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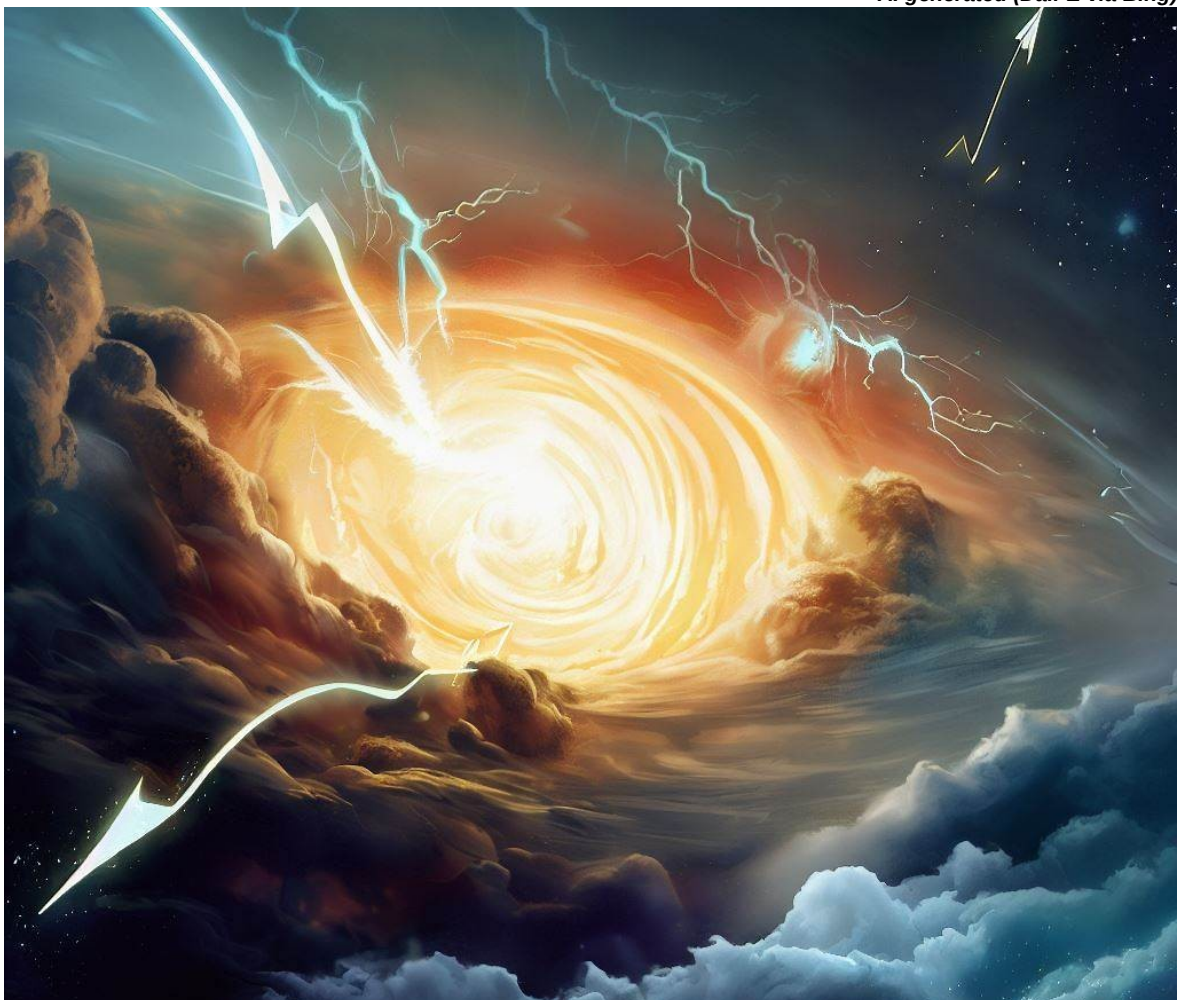


Tropical cyclogenesis

Adrien Colomb Sébastien Langlade Tarik Kriat

RA I WMO - Training course on tropical cyclones 2023

Tropical cyclogenesis

Mechanisms, bassin pattern and equatorial waves

METEO FRANCE

I) Basic concepts and pathways to genesis

- *Definition*
- *Environmental conditions*
- *Historical theories*
- *The need for a vorticity precursor*
- *Interactions with wind shear*

II) Basin configurations

1) *Monsoon trough*
2) *Near equatorial trough*
3) *Climatology*
4) *Dynamics of the MT and NET*

III) Equatorial waves

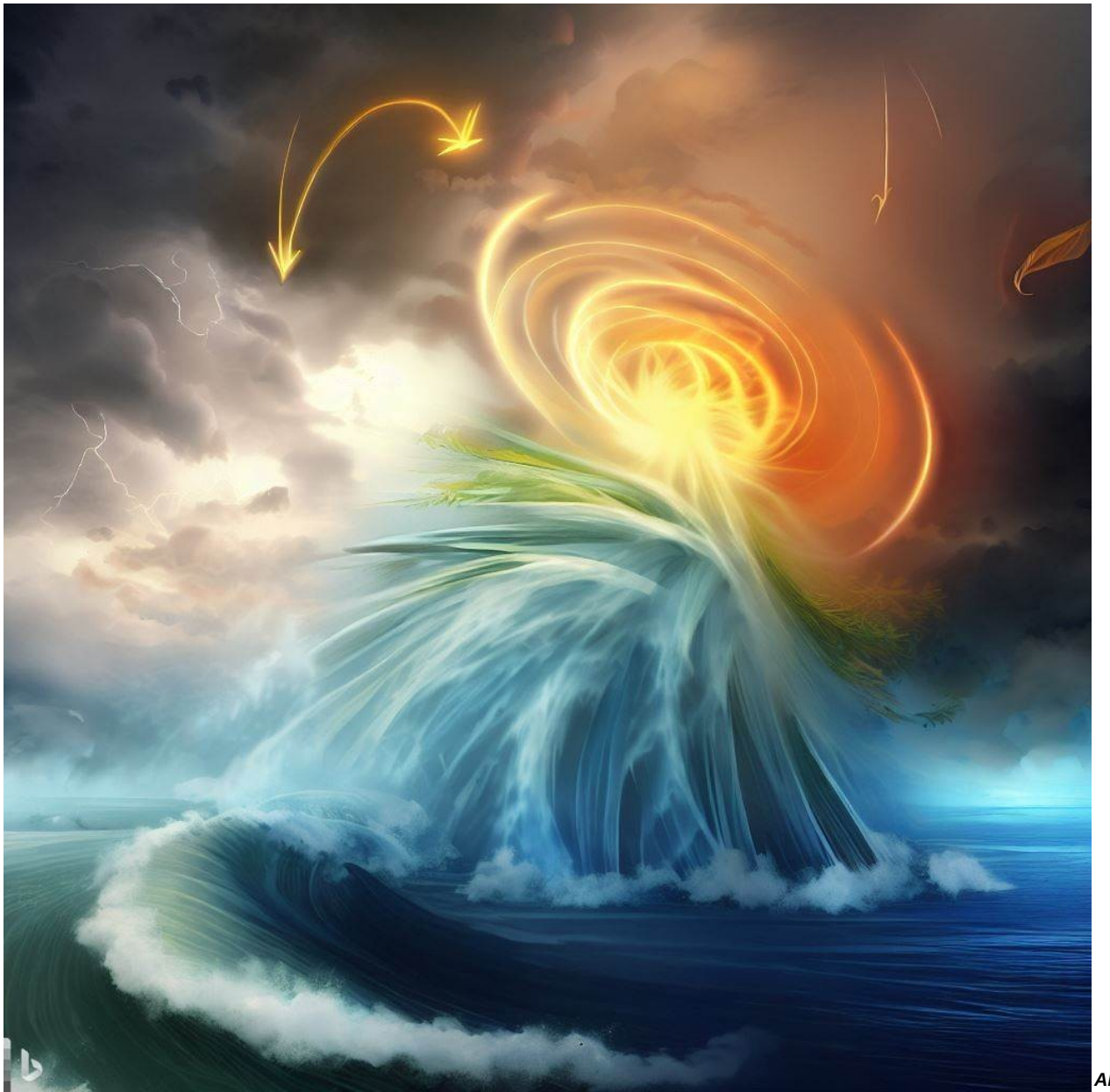
1) *Definition and presentation*
2) *Link with TCG*

IV) A few advanced notions

1) The Marsupial Paradigm
2) Vortical Hot Towers route to TCG
3) TCG at the intersection of large- and meso-scales

Tropical cyclogenesis

Basic concepts and pathways to genesis



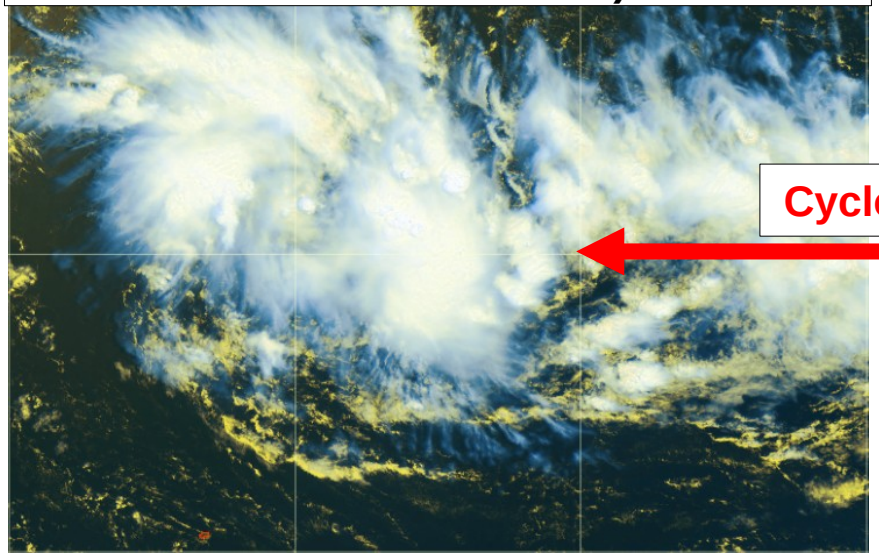
AI generated (Dall-E via Bing)

Cyclogenesis : definition

Definition : A tropical cyclogenesis (TCG) is carried out when a low pressure area has become an **autonomous** system. It no longer needs help from its environment to develop, through "**environmental forcing**".

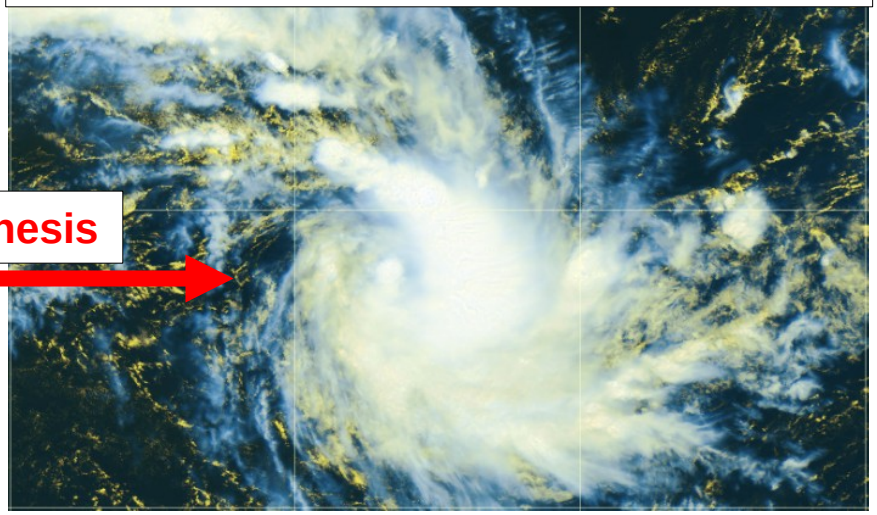
In operational terms, cyclogenesis is carried out when the stage of a tropical storm is reached. This process usually takes several days.

Non-autonomous precursor (area of disturbed weather)



Cyclogenesis

Autonomous system (tropical storm)



Src : MF Archives

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Cyclogenesis : definition

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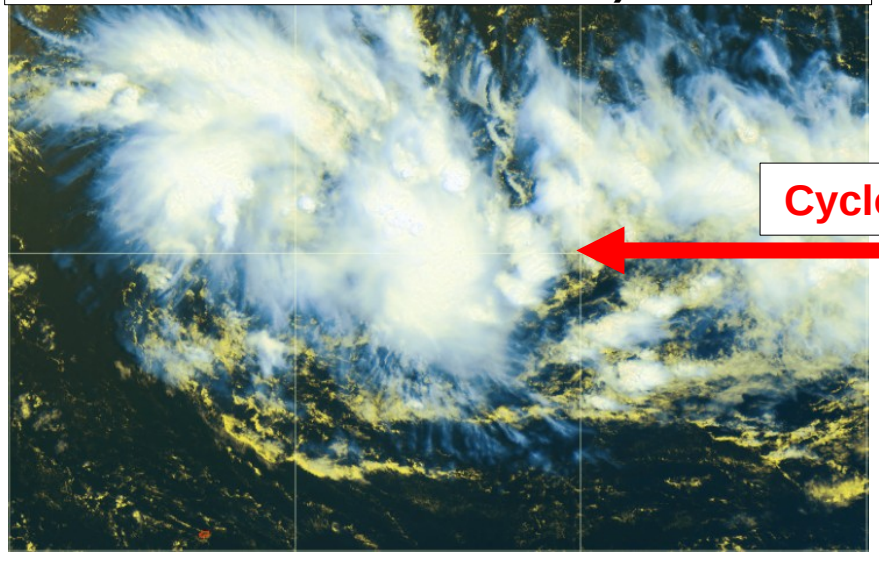

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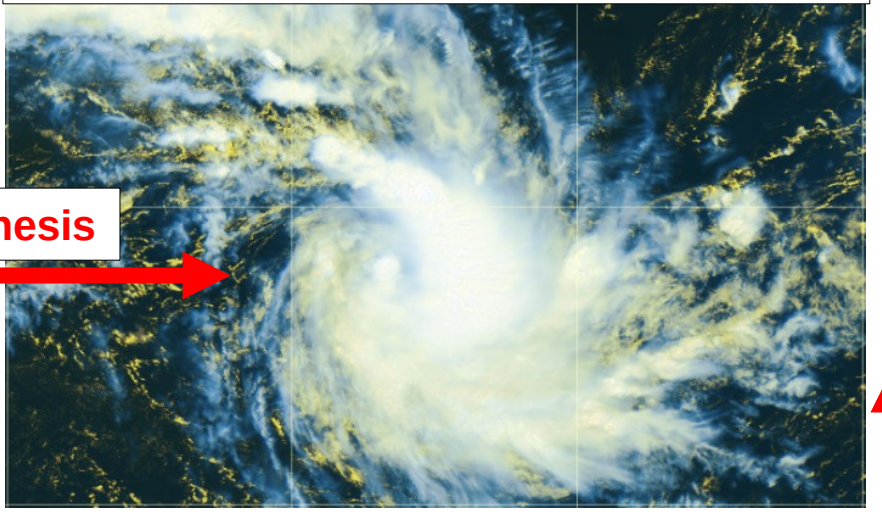
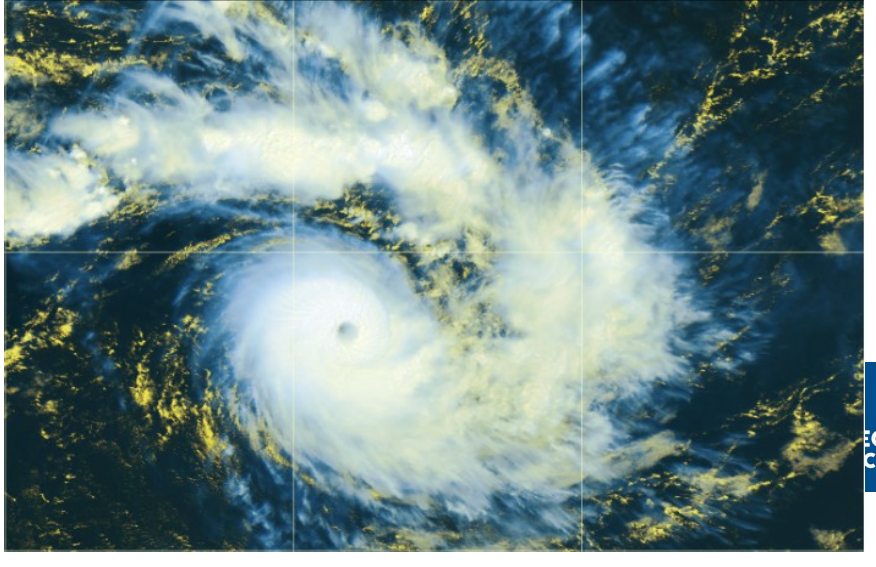


Intensification

Mature autonomous system



Cyclogenesis : basic concepts

Necessary conditions for cyclogenesis (Gray, 1968) :

- ✓ Sufficient **ocean energy** [Sea Temp. > **26°C** over at least 60 m depth]
- ✓ Generalized instability allowing deep convection
- ✓ Mid-tropospheric humidity (700/400 hPa layer)
- ✓ Latitude > **5°**
- ✓ Low vertical wind shear (**less than 15kt**)
- ✓ Vorticity of low layers (precursor)

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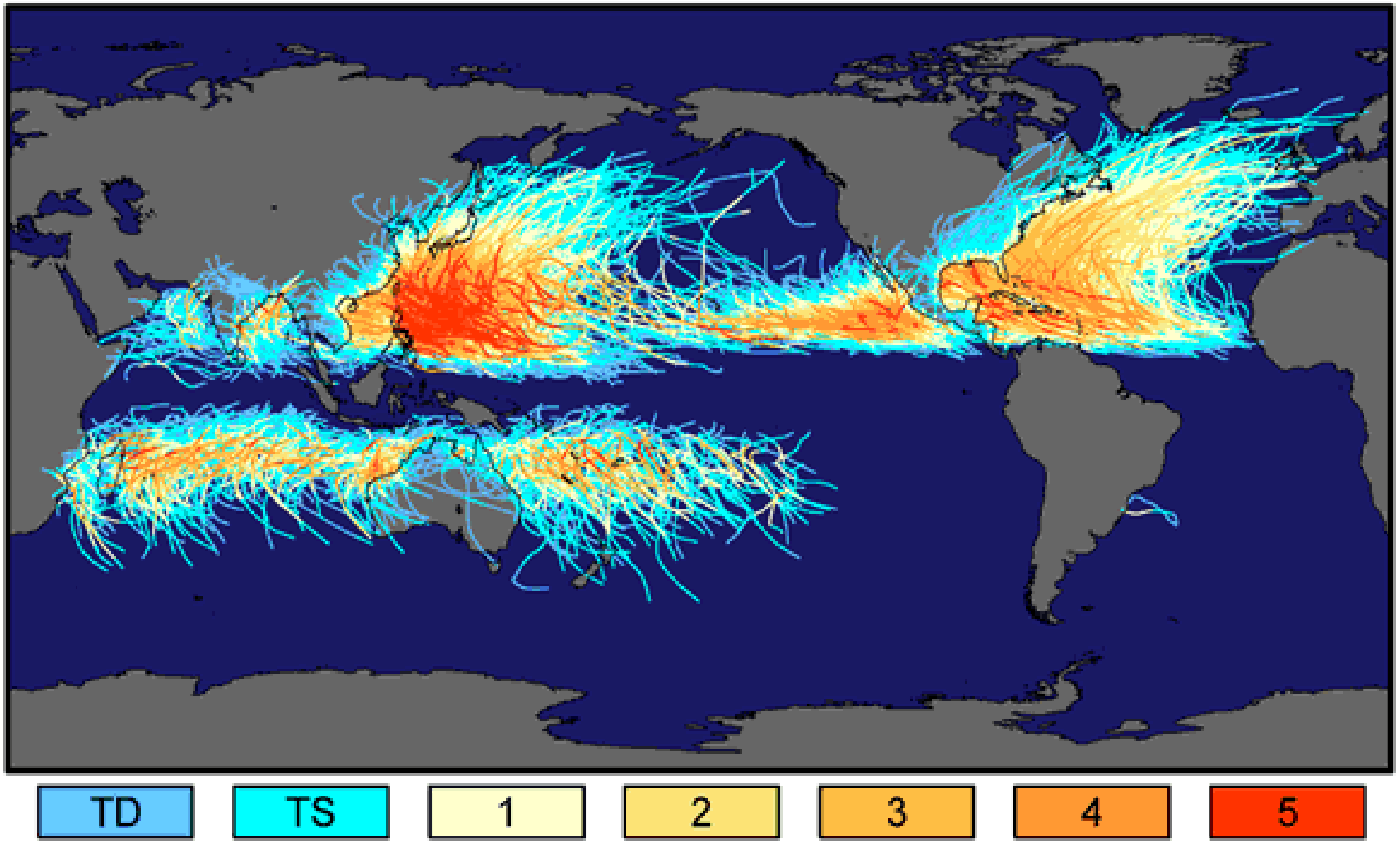
METEO FRANCE

Cyclogenesis : basic concepts

Tracks and Intensity of Tropical Cyclones, 1851-2006

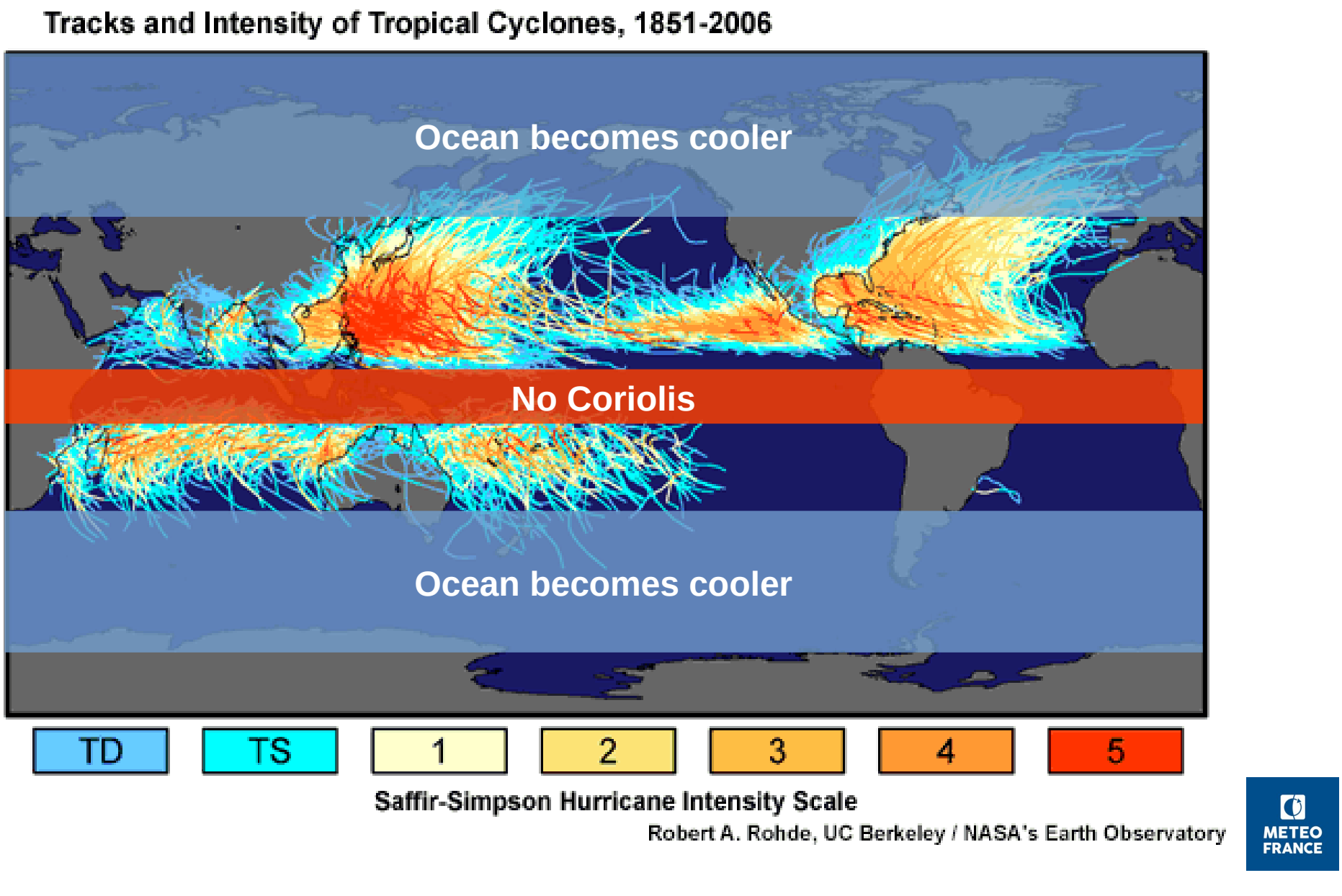


Saffir-Simpson Hurricane Intensity Scale

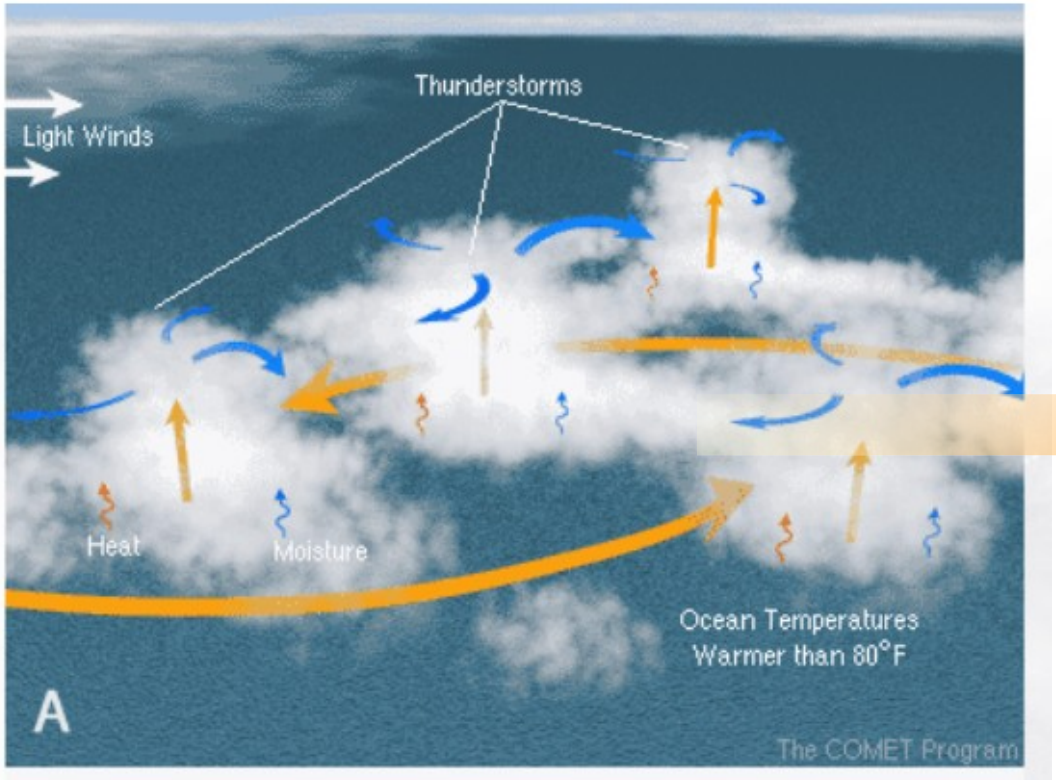
Robert A. Rohde, UC Berkeley / NASA's Earth Observatory

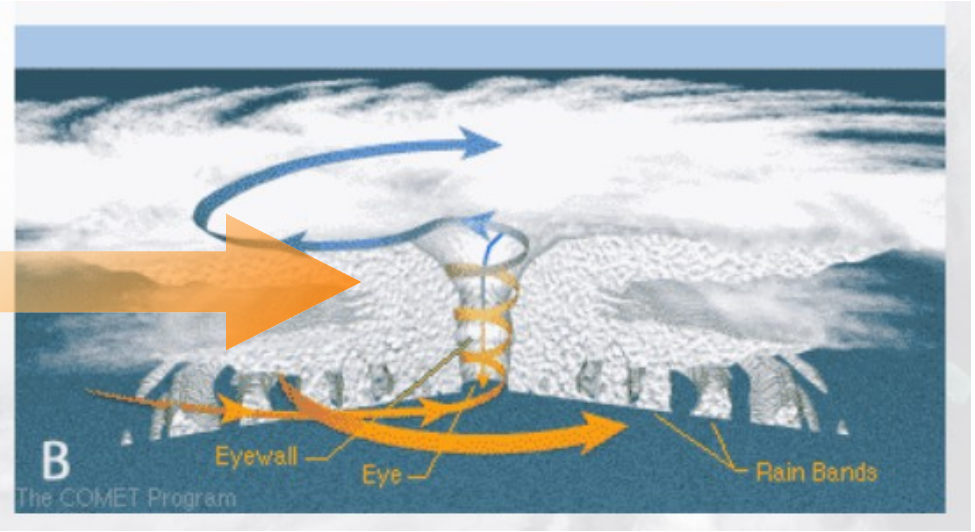
METEO FRANCE

Cyclogenesis : basic concepts



How do we go from a few MCS to a self-sustained TS ?





