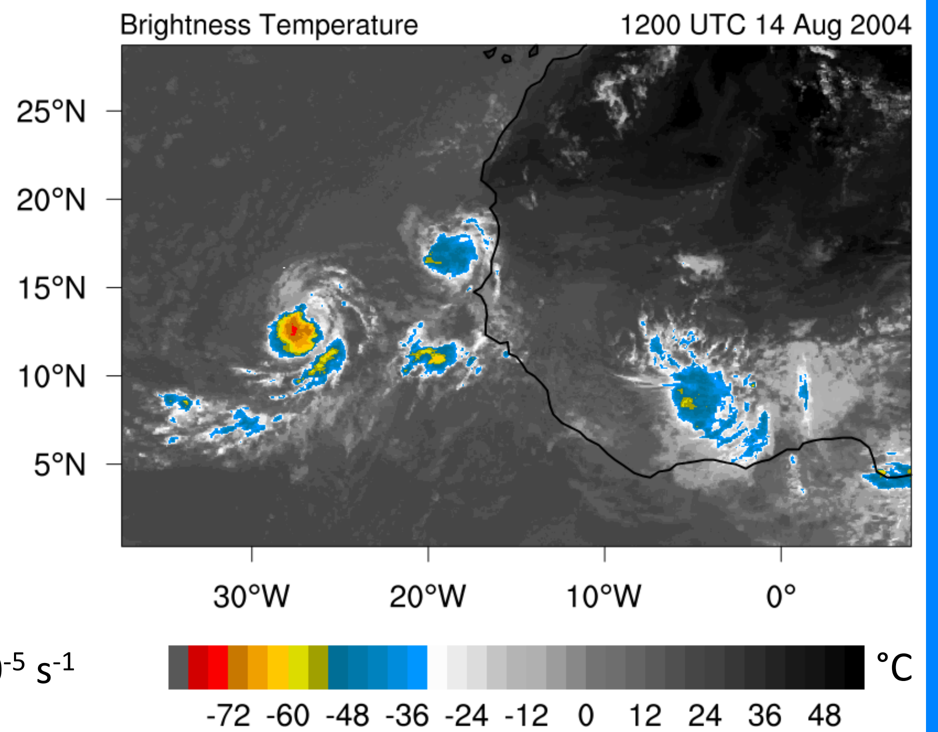

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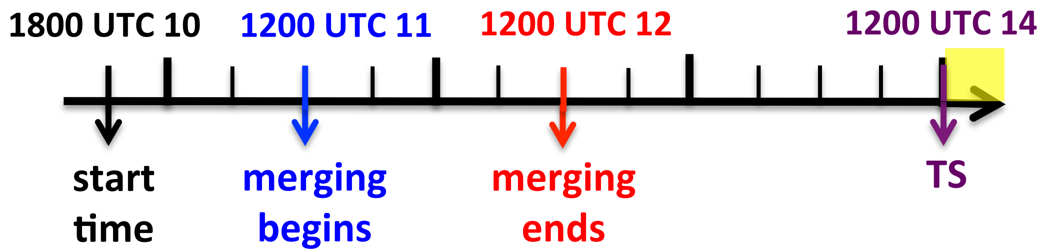

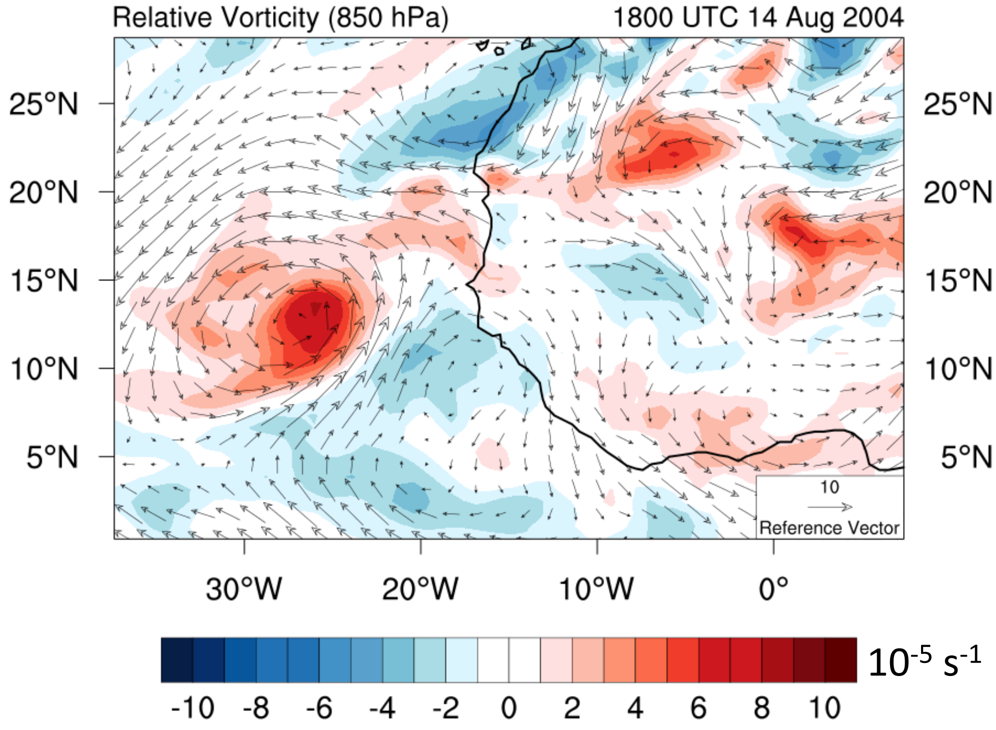

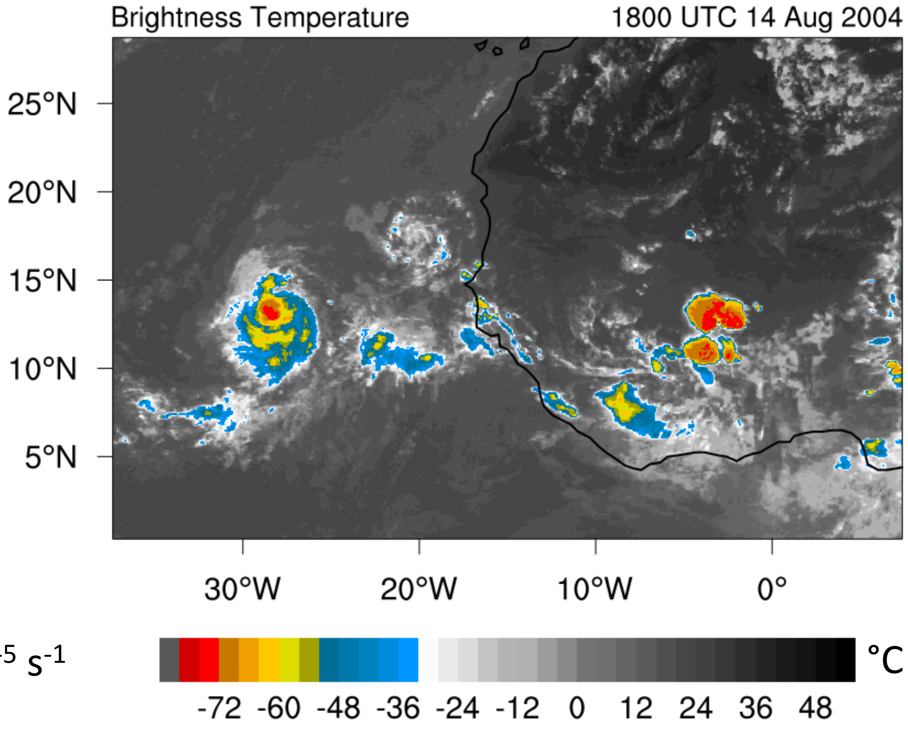

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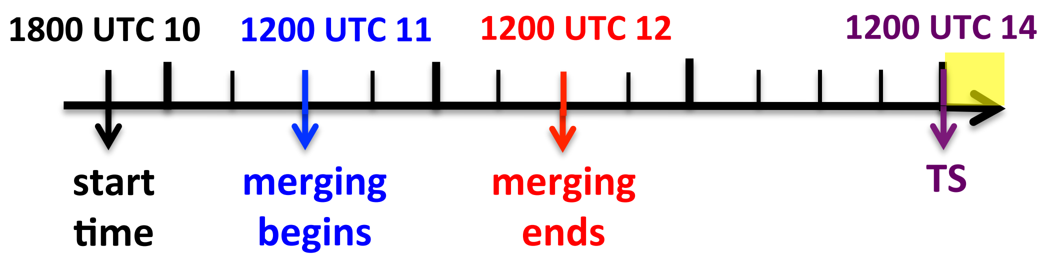

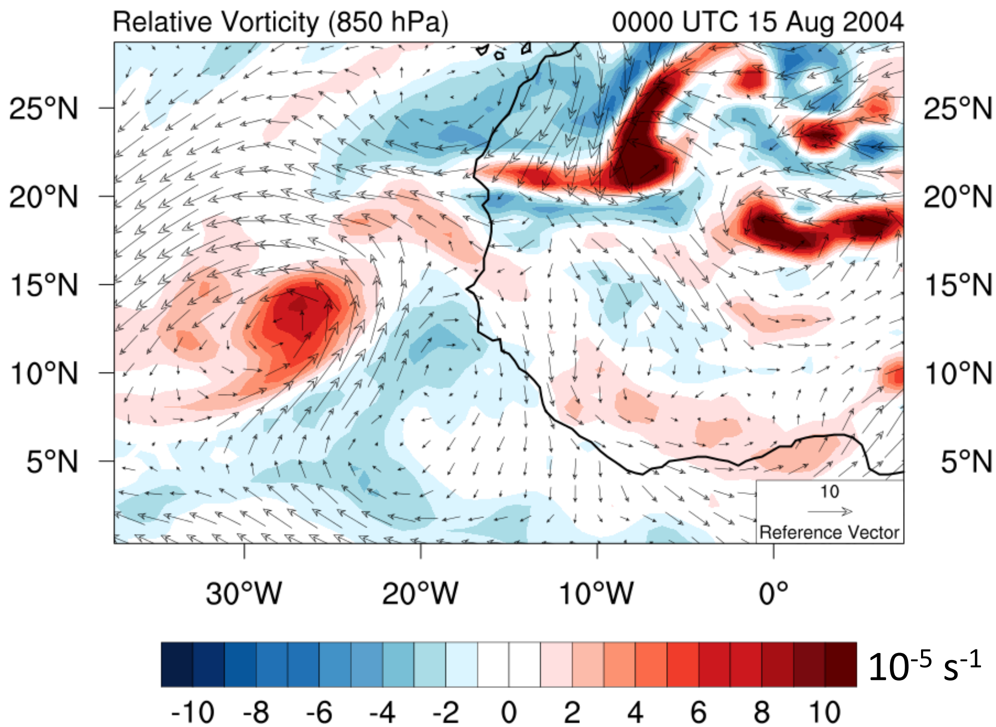

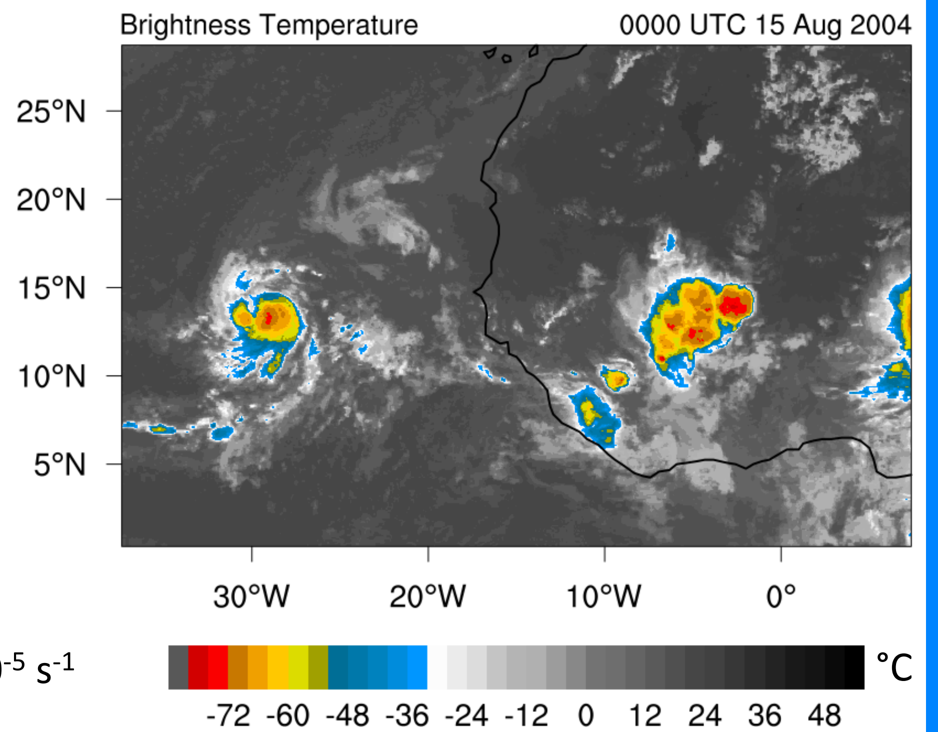

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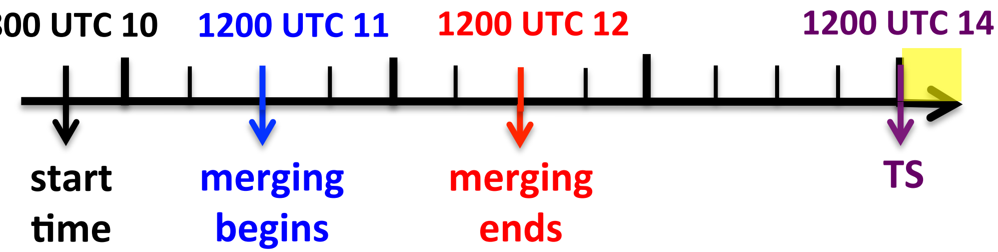
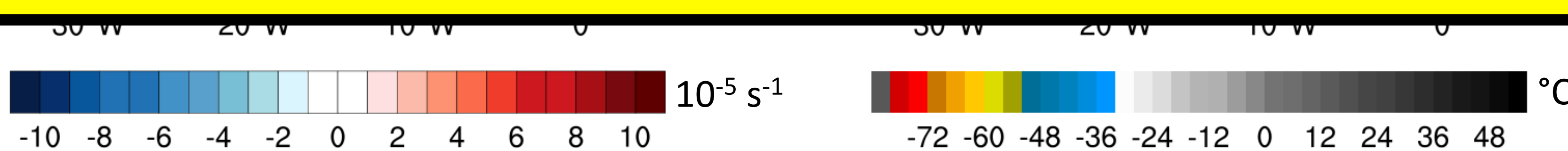


Hypothesis 1:

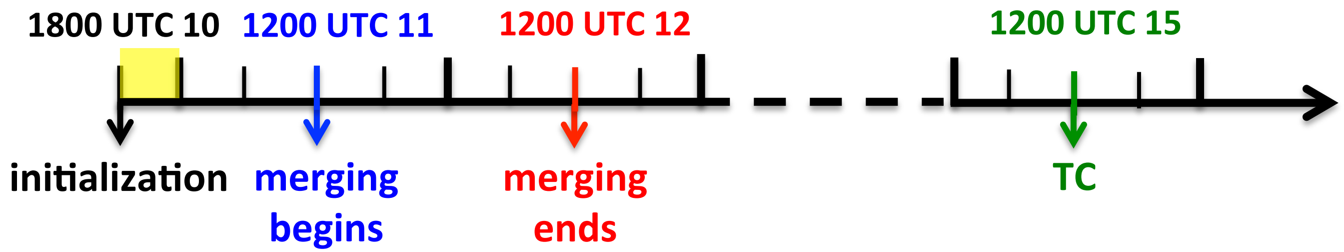
Merging between the coherent AEW_N and AEW_S is linked to the intensification of Hurricane Danielle

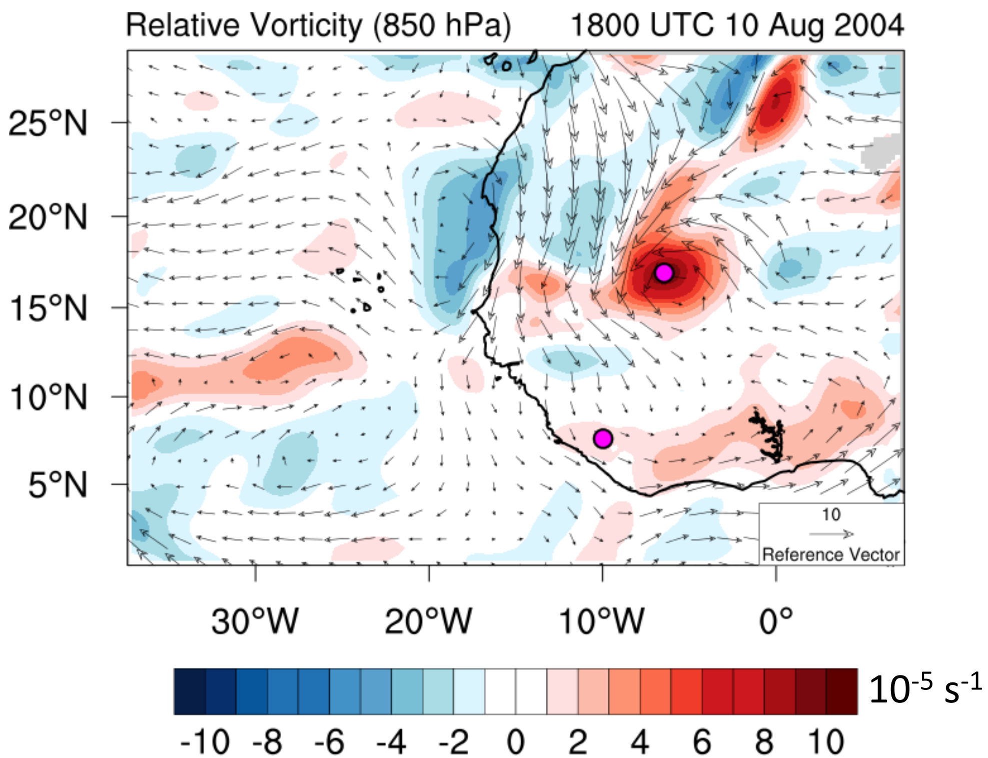
Hypothesis 2:

Although TC development would initially be frustrated after merging due to dry air associated with the AEW_N, moistening may have occurred in Hurricane Danielle from continued convection



Control Simulation





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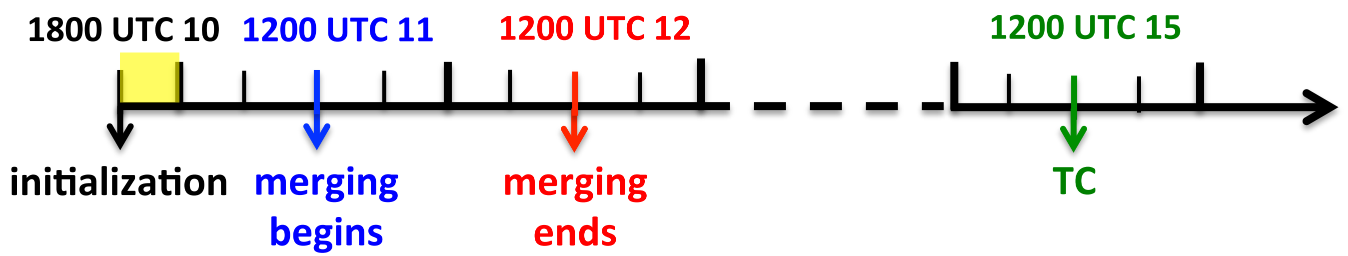

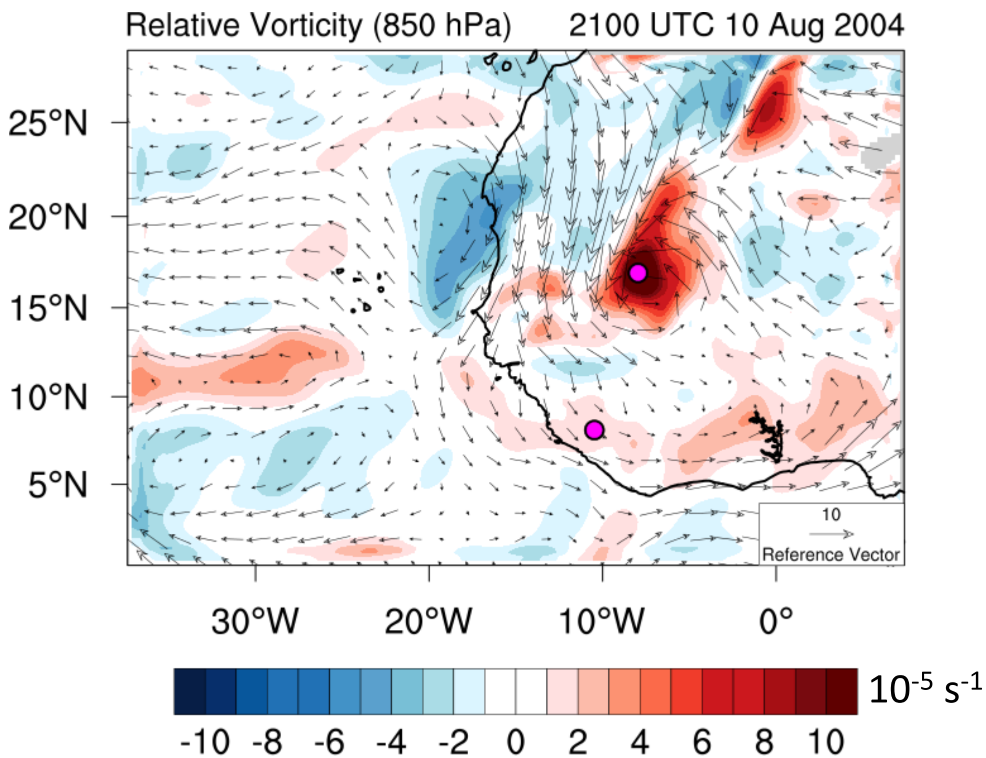

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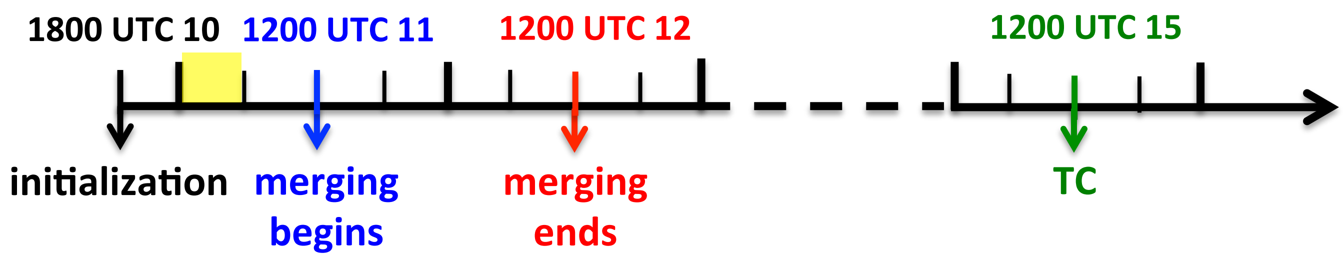

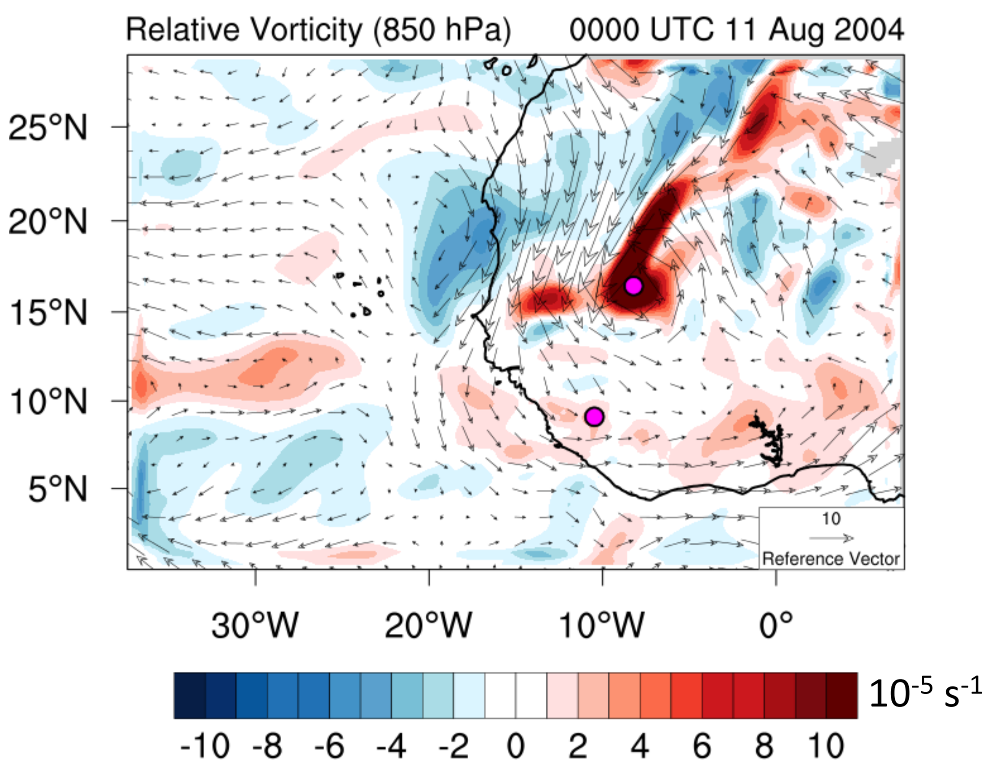

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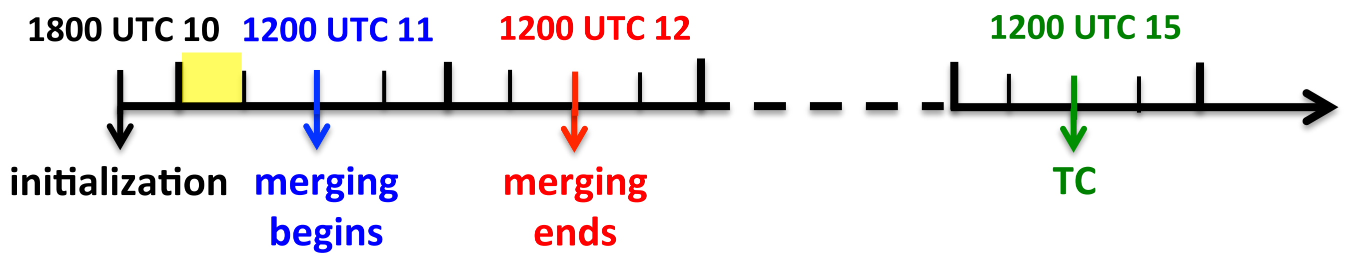

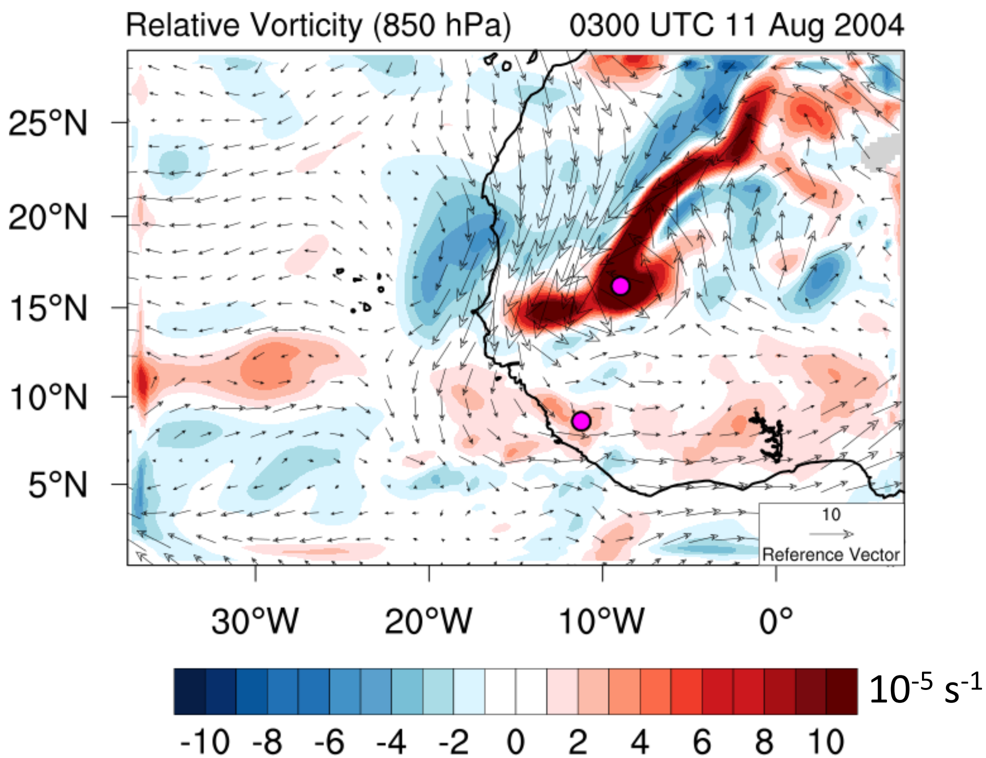

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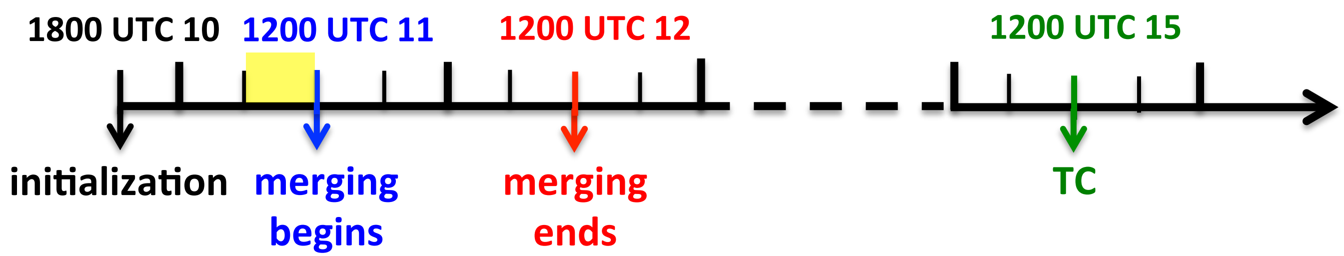

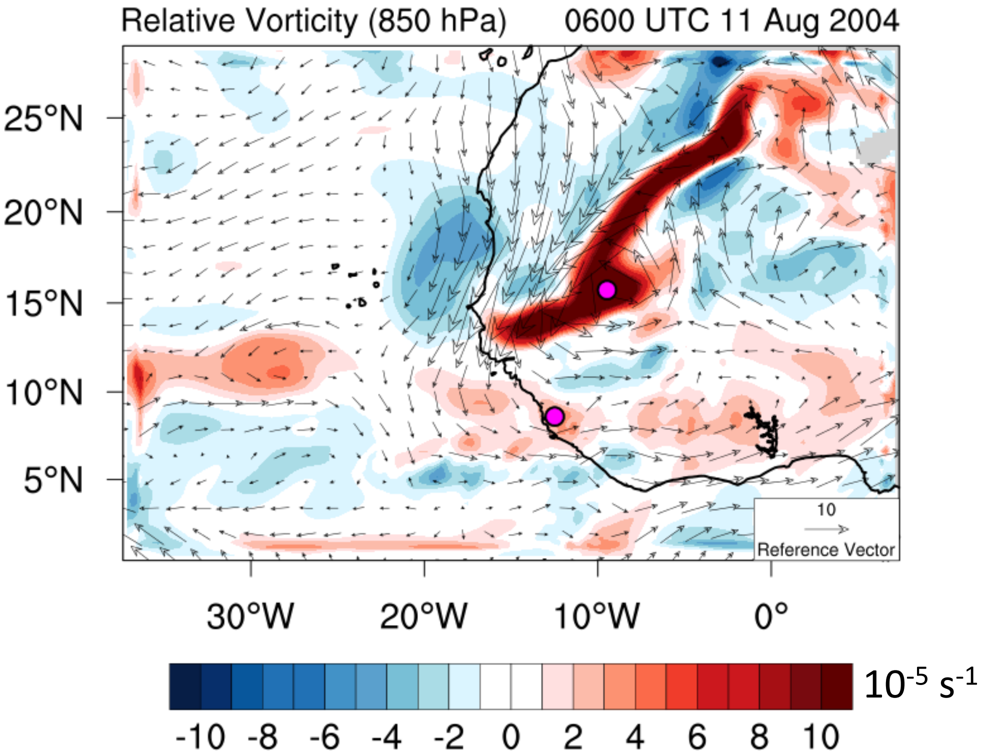

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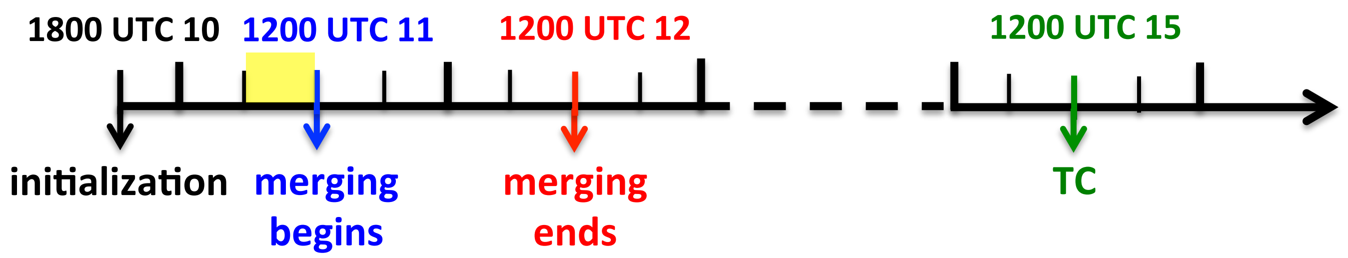

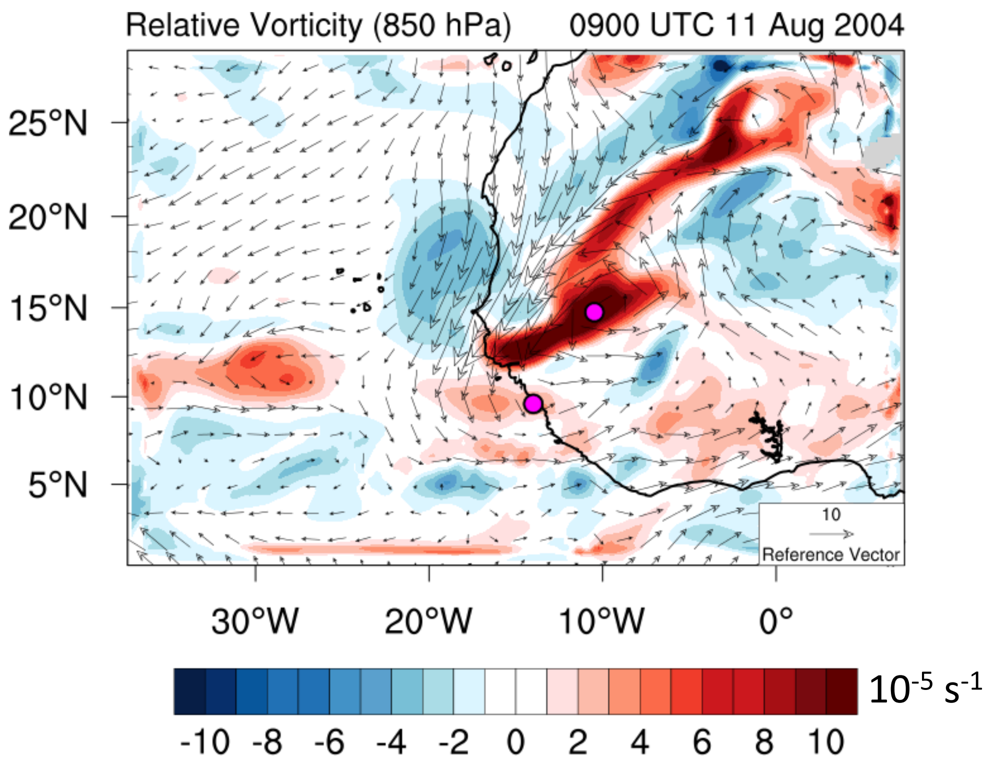

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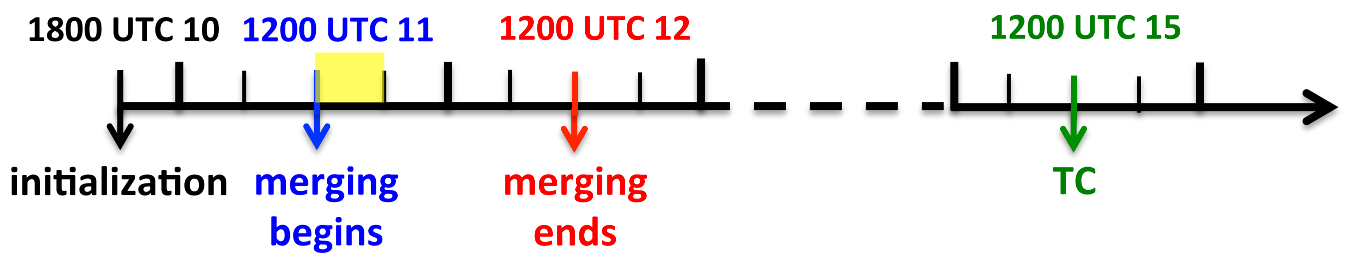

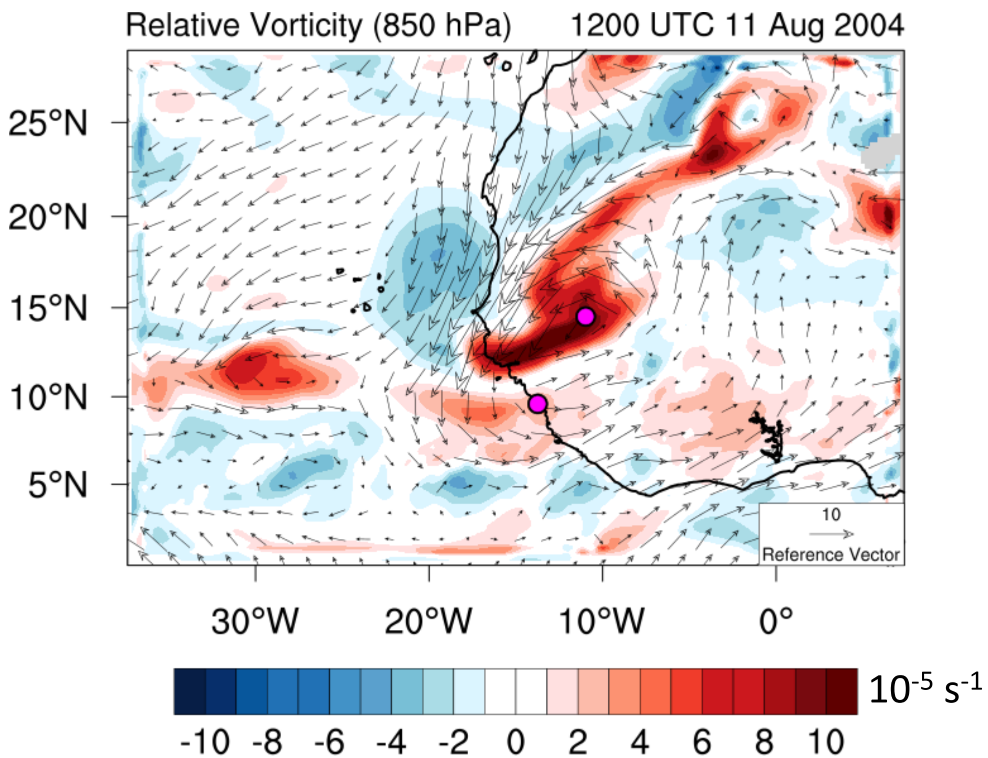

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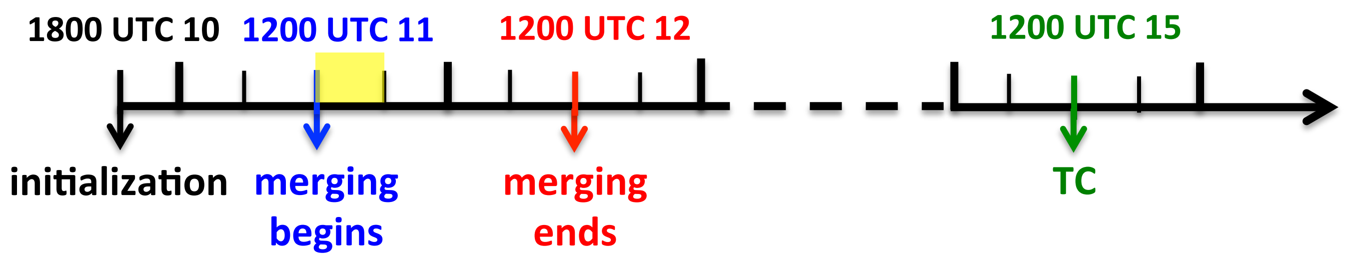

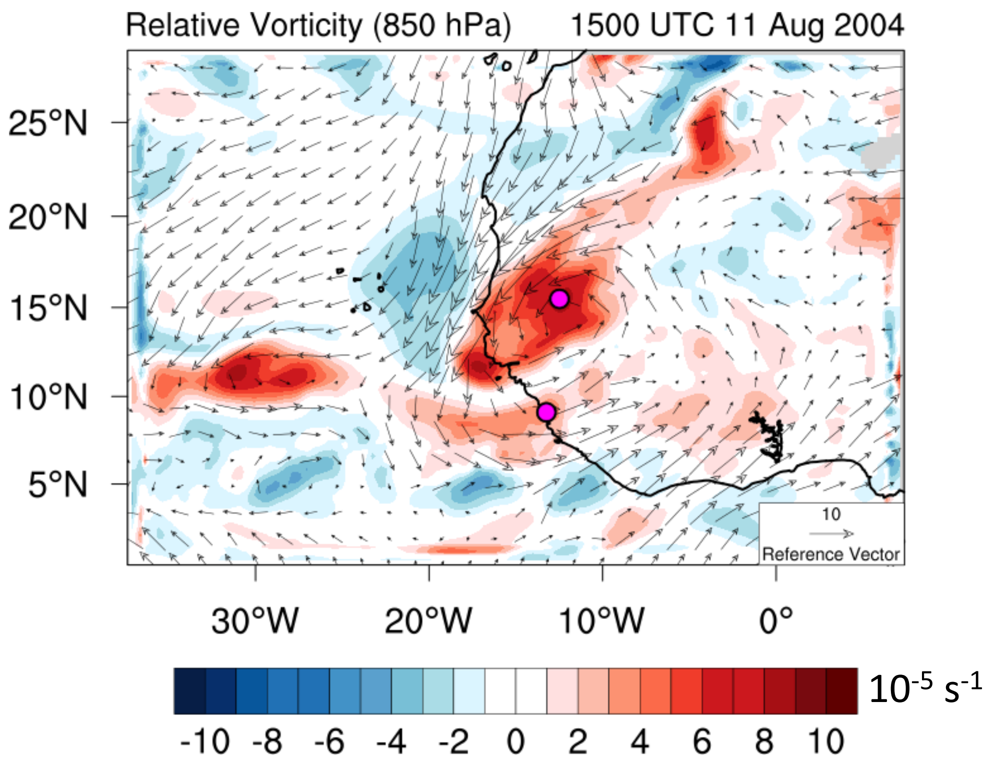

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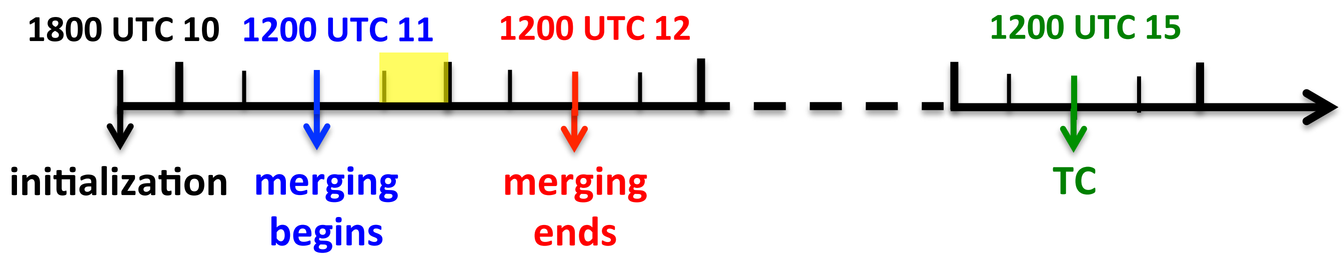

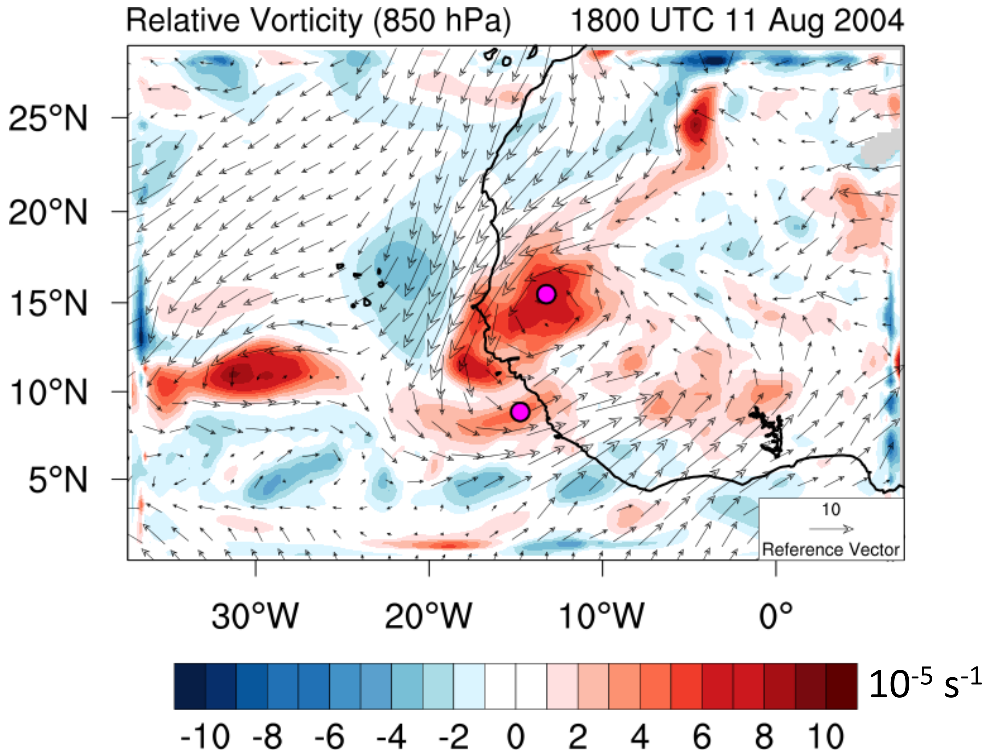

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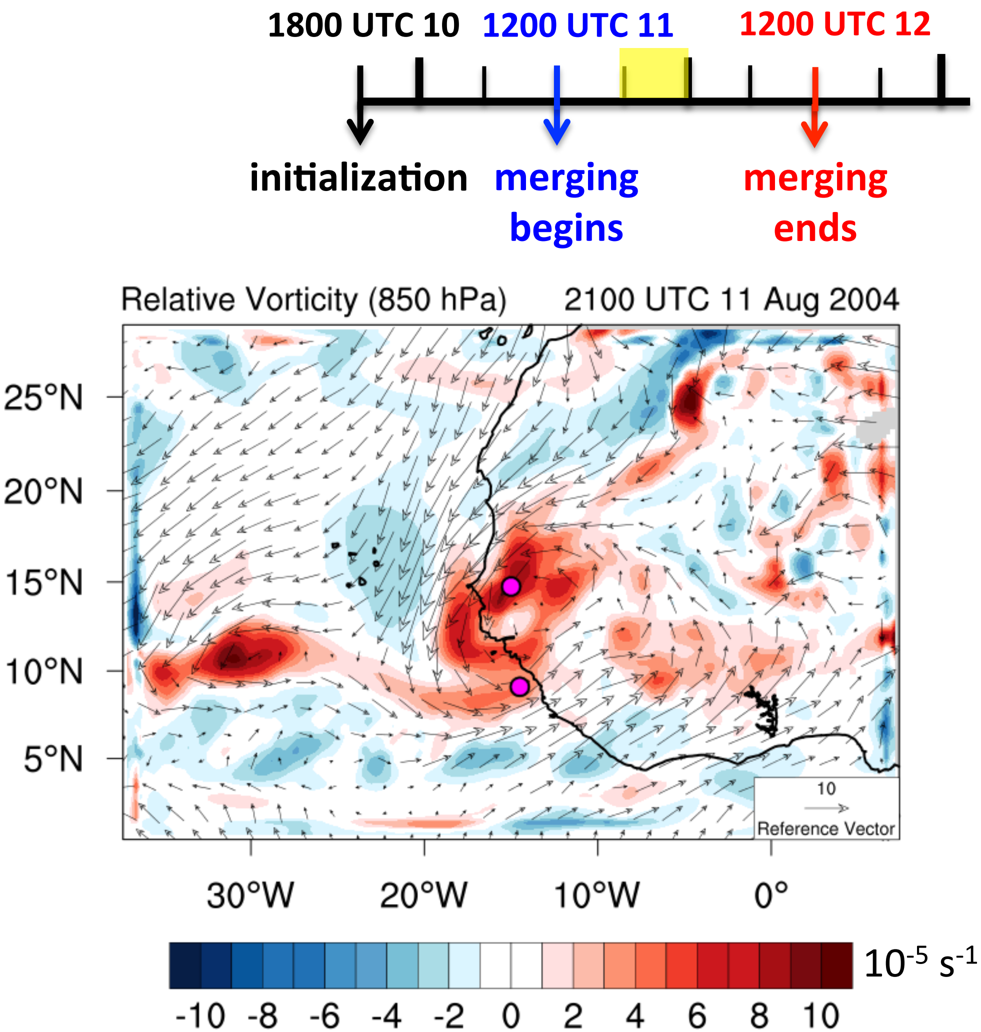

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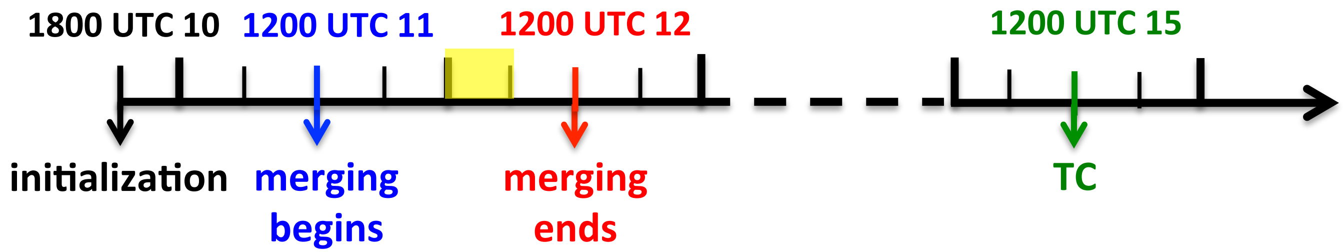

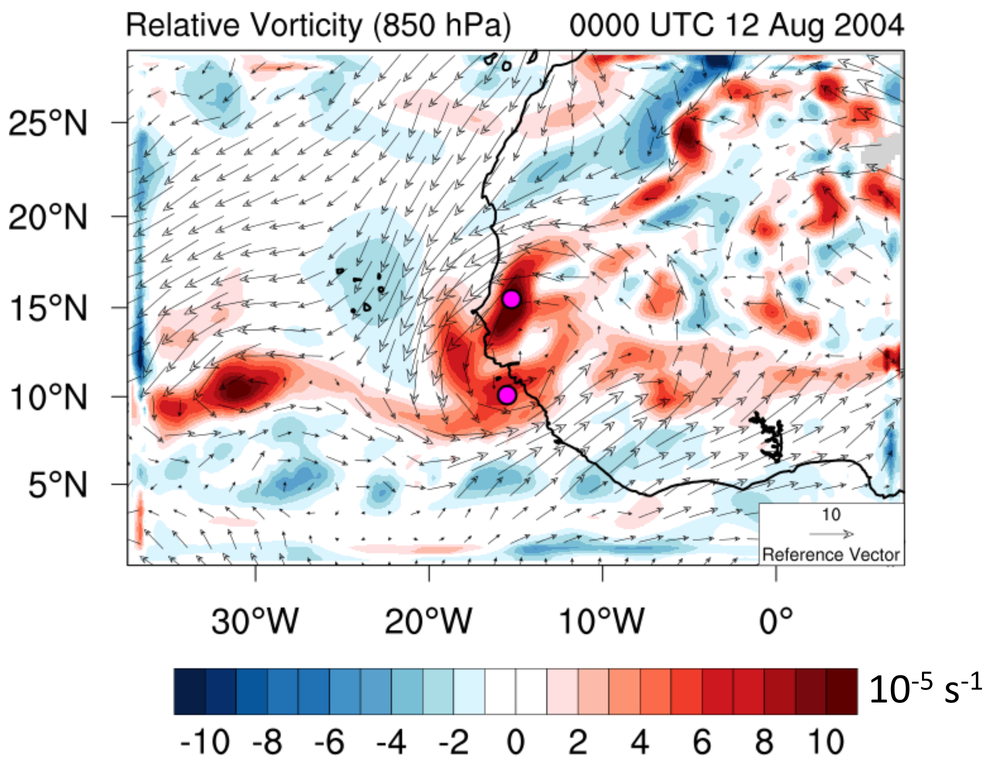

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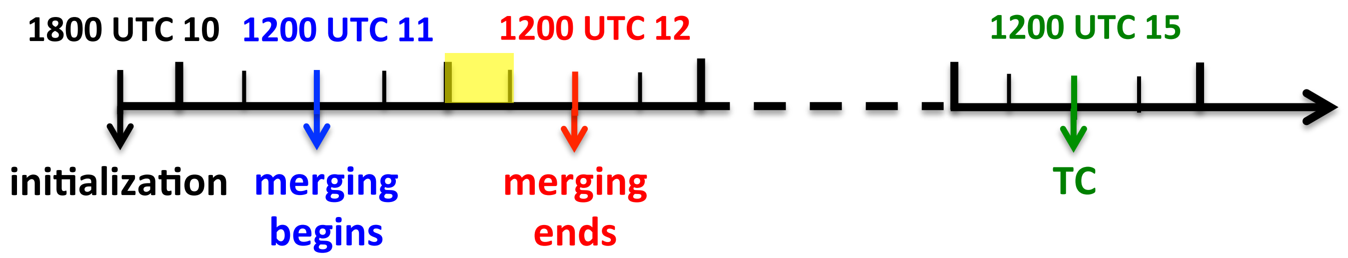

