Small-scale processes in the Atmosphere & the Oceans, and their impact on climate

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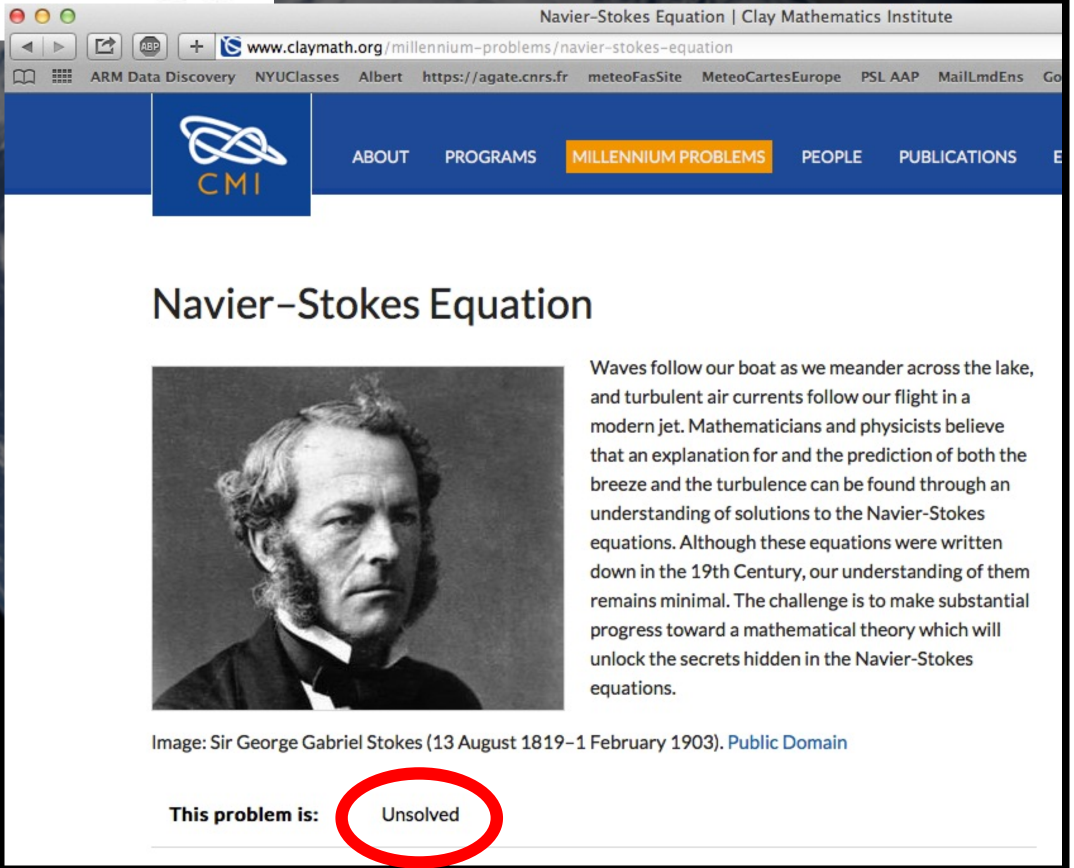
With thanks to: Oceane Richet, Bidyut Goswami, Yi-Ling Hwong, Benjamin Fildier, Sophie Abramian

Fluid motion is governed by the Navier-Stokes equations :

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \text{ ----- Continuity Equation} \quad (1)$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\frac{1}{\rho}\nabla p + \mathbf{F} + \frac{\mu}{\rho}\nabla^2 \mathbf{u}, \text{ ----- Equations of Motion} \quad (2)$$

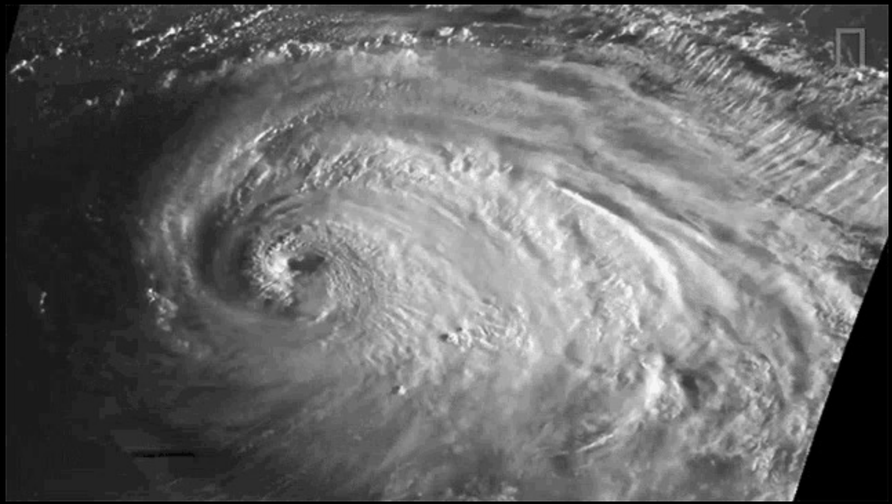
$$\rho\left(\frac{\partial \varepsilon}{\partial t} + \mathbf{u} \cdot \nabla \varepsilon\right) - \nabla \cdot (K_H \nabla T) + p\nabla \cdot \mathbf{u} = 0. \text{ ----- Conservation of Energy} \quad (3)$$



Problem is hard ! ...

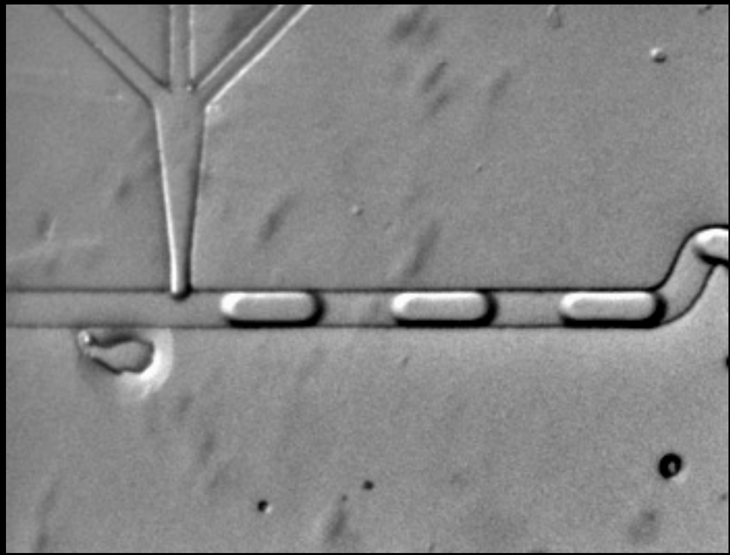
One of the seven $1 million prizes established by the Clay Mathematics Institute

Hurricane



River flow

Microfluidics



Air rings

$\Rightarrow$ solve numerically

But numerically expensive given scales involved

Global Climate Models resolution ~ 100 km

Numerical grid of a climate model

With 100km resolution, many processes need to be:

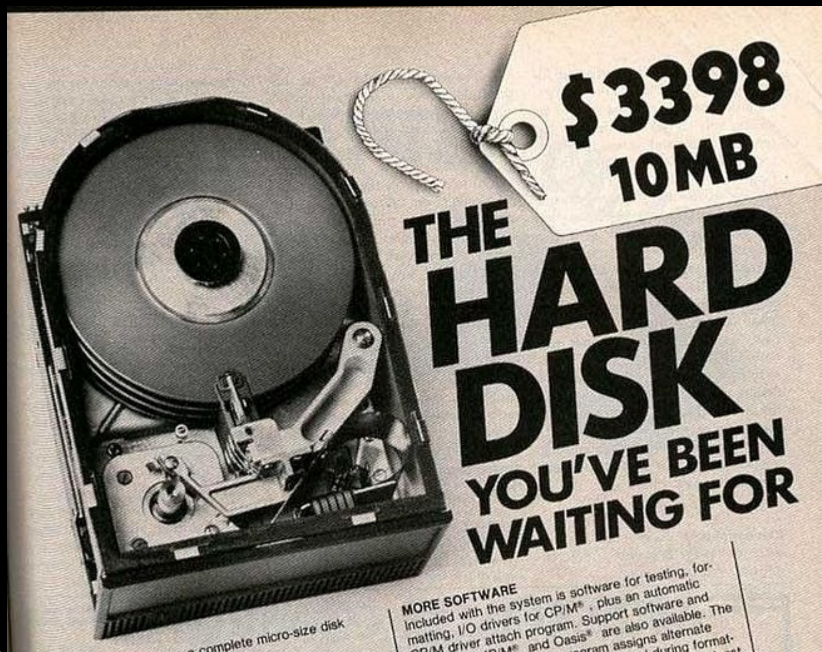
- better understood theoretically
- analyzed, particularly their impact on large scales
- parameterized if impact is important

But numerically expensive given scales involved

Global Climate Models resolution ~ 100 km

Numerical grid of a climate model

*Moore's law : computing power doubles every 2 years**
*& Cheaper memory**



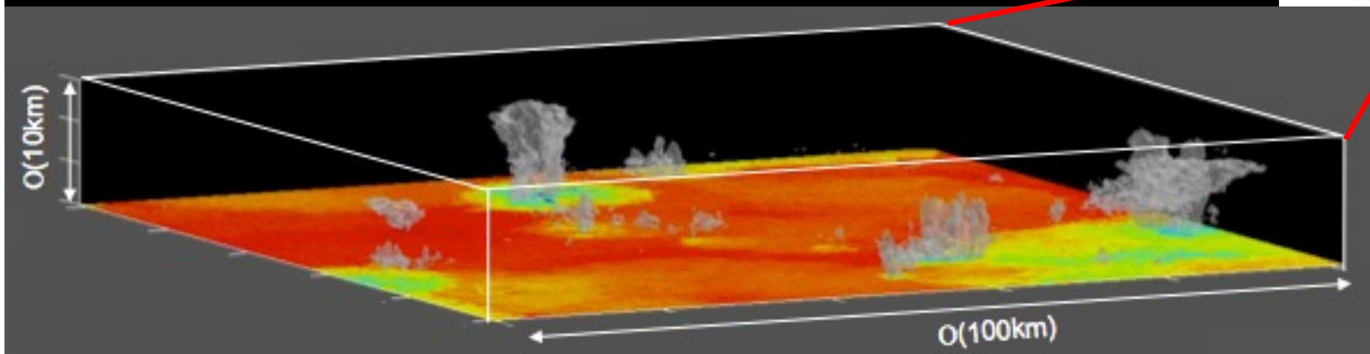
**Will come back to that …*

Two important examples:

Numerical grid of a climate model

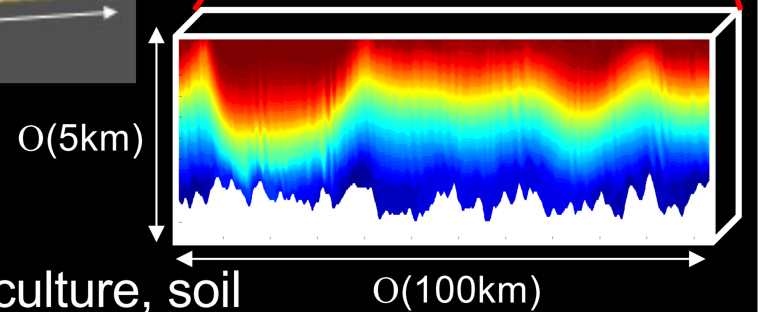
e.g. atmospheric convection, clouds and precipitation

Clouds



e.g. oceanic internal waves

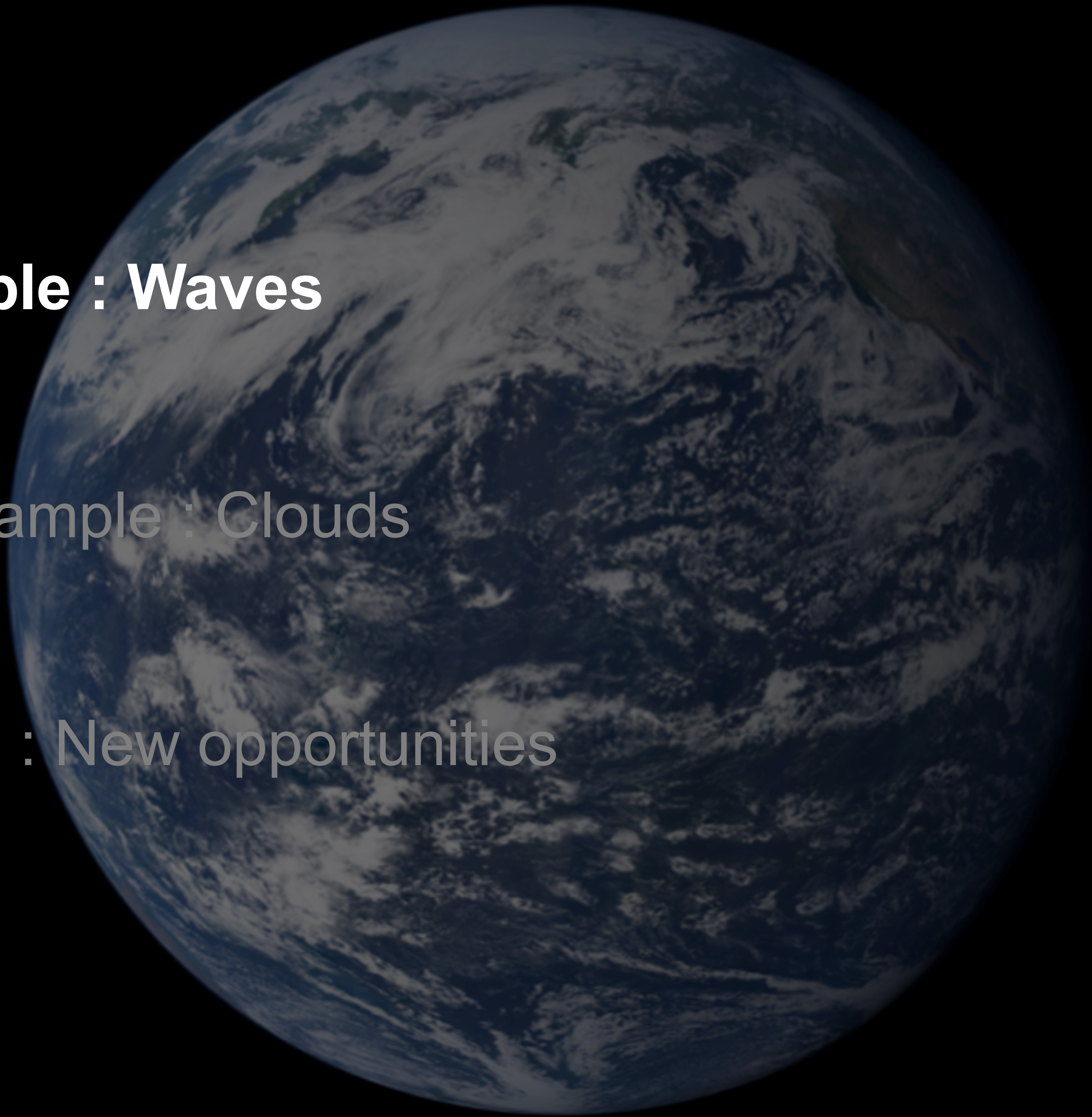
Temperature



but also:
ice, surface/atmosphere interactions (vegetation, agriculture, soil moisture, topography…), …

https://en.wikipedia.org/wiki/Parametrization_(atmospheric_modeling)

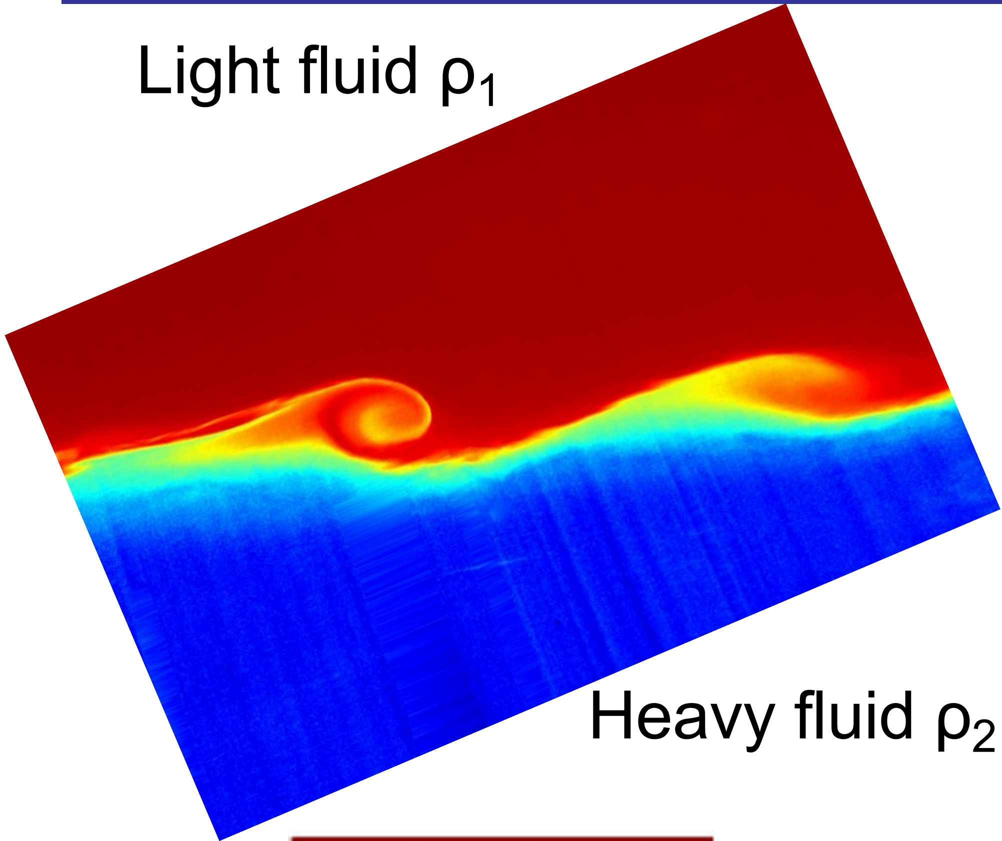
Outline



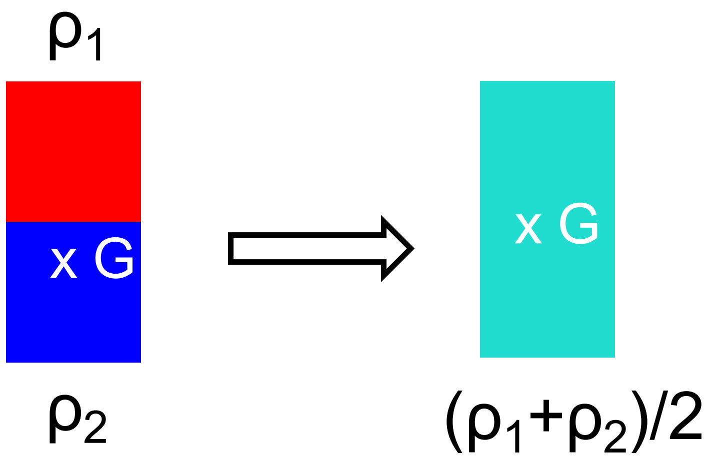
1. **Oceanic example : Waves**
2. Atmospheric example : Clouds
3. The road ahead : New opportunities

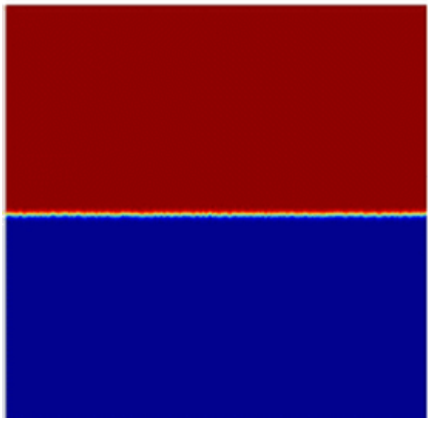
Internal waves: why do we care?