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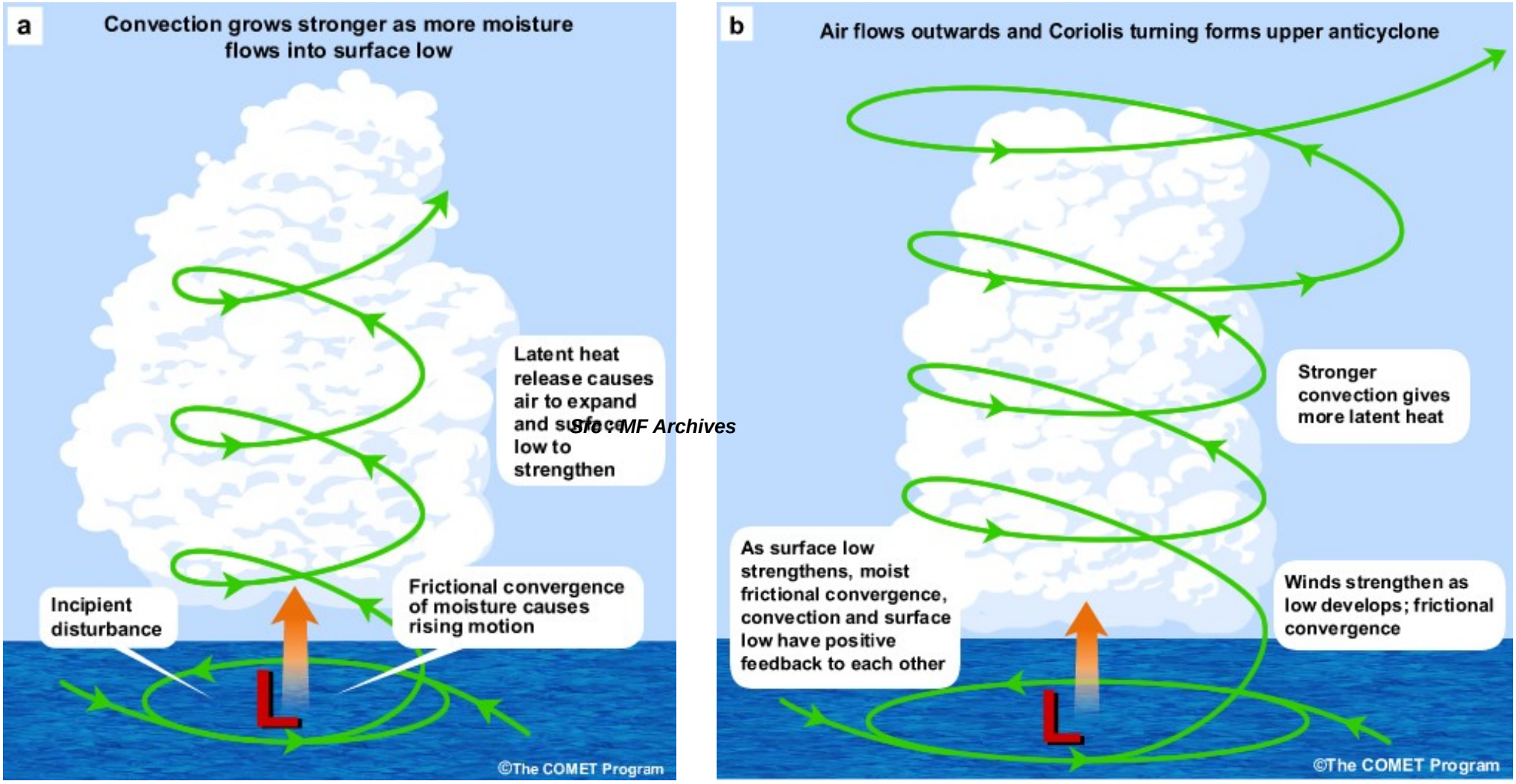

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CISK Theory (Ooyama, Charney & Elliassen, 1964) **:**

- **One of the first description of a pathway to genesis**
- **Simple scheme with an axisymmetric vortex**

METEO FRANCE

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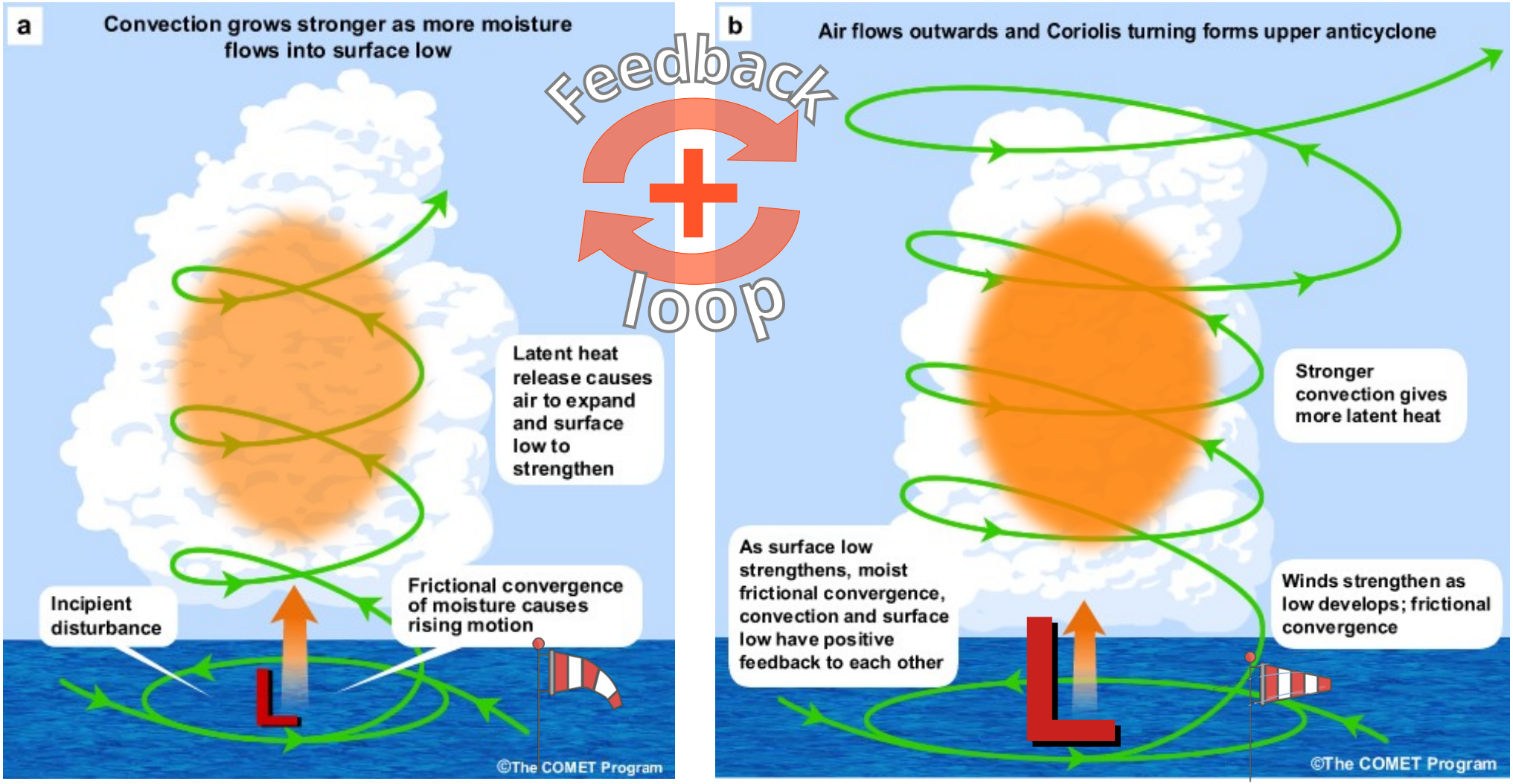

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CISK Theory (Ooyama, Charney & Elliassen, 1964) **:**

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METEO FRANCE

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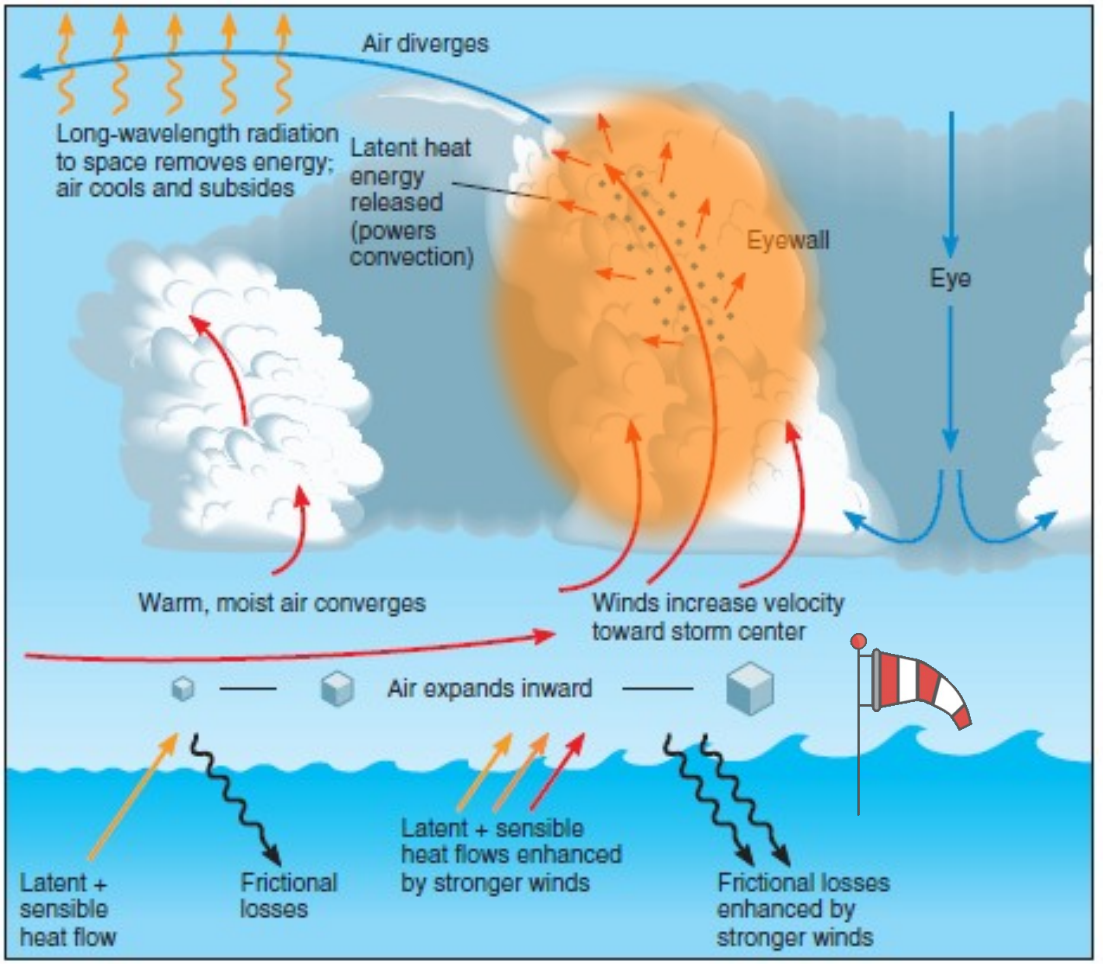

Src : Hurricane FlashCards

Figure 11.10 Energy flow within a hurricane.

WISHE Theory (Emanuel, 1986) **:**

- **Based on the role of the heat fluxes between the ocean and the boundary layer.**
- **May not be as crucial in more realistic 3D simulations (and thus, in real world situations)**

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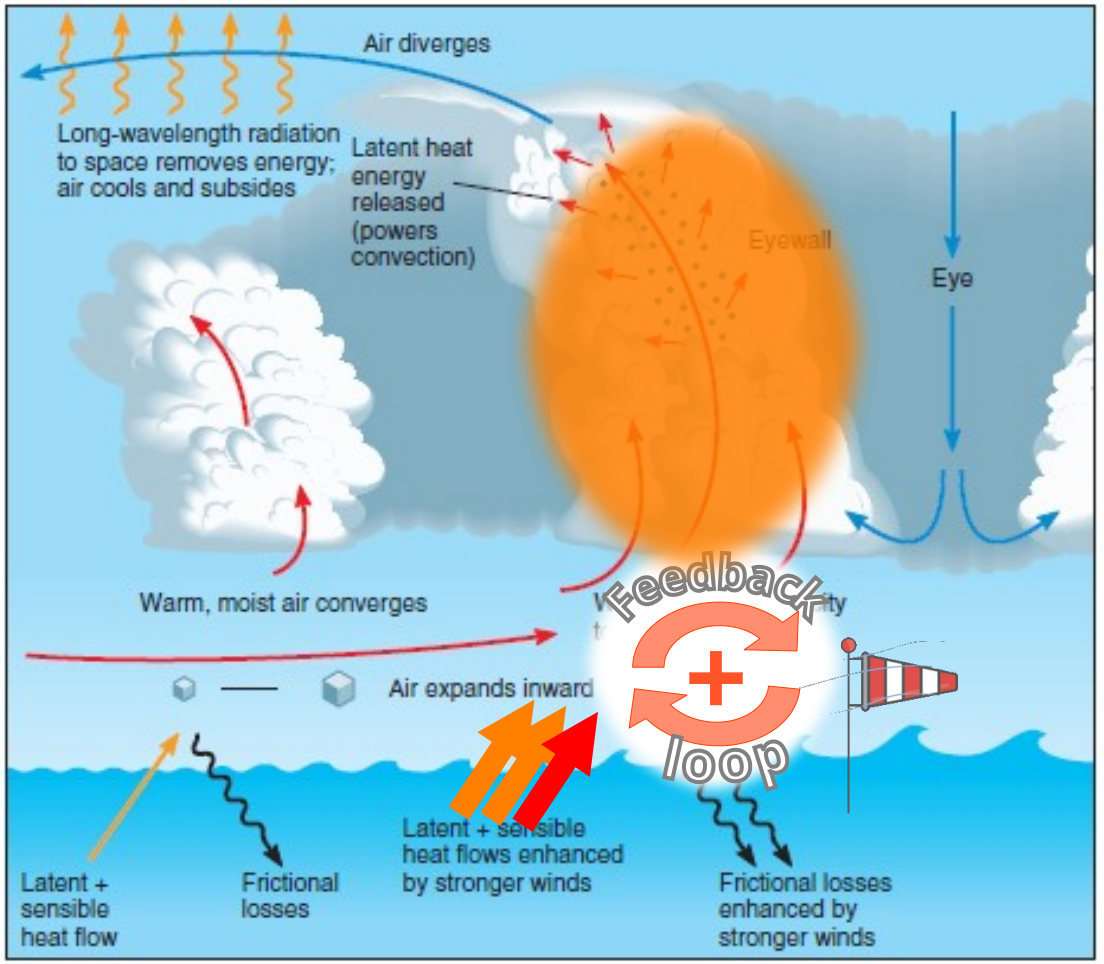

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METEO FRANCE

Cyclogenesis : basic concepts

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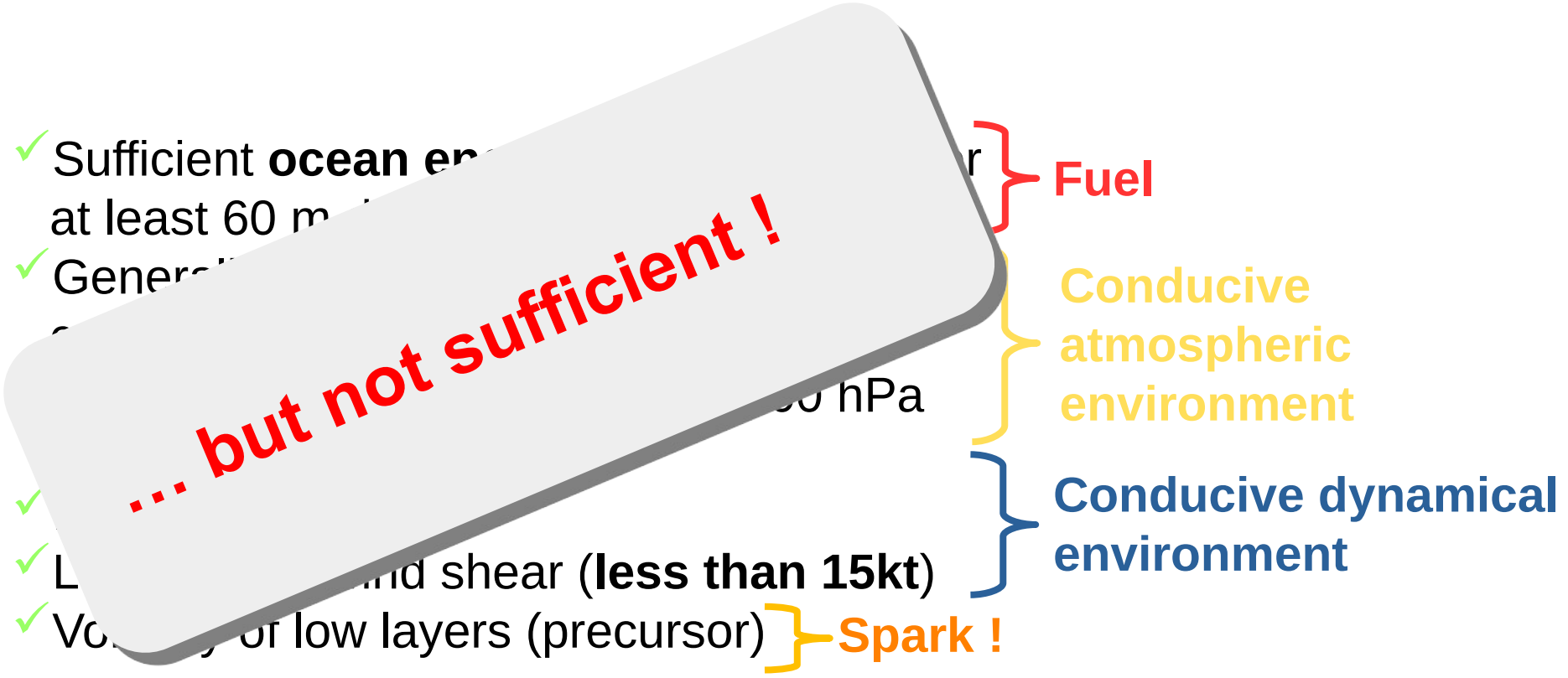

Cyclogenesis : basic concepts

TABLE 4. Average TCC density and genesis productivity by ocean basin (1982–2009). Values for the Indian Ocean basin (i.e., North Indian and South Indian regions) are only for the 1998–2009 period. The boldface indicates a higher than global value in Table 2 because the 1982–97 period is included.

Region	Density (TCC × 10^{-6} km^{-2} yr^{-1})	Genesis productivity (%)
North Atlantic	9.02	6.0
South Atlantic	2.57	0.1
Western Pacific	10.95	12.4
Eastern Pacific	11.47	6.0
South Pacific	6.59	3.8
North Indian	10.51	7.0
South Indian	5.93	8.5
Global	7.69	**7.1**

Hennon et al, 2012

Fraction of persistent convective clusters (>24hrs) that resulted in cyclogenesis

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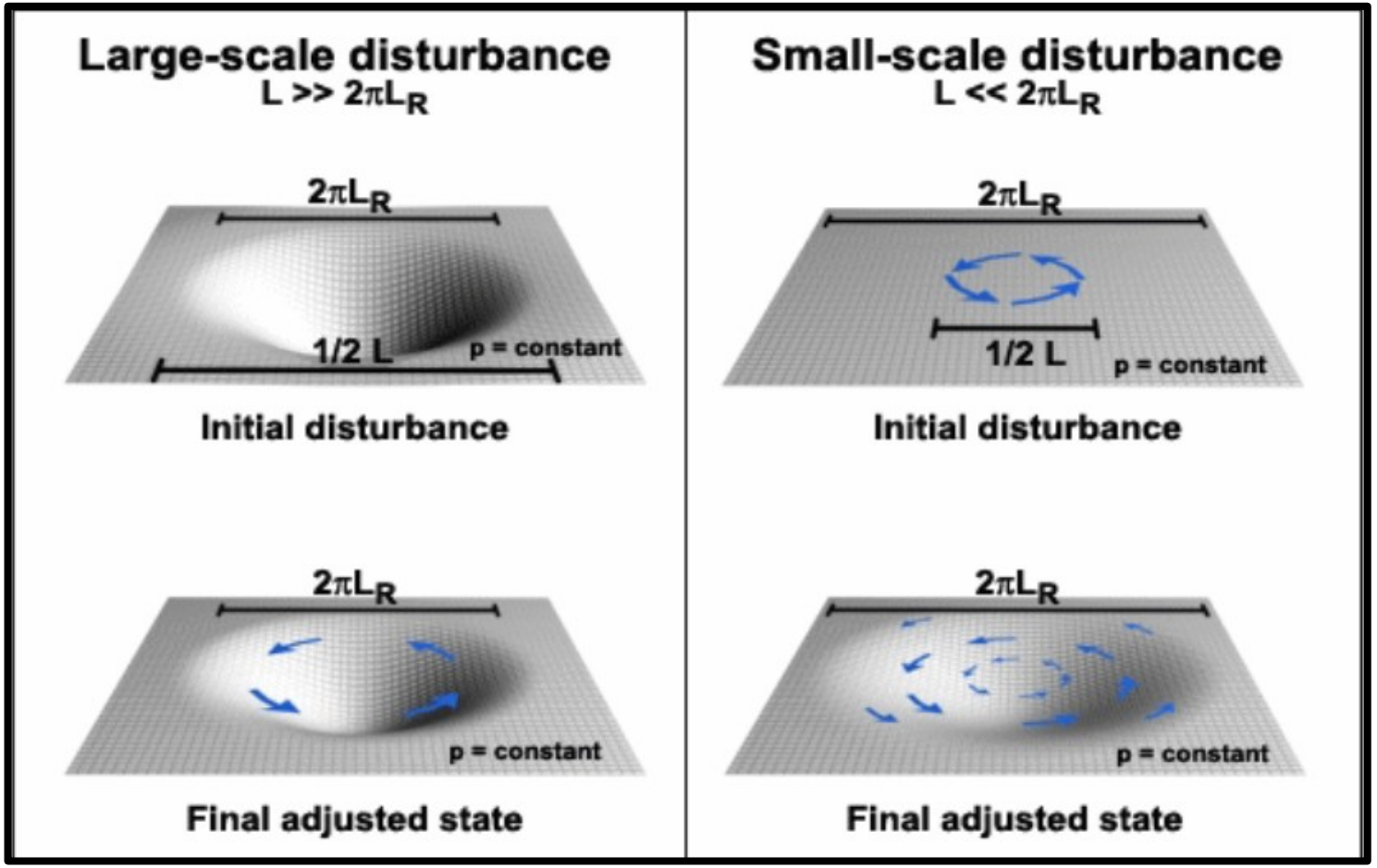
Why do we need a precursor :
The Rossby radius of deformation L_R

$$L_R = \frac{N.H}{f+\xi}$$

Buoyancy / Gravity waves

Rotational effects

N, *Brunt Vaïsäla freq.*
H, *vertical depth*
f, *Coriolis parameter*
ξ, *relative vorticity*



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→ Defines the critical horizontal dimension beyond which a perturbation will result in a significant change in the wind and pressure fields (through geostrophic adjustment).

→ In the tropics, L_R is, by nature, very large (> 10 000 km) since the Coriolis parameter (***f***) is low …

METEO FRANCE

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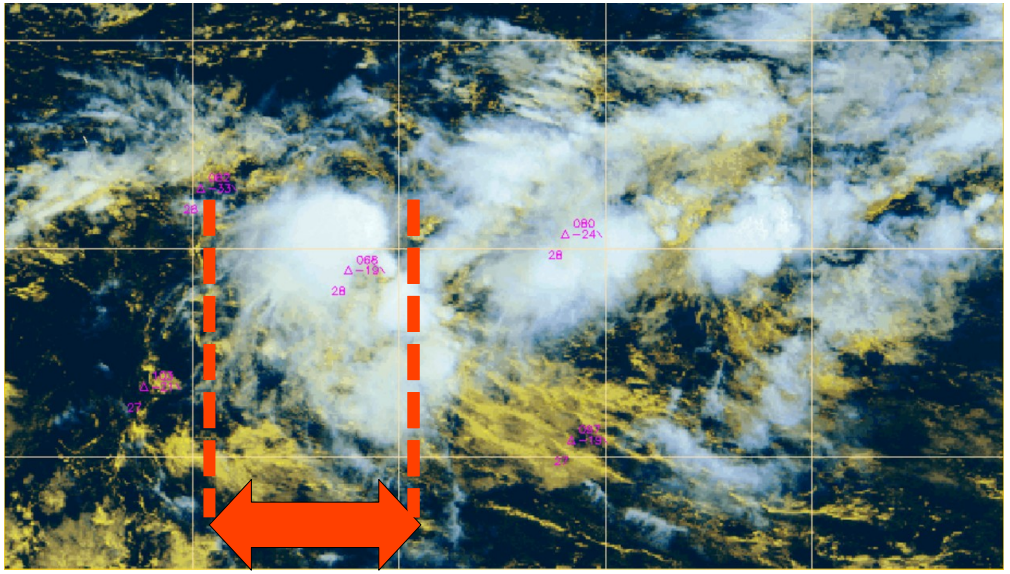
So we need a significant *ξ* to compensate the lack of *f* !

METEO FRANCE

- **Why do we need a precursor :**
  The Rossby radius of deformation L_R



$L < L_R$

Src : MF Archives

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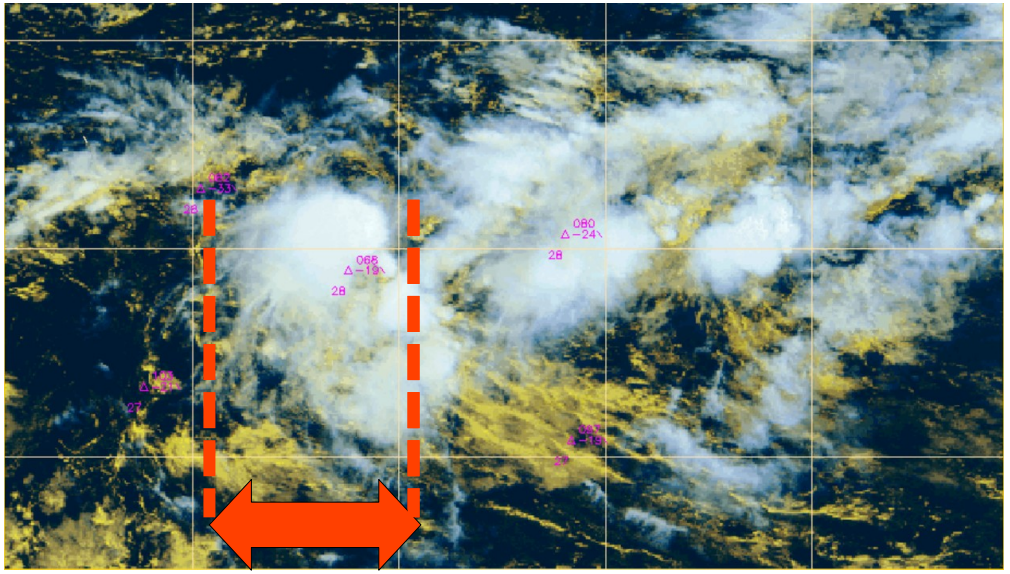

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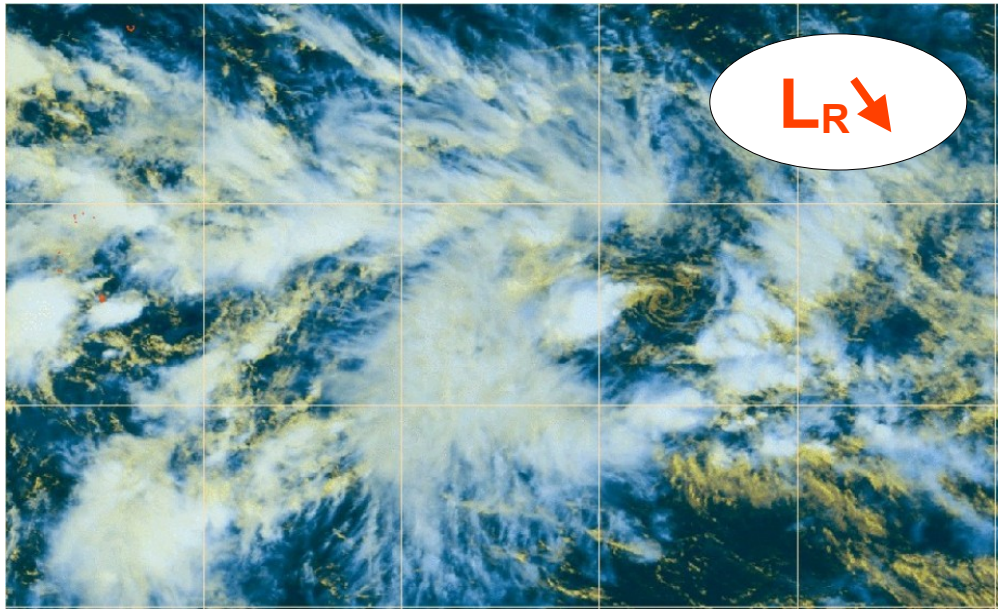

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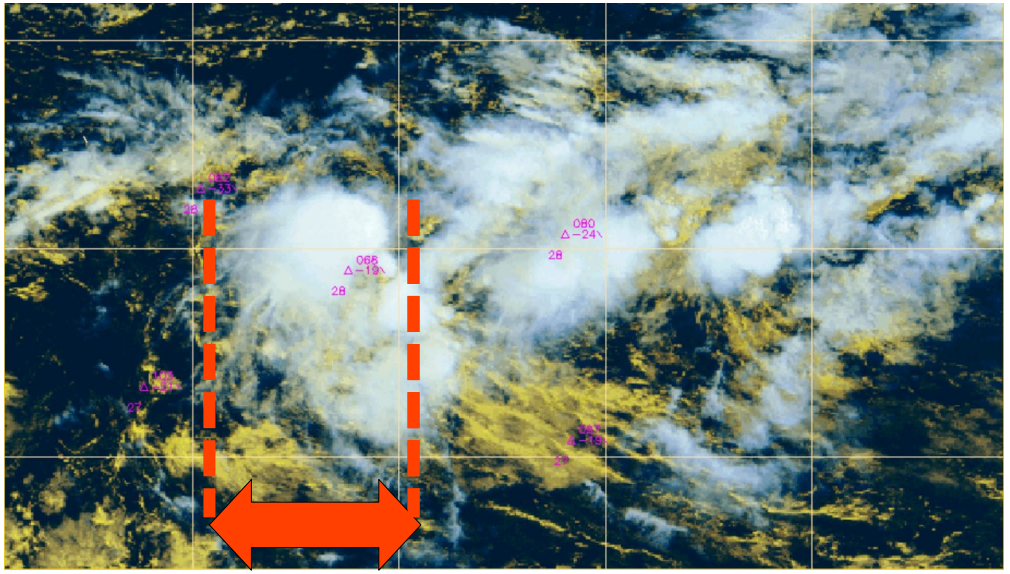

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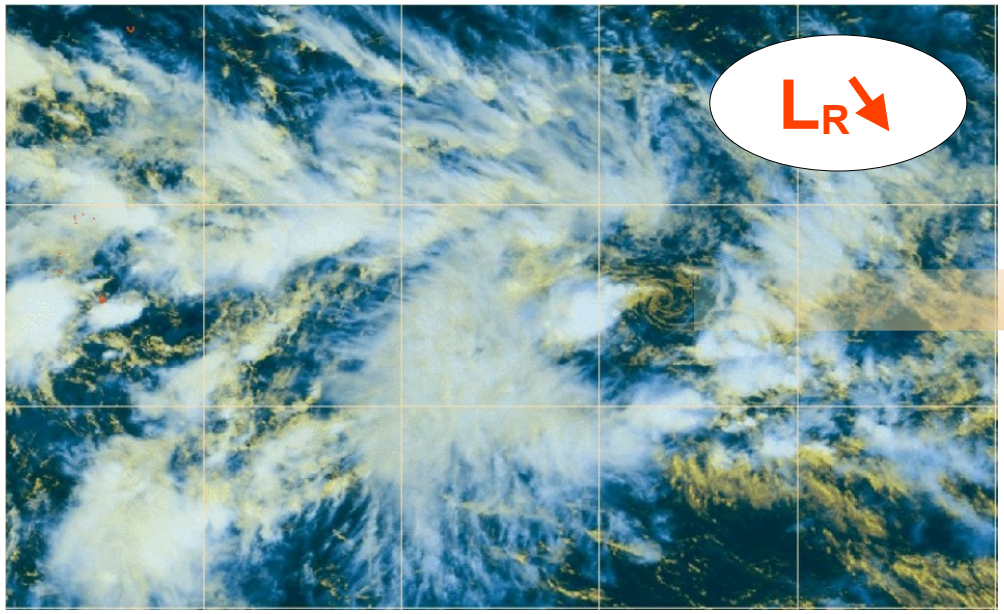