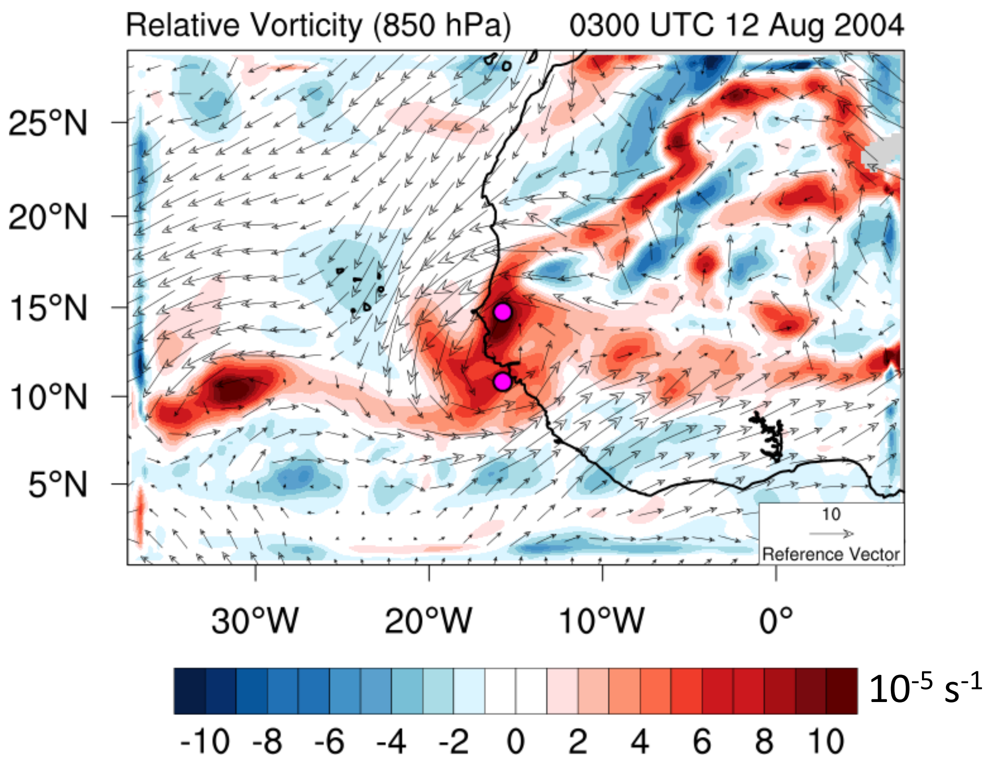

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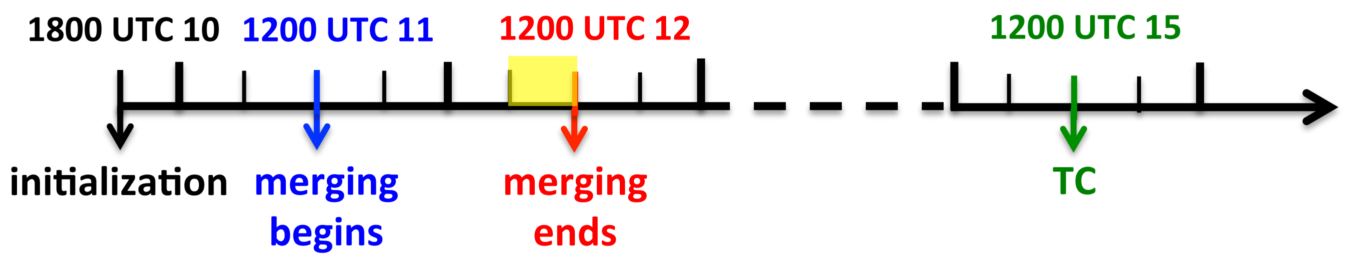

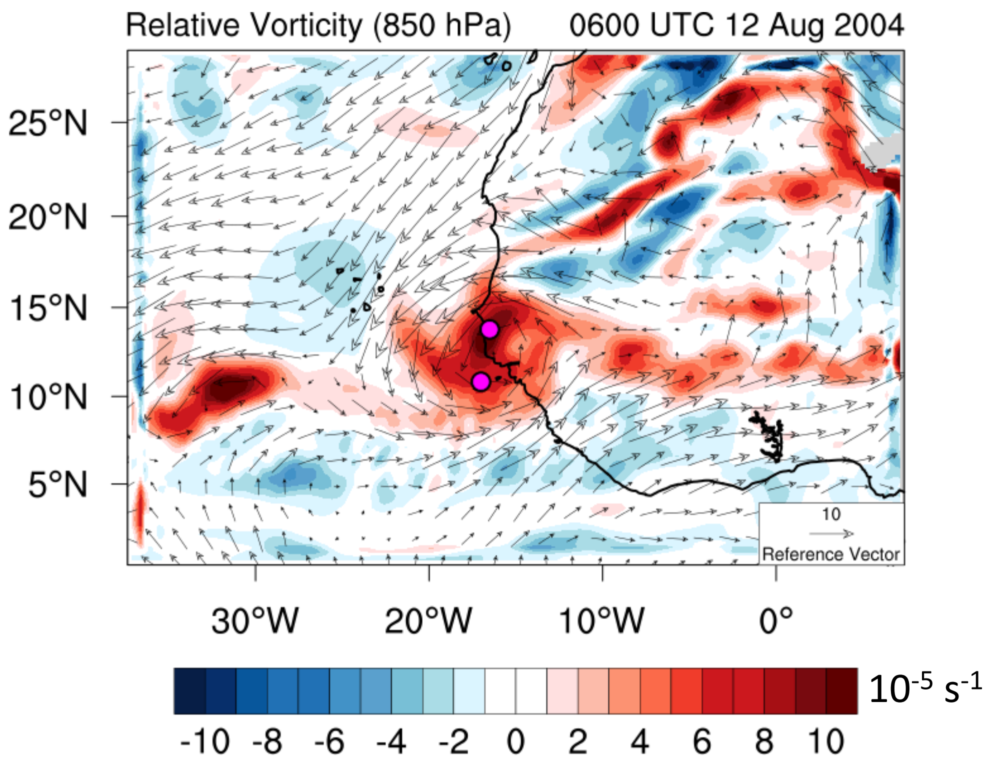

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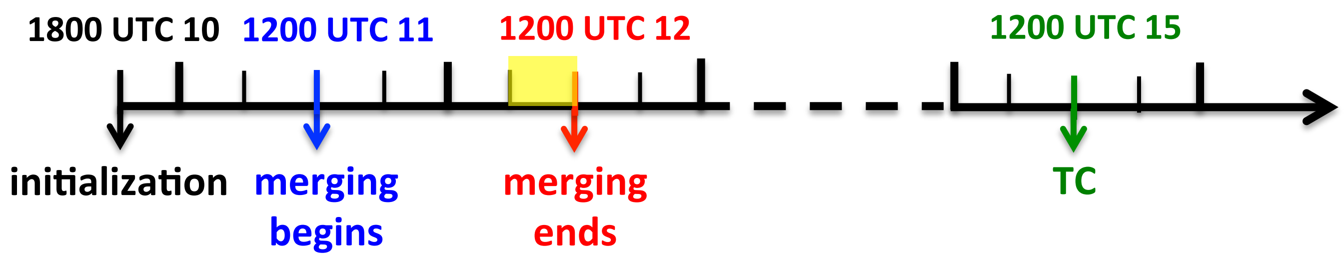

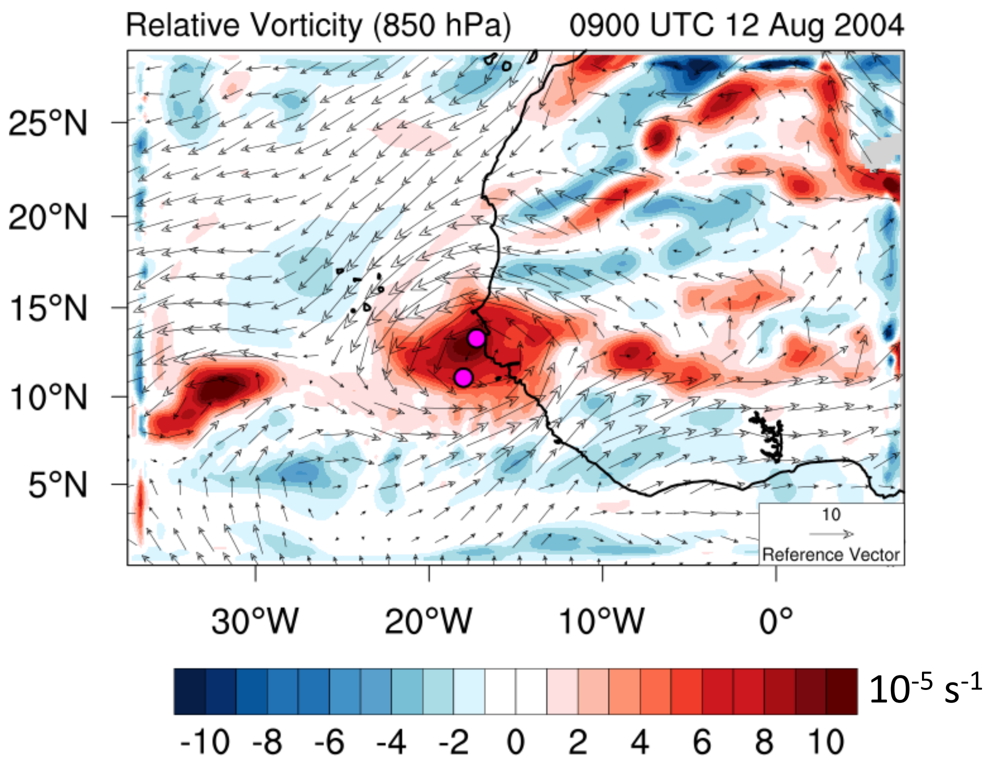

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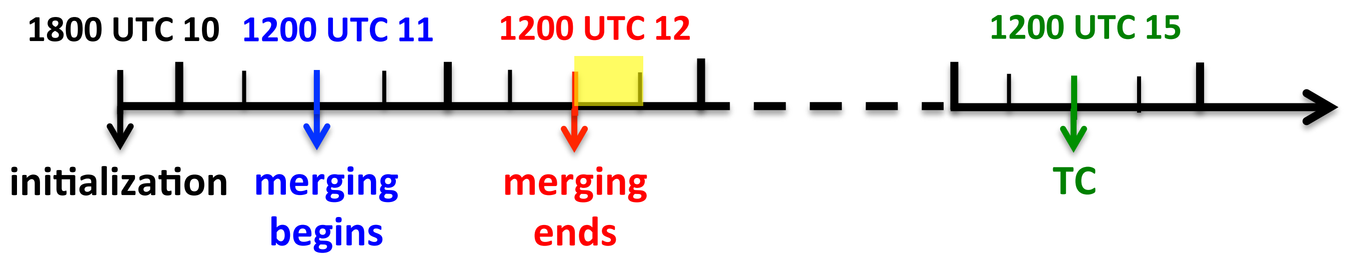

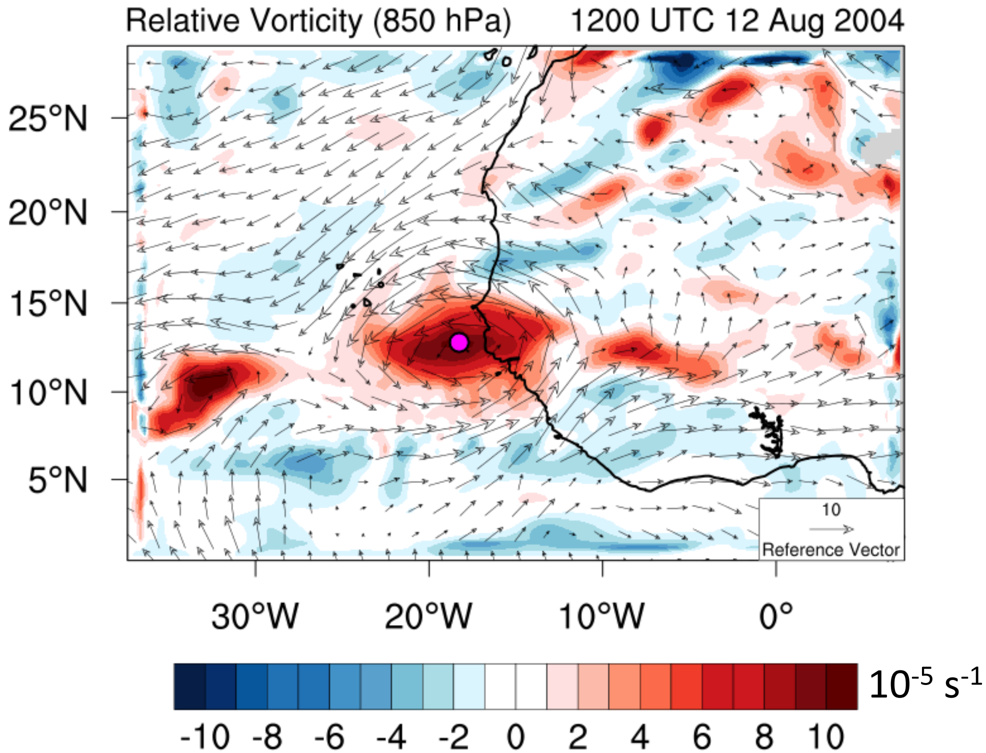

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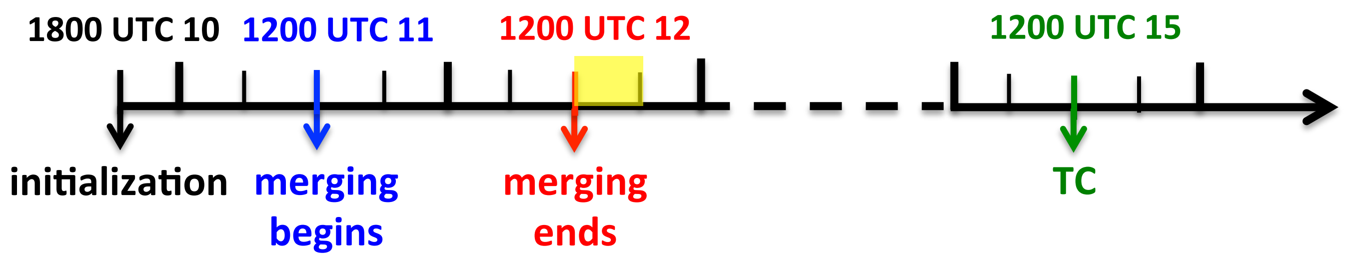

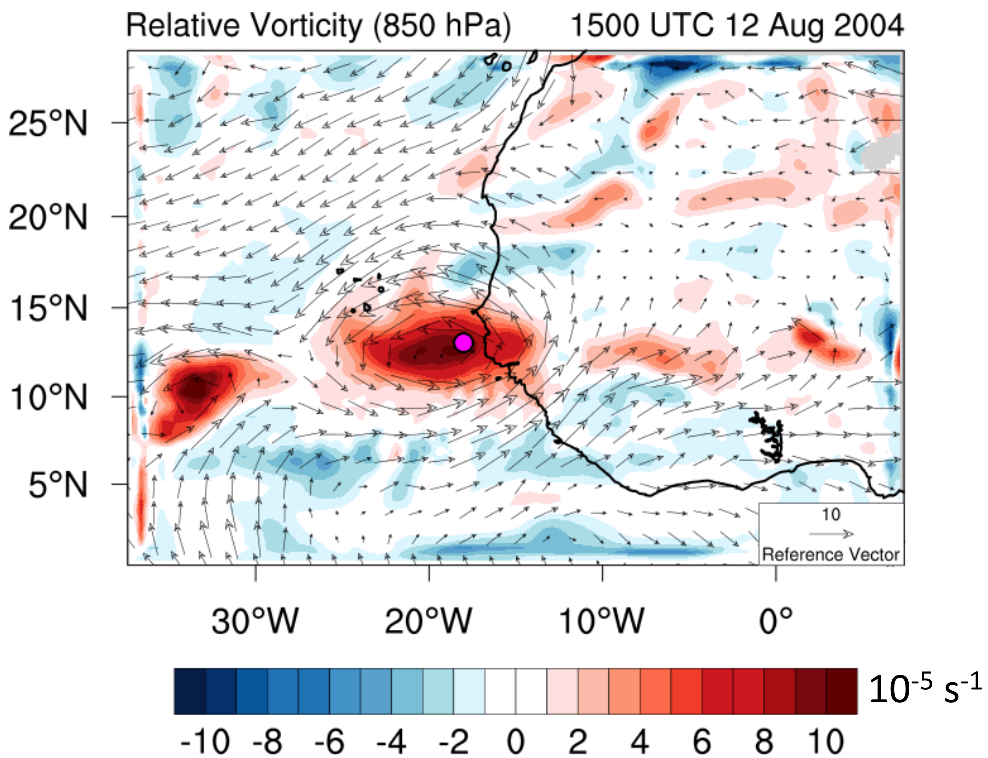

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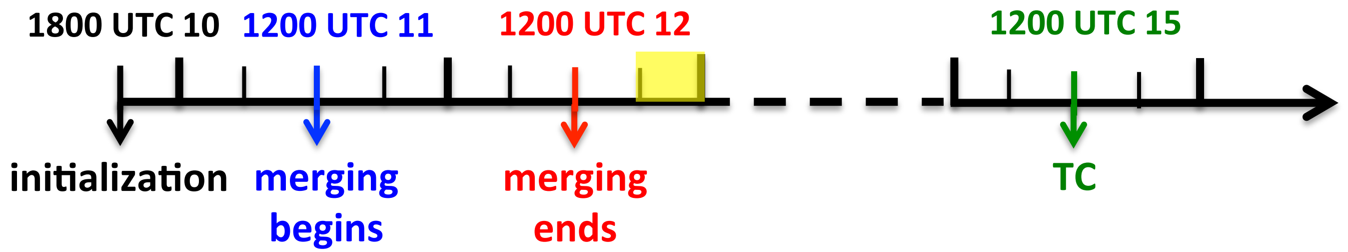

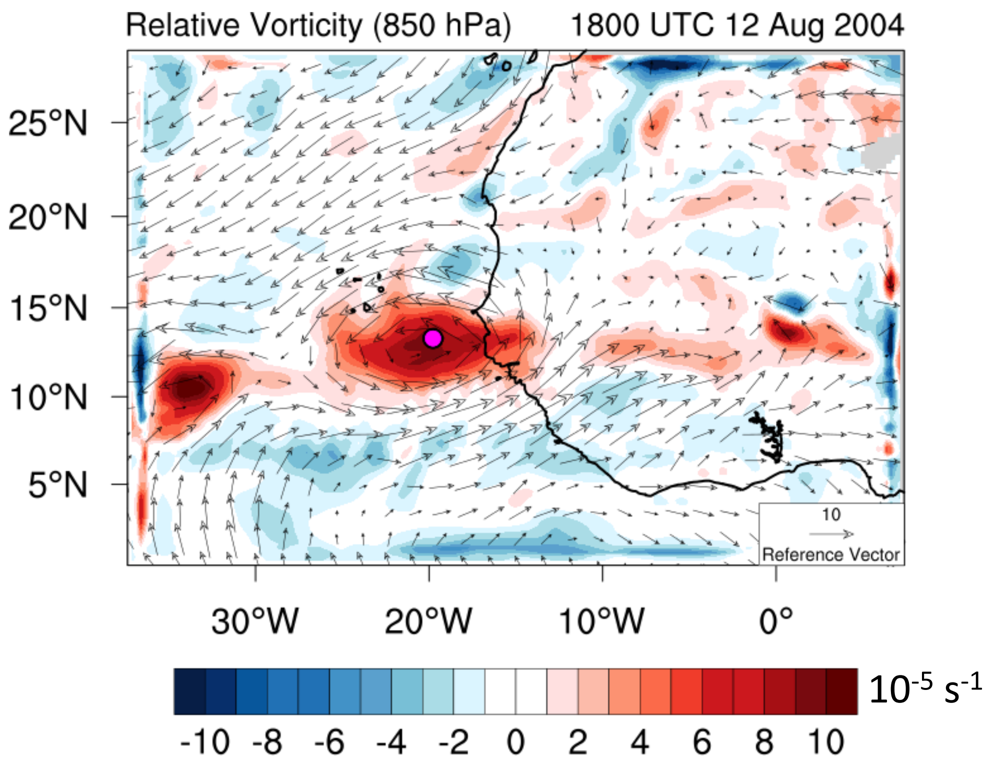

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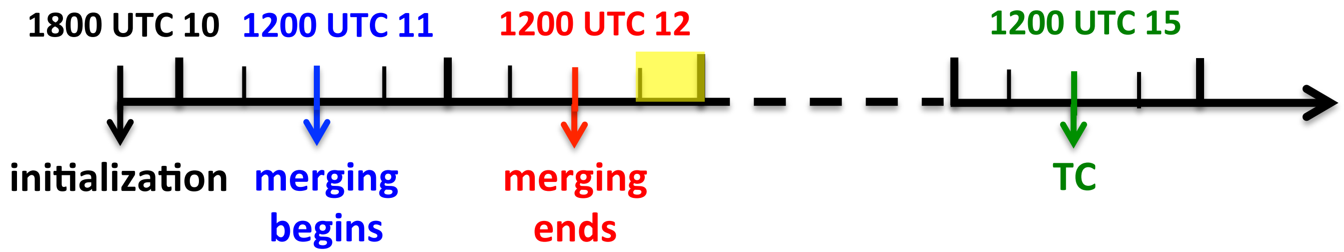

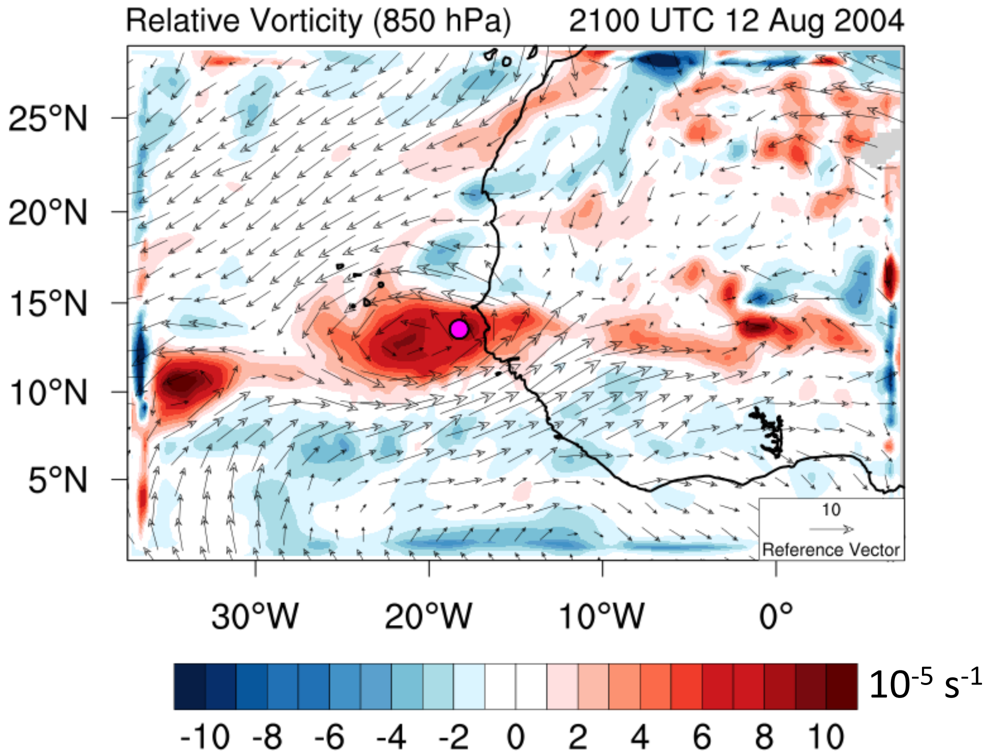

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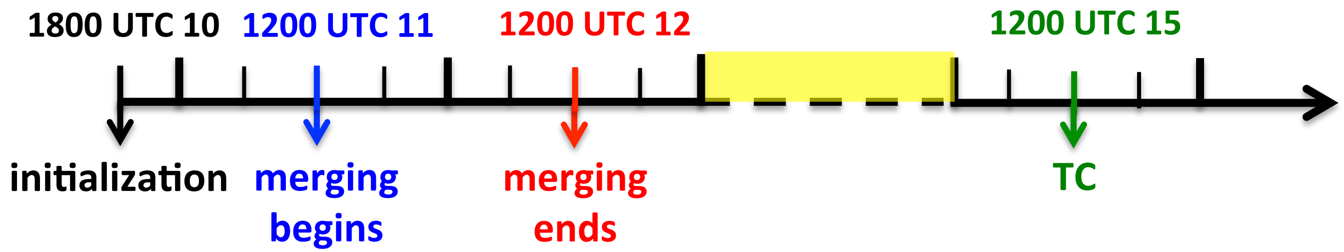

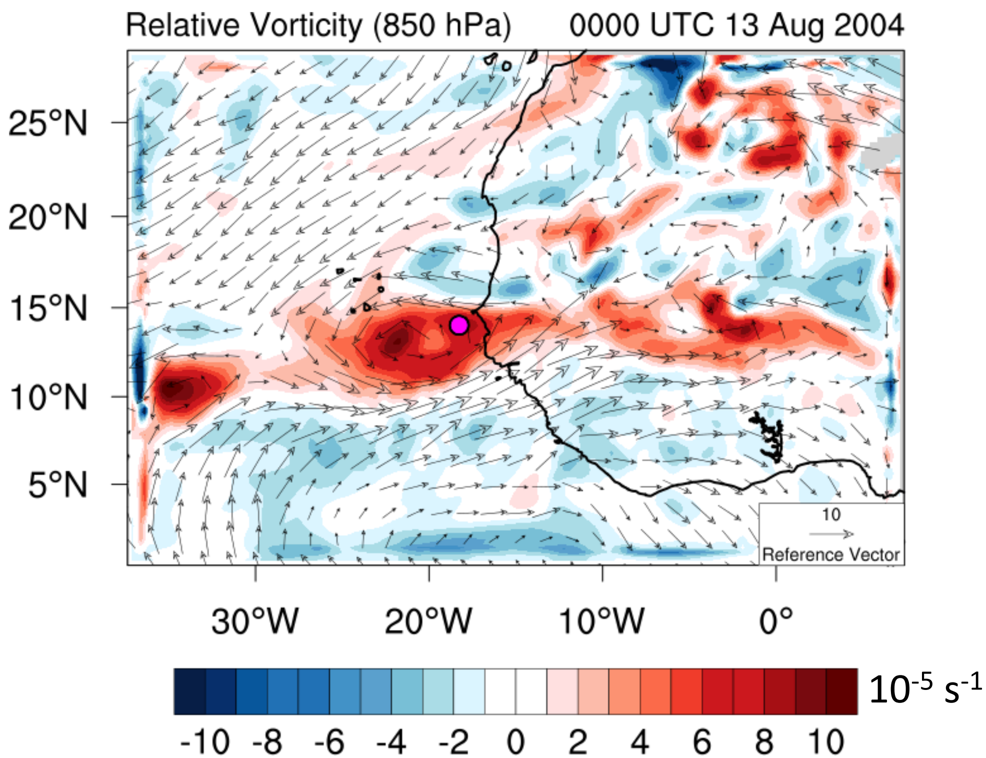

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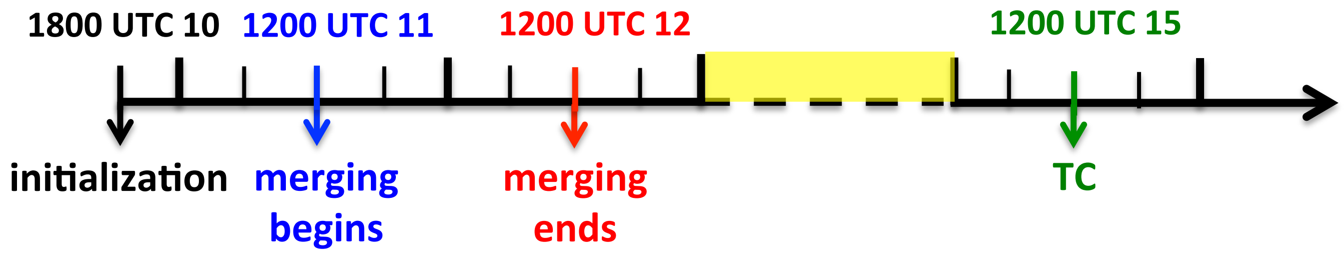

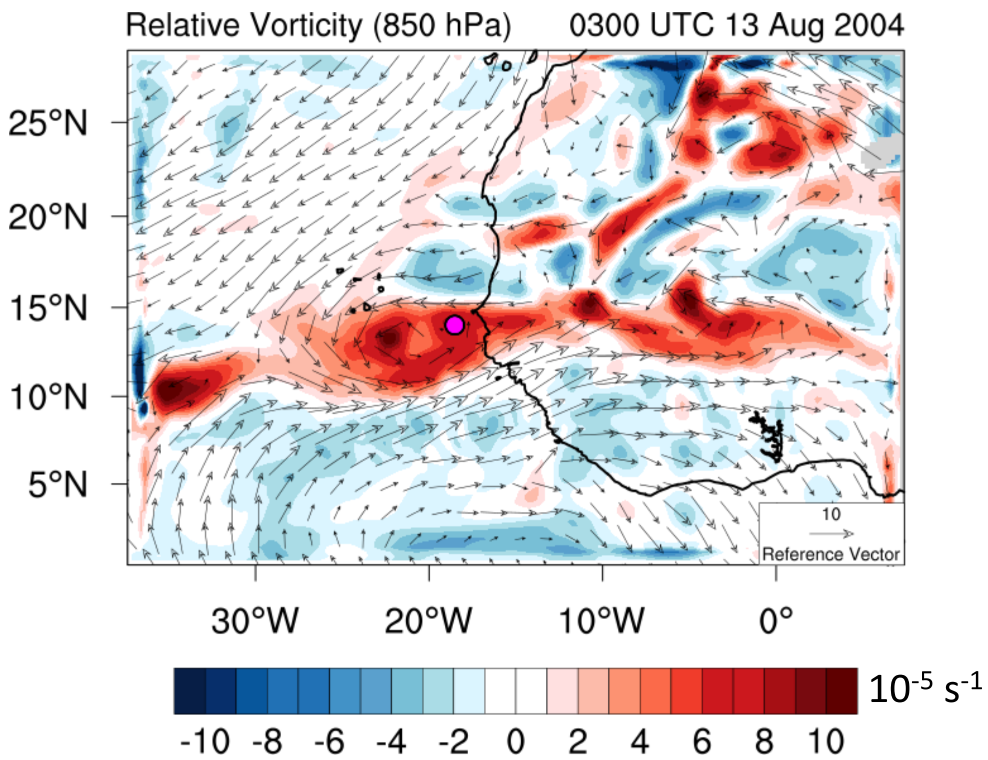

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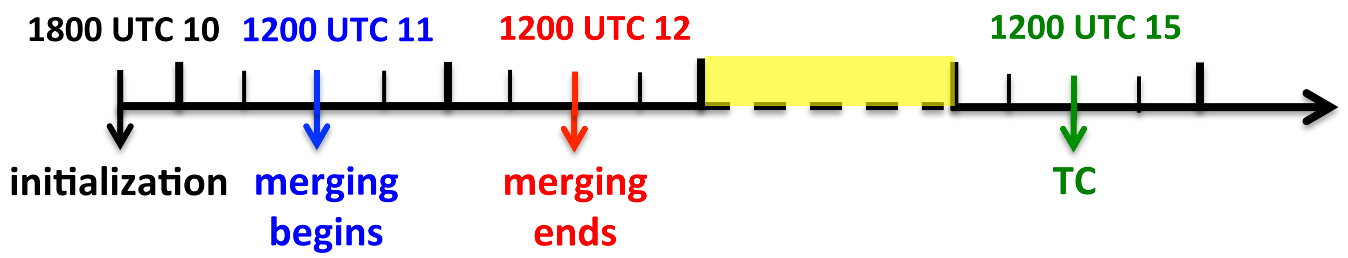

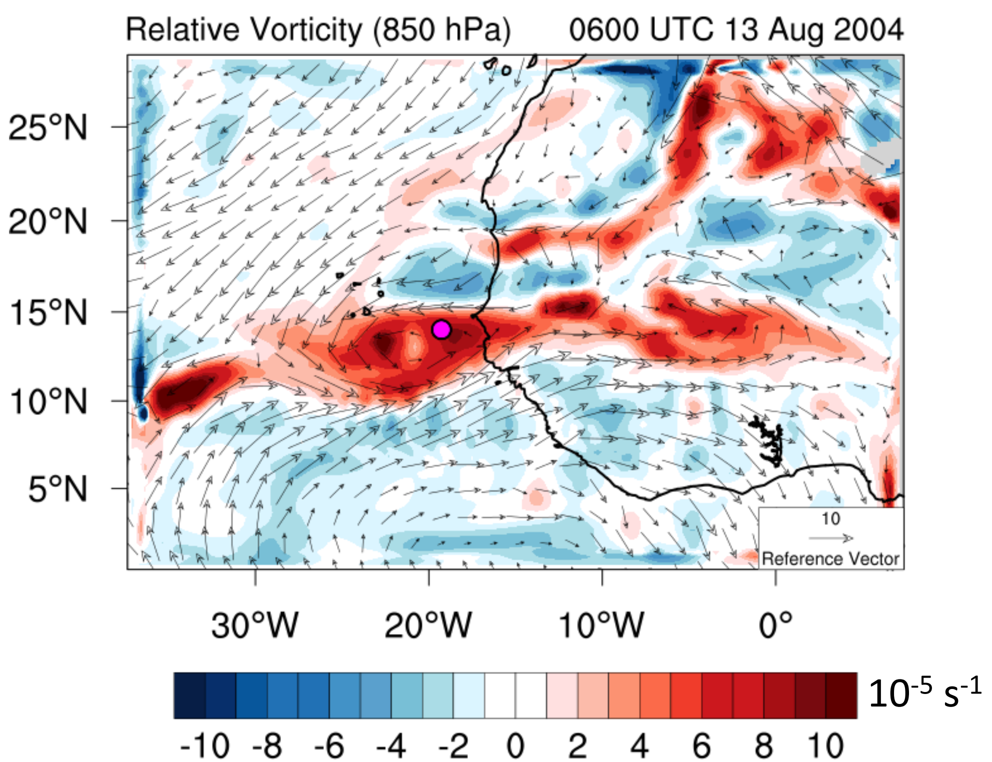

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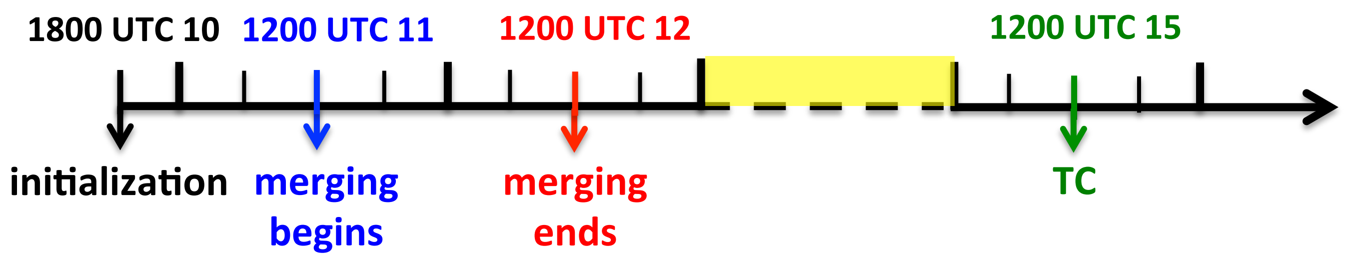

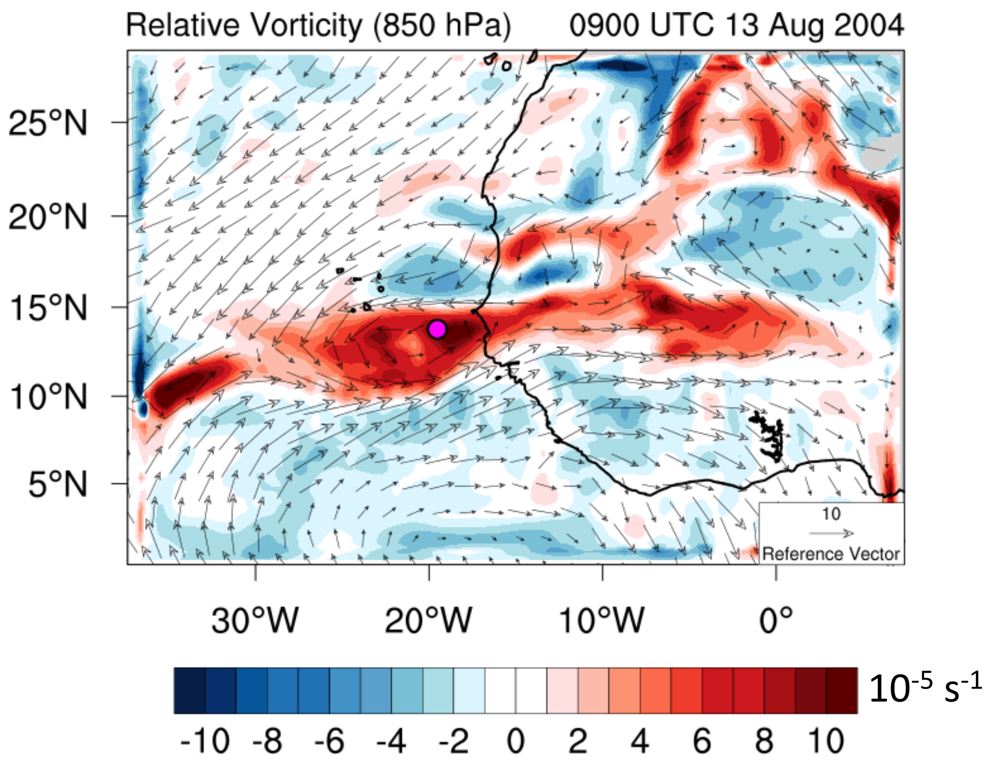

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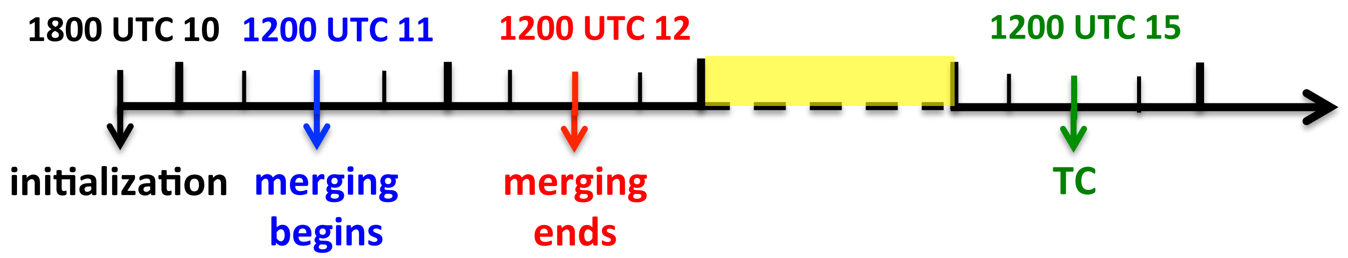

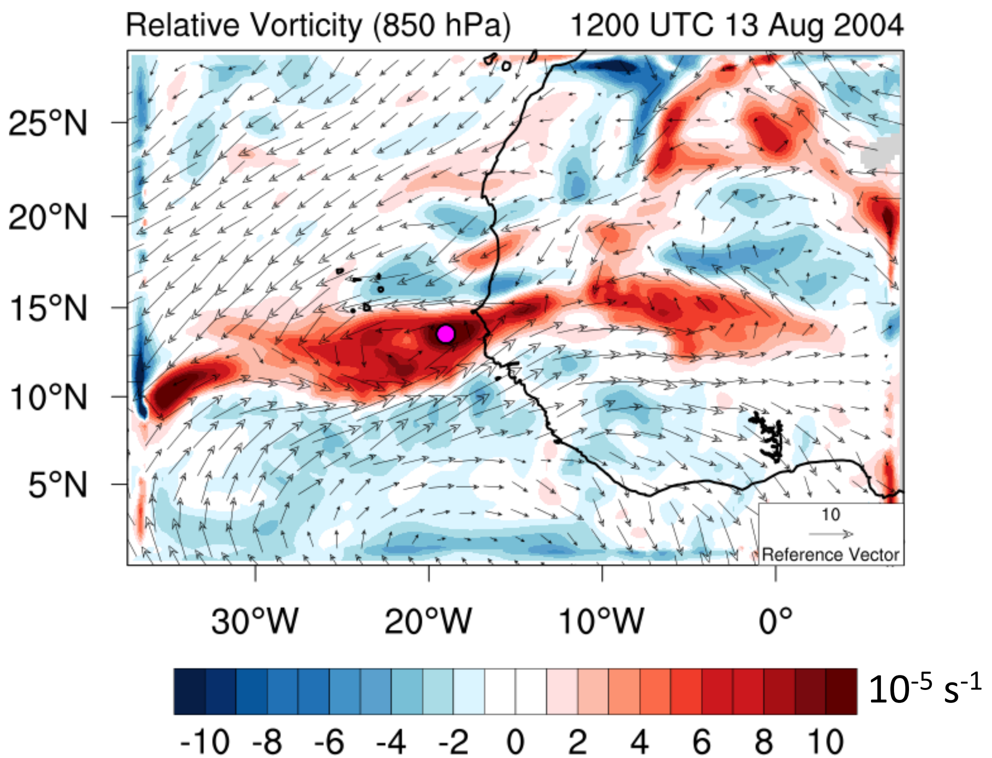

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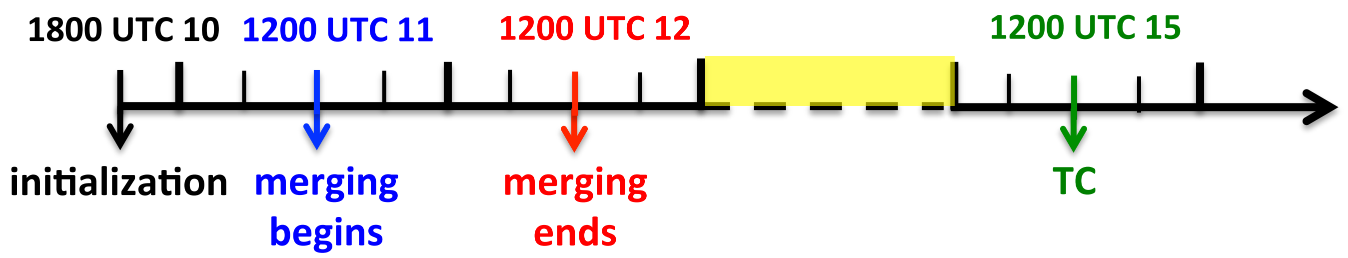

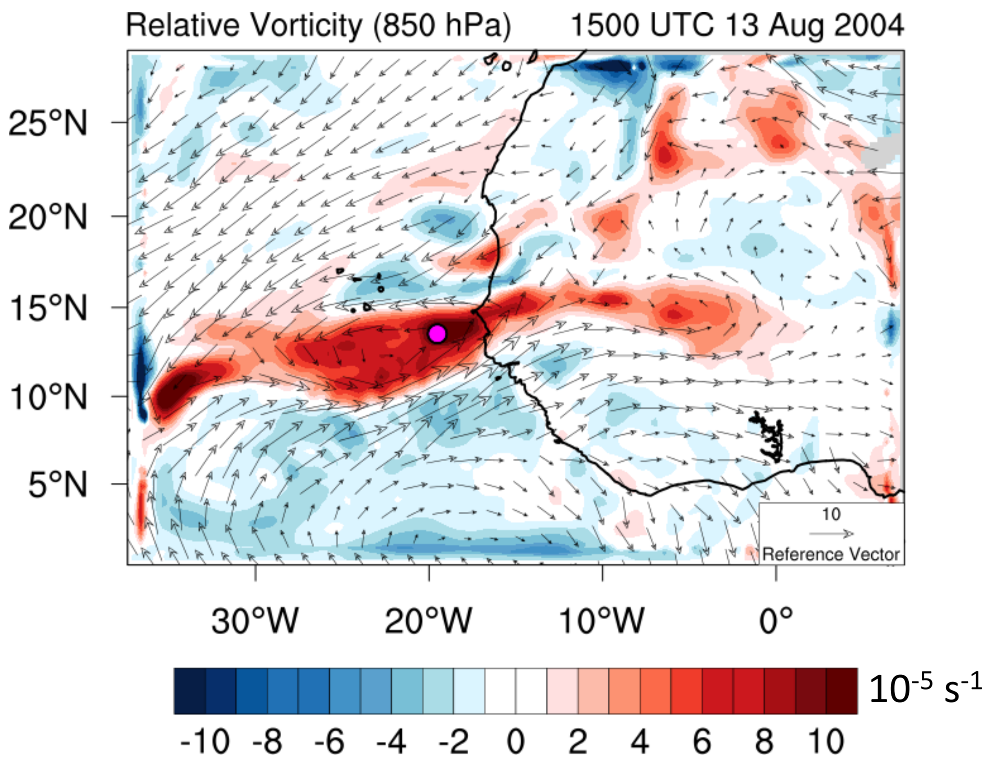

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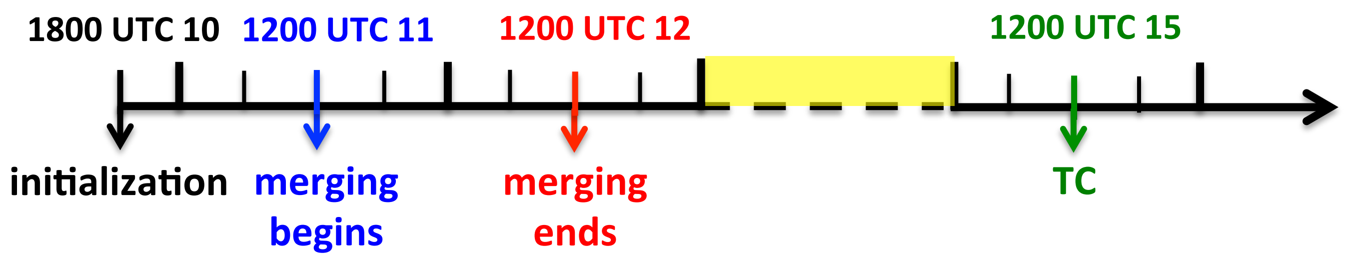

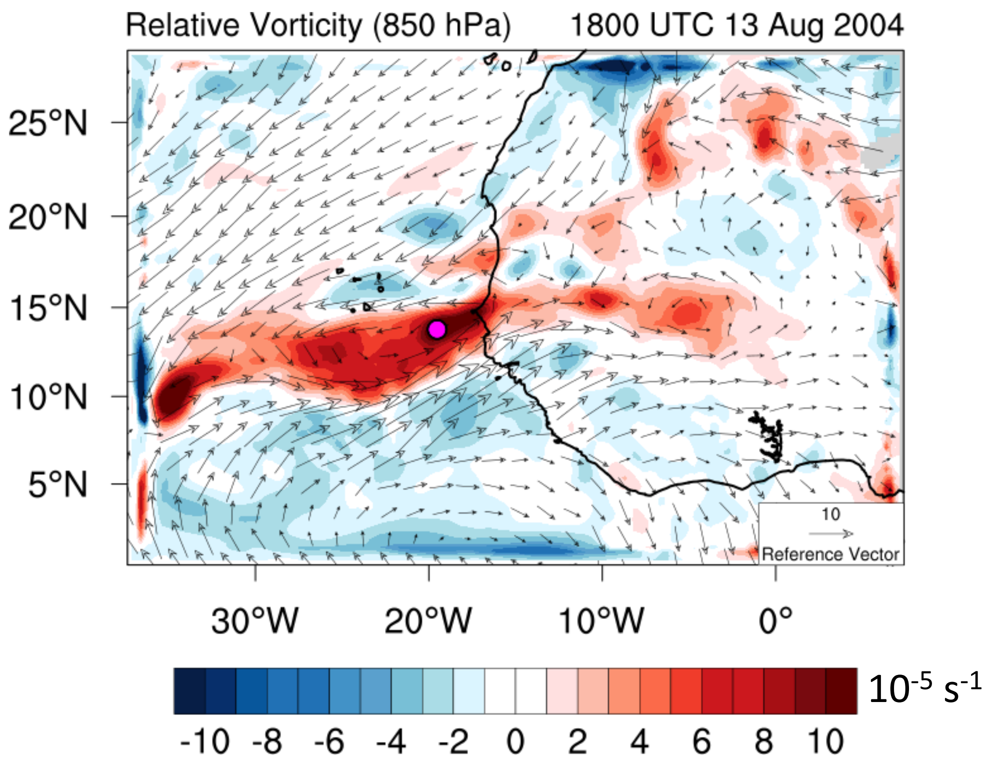

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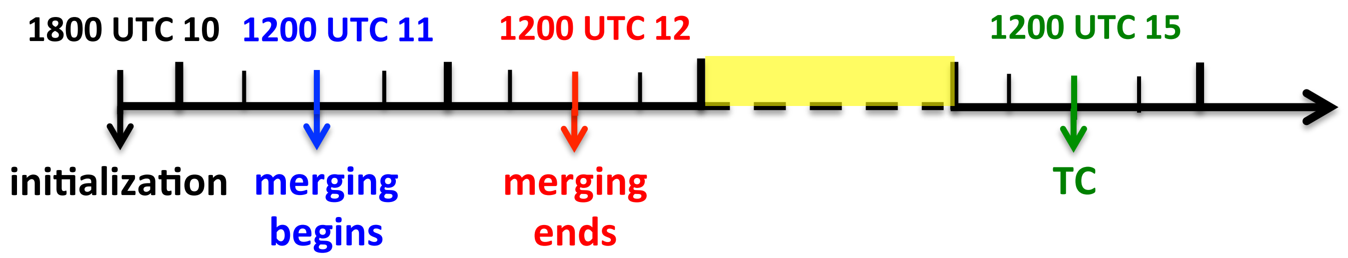

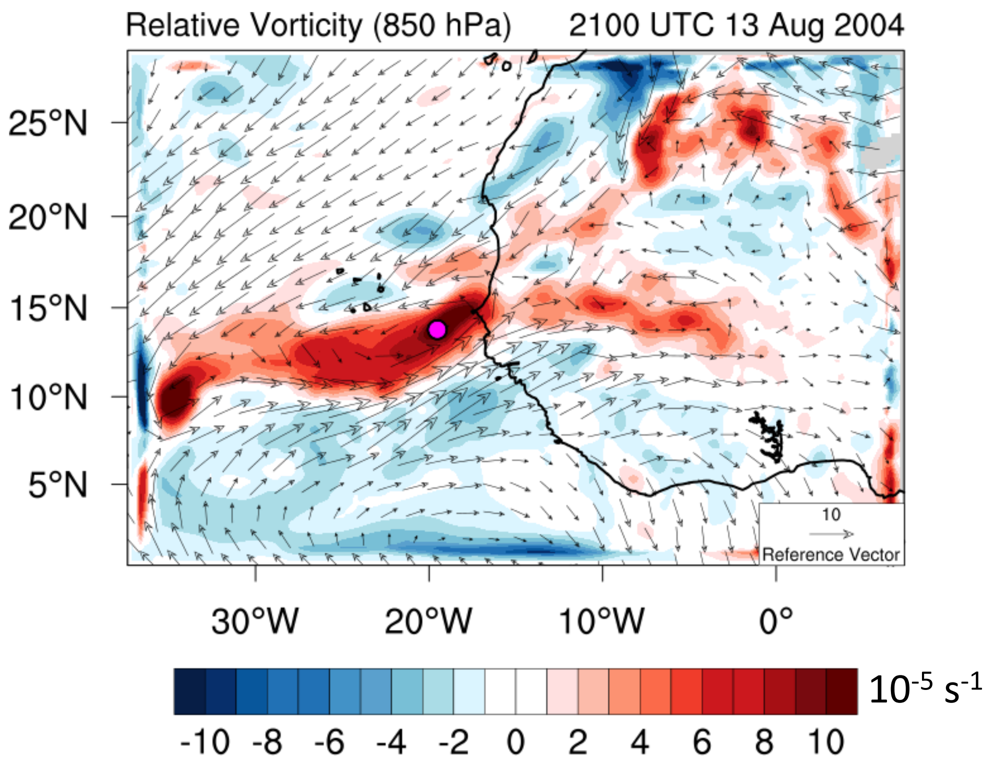

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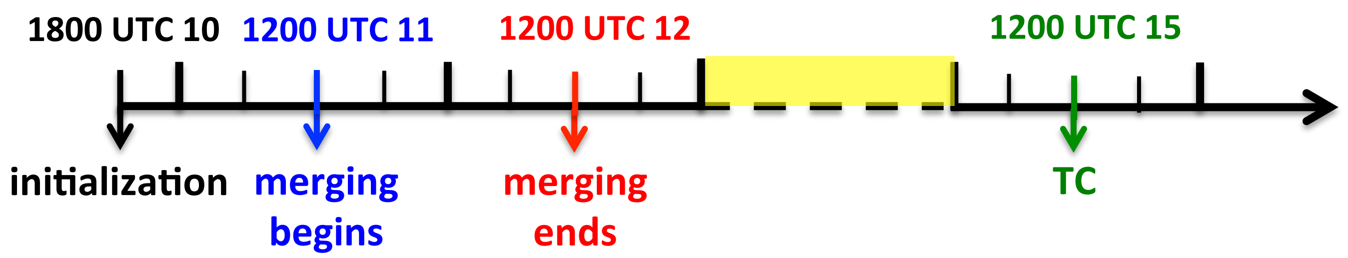

