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# “The physics of climate and climate change with models, observations and HPCF tools”

**Giornata di Orientamento alla scelta delle Tesi in FISICA**

05/04/2024

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# TEMATICHE

Modellazione atmosferica

Navier-Stokes equations

Osservazioni e Modellazione atm. (RIMU)

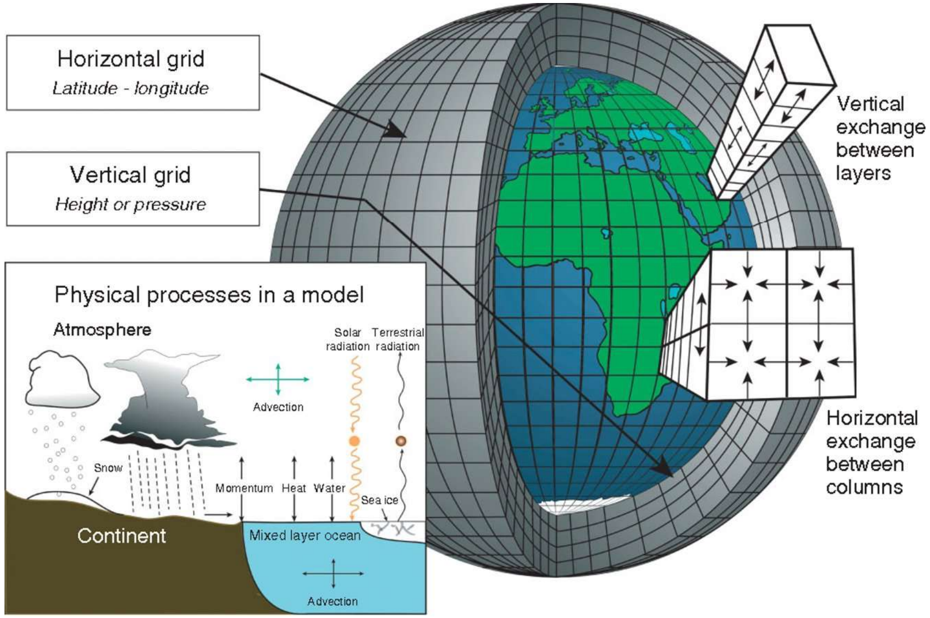
Cicloni tropicali ed extra-tropicali

Convezione in atmosfera

Radiative-Convective  Equilibrum (RCE)

Applicazioni climatiche: rianalisi  ERA5 e strumenti di statistica correlati: ensemble, stochastic parameterizations

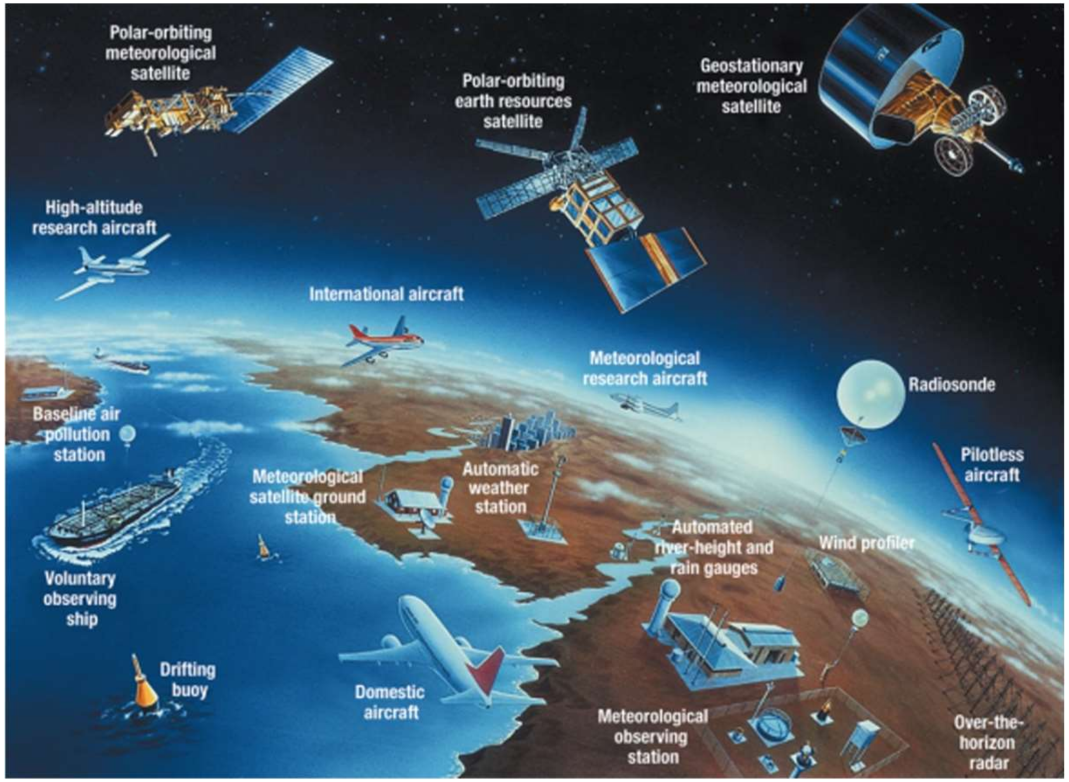
# Modelli numerici




Source: PNAS journal

Fluidodinamica teorica ed applicata allo studio dell'atmosfera

# Osservazioni




Dati assimilati dai modelli globali e ad area limitata

**WMO WIGOS, Sistema integrato globale delle osservazioni**

Source: https://public.wmo.int/en/about-us/vision-and-mission/wmo-integrated-global-