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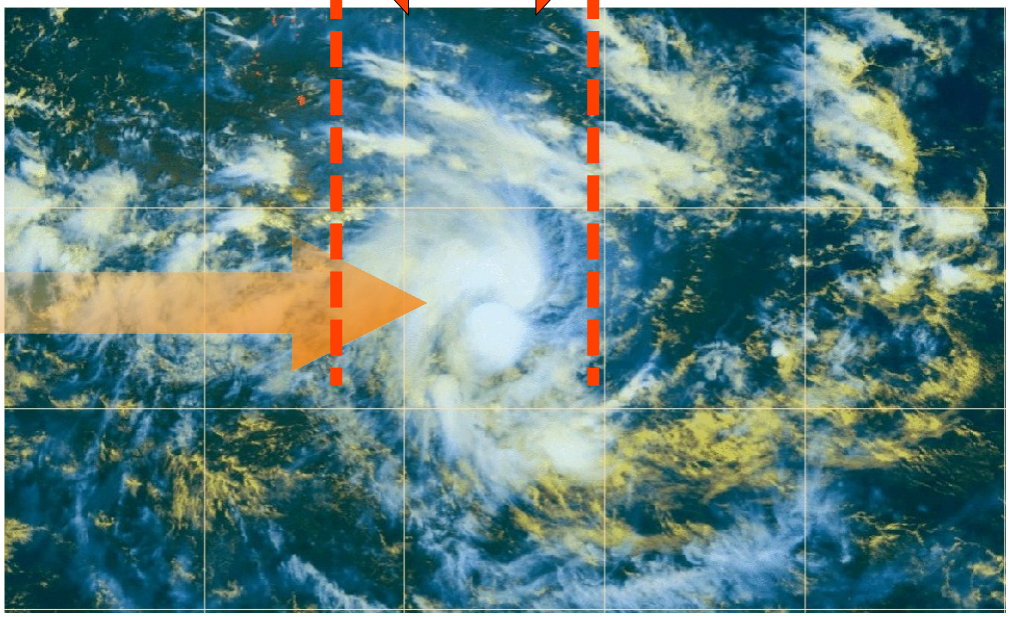
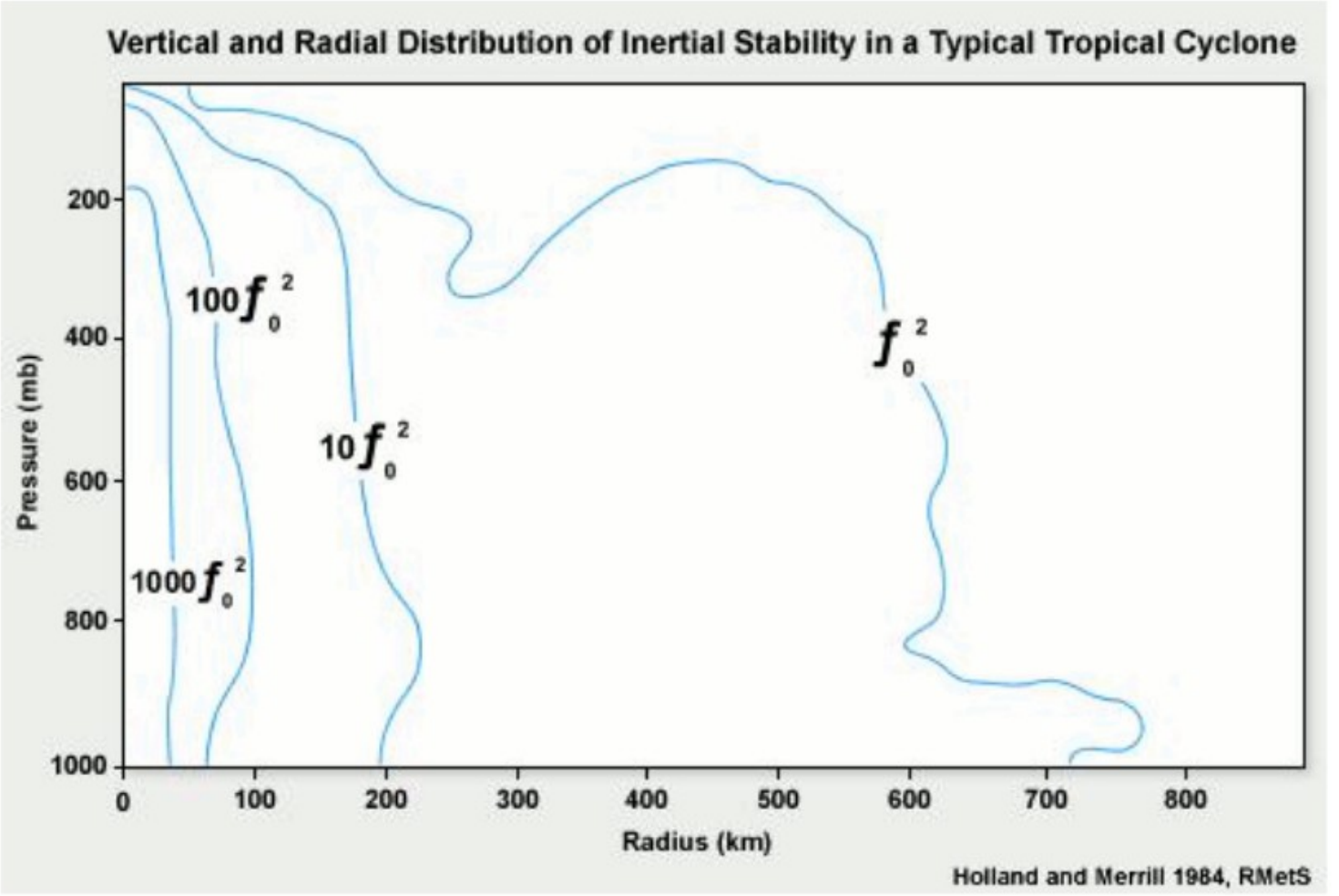


Cyclogenesis : the importance of vortex stability



Src : COMET Program

Figure 4.2. Vertical and radial distribution of the inertial stability in a typical tropical cyclone. To illustrate the contribution to inertial stability of the storm winds compared to its environment, the inertial stability values have been scaled by *f0*, the value of the Coriolis parameter at the storm center. Figure adapted by COMET from Holland and Merrill (1984) and obtained from http://www.meted.ucar.edu/tropical/textbook/ch10/tropcyclone_10_2_2_2.html.

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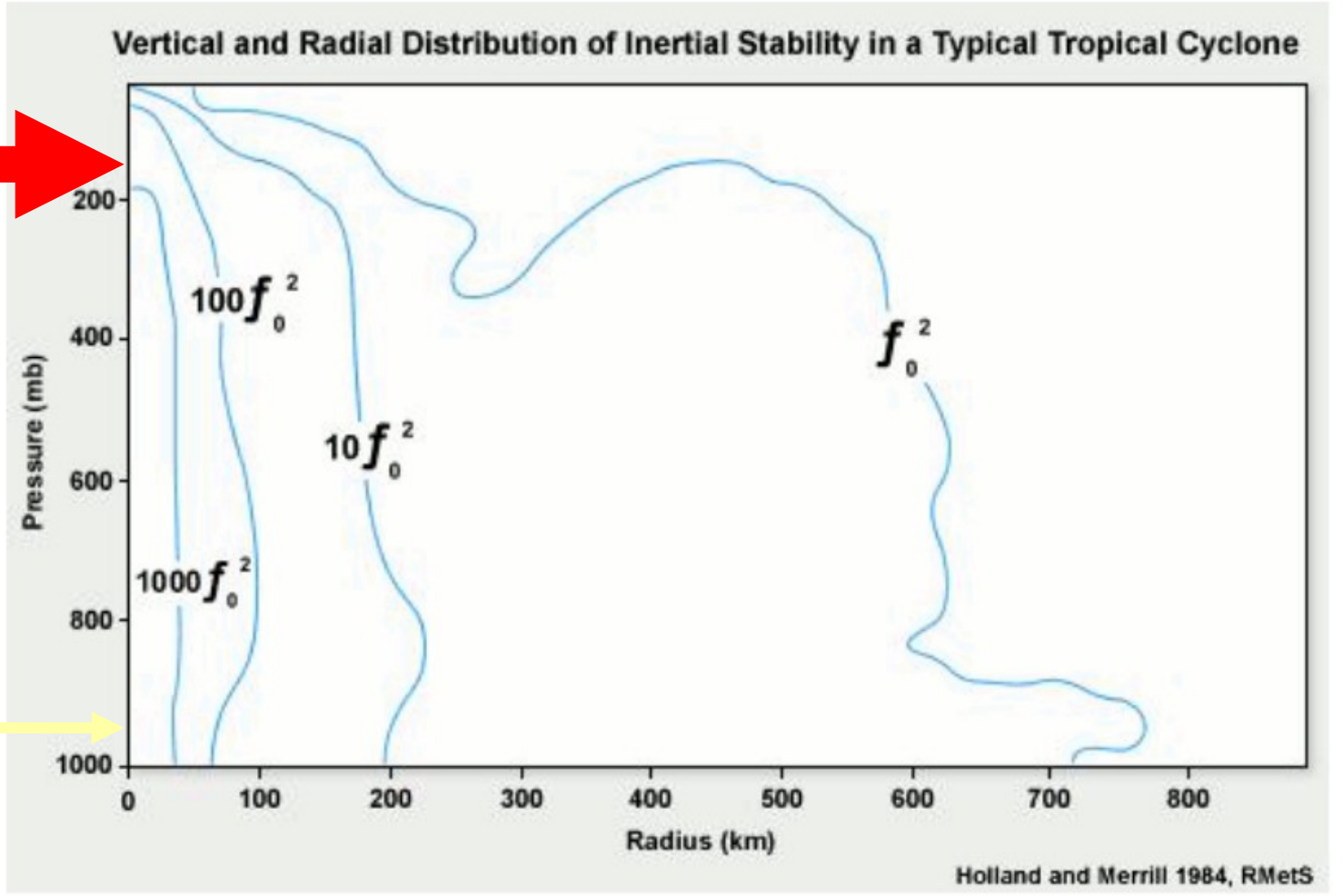

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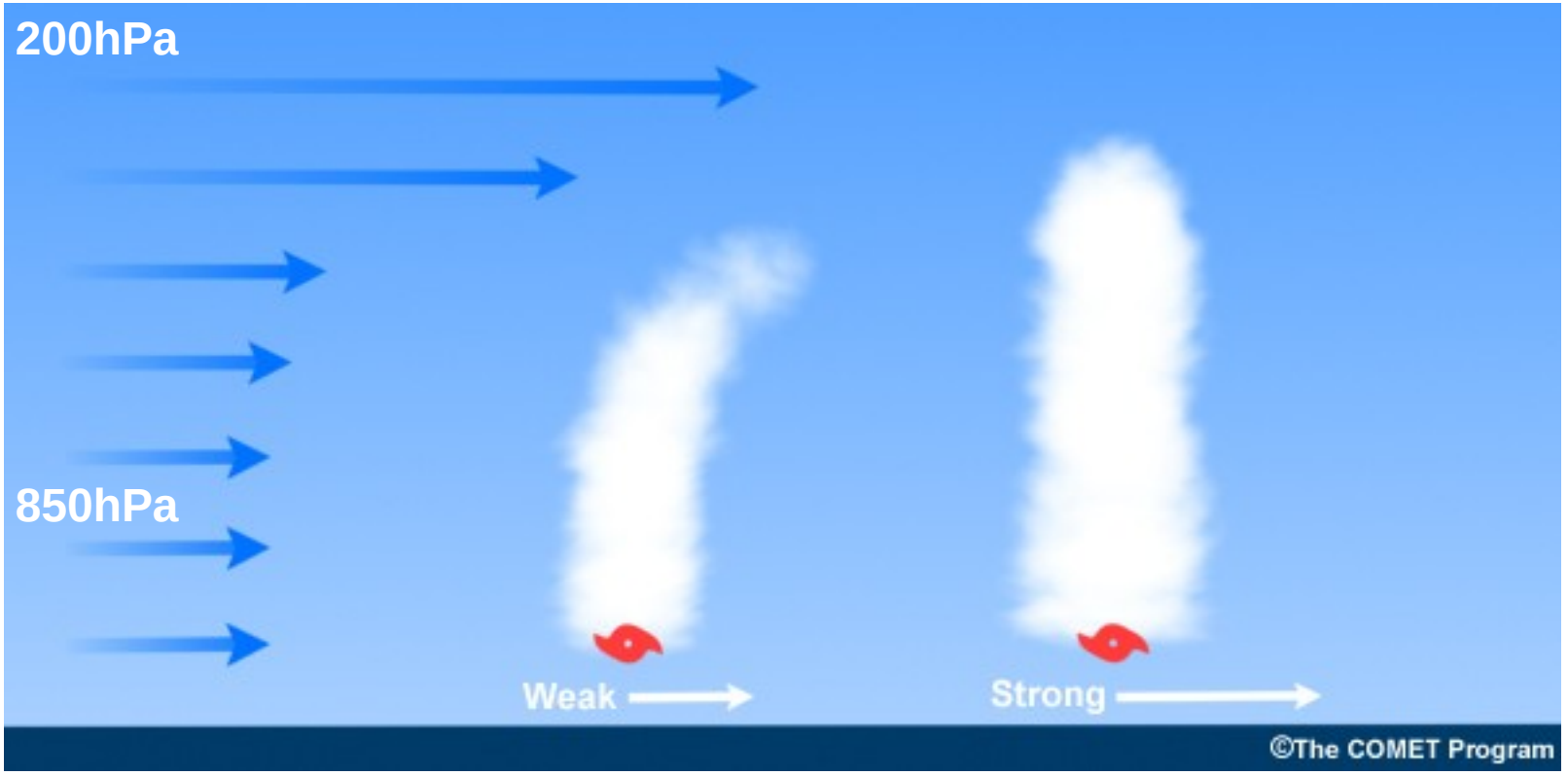
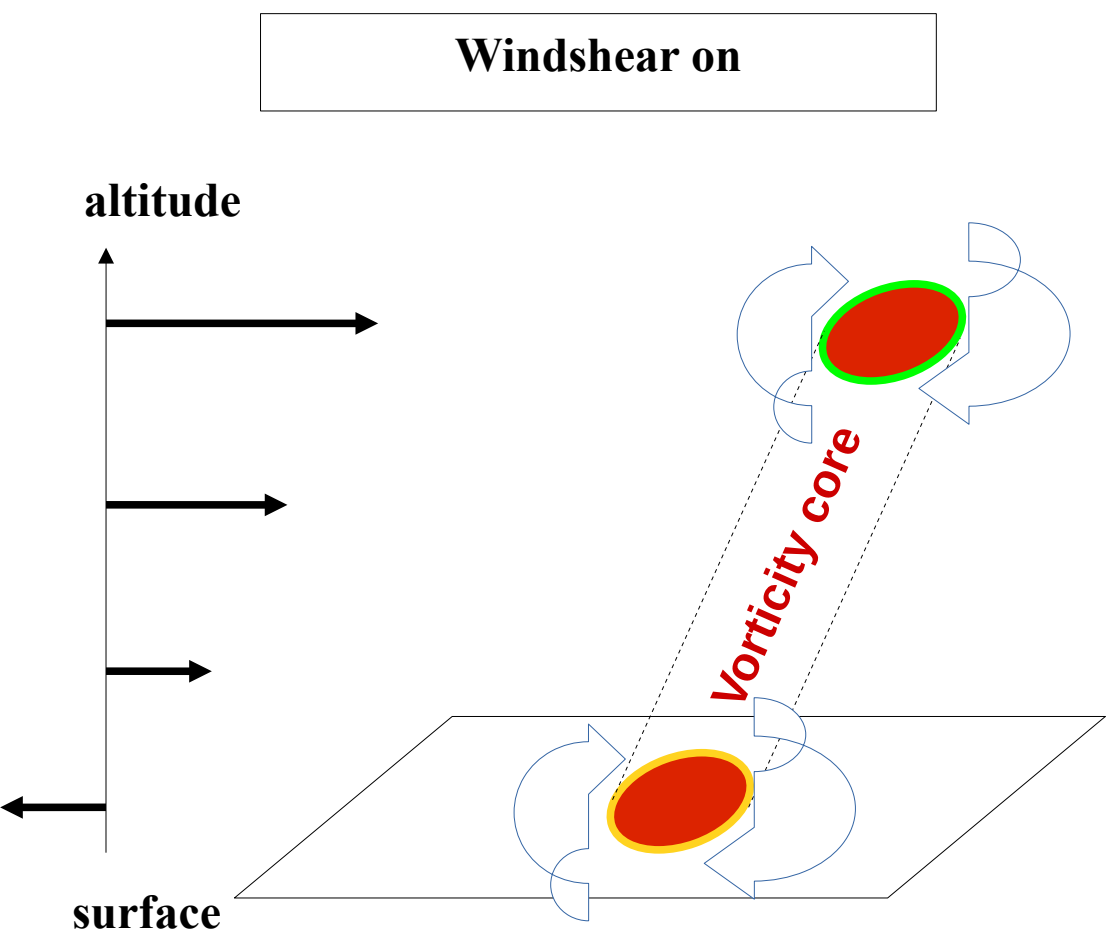
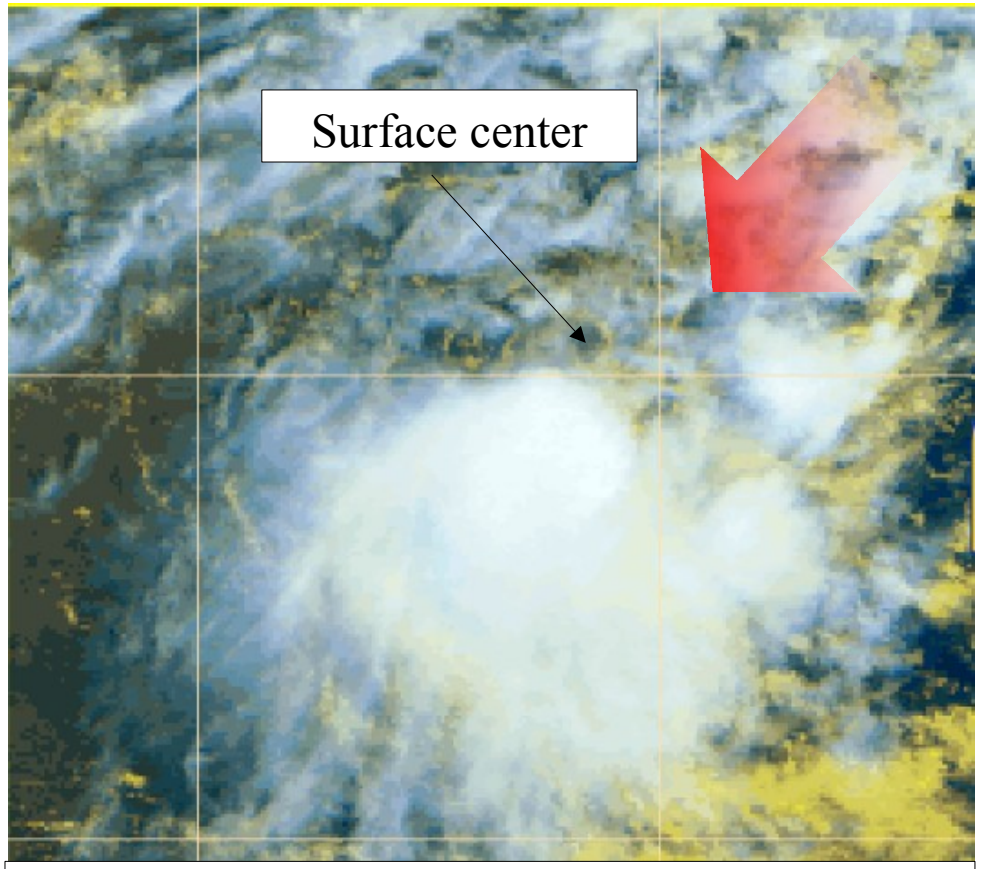


Src : COMET Program

• The windshear in the cyclogenesis process

Src : MF Archives





Laborious cyclogenesis under Northeasterly shear conditions

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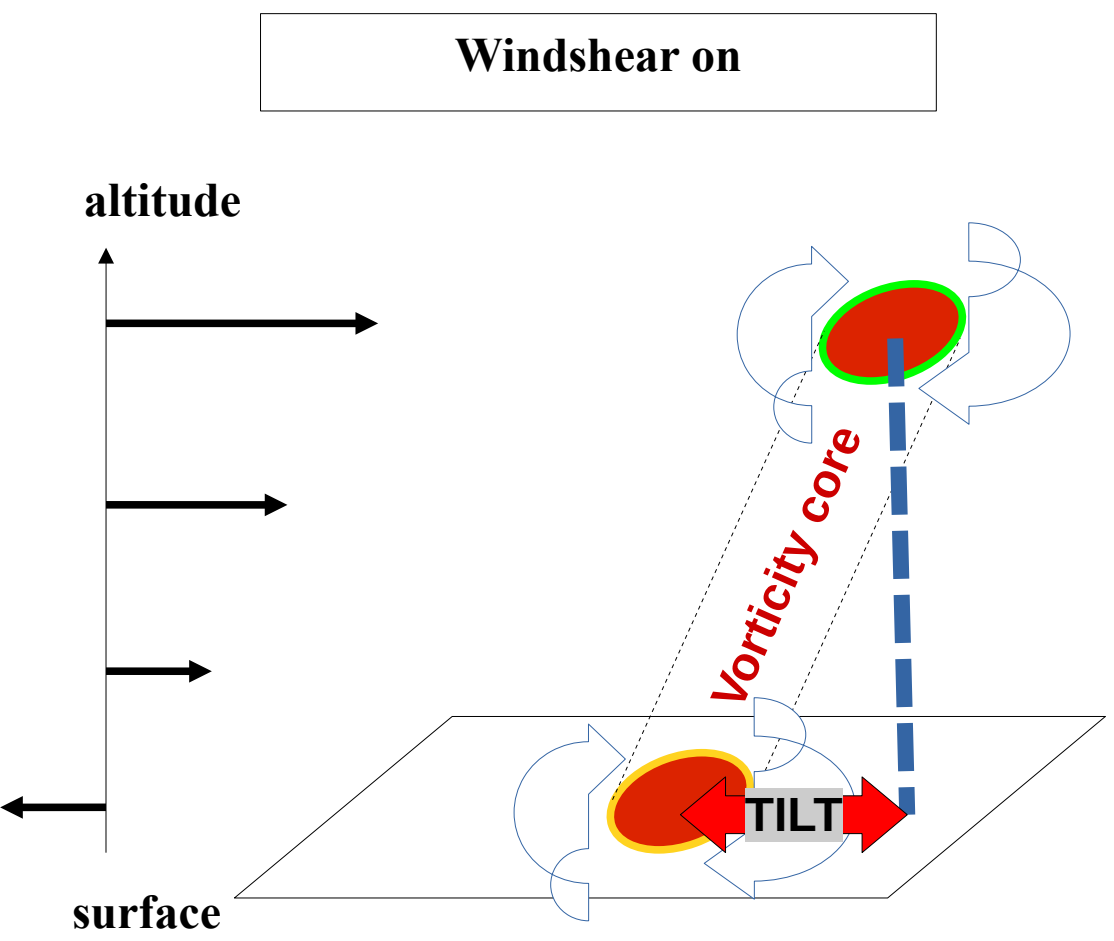
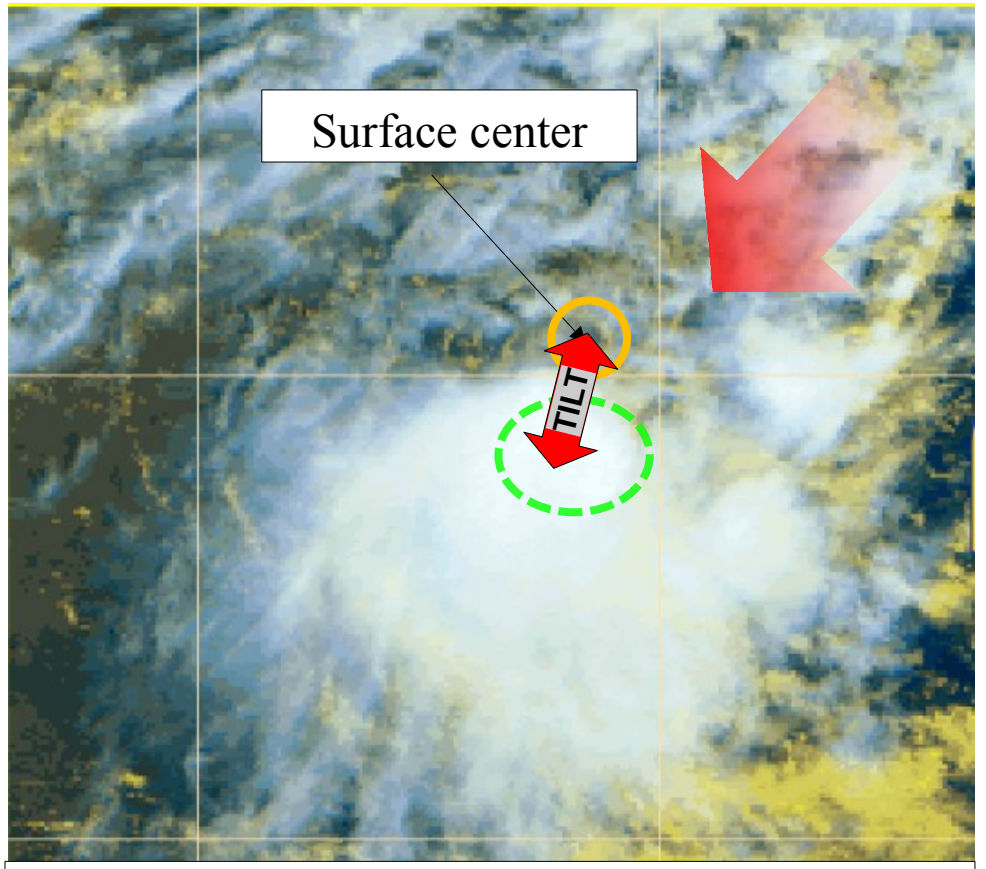




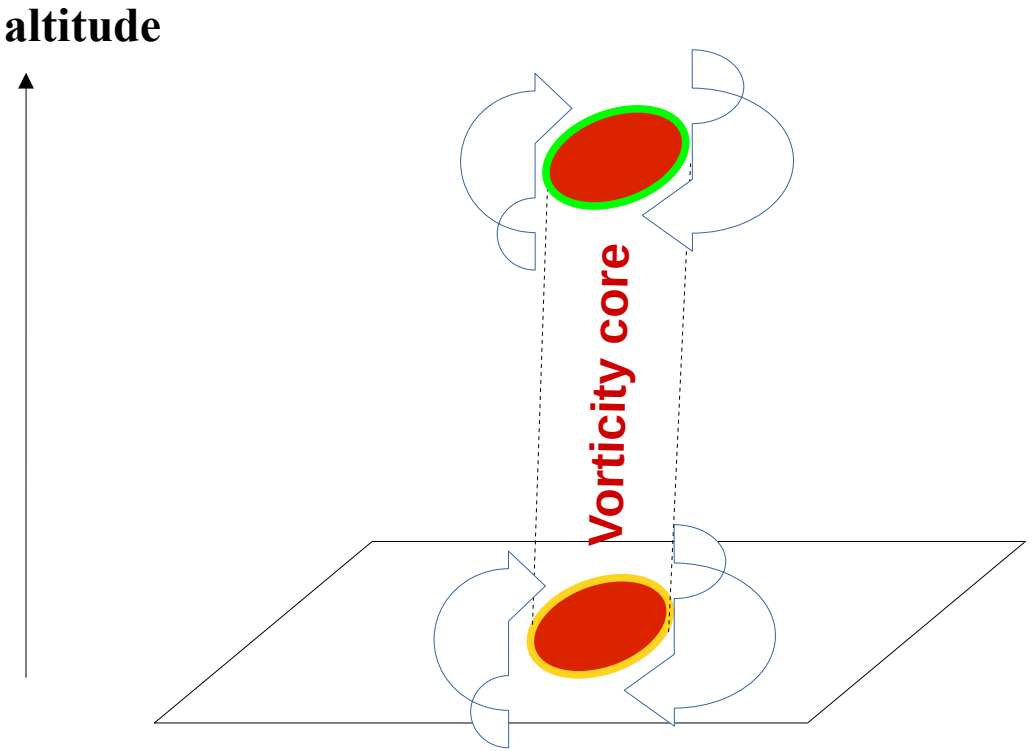
Laborious cyclogenesis under Northeasterly shear conditions

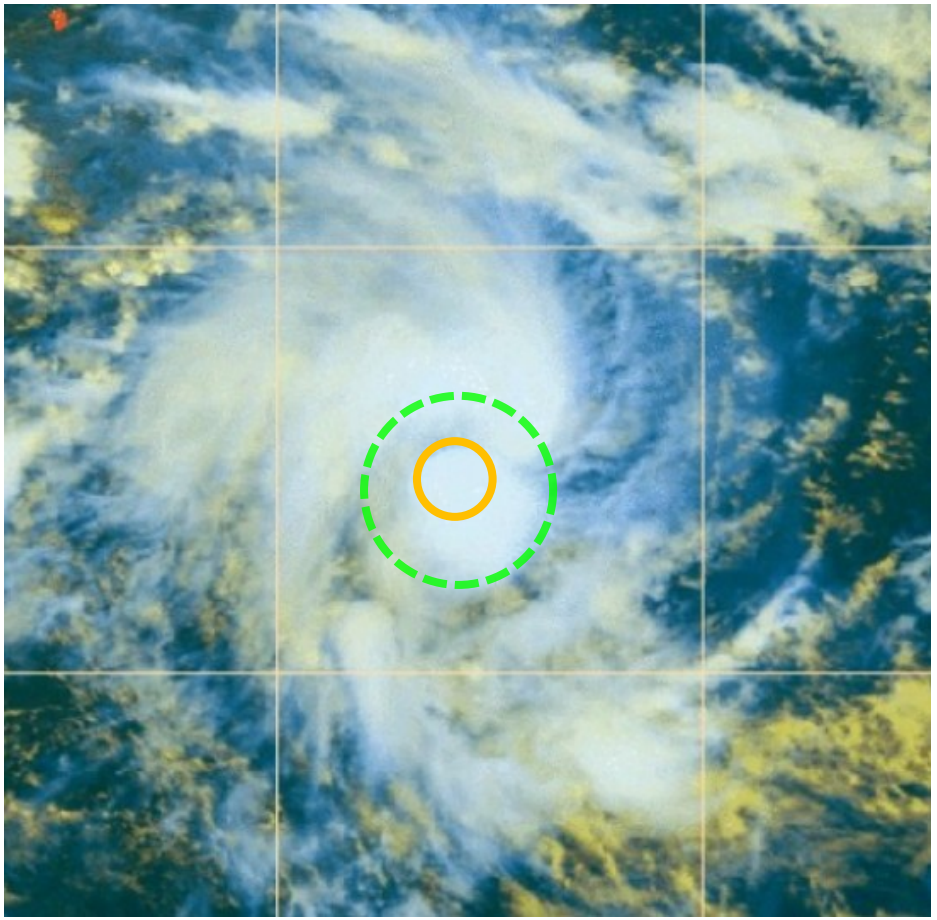
→ Misaligned low and mid-levels vortices can slow down or even impede the TCG process

• The windshear in the cyclogenesis process

Src : MF Archives

Windshear off





→ When low and mid-levels vortices finally align (through strong convective bursts and/or weakening of the shear constraint), TCG occurs.