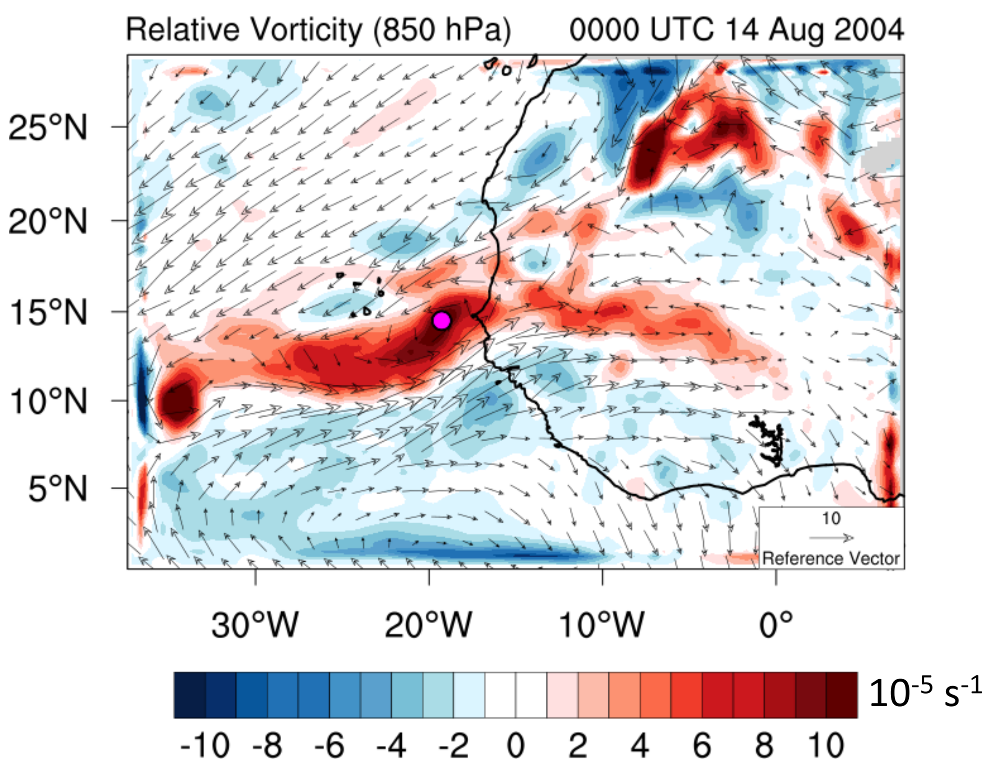

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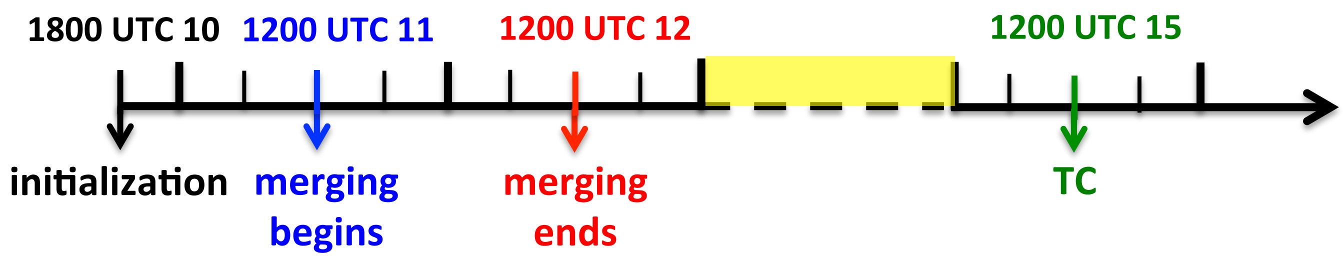

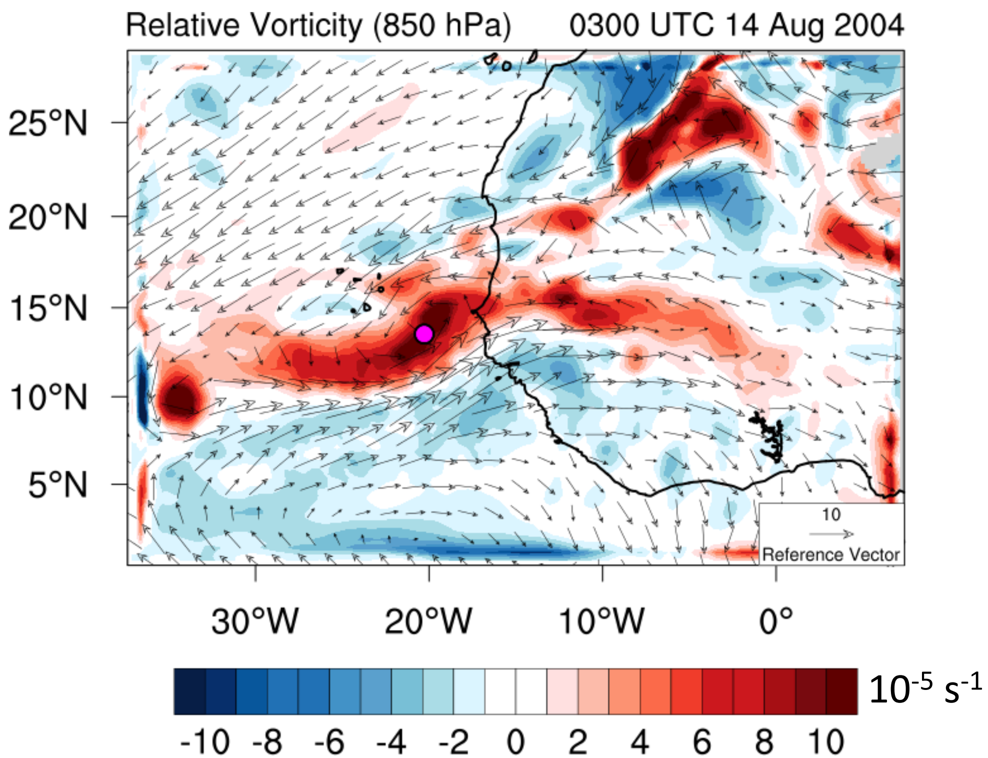

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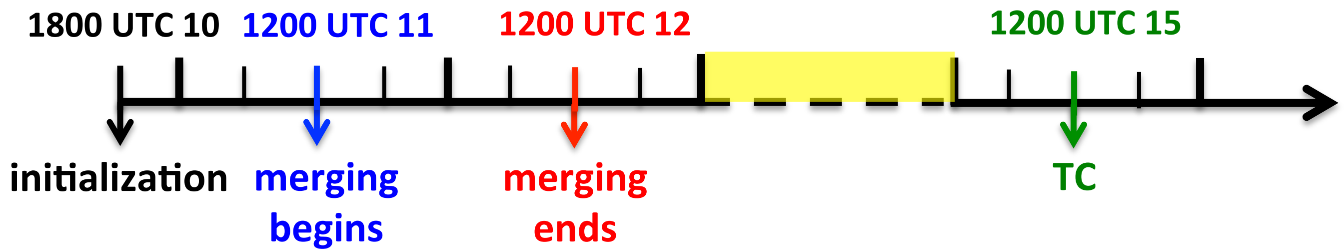

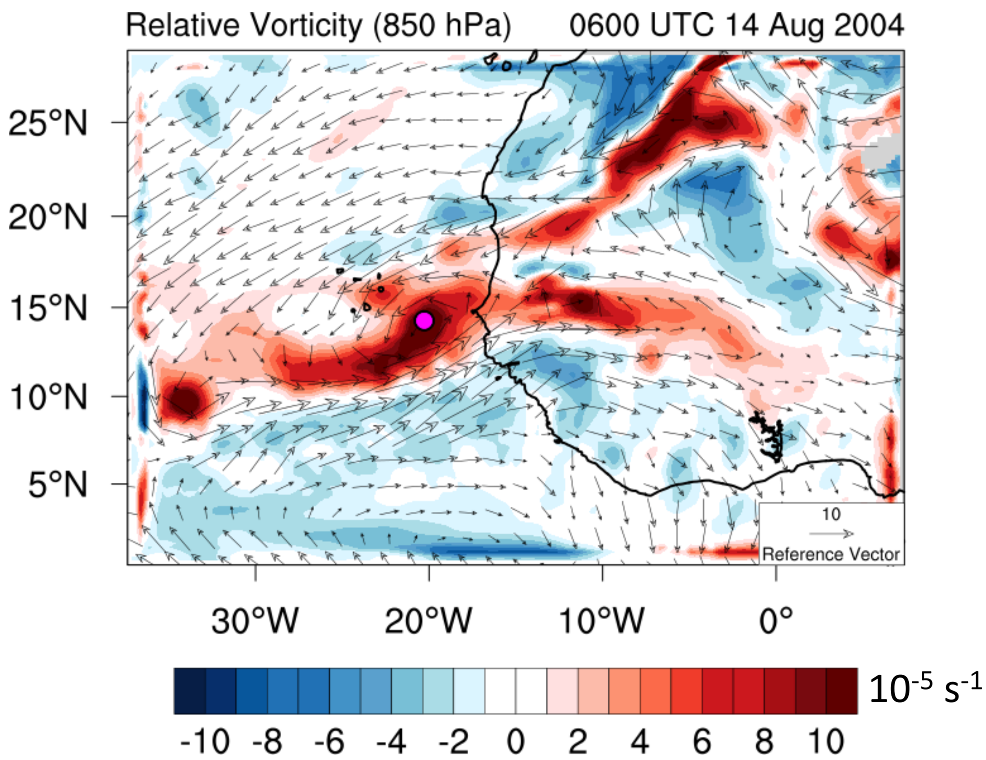

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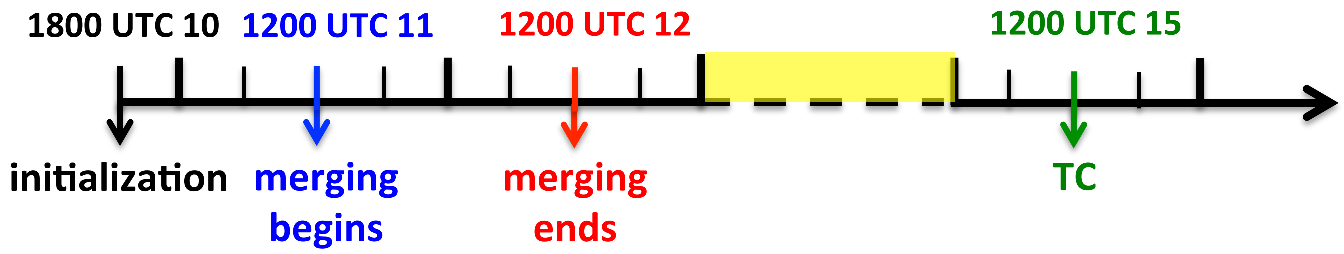

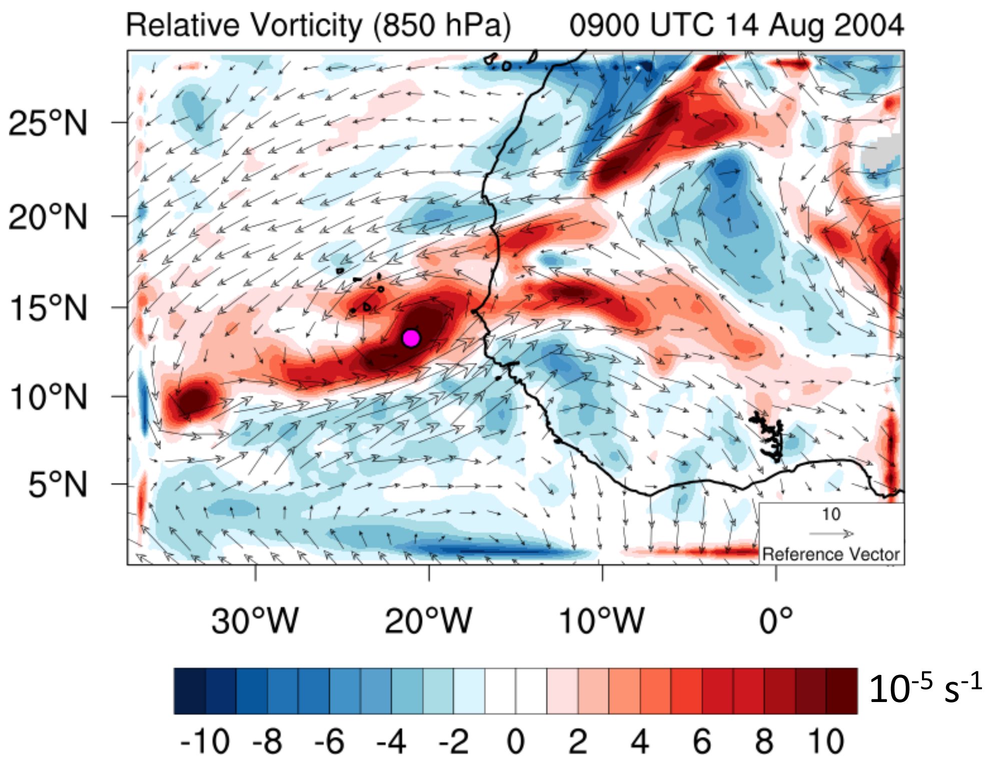

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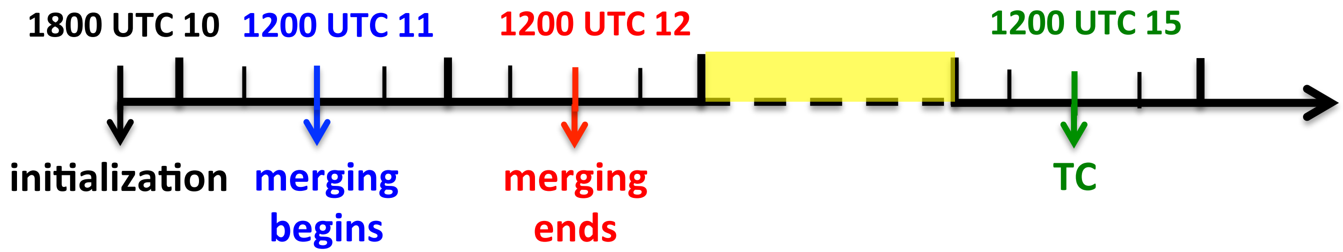

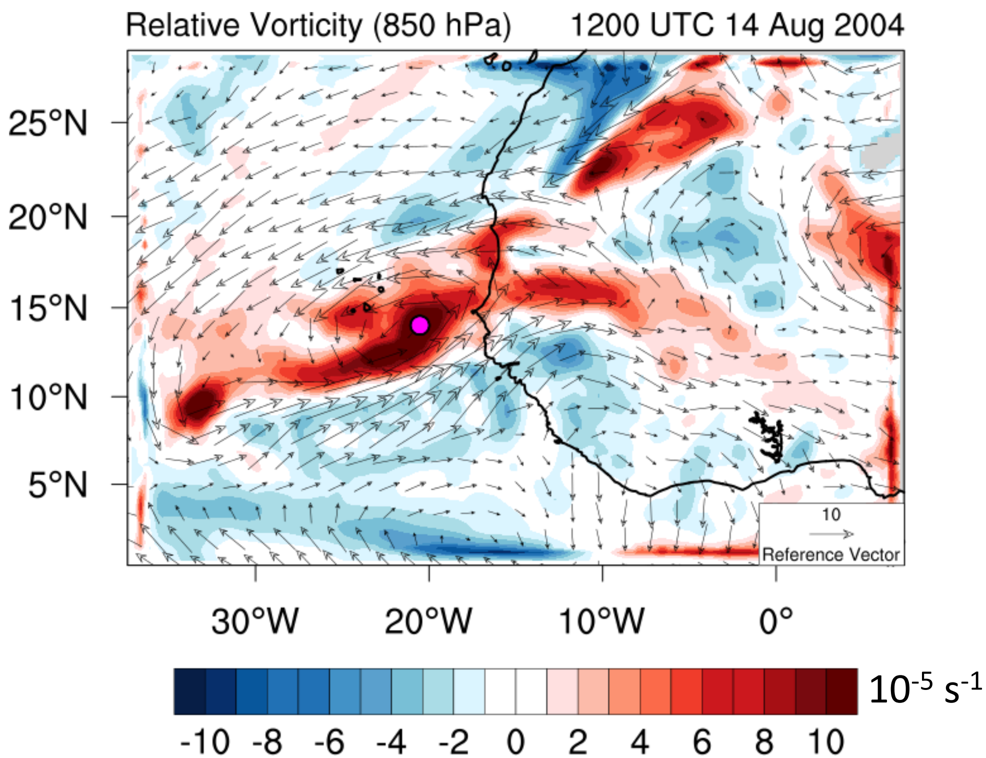

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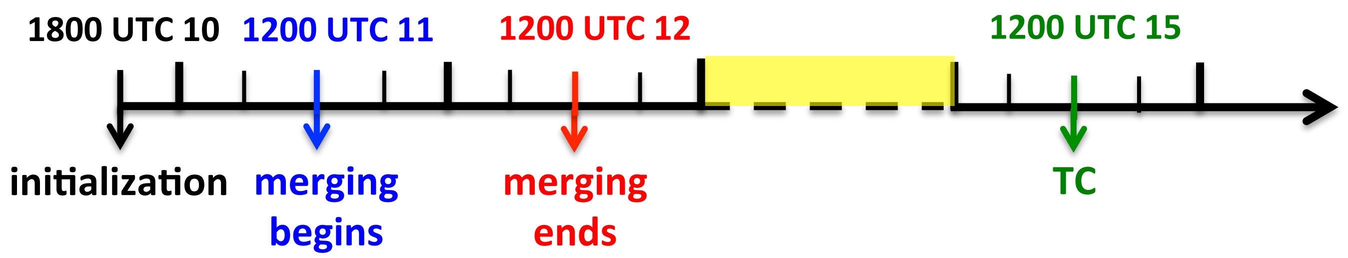

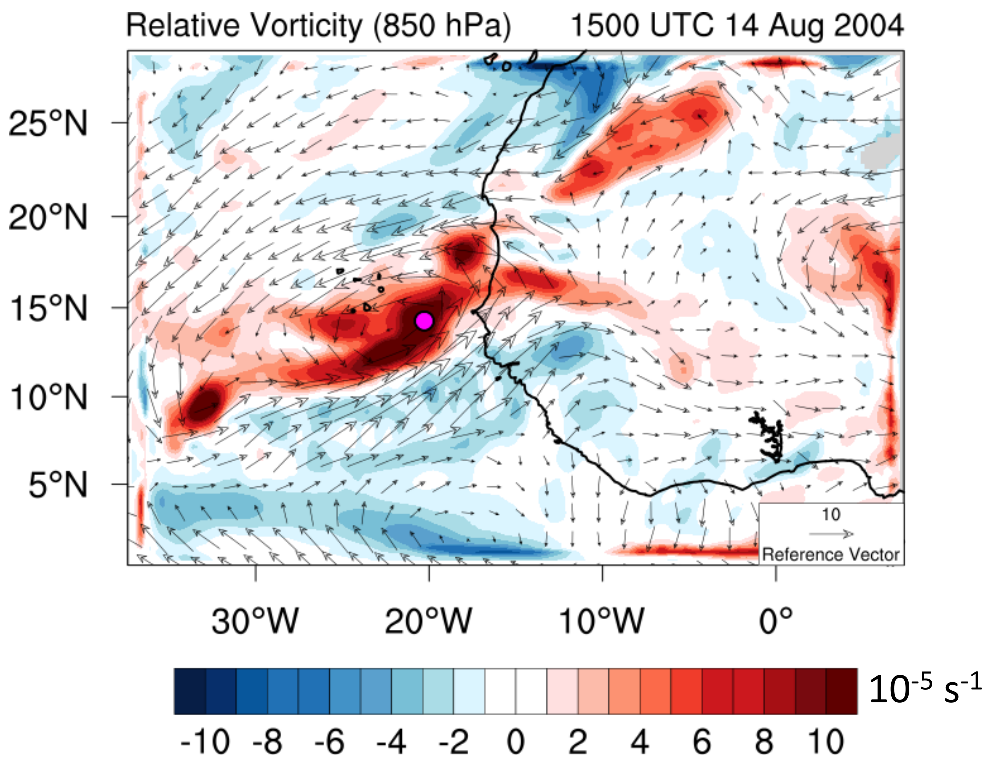

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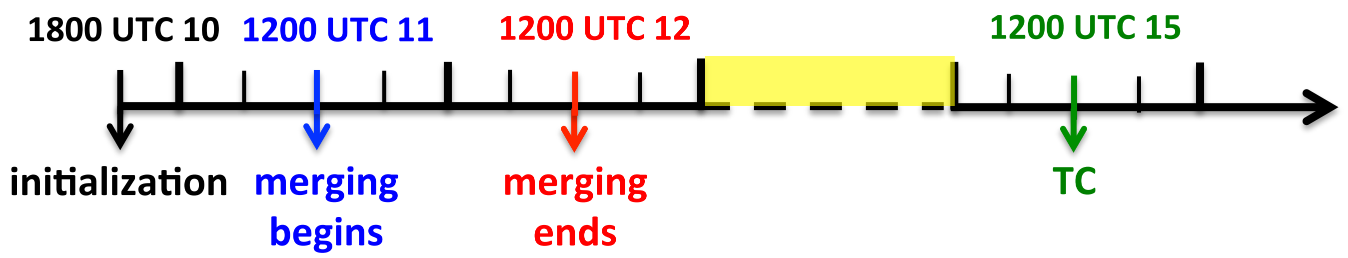

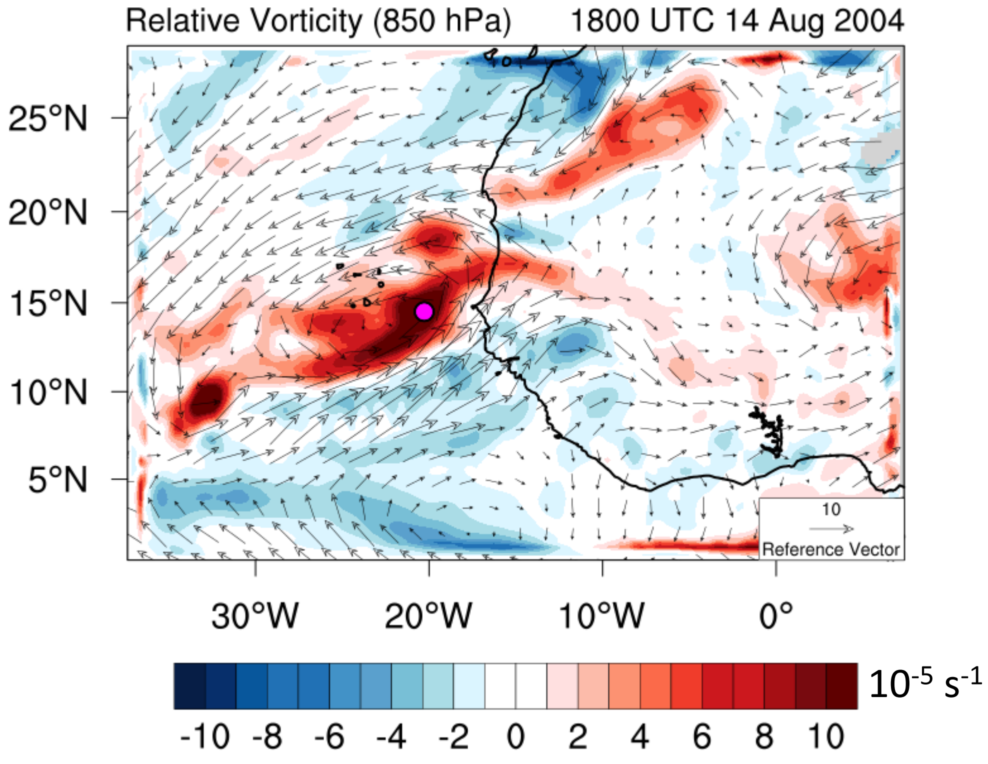

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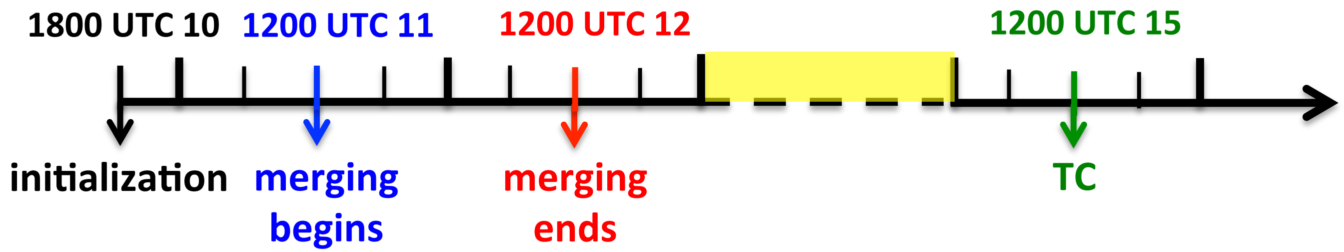

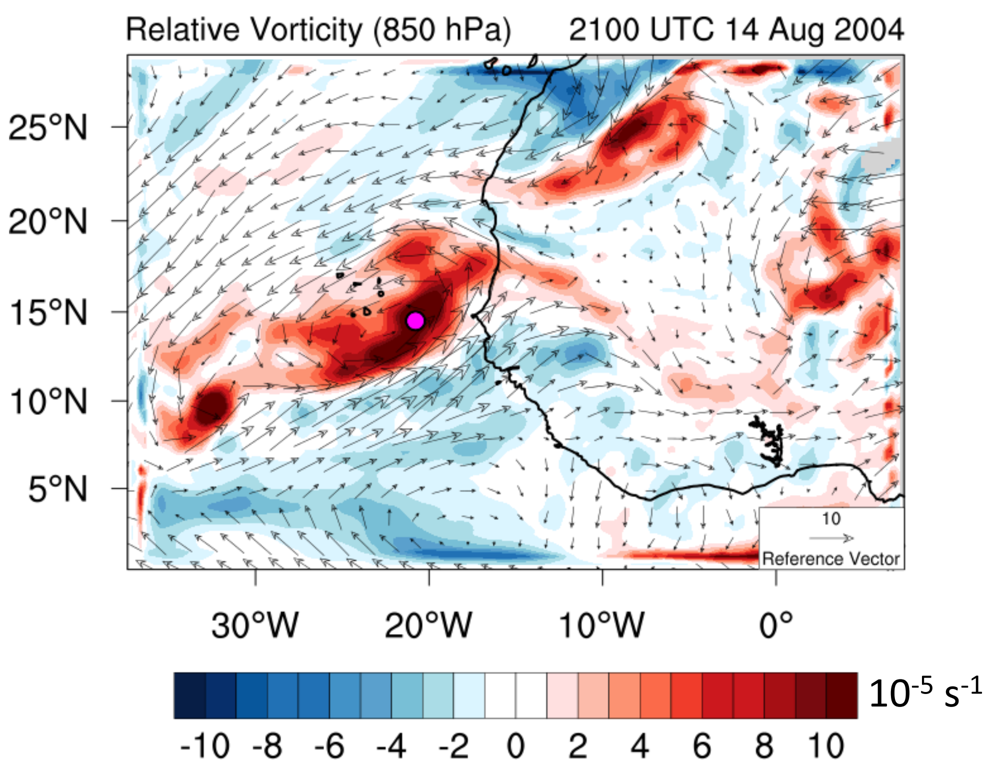

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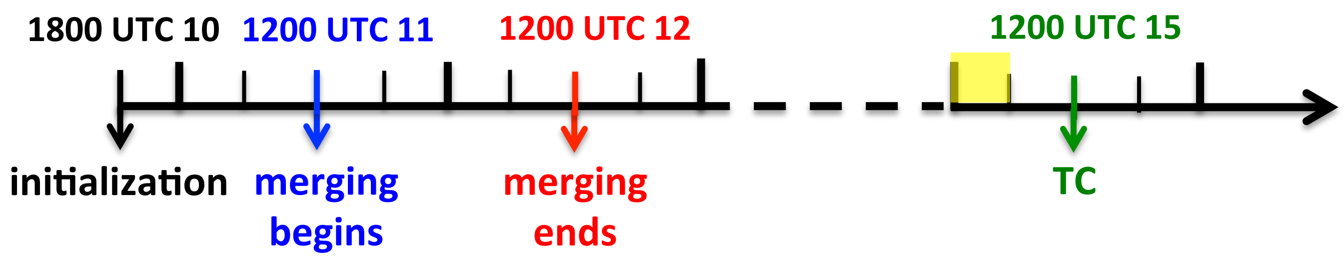

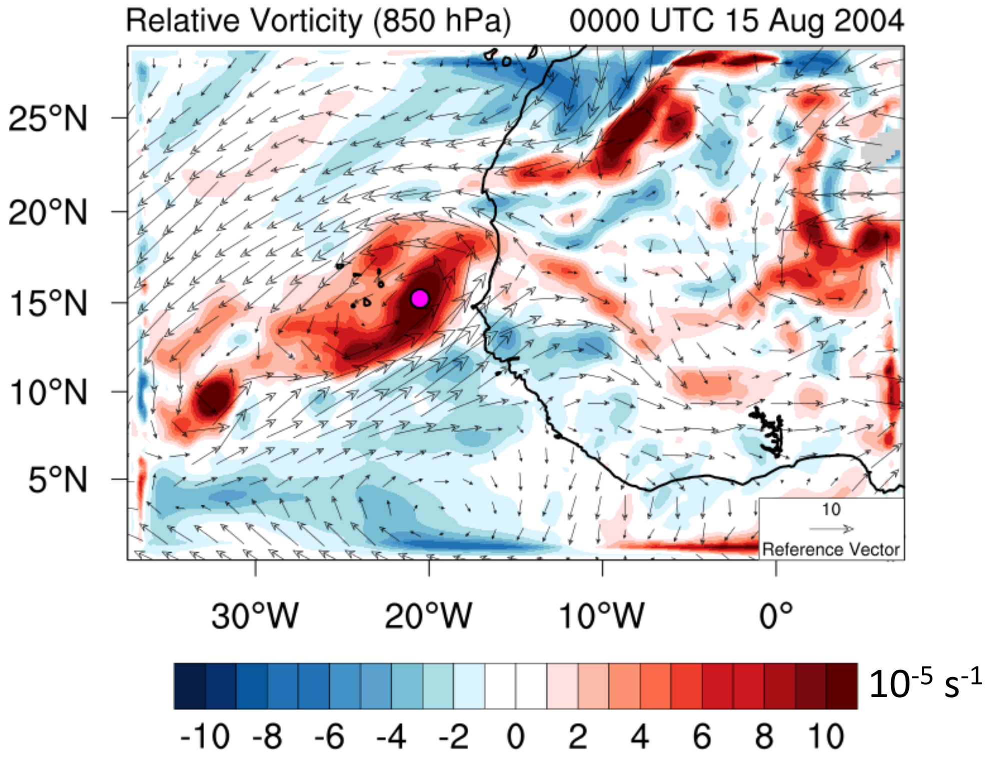

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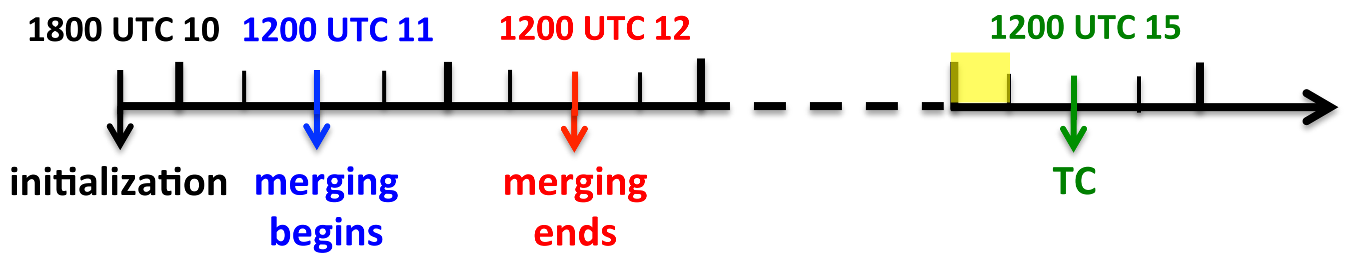

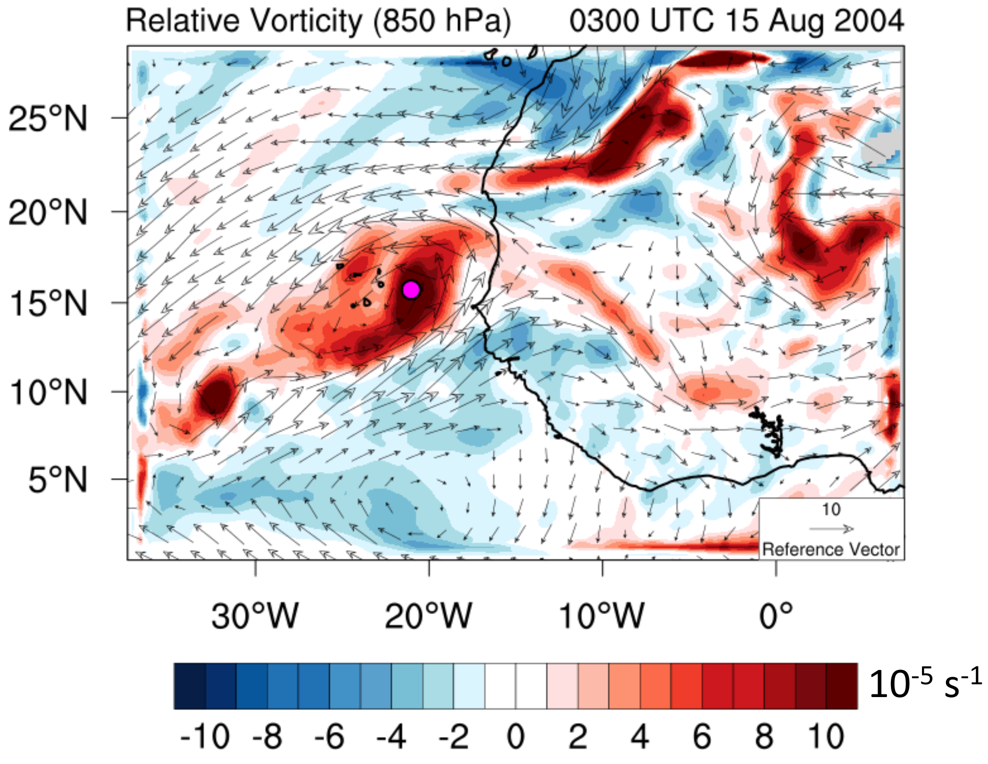

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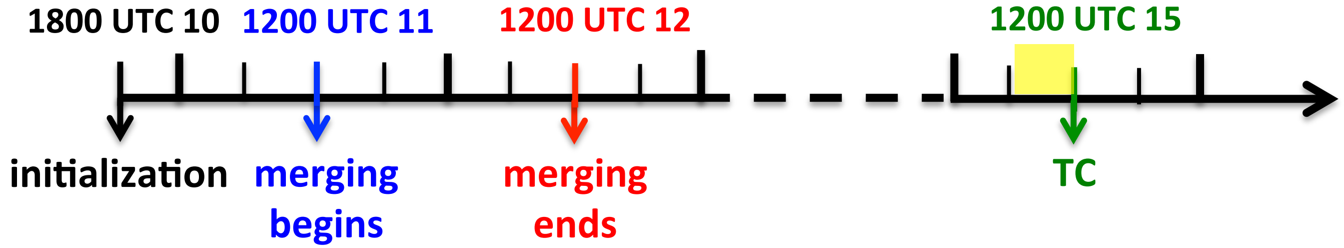

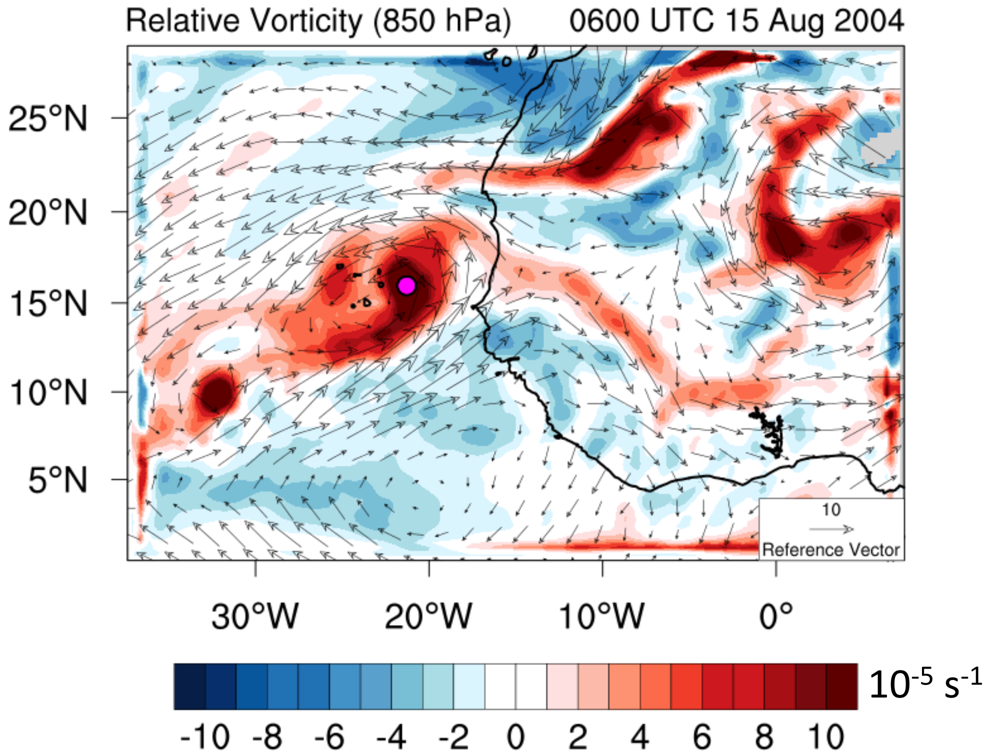

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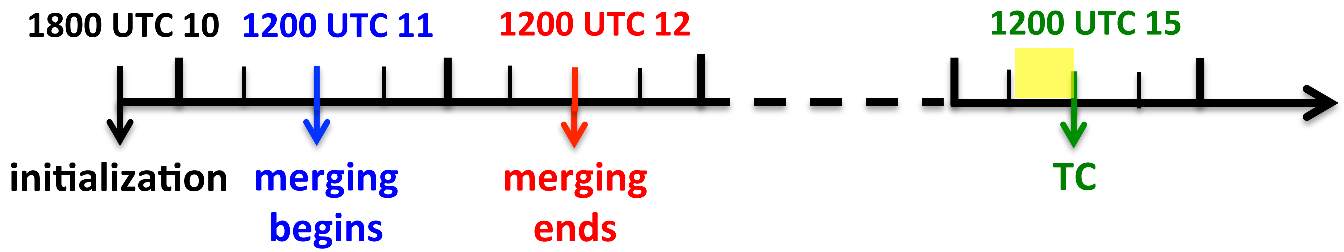

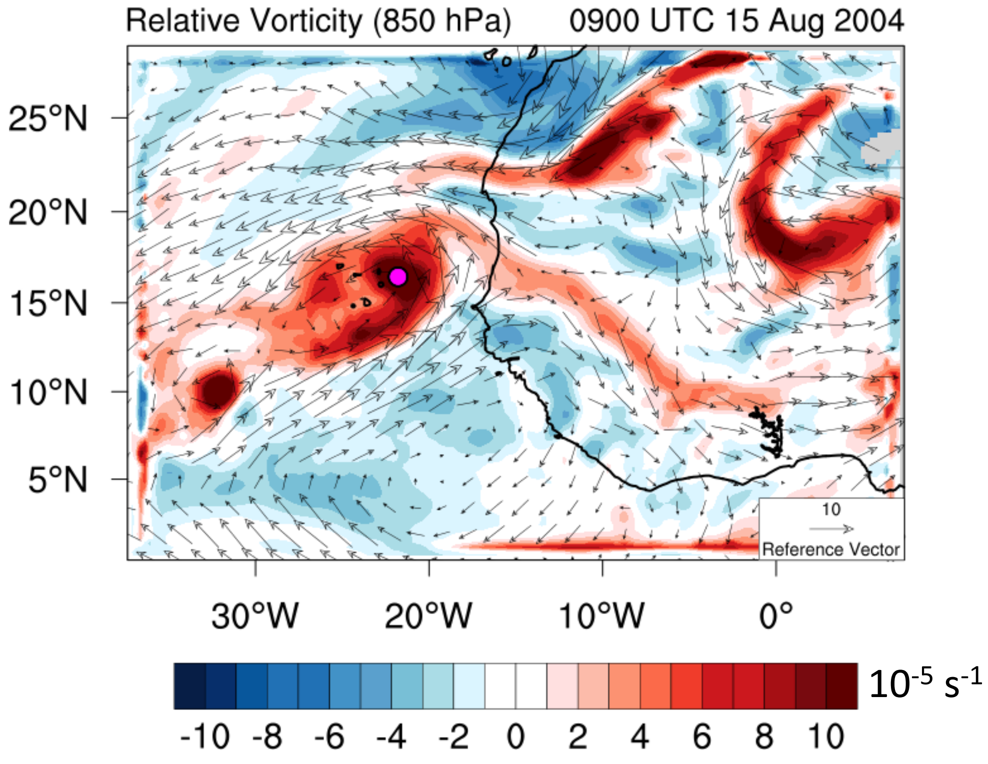

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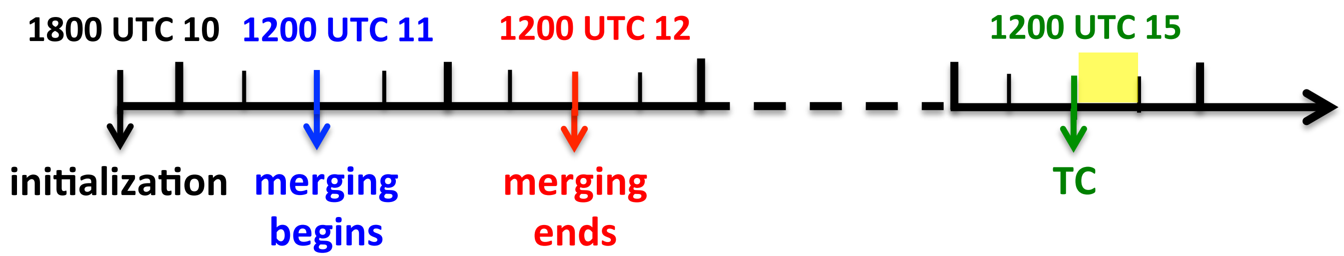

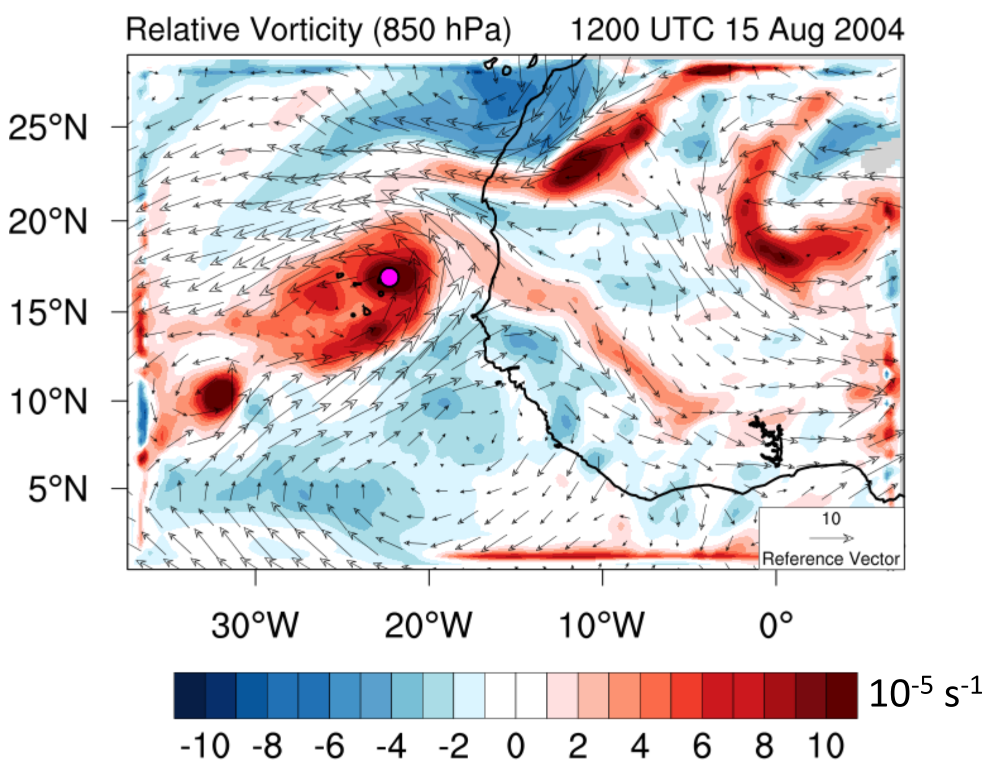

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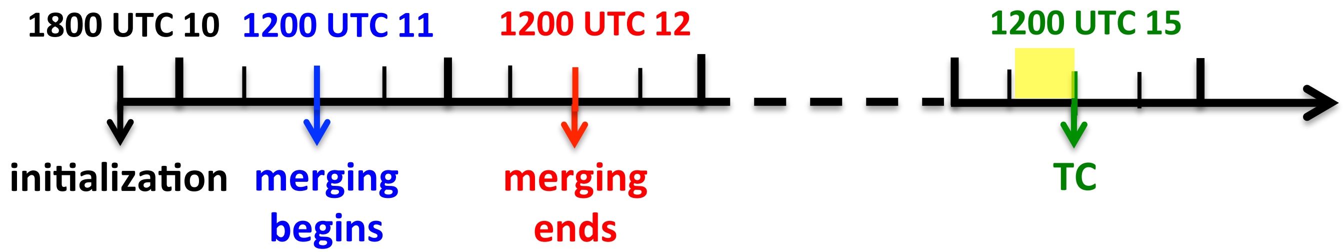
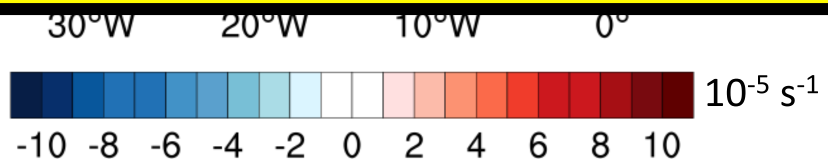


- **The development of a TC circulation occurs at a different location and time than observations**
- **However, the timing, placement, and shape of the merging process in the model appears to realistically capture the evolution in the ERA-Interim**
- **What about moisture field?**



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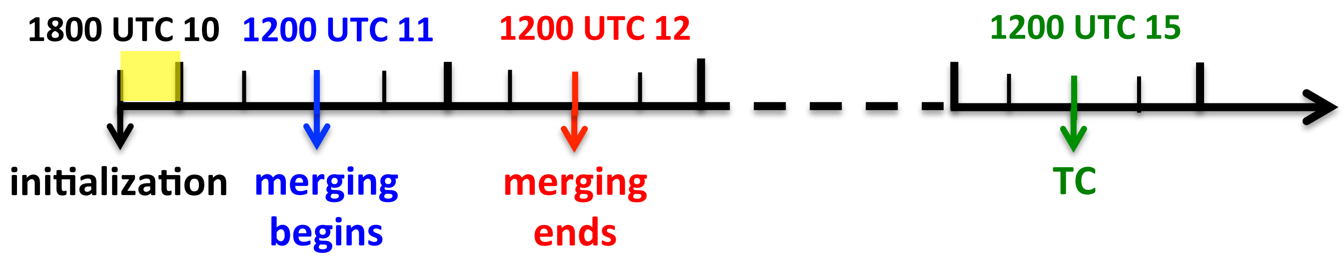

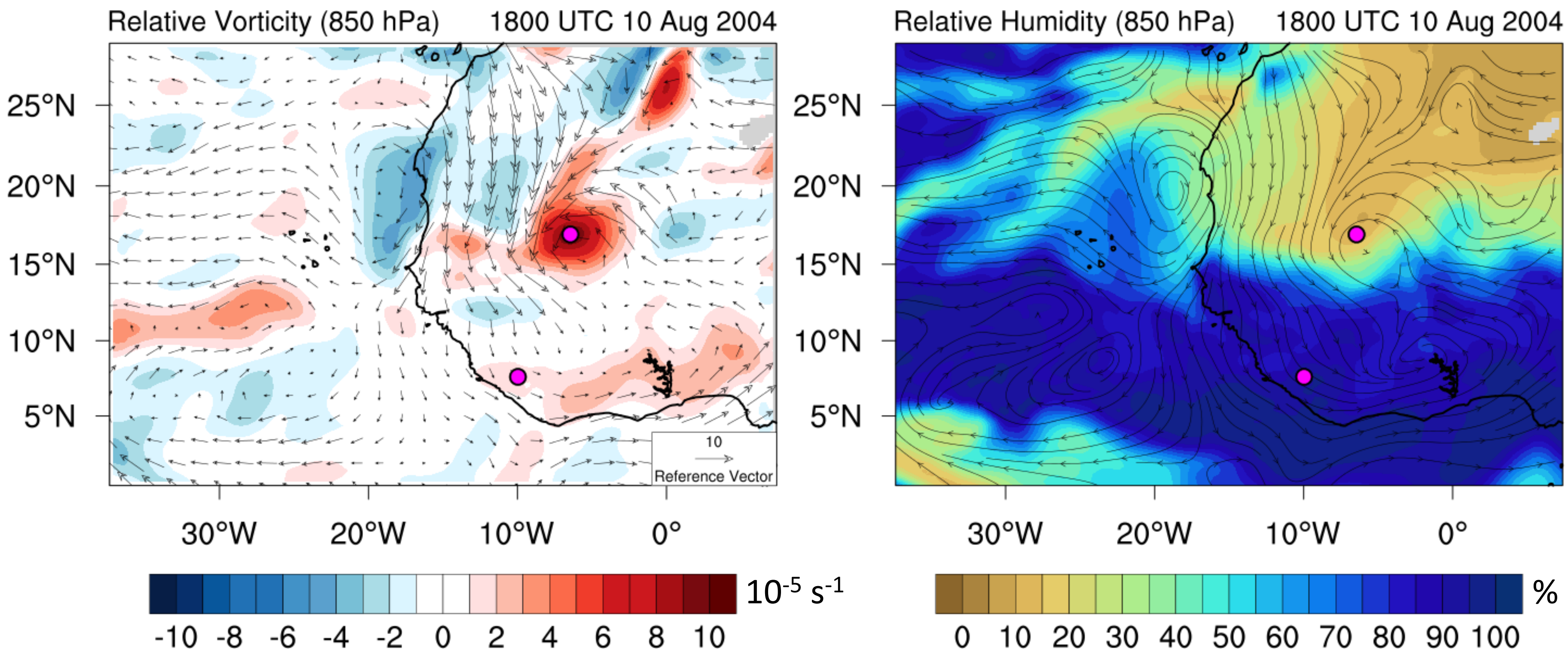

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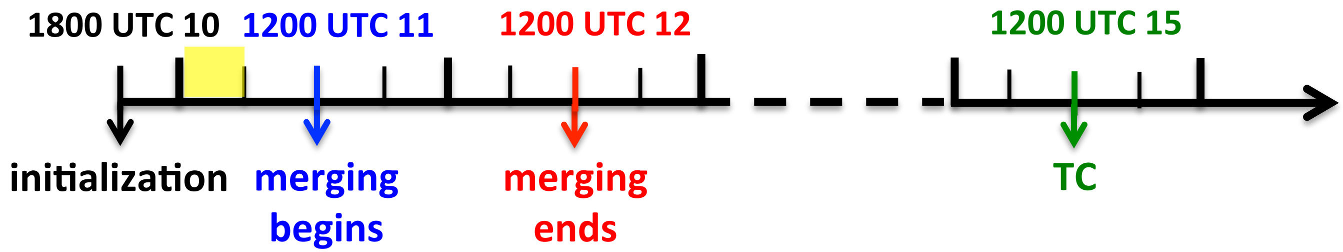