Light fluid ρ_1



Heavy fluid ρ_2





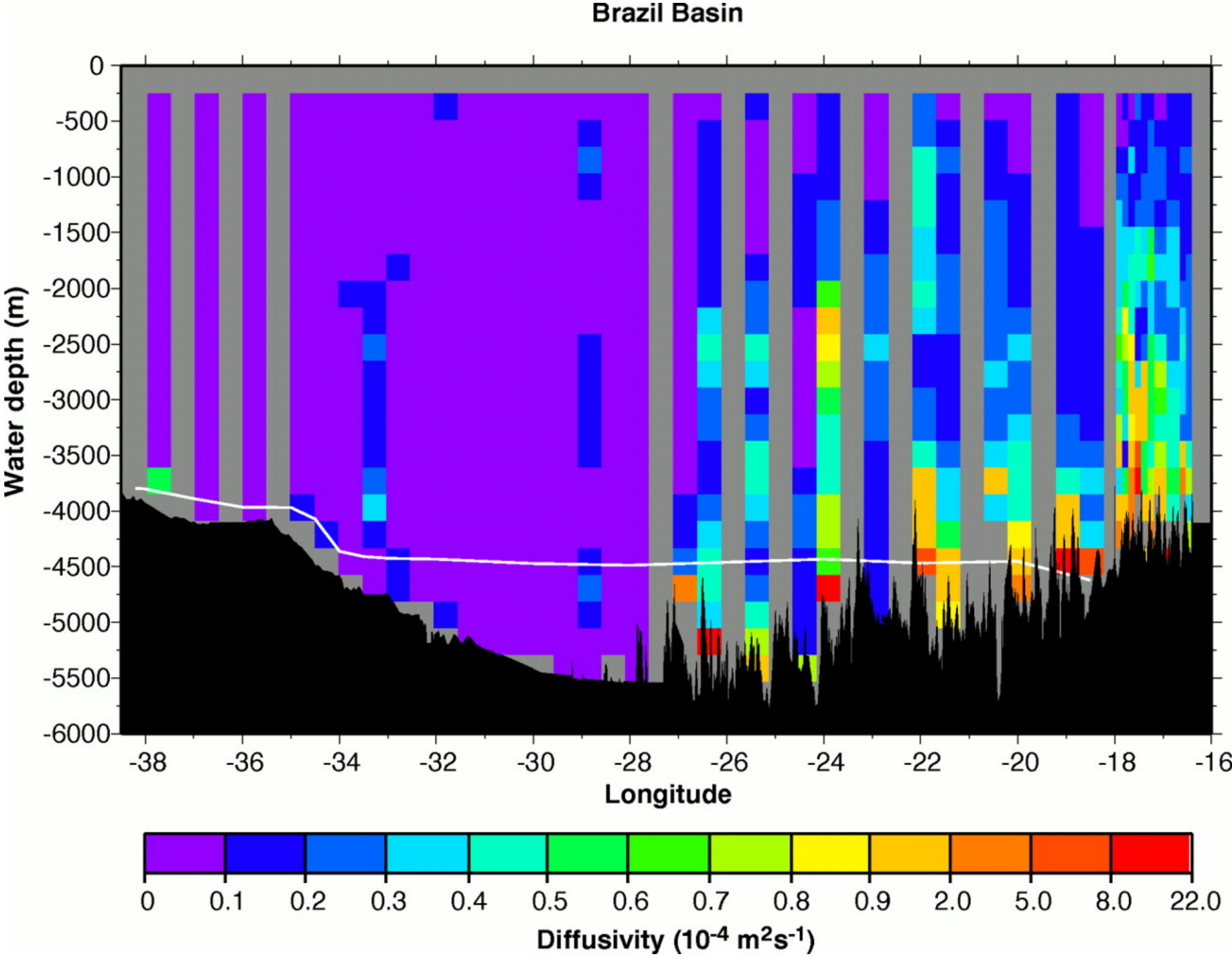
Center of gravity raised by vertical mixing

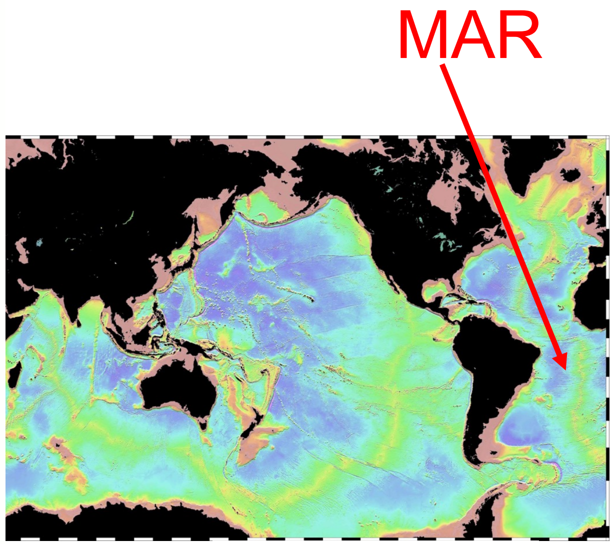
$\Rightarrow$ Energy lost by wave & gained by fluid

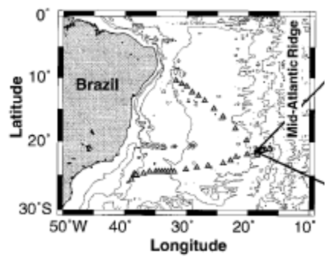
[Staquet & Sommeria 2002]

Internal waves: why do we care?

Observed enhanced vertical mixing above rough topography





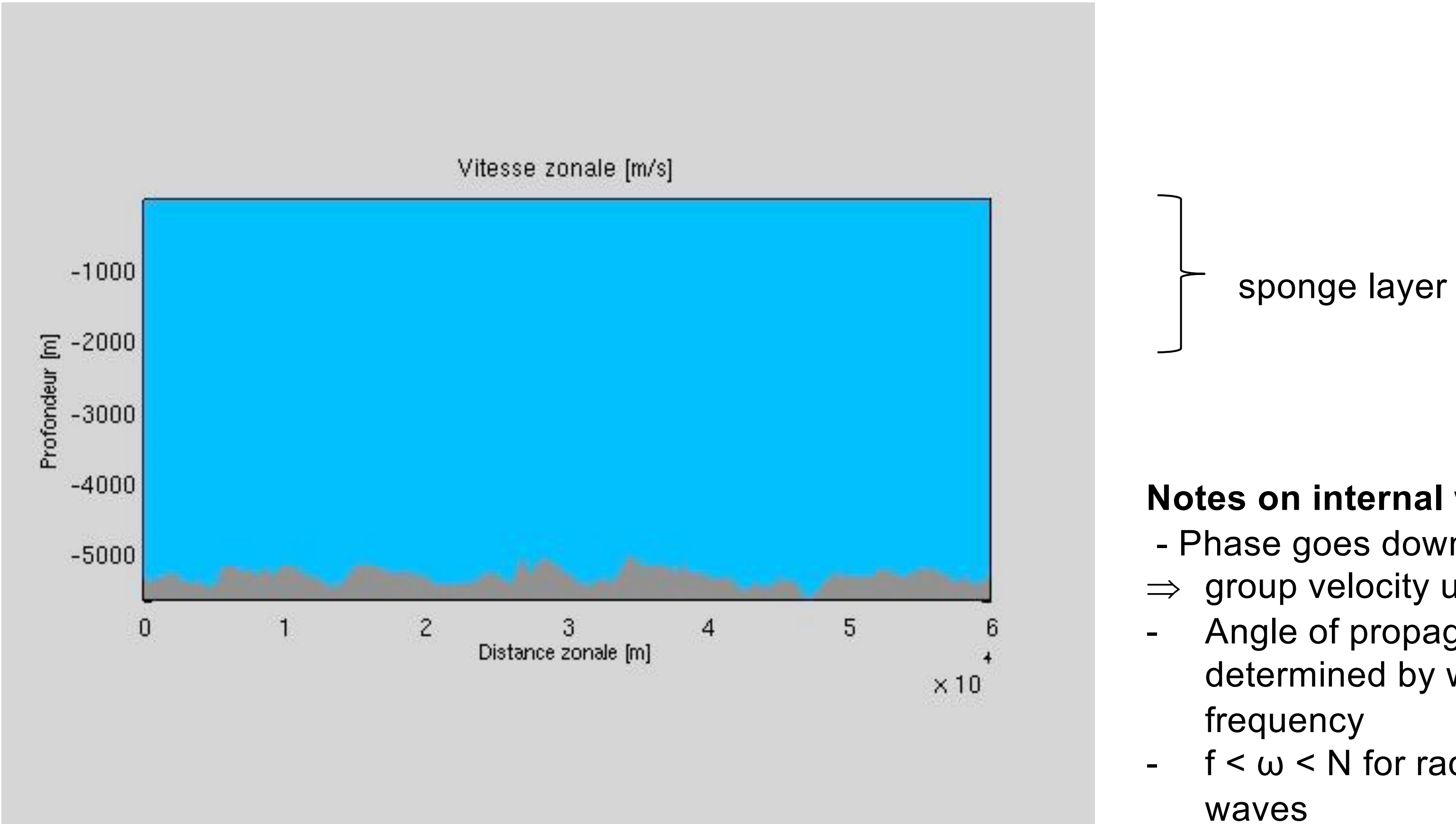


[Polzin, Toole, Ledwell and Schmitt, Science 97]

Internal waves: why do we care?

Internal tides = Internal waves in stratified fluid generated by the interaction between topography and the barotropic tide *[review Garrett & Kunze 2007]*

Internal tides in Direct Numerical Simulation with the model MITgcm



Notes on internal waves :

- Phase goes down

⇒ group velocity up

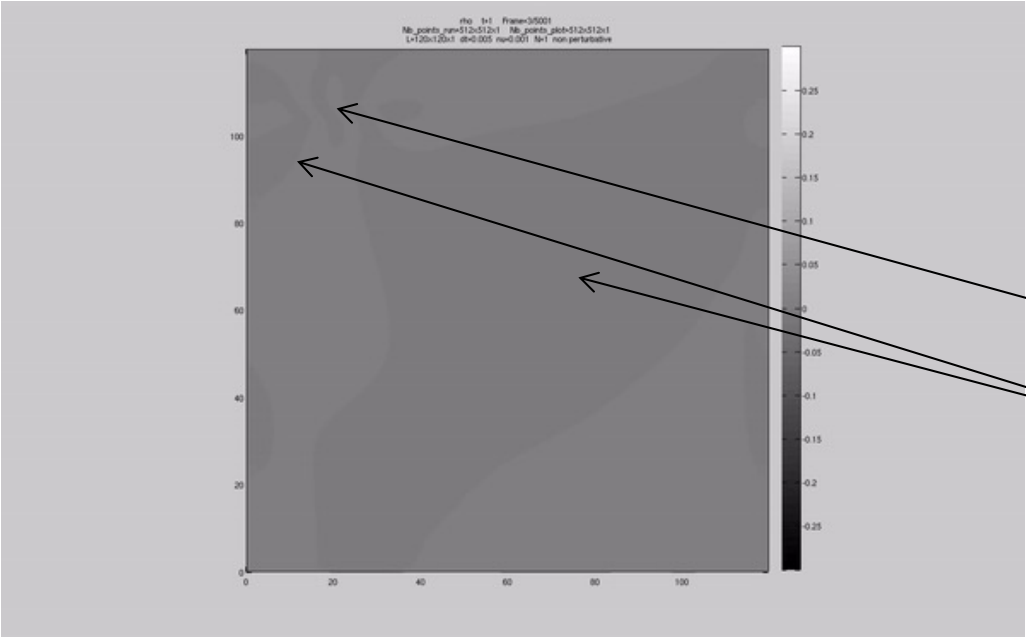
- Angle of propagation determined by wave frequency
- $f < \omega < N$ for radiating waves

Where/Why do they break ?

Nonlinearities: catastrophic dissipation via PSI?

Is there « catastrophic » dissipation at a critical latitude via PSI (Parametric Subharmonic Instability) ? *[McKinnon Winters 2005]*

Simulation of an unstable wave (courtesy Gaetan Lerisson, LadHyX)



Triadic resonant instability

- Instability mode of the form :

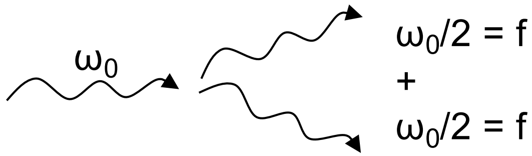
  $\vec{k_0} = \vec{k_1} + \vec{k_2}$

  $\omega_0 = \omega_1 + \omega_2$

0 ⇔ primary wave

1&2 ⇔ secondary waves

PSI = Parametric Subharmonic Instability



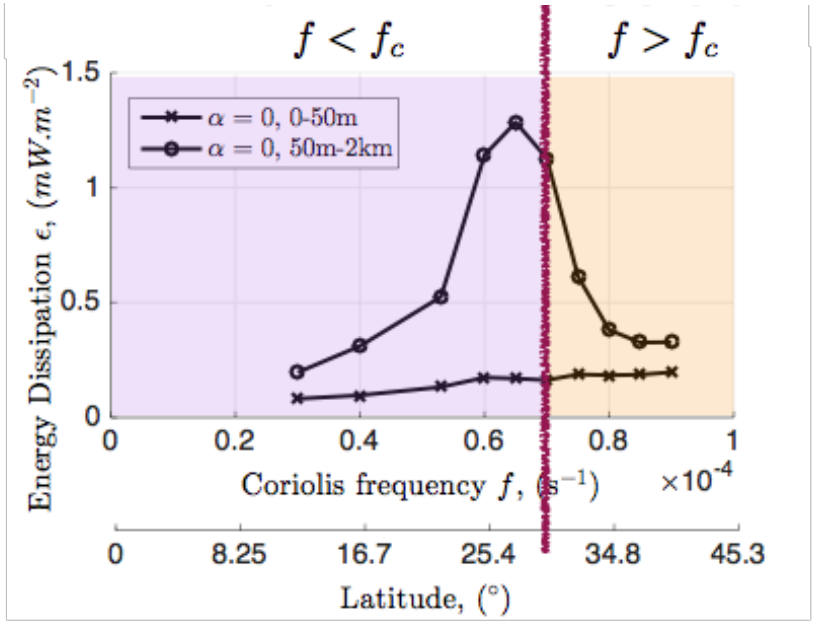
is a special case where : $\omega_1 = \omega_2 = \omega_0/2$

Critical latitude 29 deg ⇔ $f \sim \omega_0/2$ *(secondary waves are near-inertial waves)*

Nonlinearities: catastrophic dissipation via PSI?