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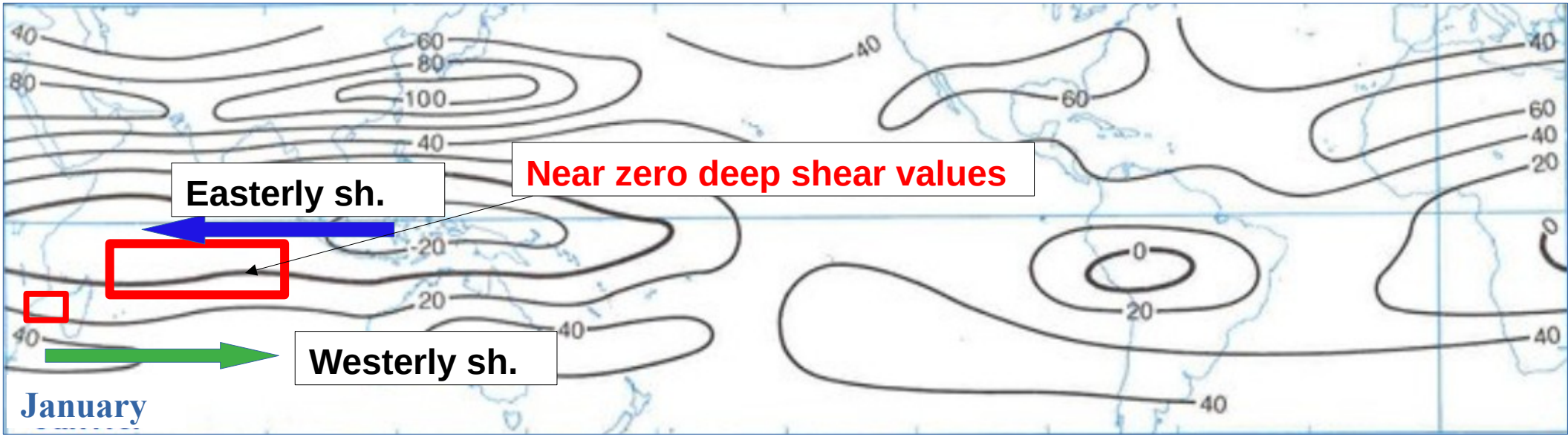
The windshear in the cyclogenesis process

Src : MF Archives

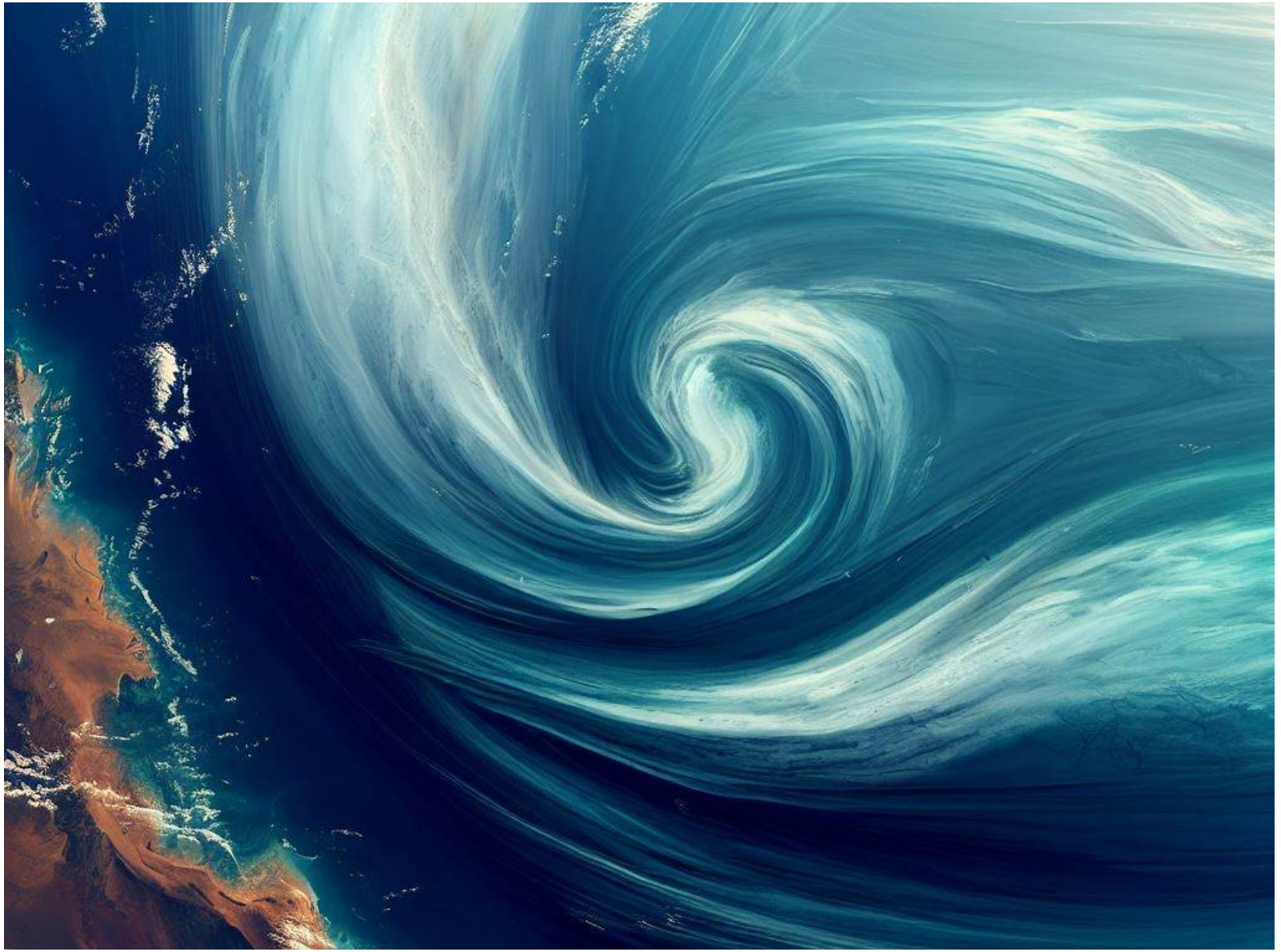


January climatology of the zonal component of the deep shear: U200 - U850 (in kt)

→ Weak vertical wind shear (< 20 kt) is observed within the SWIO development zones (especially for the cyclogenesis zone in the central Indian Ocean - this is less true for the secondary zone of the Mozambique Channel)

Tropical cyclogenesis

Basins configurations



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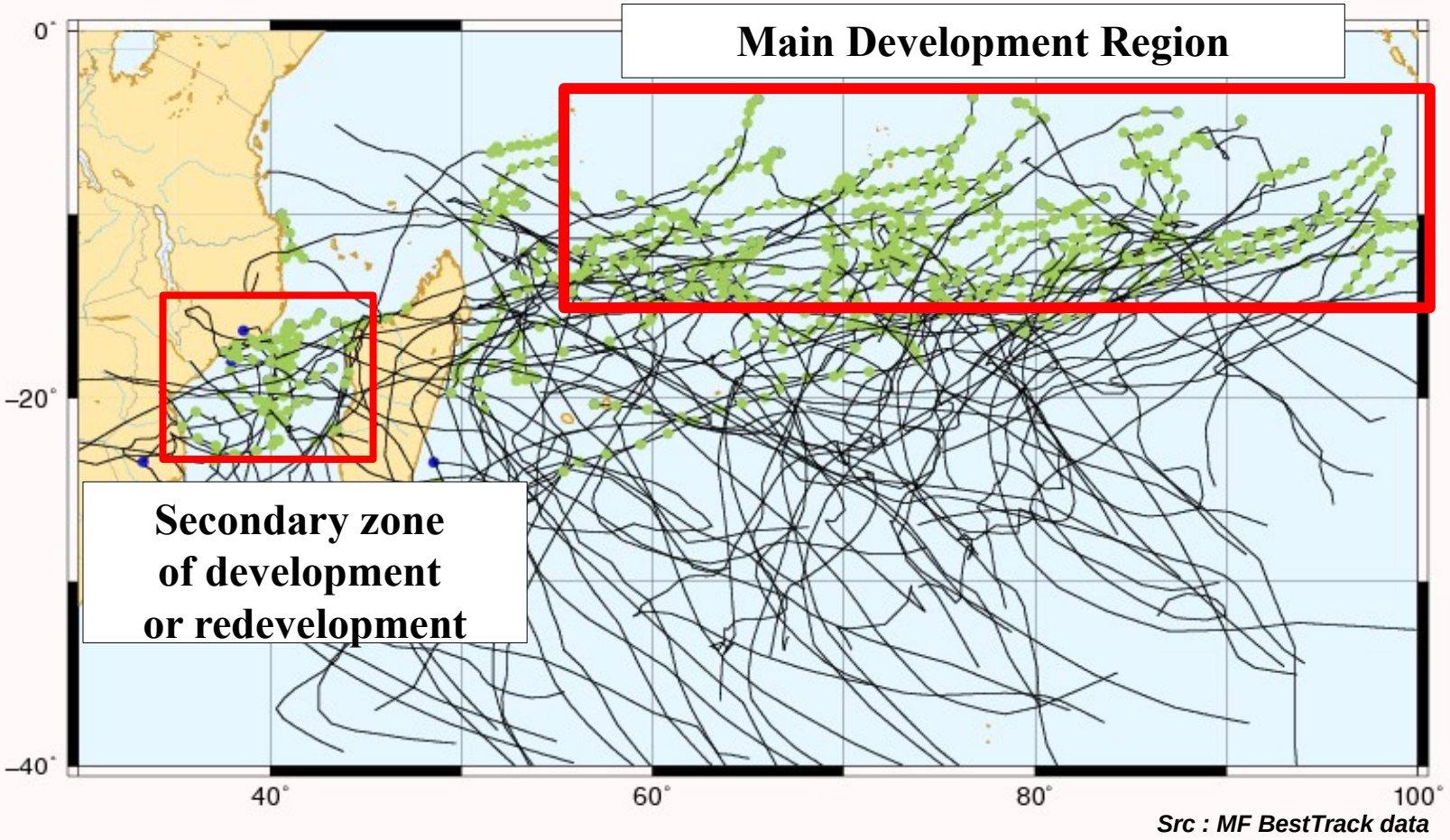
Location of cyclogenesis processes on the SWIO (2010/2011-2020/2021)

In green, portions of tracks before the tropical storm stage



10°S ± 5°

- **Basin pattern / Bassin configuration**

Definition : Seasonal and specific low levels wind patterns over the tropical ocean. They are observed on a monthly timescale.

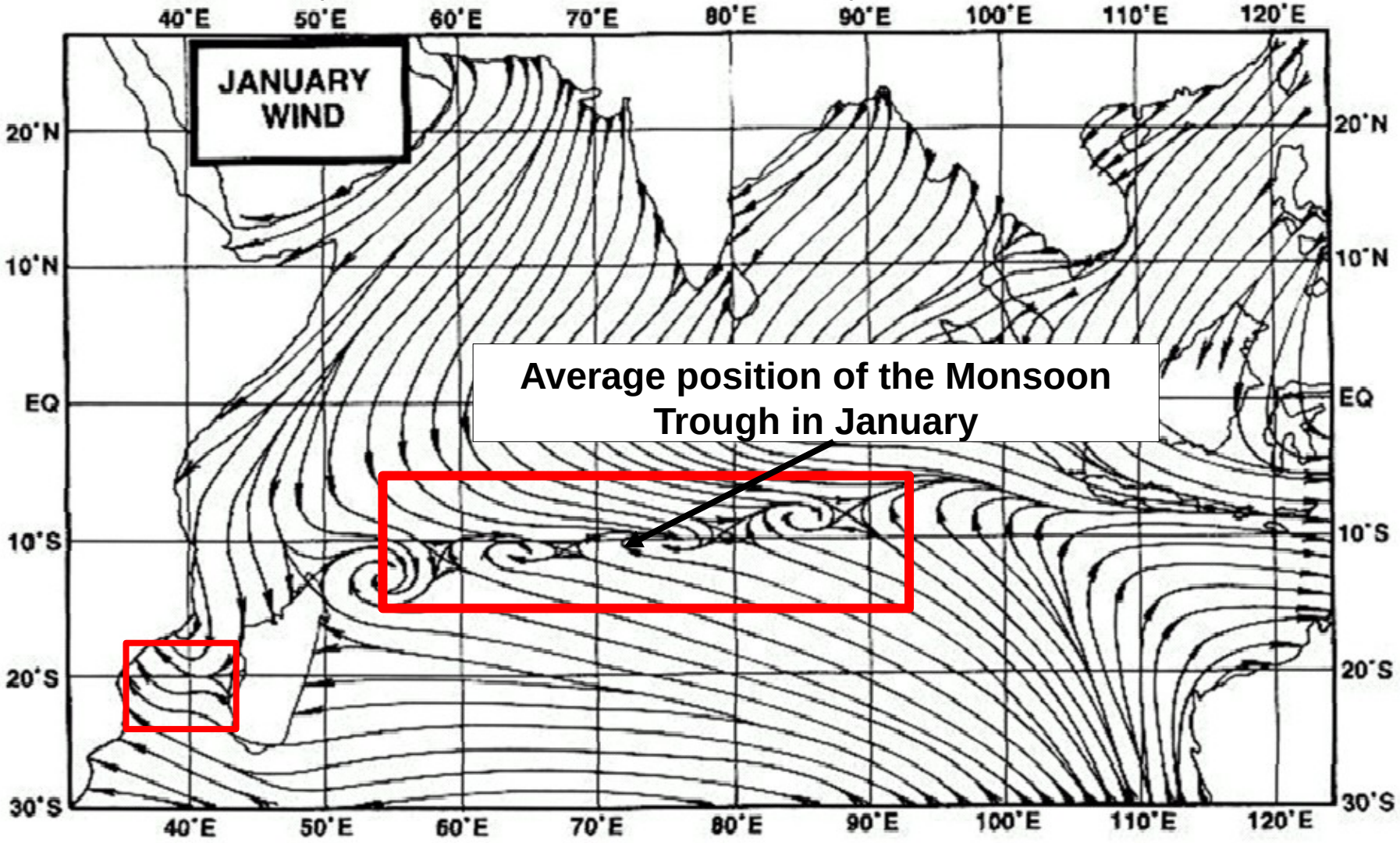


Figure 2.6. Mean surface level streamline analyses over the Indian Ocean for January (Sadler, 1975).

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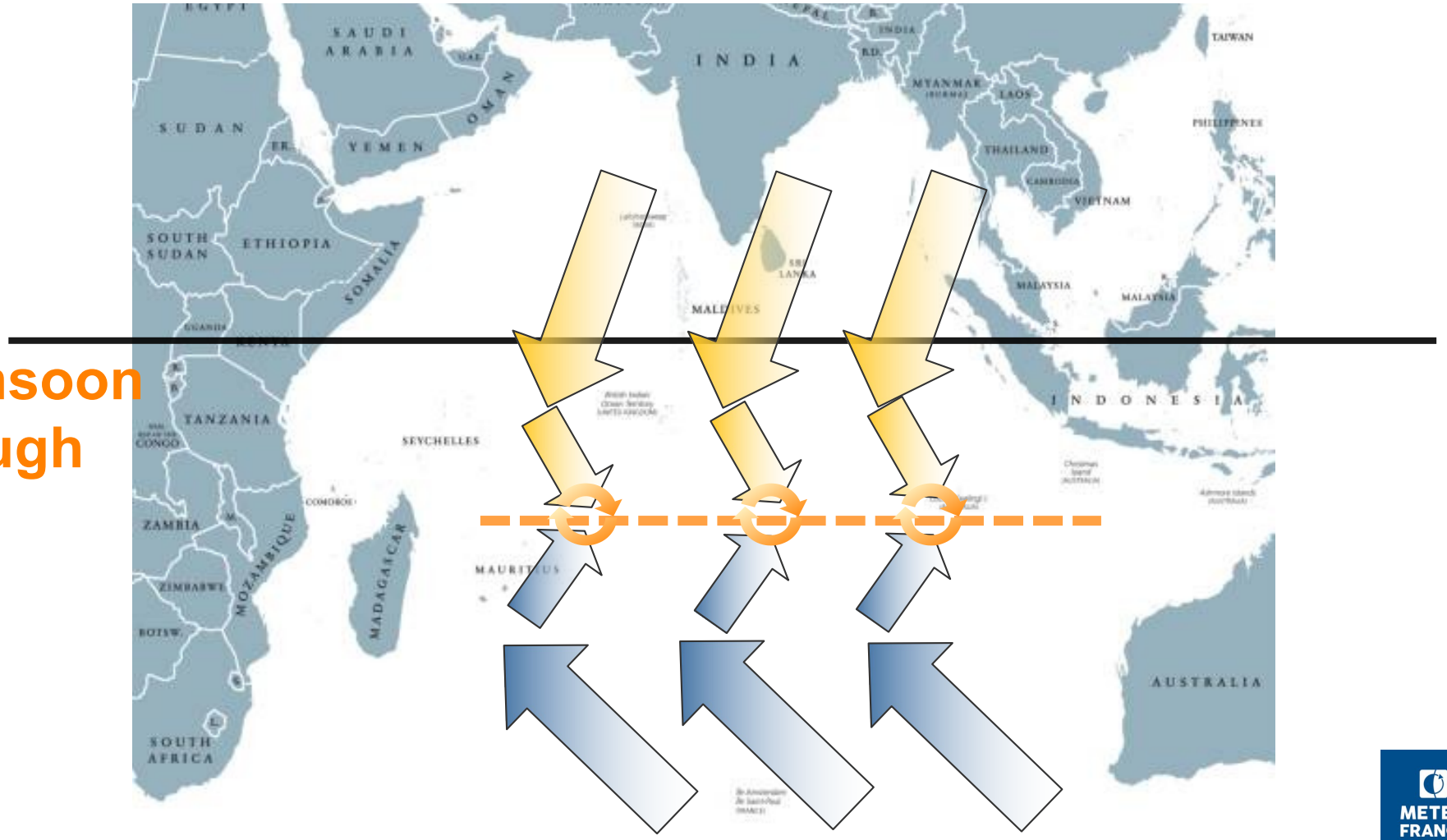
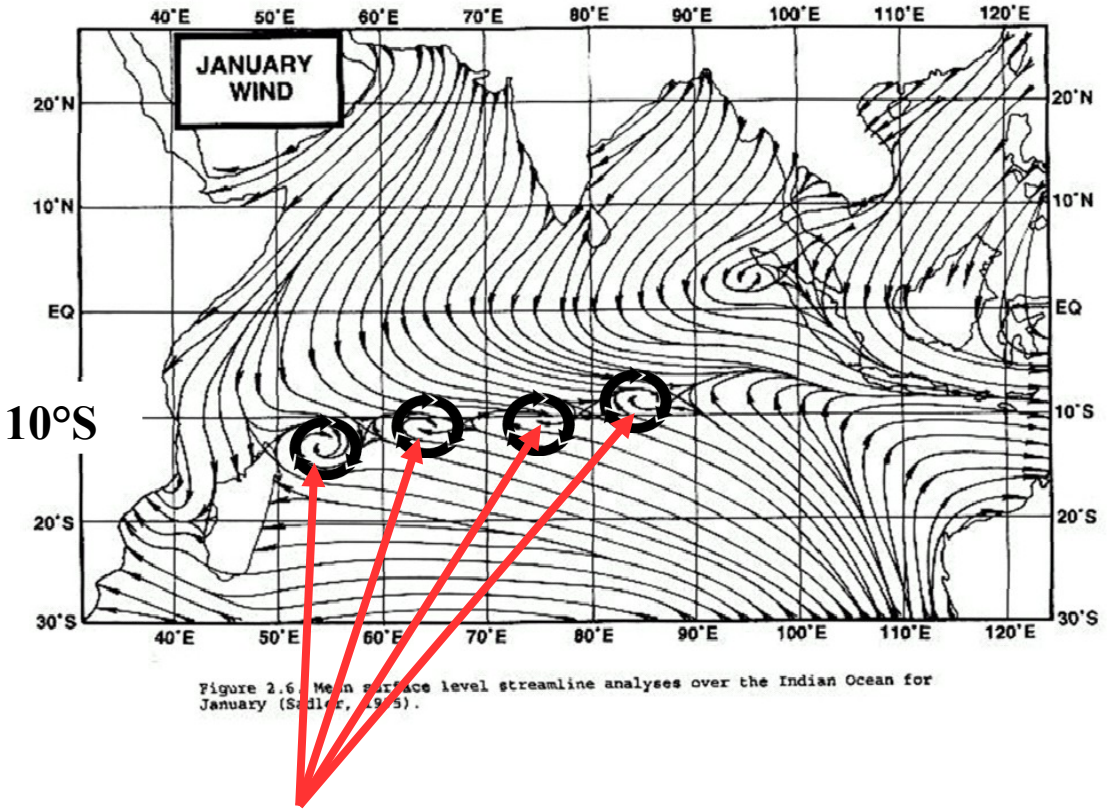


- **Basin Configuration**
  Conceptual model of the Monsoon Trough (MT)



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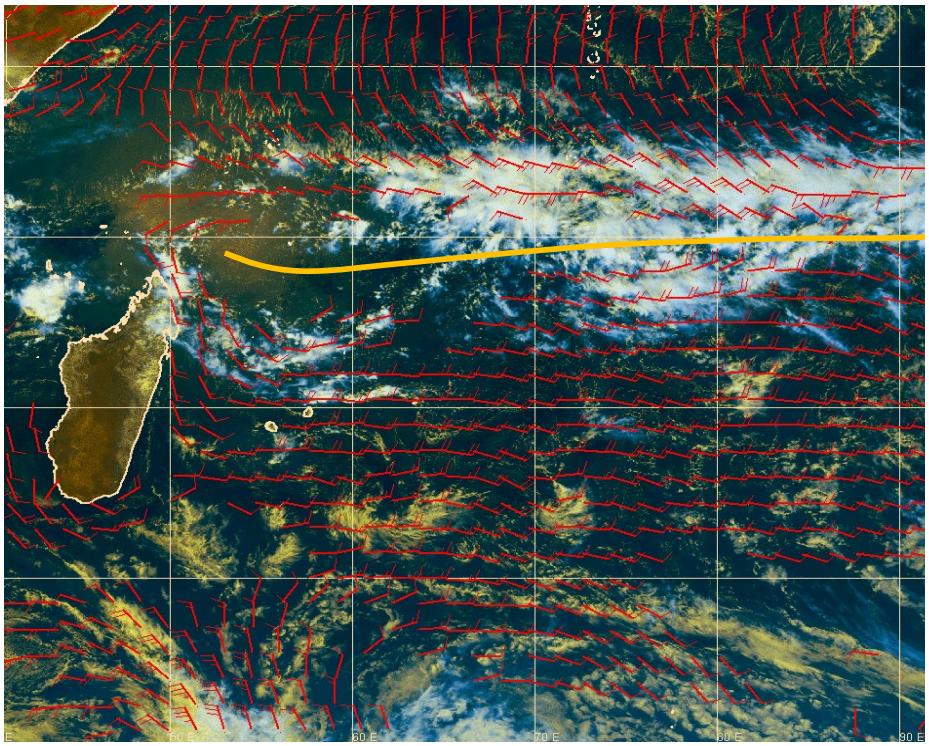
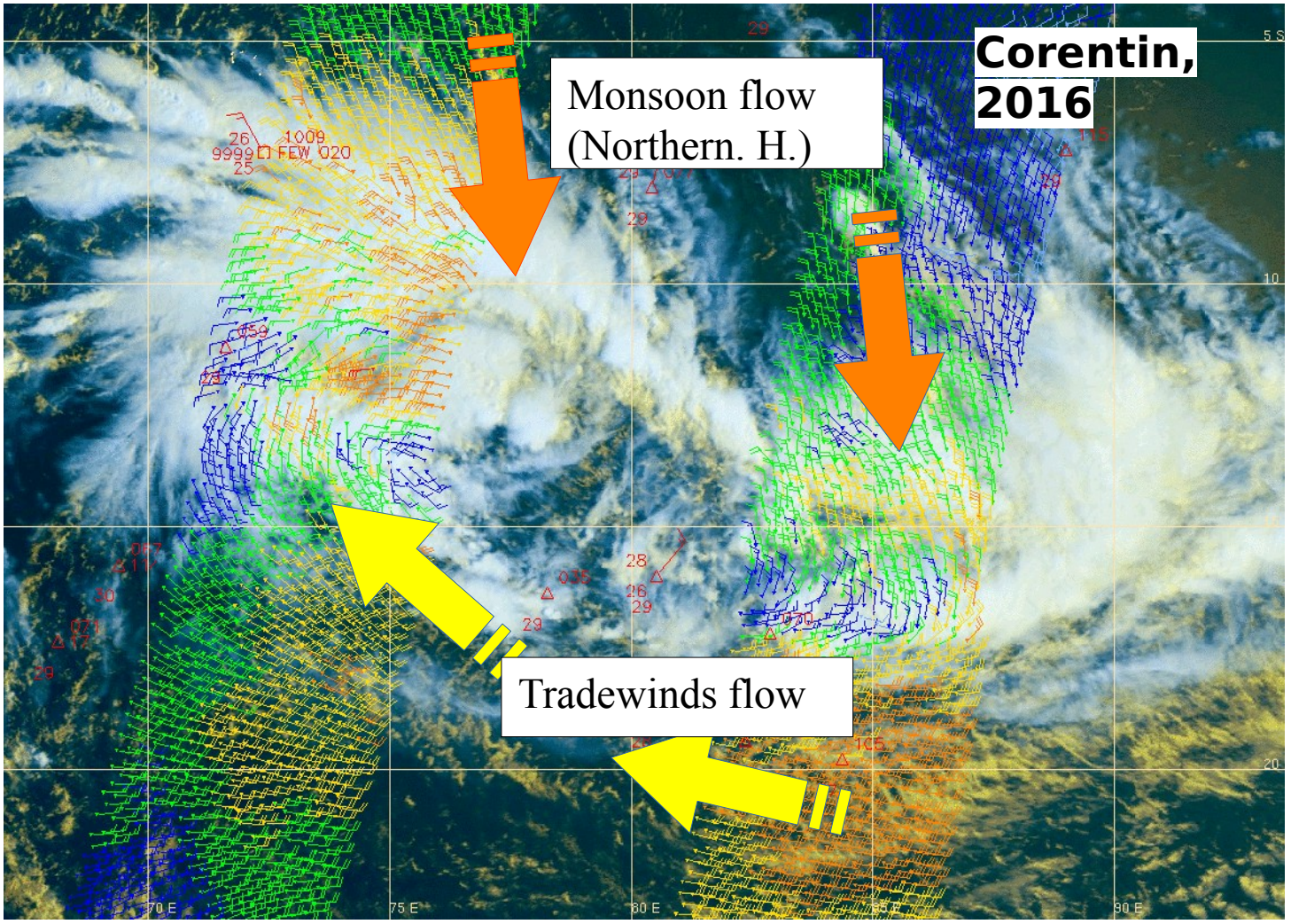


Strongly enhance low levels vorticity in the Monsoon Trough. This is the most common configuration for the heart of the season (~ January to March).

METEO FRANCE

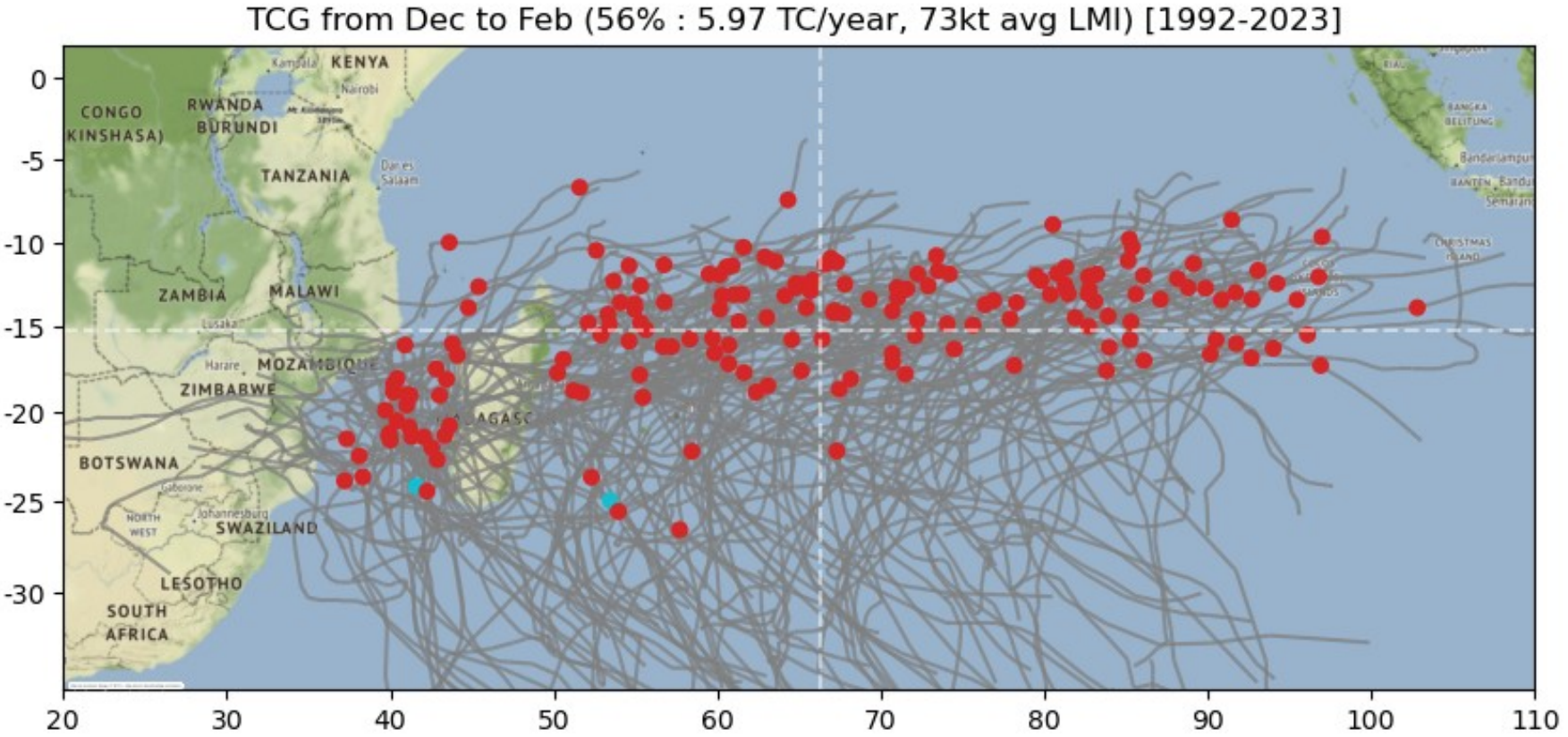
- **The dynamics of the Monsoon trough, a synoptic or supra-synoptic low-level forcing**

Src : MF Archives



Renforcement de la convergence entre les flux de moussons et d'alizés

- **Basin pattern / Bassin configuration**



TCG locations in **Red** (first point with intensity of a Moderate TS), in **Cyan** if Subtropical System.