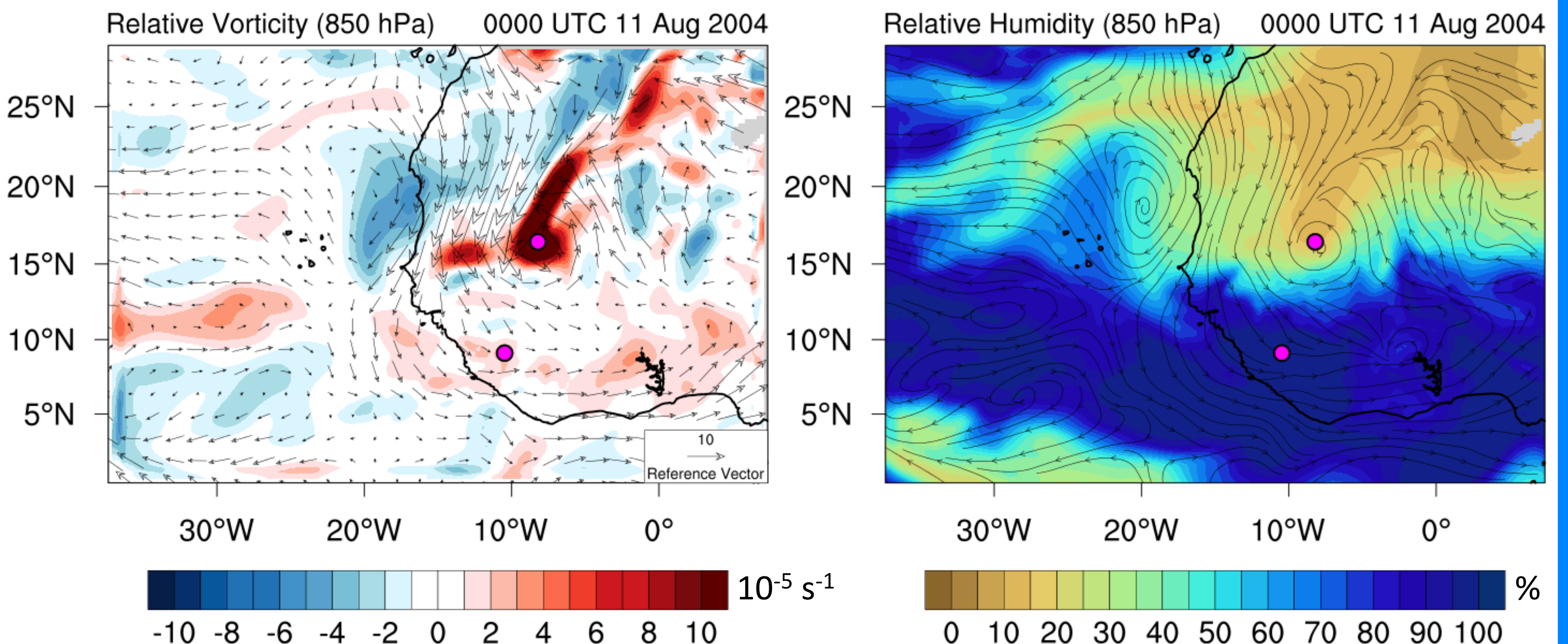

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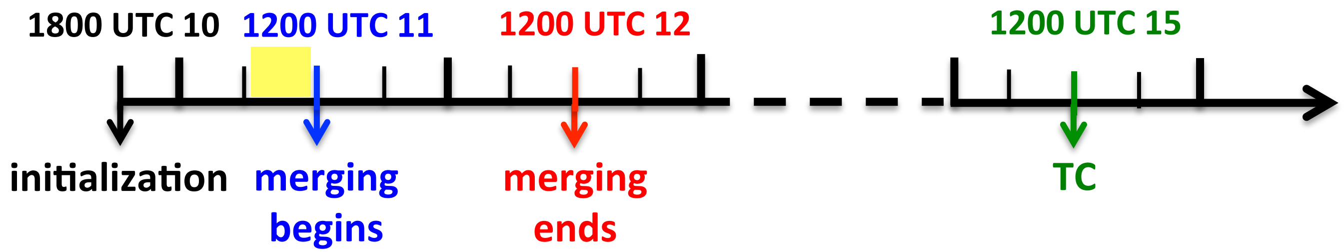

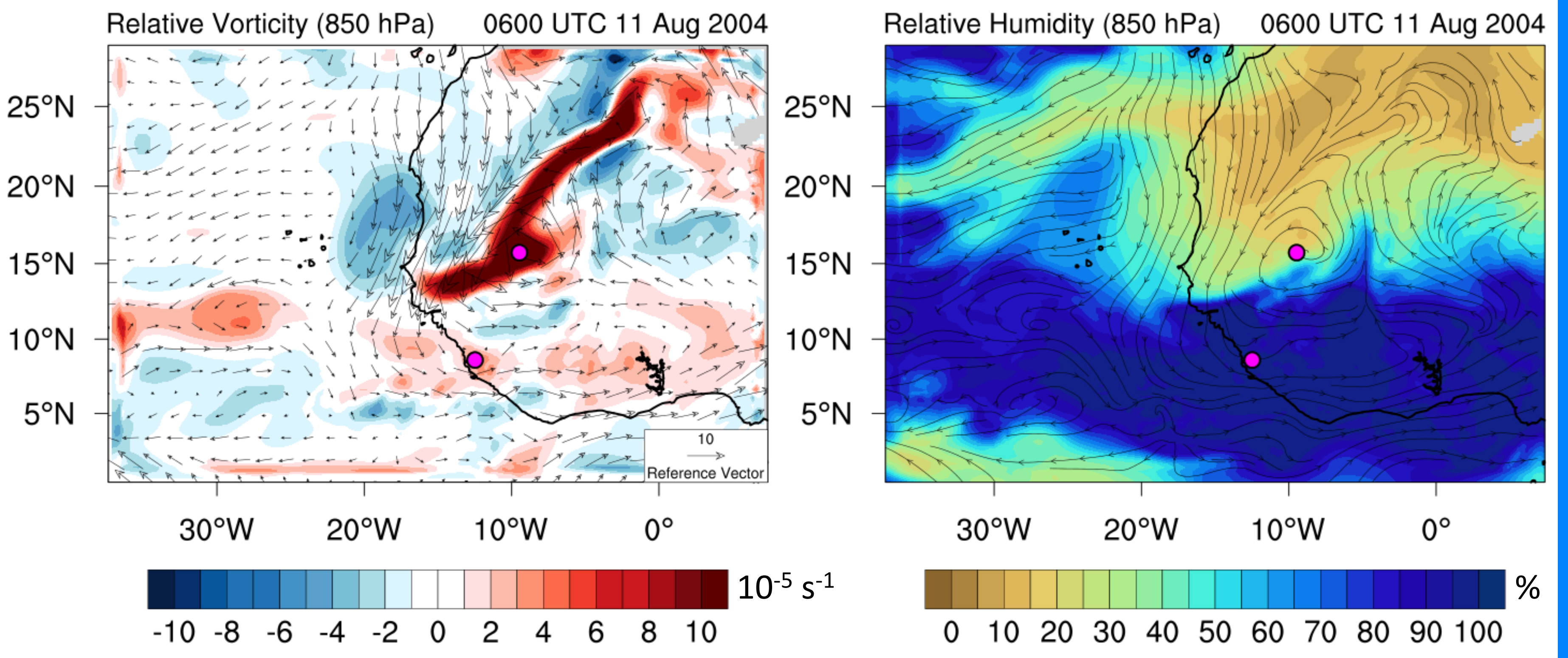

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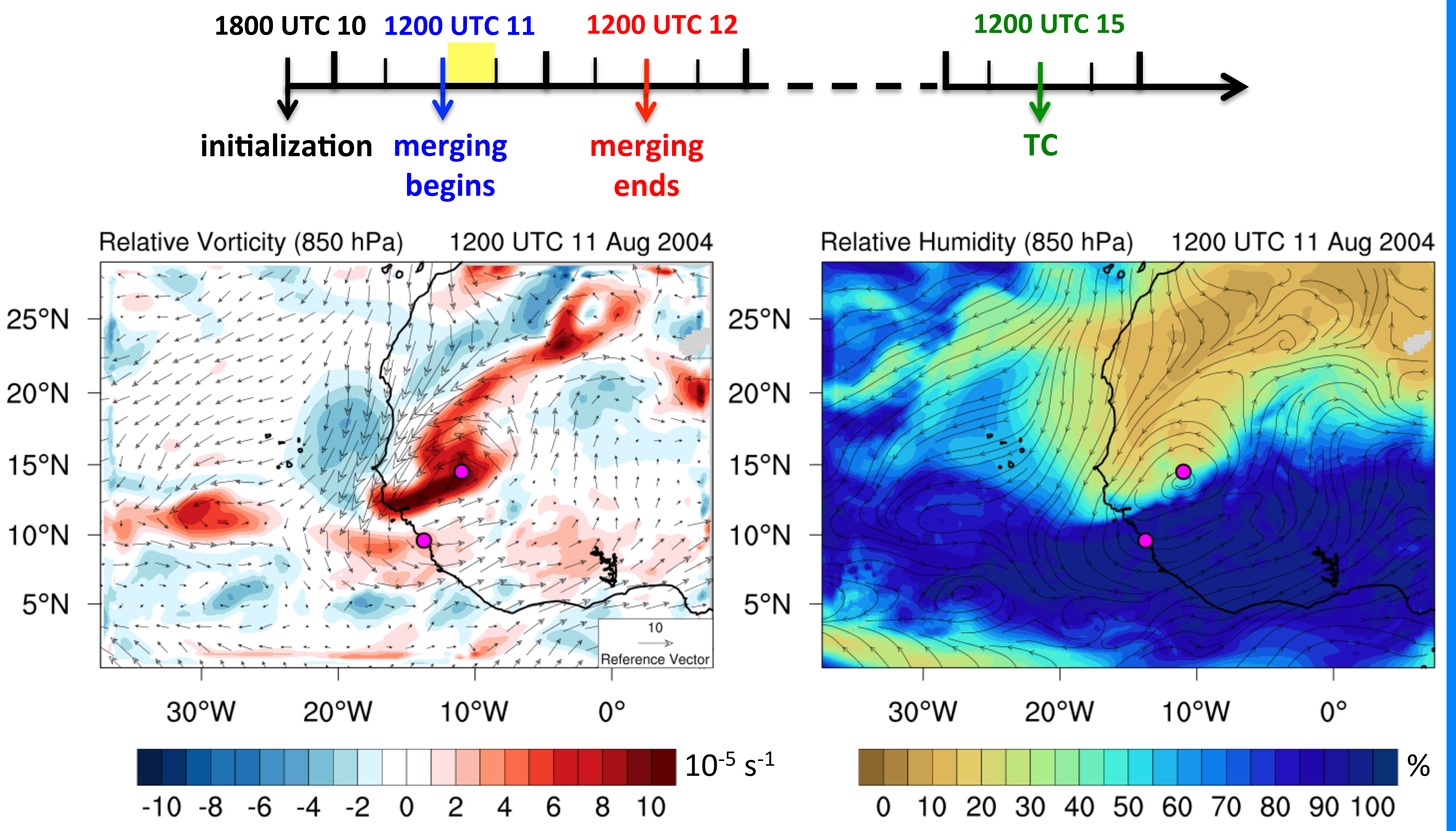

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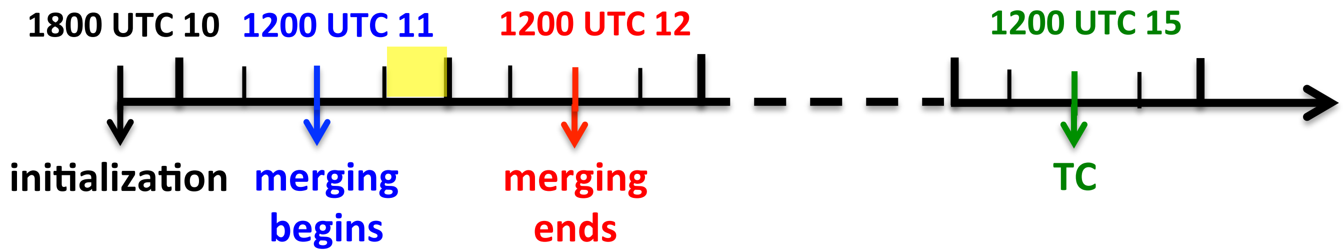

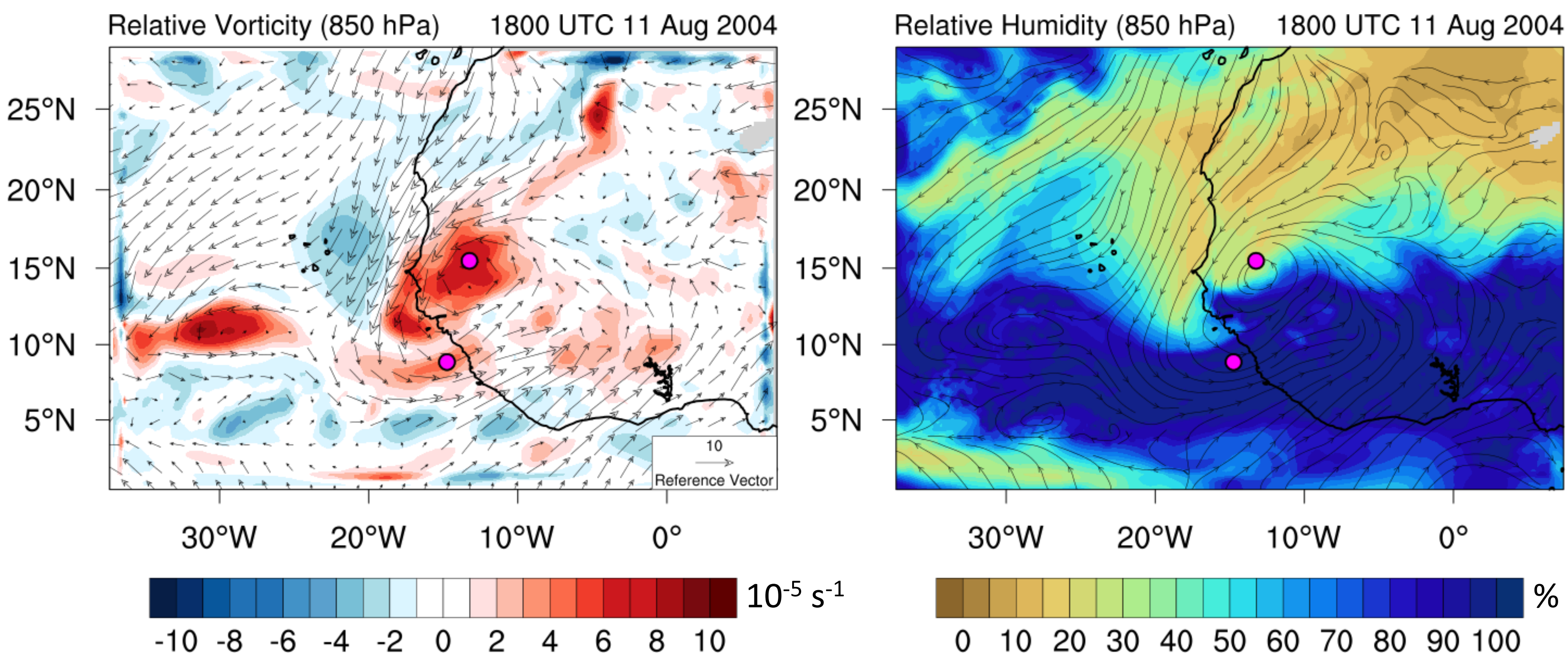

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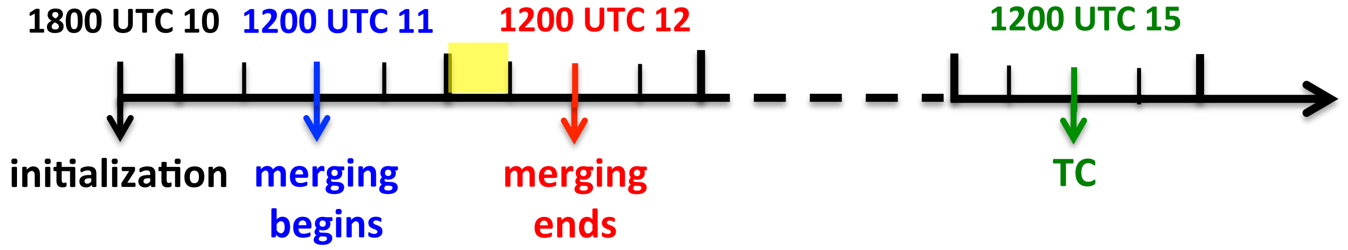

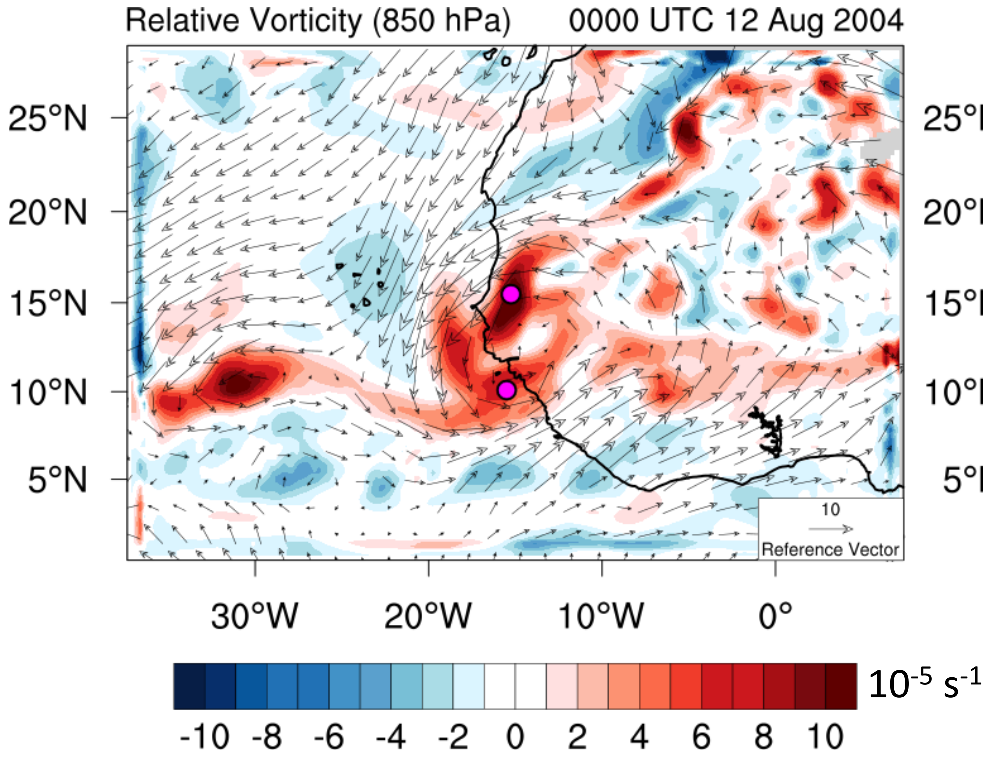

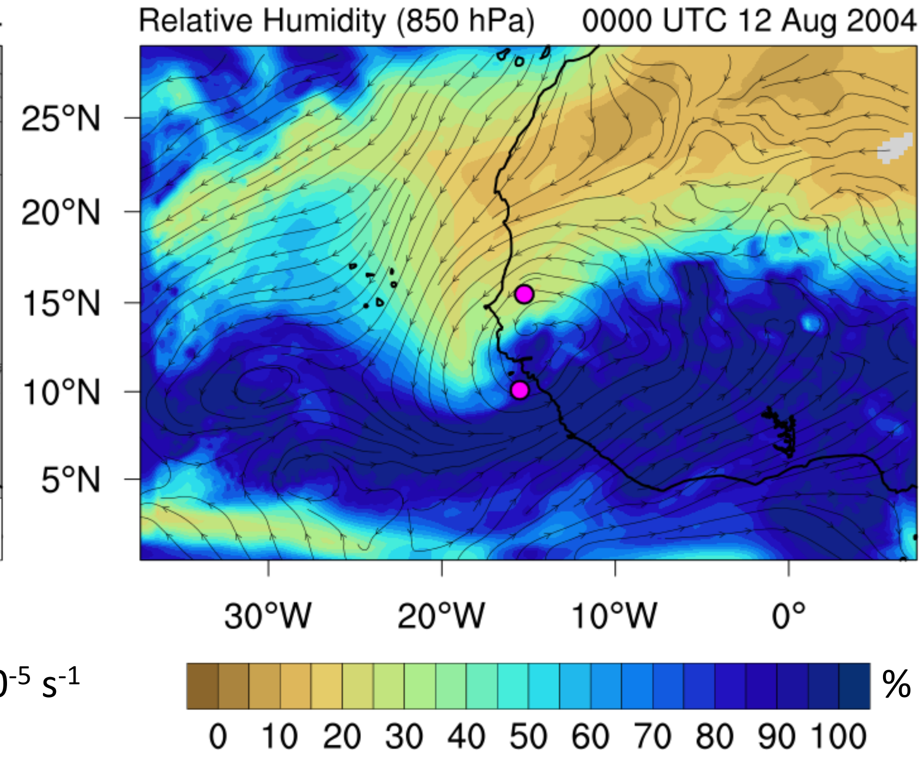

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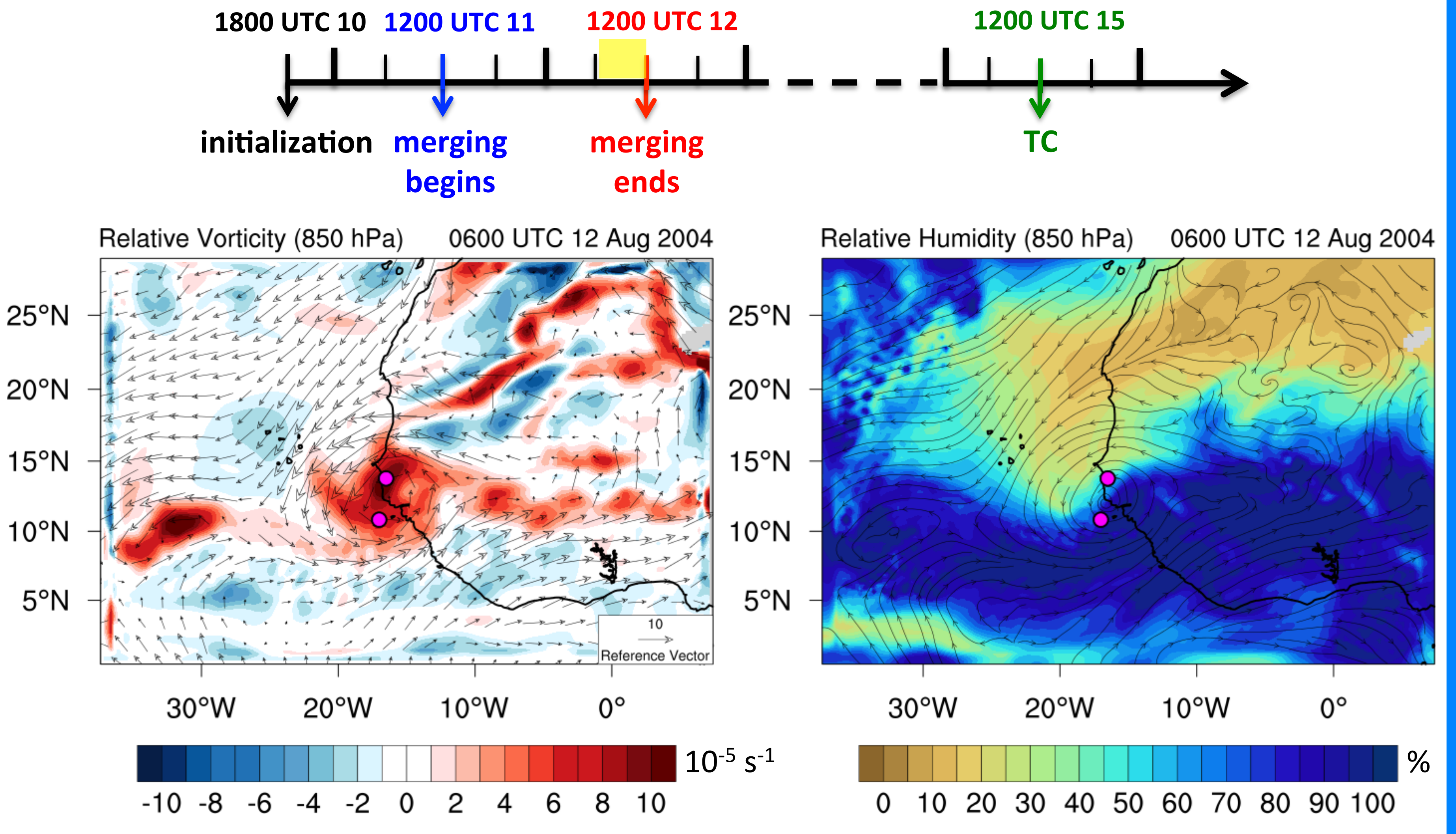

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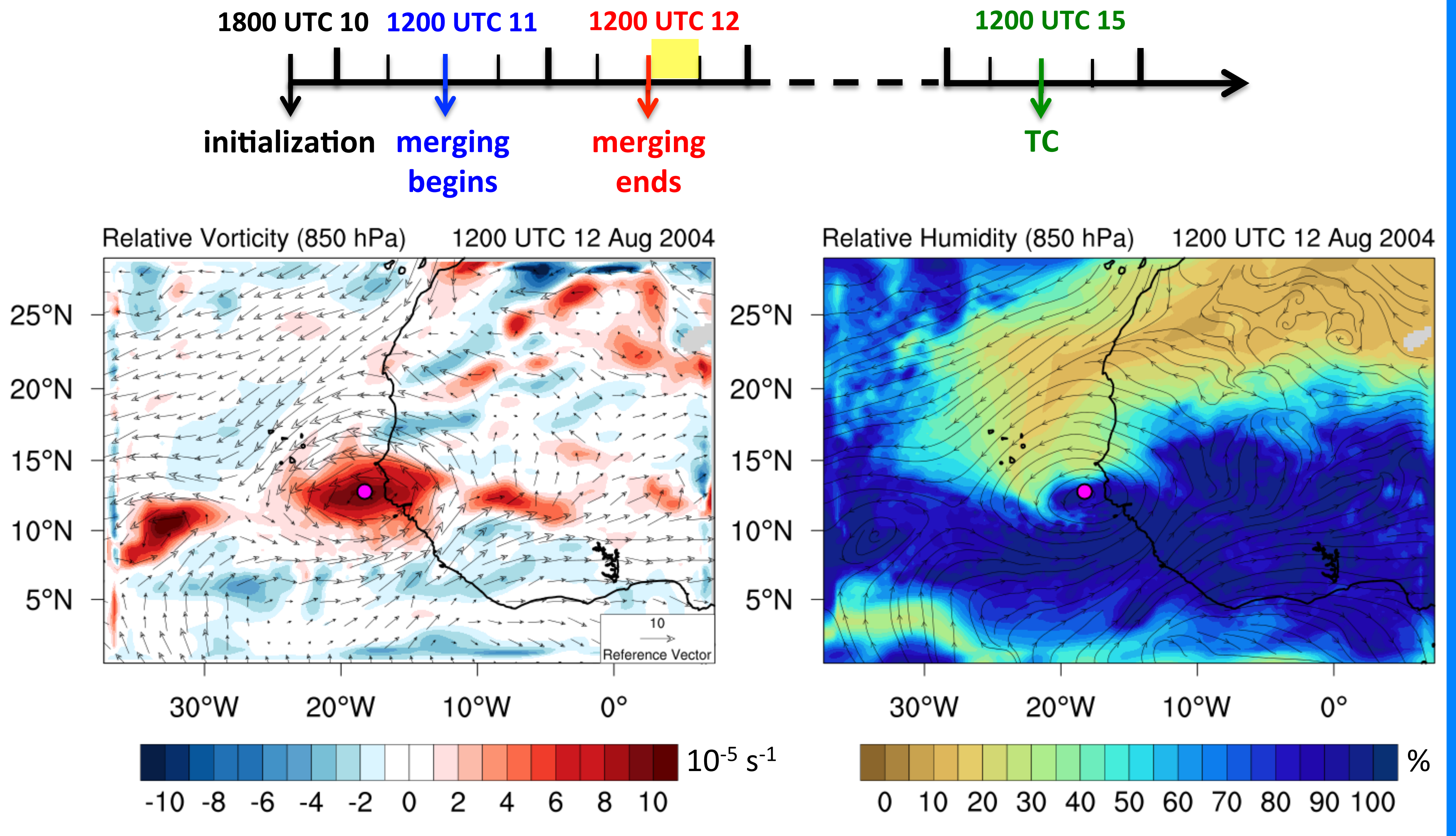

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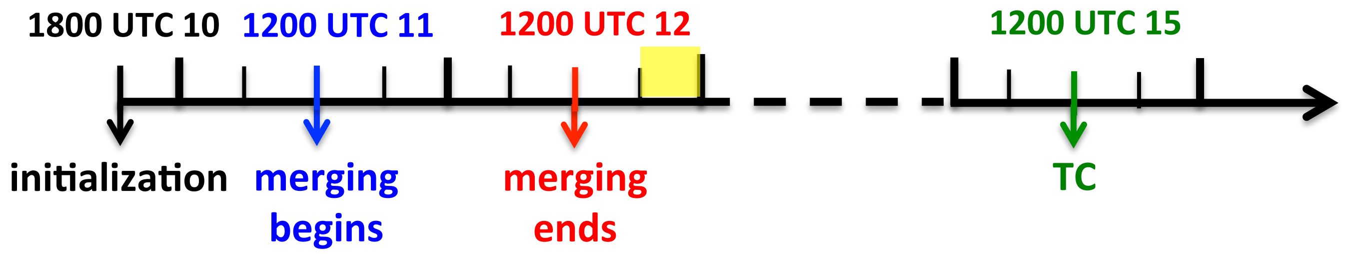

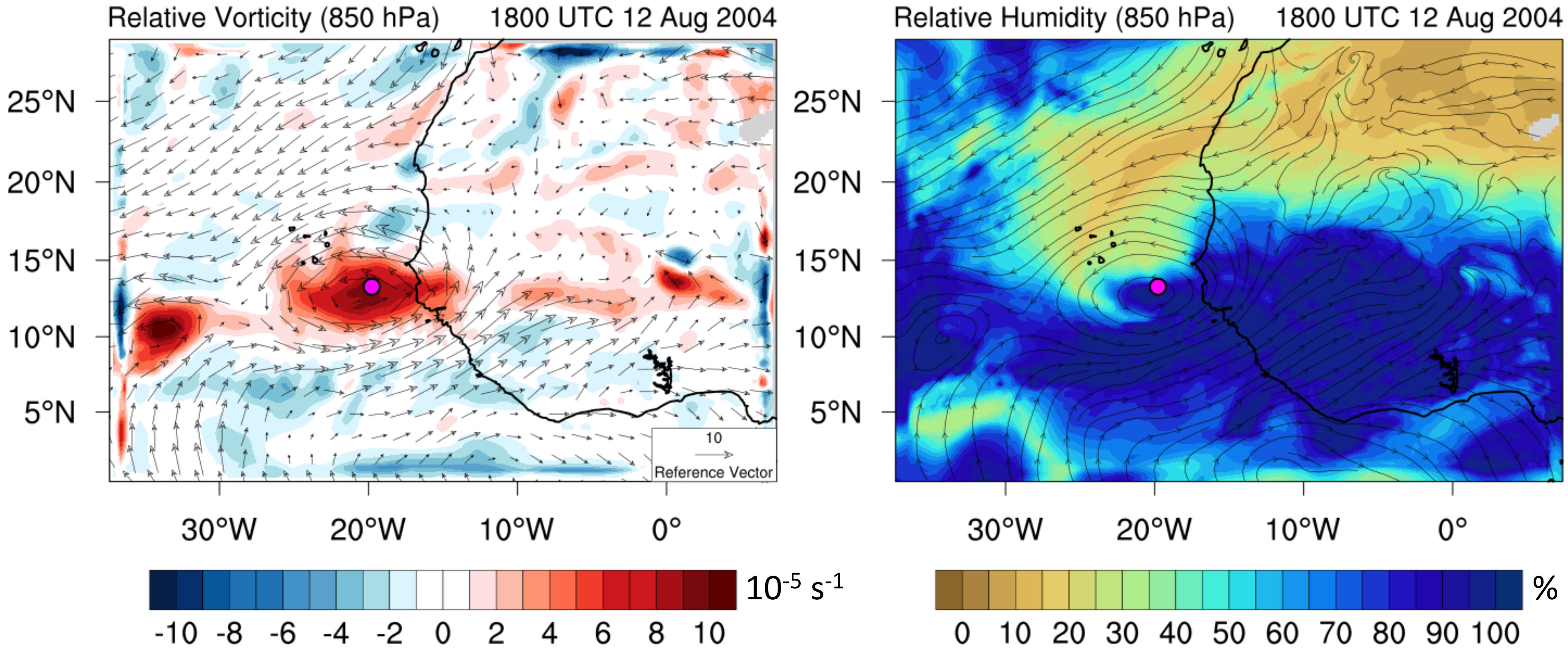

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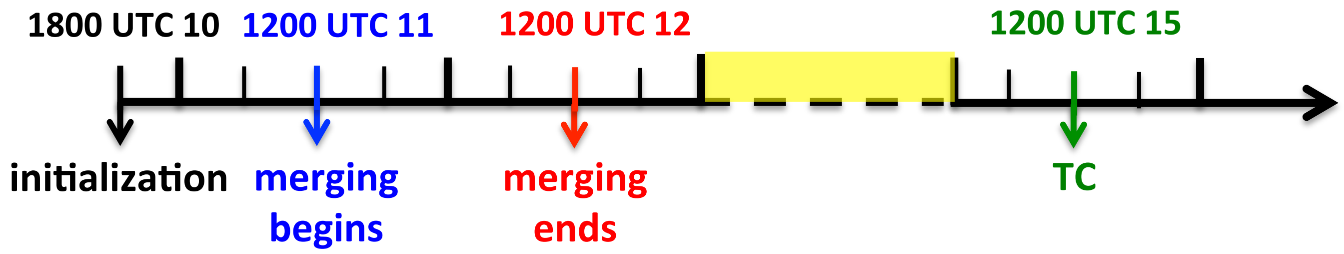

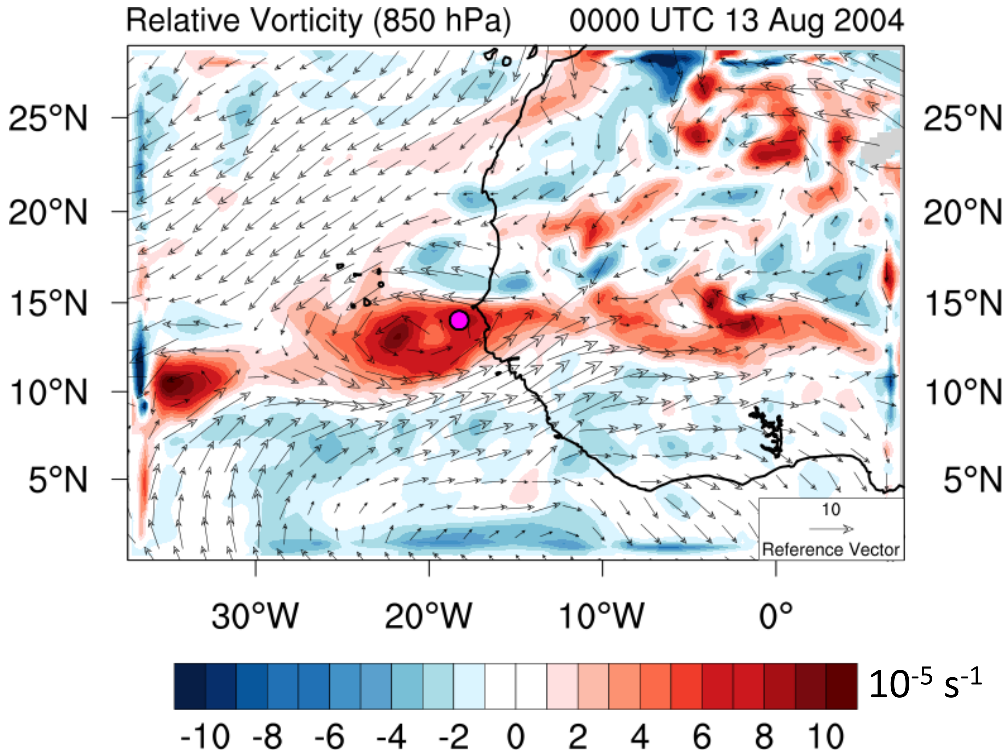

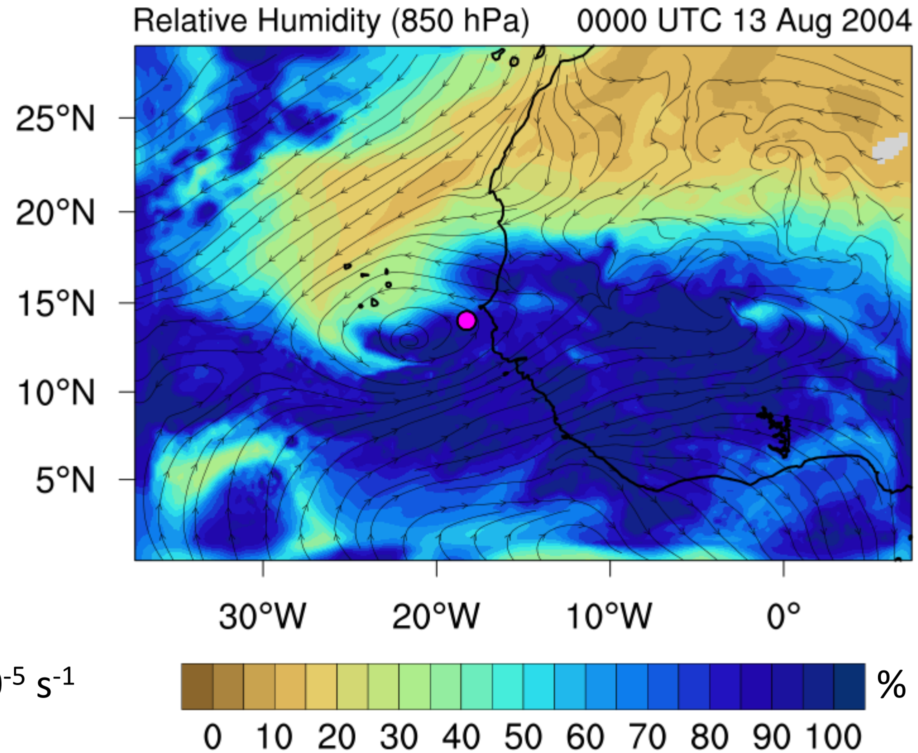

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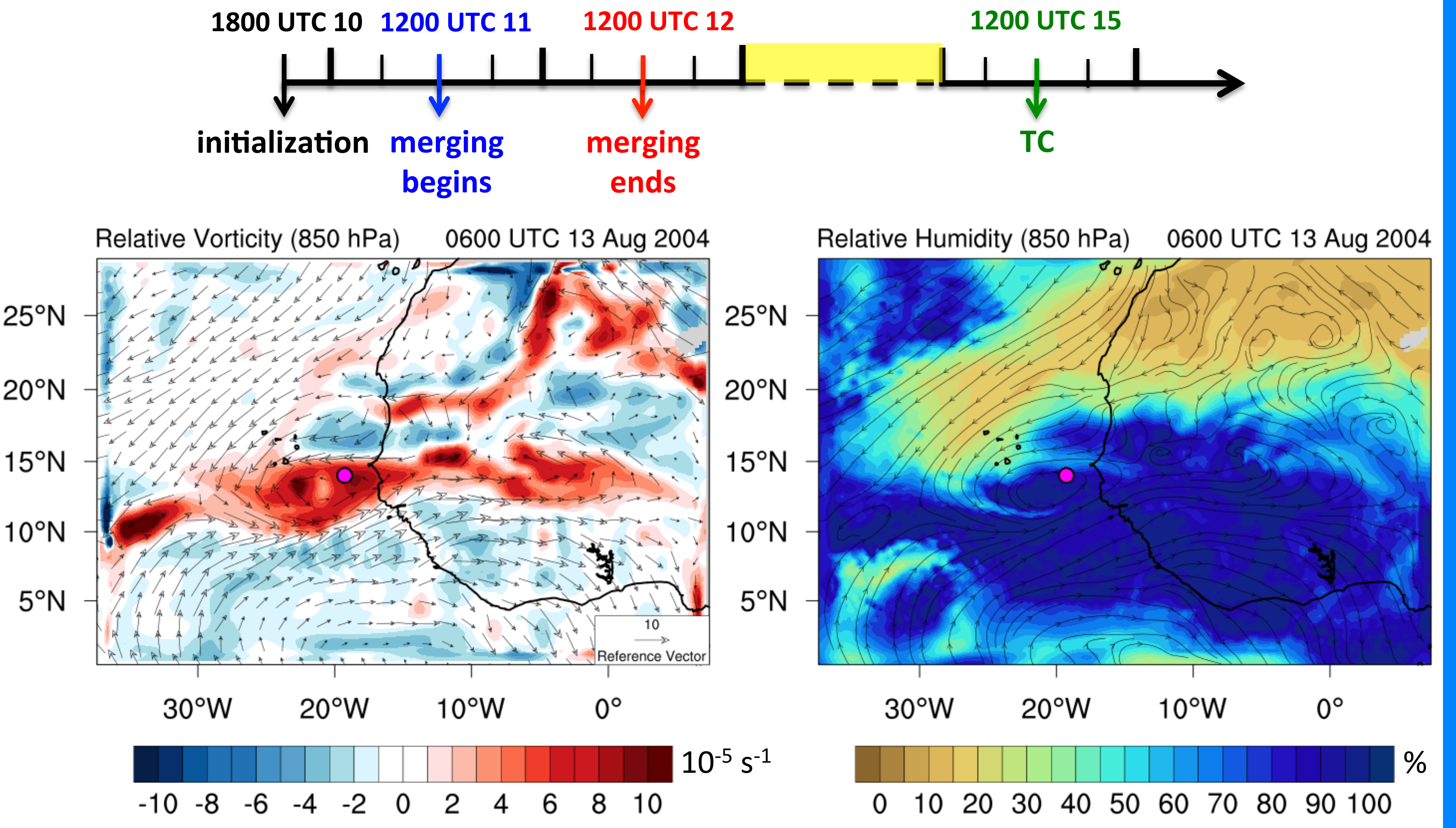

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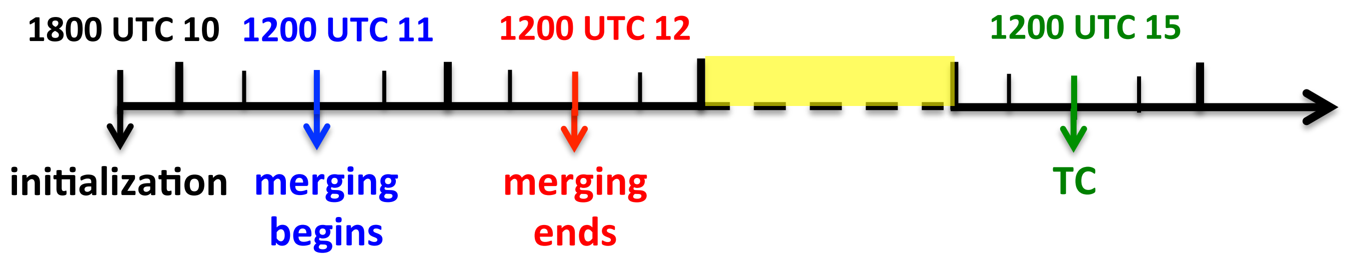

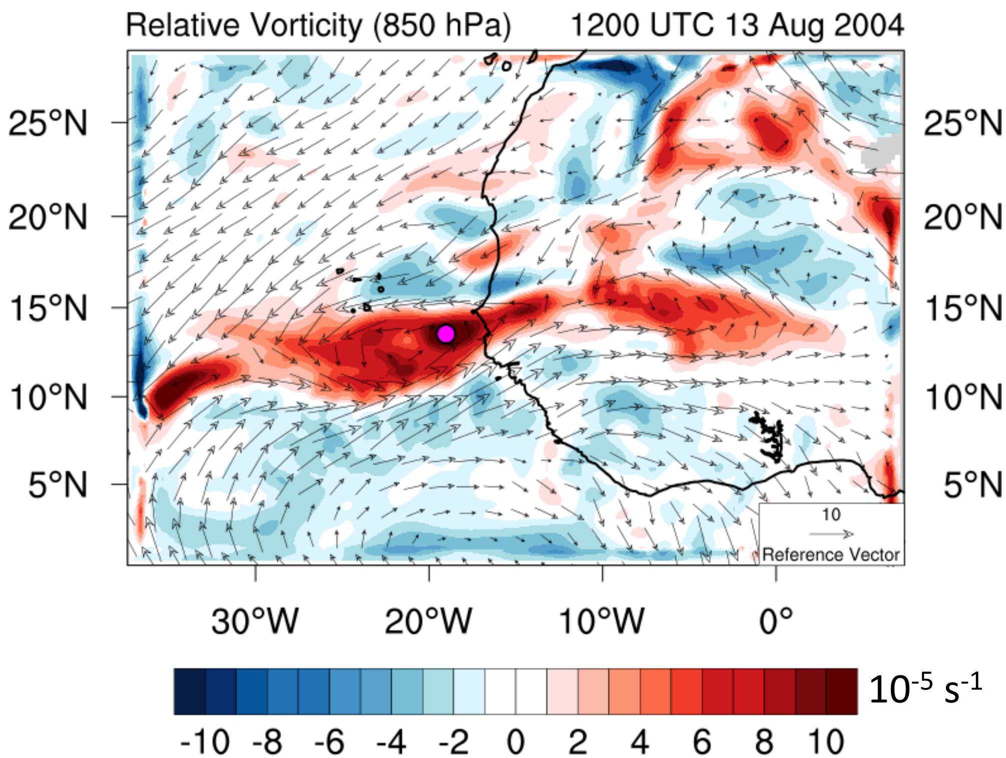

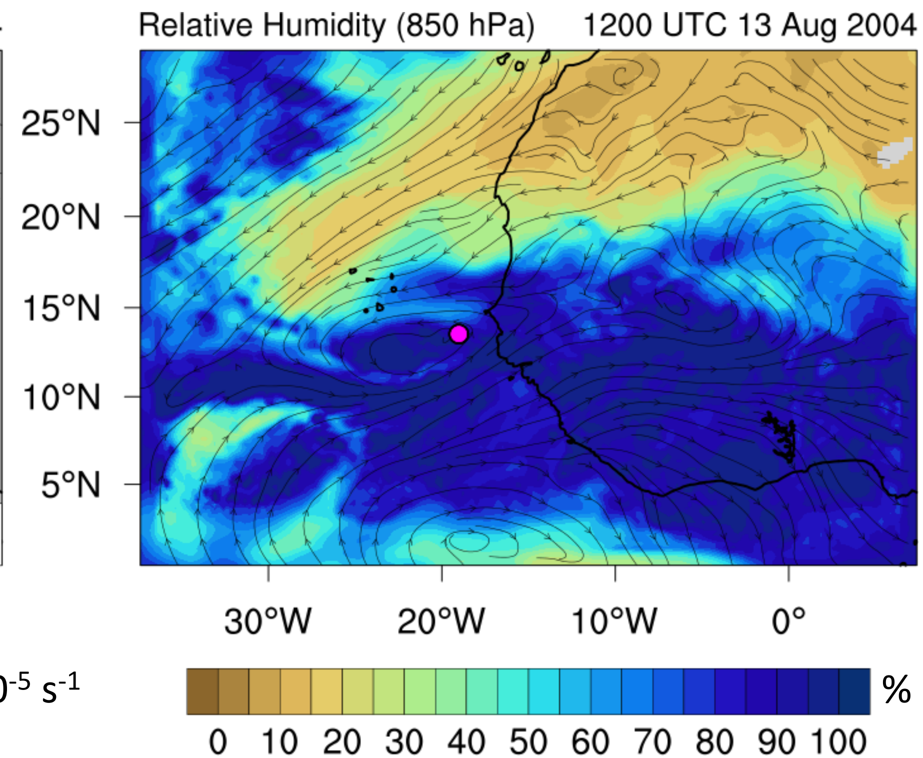

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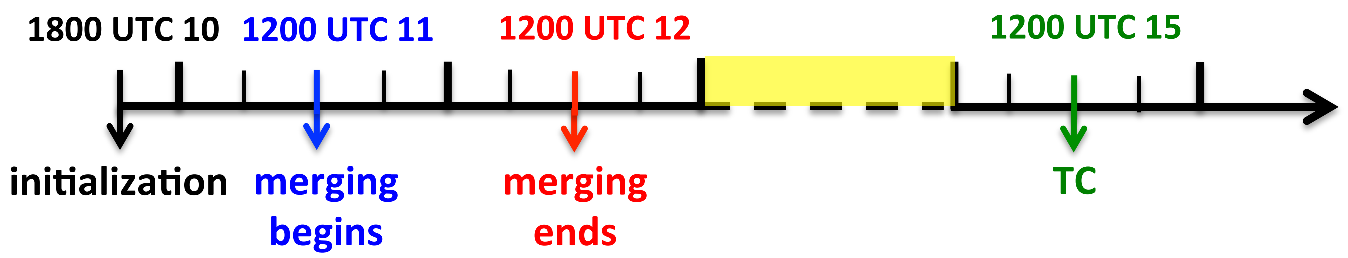

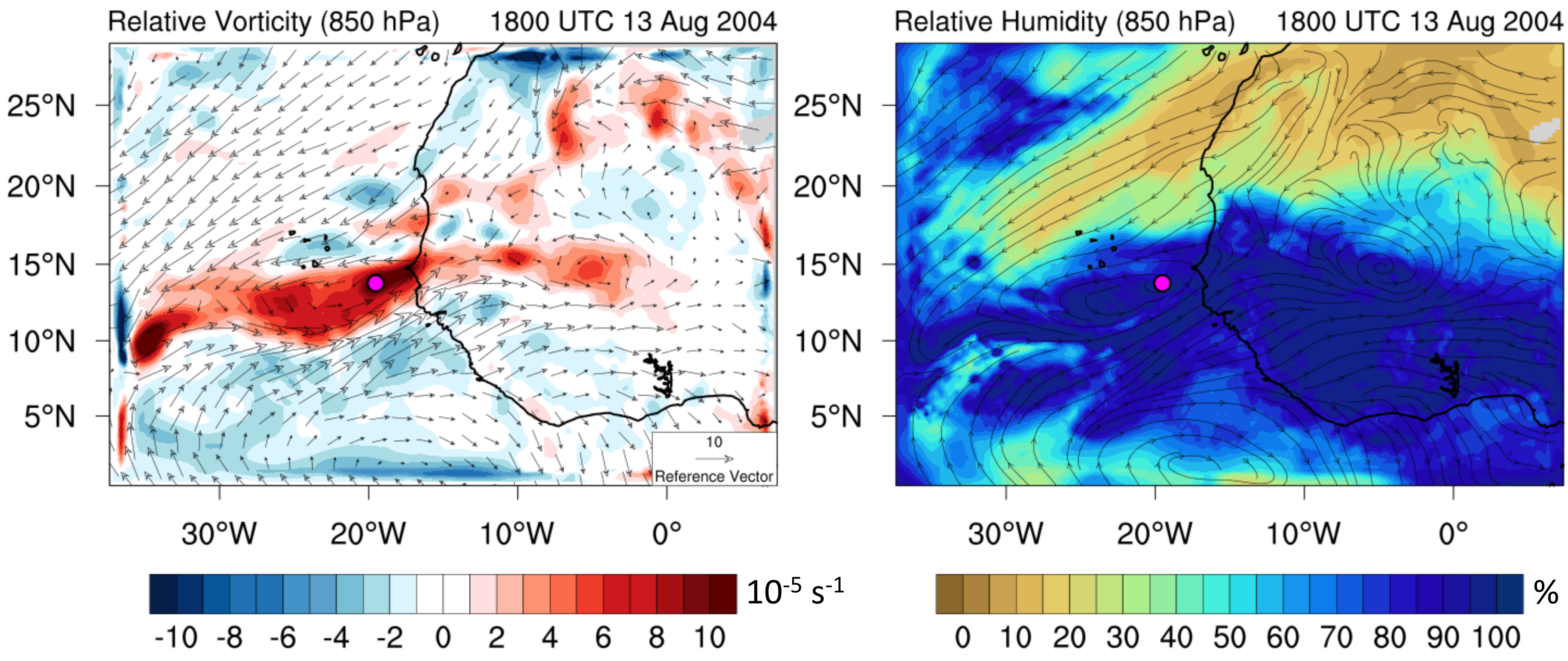

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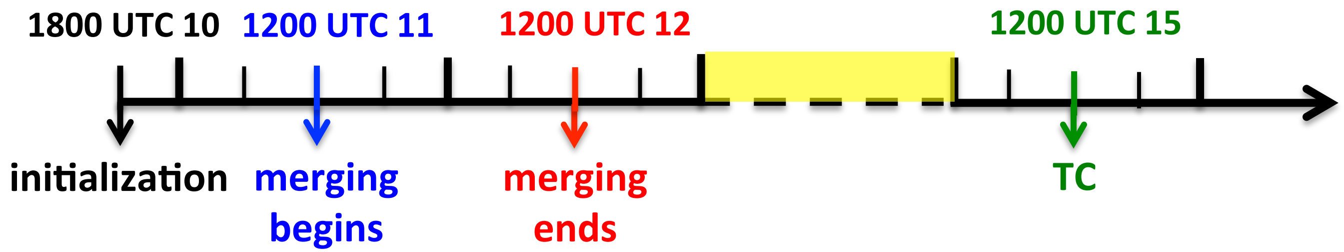