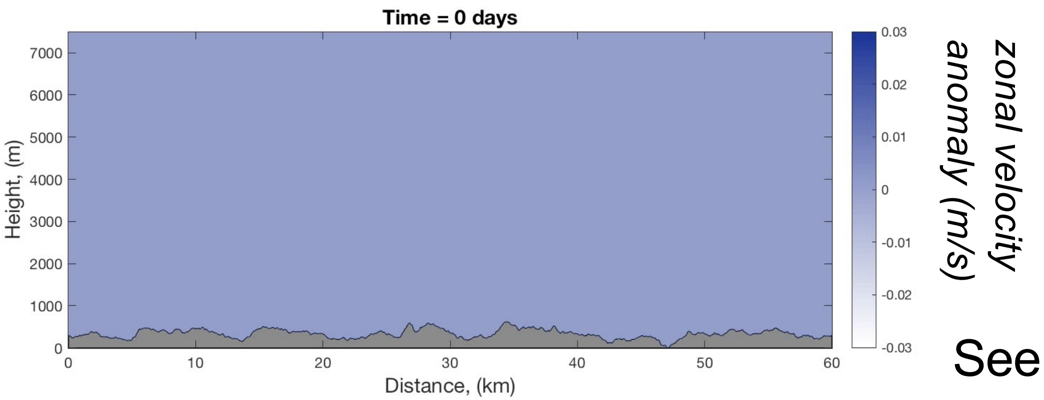
Enhanced dissipation at the critical latitude in simulations (MITgcm)

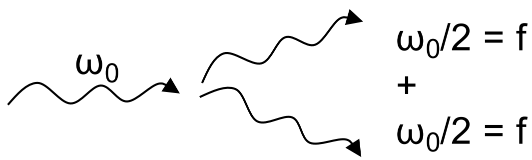
29 lat ⇔ $f_c \sim \omega_0 / 2$



[Nikurashin Legg 2011]

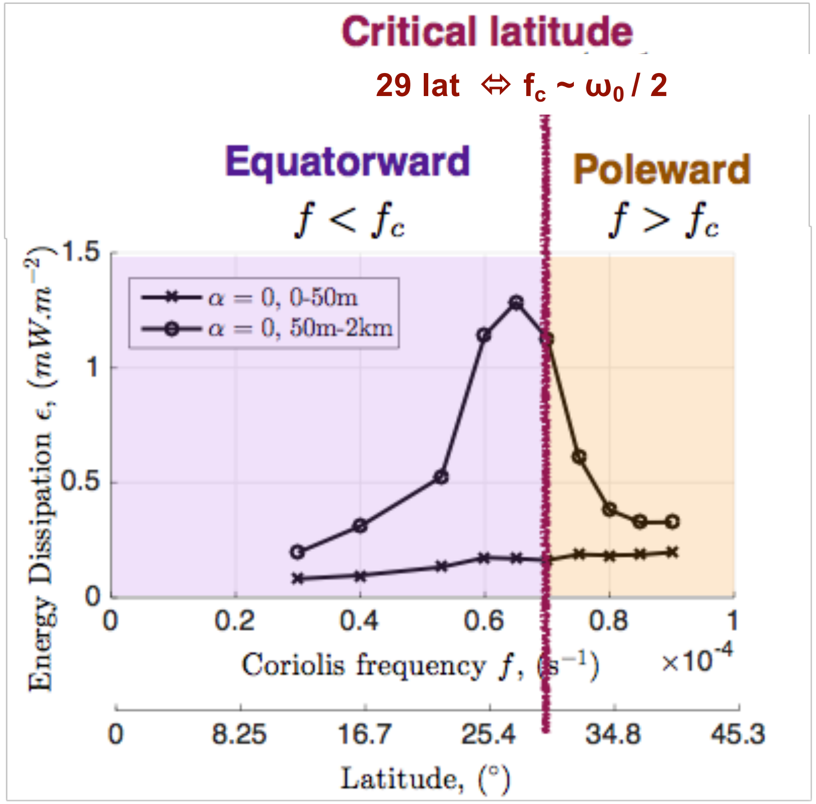
Simulation at the critical latitude => near-inertial waves visible *[courtesy: Océane Richet]*

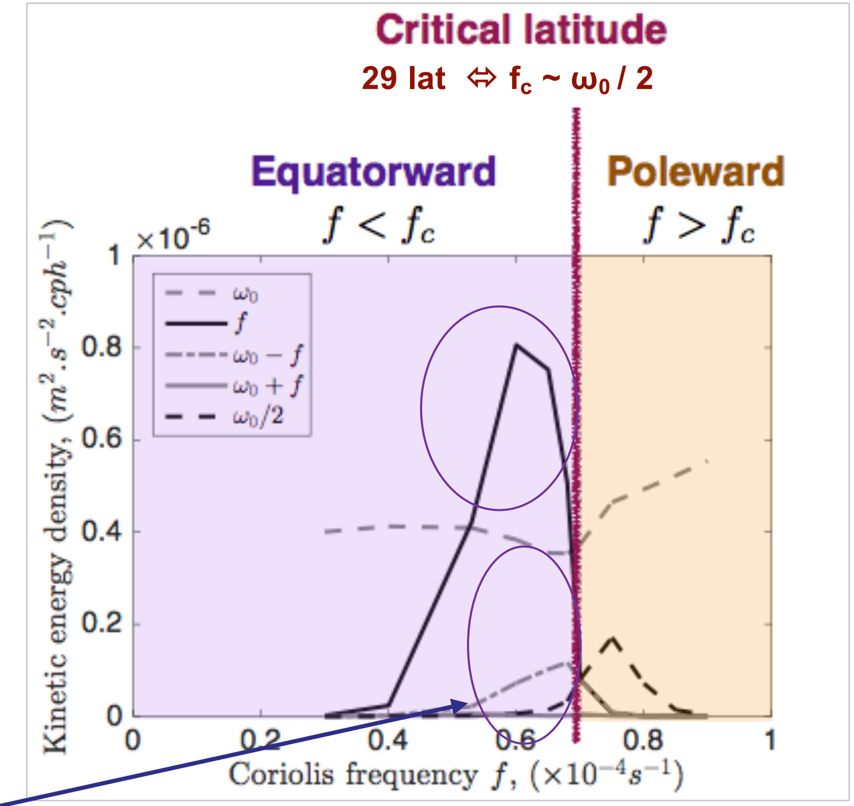




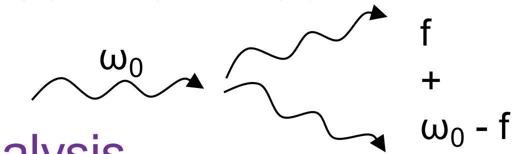
Seems consistent with PSI. Is it?

Nonlinearities: catastrophic dissipation via PSI?





⇒ Equatorward : dominant triad

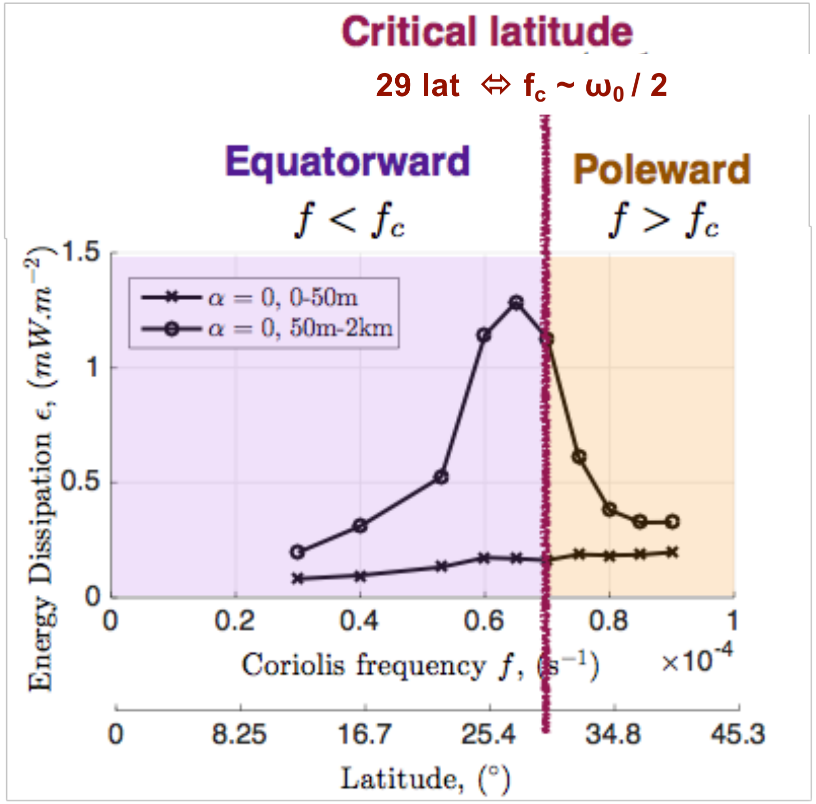


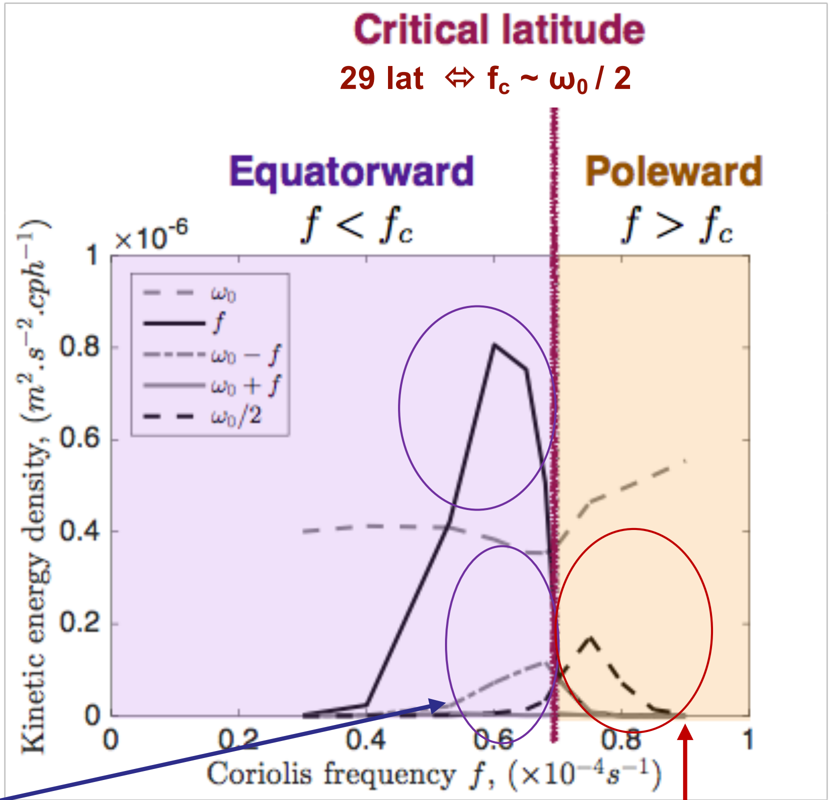
Linear Stability analysis

⇒ Enhanced dissipation because

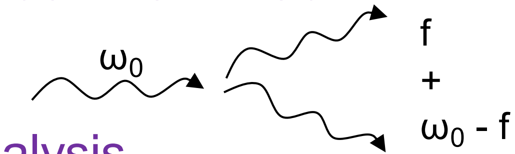
- increased growth rate of triadic resonant instability
- smaller scale waves

Nonlinearities: catastrophic dissipation via PSI?





⇒ Equatorward : dominant triad



Poleward : evanescent waves at $\omega_0/2$
i.e. near-inertial waves consistent with theoretical extension of PSI
[Young, Tsang, Balmforth, 2008]

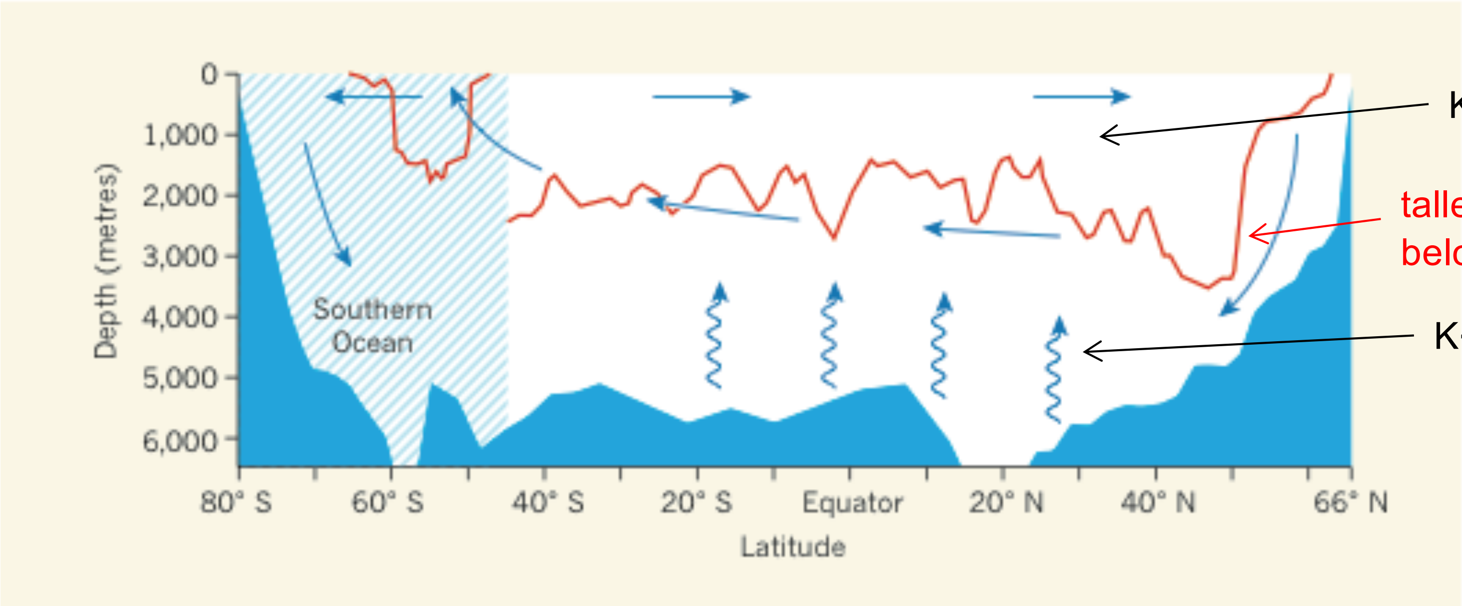
Linear Stability analysis
⇒ Enhanced dissipation because
- increased growth rate of triadic resonant instability
- smaller scale waves

Not robust to mean current (Doppler effects on 2ndary waves)

[Richet, Muller, Chomaz 2017; Richet Chomaz Muller 2018]

Emerging model of deep-ocean circulation

(from models and observations)



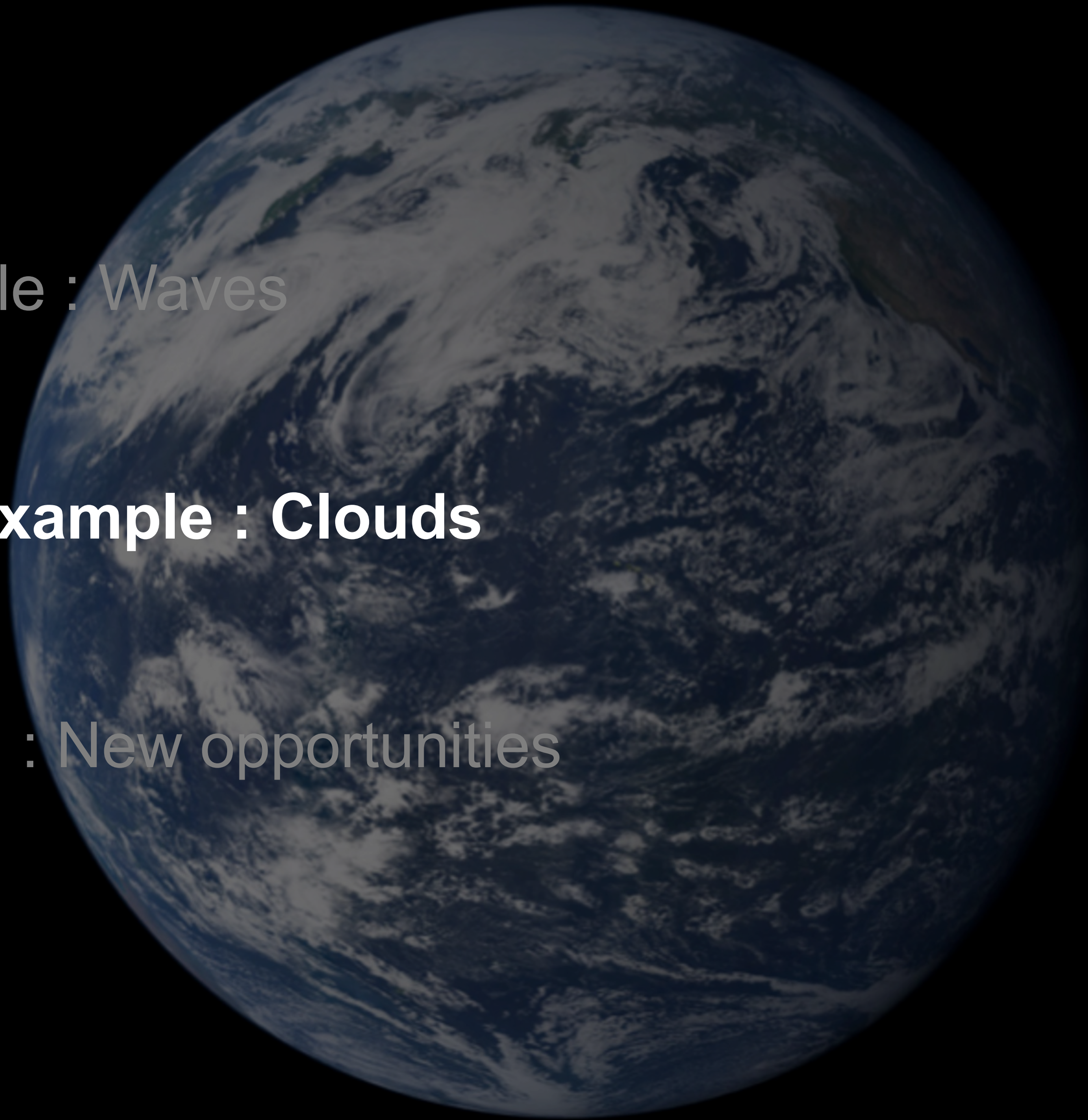
- dense Antarctic Bottom Water (AABW) sinks at high latitudes
- mixing processes lift up deep waters to mid-depths (~1000m - 2000m?)
- these deep waters return to the surface at these depths via the Southern Ocean