Src : MF BestTrack Data

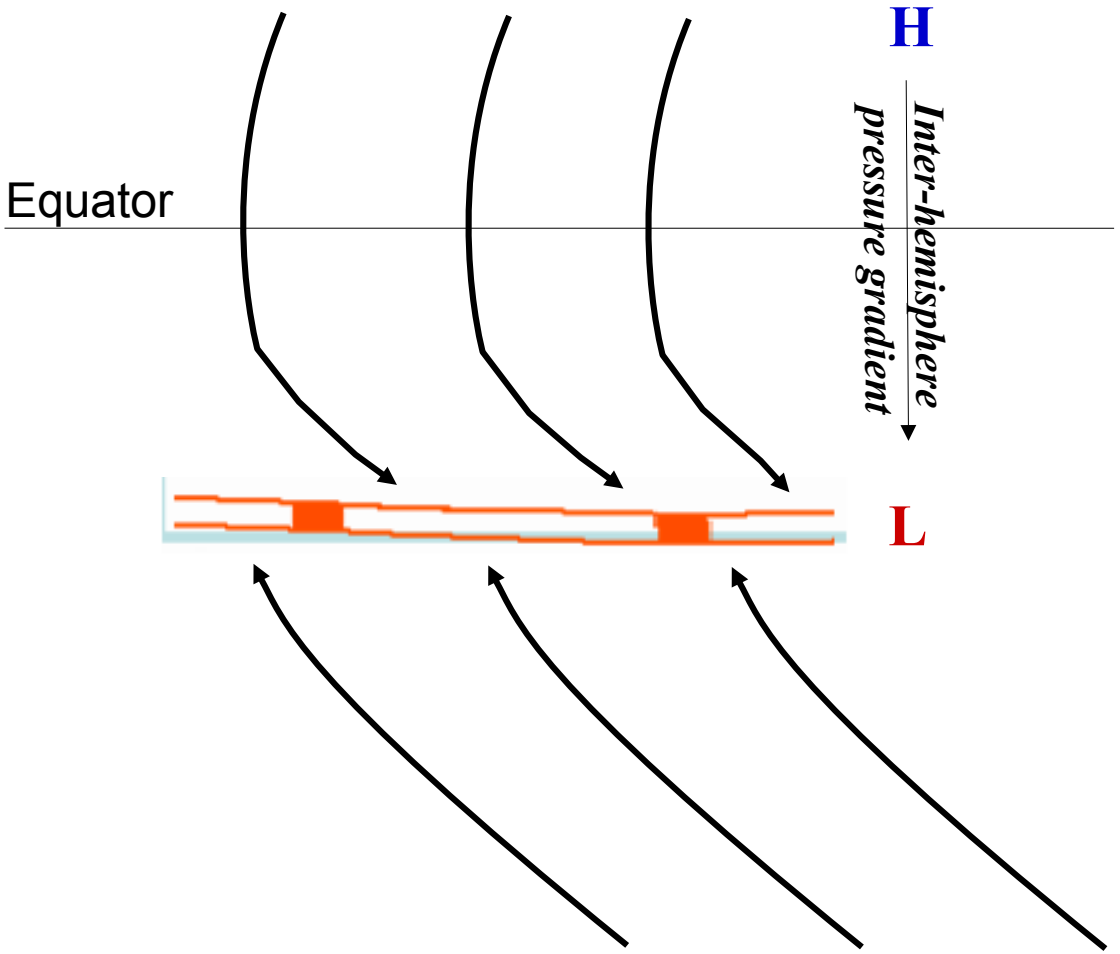
Associated tracks in **Grey**

Averaged lat and lons for the TCG of the sample shown by dotted white lines.

- **Basin Configuration**
  Conceptual model of the Monsoon Trough (MT)

Overseas MT

Definition : Low tropospheric trough located in the mixing zone between the monsoon flow and the trade wind flow. The winds on the equatorial side of this trough have a strong meridional component as they cross the equator.



- **From the surface up to 850 hPa**
- **Strongest vorticity** along the axis
- Large scale **moisture convergence**

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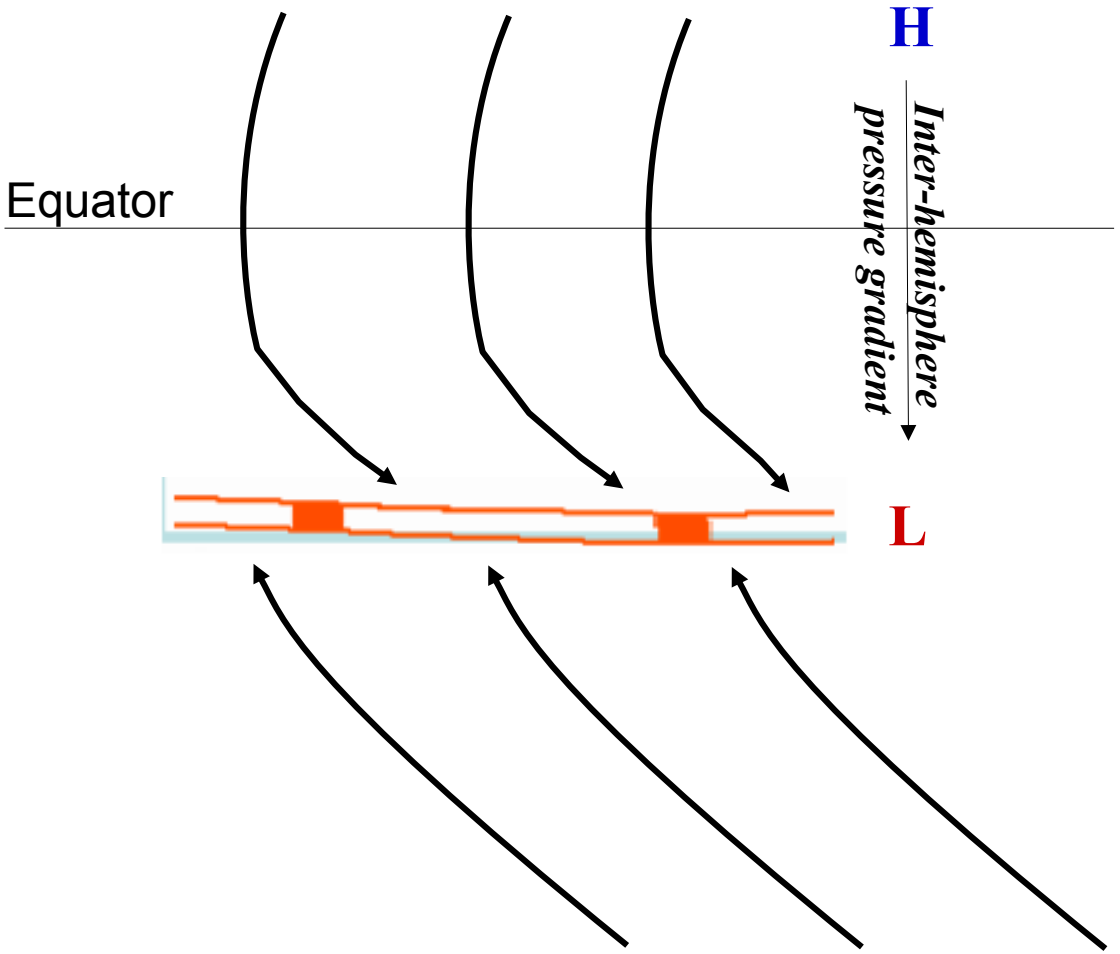

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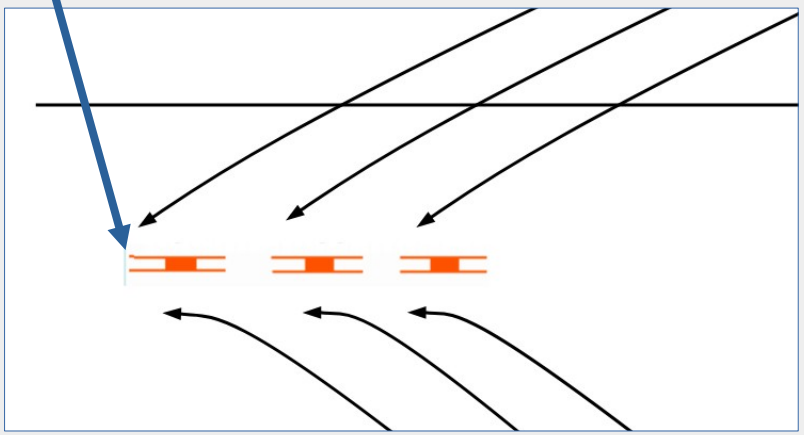
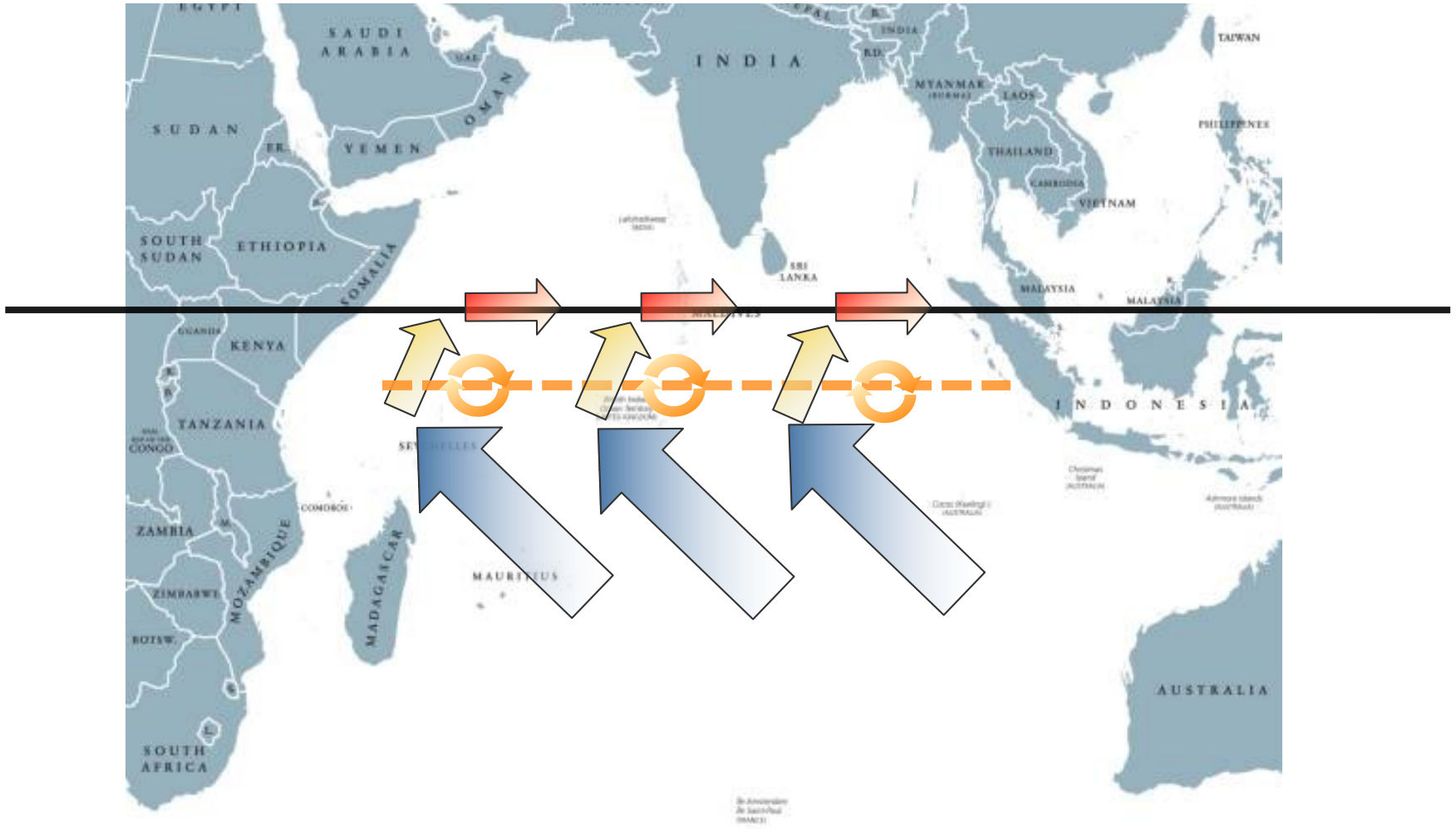
This is not a MT. This is the Tradewinds Meteorological Equator.



rface up to 850 hPa
rticity along the axis
noisture convergence

METEO FRANCE

- **Basin Configuration**
  Conceptual model of the Near Equatorial Trough (NET)



Definition : Low tropospheric trough with strong zonal winds on its equatorial side

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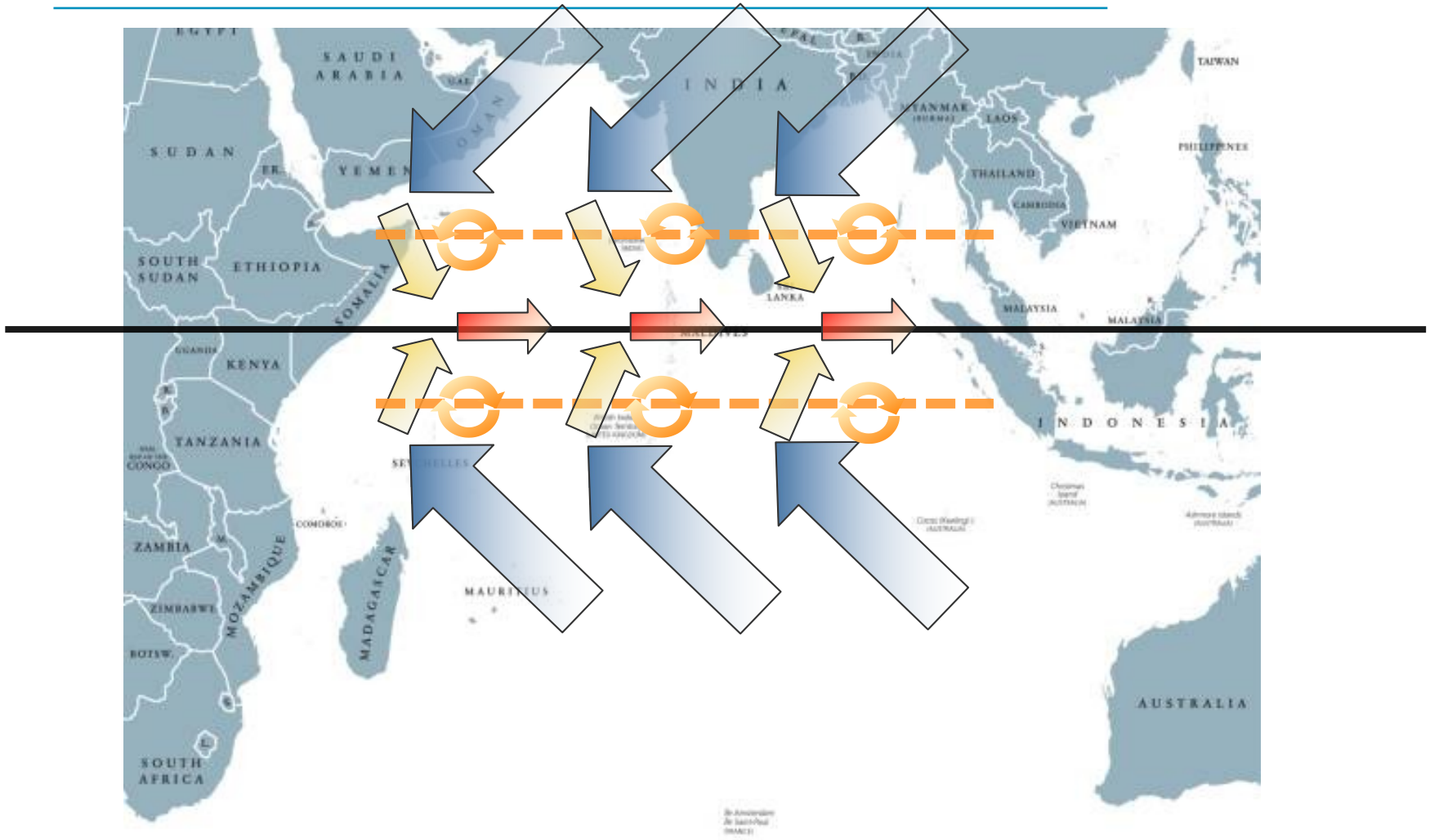
  Conceptual model of the Near Equatorial Trough (NET)



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METEO FRANCE

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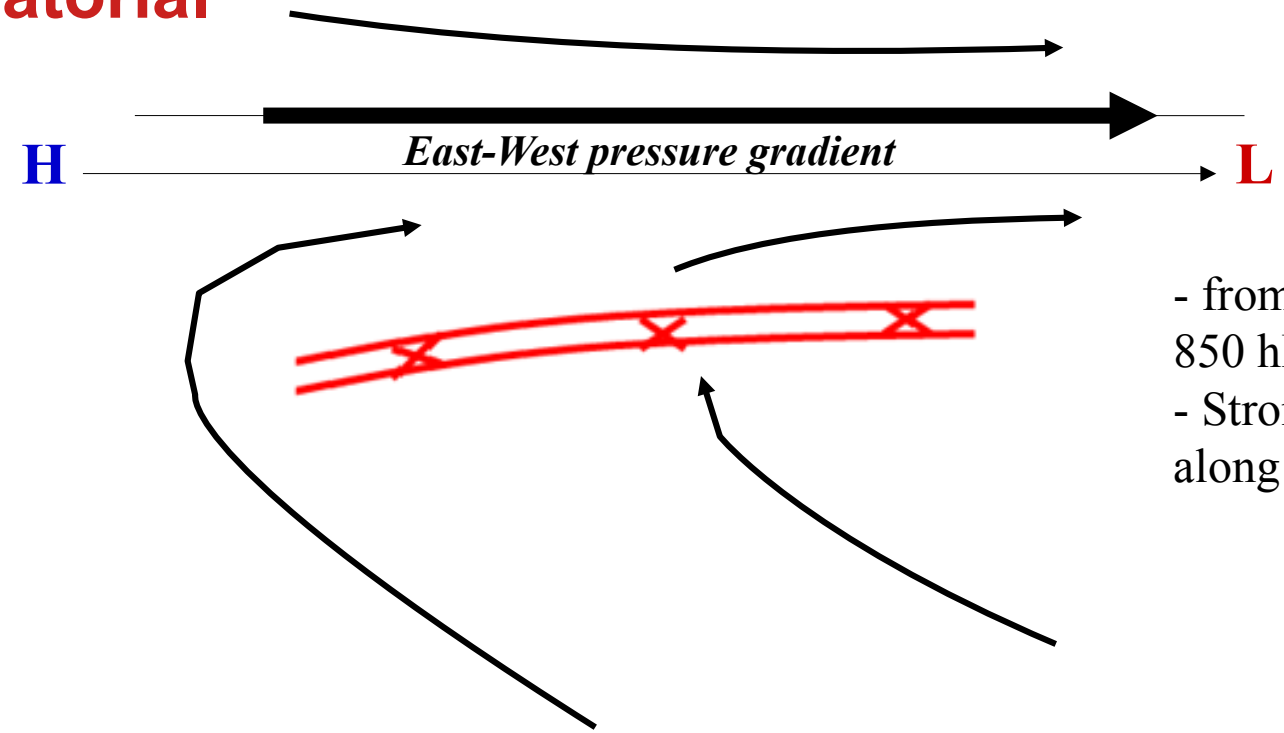
Near Equatorial Trough



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METEO FRANCE

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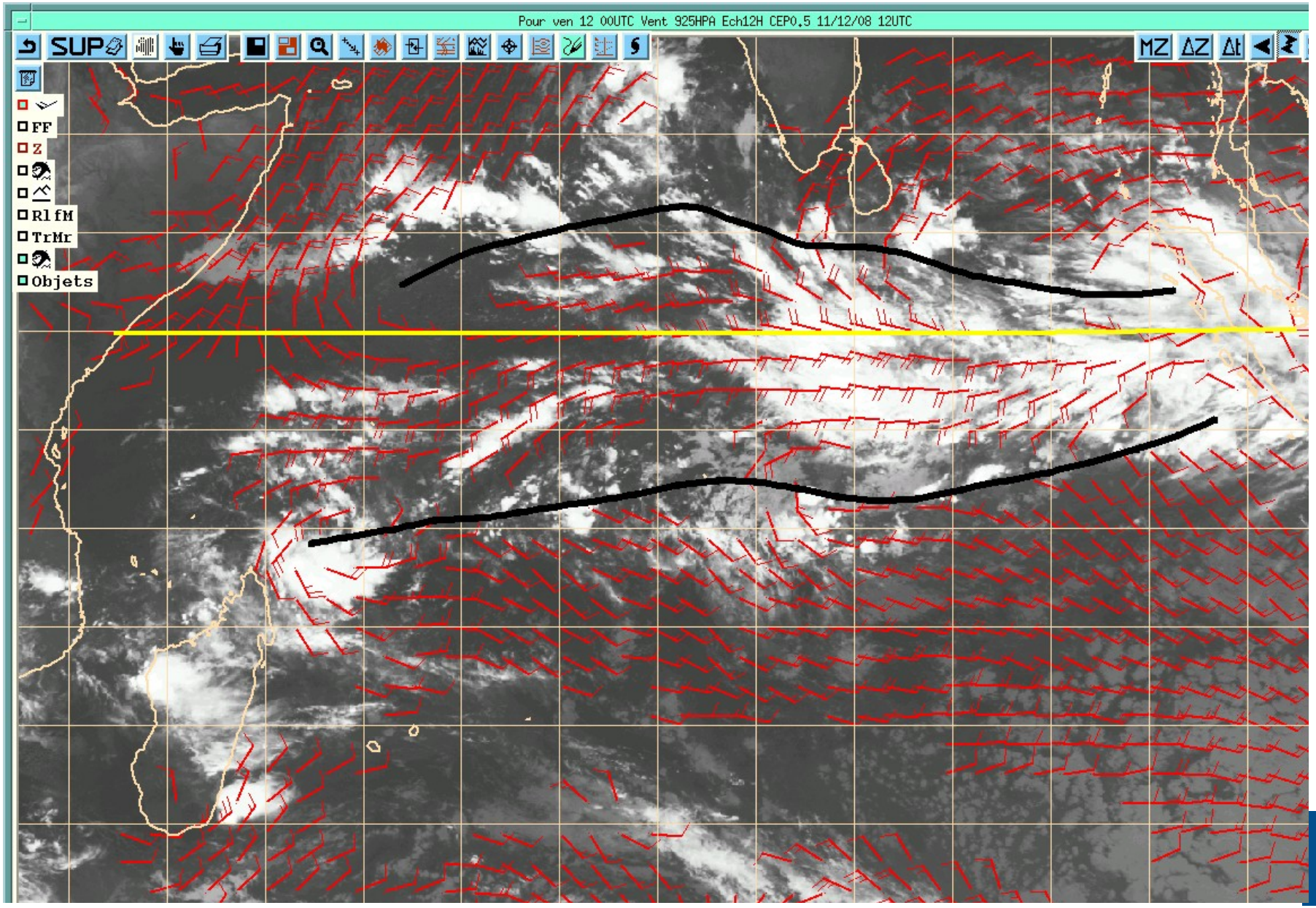

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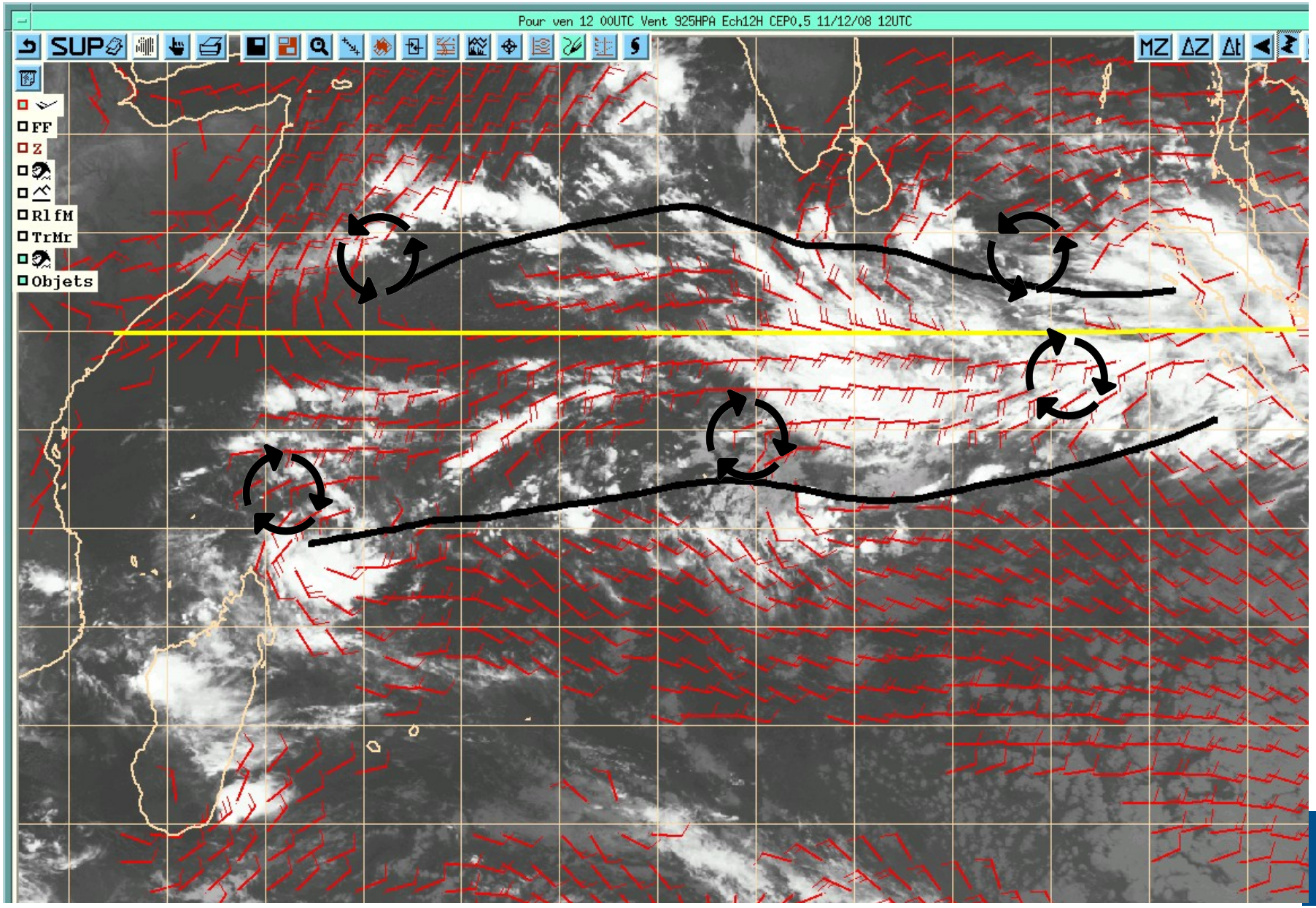

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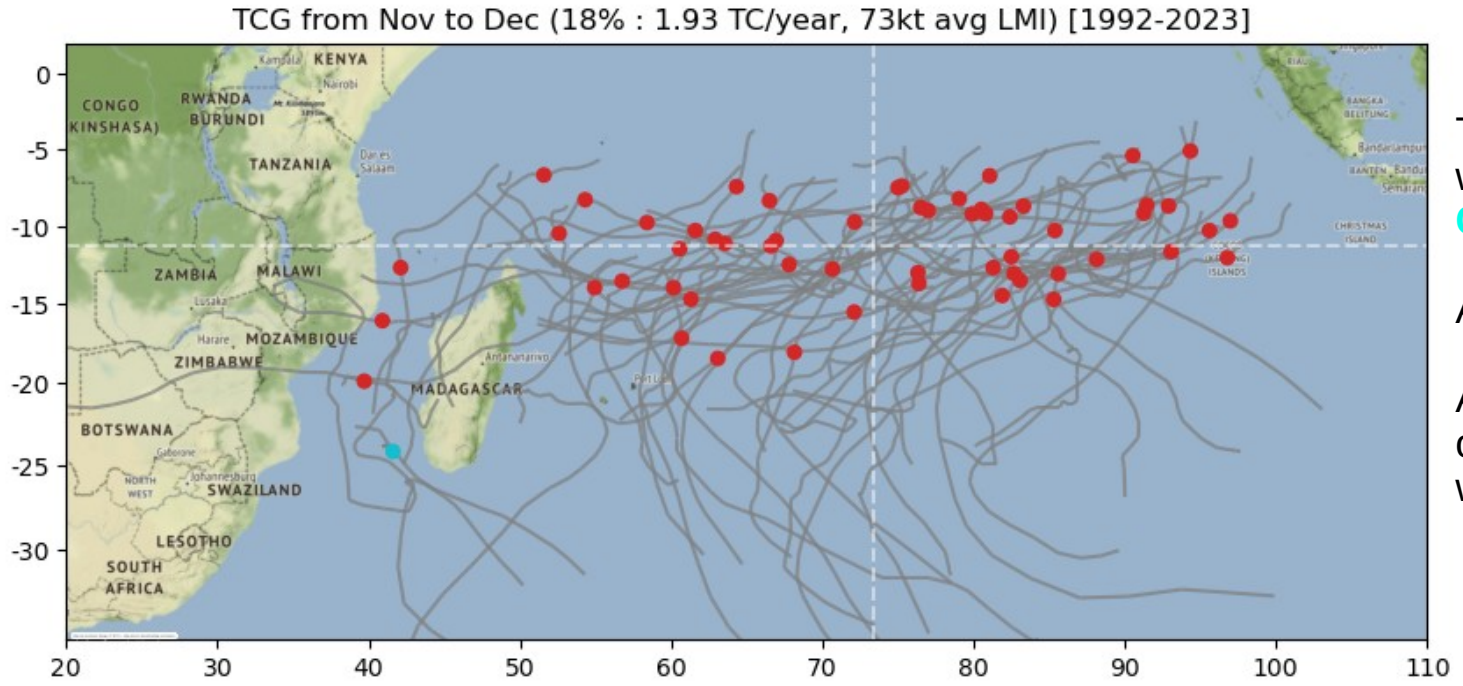

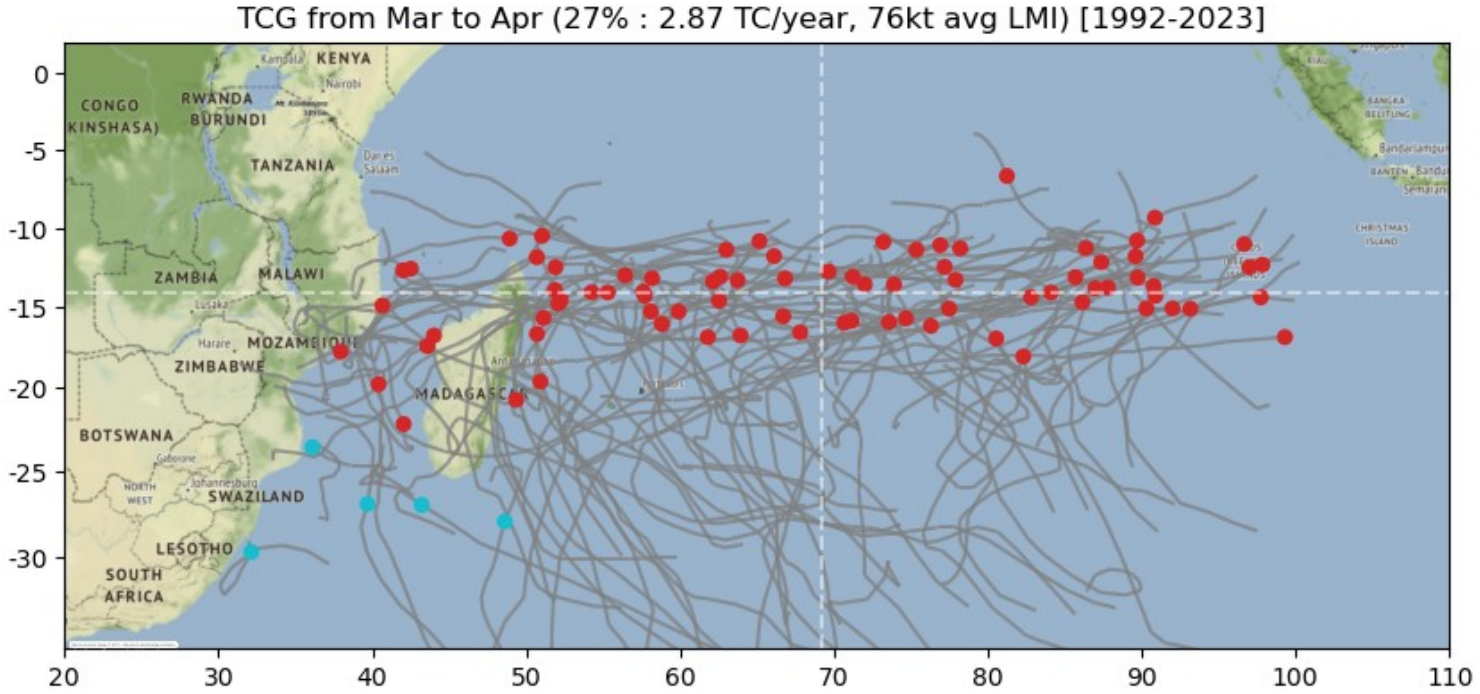

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Averaged lat and lons for the TCG of the sample shown by dotted white lines.