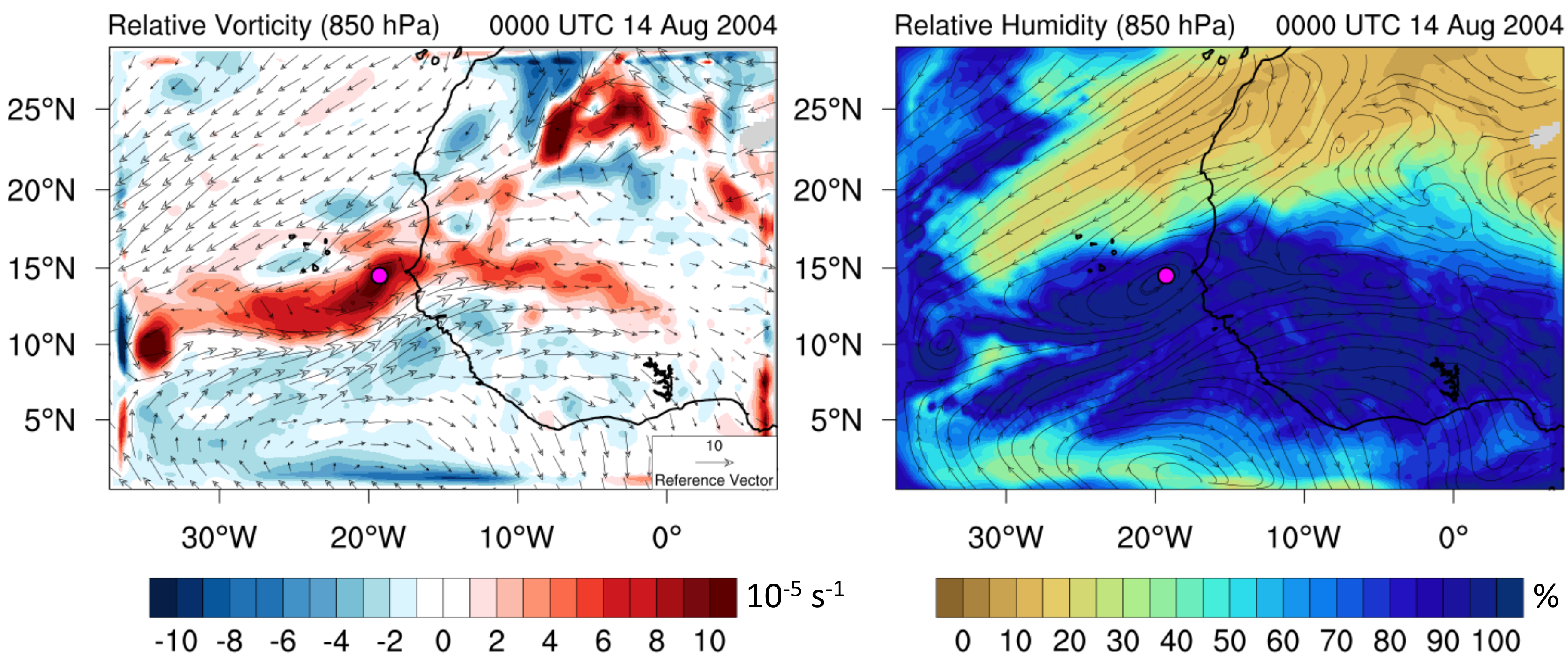

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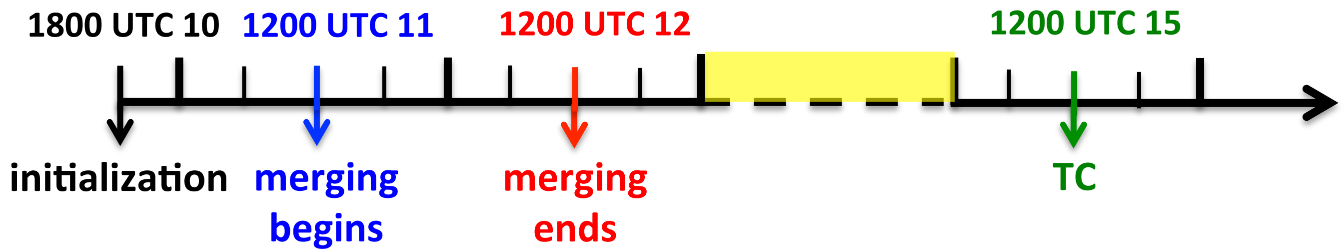

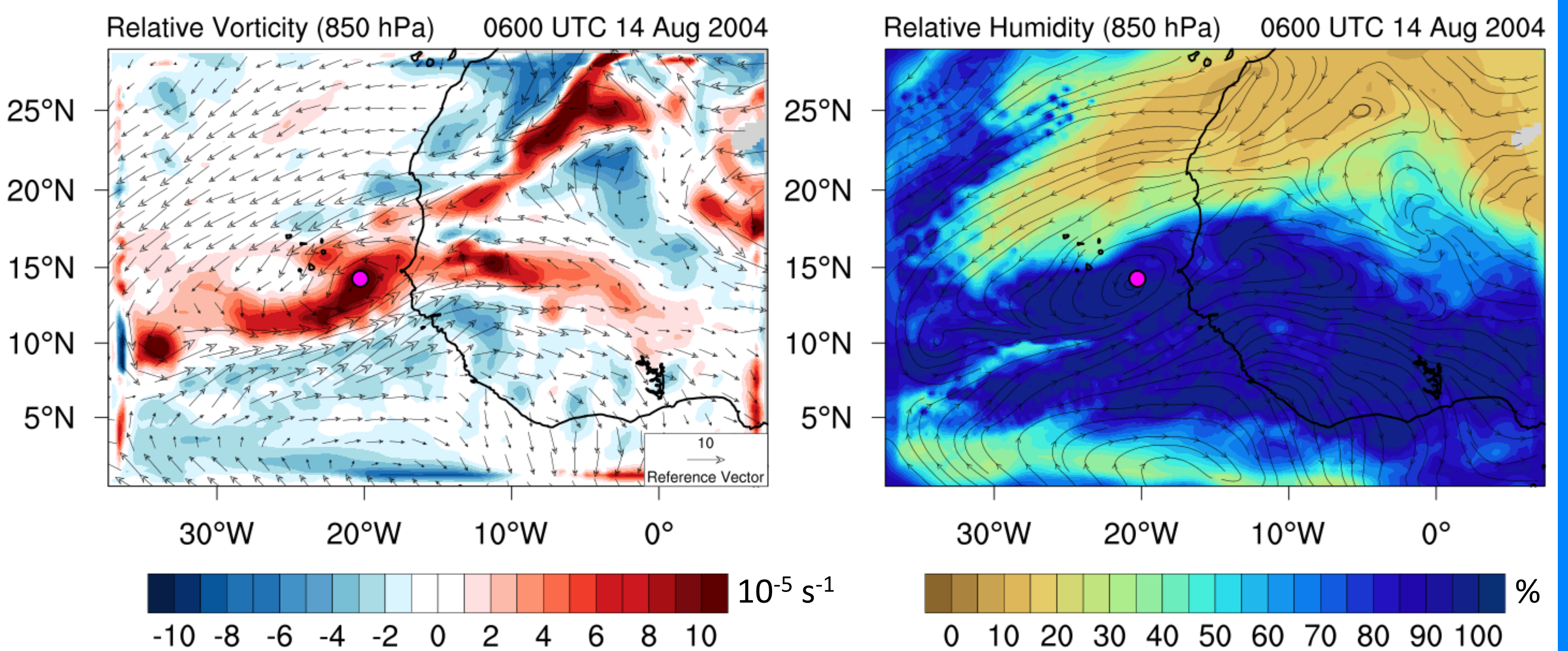

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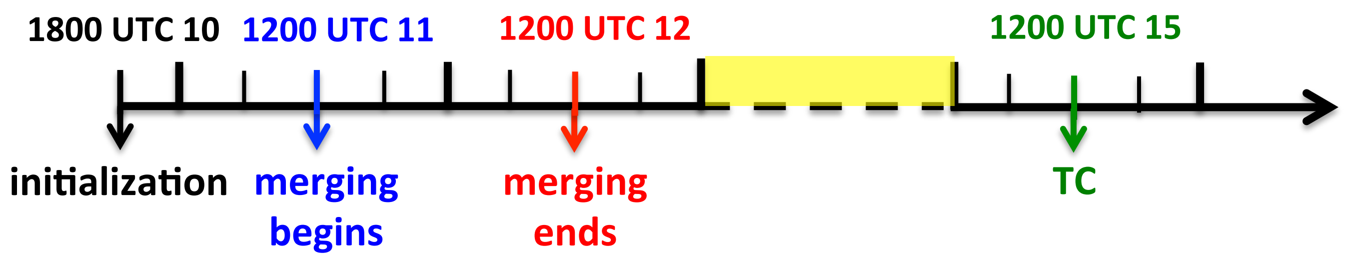

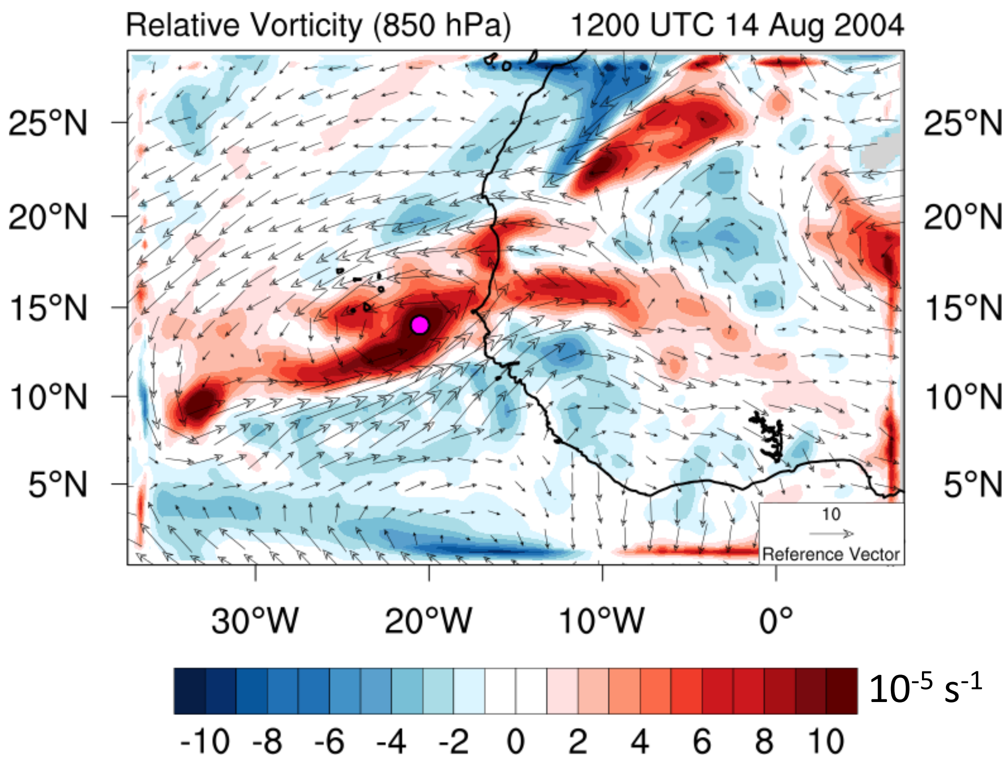

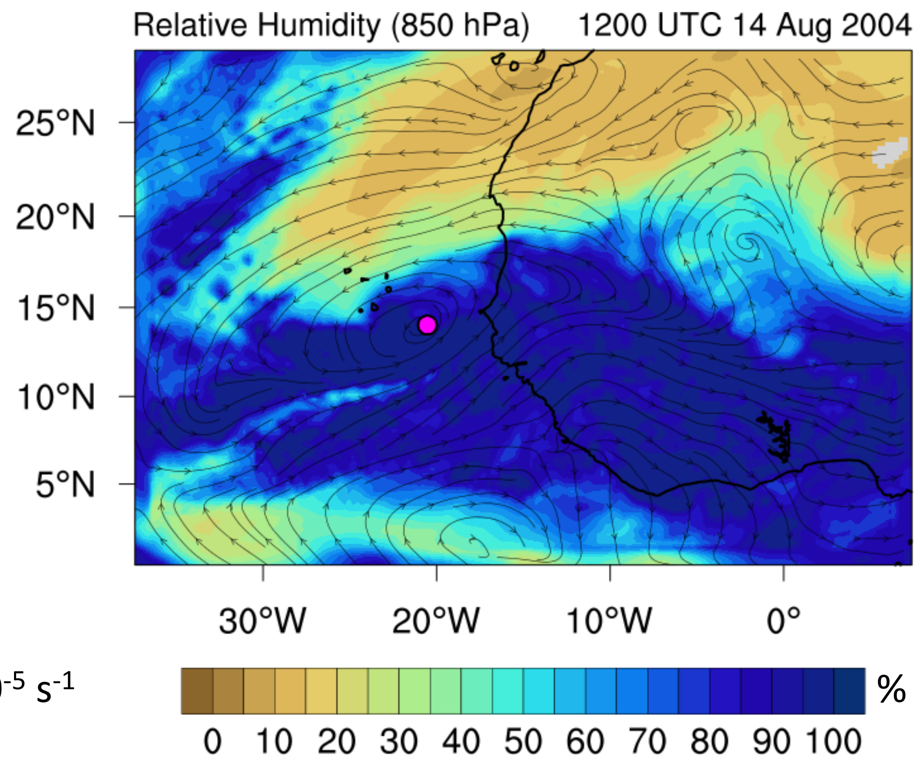

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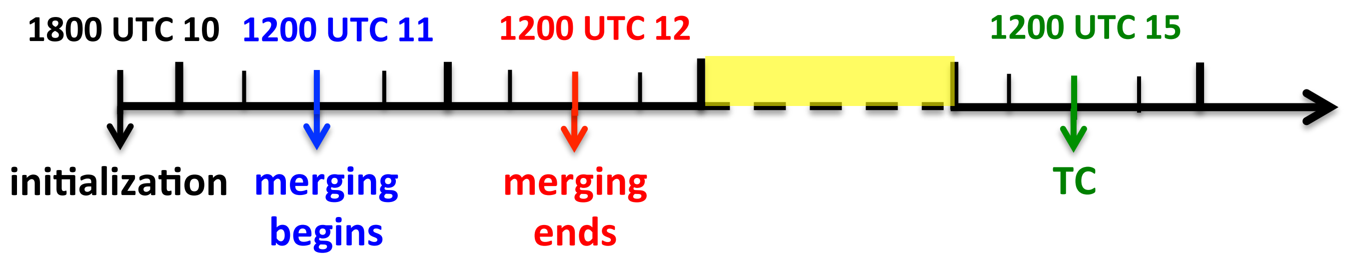

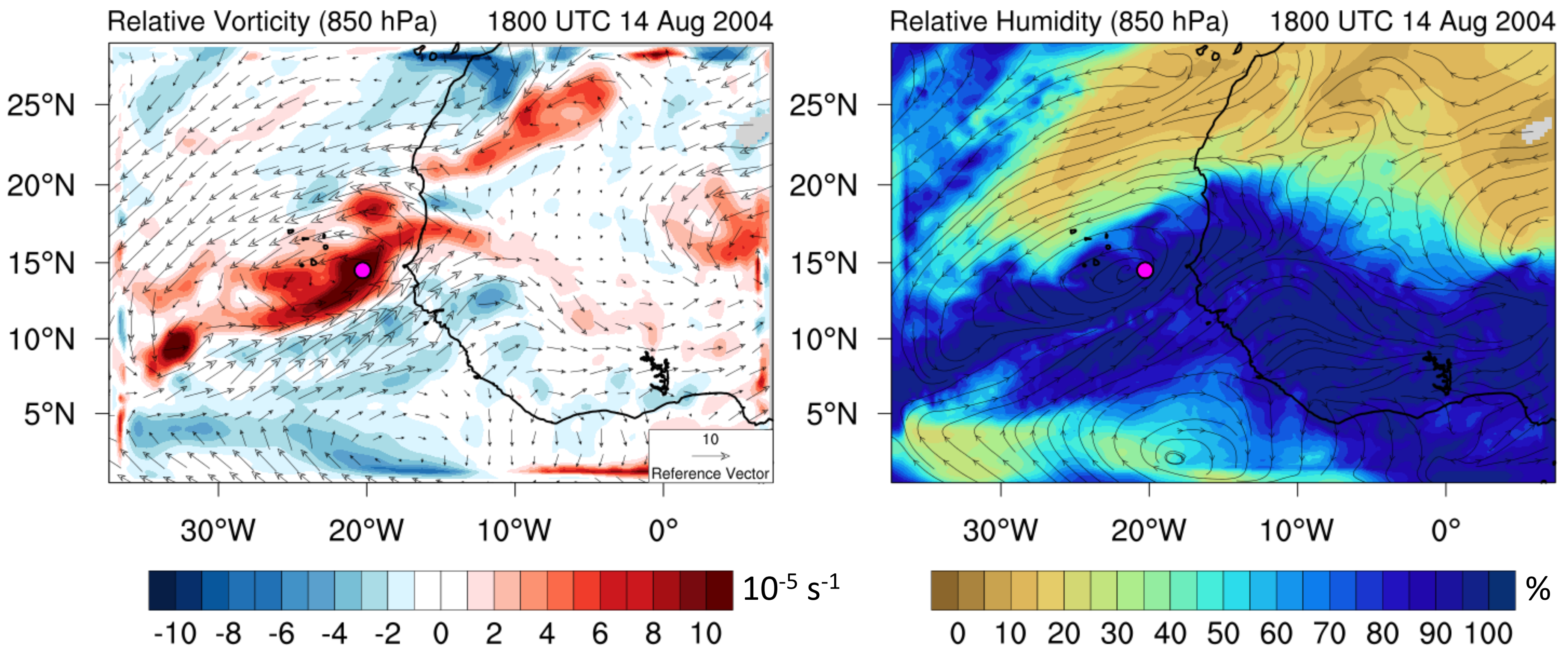

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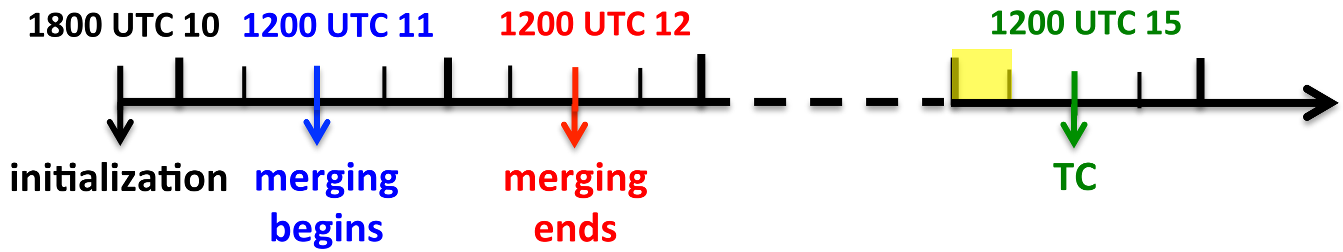

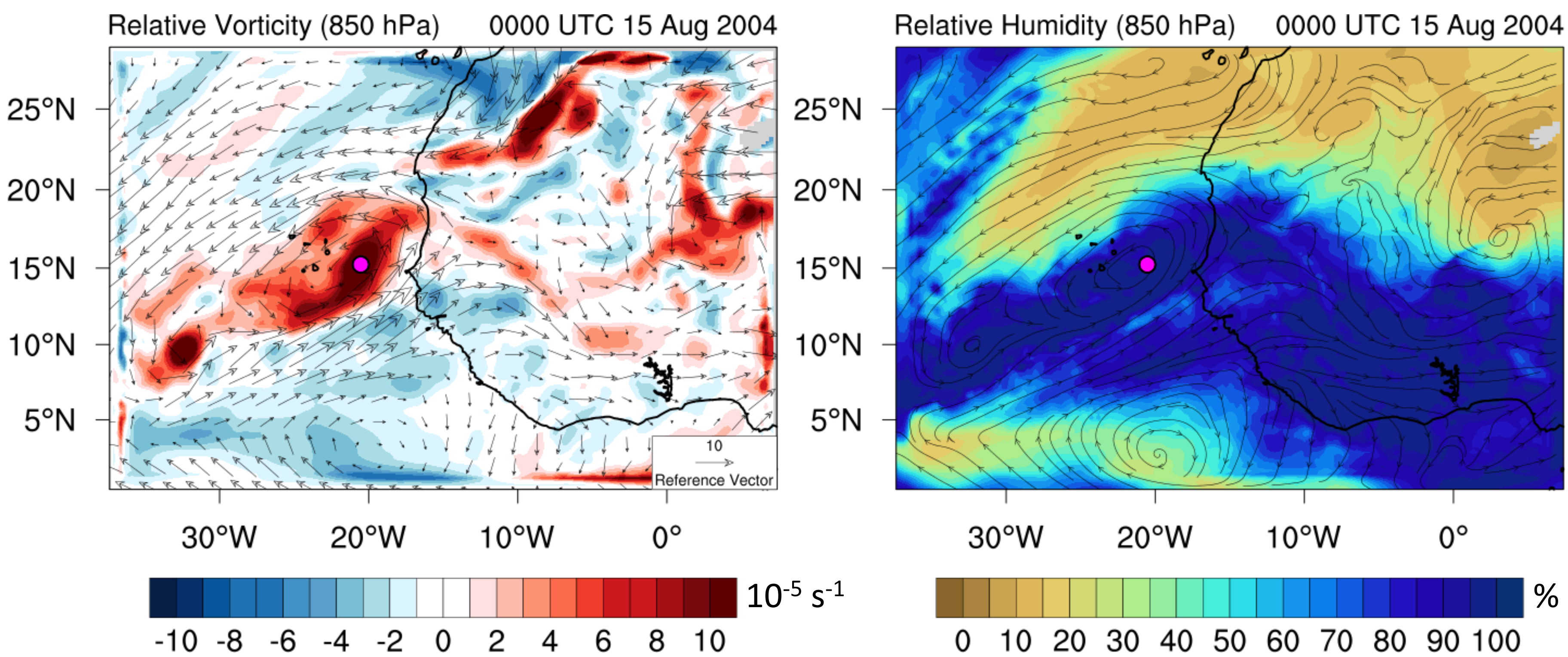

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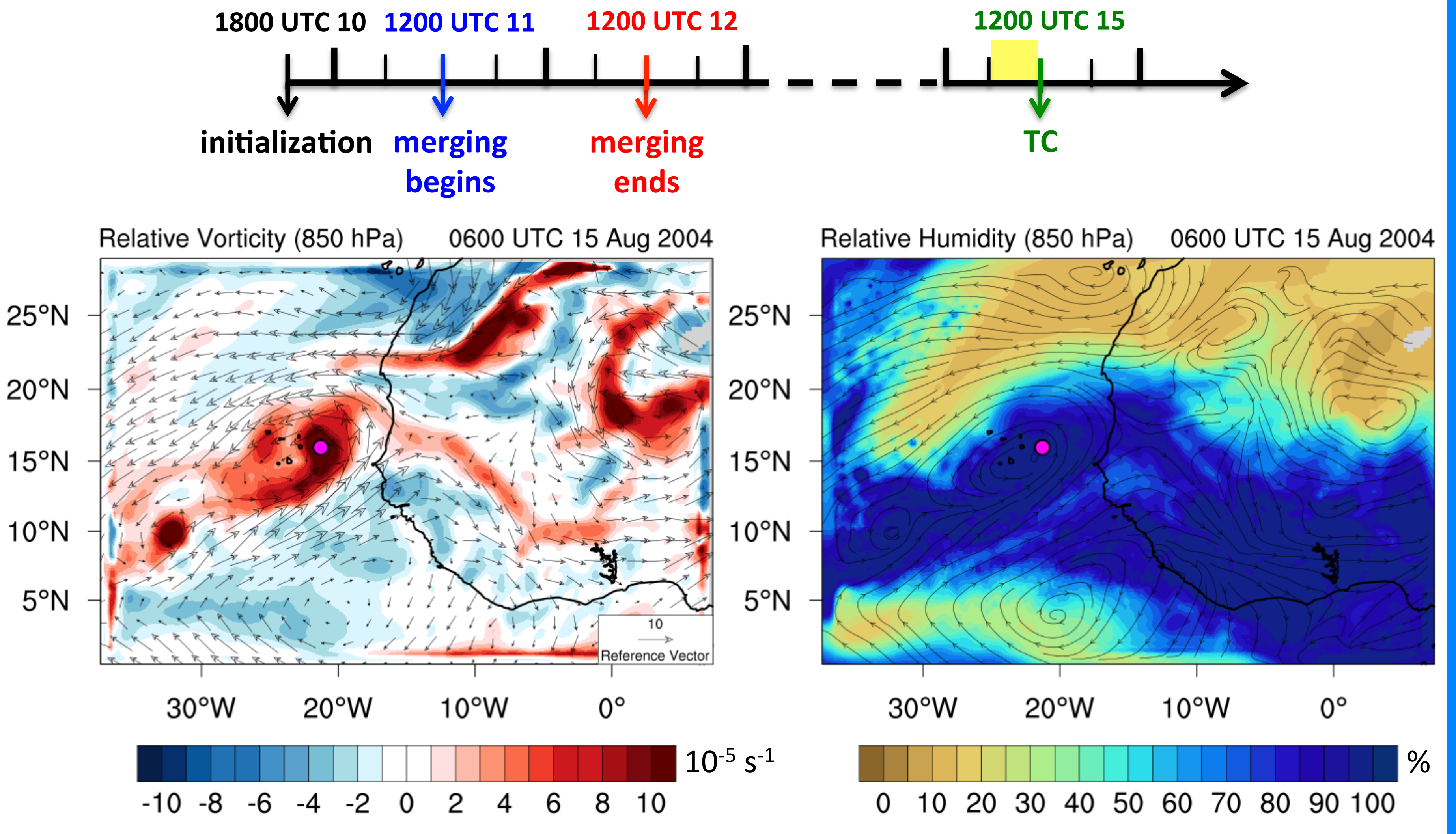

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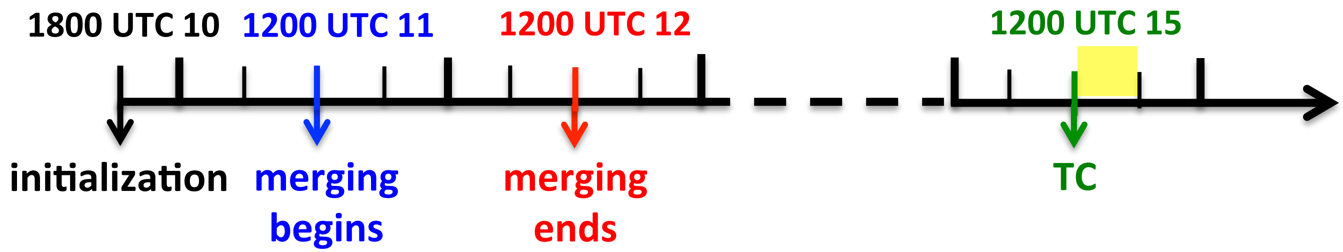

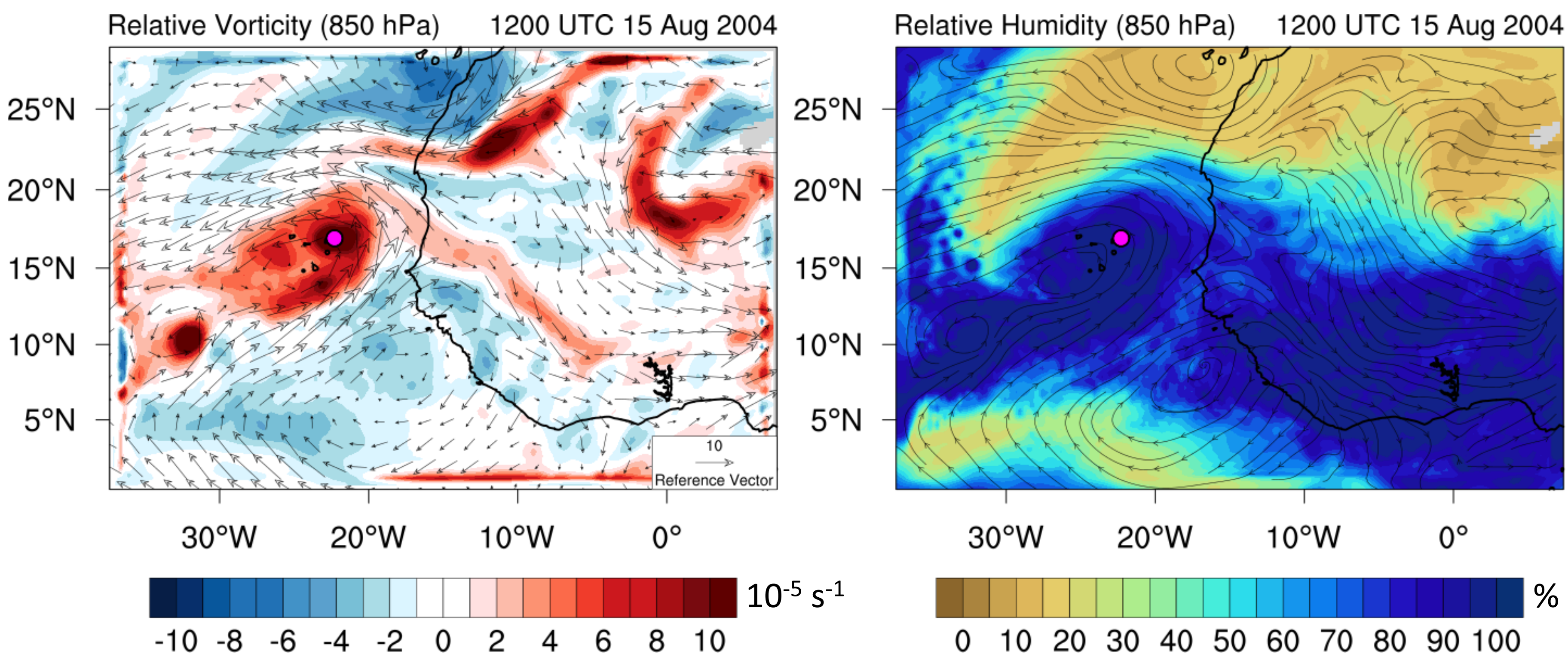

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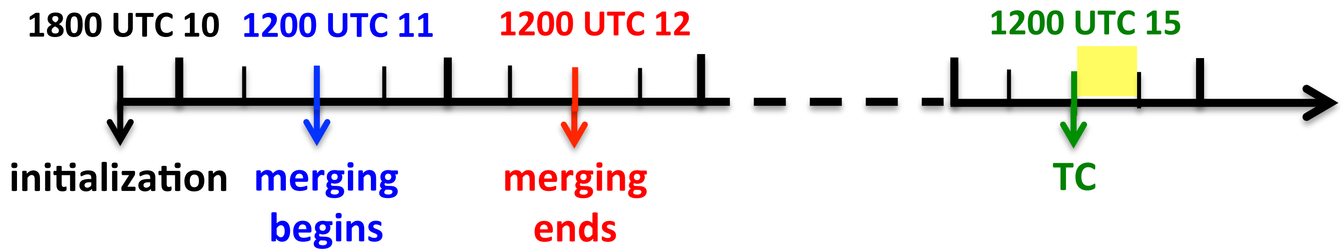

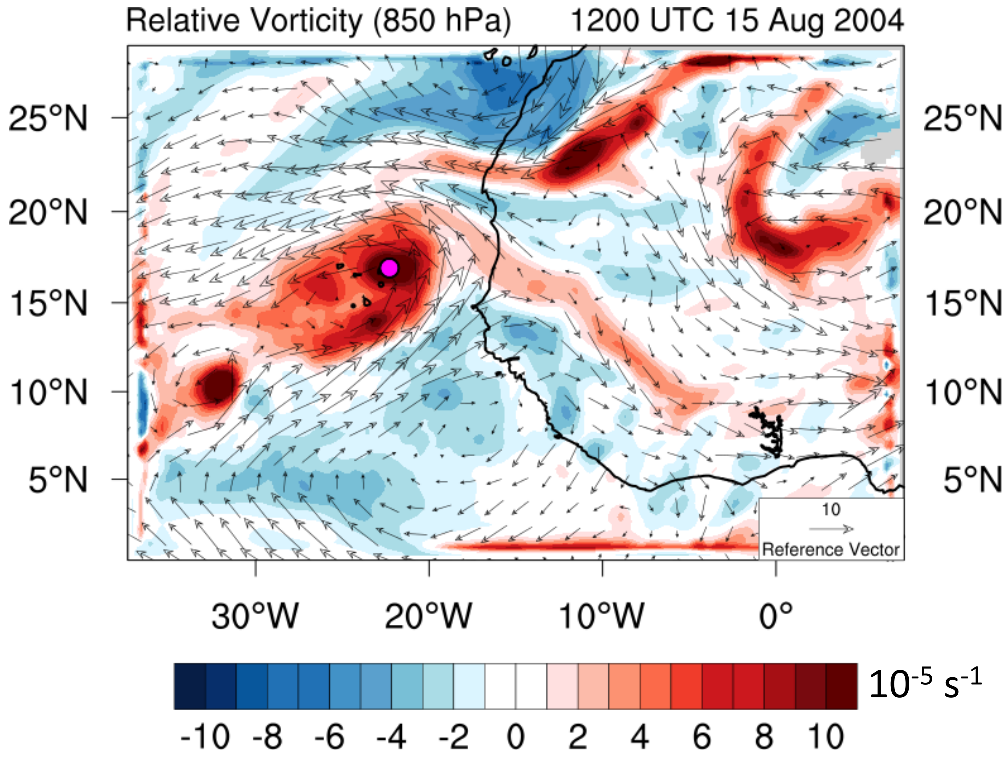

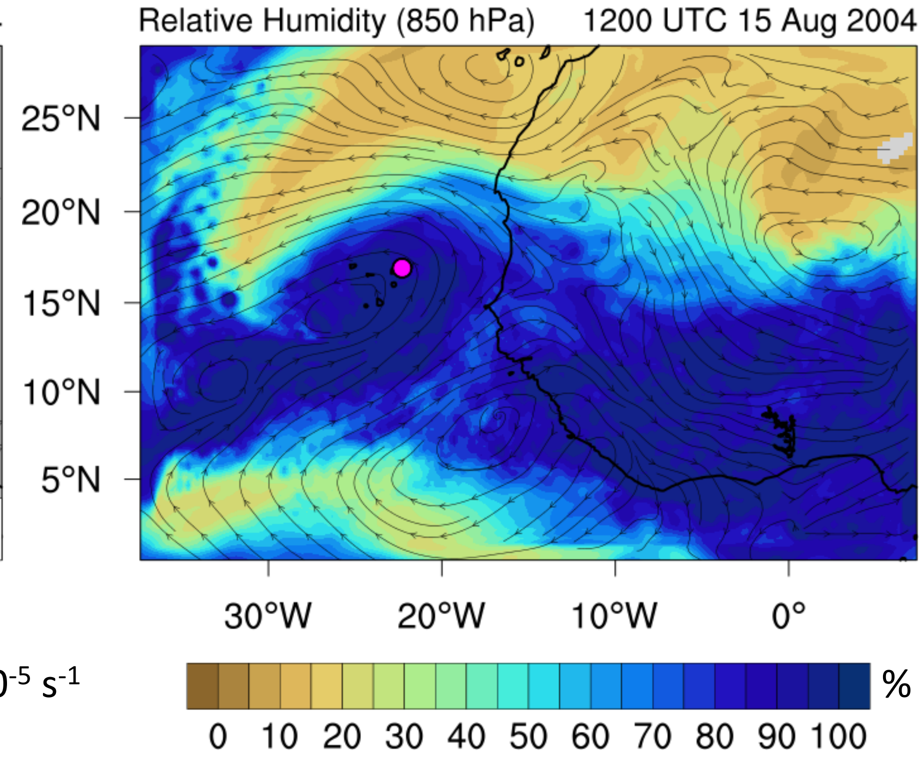

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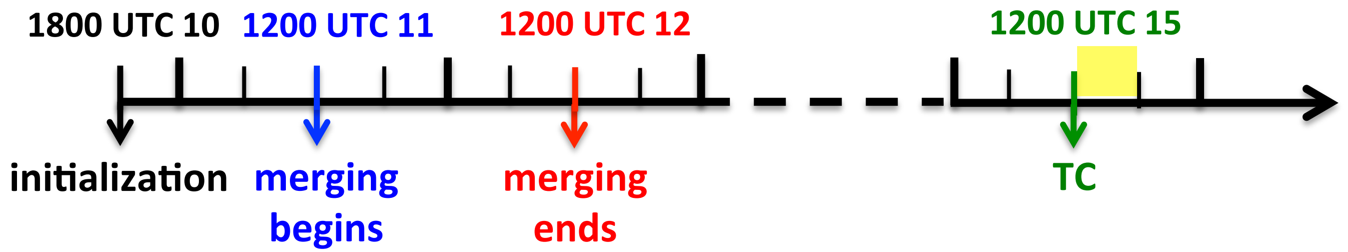
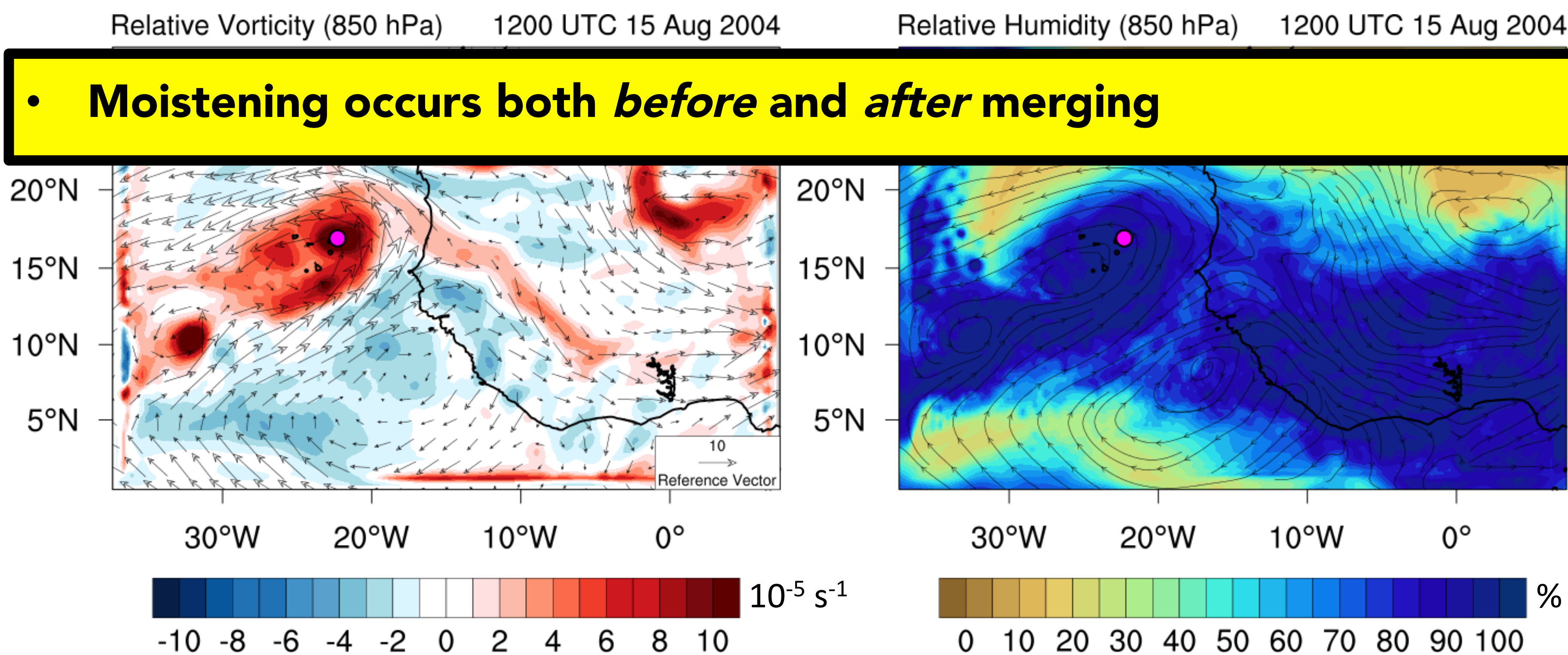
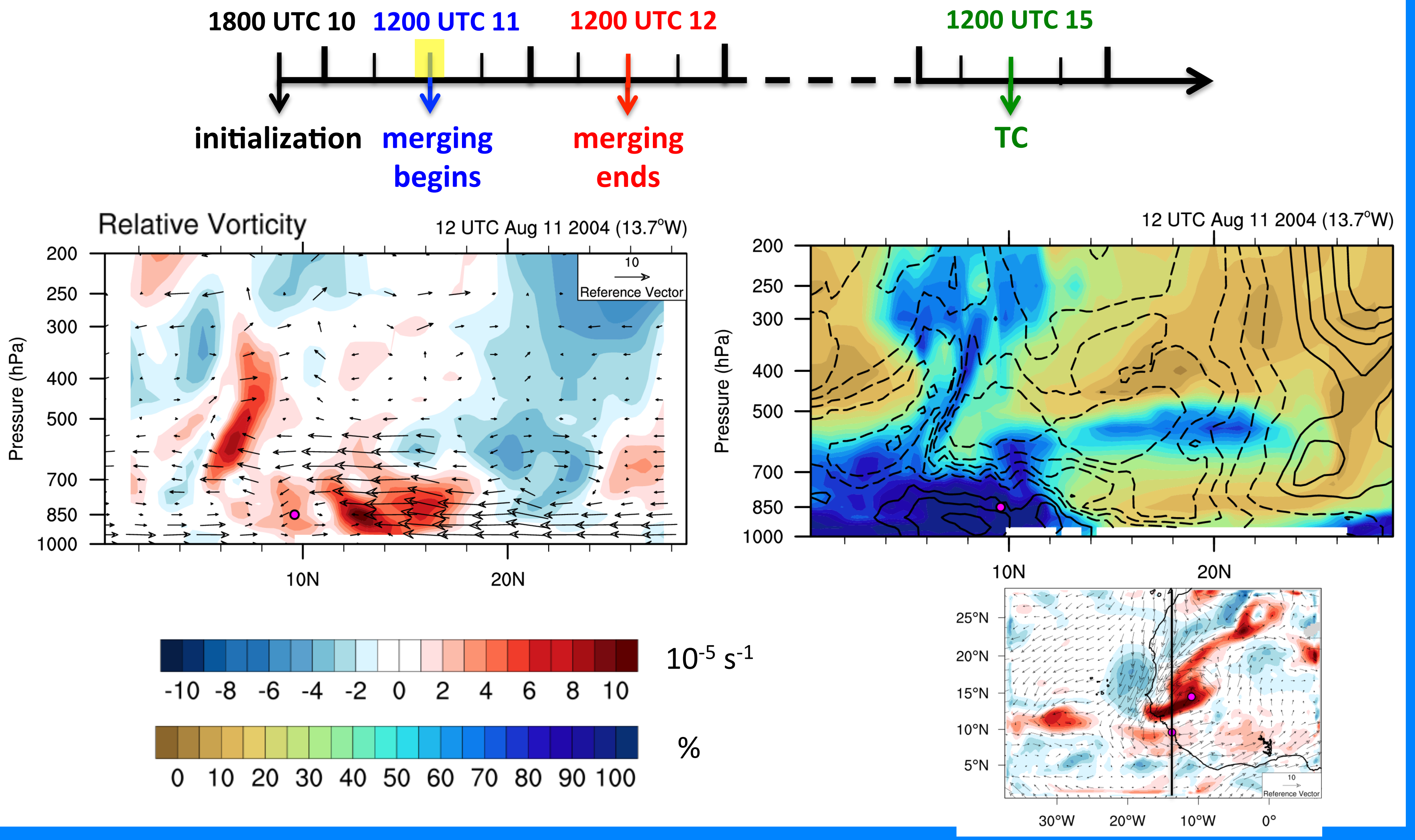


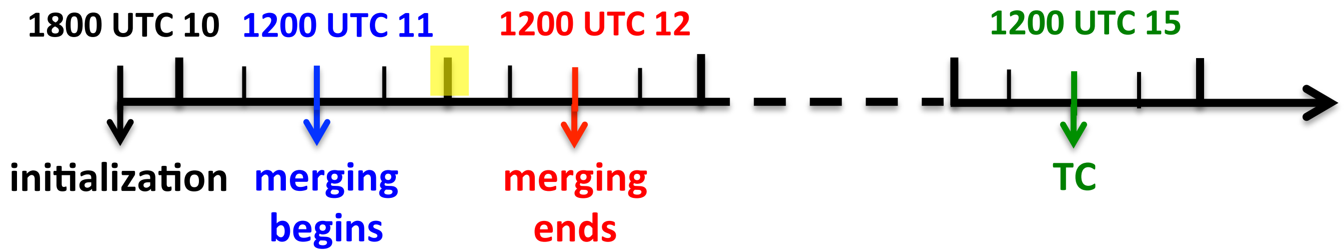
- **Moistening occurs both *before* and *after* merging**

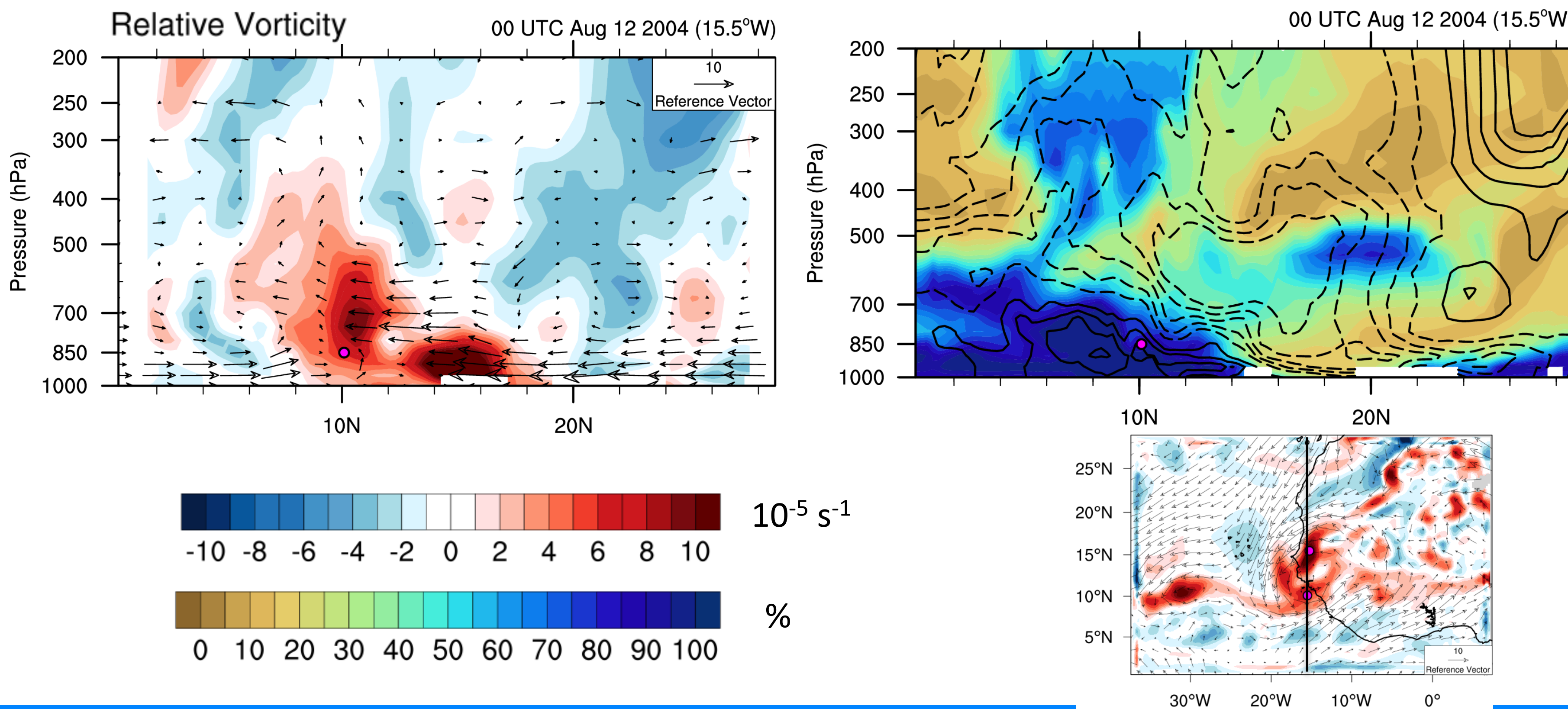


North-South Cross Section



North-South Cross Section





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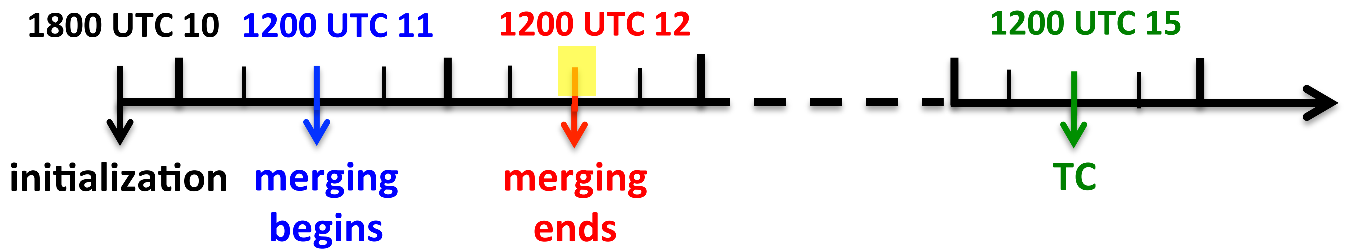

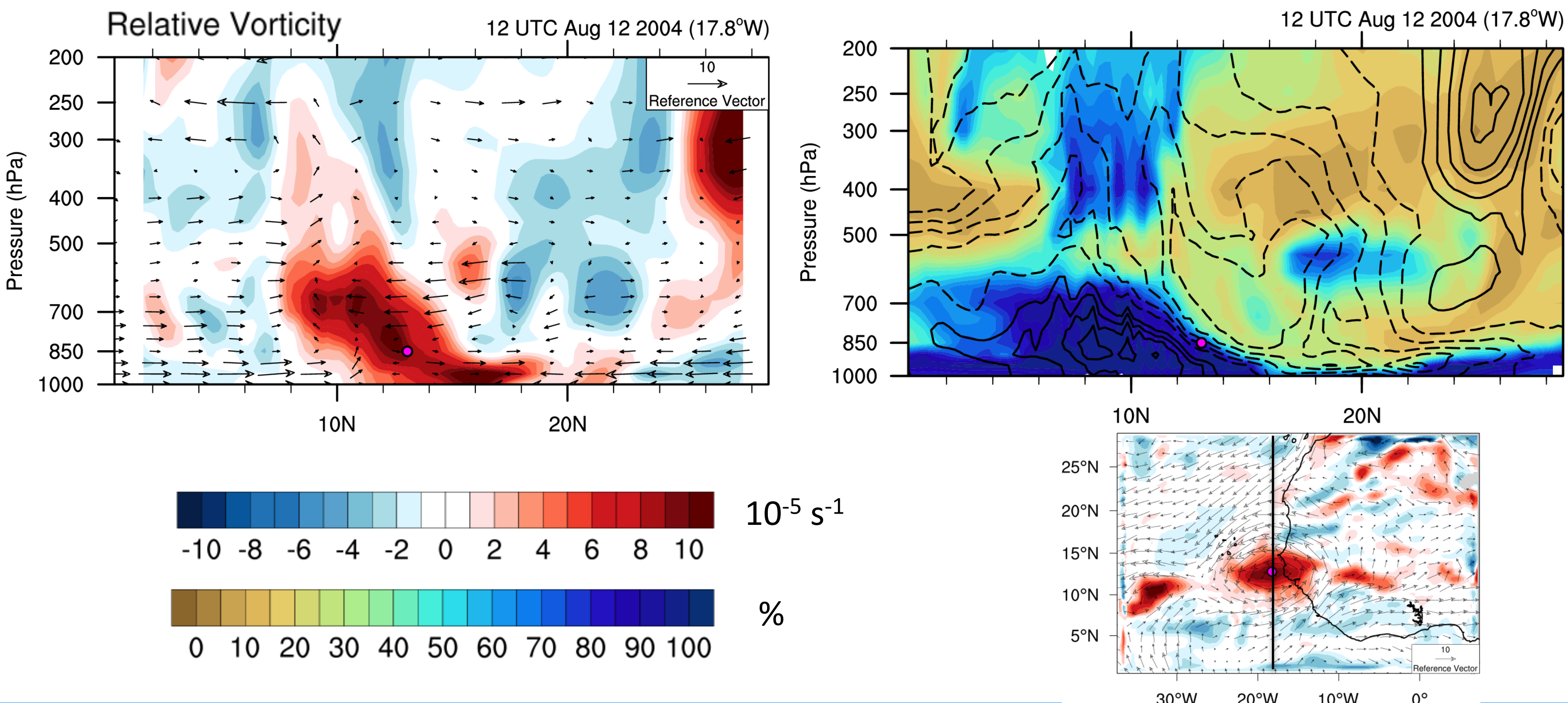

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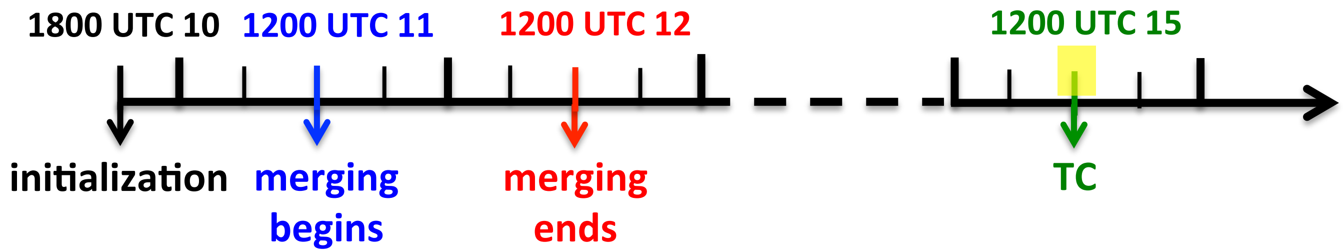