[Wunsch & Ferrari 2004; Lumpkin & Speer 2007; Ferrari 2014; Waterhouse et al 2014]

- BUT large uncertainty on spatial inhomogeneity of wave-induced mixing
- Remotely dissipating internal tides could contribute to AABW consumption : 1 to 28 Sv (!) depending on amount and vertical structure

[De Lavergne et al 2016 a; De Lavergne et al 2016 b]

Outline

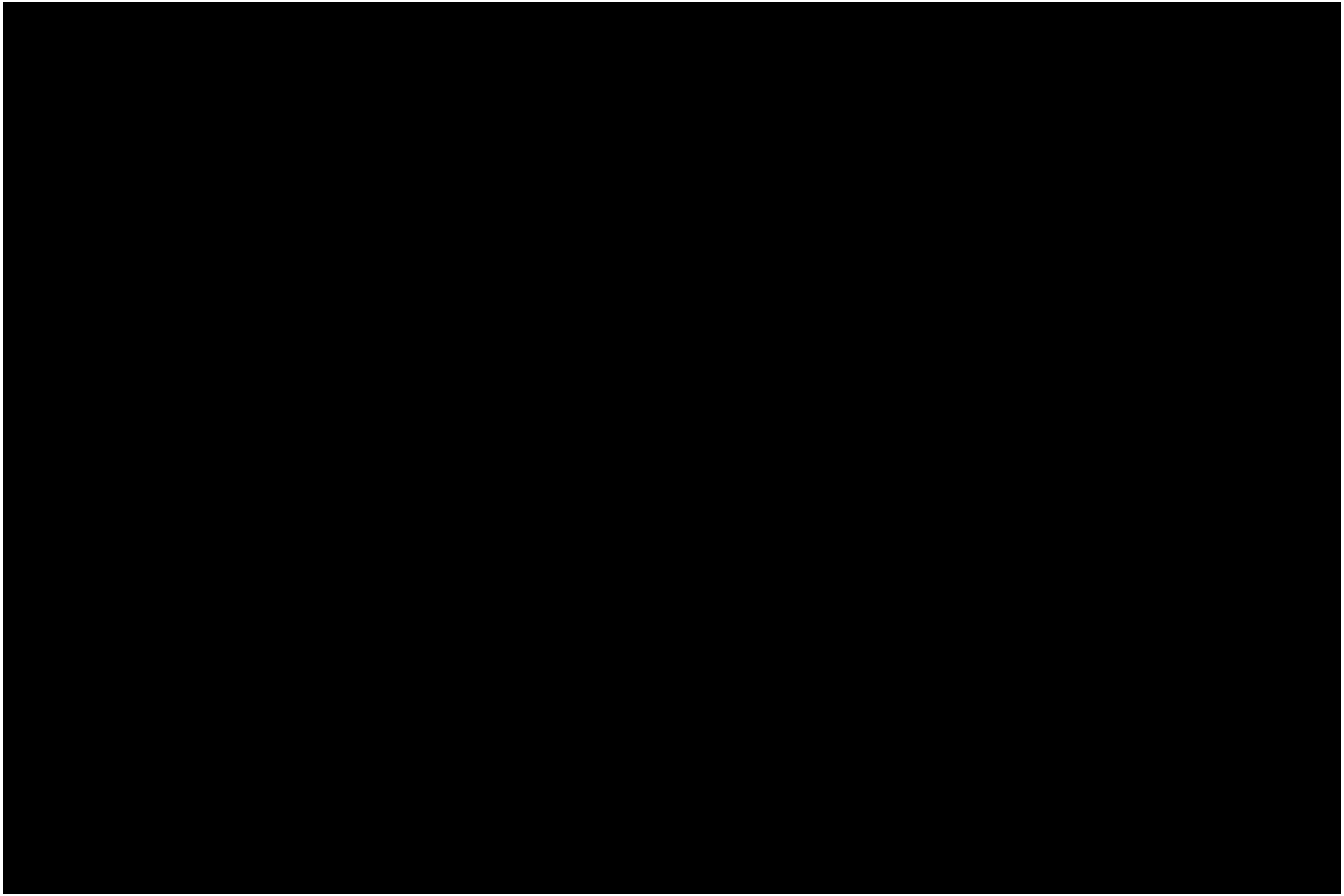


1. Oceanic example : Waves

2. **Atmospheric example : Clouds**

3. The road ahead : New opportunities

Courtesy: Octave Tessiot

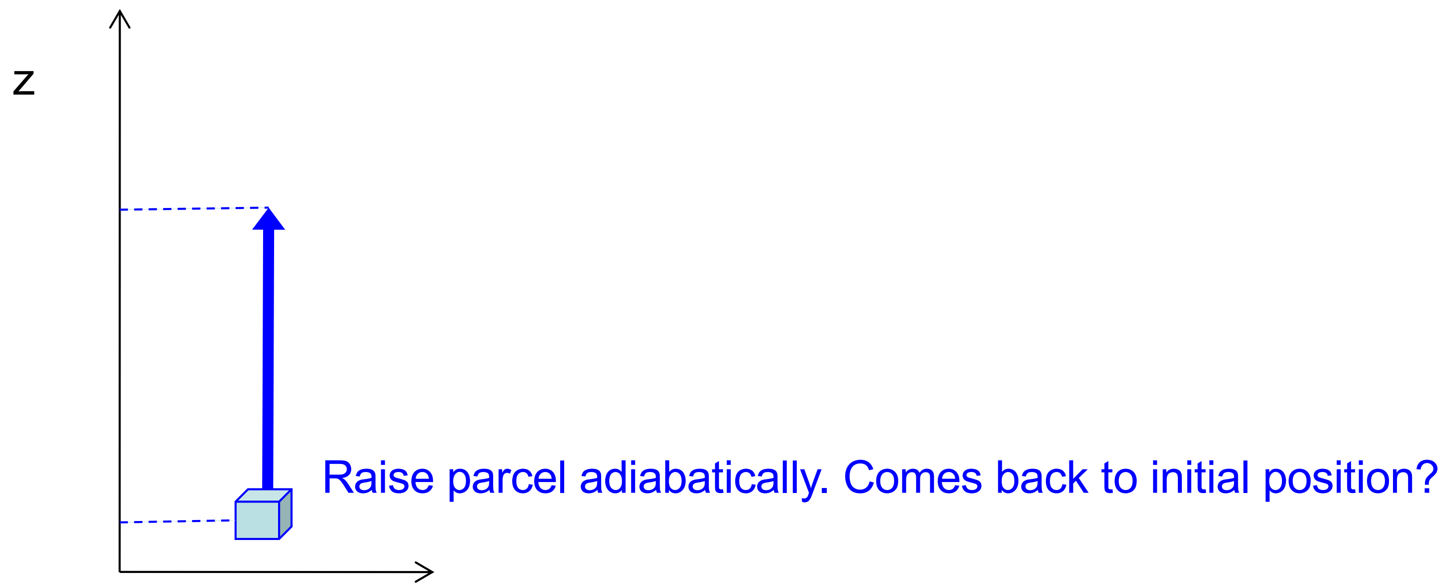


Courtesy : Octave Tessiot

Dry convection

T decreases with height.
But p as well.

Density = $\rho(T,p)$.
How determine stability? The parcel method

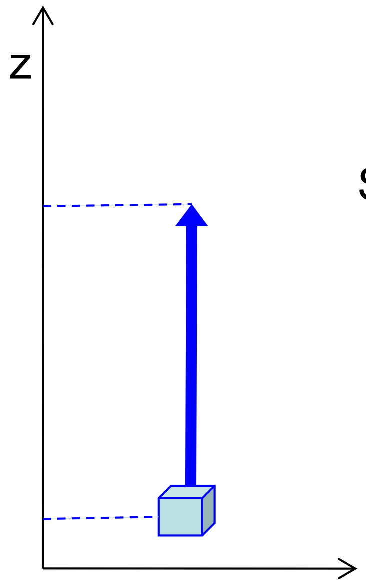


Dry convection

Potential temperature $\theta = T\,(p_0 / p)^{R/cp}$ conserved under adiabatic displacements :

Adiabatic displacement

1st law thermodynamics: d(internal energy) = Q (heat added) – W (work done by parcel)



$$c_p\, dT = 1/\rho\, d(p)$$

Since $p = \rho R T$, $\quad c_p\, dT / T = R\, dp / p$

$$\Rightarrow\ d\ \ln (T / p^{R/cp}) = 0$$

$$\Rightarrow\ T / p^{R/cp} = \text{constant}$$

Hence $\theta = T\,(p_0 / p)^{R/cp}$ potential temperature is conserved under adiabatic displacement

(R=gaz constant of dry air; c_p=specific heat capacity at constant pressure; $R/c_p \sim 0.286$ for air)

Moist convection

$$\frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} = -\nabla \frac{p}{\rho_0} + b\mathbf{z} + F^{\mathbf{u}}, \quad 1.$$

$$\nabla \cdot (\rho_0 \mathbf{u}) = 0, \quad 2.$$

$$\frac{1}{\theta_0}\frac{\mathrm{D}\theta}{\mathrm{D}t} + \frac{w}{\theta_0}\frac{\mathrm{d}\theta_0}{\mathrm{d}z} = \frac{1}{c_\mathrm{p} T}(\dot{\theta}_\mathrm{rad} + L_\mathrm{v}\dot{r}_\mathrm{l} + \dot{\theta}_\mathrm{sfc}) + F^{\theta}, \quad 3.$$

$$\frac{\mathrm{D}r}{\mathrm{D}t} = -\dot{r}_\mathrm{l} + \dot{r}_\mathrm{sfc} + F^{r}, \quad 4.$$

Reviews:
Stevens AREPS 2005;
Muller et al ARFM 2022

Equivalent potential temperature :

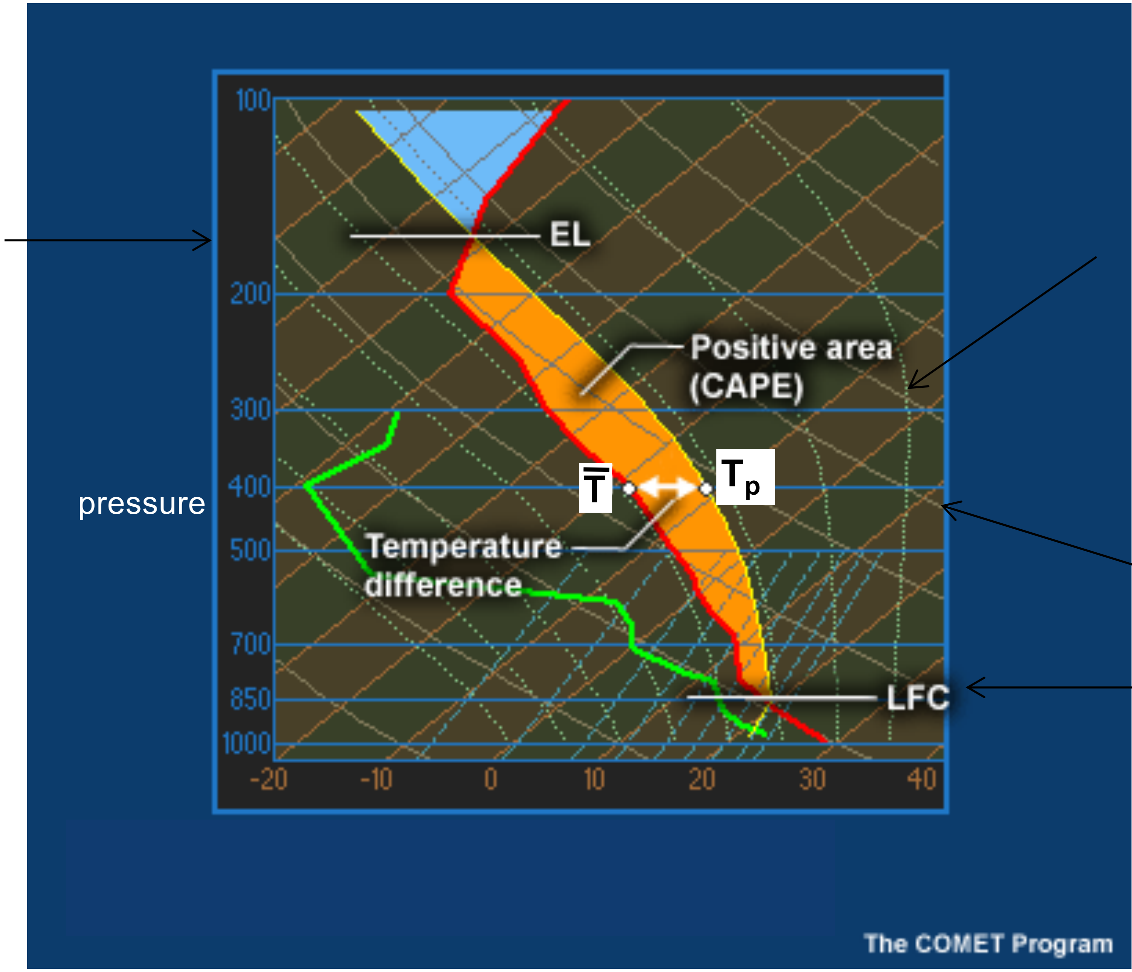
$\theta_e = T\,(p_0 / p)^{R/c_p}\, e^{L_v r_v / (c_p T)}$ approximately conserved under adiabatic displacements

When is an atmosphere unstable to moist convection ?

Skew T diagram (isoT slanted), atmospheric T in red

EL equilibrium level

Moist adiabat θ_e= cstt



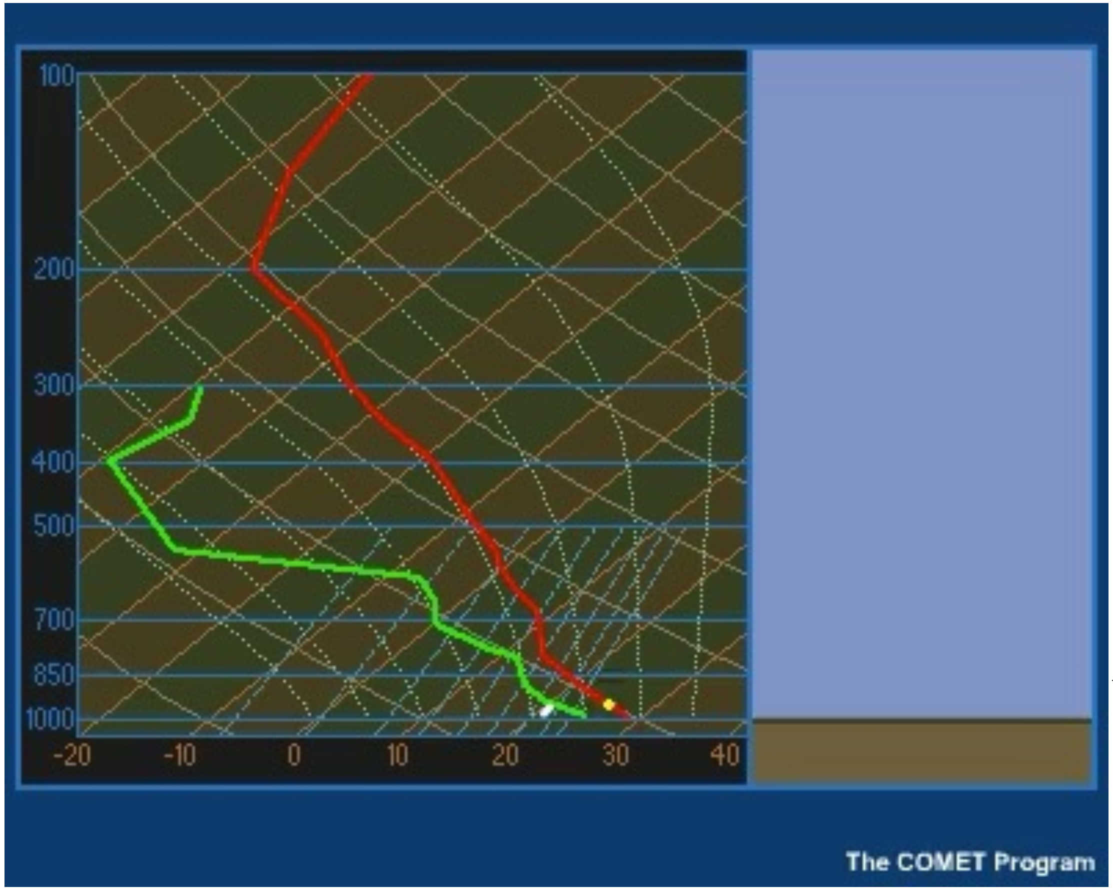
Dry adiabat θ = cstt

LFC level of free convection (= LCL lifted condensation level for simplicity)