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METEO FRANCE

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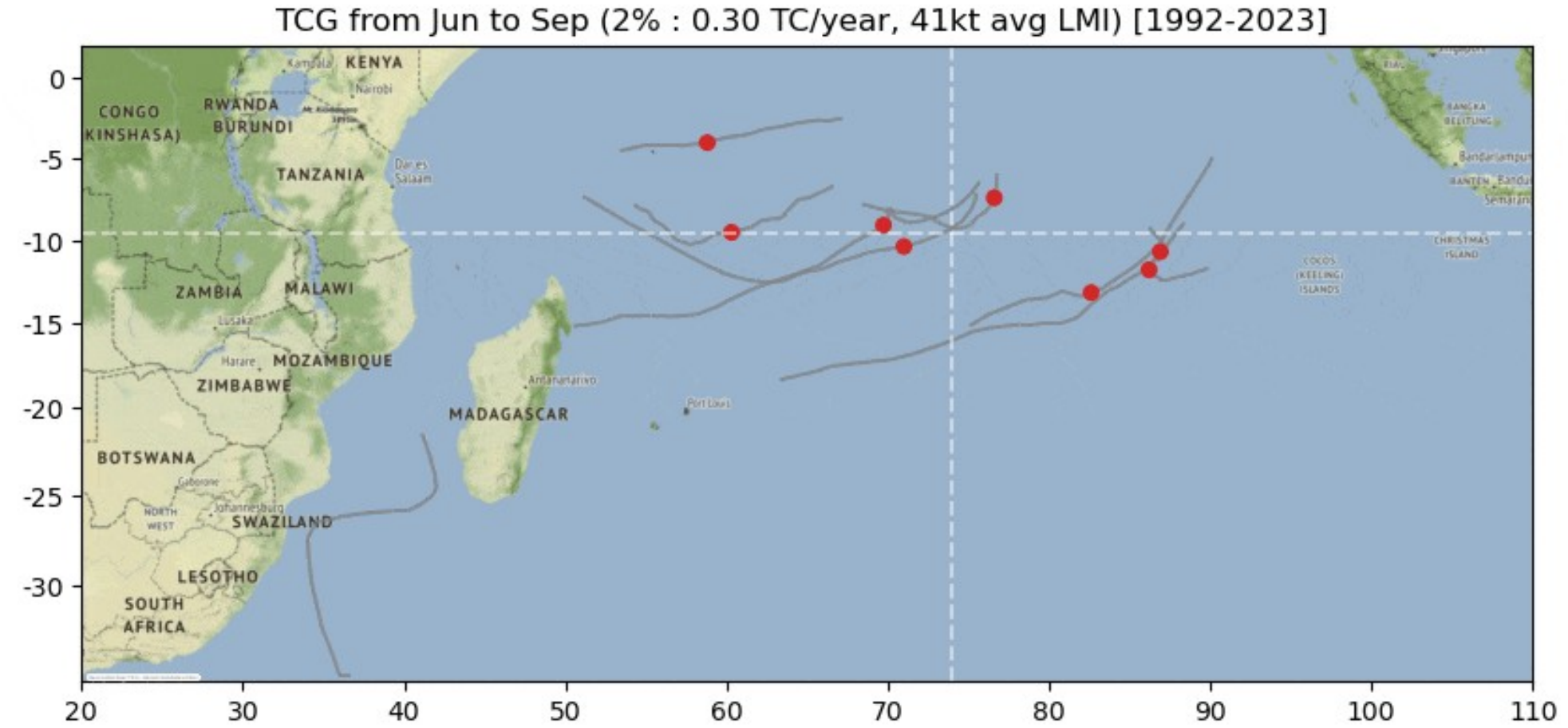

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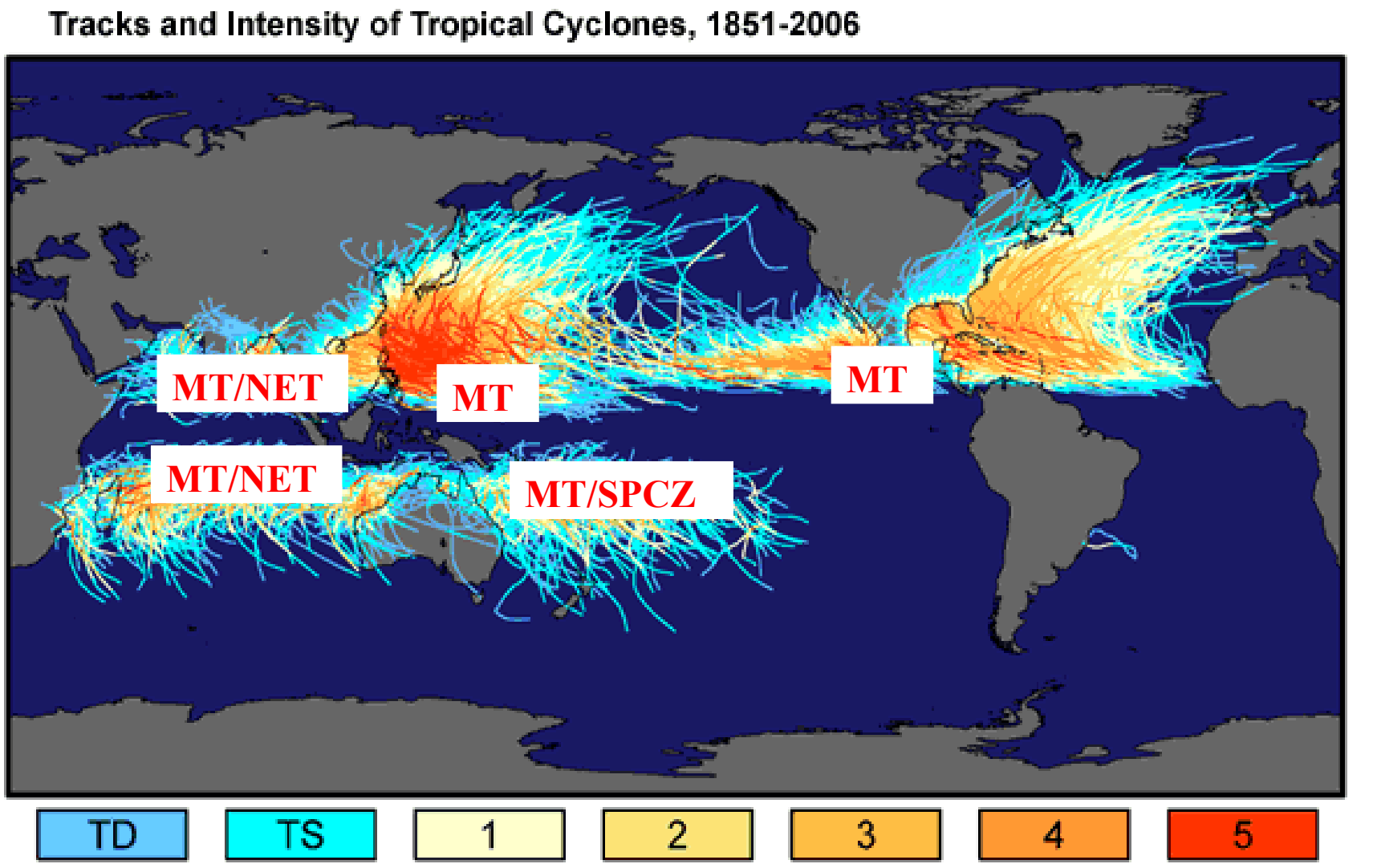
• Cyclogenesis : Bassin configurations worldwide

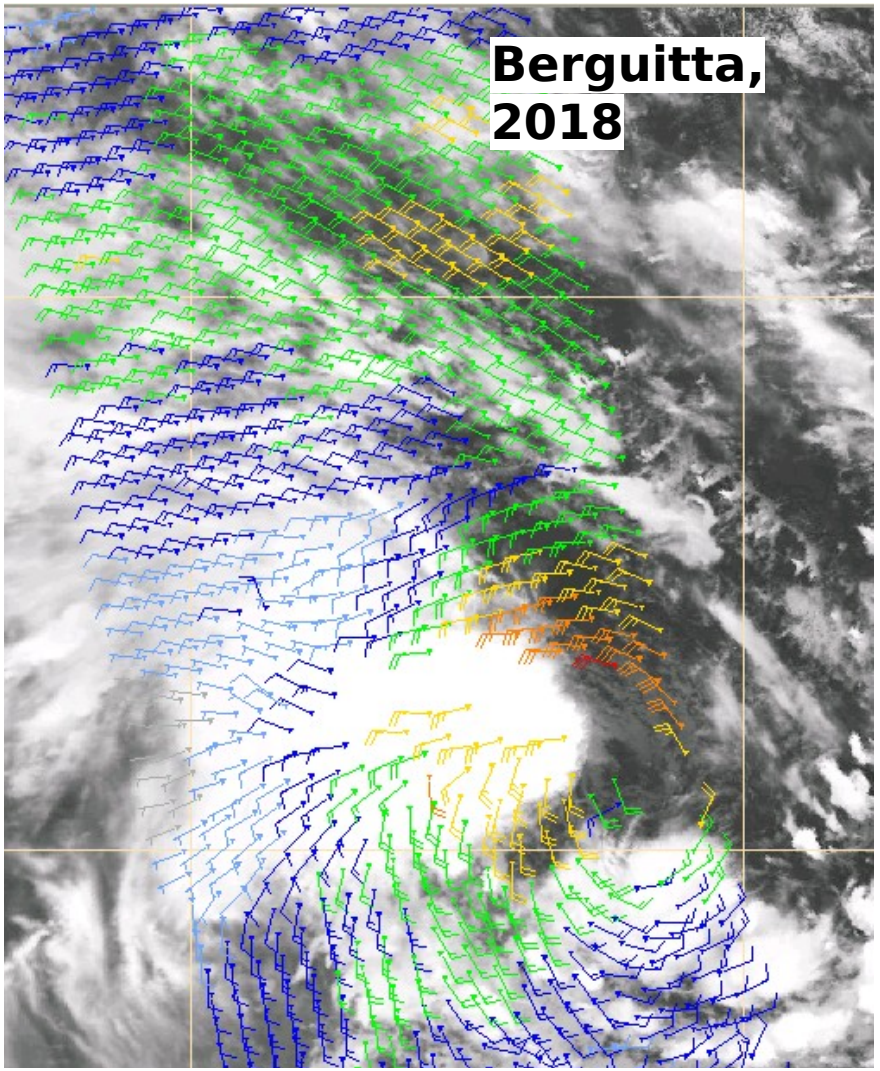


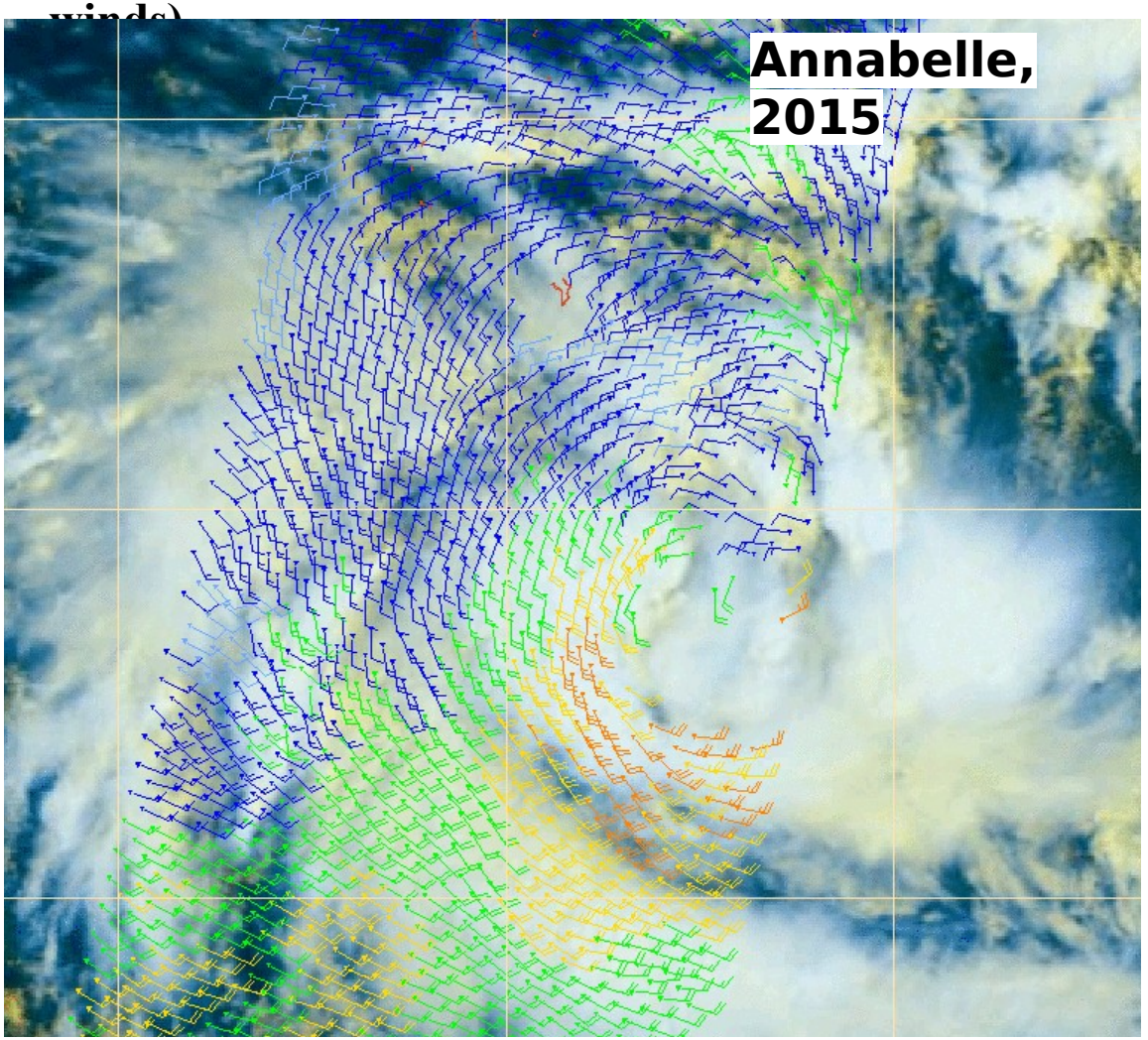
Src : COMET Program

- **Low levels convergence enhancement: the spark that starts the cyclogenesis**

These wind surges can occur on both sides of the traffic:

Equatorial (« westerly surge » = monsoon) **and/or tradewinds side** (strengthening trade winds)





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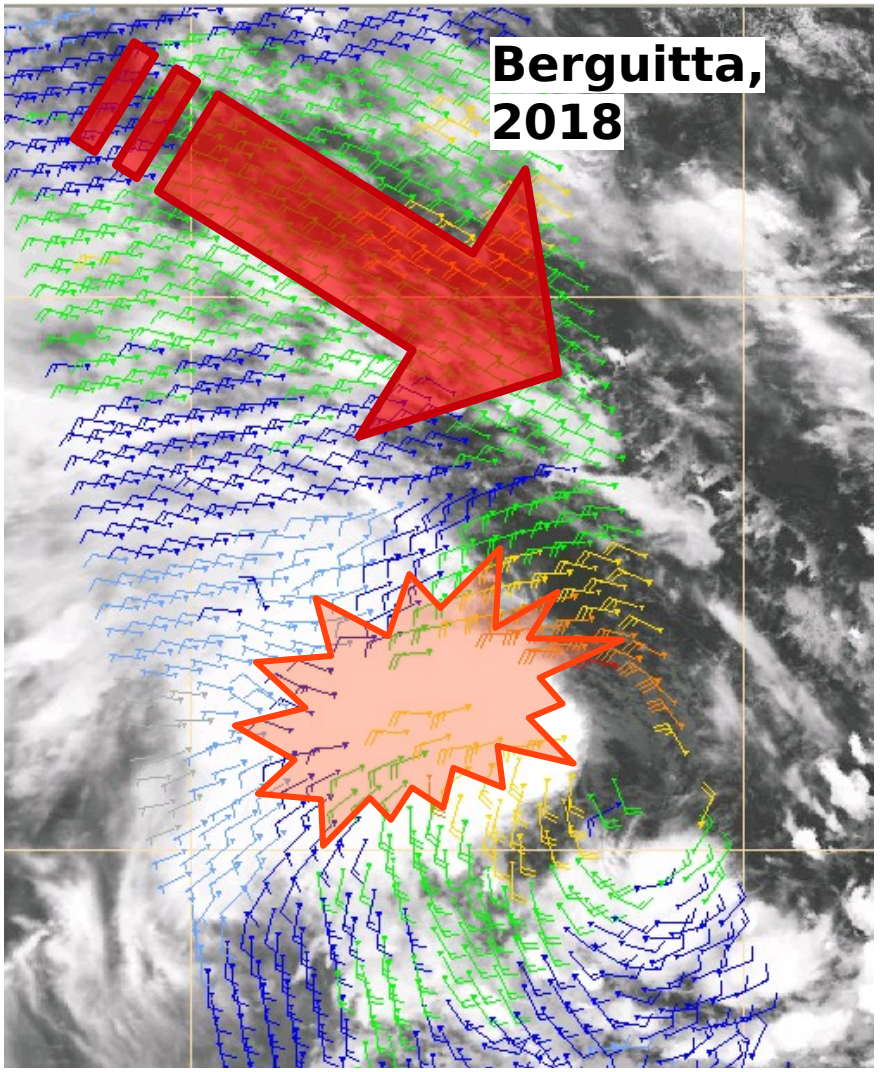
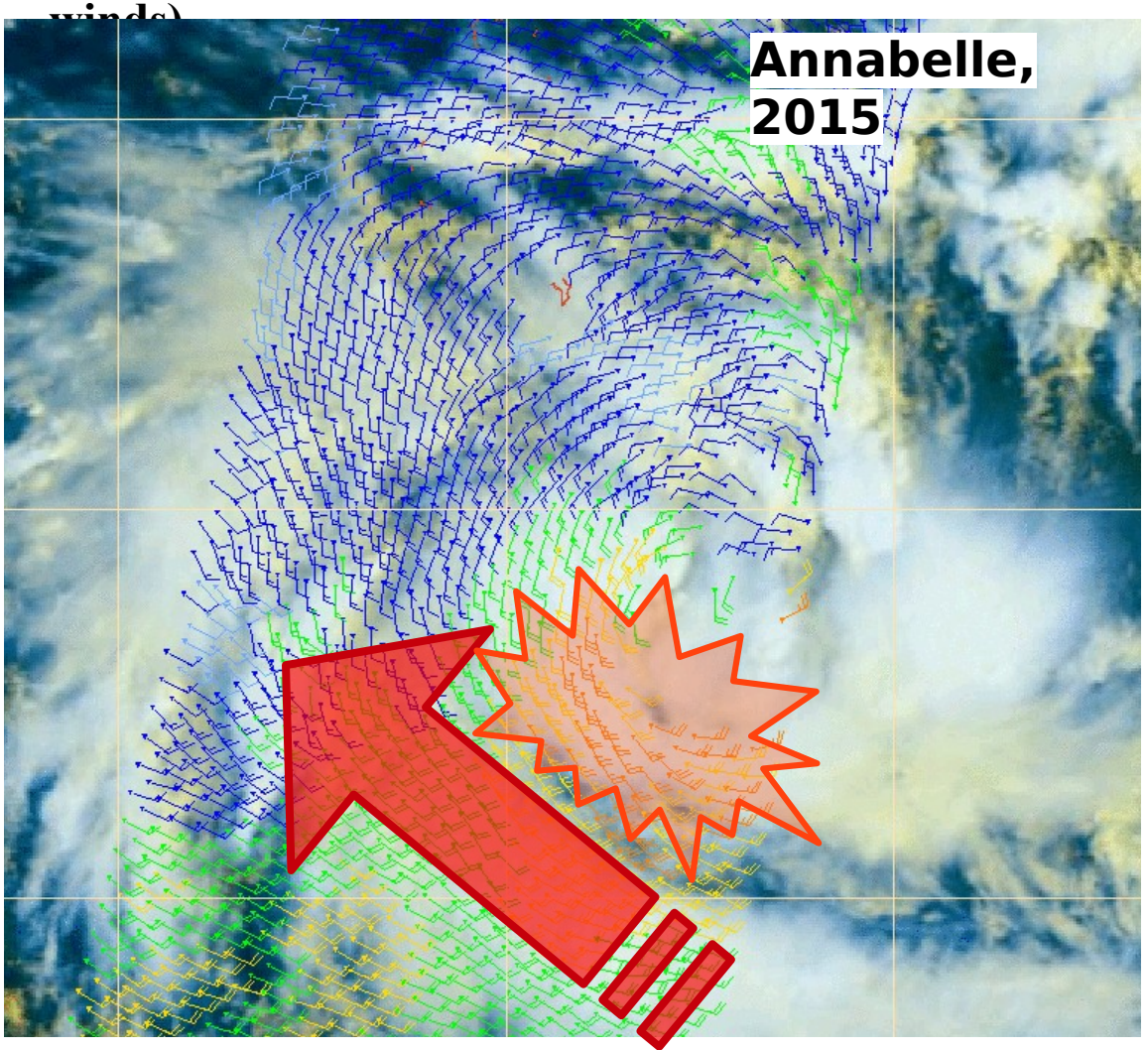
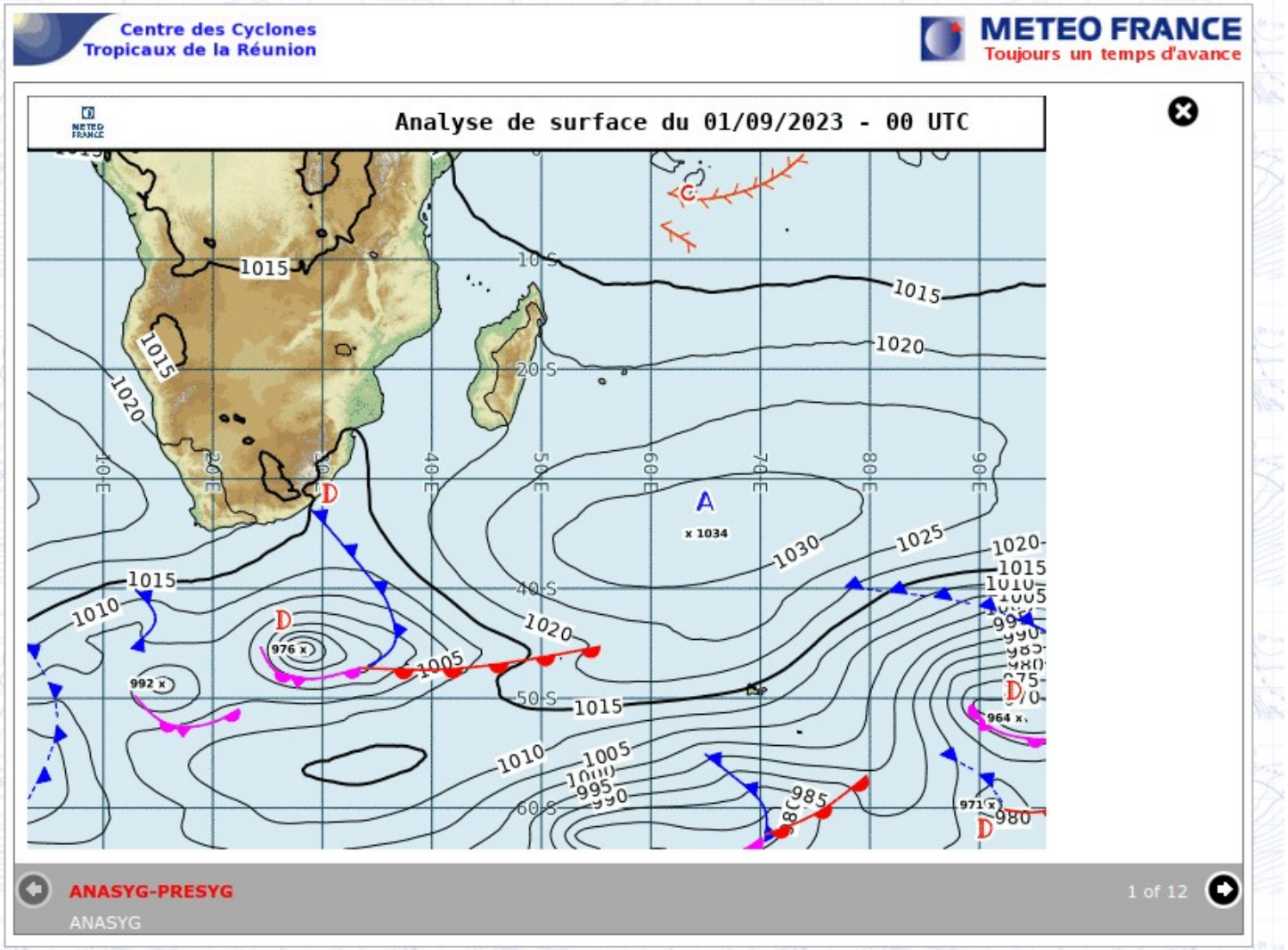




Src : MF Archives

- **Webcmrs**

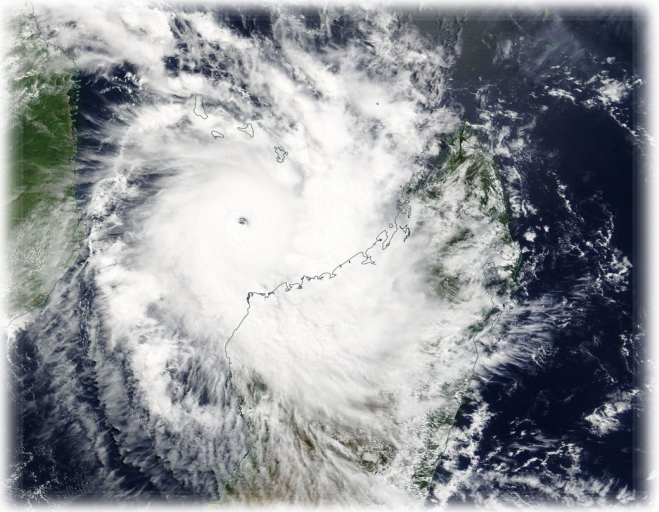
Current situation | Cyclogenesis | Operational products | RSMC archives |
About the RSMC | Research | Links | Education | Contact |



- **Basin Configuration**
  Conclusive remarks

→The preferred basin configurations in the SWIO basin during the warm season (November to April) are the Monsoon Trough (mid-season) and the Near Equatorial Trough (early/late season)

→ In the SWIO basin, a MT or NET configuration is, in the vast majority of cases, a **prerequisite for cyclogenesis** due to the strengthening of the low-level vorticity and the convergence of moisture



Tropical cyclogenesis

The role of equatorial waves

AI generated (Dall-E via Bing)

Equatorial waves

Definition : An equatorial wave materializes the **propagation of an atmospheric disturbance** on a planetary scale. It is **coupled to convection**: strong convective burst give rise to it and the propagation of the wave favors in turn convection.
It remains channeled in the near equatorial zone (± 15°) by the equatorial waveguide but also by the seasonal shift of the ITCZ.