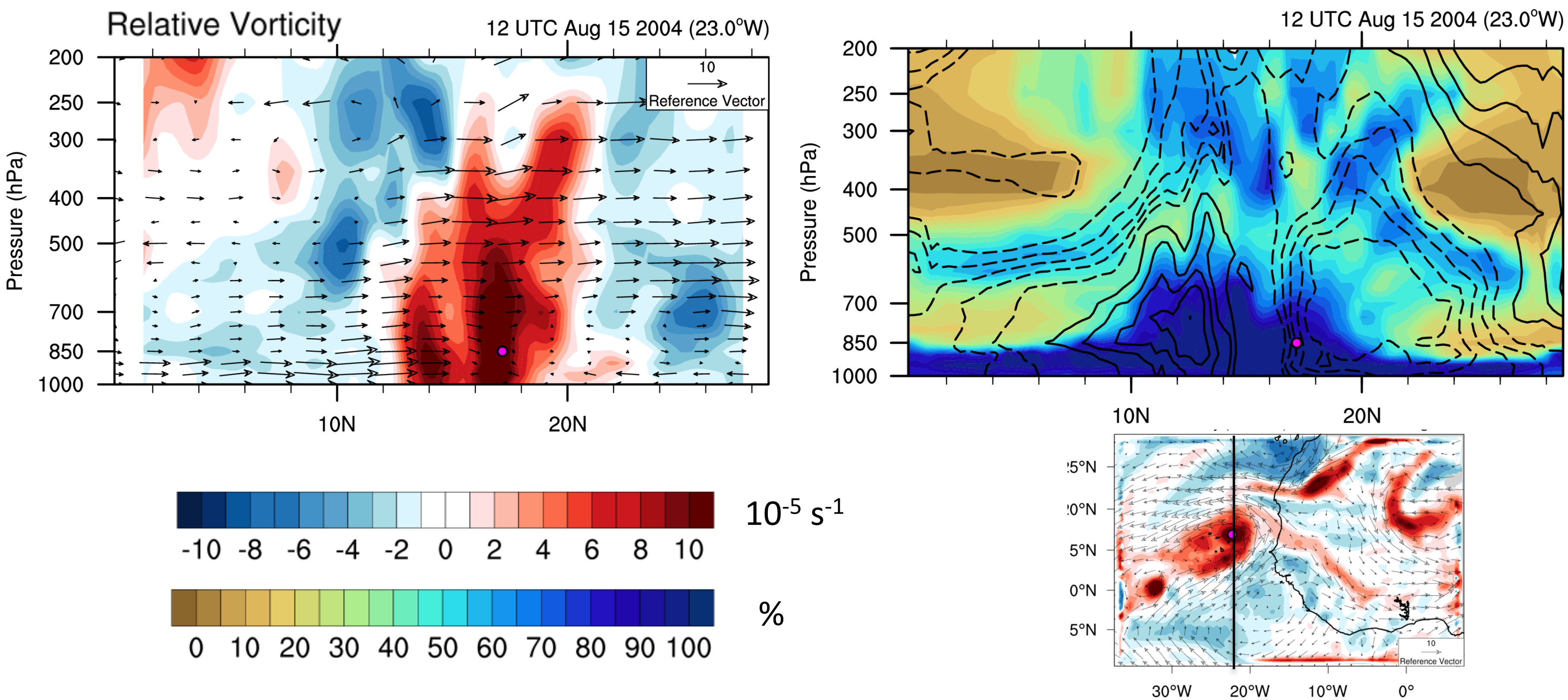

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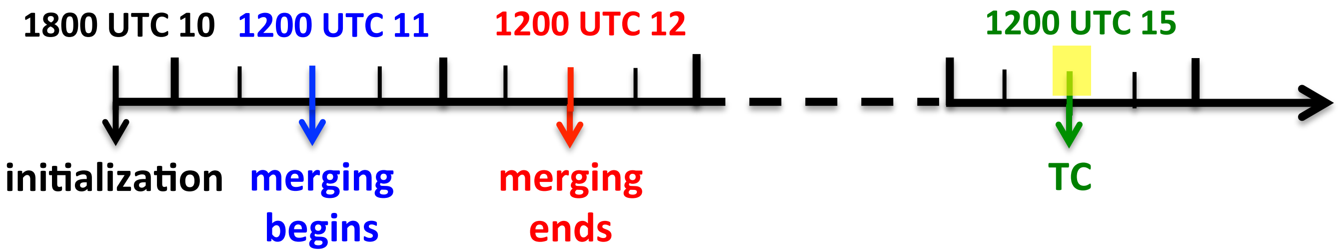
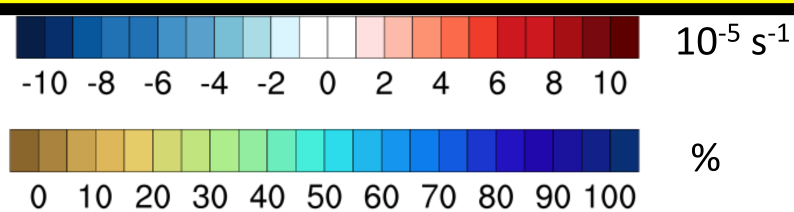
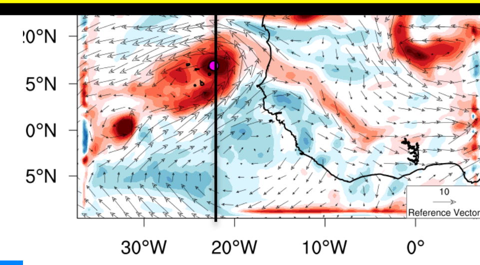


- The AEW_N appears to play a significant role in amplifying the low-level vorticity associated with the AEW_S
- To isolate the importance of the AEW_N in low-level vorticity generation, a separate model simulation is conducted with the AEW_N removed from the initial conditions

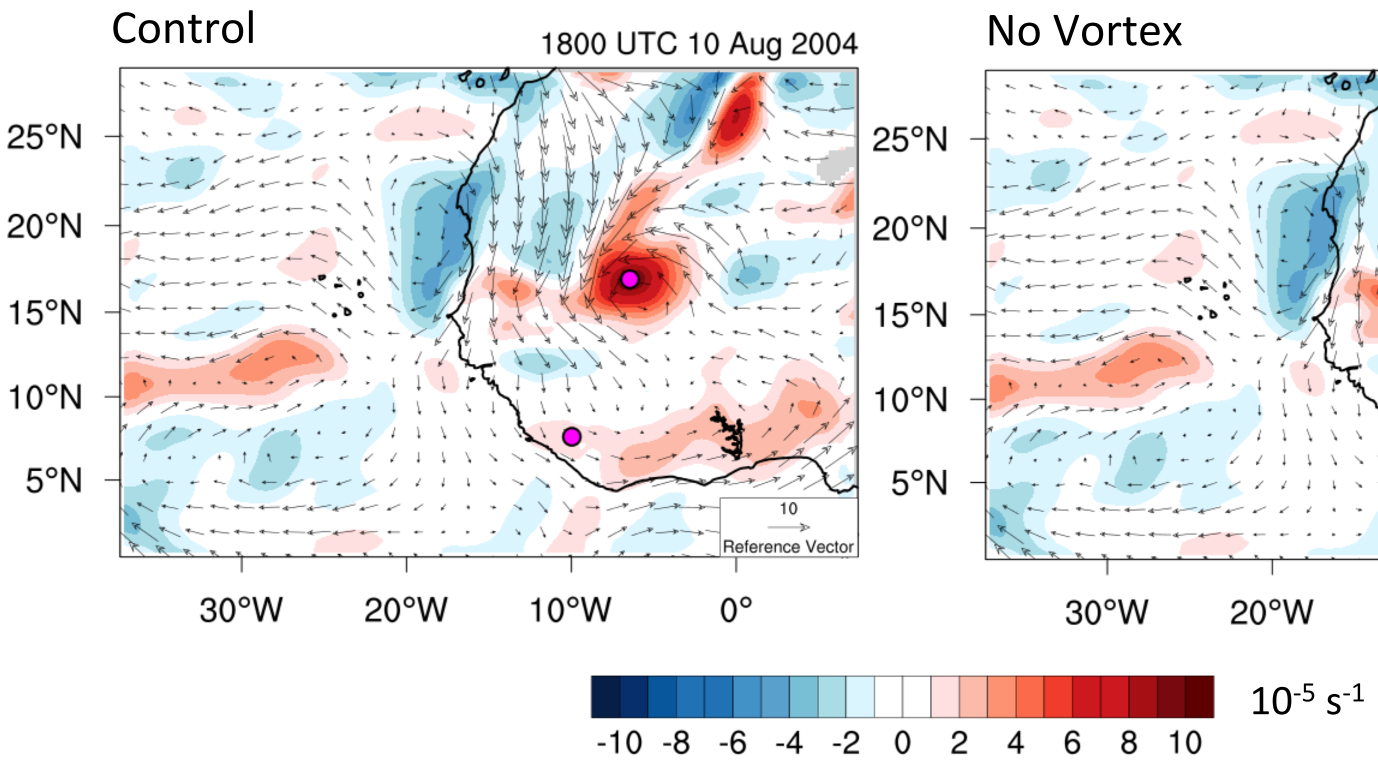




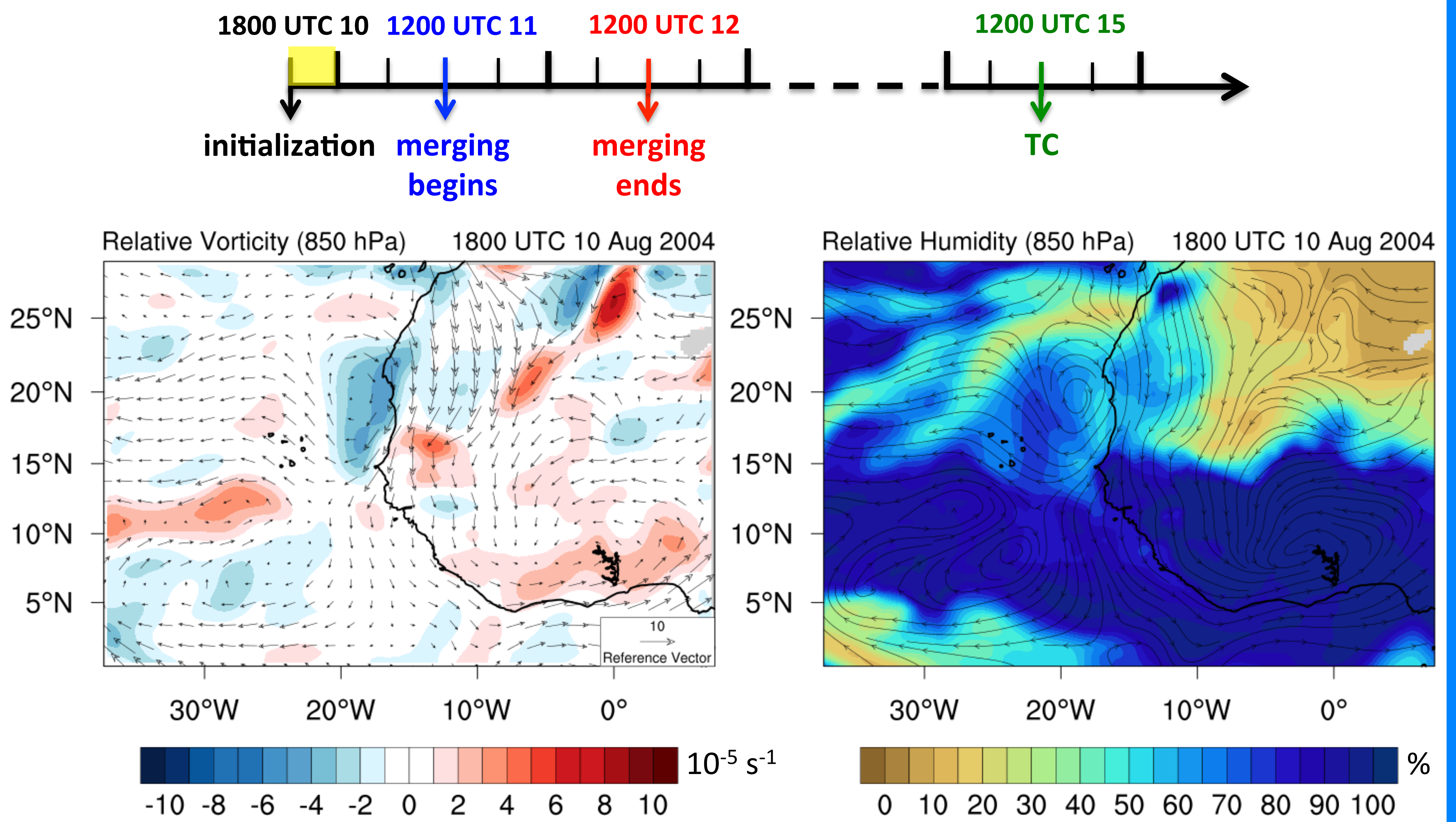
No Vortex Simulation

WRF built-in TC removal routine

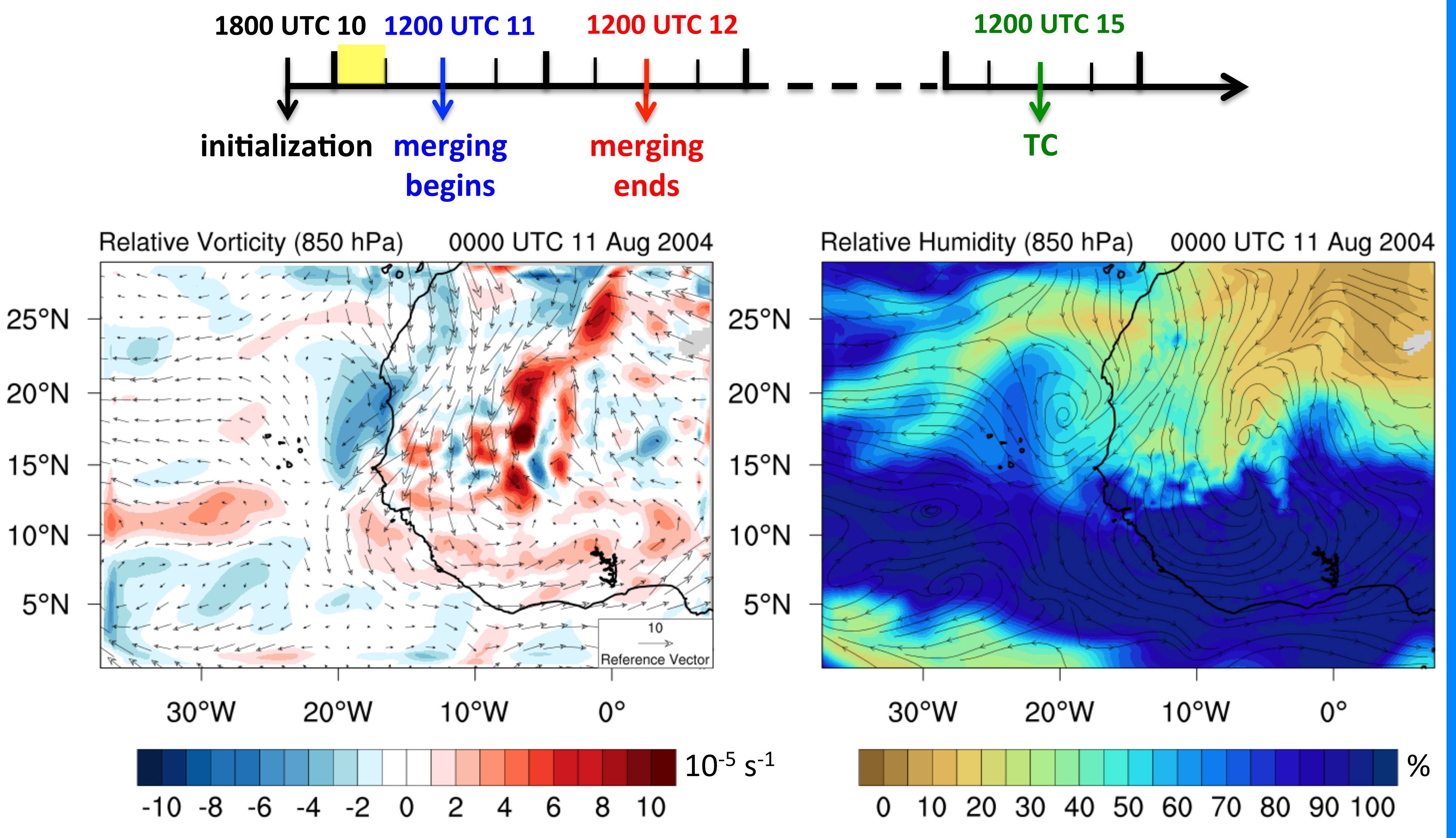
- removes **symmetric** and **balanced** components of the wind, temperature, and geopotential.