CAPE: convective available potential energy

Parcel = yellow dot

EL equilibrium level

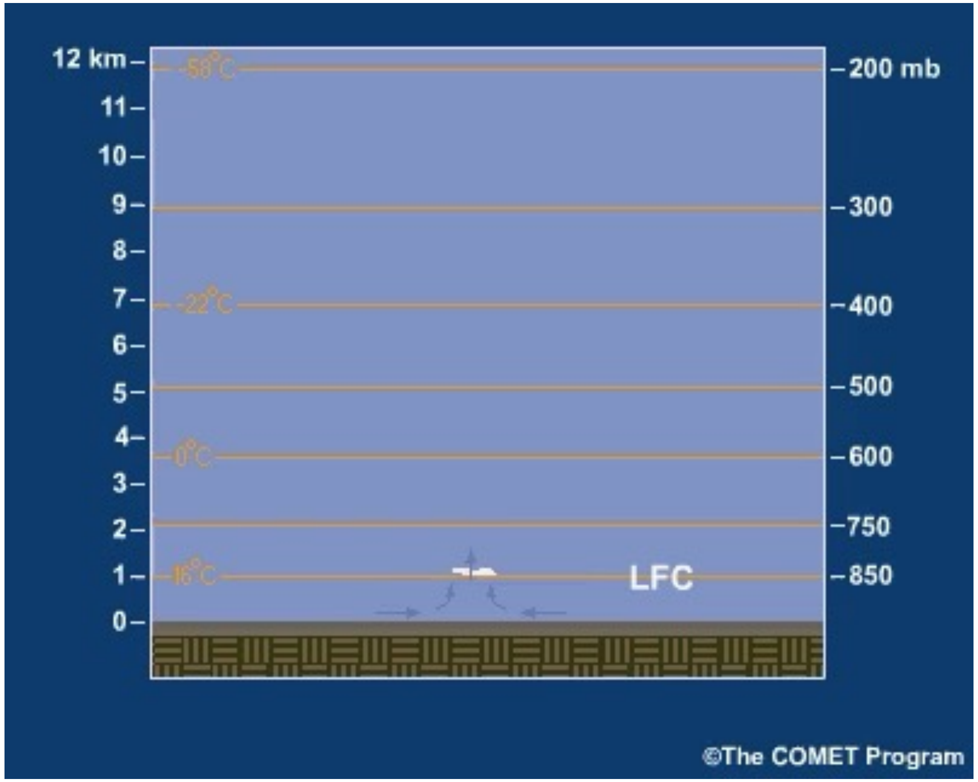


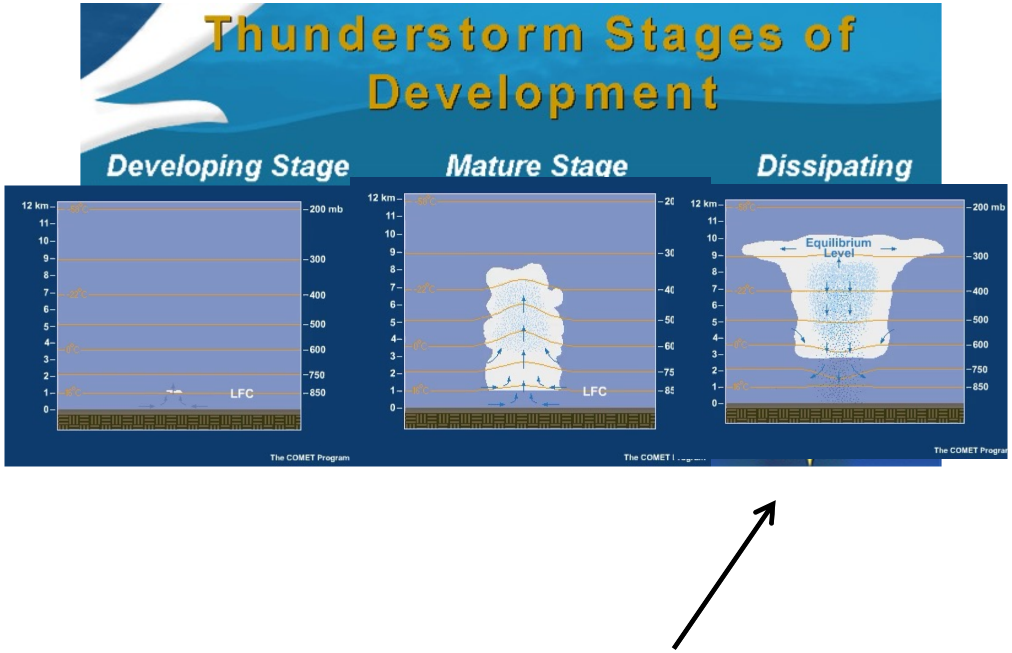
LFC level of free convection

CAPE: convective available potential energy

If enough atmospheric instability present, cumulus clouds are capable of producing serious storms!!!

Strong updrafts develop in the cumulus cloud => mature, deep cumulonimbus cloud. Associated with heavy rain, lightning and thunder.





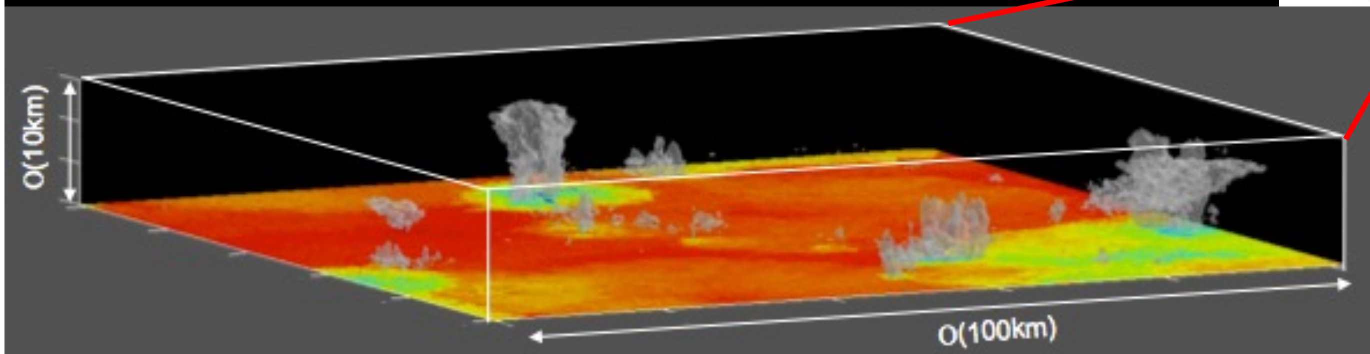
Evaporative driven cold pools

For more: see « atmospheric thermodynamics » by Bohren and Albrecht;
Houze book: « Cloud Dynamics »;
Muller – Cloud chapter, Les Houches Summer School Lecture Notes

Numerical grid of a climate model

e.g. atmospheric convection, clouds and precipitation

Clouds

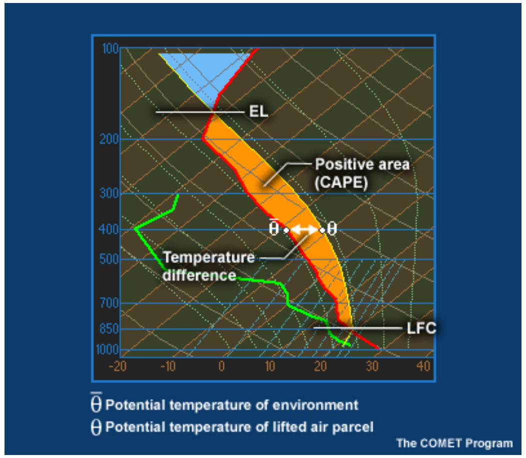


Convective parameterizations “mimic” moist convection

Key ingredients :

Moist convection consumes CAPE

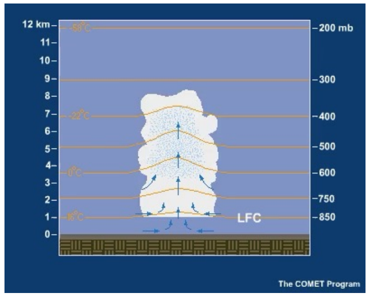
$$\frac{dCAPE}{dt} = -\frac{CAPE}{\tau}$$



Arakawa Schubert 1974

Moist convection (M_u=upward mass flux) acts as an entraining plume

$$\frac{\partial Mu}{dz} = M_u\ (\varepsilon - \delta)$$



Hohenegger Bretherton 2011

Numerical grid of a climate model

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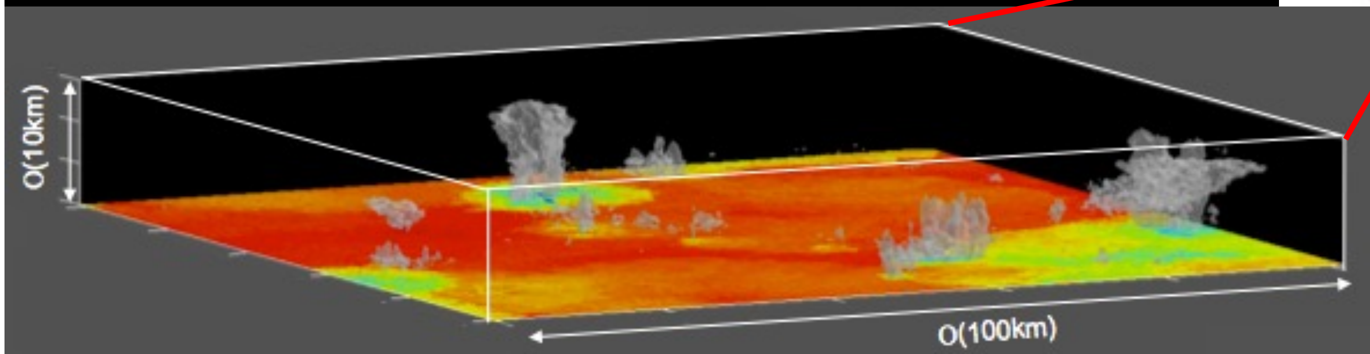
Clouds



$$\frac{dCAPE}{dt} = -\frac{CAPE}{\tau}$$

Should be the same over ocean and land?

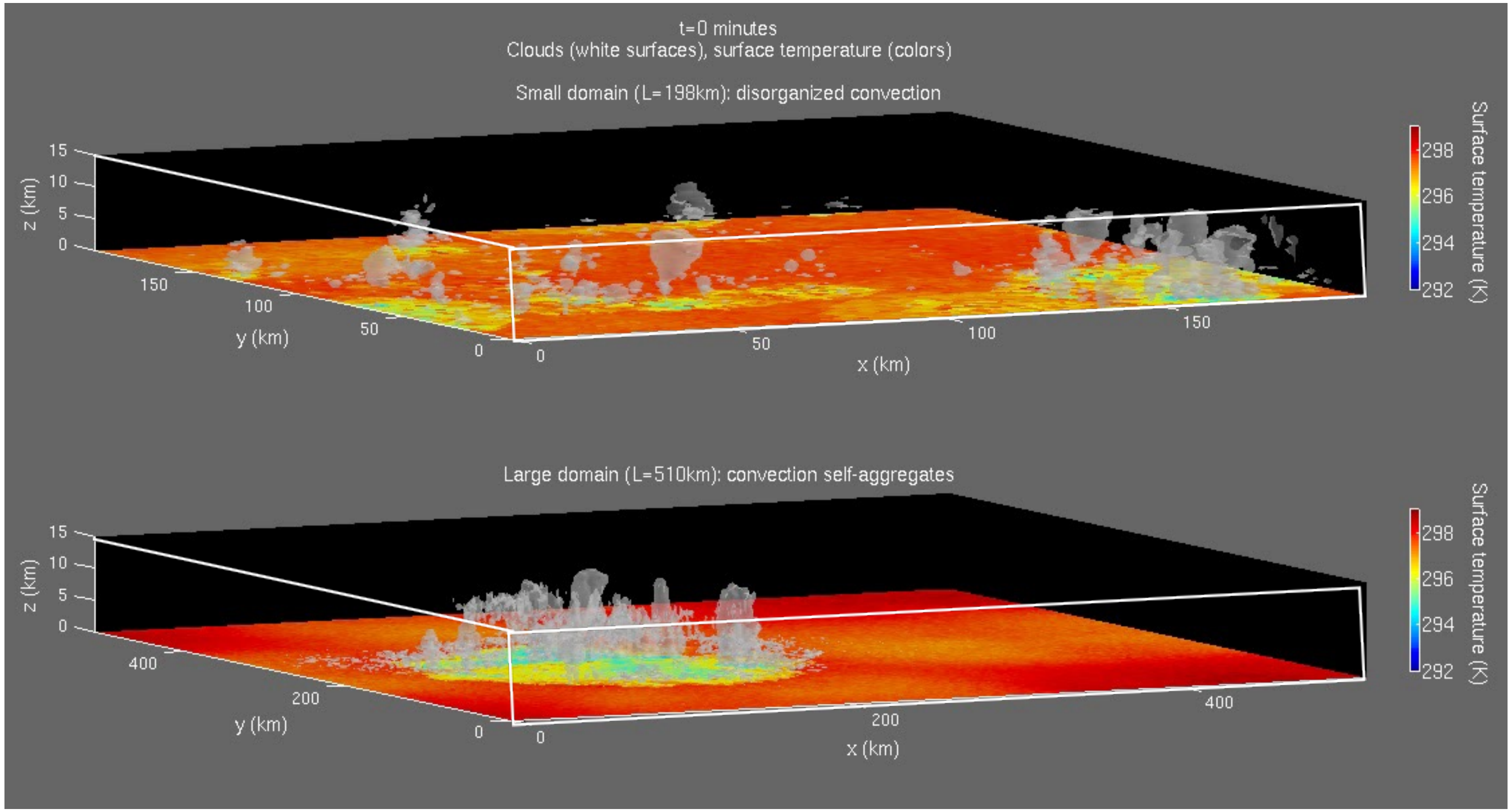
Goswami et al, in prep

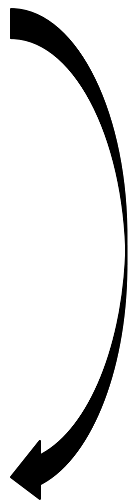
Does convection only depend on large-scale mean properties?

Mapes Neale 2011;
Hwong et al, submitted

Self-aggregation

Clouds over near-surface temperature in cloud-resolving model SAM *[Khairoutdinov & Randall, JAS 2003]*





- SST=300K uniform
- Doubly periodic
- No Coriolis (f=0)
- No large-scale forcing

Self Aggregation = Instability of disorganized Radiative-Convective Equilibrium "pop corn" state

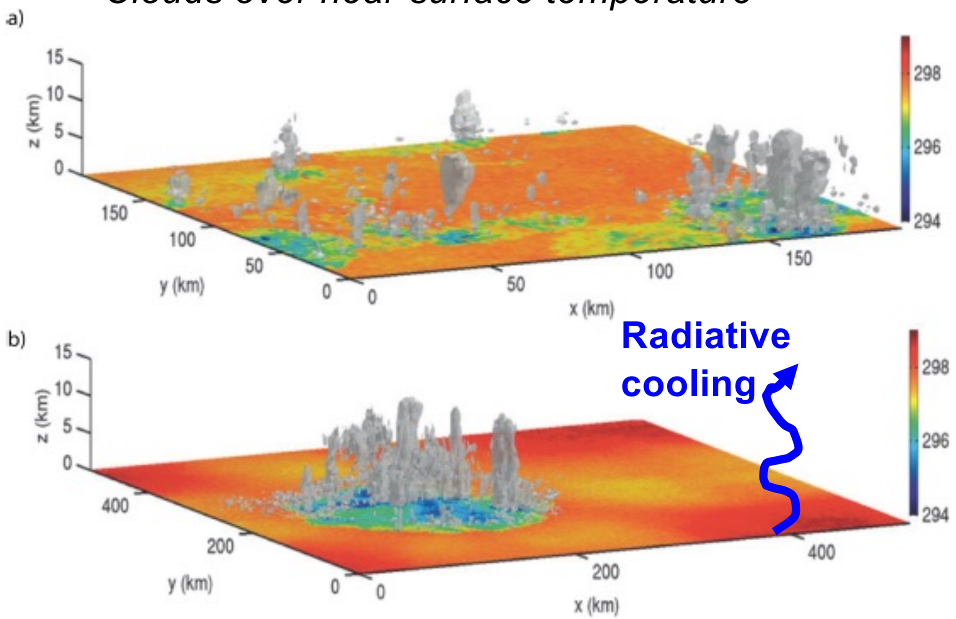
[Bretherton, Blossey, Khairoutdinov, 2005; Muller, Held 2012; Emanuel, Wing, Vincent 2013; Wing Emanuel 2013; Jeevanjee Romps 2013; Khairoutdinov Emanuel, 2013; Shi Bretherton 2014; Tobin, Bony, Roca, 2012; Tobin et al, 2013; Muller Bony 2015; Arnold Randall 2015; Coppin Bony 2015; Mapes 2016; Holloway Woolnough 2016; Tompkins Semie 2017; Wing Holloway Emanuel Muller 2017; Becker Bretherton Hohenegger Stevens 2018; Muller Romps 2018; Fildier et al 2021; Muller et al 2022 ARFM …]

Self-aggregation

⇒ Need to understand dynamics of mesoscale systems

Cloud-Resolving Model (CRM) "SAM" *[Khairoutdinov, M.F. and Randall, D.A., JAS 2003]*

Clouds over near-surface temperature



[Muller et al ARFM 2022]

Aggregation linked to radiative peak

$$\mathscr{H}^{\dagger} = -\frac{g}{C_p}\frac{1+\alpha}{p^{\dagger}}\frac{\varphi_s}{\varphi_t}\pi\tilde{B}\frac{\Delta\tilde{\nu}}{e}$$