Src : BOM YouTube

METEO FRANCE

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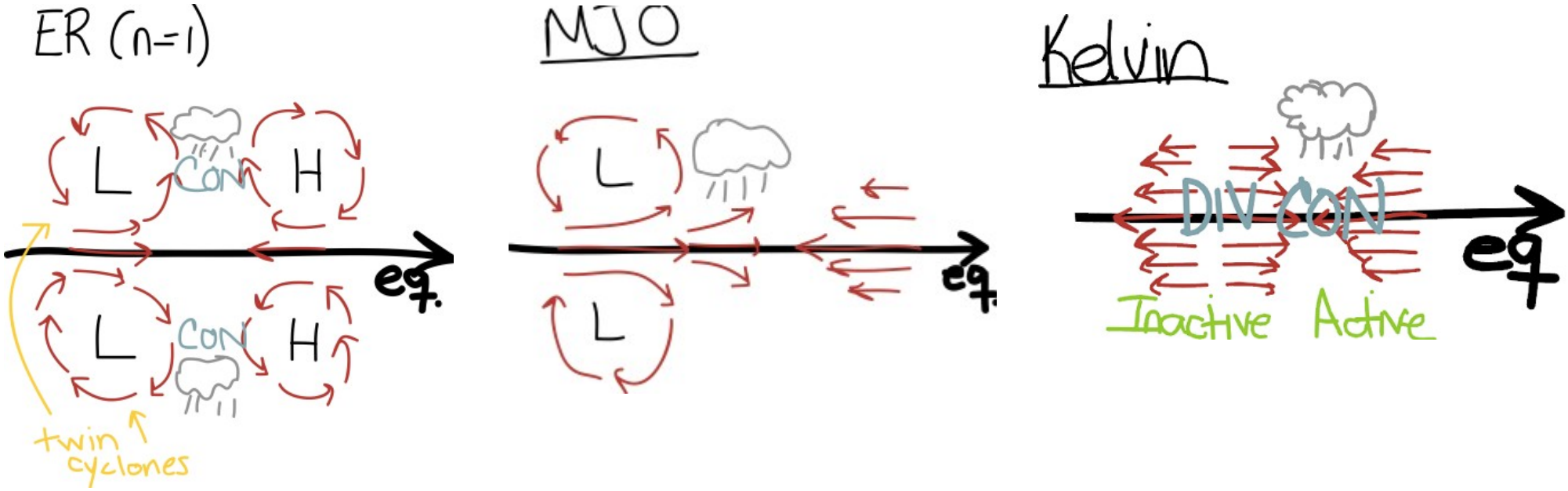

Equatorial waves bring predictability on an intra-seasonal (monthly) scale.

METEO FRANCE

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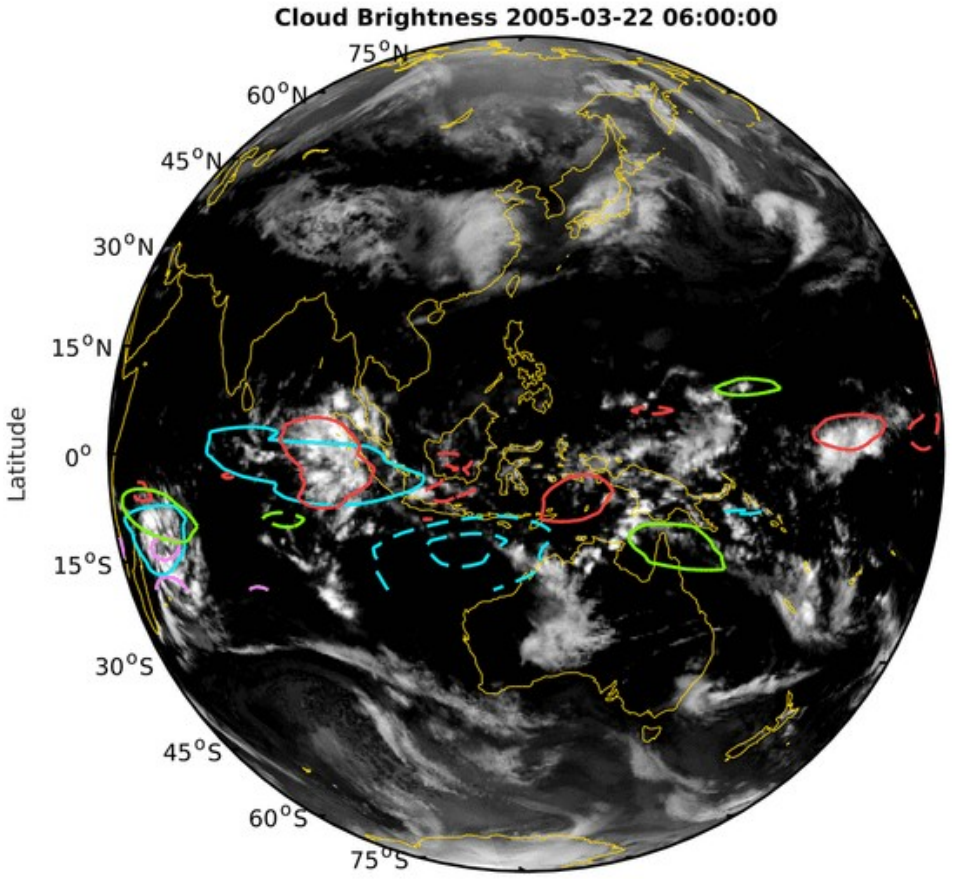


MJO

Kelvin waves

Kelvin waves in the MJO envelope.

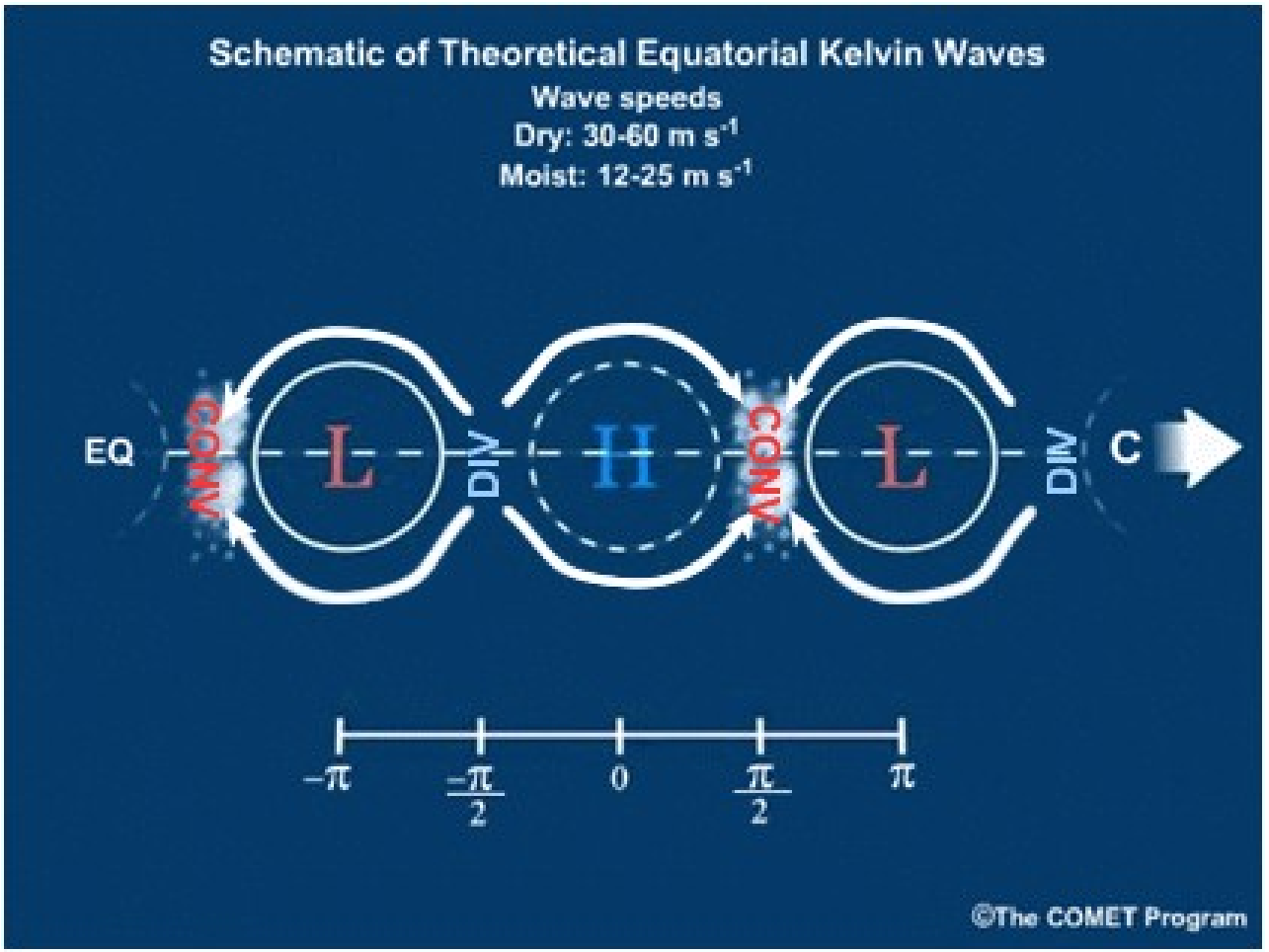
Equatorial Rossby waves

Src : afadames.com

METEO FRANCE

Kelvin waves

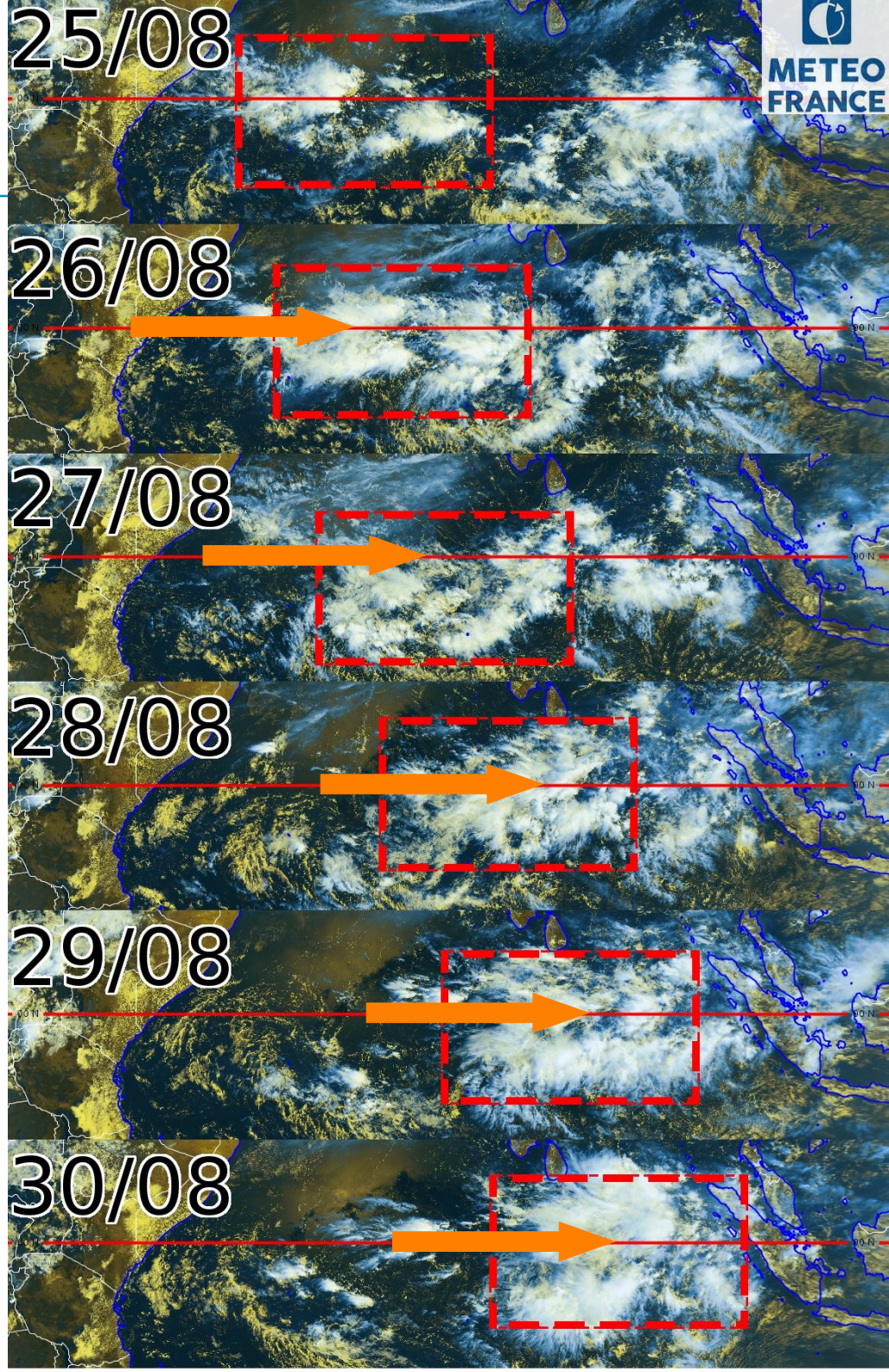
Propagation : Eastwards
Period ≈ 3/7 days
Consequences : enhanced convection ahead of a westerly wind surge



Src : COMET Program

Kelvin wave

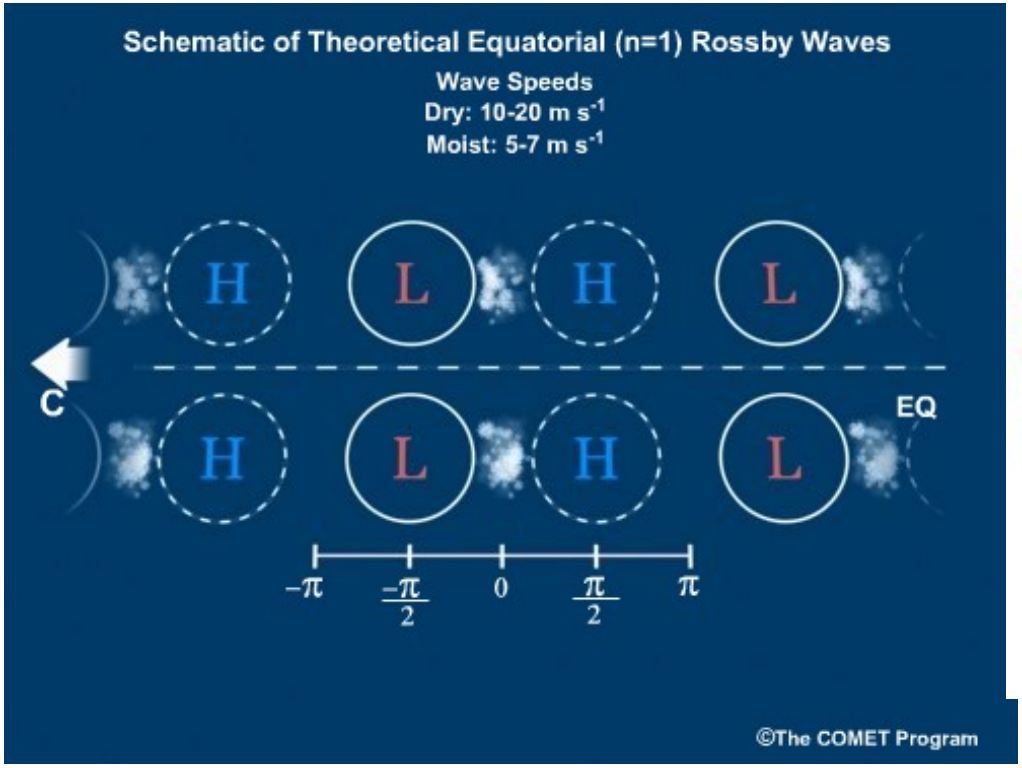
Propagation of a Kelvin wave over the Indian ocean

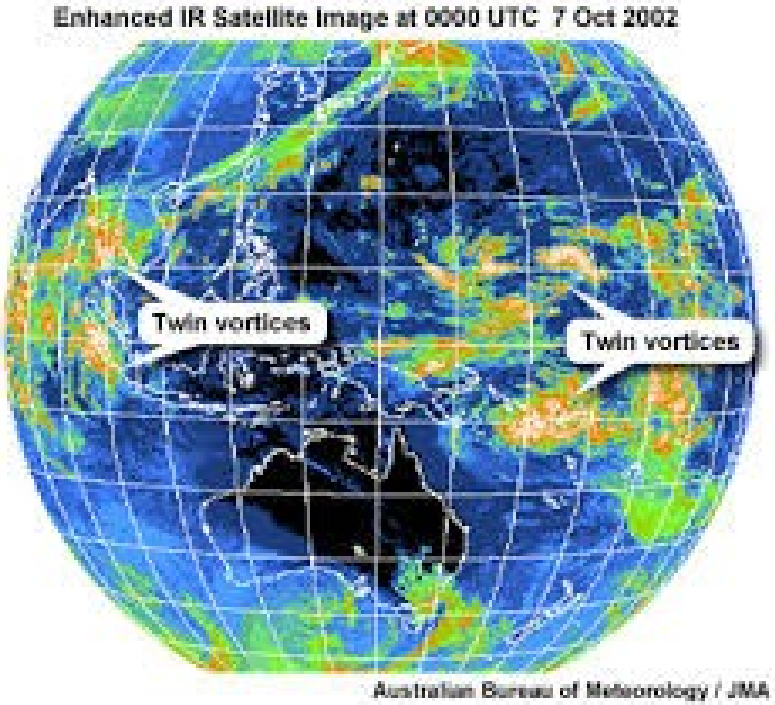


Src : MF Archive

Equatorial Rossby (ER)

Propagation : Westwards
Period ≈ 10/20 days
Consequences : Symmetrical cyclonic vortexes on both sides of the meteorological equator (varies with the season)

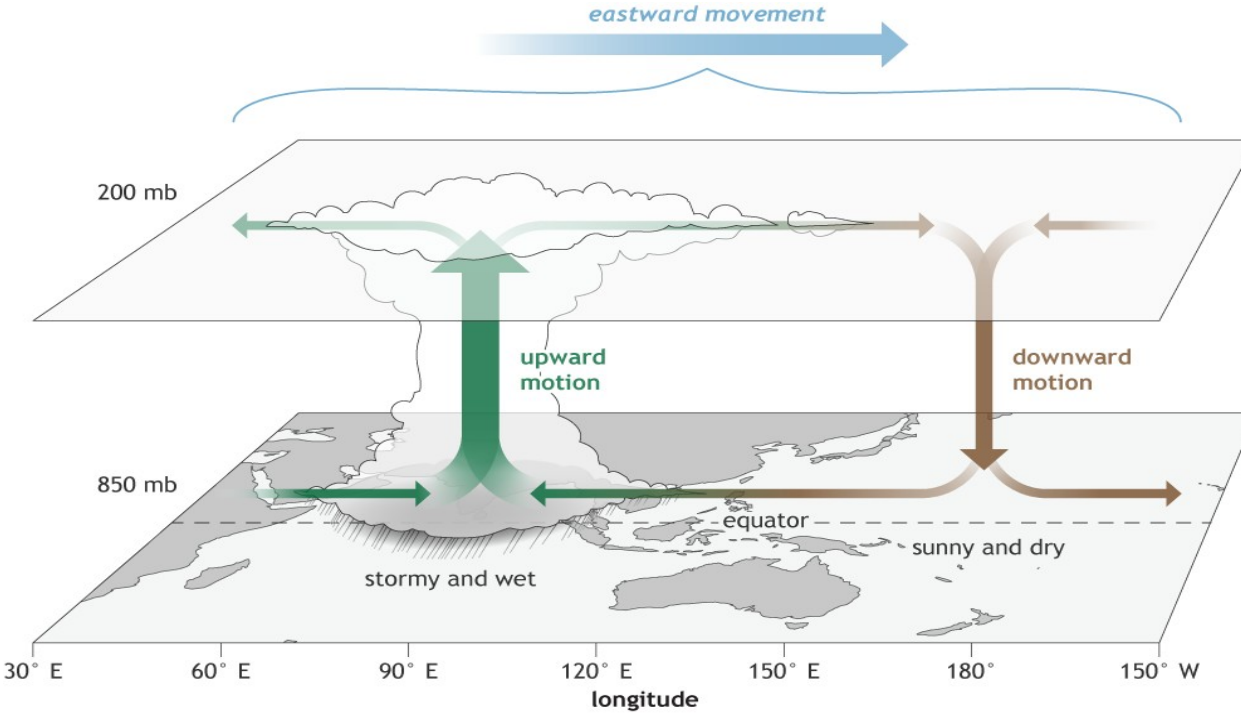


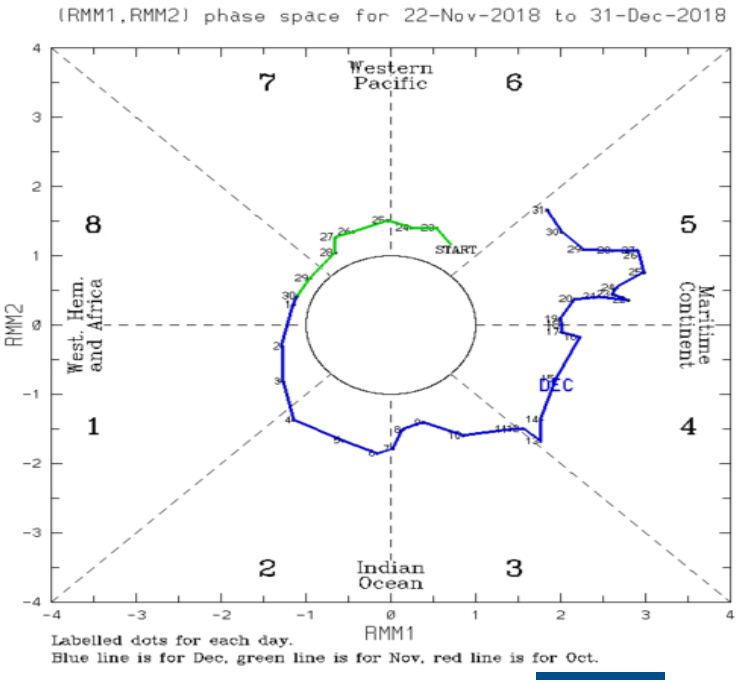


Src : COMET Program

Madden-Julian Oscillation (MJO)

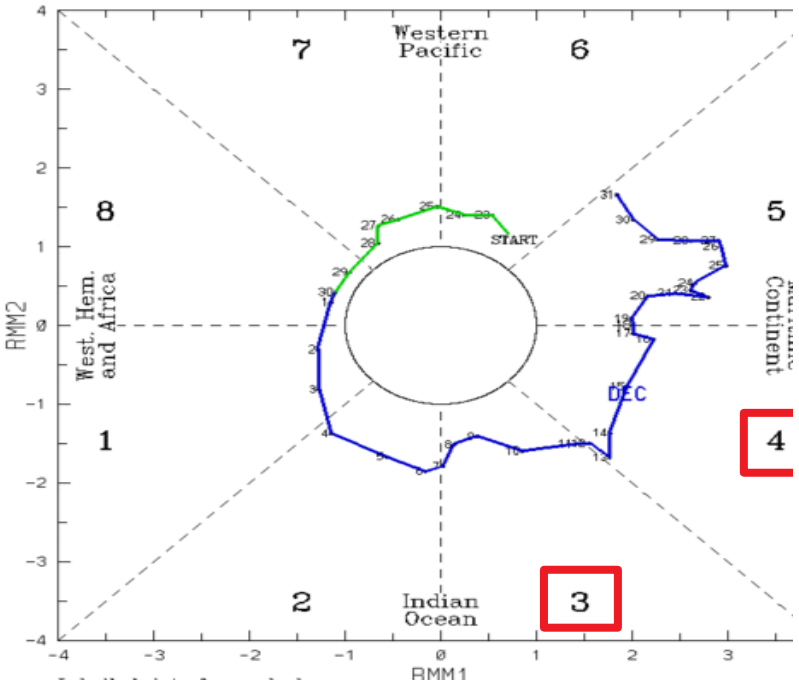
Propagation : Eastwards
Period > 30 jours
Consequences : Succession of enhanced / suppressed large scale deep convection over the Indo-Pacific area within slow moving Walker cells. Modulating influence on tropical cyclogenesis at intra-seasonal time-scale for this region.

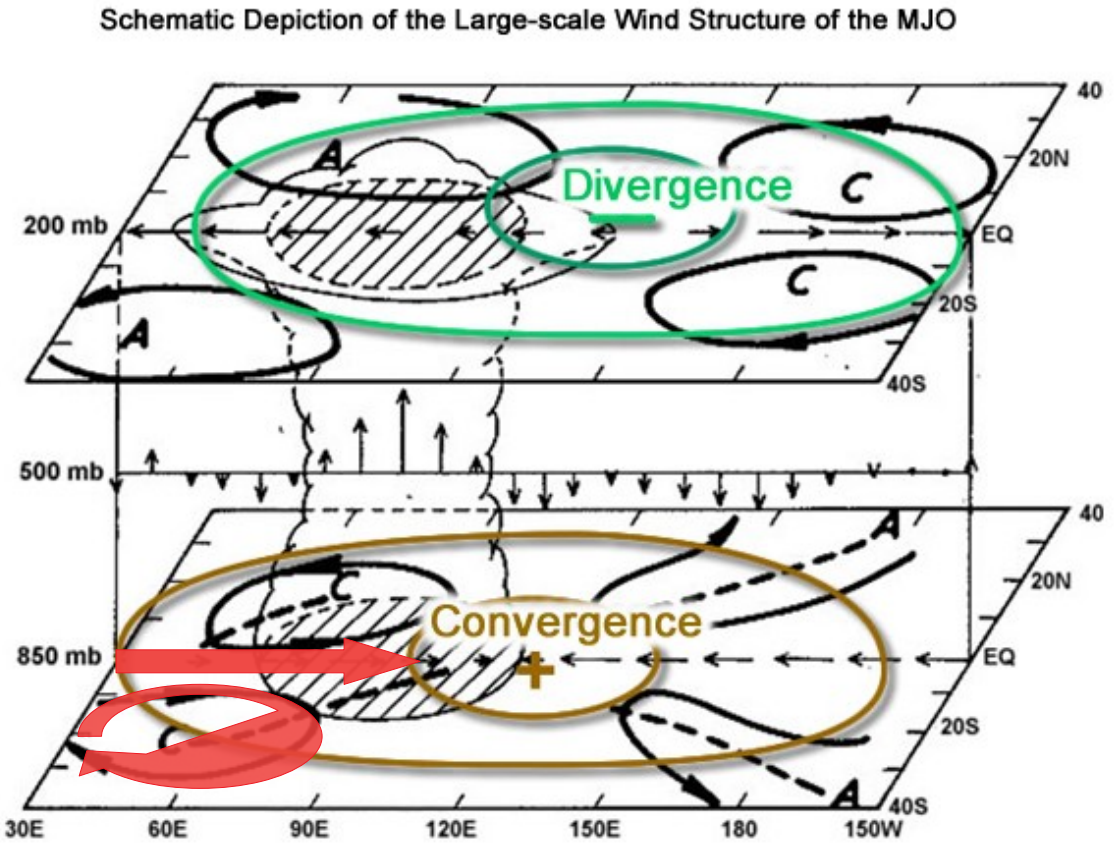




Src : NOAA Climate

Madden-Julian Oscillation (MJO)





Over the SWIO, cyclogenesis often occurs at the back of the active MJO phase, when the RMM index is in position 3 and 4.

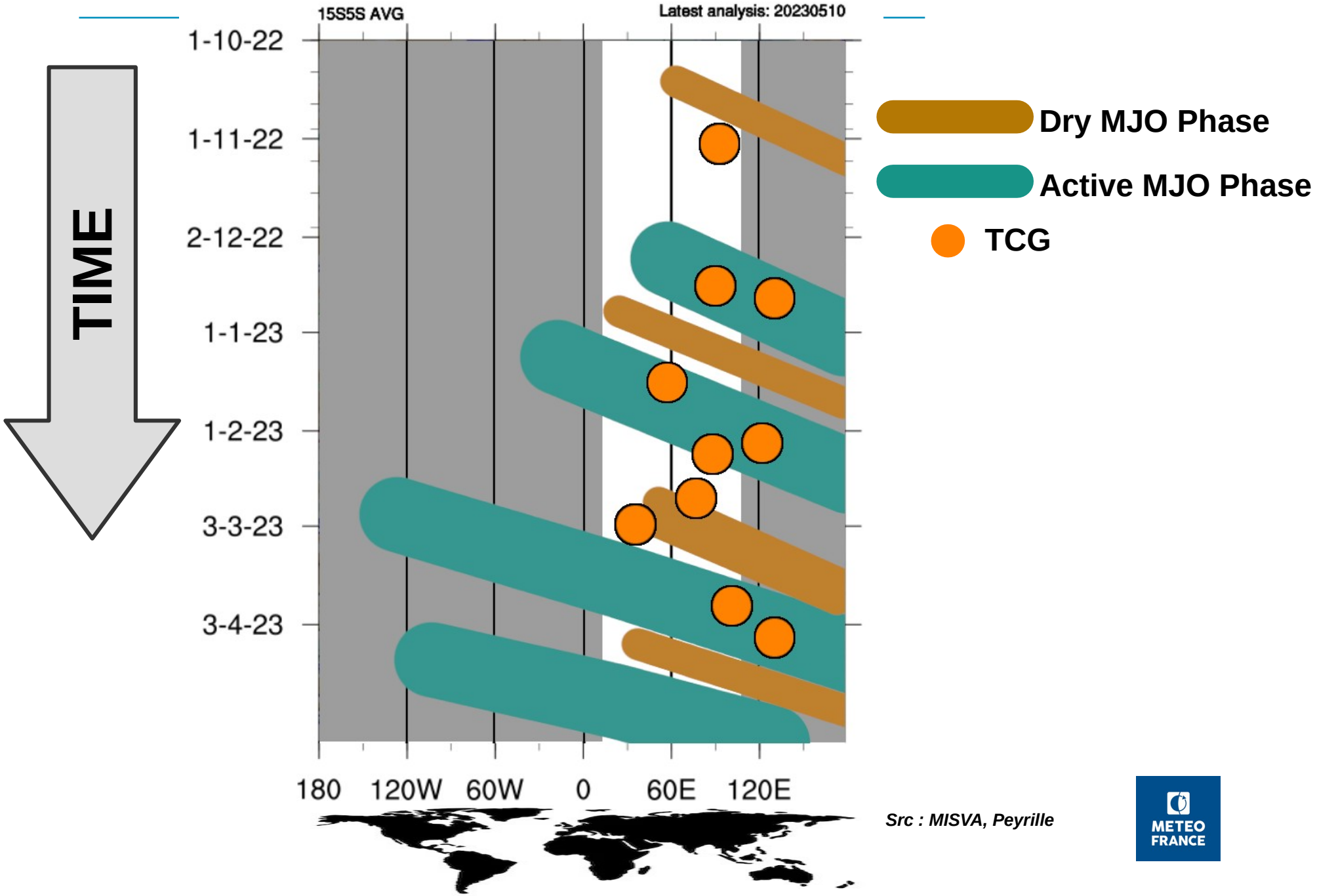
Tropical Waves influence on TCG

Tropical Waves favor TCG by :
→ Increasing deep convection and creating conducive conditions
→ Creating background vorticity that decreases Rossby's radius of deformation

It is especially true when two waves cross path, typically Eastward moving Kelvin or Mjo with a westward moving Equatorial Rossby

METEO FRANCE

Remember last summer...