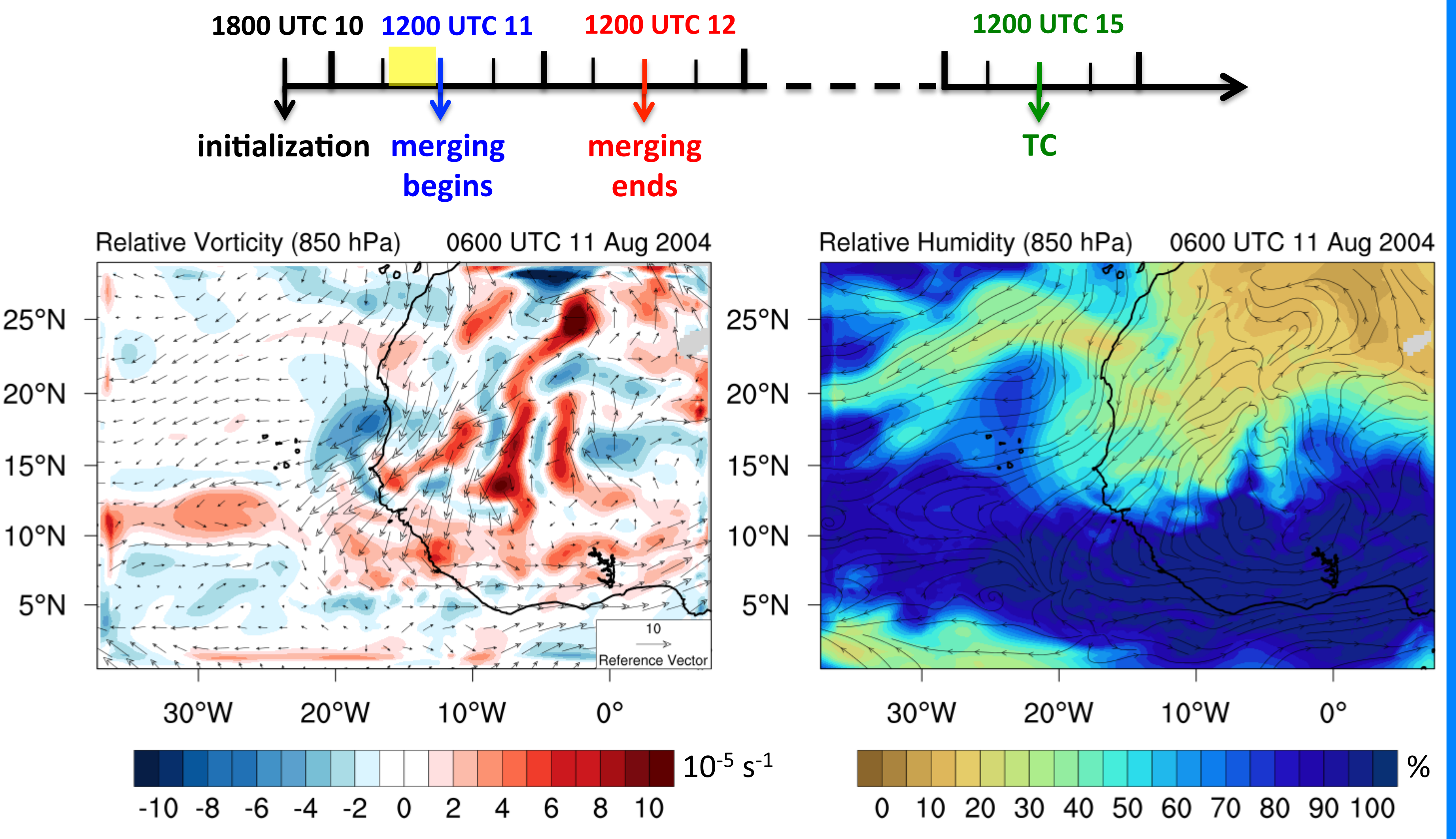
No Vortex Evolution



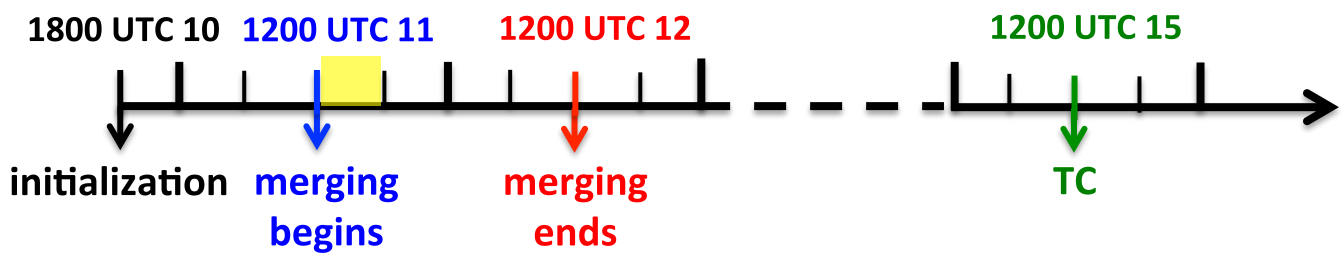
No Vortex Evolution

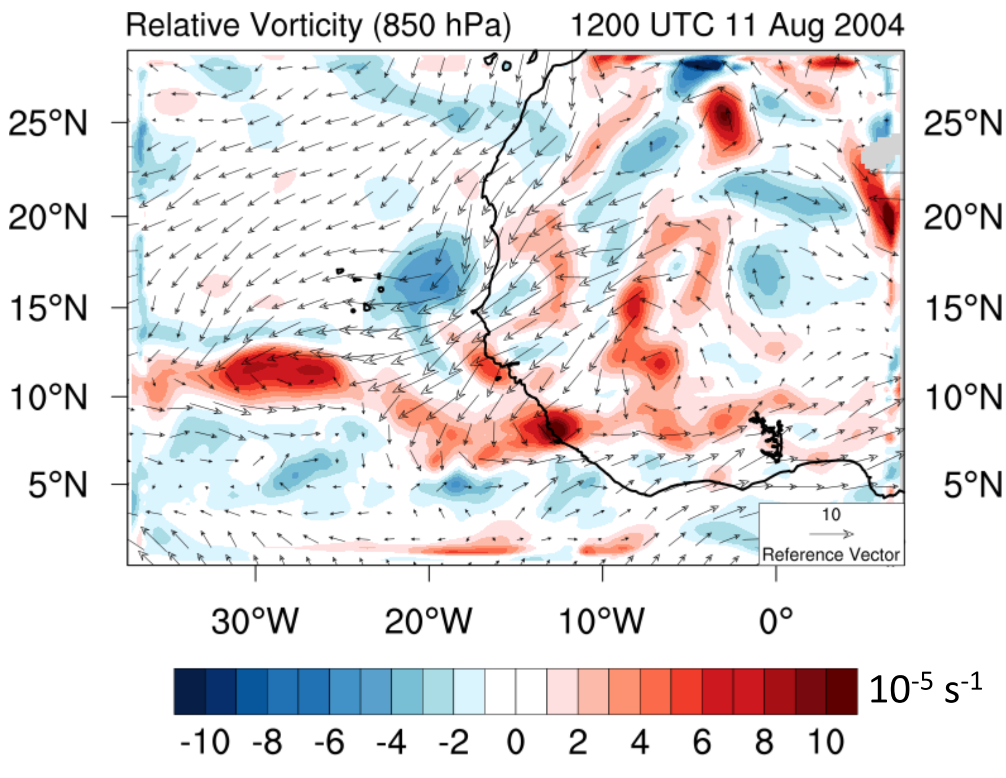


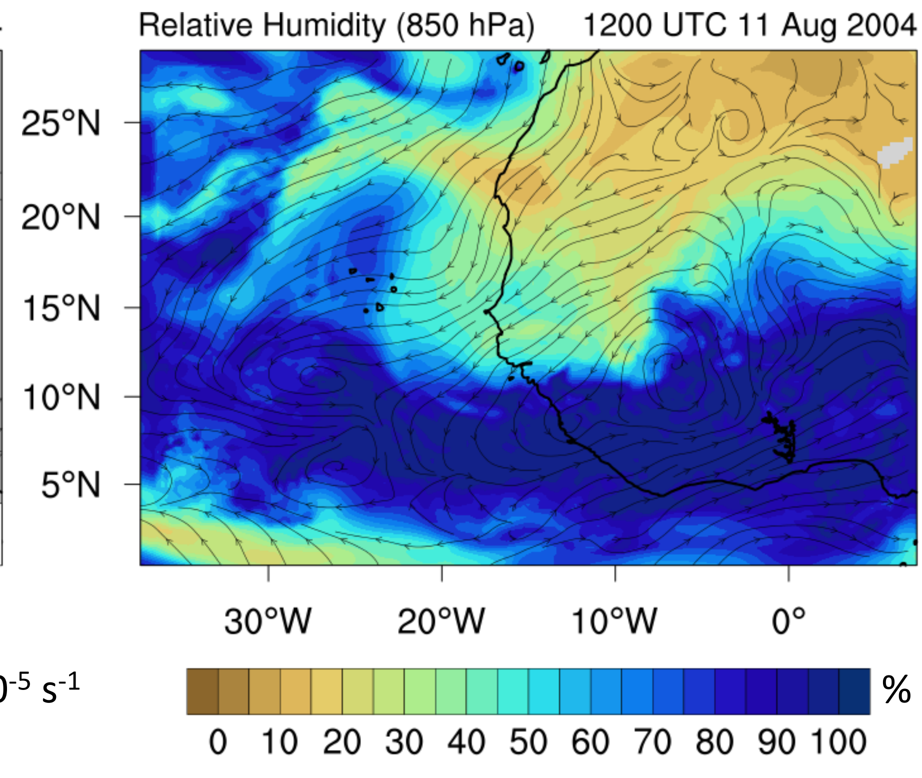
No Vortex Evolution



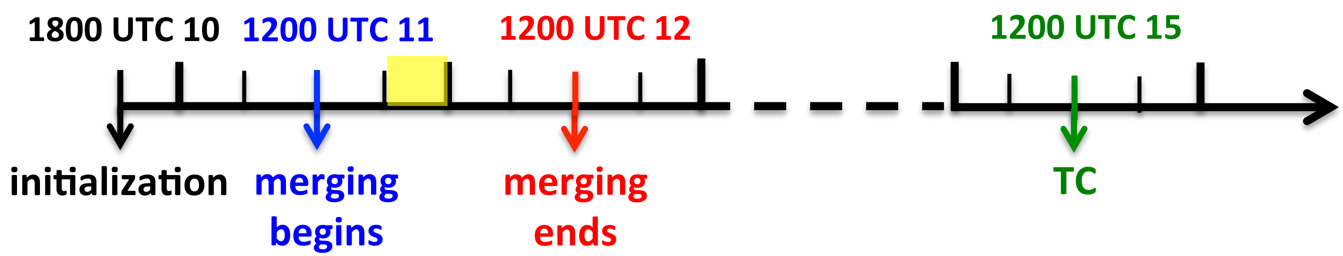
No Vortex Evolution

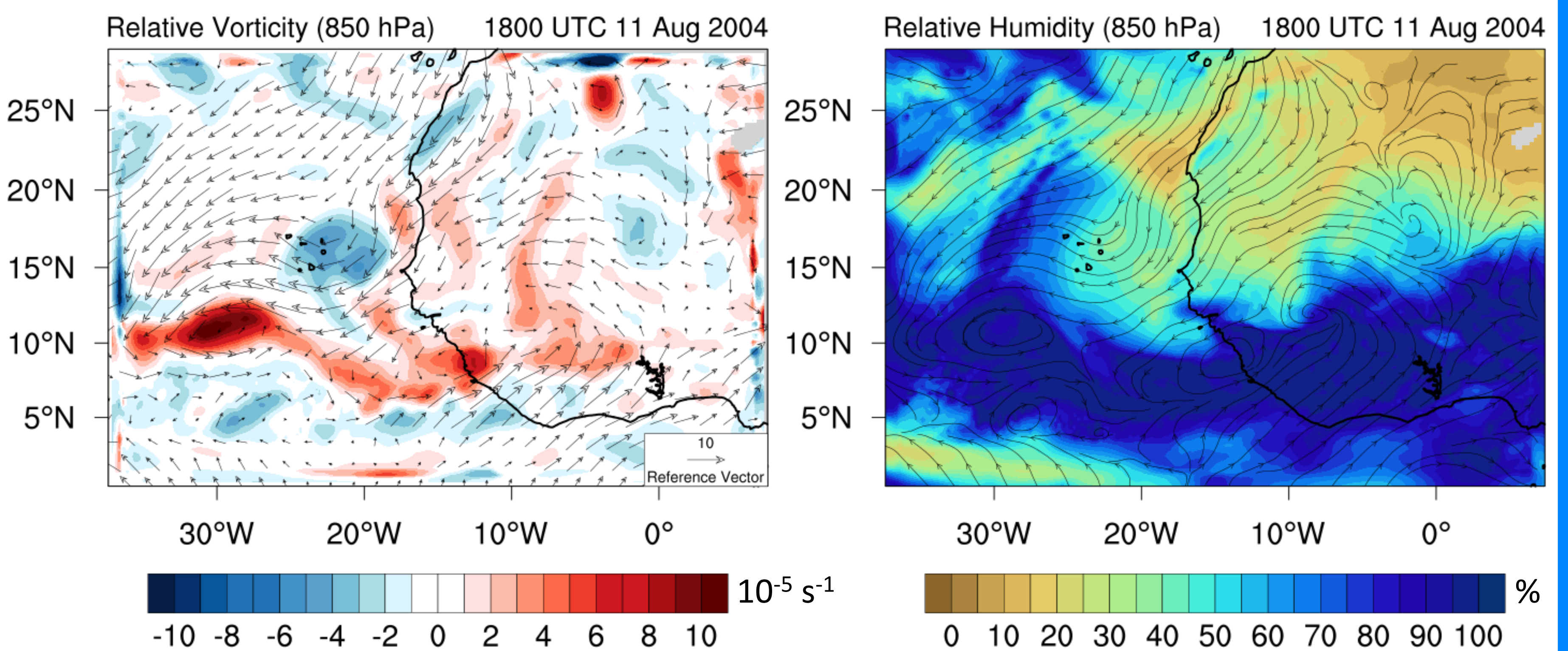




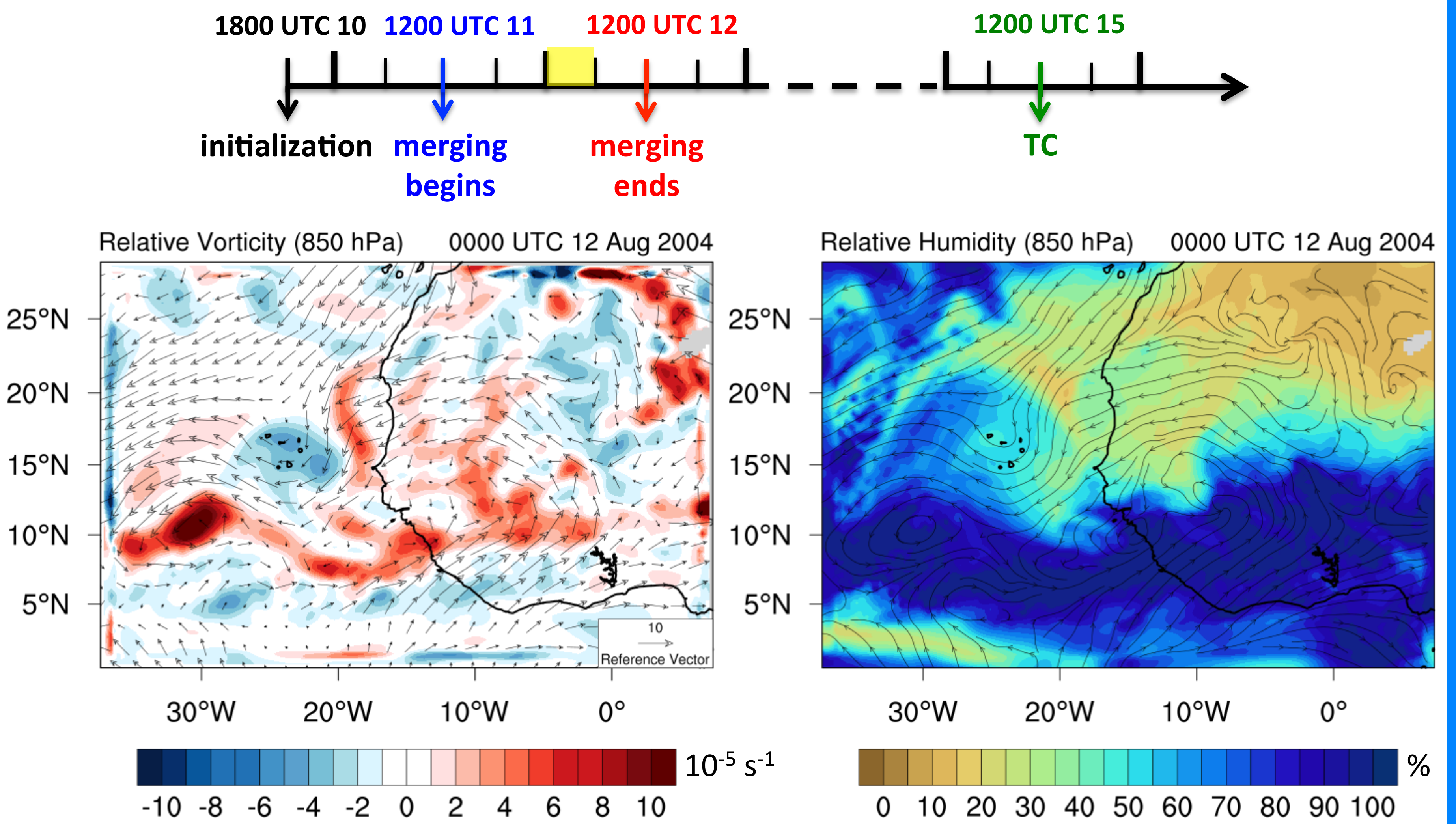


No Vortex Evolution

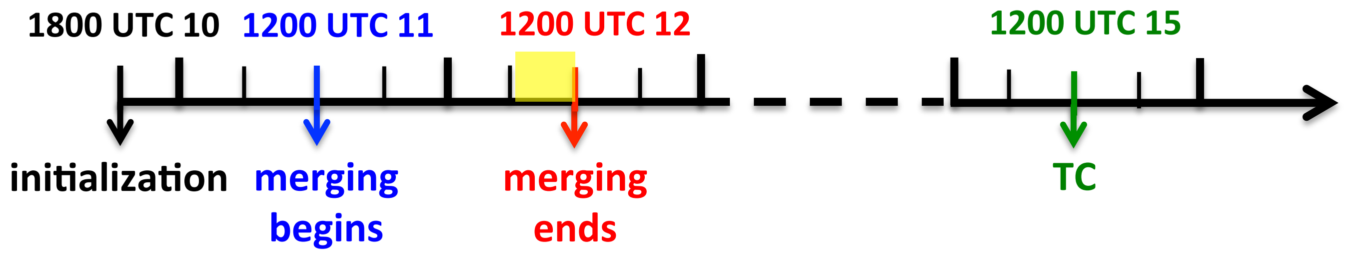


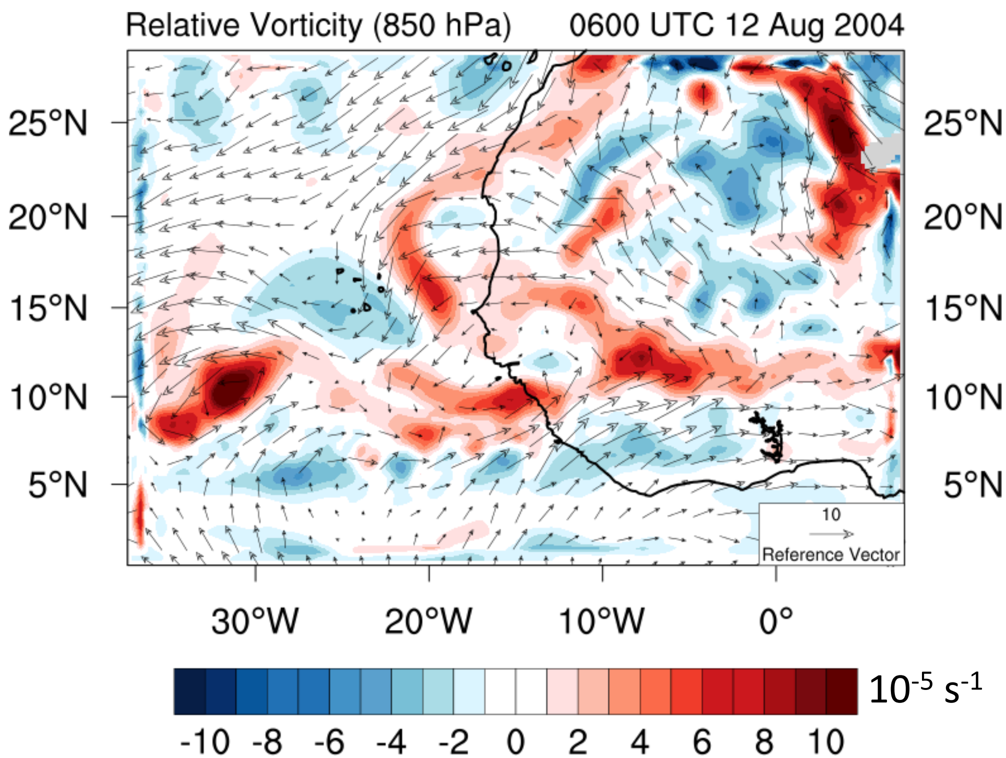


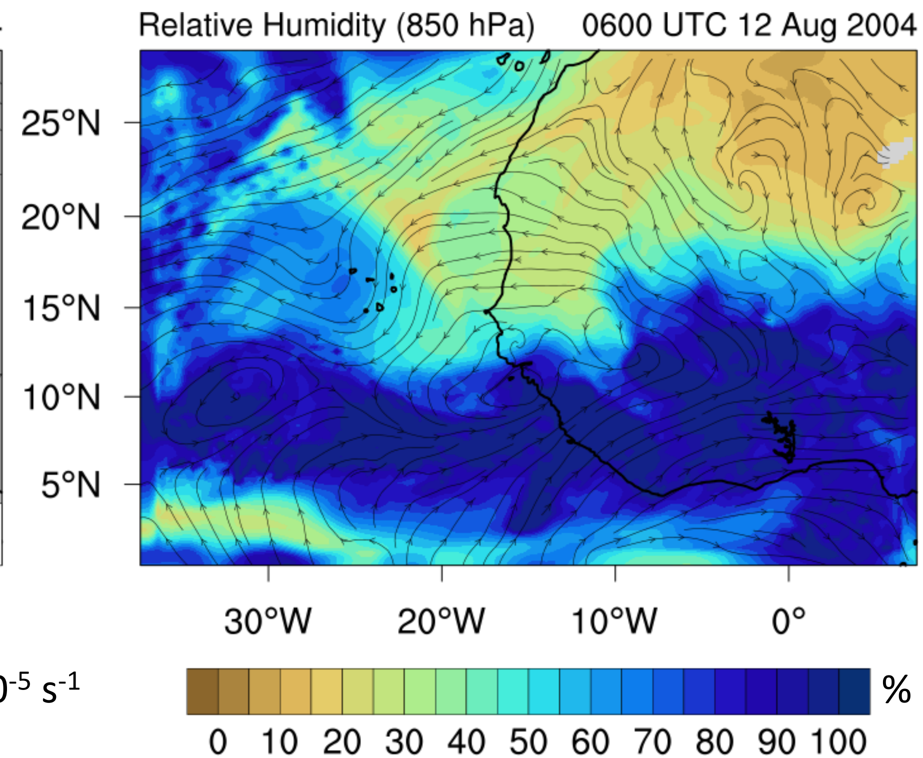
No Vortex Evolution



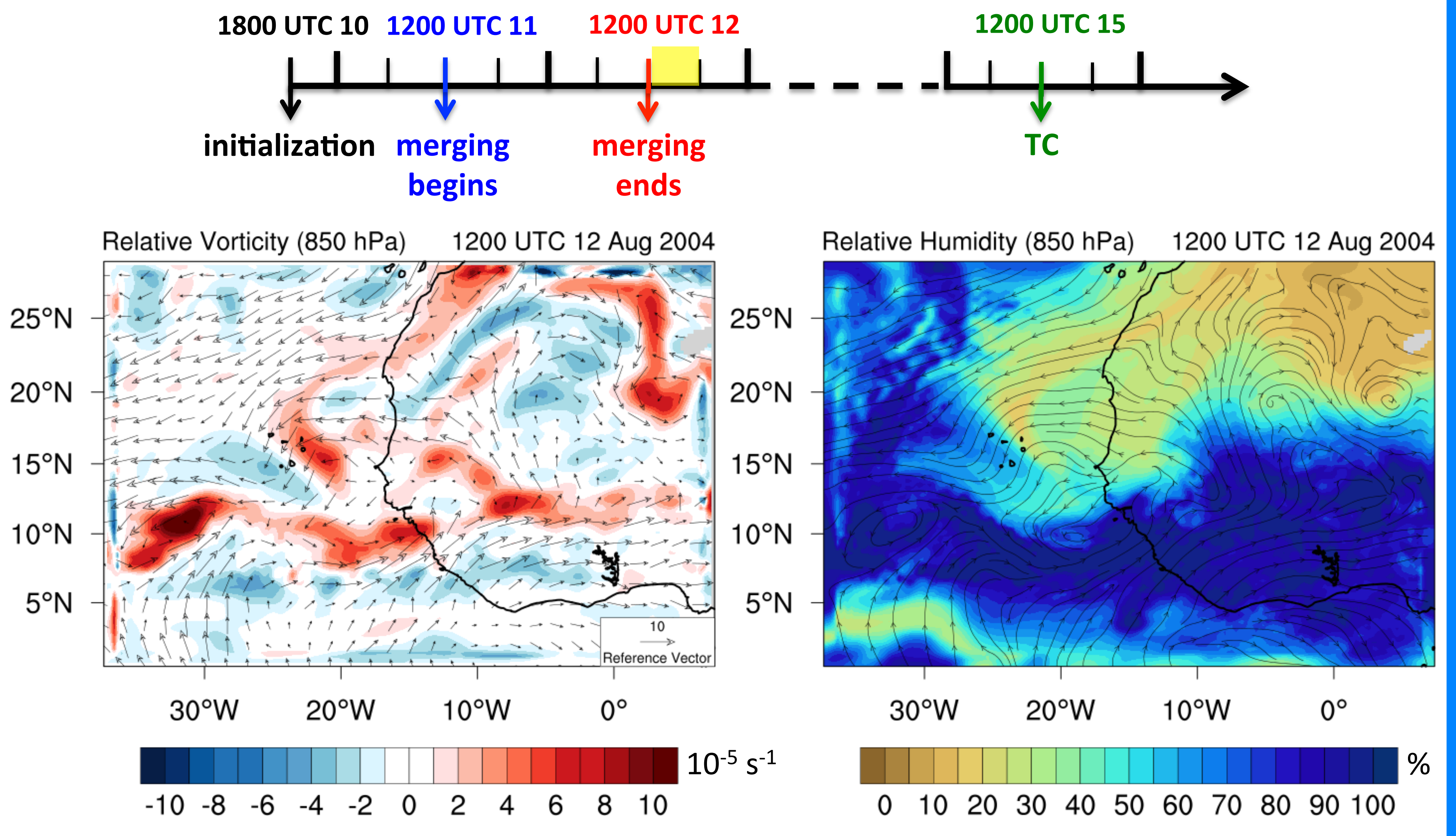
No Vortex Evolution



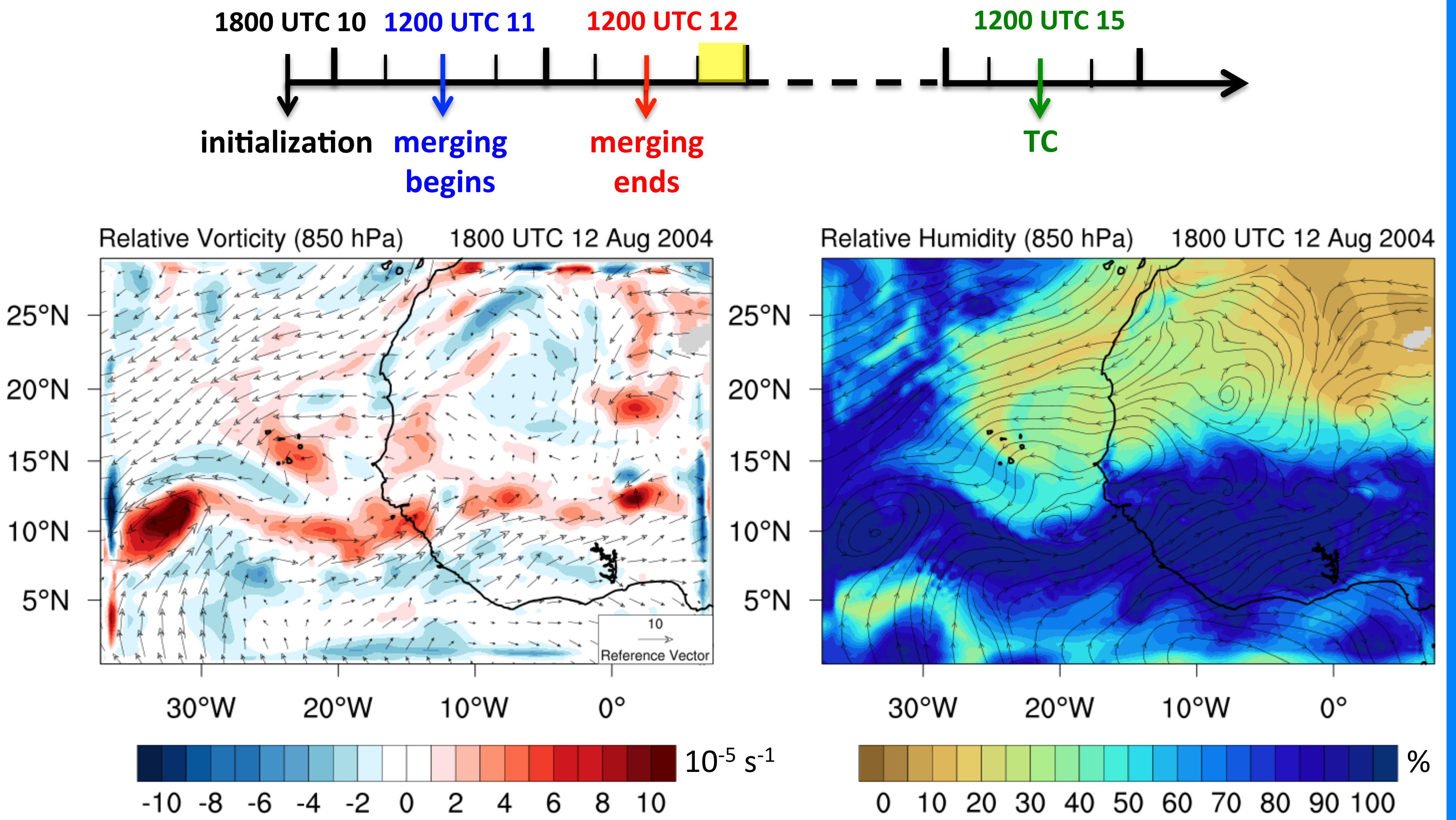




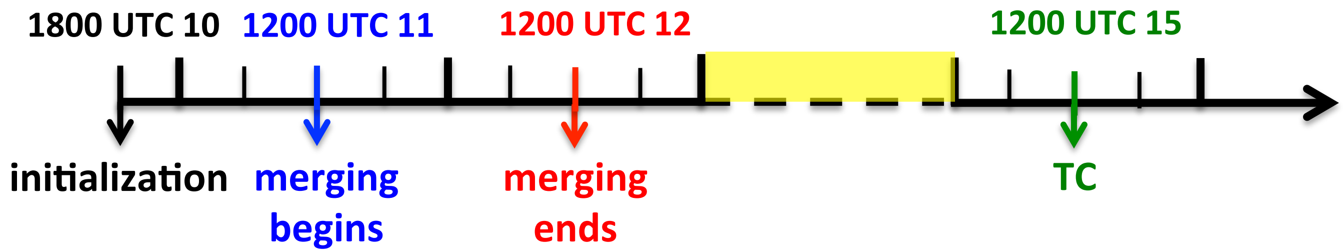
No Vortex Evolution

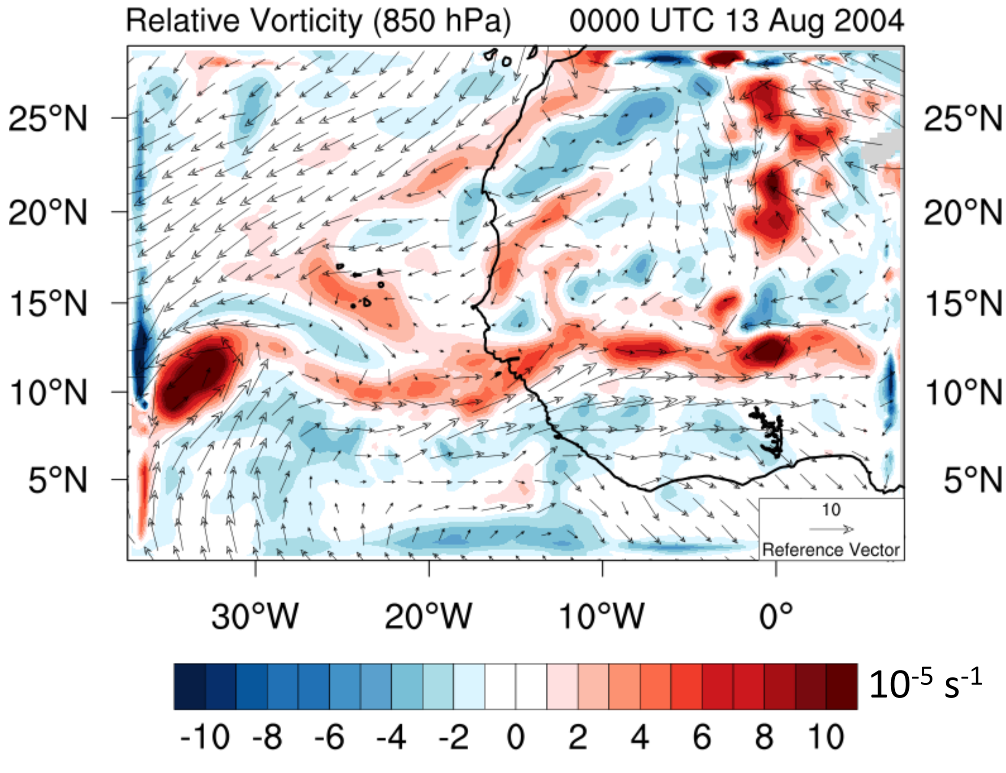


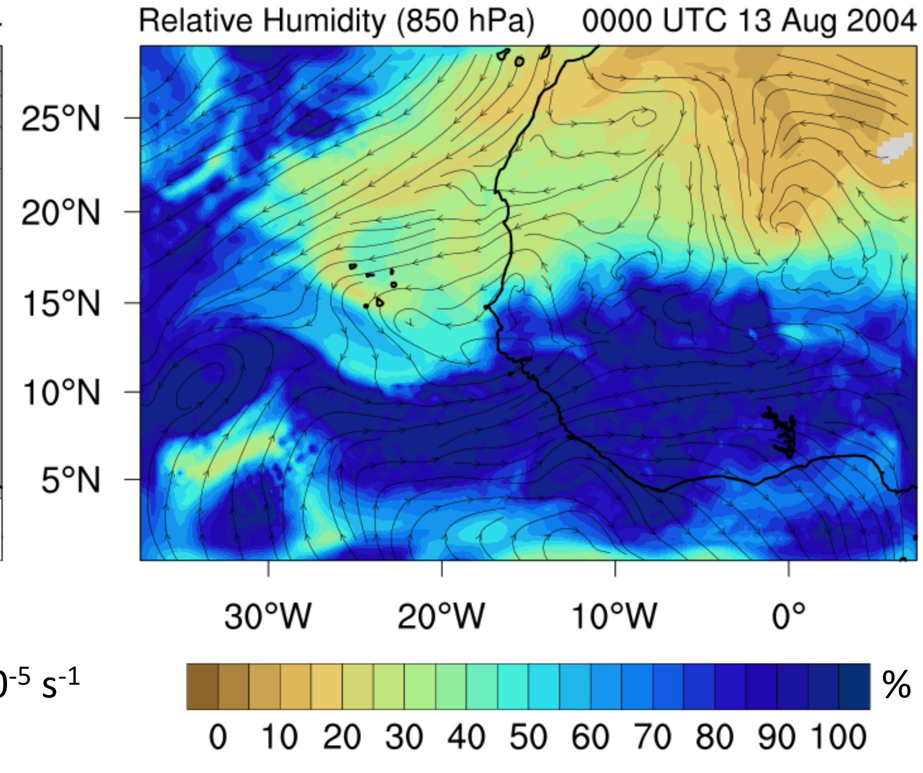
No Vortex Evolution



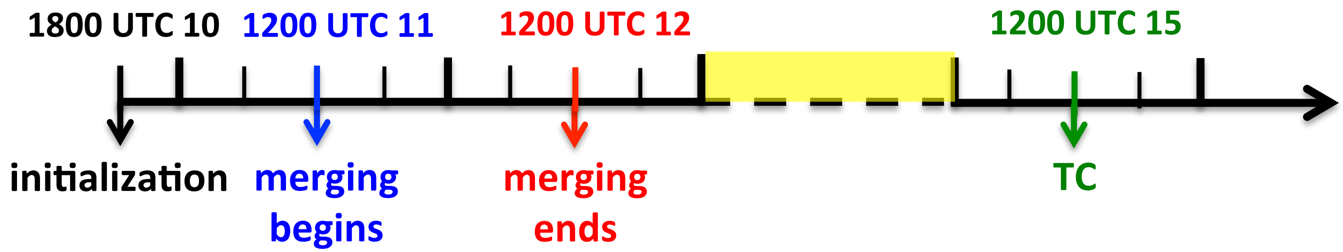
No Vortex Evolution

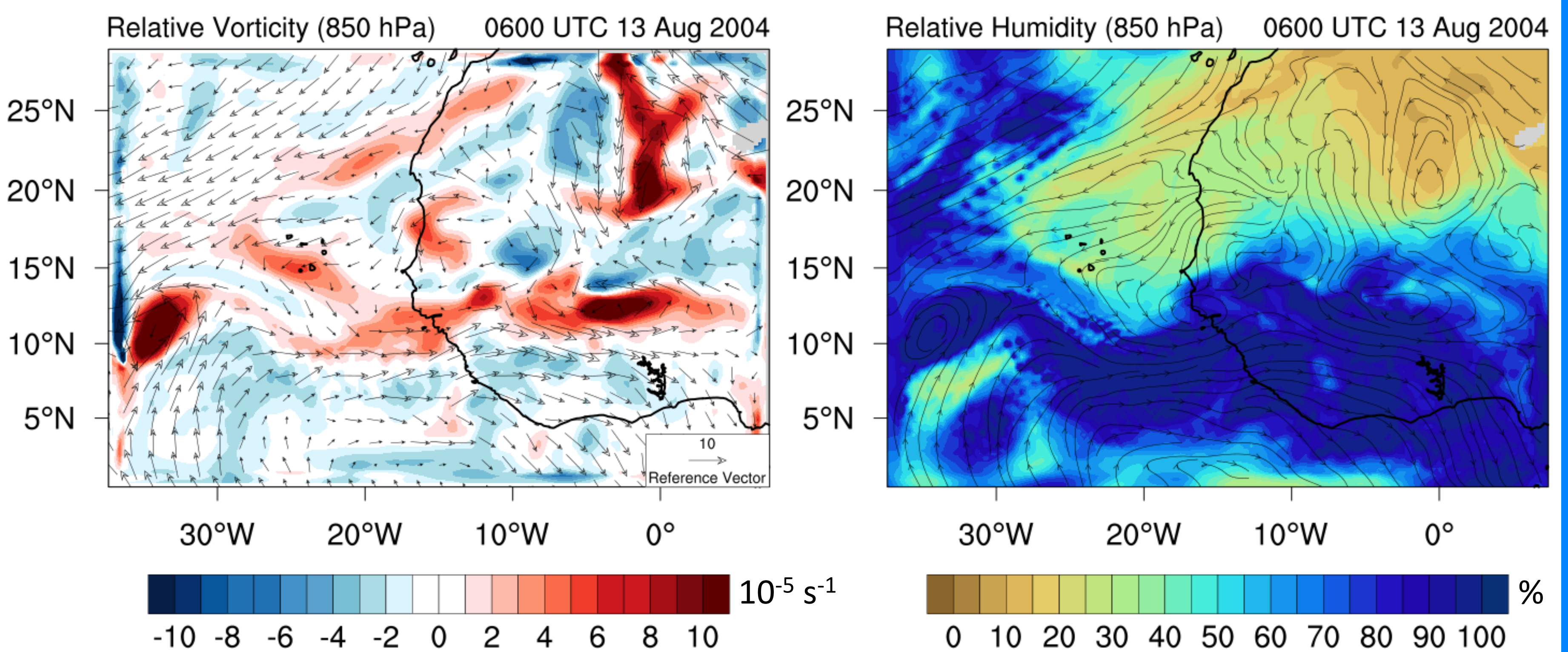




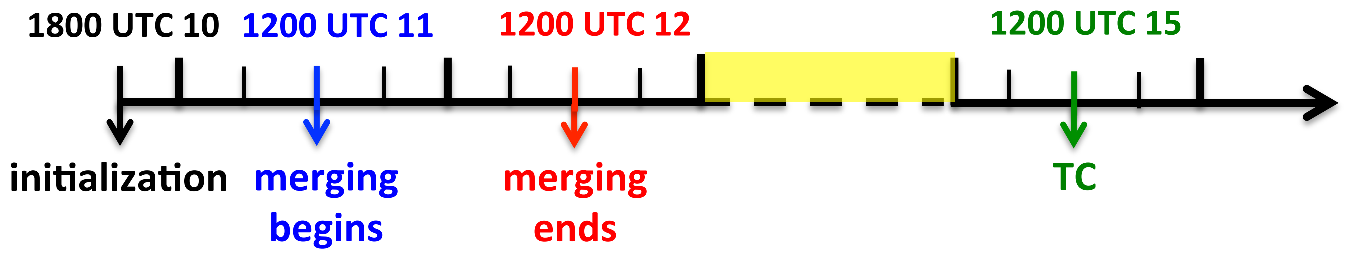


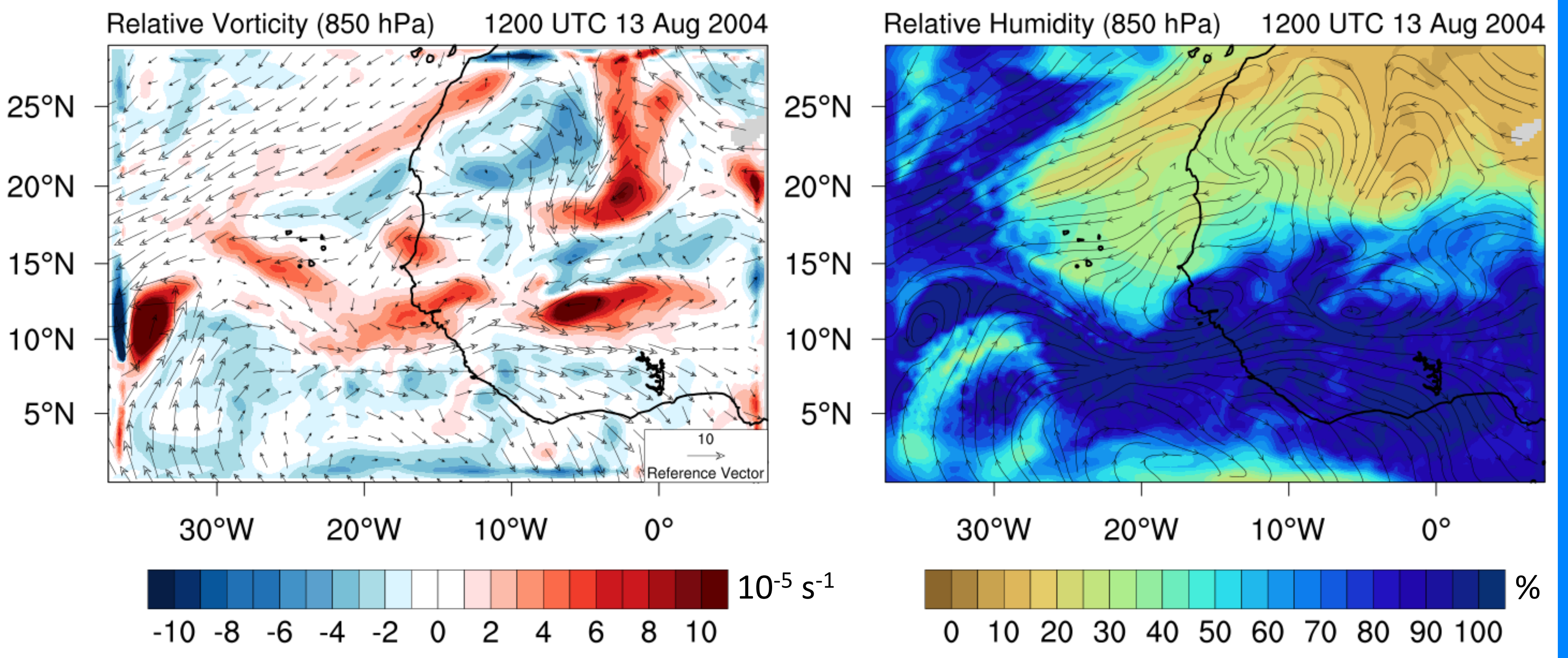
No Vortex Evolution



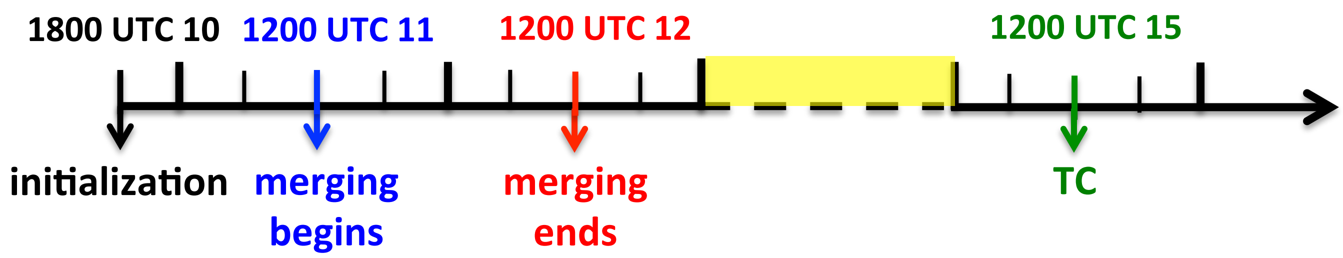


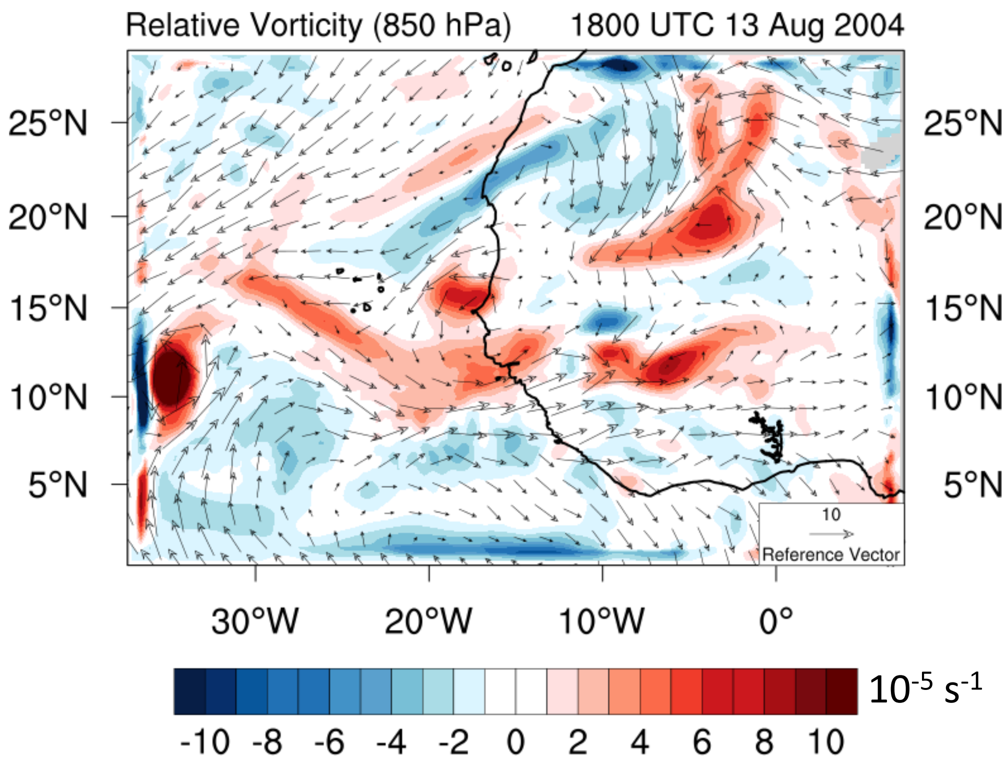
No Vortex Evolution

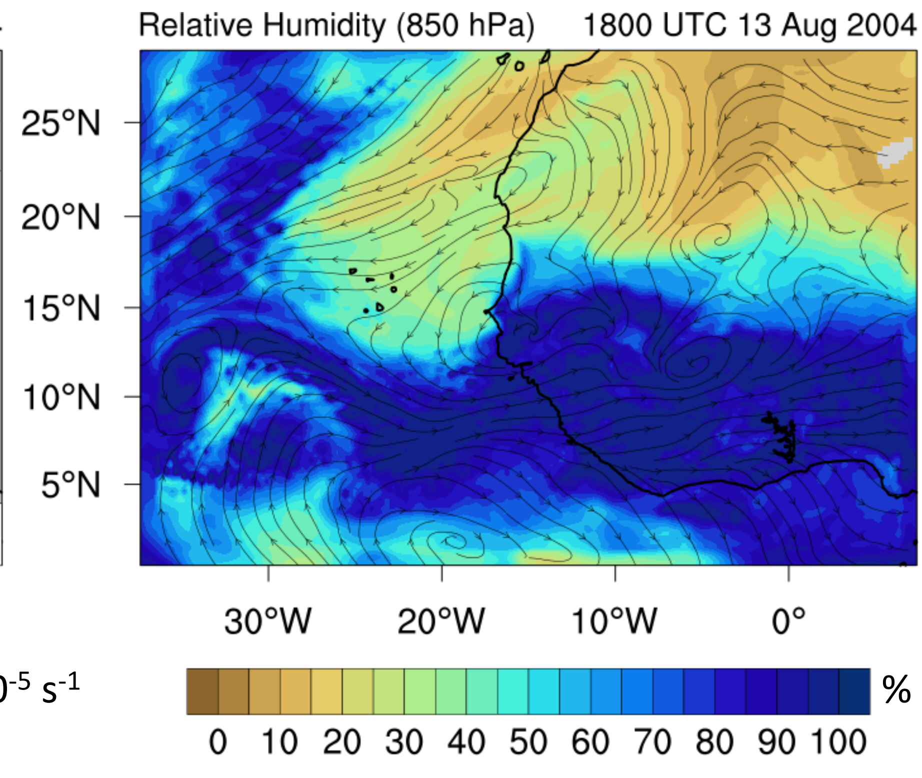




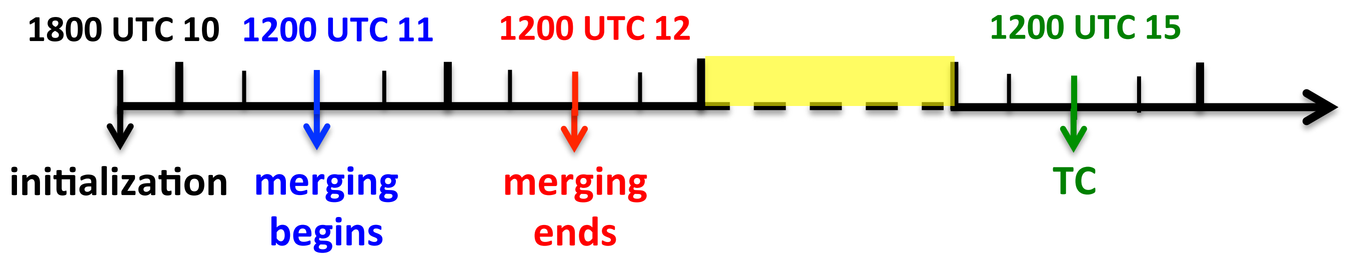
No Vortex Evolution

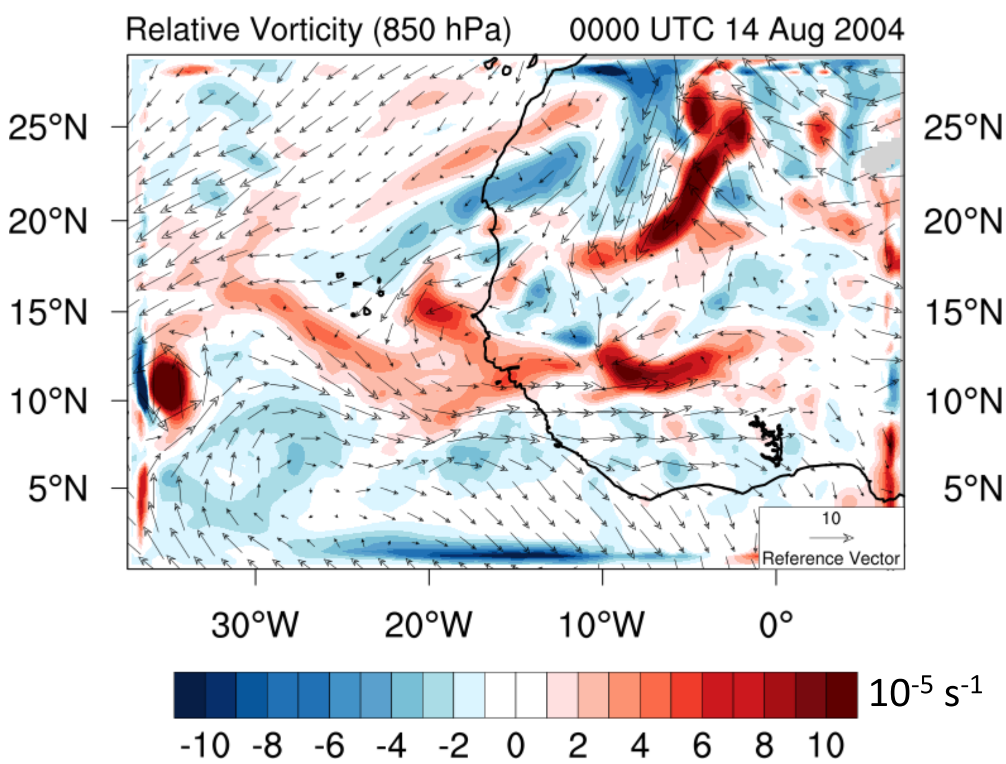


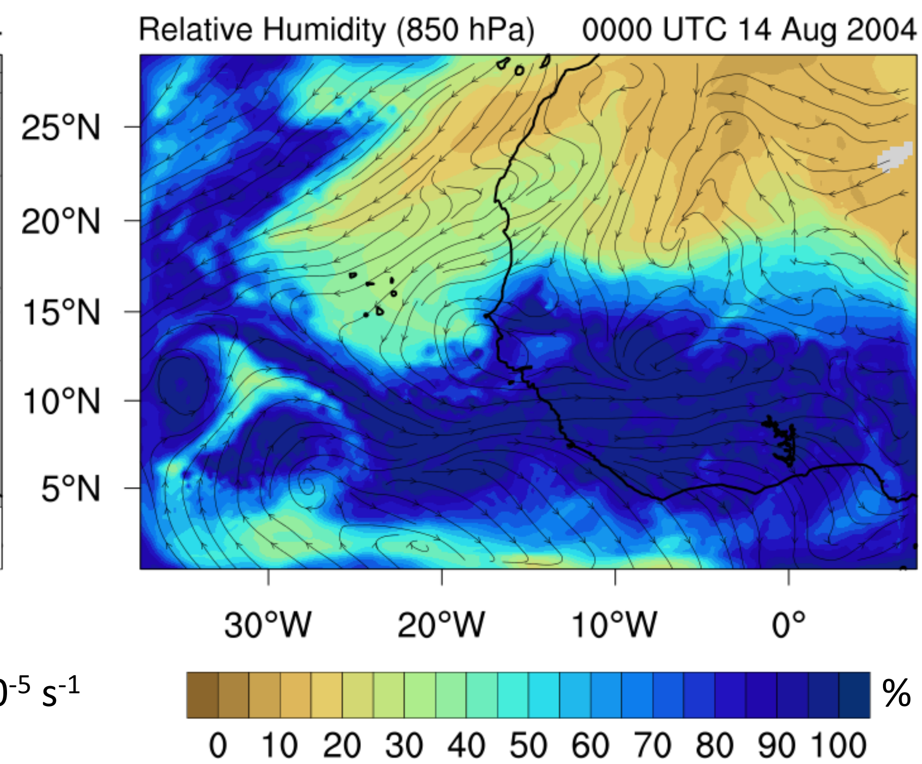




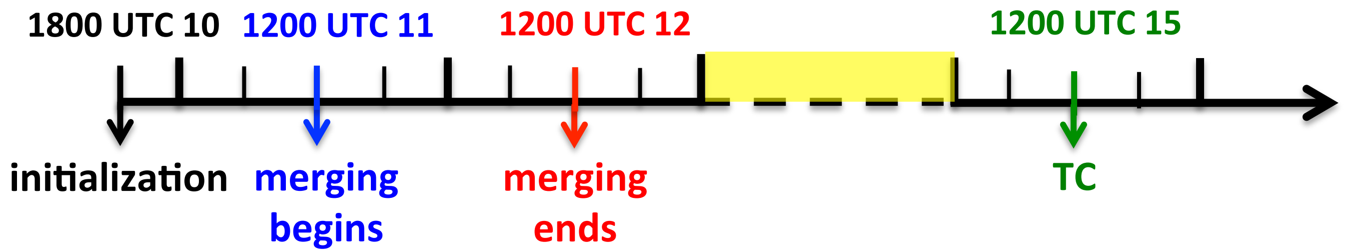
No Vortex Evolution

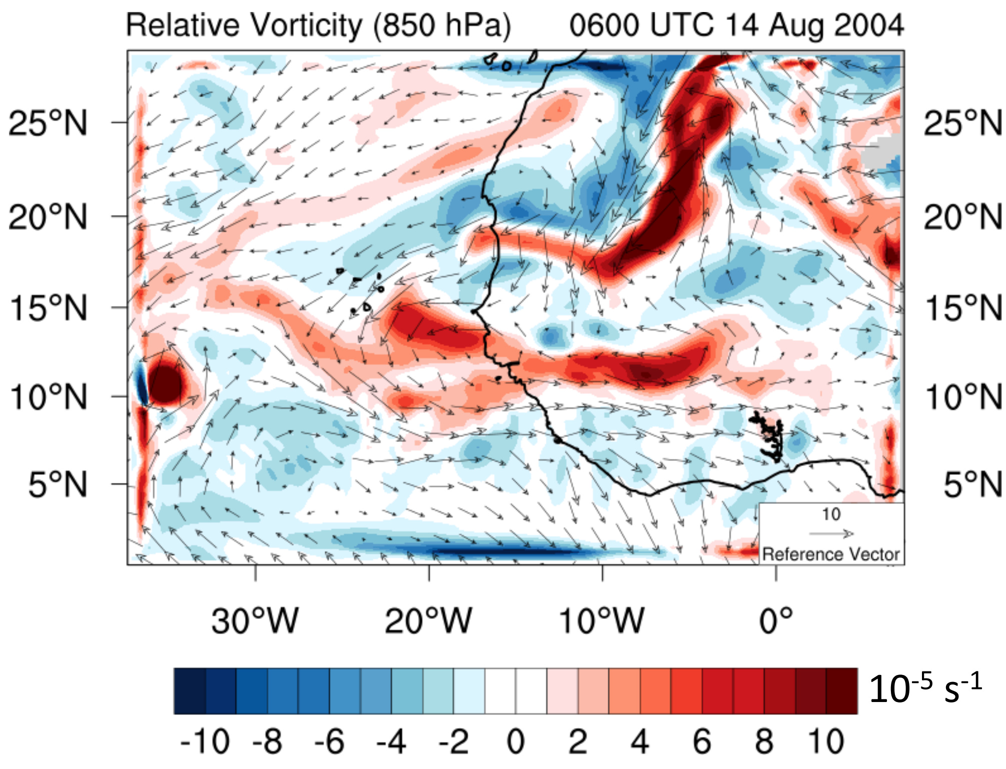


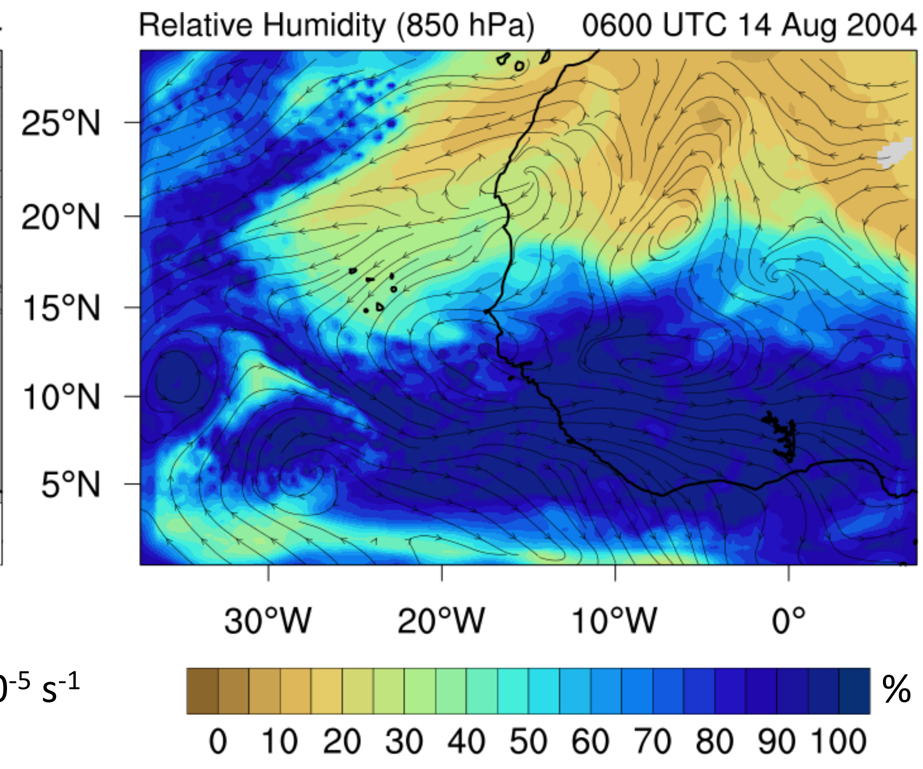




No Vortex Evolution







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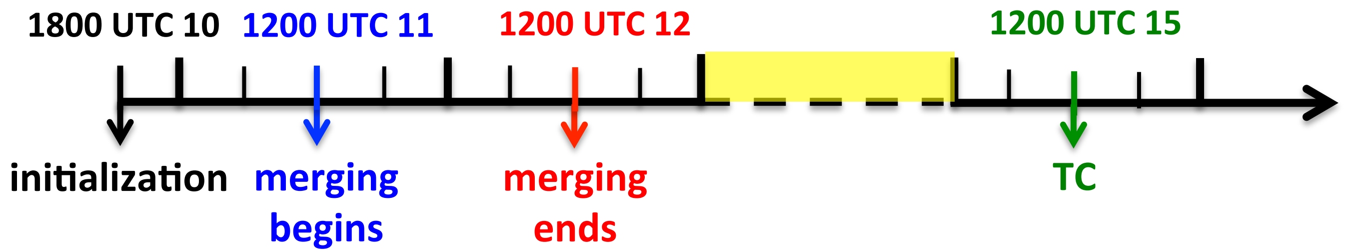
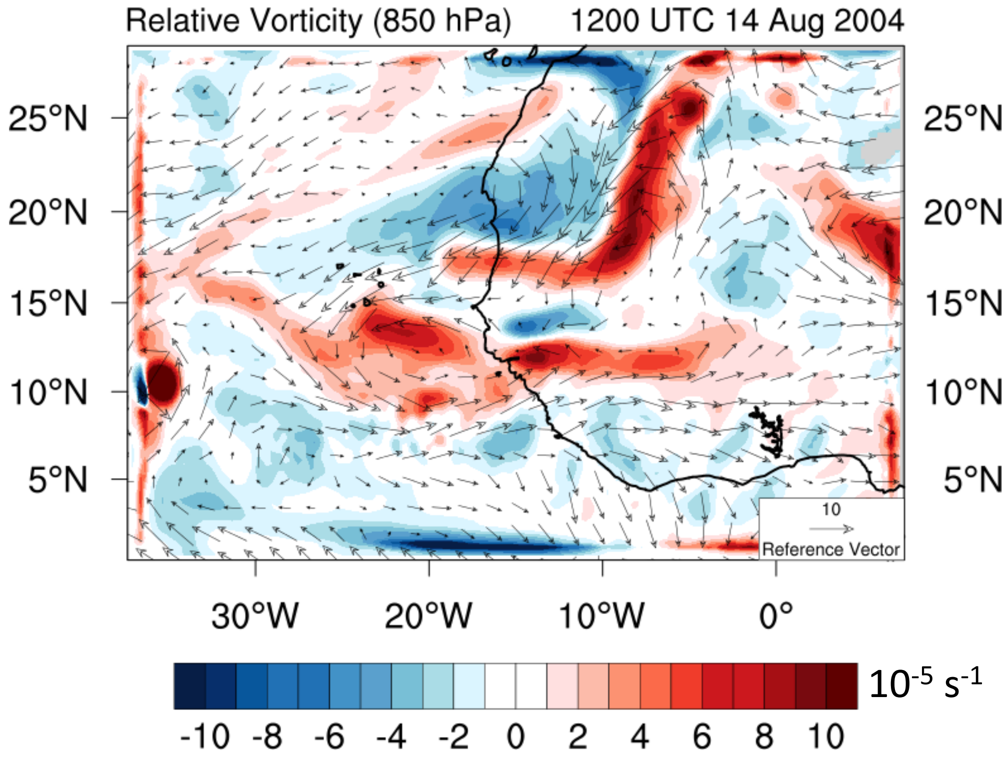
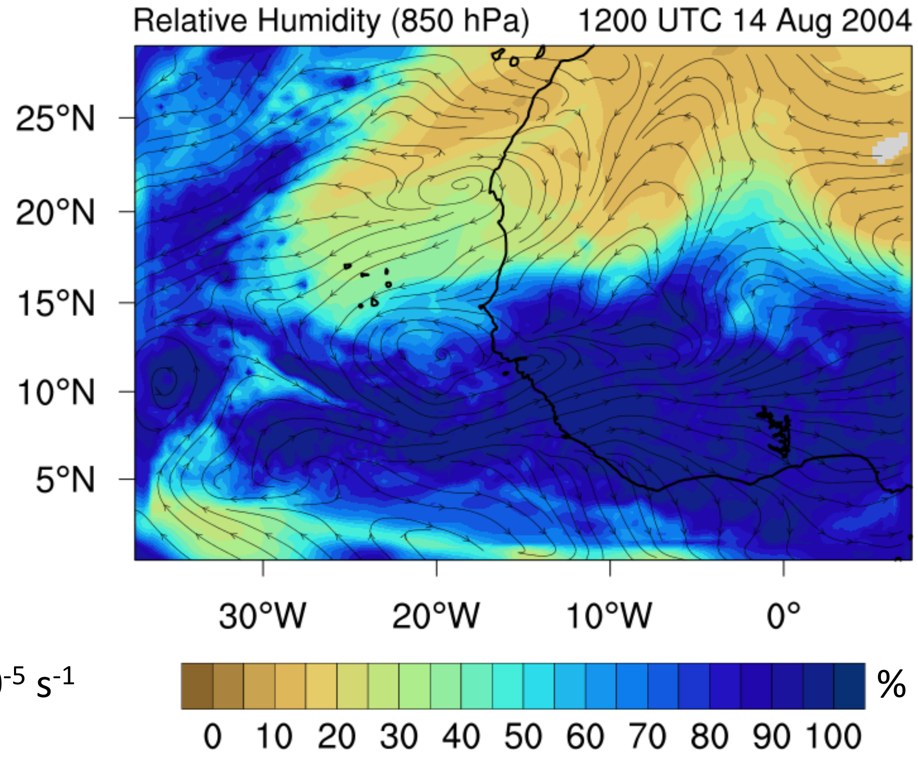
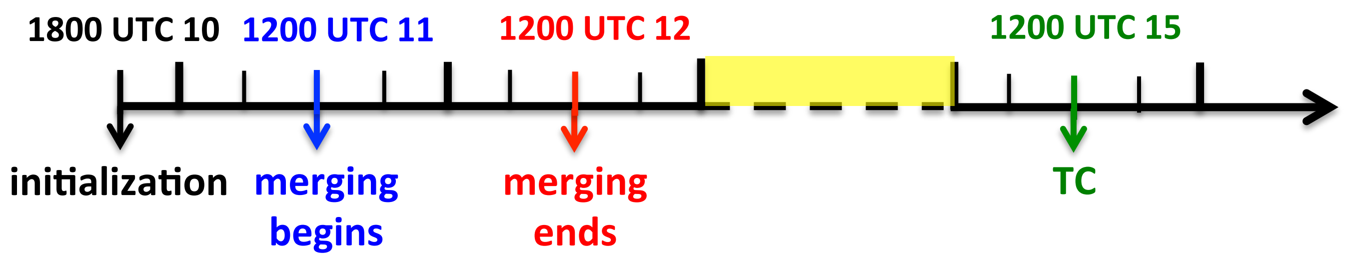
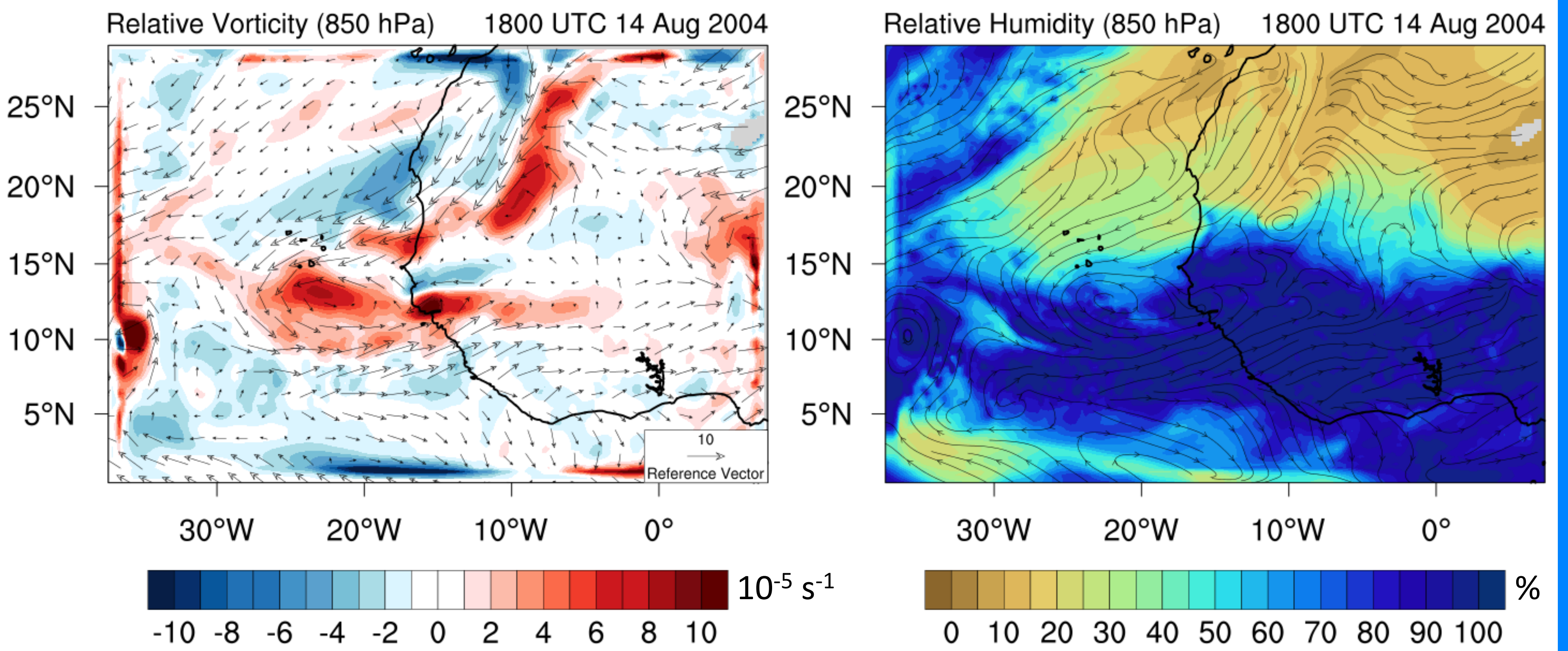




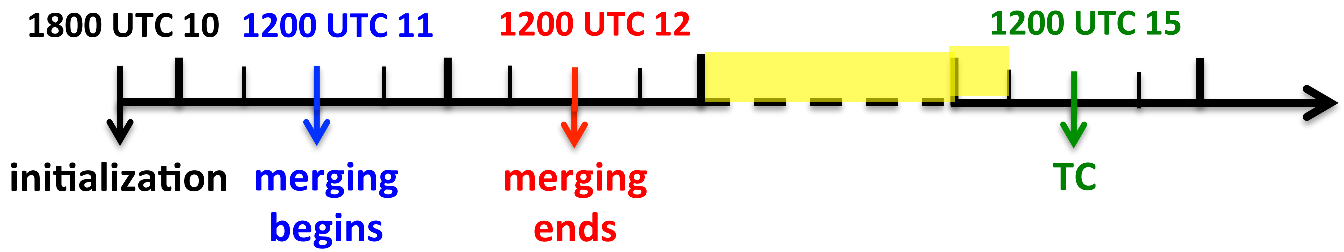


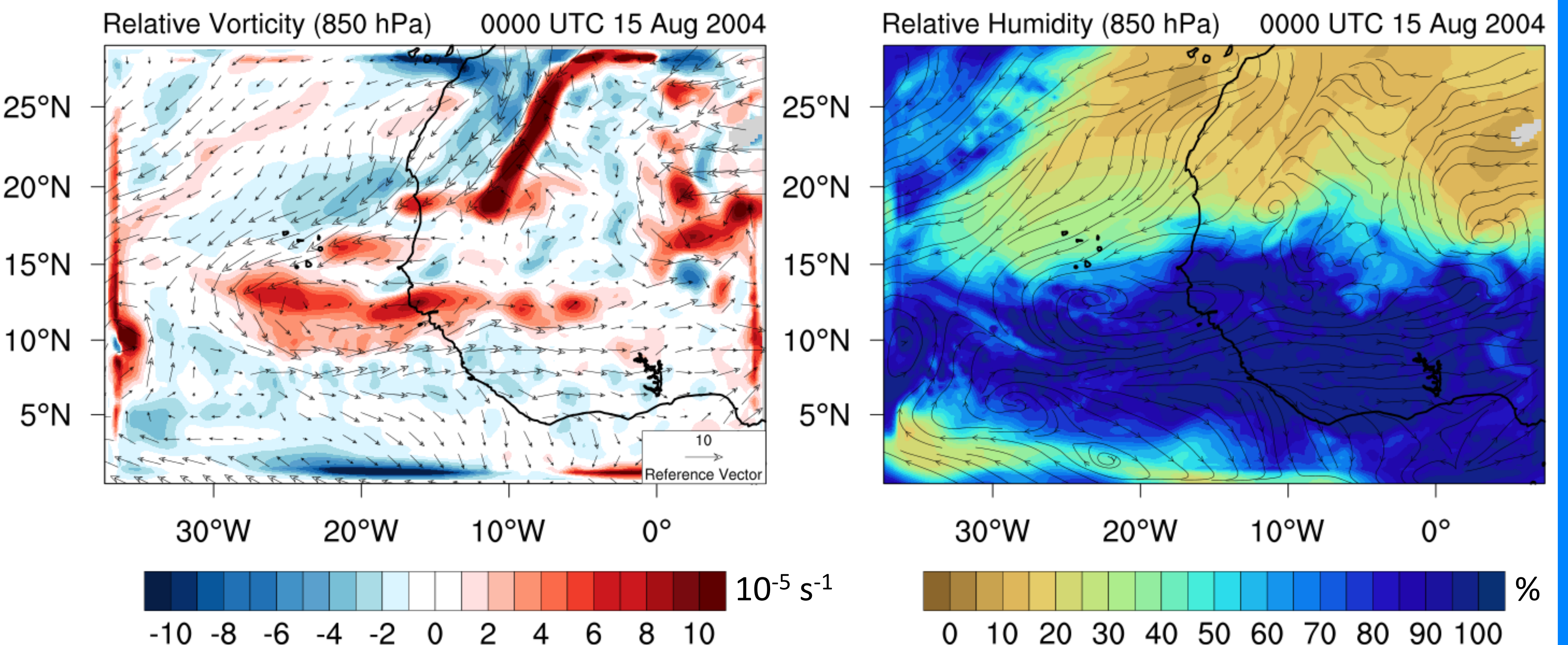
No Vortex Evolution



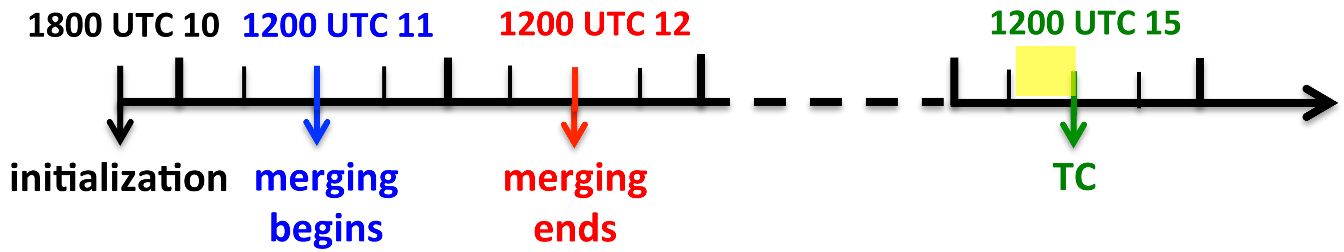


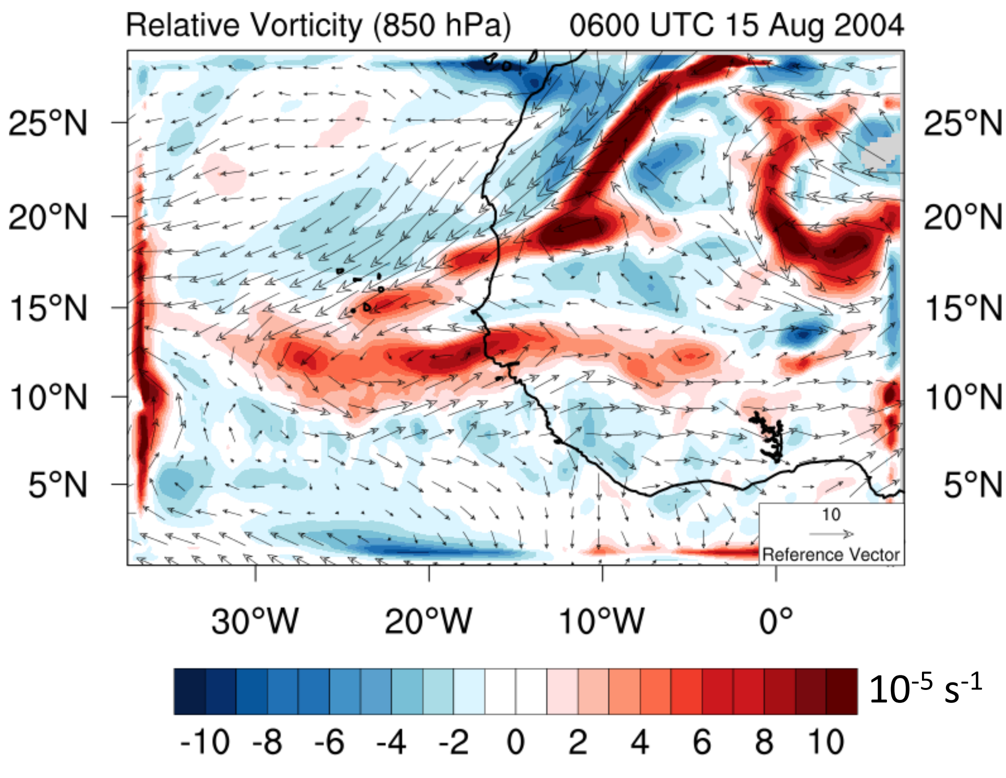
No Vortex Evolution

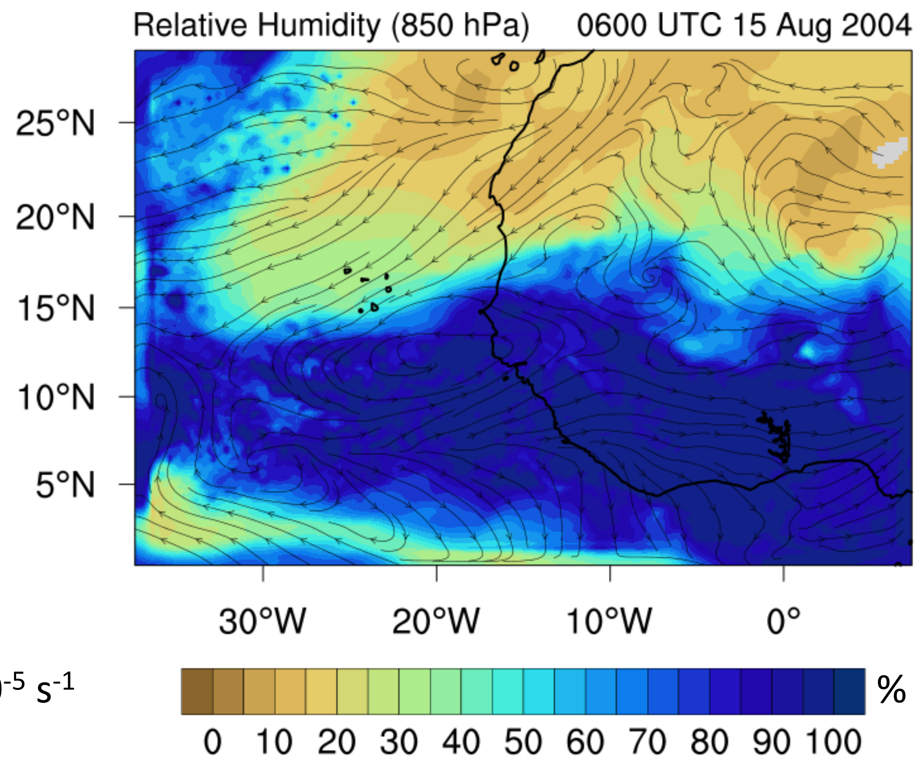




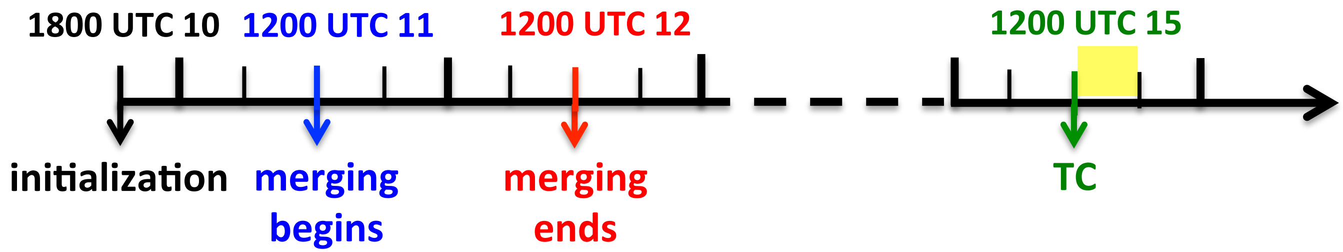
No Vortex Evolution

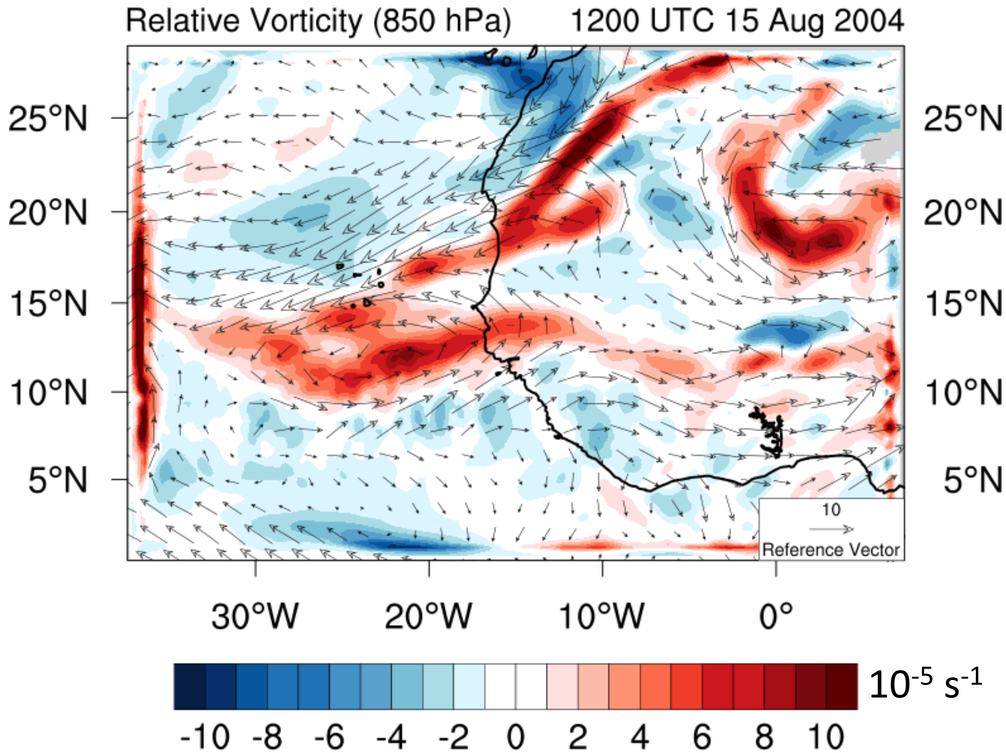


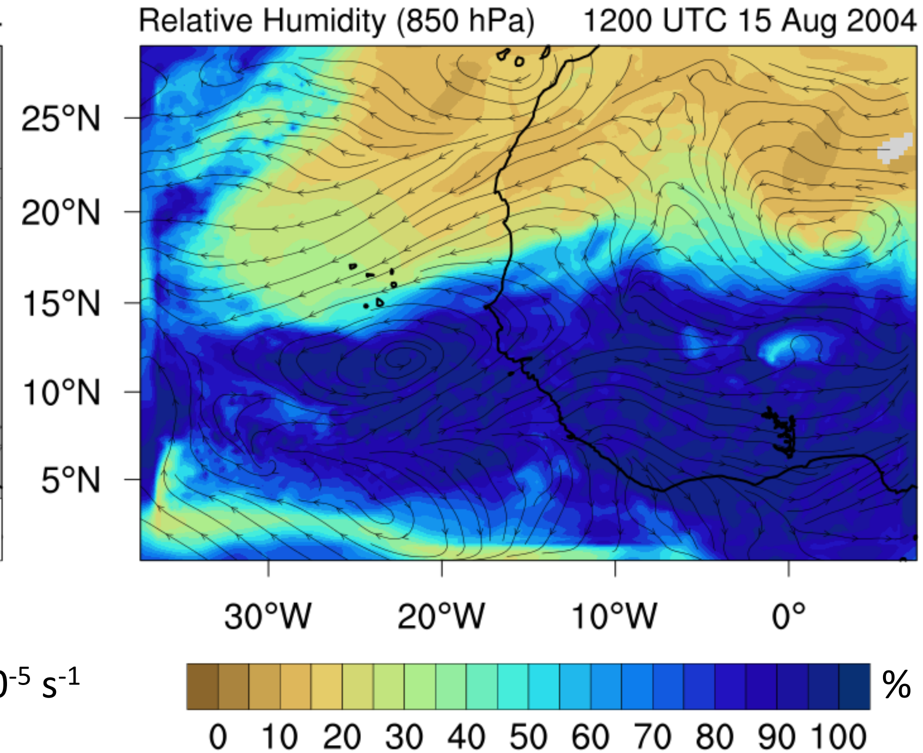




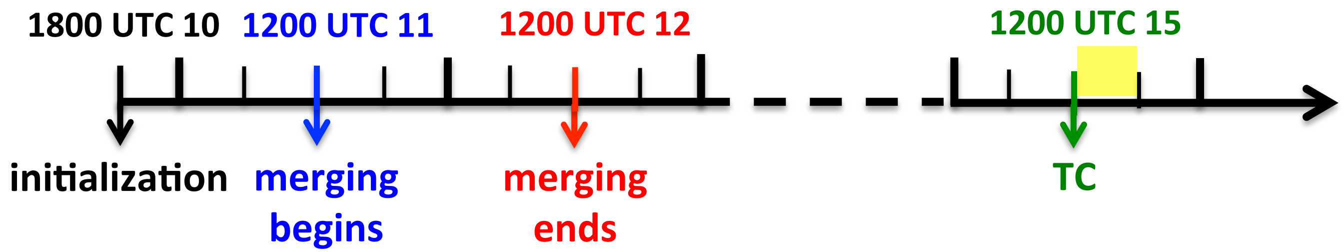
No Vortex Evolution

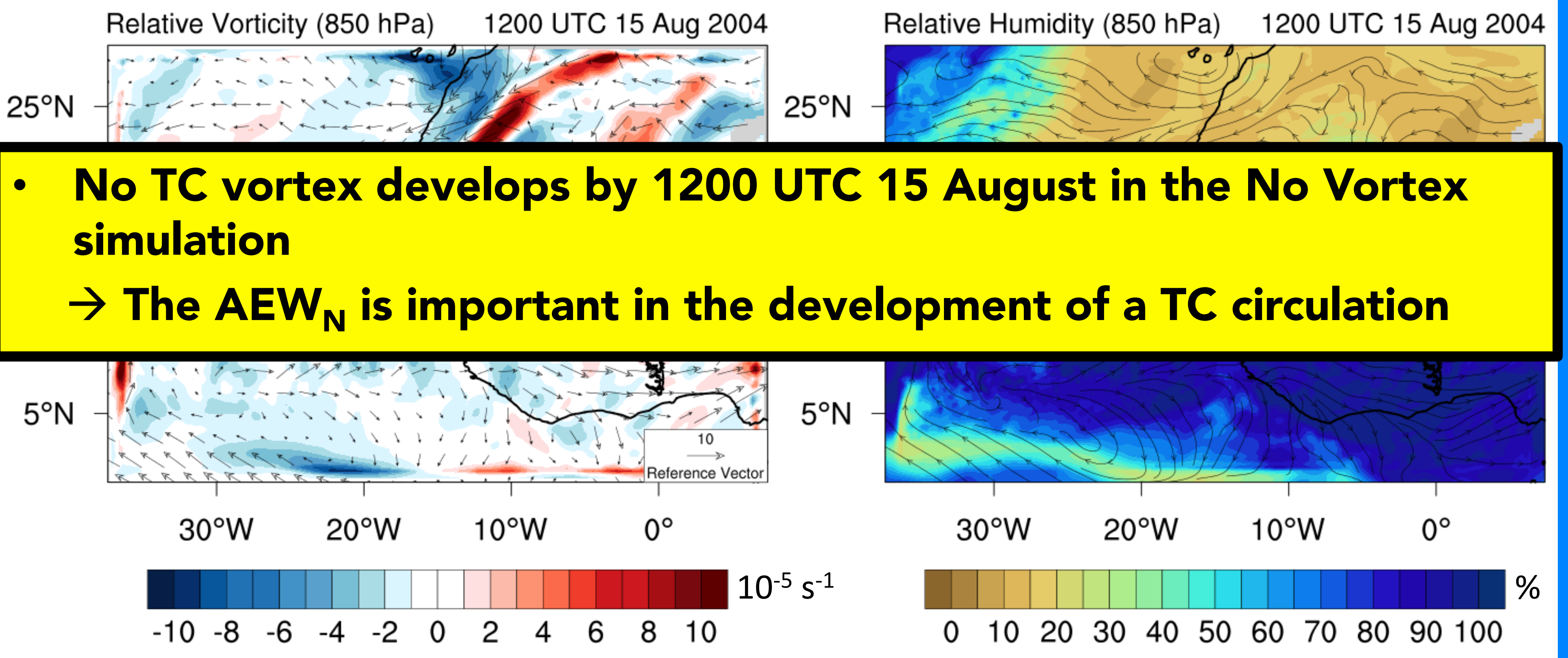






No Vortex Evolution





- **No TC vortex develops by 1200 UTC 15 August in the No Vortex simulation**

  → The AEW_N is important in the development of a TC circulation

Vorticity Budget

Temporal rate of change in area-averaged vorticity

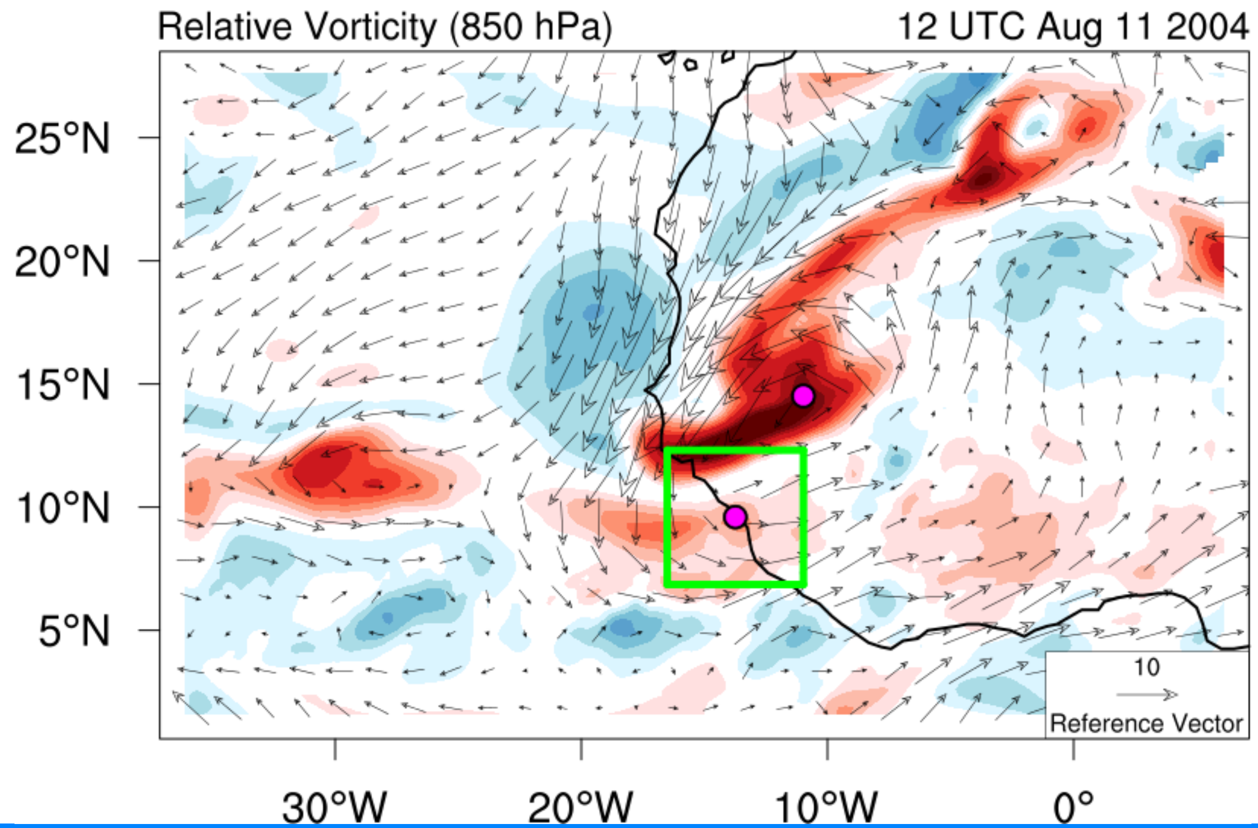
$$\frac{\partial \tilde{\zeta}}{\partial t} = -\bar{\eta}\tilde{\delta} - \frac{1}{A}\oint \eta' \mathbf{V}'_h \cdot \hat{\mathbf{n}}\, dl + \frac{1}{A}\oint \omega \left(\hat{\mathbf{k}} \times \frac{\partial \mathbf{V_h}}{\partial p}\right) \cdot \hat{\mathbf{n}}\, dl + \frac{1}{A}\oint \left(\hat{\mathbf{k}} \times \mathbf{F}\right) \cdot \hat{\mathbf{n}}\, dl$$

stretching — eddy vorticity flux — tilting — friction

Vorticity Budget

$$\frac{\partial \tilde{\zeta}}{\partial t} = -\bar{\eta}\tilde{\delta} - \frac{1}{A}\oint \eta' \mathbf{V}'_h \cdot \hat{\mathbf{n}}\, dl + \frac{1}{A}\oint \omega \left(\hat{\mathbf{k}} \times \frac{\partial \mathbf{V_h}}{\partial p}\right) \cdot \hat{\mathbf{n}}\, dl + \frac{1}{A}\oint \left(\hat{\mathbf{k}} \times \mathbf{F}\right) \cdot \hat{\mathbf{n}}\, dl$$