[Fildier, Muller, Pincus, Fueglistaler 2023]

Self-aggregation

⇒ Need to understand dynamics of mesoscale systems
⇒ And links with precip extremes…

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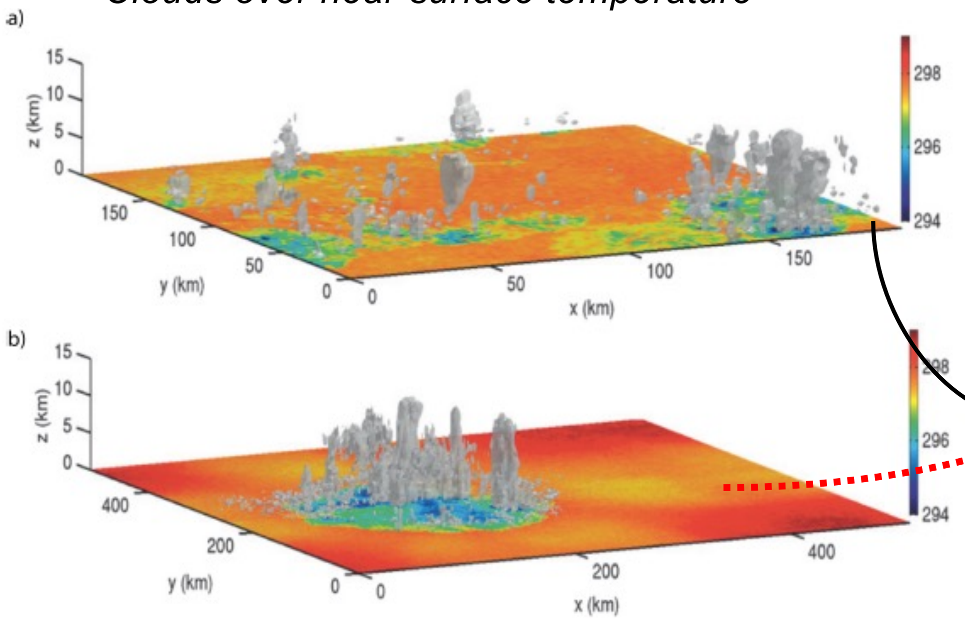
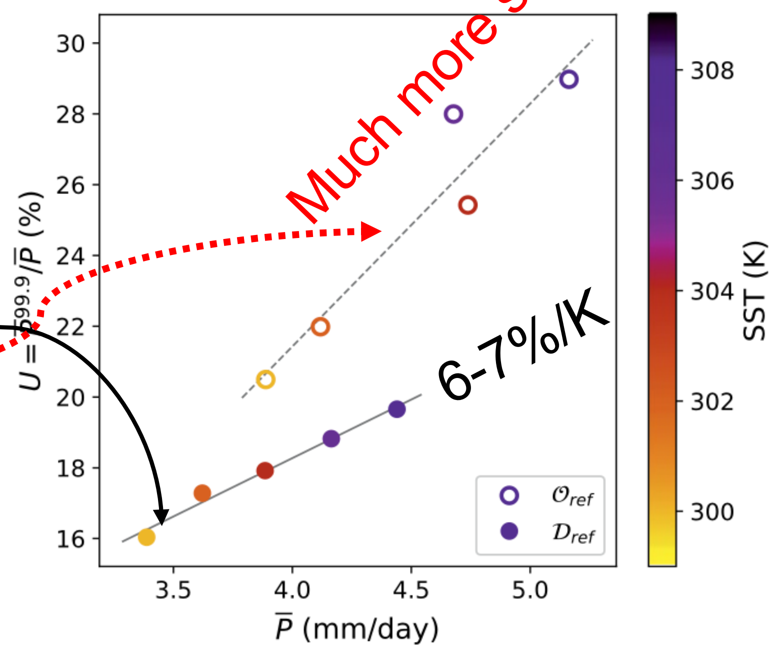
Clouds over near-surface temperature



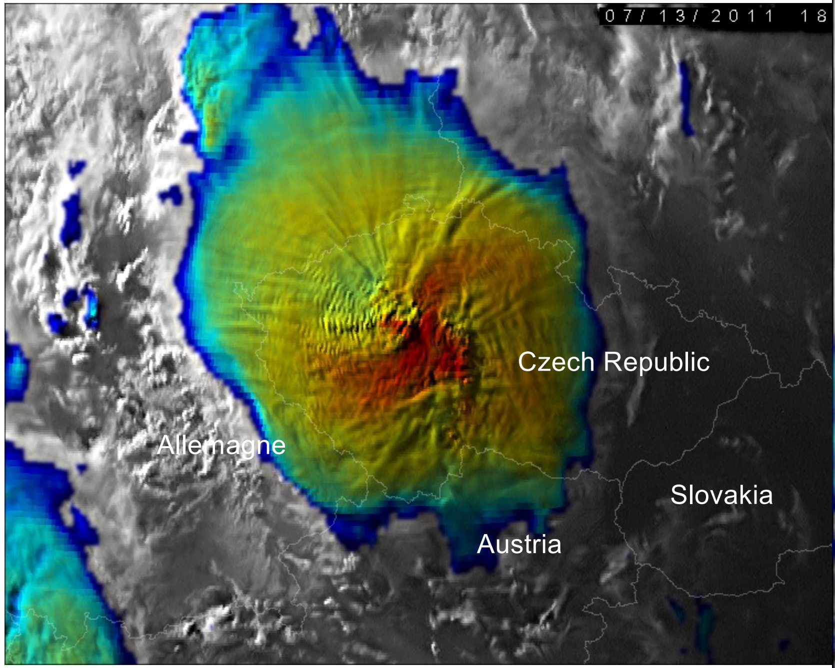


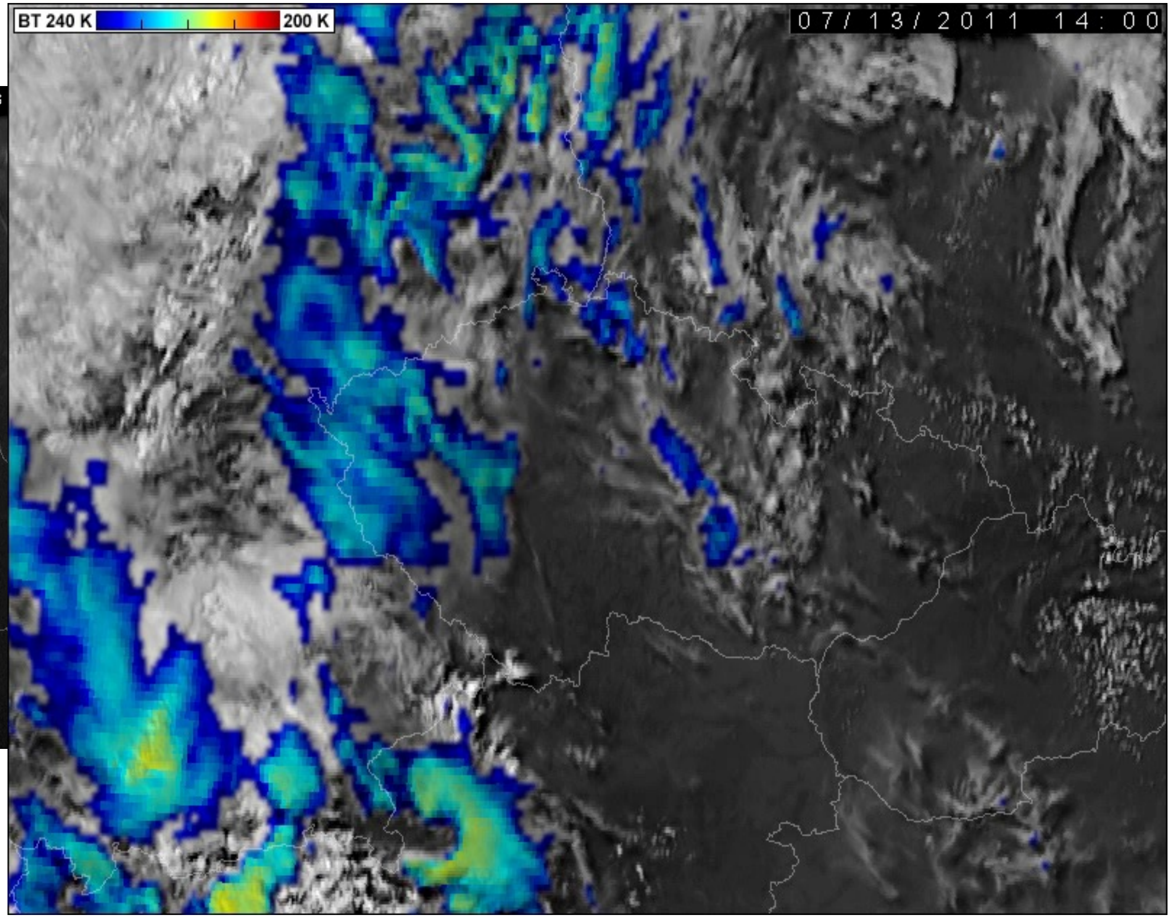
Much more sensitive to warming!

[Fildier Collins Muller 2021]

Convective organization: MCCs

Mesoscale convective systems: include Mesoscale Convective Complexes (MCCs), squall lines, hurricanes…





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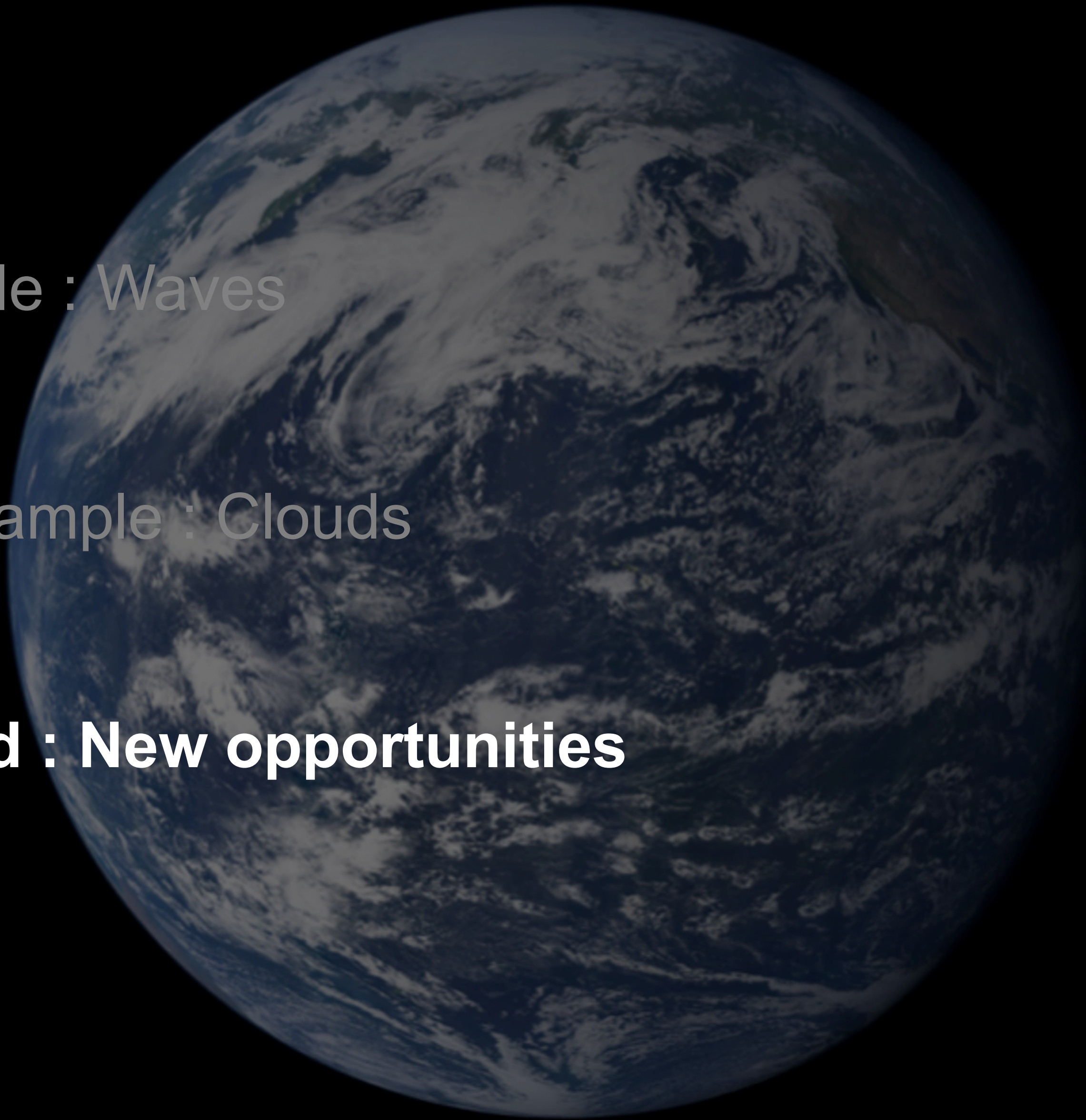
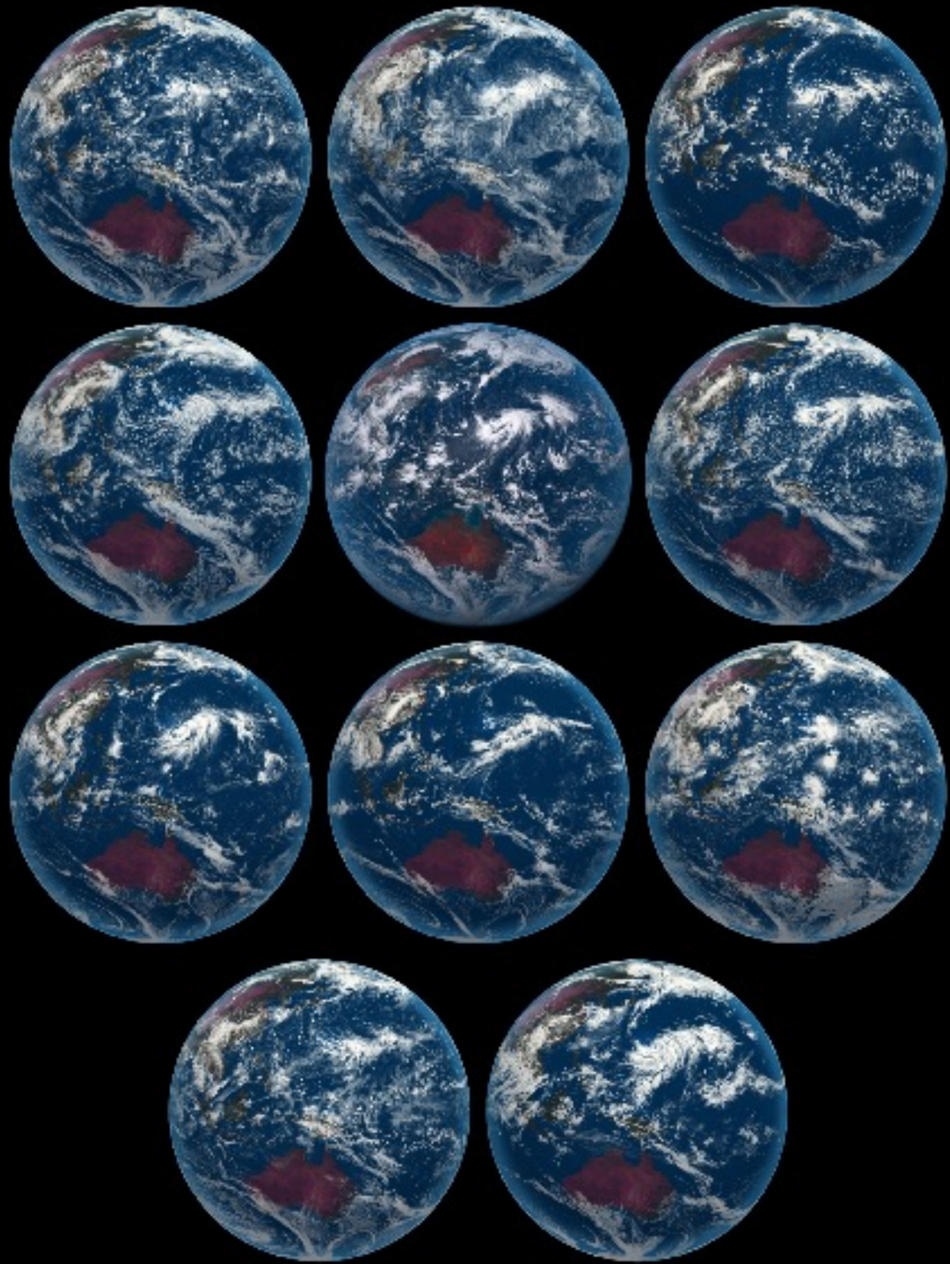
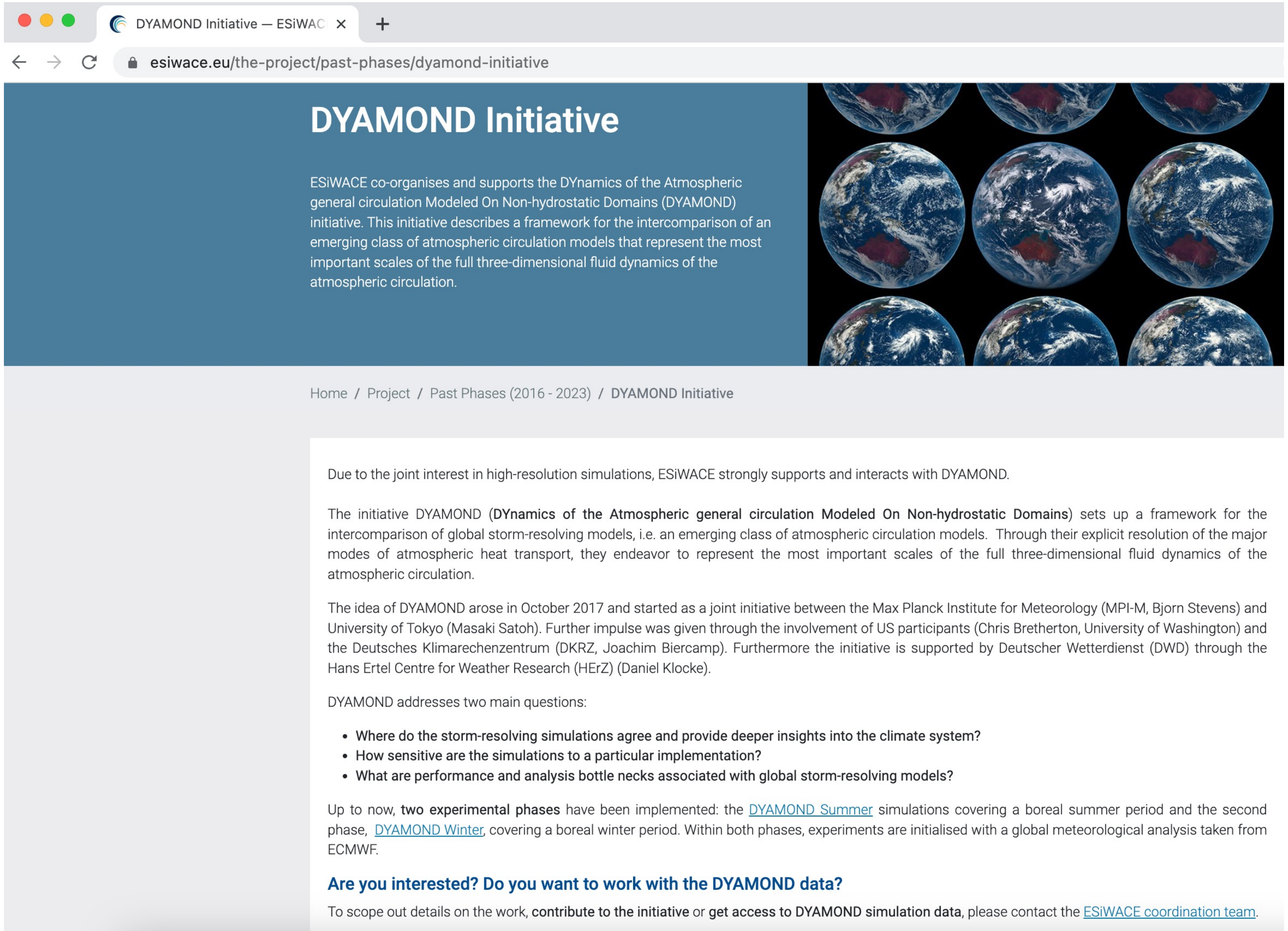
2. Atmospheric example : Clouds
3. **The road ahead : New opportunities**