Src : MISVA, Peyrille

METEO FRANCE

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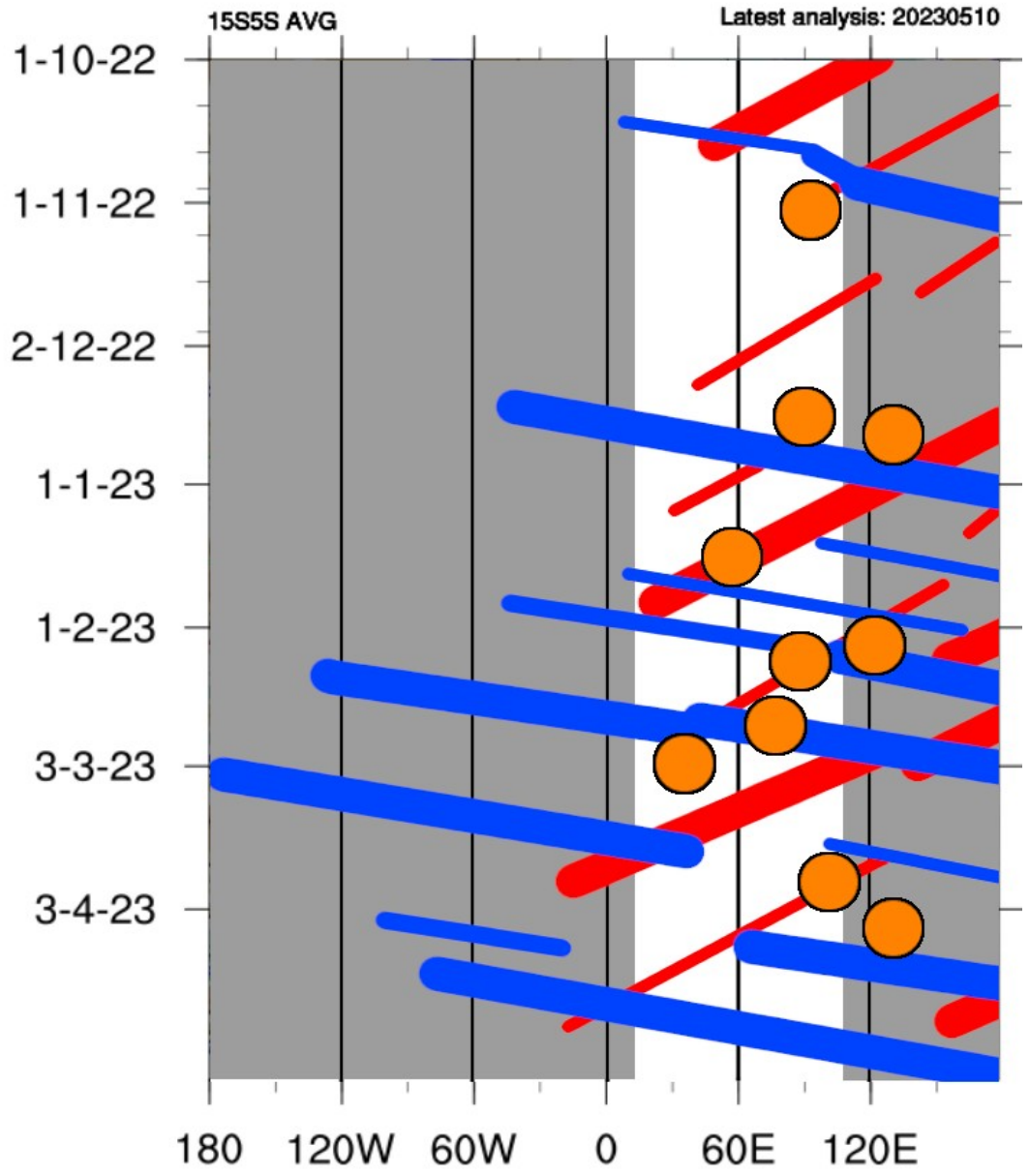


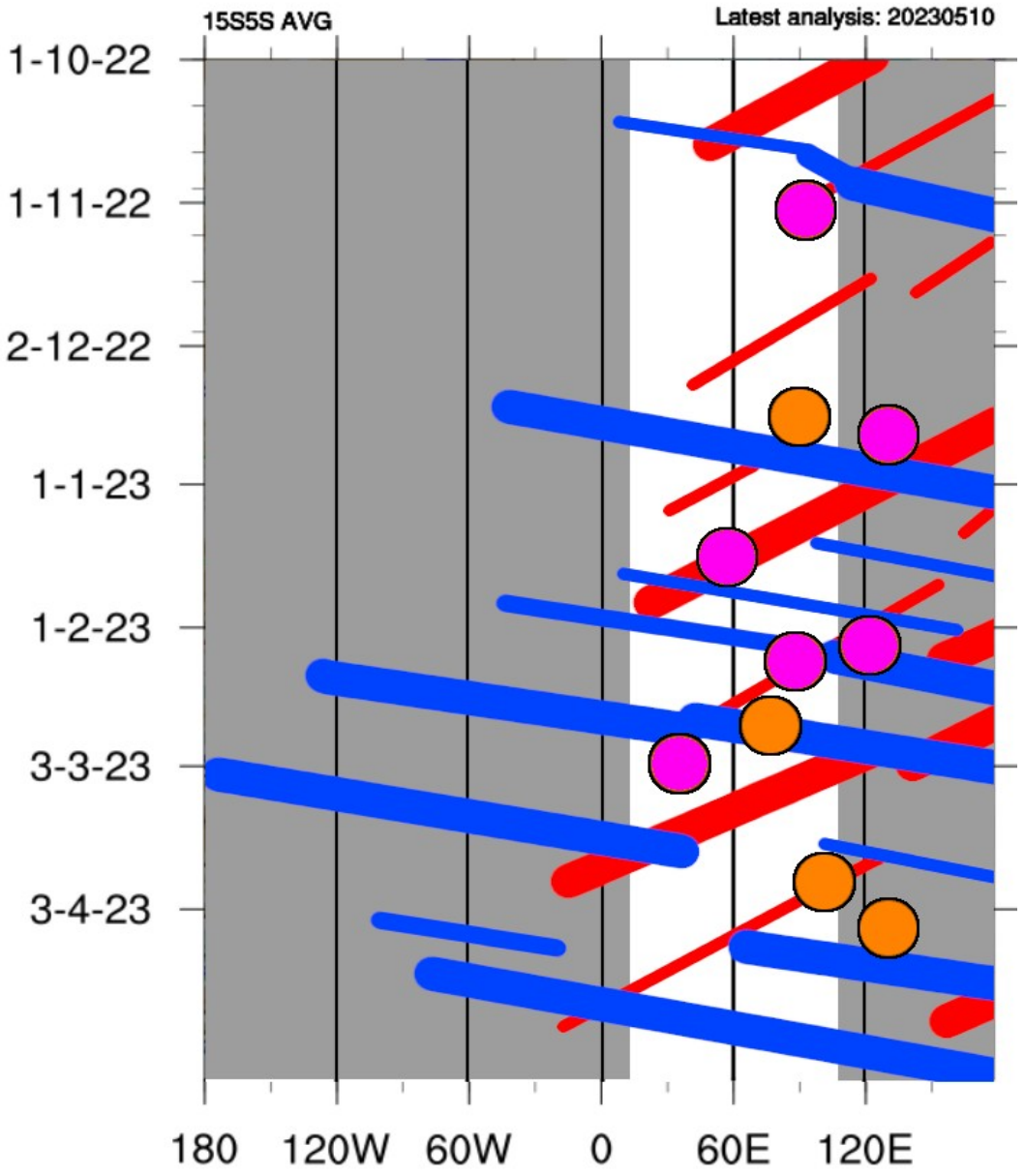
Active ER Wave

Active Kelvin Wave

TCG

Src : MISVA, Peyrille

Remember last summer...



Active ER Wave

Active Kelvin Wave

TCG

Src : MISVA, Peyrille

METEO FRANCE

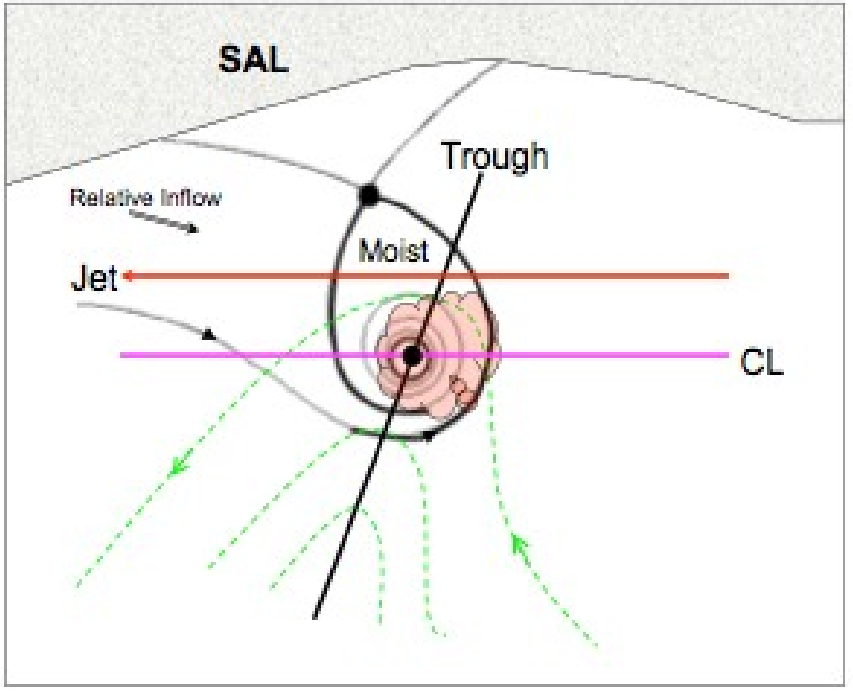
Tropical cyclogenesis

A few advanced notions

AI generated (Dall-E via Bing)

The Marsupial Paradigm

The areas of vorticities associated with Tropical Waves are thought to form a protective « pouch » of conducive environment, with little to no exchange with the outside.

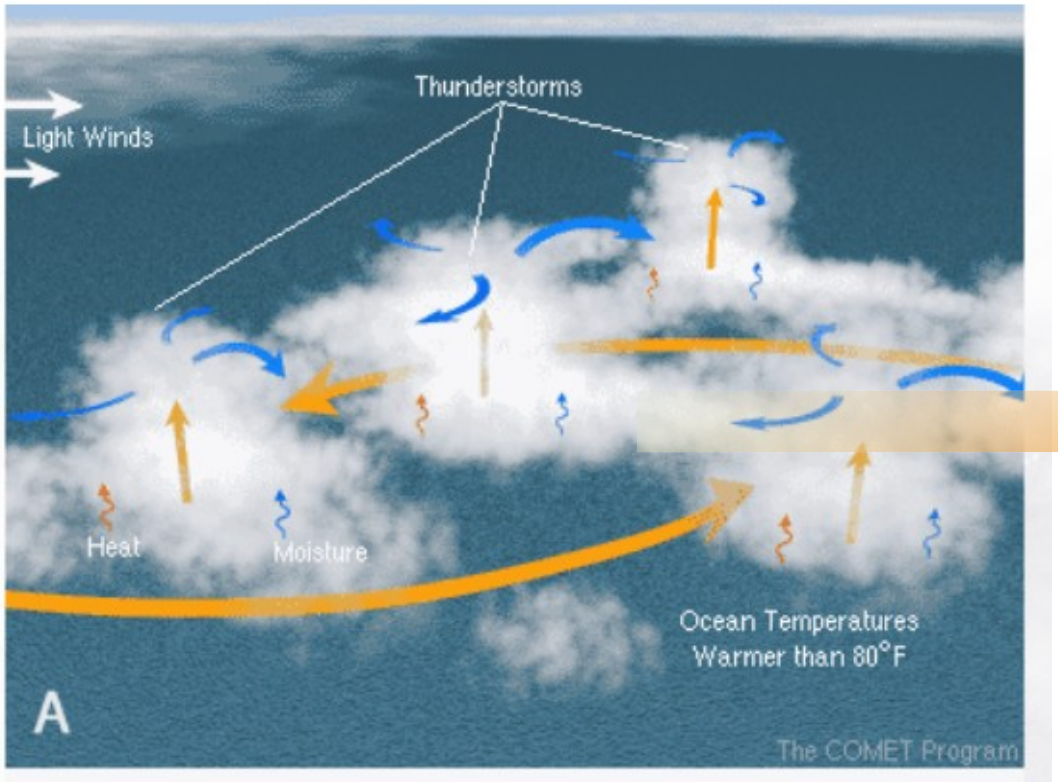


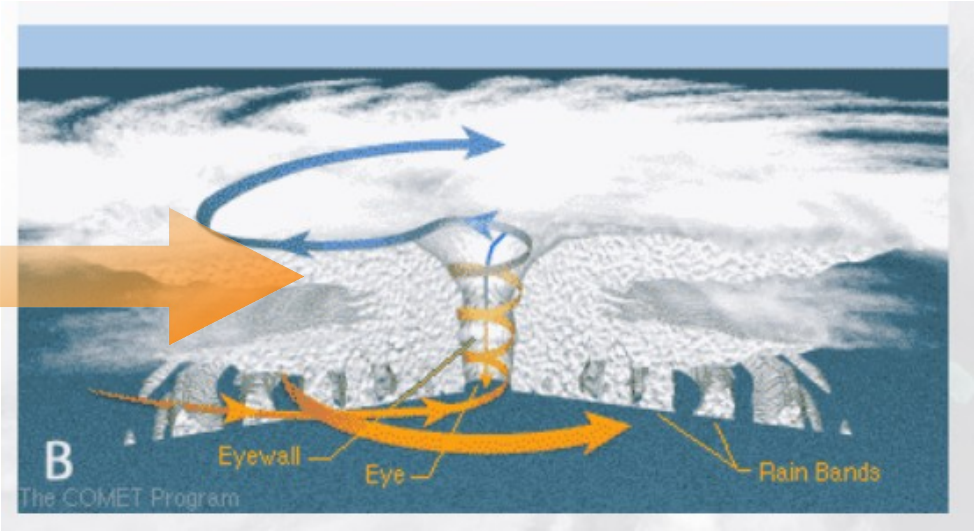
From Wang et al. 2010

- Air inside of the pouch is continually moistened by convective bursts.
- Pouch offers protection from dry air intrusions.
- Originally created from Easterly waves over North Atlantic
- Currently being generalized to other basins and types of waves (**ER**)

METEO FRANCE

In reality, pre-TC systems are not really symmetric...





Src : COMET Program

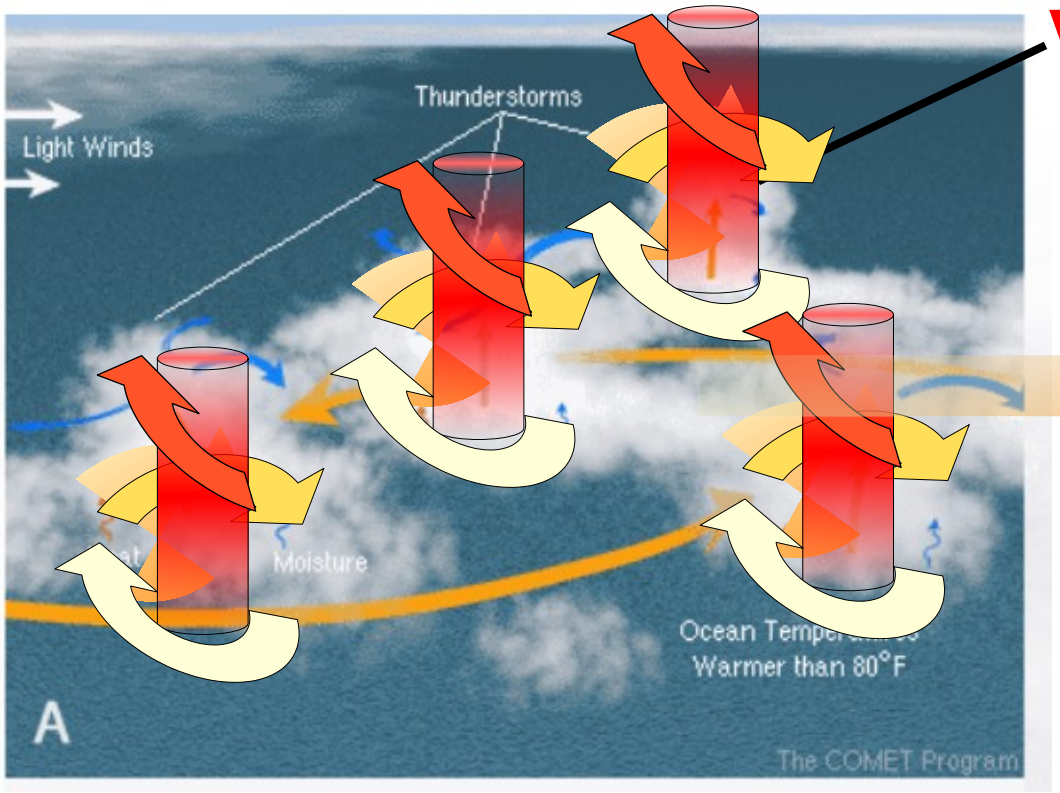
Vortical Hot Towers (VHTs) develop inside the pouch circulation. They are the 'building blocks' of the future TC vortex, as they gradually merge and migrate towards the center.

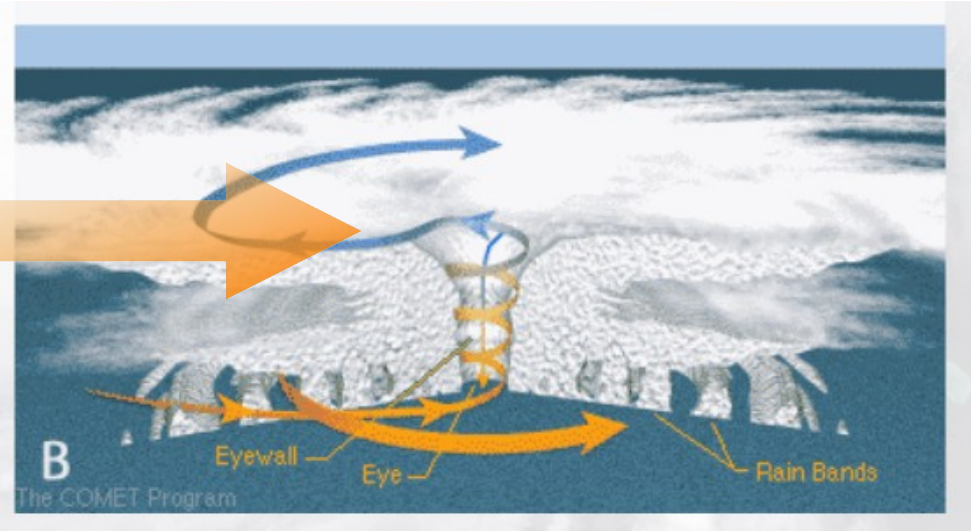
This VHT pathway first formalized by Montgomery et al, 2006 appears to be :

→ Closer to real-world TCG with a 3D framework
→ Taking into account asymetries observed in reeal-life TCG scenarios

METEO FRANCE

How do we go from a few MCS to a self-sustained TS ?





Src : COMET Program

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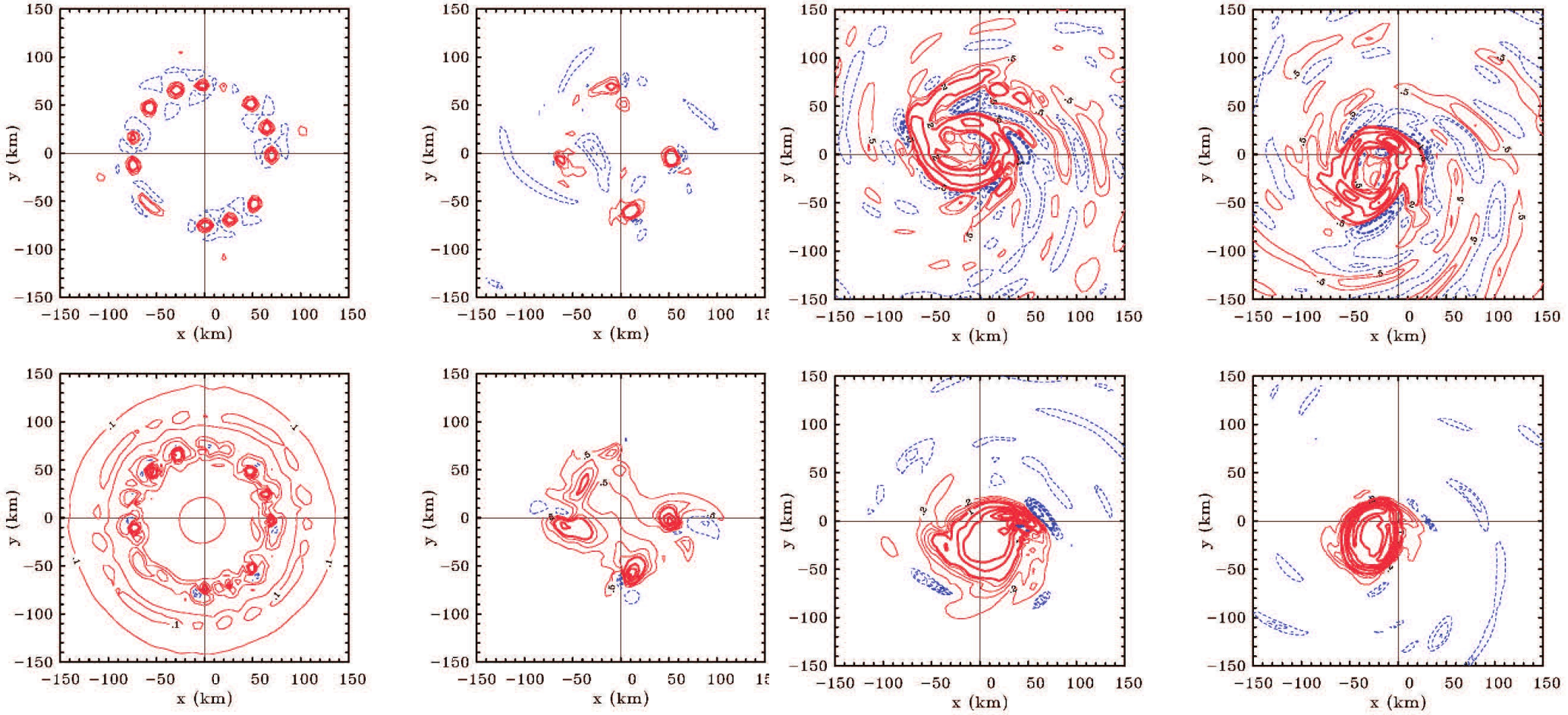
→ Taking into account asymetries observed in reeal-life TCG scenarios

METEO FRANCE

How do we go from a few MCS to a self-sustained TS ?

9,75 hrs **24 hrs** **48 hrs** **96 hrs**



Figures from Montgomery, 2014

Vertical velocities (850 hPa): top line
Vorticity (850 hPa) : bottom line

METEO FRANCE

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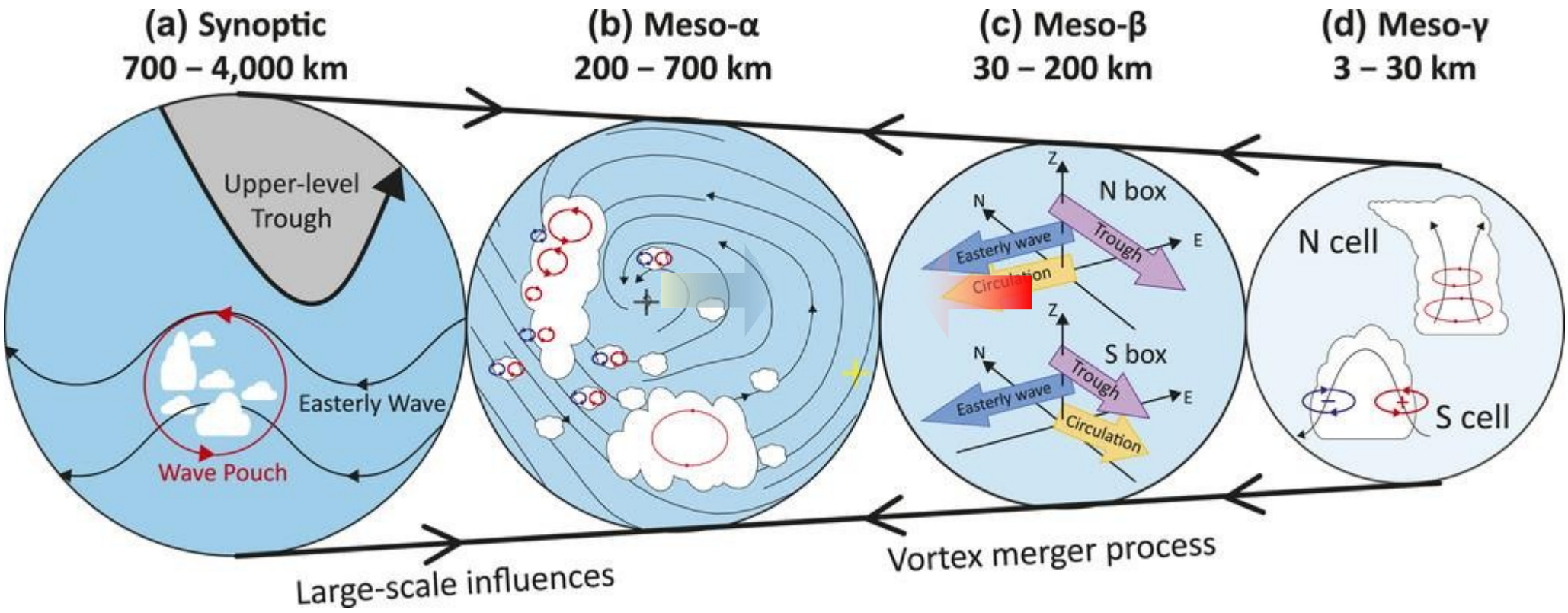

Adapted from Nam and Bell (2021).

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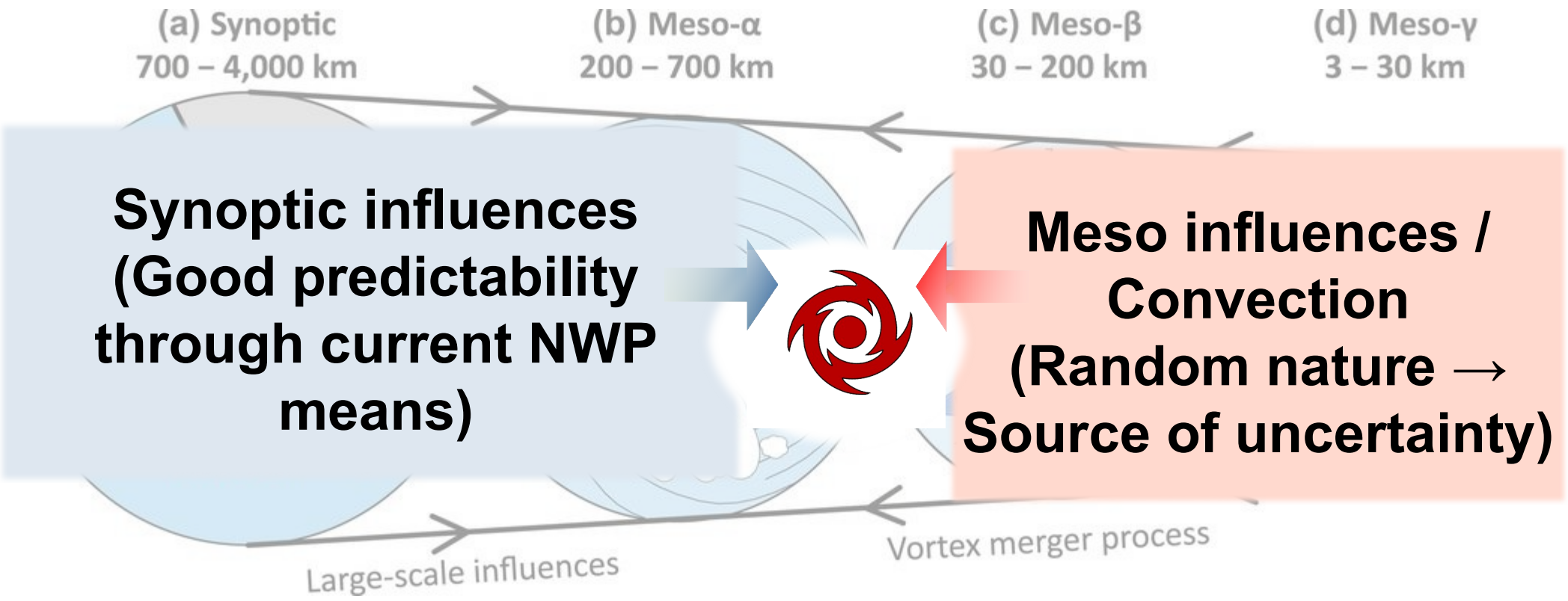

Synoptic influences (Good predictability through current NWP means)

Meso influences / Convection (Random nature → Source of uncertainty)

Adapted from Nam and Bell (2021).

Take away messages

→ Cyclogenesis corresponds to the **initial intensification phase** of a tropical low pressure system.

→ Once initiated, the **positive feedback loop** between the release of latent heat by deep convection, lowering of central pressure and strengthening of surface winds, does not need input from the environment to continue. **TC becomes autonomous.**

→ The presence of a **well defined vorticity precursor** in the low-levels is key in the default pathway to cyclogenesis over the SWIO.

→ **Specific basin configurations and tropical waves** influence TCG by creating precursors and promoting deep convection.

→ Research is still under way on the subject of TCG on various aspects of the problem : interactions between waves, cloud microphysics.

METEO FRANCE

AI generated (Dall-E via Bing)