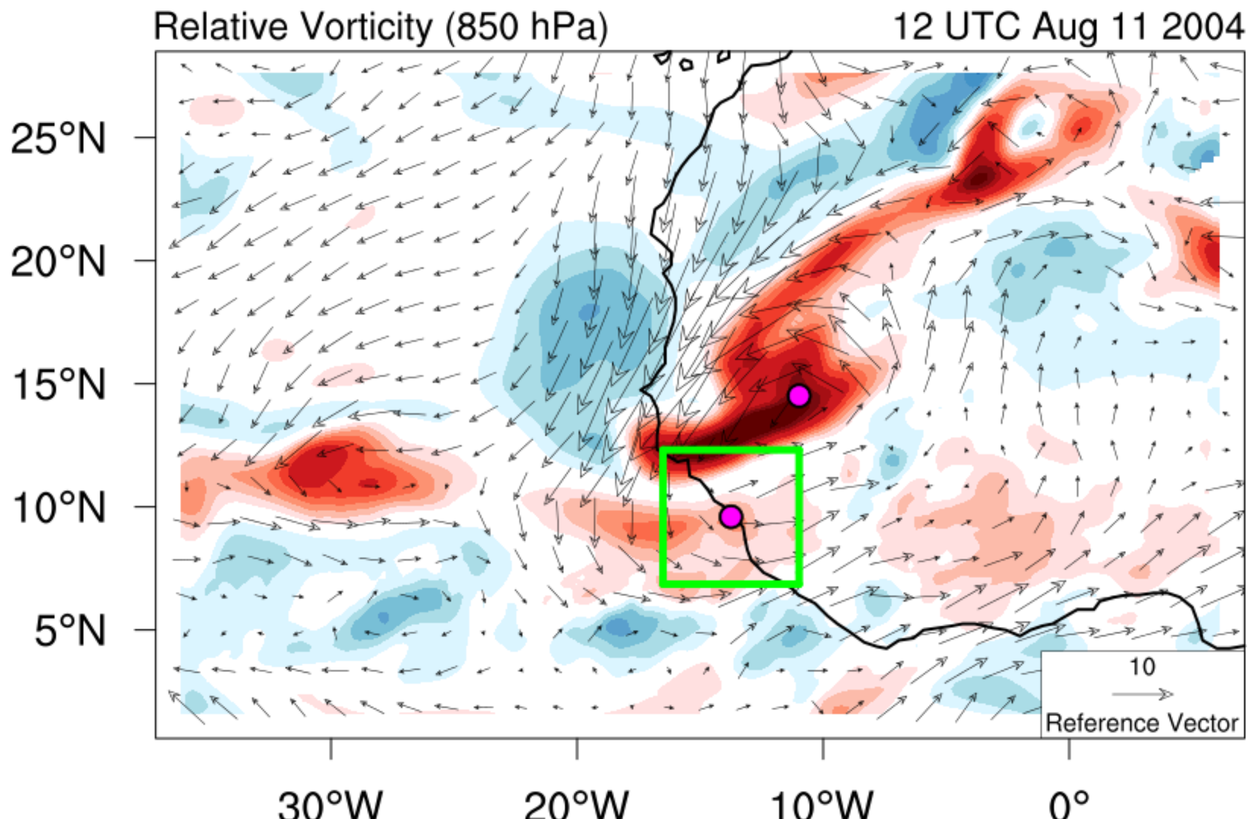
stretching | **eddy vorticity flux** | **tilting** | **friction**



Vorticity Budget

$$\frac{\partial \zeta}{\partial t} = -\bar{\eta}\tilde{\delta} - \frac{1}{A}\oint \eta' \mathbf{V}'_h \cdot \hat{\mathbf{n}}\, dl + \frac{1}{A}\oint \omega \left(\hat{\mathbf{k}} \times \frac{\partial \mathbf{V_h}}{\partial p}\right) \cdot \hat{\mathbf{n}}\, dl + \frac{1}{A}\oint \left(\hat{\mathbf{k}} \times \mathbf{F}\right) \cdot \hat{\mathbf{n}}\, dl$$

stretching | **eddy vorticity flux** | **tilting** | **friction**



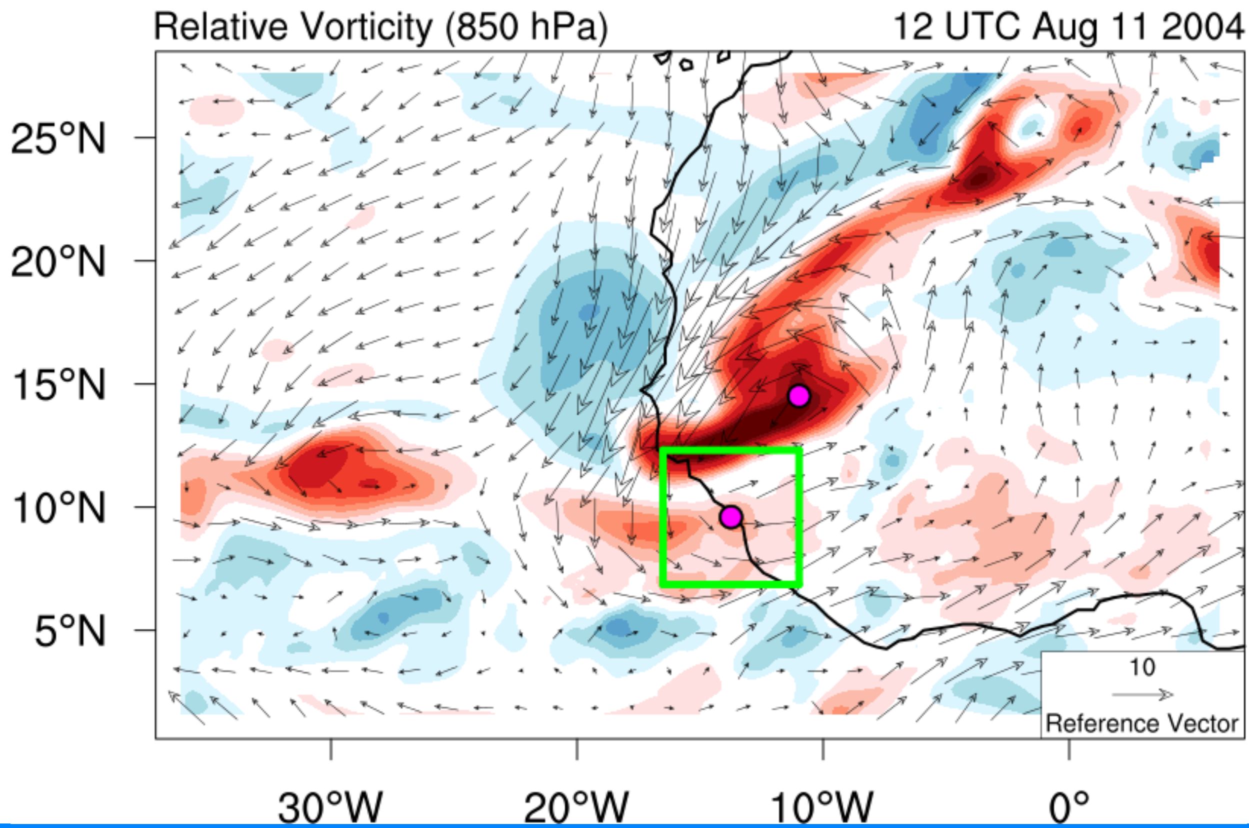
$$-\frac{1}{A}\oint \eta' \mathbf{V}'_h \cdot \hat{\mathbf{n}}\, dl$$

–

Vorticity Budget

$$\frac{\partial \tilde{\zeta}}{\partial t} = -\bar{\eta}\tilde{\delta} - \frac{1}{A}\oint \eta' \mathbf{V'}_h \cdot \hat{\mathbf{n}}\, dl + \frac{1}{A}\oint \omega \left(\hat{\mathbf{k}} \times \frac{\partial \mathbf{V_h}}{\partial p}\right) \cdot \hat{\mathbf{n}}\, dl + \frac{1}{A}\oint \left(\hat{\mathbf{k}} \times \mathbf{F}\right) \cdot \hat{\mathbf{n}}\, dl$$

stretching | **eddy vorticity flux** | **tilting** | **friction**



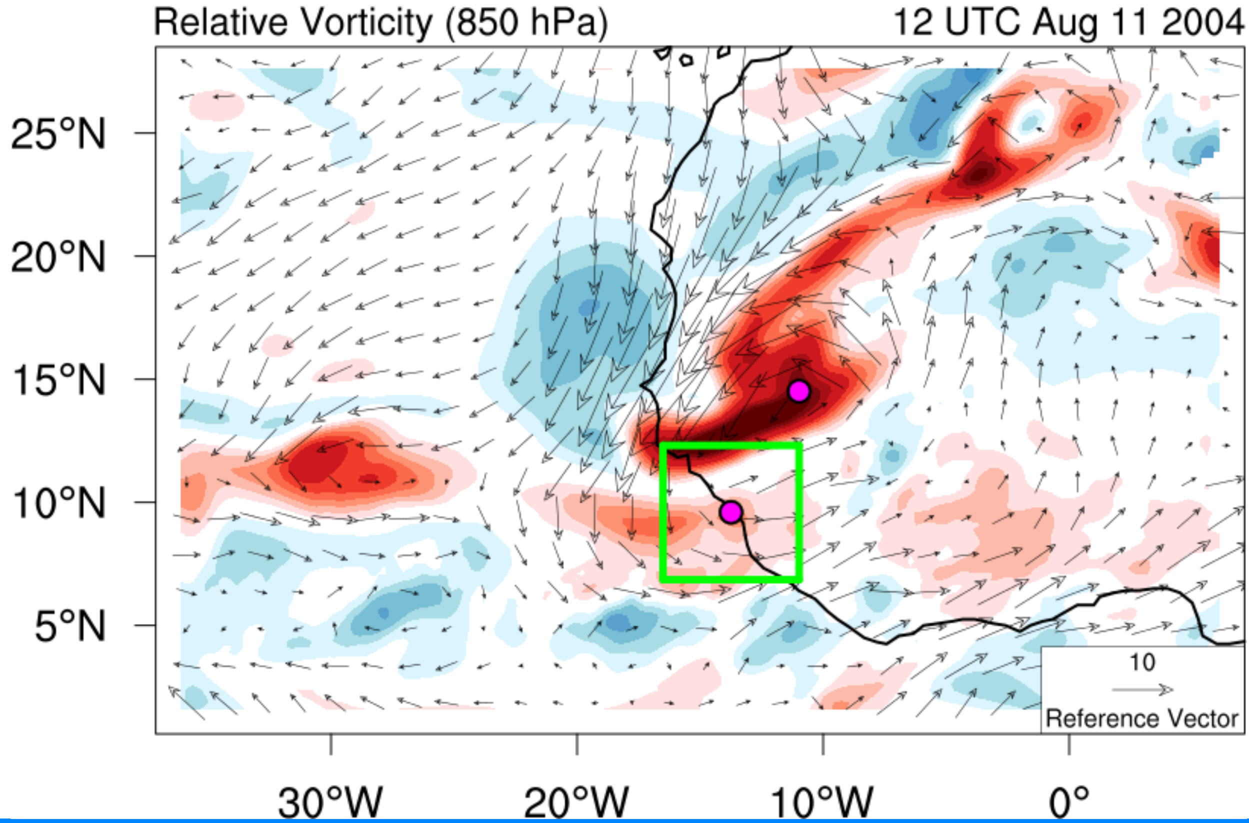
$$-\frac{1}{A}\oint \eta' \mathbf{V'}_h \cdot \hat{\mathbf{n}}\, dl$$

− +

Vorticity Budget

$$\frac{\partial \tilde{\zeta}}{\partial t} = -\bar{\eta}\tilde{\delta} - \frac{1}{A}\oint \eta' \mathbf{V}'_h \cdot \hat{\mathbf{n}}\, dl + \frac{1}{A}\oint \omega\left(\hat{\mathbf{k}} \times \frac{\partial \mathbf{V_h}}{\partial p}\right) \cdot \hat{\mathbf{n}}\, dl + \frac{1}{A}\oint (\hat{\mathbf{k}} \times \mathbf{F}) \cdot \hat{\mathbf{n}}\, dl$$

stretching | **eddy vorticity flux** | **tilting** | **friction**



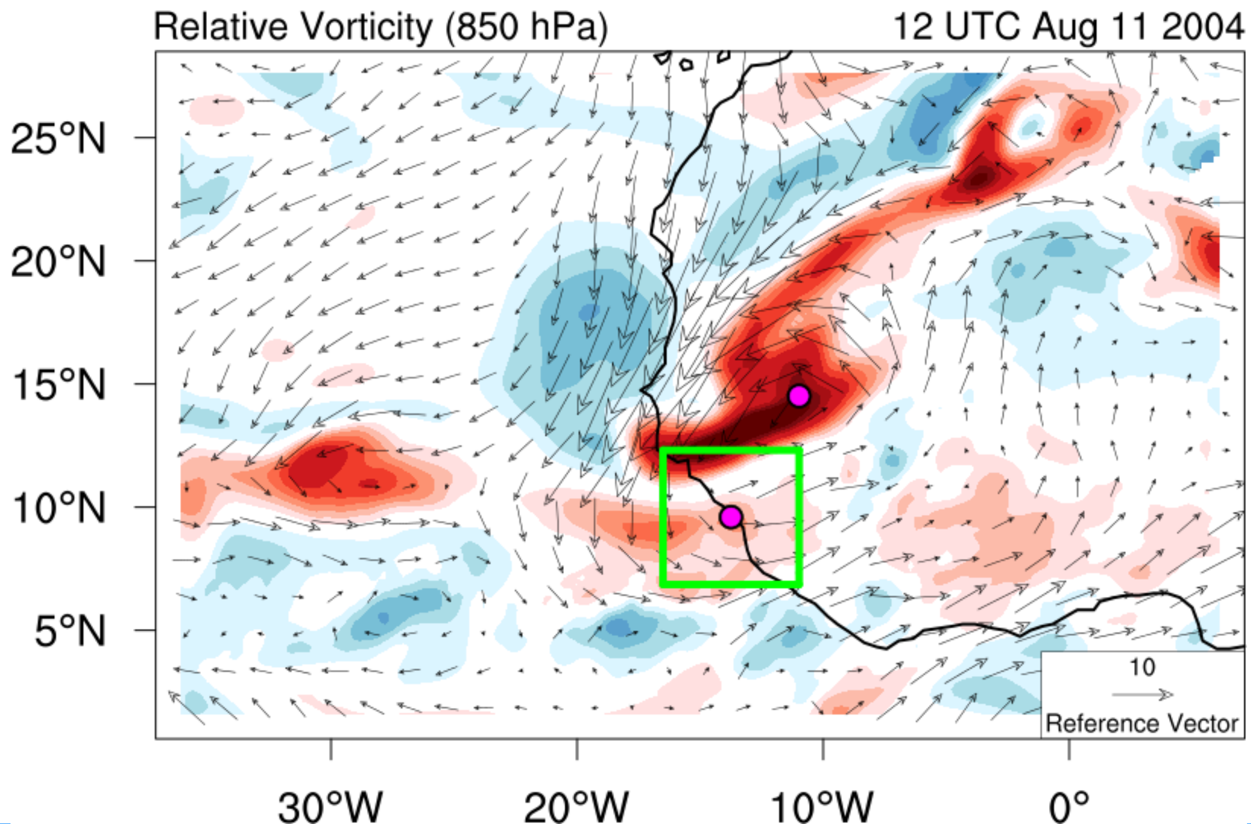
$$-\frac{1}{A}\oint \eta' \mathbf{V}'_h \cdot \hat{\mathbf{n}}\, dl$$

− + +

Vorticity Budget

$$\frac{\partial \tilde{\zeta}}{\partial t} = -\bar{\eta}\tilde{\delta} - \frac{1}{A}\oint \eta' \mathbf{V'}_h \cdot \hat{\mathbf{n}}\, dl + \frac{1}{A}\oint \omega\left(\hat{\mathbf{k}} \times \frac{\partial \mathbf{V_h}}{\partial p}\right) \cdot \hat{\mathbf{n}}\, dl + \frac{1}{A}\oint (\hat{\mathbf{k}} \times \mathbf{F}) \cdot \hat{\mathbf{n}}\, dl$$

stretching | **eddy vorticity flux** | **tilting** | **friction**



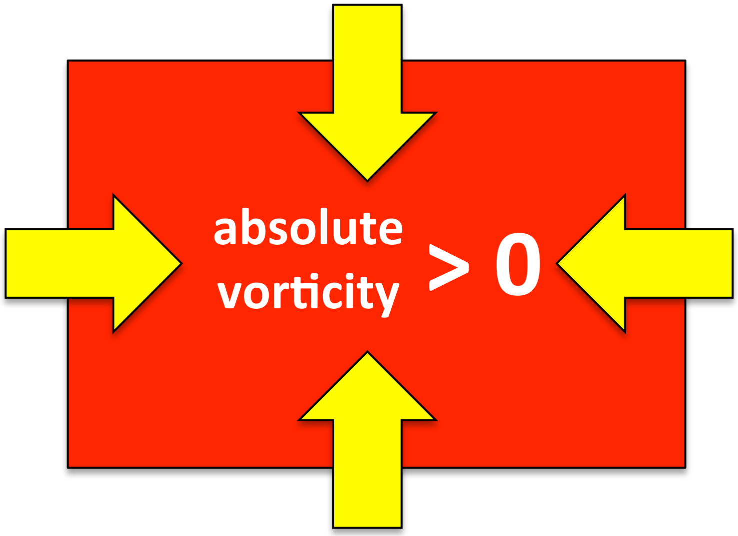
$$-\frac{1}{A}\oint \eta' \mathbf{V'}_h \cdot \hat{\mathbf{n}}\, dl$$

− +   + −

Vorticity Budget

$$\frac{\partial \bar{\zeta}}{\partial t} = -\bar{\eta}\tilde{\delta} - \frac{1}{A}\oint \eta' \mathbf{V'}_h \cdot \hat{\mathbf{n}}\, dl + \frac{1}{A}\oint \omega \left(\hat{\mathbf{k}} \times \frac{\partial \mathbf{V_h}}{\partial p}\right) \cdot \hat{\mathbf{n}}\, dl + \frac{1}{A}\oint (\hat{\mathbf{k}} \times \mathbf{F}) \cdot \hat{\mathbf{n}}\, dl$$

stretching | eddy vorticity flux | tilting | friction

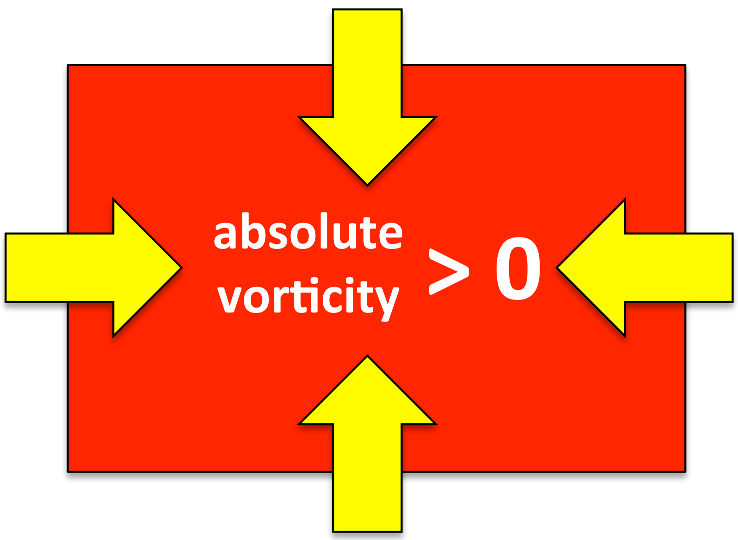


Vorticity Budget

$$\frac{\partial \zeta}{\partial t} = -\bar{\eta}\tilde{\delta} - \frac{1}{A}\oint \eta' \mathbf{V}'_h \cdot \hat{\mathbf{n}}\, dl + \frac{1}{A}\oint \omega \left(\hat{\mathbf{k}} \times \frac{\partial \mathbf{V_h}}{\partial p}\right) \cdot \hat{\mathbf{n}}\, dl + \frac{1}{A}\oint \left(\hat{\mathbf{k}} \times \mathbf{F}\right) \cdot \hat{\mathbf{n}}\, dl$$

stretching | **eddy vorticity flux** | **tilting** | **friction**

$$-\bar{\eta}\tilde{\delta}$$



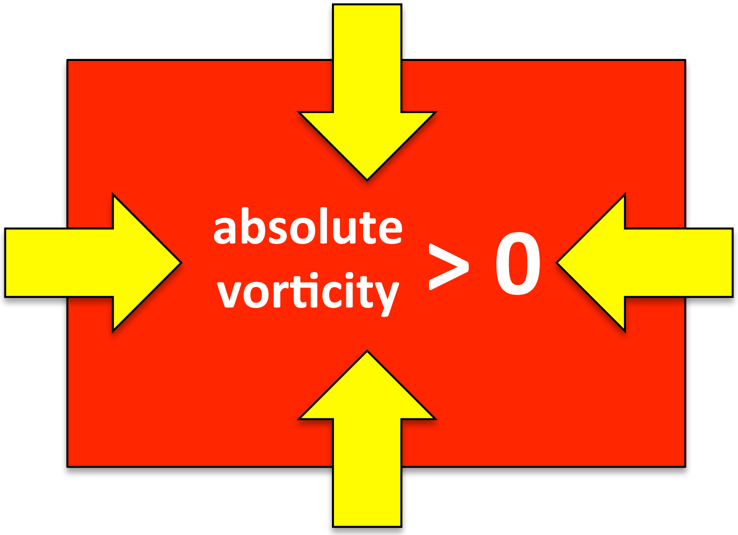
Vorticity Budget

$$\frac{\partial \bar{\zeta}}{\partial t} = -\bar{\eta}\tilde{\delta} - \frac{1}{A}\oint \eta' \mathbf{V'}_h \cdot \hat{\mathbf{n}}\, dl + \frac{1}{A}\oint \omega \left(\hat{\mathbf{k}} \times \frac{\partial \mathbf{V_h}}{\partial p}\right) \cdot \hat{\mathbf{n}}\, dl + \frac{1}{A}\oint \left(\hat{\mathbf{k}} \times \mathbf{F}\right) \cdot \hat{\mathbf{n}}\, dl$$

stretching | **eddy vorticity flux** | **tilting** | **friction**

$$-\bar{\eta}\tilde{\delta}$$

− +



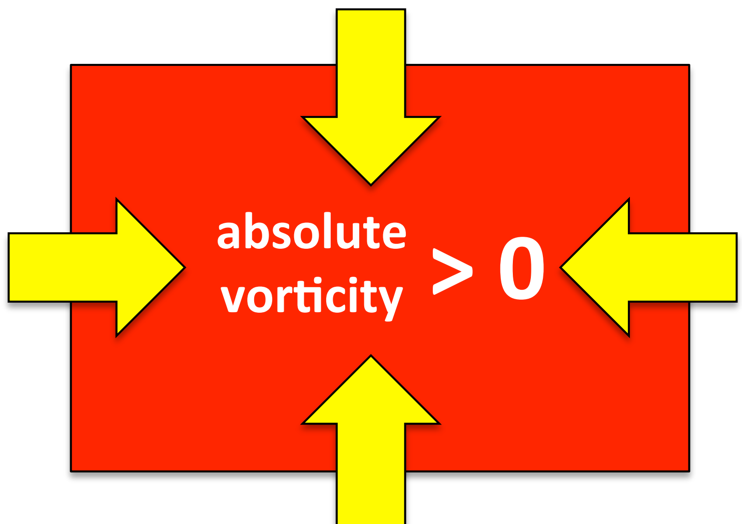
Vorticity Budget

$$\frac{\partial \zeta}{\partial t} = -\bar{\eta}\tilde{\delta} - \frac{1}{A}\oint \eta' \mathbf{V}'_h \cdot \hat{\mathbf{n}}\, dl + \frac{1}{A}\oint \omega \left(\hat{\mathbf{k}} \times \frac{\partial \mathbf{V_h}}{\partial p}\right) \cdot \hat{\mathbf{n}}\, dl + \frac{1}{A}\oint \left(\hat{\mathbf{k}} \times \mathbf{F}\right) \cdot \hat{\mathbf{n}}\, dl$$

stretching | **eddy vorticity flux** | **tilting** | **friction**

$$-\bar{\eta}\tilde{\delta}$$

− + −



Vorticity Budget

$$\frac{\partial \bar{\zeta}}{\partial t} = -\bar{\eta}\tilde{\delta} - \frac{1}{A}\oint \eta' \mathbf{V}'_h \cdot \hat{\mathbf{n}}\, dl + \frac{1}{A}\oint \omega \left(\hat{\mathbf{k}} \times \frac{\partial \mathbf{V_h}}{\partial p}\right) \cdot \hat{\mathbf{n}}\, dl + \frac{1}{A}\oint (\hat{\mathbf{k}} \times \mathbf{F}) \cdot \hat{\mathbf{n}}\, dl$$

stretching **eddy vorticity flux** **tilting** **friction**

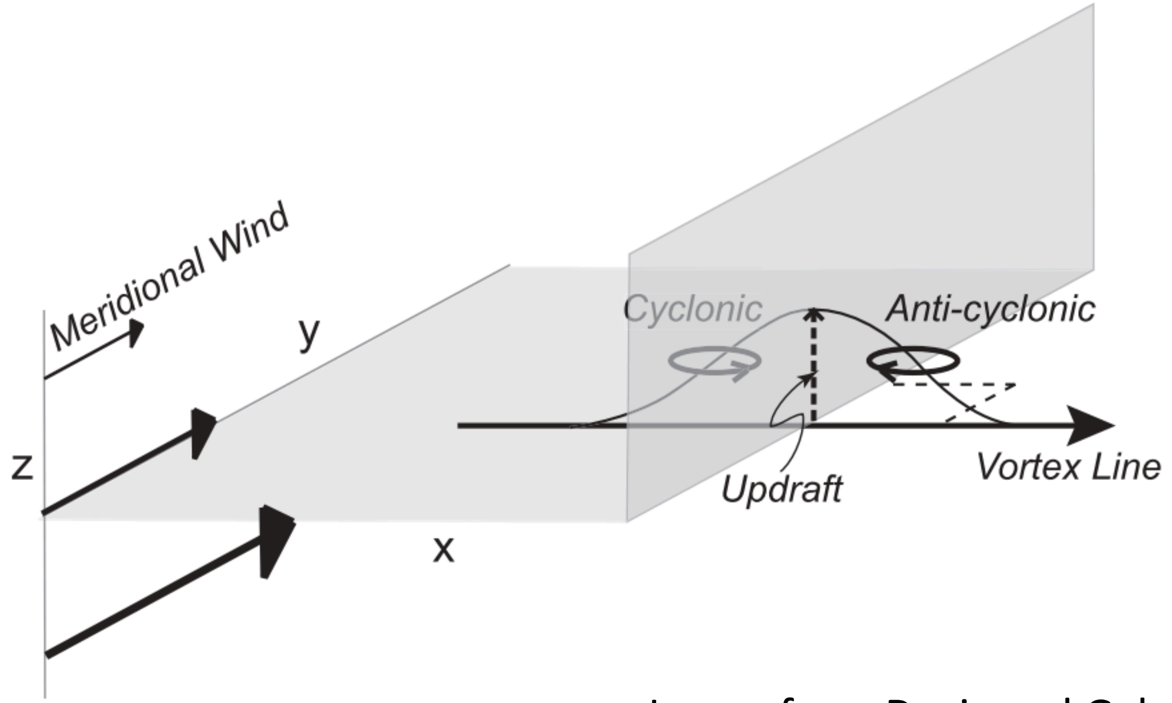
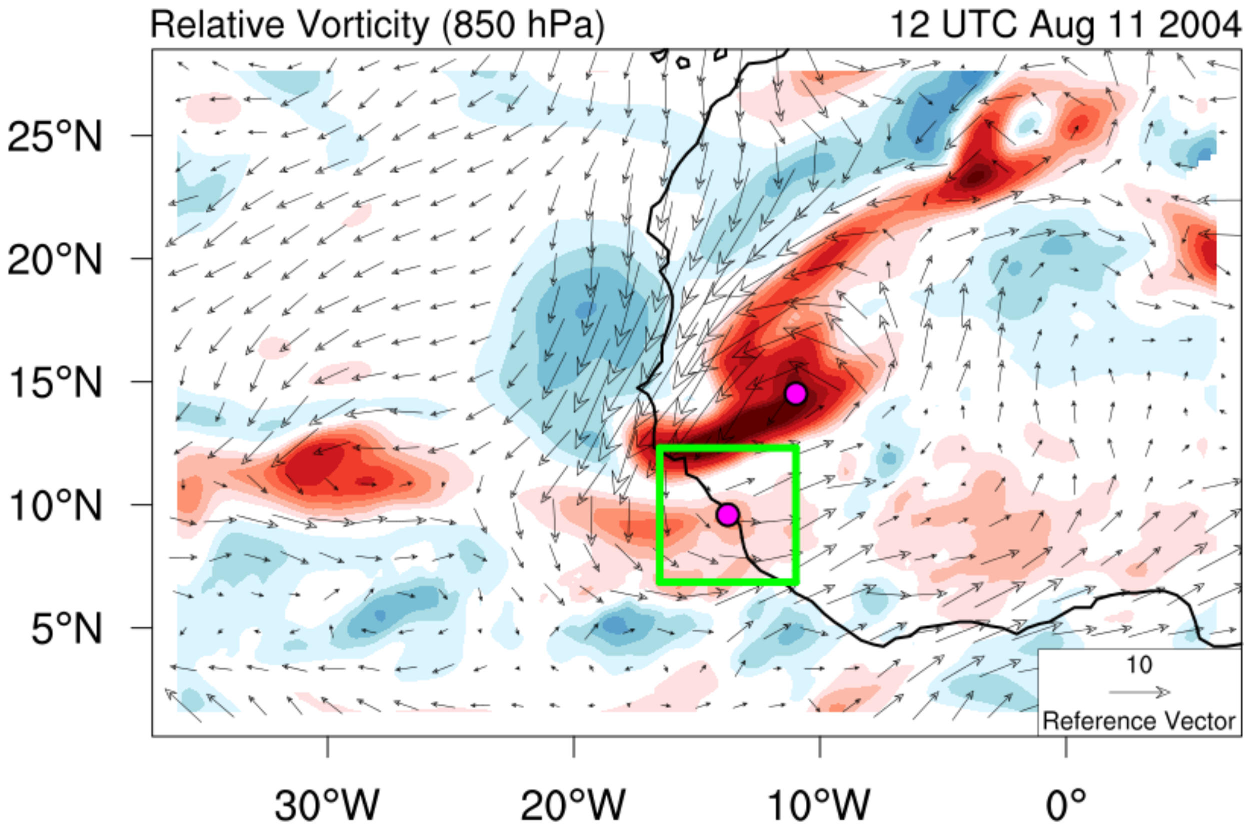


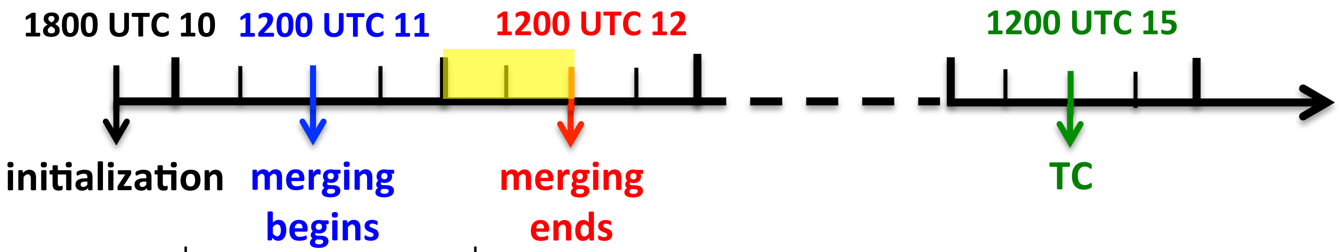
Image from Davis and Galarneau (2009)

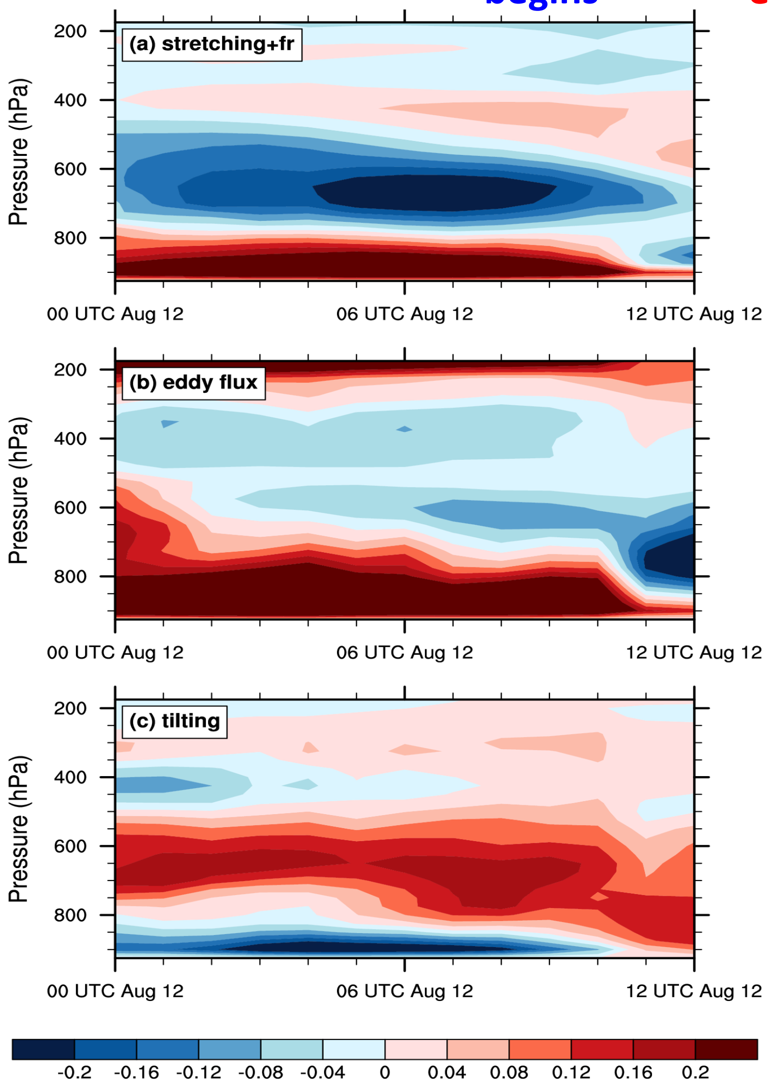
Vorticity Budget

$$\frac{\partial\tilde{\zeta}}{\partial t} = -\bar{\eta}\tilde{\delta} - \frac{1}{A}\oint \eta' \mathbf{V'}_h \cdot \hat{\mathbf{n}}\, dl + \frac{1}{A}\oint \omega \left(\hat{\mathbf{k}} \times \frac{\partial \mathbf{V_h}}{\partial p}\right) \cdot \hat{\mathbf{n}}\, dl + \frac{1}{A}\oint (\hat{\mathbf{k}} \times \mathbf{F}) \cdot \hat{\mathbf{n}}\, dl$$

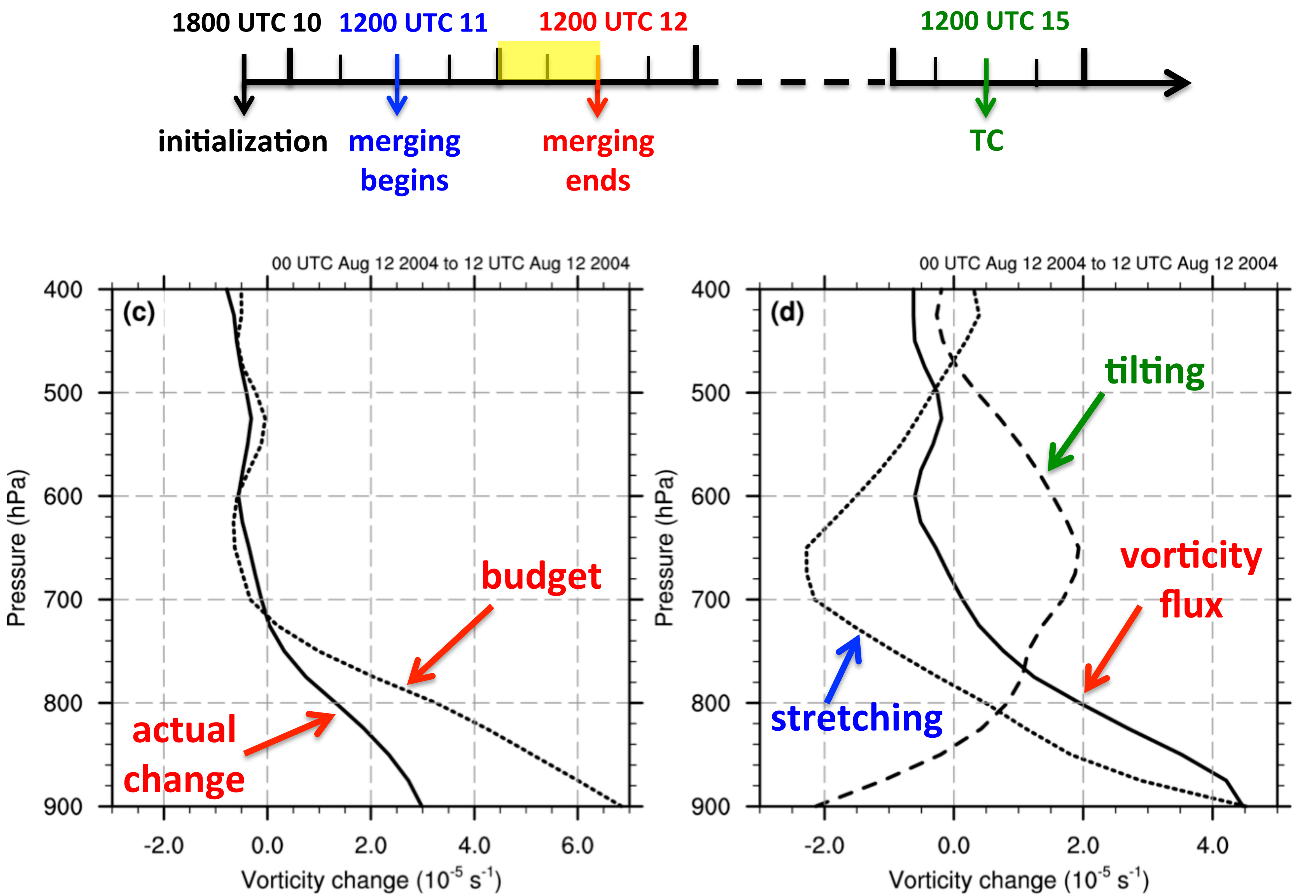
stretching **eddy vorticity flux** **tilting** **friction**







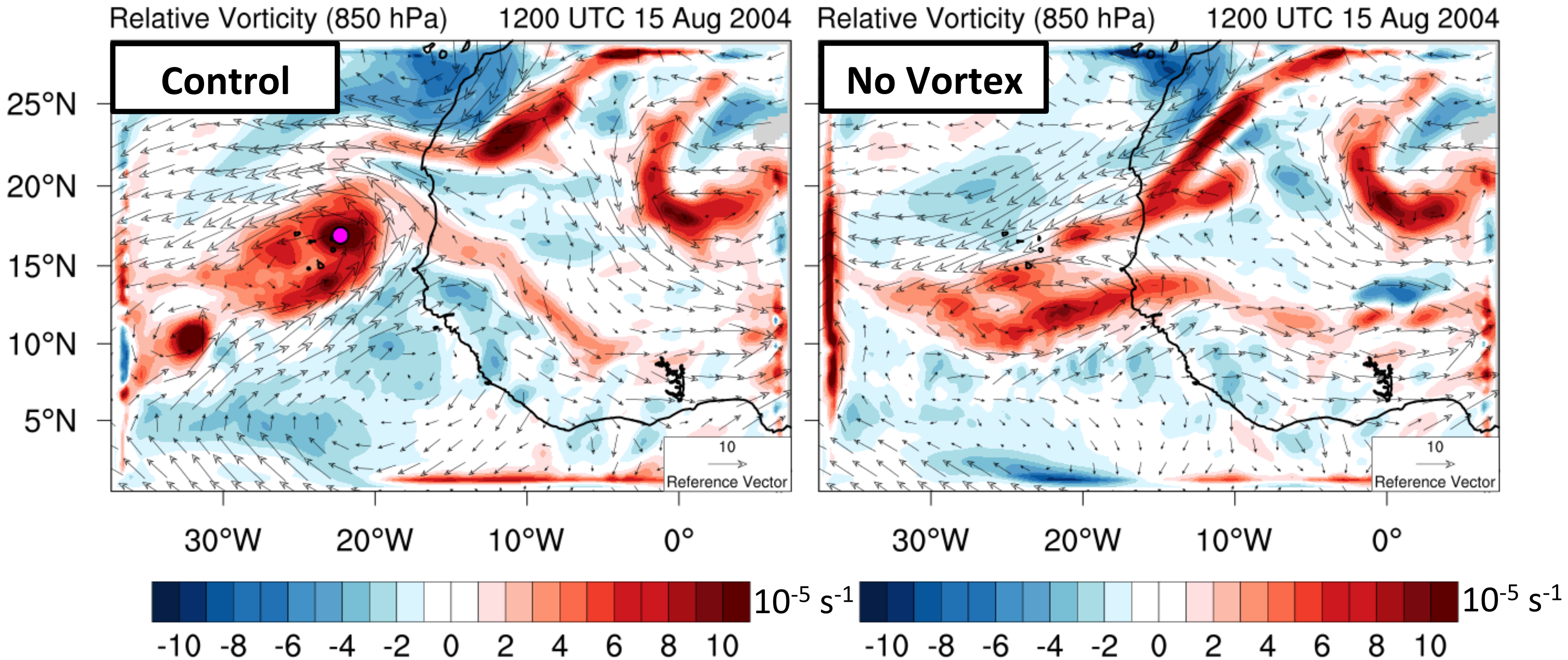
- Stretching has vertical dipole (upward motion)
- Eddy vorticity flux has comparable magnitude as stretching
- Tilting is positive at mid-levels



1800 UTC 10
1200 UTC 11
1200 UTC 12
1200 UTC 15
initialization
merging begins
merging ends
TC
00 UTC Aug 12 2004 to 12 UTC Aug 12 2004
(c)
budget
actual change
Pressure (hPa)
Vorticity change (10^-5 s^-1)
00 UTC Aug 12 2004 to 12 UTC Aug 12 2004
(d)
tilting
vorticity flux
stretching
Pressure (hPa)
Vorticity change (10^-5 s^-1)

Conclusions

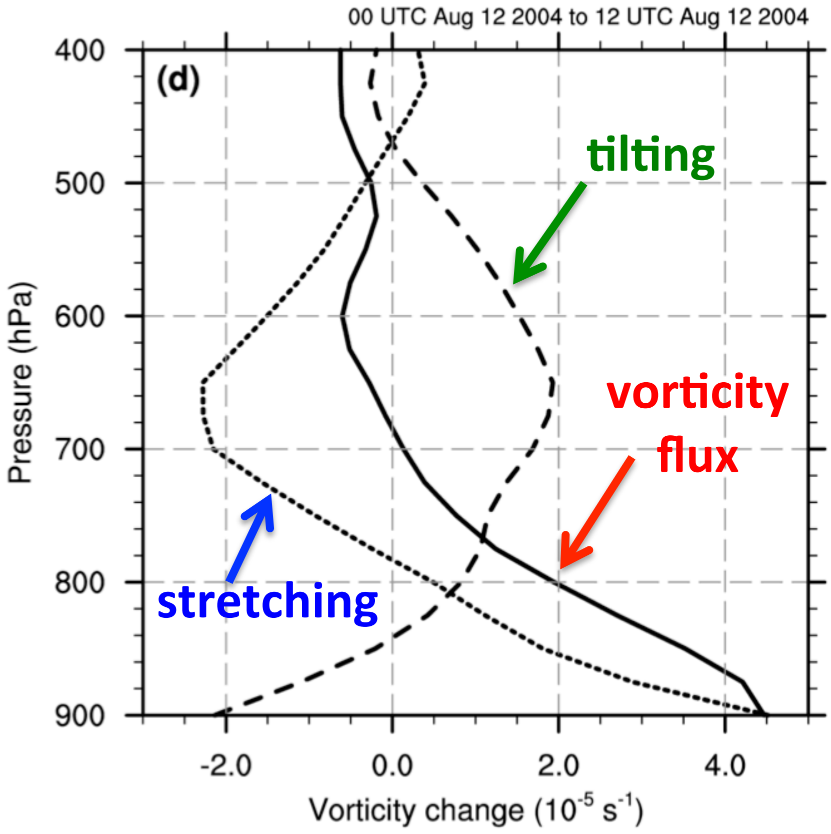
1. Can an AEW_N contribute to tropical cyclogenesis?
    - ❖ Control simulation developed a TC, while the No Vortex simulation did not
    - ❖ AEW_Ns can contribute to tropical cyclogenesis



Conclusions

2. What is the relative or collective importance of AEW_Ns and AEW_Ss on tropical cyclogenesis?

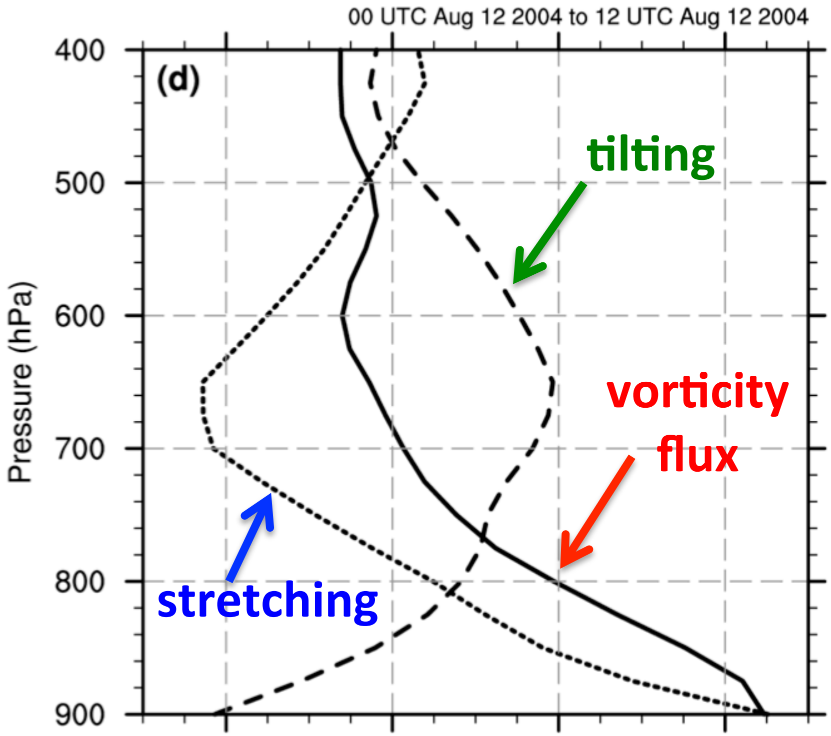
- ❖ **Merging at least as important as diabatic processes at increasing the low-level vorticity of the merged vortex**



Conclusions

2. What is the relative or collective importance of AEW_Ns and AEW_Ss on tropical cyclogenesis?

- **Merging at least as important as diabatic processes at increasing the low-level vorticity of the merged vortex**



When forecasting tropical cyclogenesis, it may be important to consider AEW_N!

Acknowledgements

- **Dr. Kristen Corbosiero**
- **Kevin Tyle**
- **Dr. Alan Brammer**
- **Dr. Ryan Torn**
- **Dr. Rob Fovell**
- **Dr. Chris Thorncroft**
- **Rosimar Rios-Berrios**
- **Philippe Papin**

Links

Simulations:
http://www.atmos.albany.edu/student/jalland/Images/ATM_741/Danielle_2004/

Control-tangential wind:
http://www.atmos.albany.edu/student/ymcheng/ATM741/with-vortex/vt-850.html

Interim tangential wind:
http://www.atmos.albany.edu/student/ymcheng/ATM741/with-vortex/vt-850-interim.html

tangential wind time series (10m)
http://www.atmos.albany.edu/student/ymcheng/ATM741/with-vortex/vt-time-series-10m.png

tangential wind time series (850)
http://www.atmos.albany.edu/student/ymcheng/ATM741/with-vortex/vt-time-series-850.png

budget friction term:
http://www.atmos.albany.edu/student/ymcheng/ATM741/with-vortex/budget-12hr-fr.html

TRMM precip vs WRF:
http://www.atmos.albany.edu/student/ymcheng/ATM741/precip/precip.html