Stevens et al 2019

Dyamond : ~1 month. ~3-5 km resolution. All open access on dkrz :
https://www.esiwace.eu/the-project/past-phases/dyamond-initiative



DYAMOND Initiative — ESiWAC

esiwace.eu/the-project/past-phases/dyamond-initiative

DYAMOND Initiative

ESiWACE co-organises and supports the DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains (DYAMOND) initiative. This initiative describes a framework for the intercomparison of an emerging class of atmospheric circulation models that represent the most important scales of the full three-dimensional fluid dynamics of the atmospheric circulation.

Home / Project / Past Phases (2016 - 2023) / **DYAMOND Initiative**

Due to the joint interest in high-resolution simulations, ESiWACE strongly supports and interacts with DYAMOND.

The initiative DYAMOND (**DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains**) sets up a framework for the intercomparison of global storm-resolving models, i.e. an emerging class of atmospheric circulation models. Through their explicit resolution of the major modes of atmospheric heat transport, they endeavor to represent the most important scales of the full three-dimensional fluid dynamics of the atmospheric circulation.

The idea of DYAMOND arose in October 2017 and started as a joint initiative between the Max Planck Institute for Meteorology (MPI-M, Bjorn Stevens) and University of Tokyo (Masaki Satoh). Further impulse was given through the involvement of US participants (Chris Bretherton, University of Washington) and the Deutsches Klimarechenzentrum (DKRZ, Joachim Biercamp). Furthermore the initiative is supported by Deutscher Wetterdienst (DWD) through the Hans Ertel Centre for Weather Research (HErZ) (Daniel Klocke).

DYAMOND addresses two main questions:

- **Where do the storm-resolving simulations agree and provide deeper insights into the climate system?**
- **How sensitive are the simulations to a particular implementation?**
- **What are performance and analysis bottle necks associated with global storm-resolving models?**

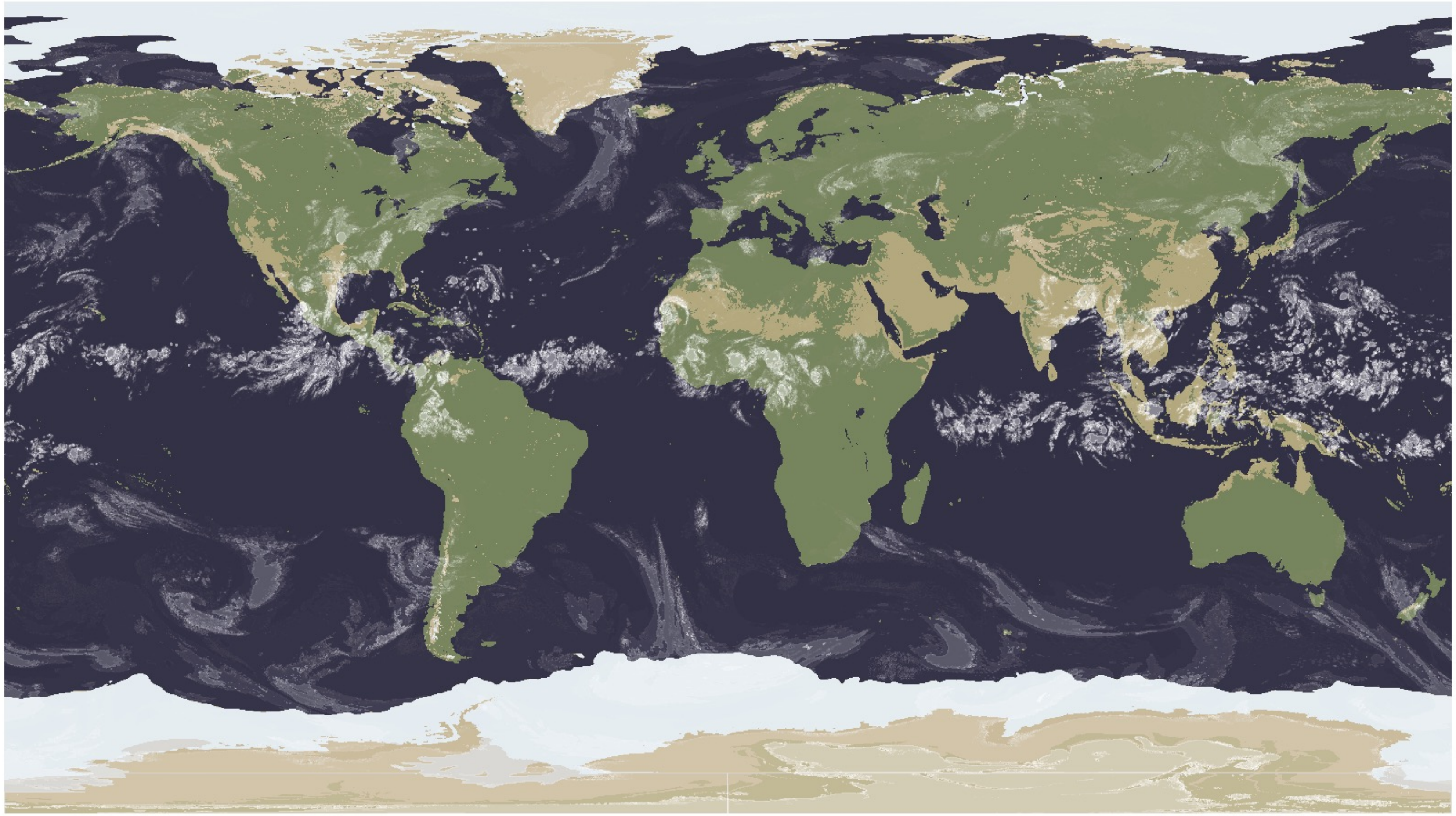
Up to now, **two experimental phases** have been implemented: the DYAMOND Summer simulations covering a boreal summer period and the second phase, DYAMOND Winter, covering a boreal winter period. Within both phases, experiments are initialised with a global meteorological analysis taken from ECMWF.

Are you interested? Do you want to work with the DYAMOND data?

To scope out details on the work, **contribute to the initiative** or **get access to DYAMOND simulation data**, please contact the ESiWACE coordination team.

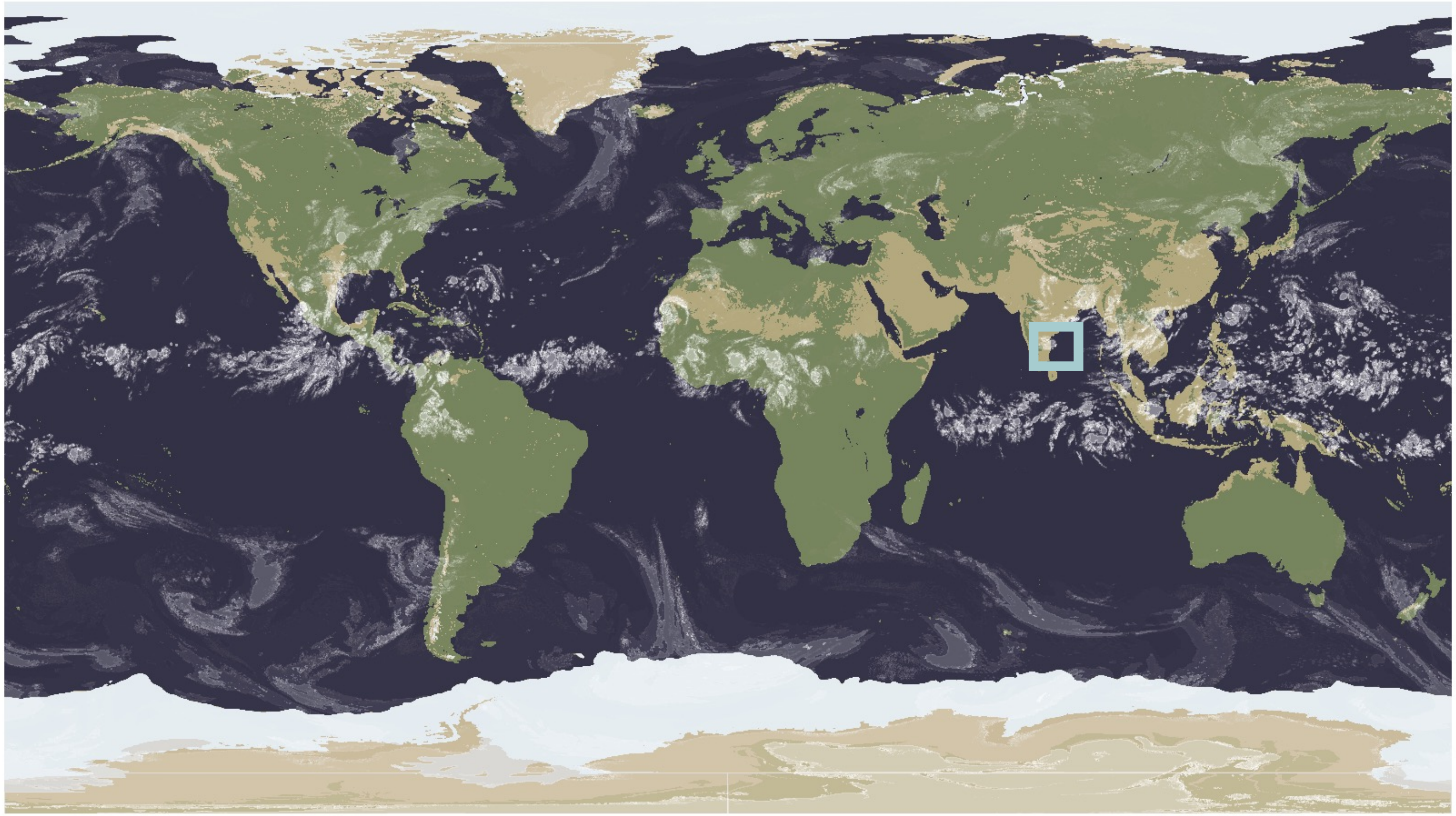
NextGems : 2 models. 30 years. <5 km res

Dyamond SAM Simulations



Courtesy: Sophie Abramian

Dyamond SAM Simulations



Courtesy: Sophie Abramian

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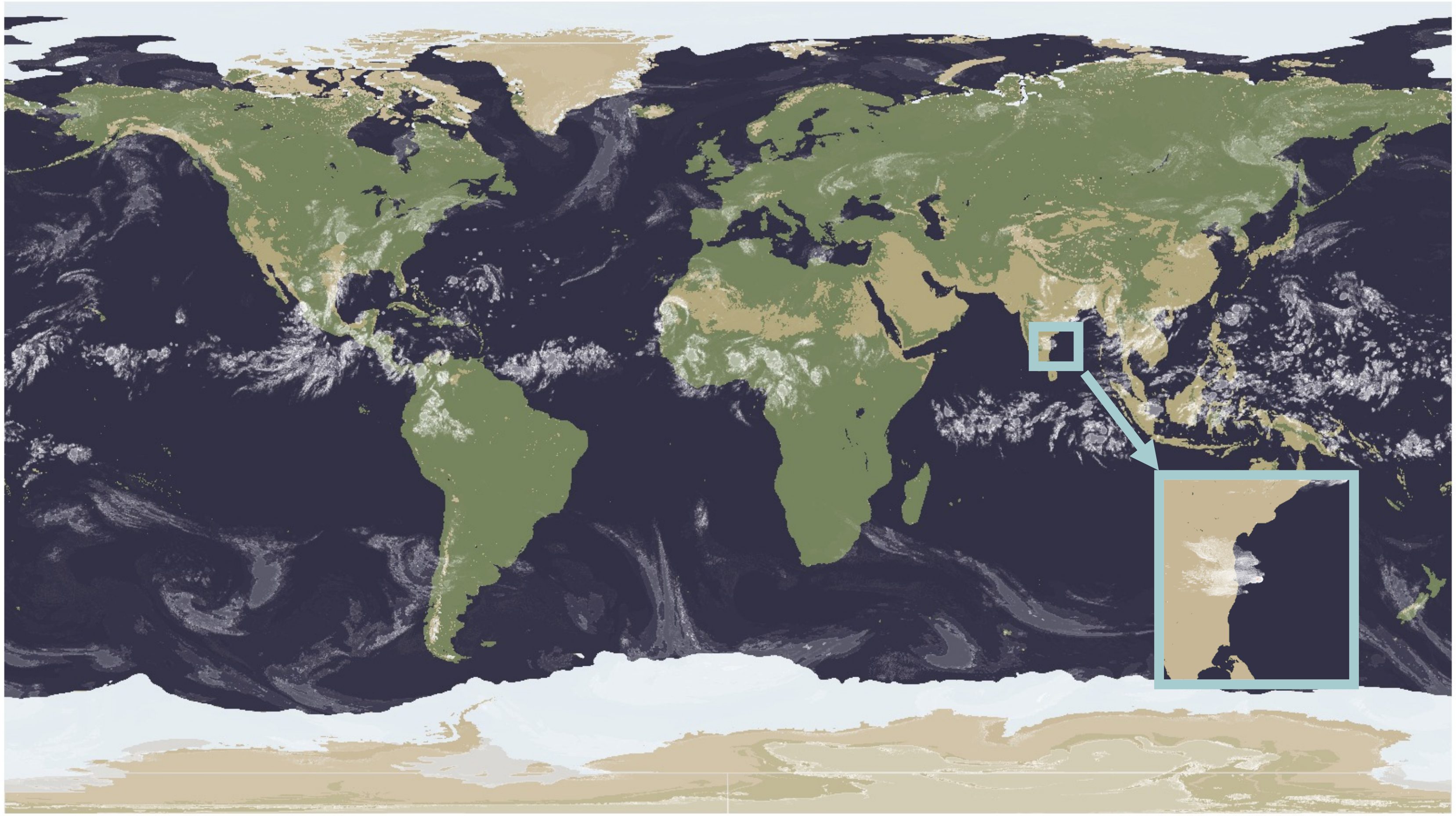
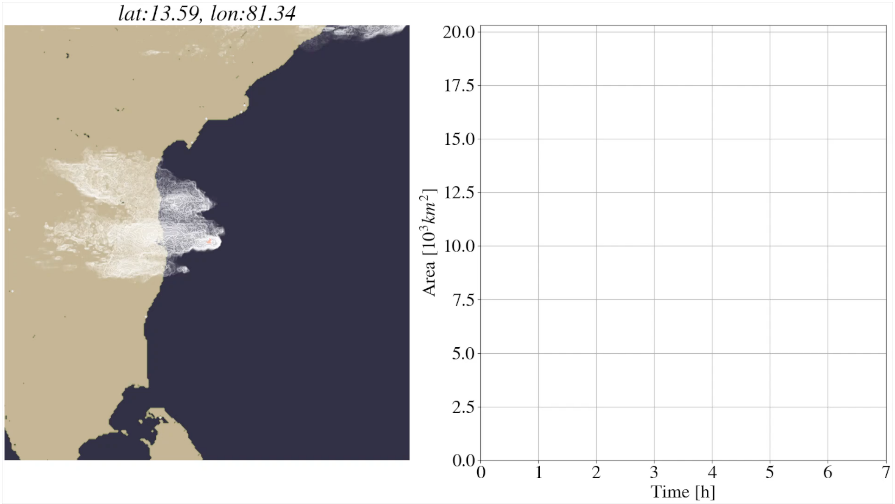


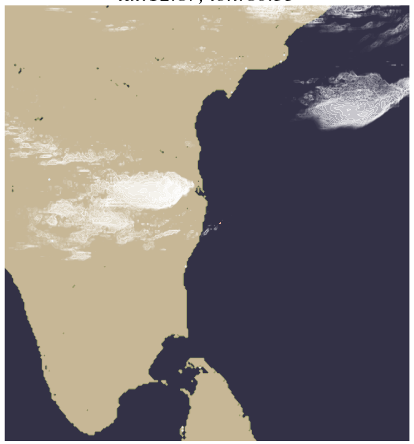
Courtesy: Sophie Abramian

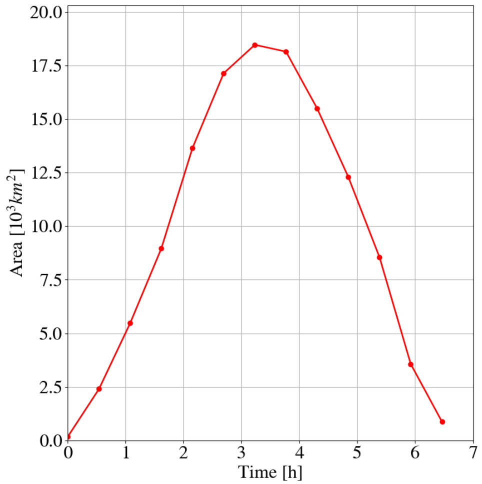
MCS in Dyamond Stimulations



Courtesy: Sophie Abramian

Life Cycle of MCS





Courtesy: Sophie Abramian

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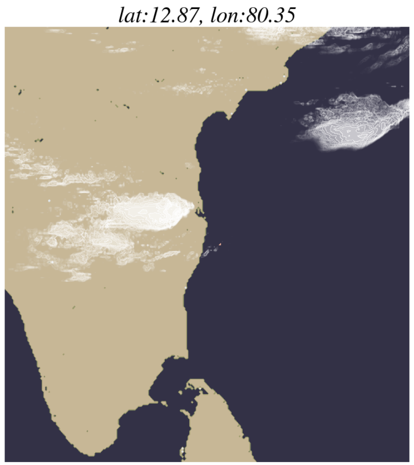

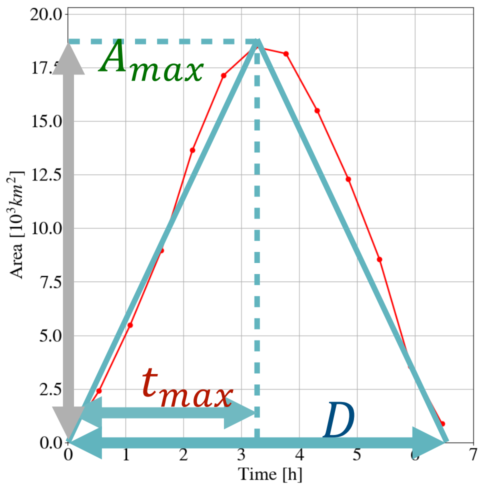

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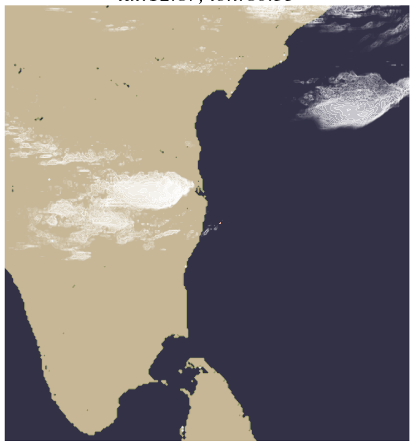
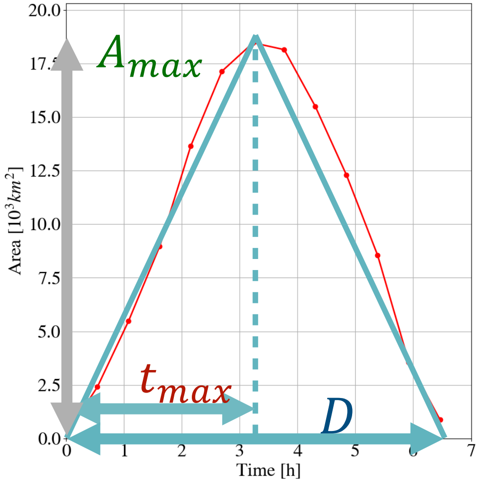
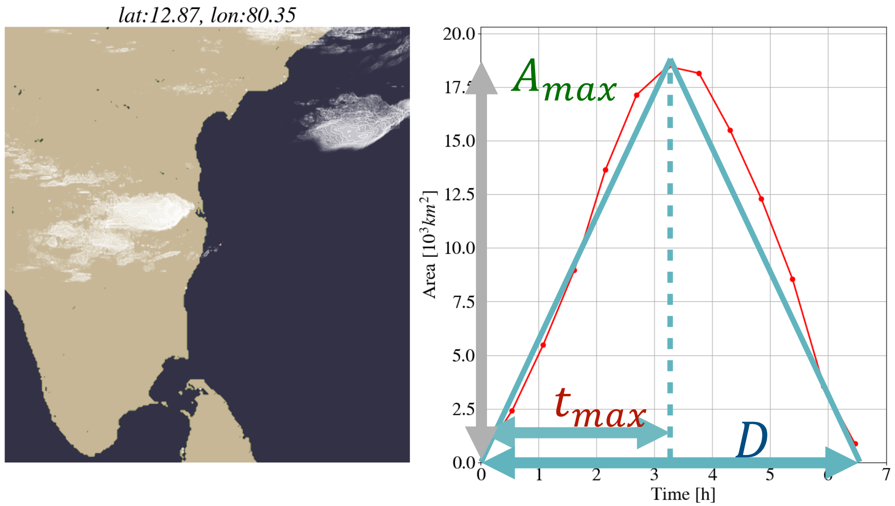




Knowing the environment of the system ***at the beginning of its life cycle,***
what can we conclude about its total duration, its area and the moment of maximum extension?

Courtesy: Sophie Abramian

Life Cycle of MCS



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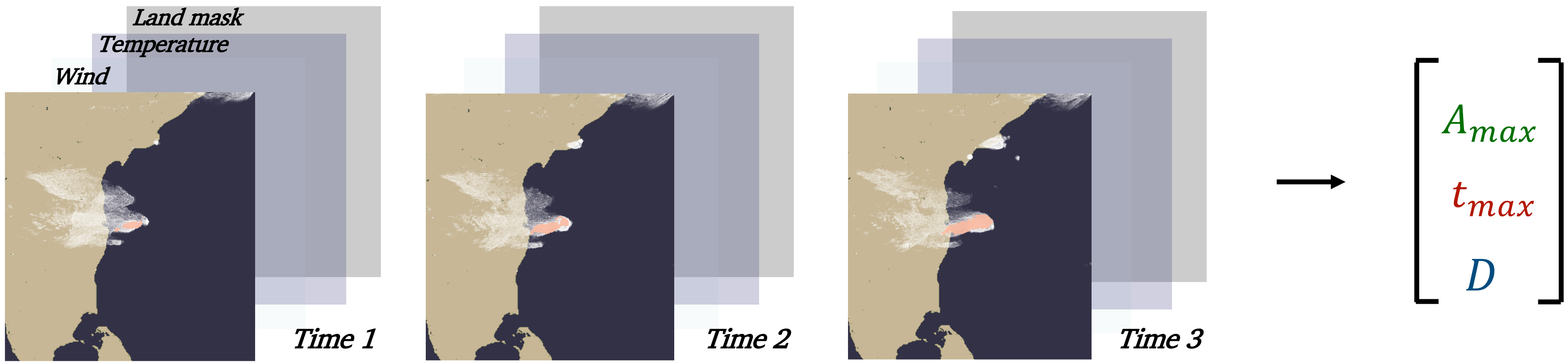
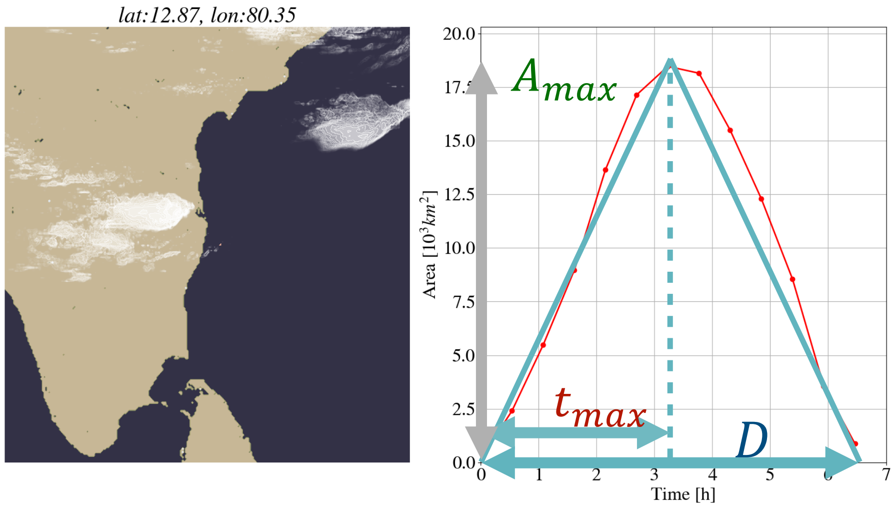


Courtesy: Sophie Abramian

Life Cycle of MCS



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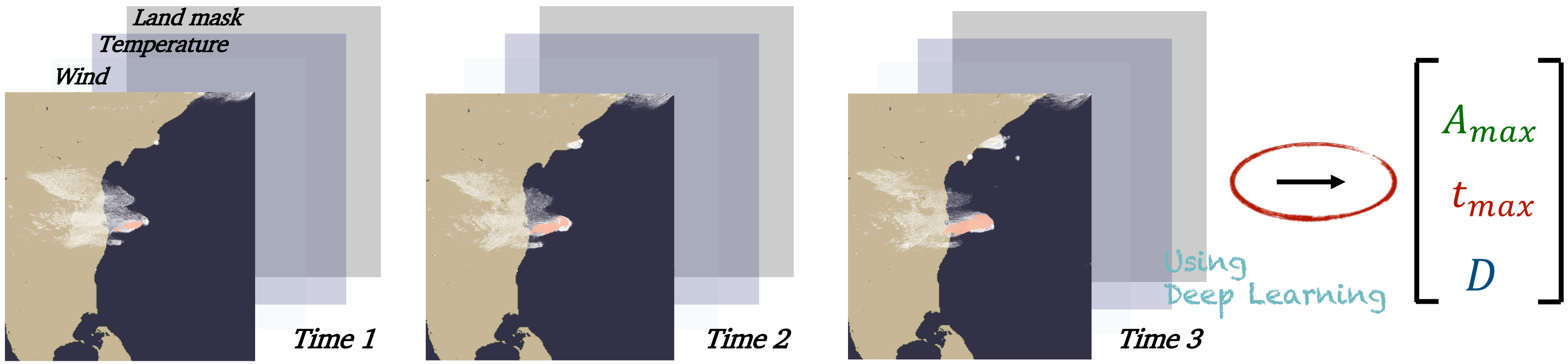
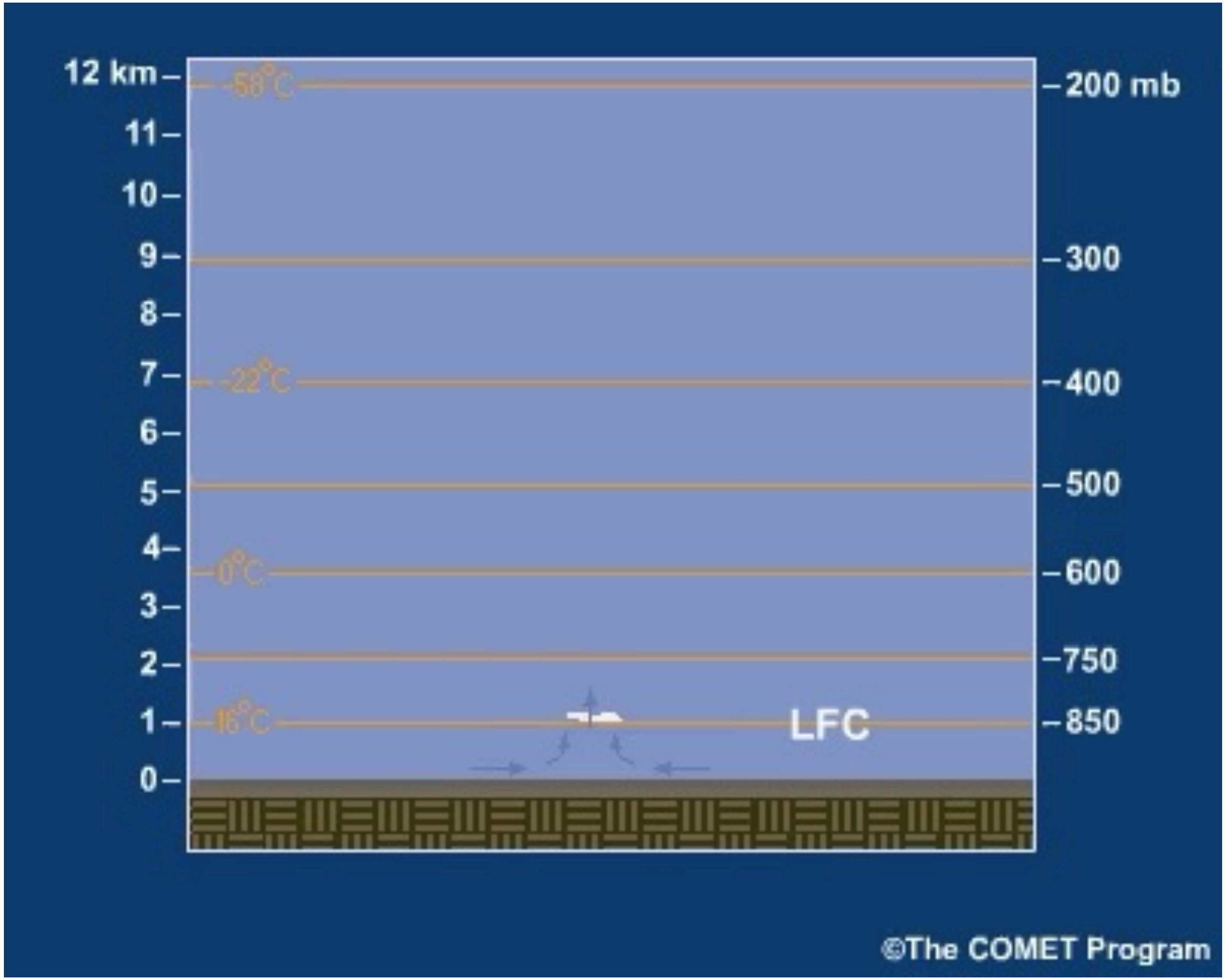


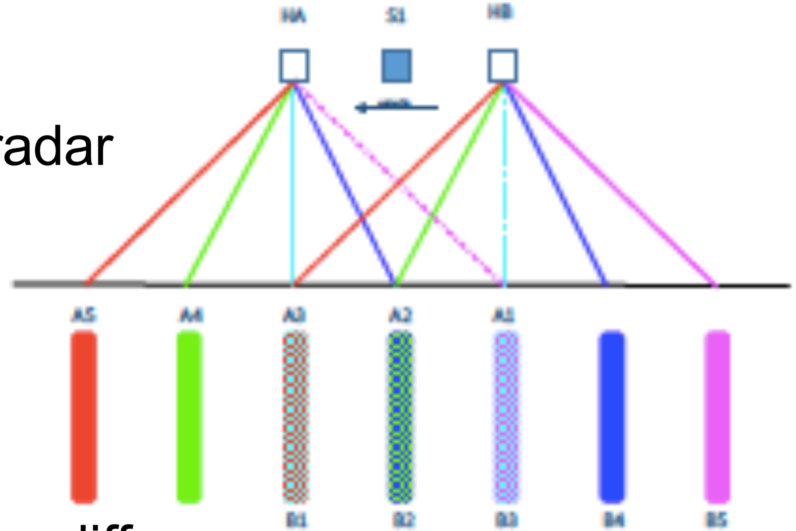
Courtesy: Sophie Abramian

Still parameterizations : Microphysics, SGS …



HARMONY

Harmony HA; Sentinel 1; Harmony HB



Two identical satellites with synthetic aperture radar

Also multibeam thermal-infrared instrument

Data at high resolution (kilometric)

⇒In absence of clouds, sea-surface temperature differences
⇒height-resolved cloud movements
⇒interactions between the air and the ocean surface

Thank you for your attention !