# Modelli e strumenti

**Integrated Forecasting System ECMWF**

**Weather Research & Forecasting Model (WRF)** U.S. NSF **National Center for Atmospheric Research**

**System For Atmospheric Modeling**

**Python; C++ etc**

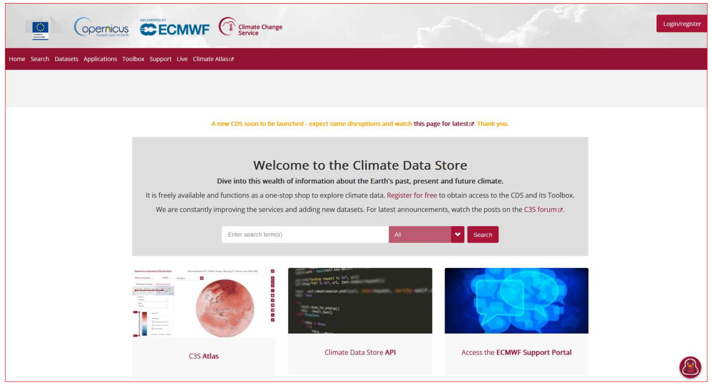
**Python Jupyter Notebooks**

**NCL** http://www.ncar.ucar.edu;

METVIEW …..

# Osservazioni

COPERNICUS CDS




E-OBS gridded dataset

**ESA Cloud Climate Change Initiative (CCI) Dataset Collection**

**The CEDA Archive**

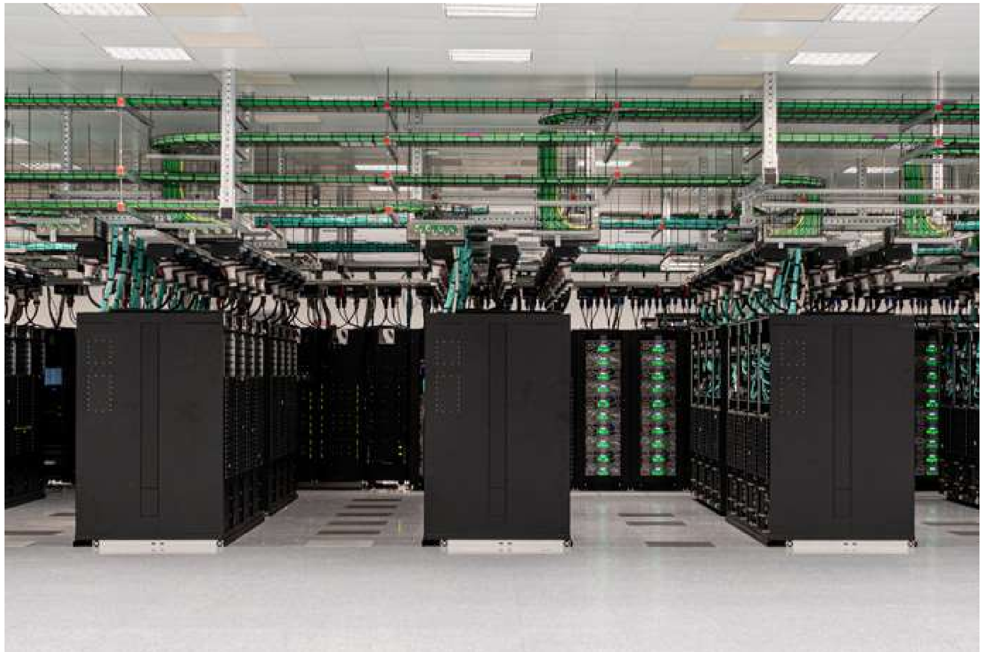
**Etc.etc.**

ECMWF

Copernicus
Europe's eyes on Earth

HPFC: High Performance Computer Facility

Atos Sequana XH2000 system configuration



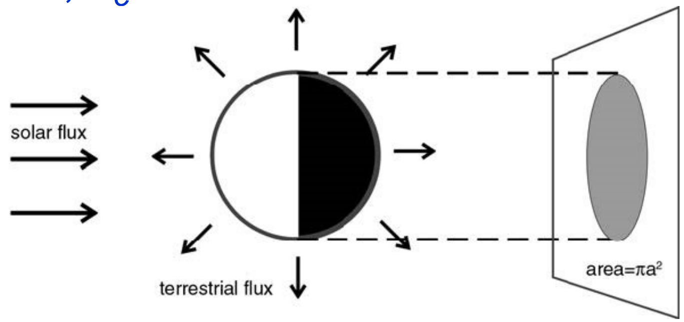
# Application to Terrestrial Radiation: using the Stefan-Boltzmann equation and geometric argument

Effective emission temperature, $T_e$:

Solar constant

$$\sigma T_e^4 \equiv \frac{S_0}{4}\left(1 - a_p\right)$$

Planetary albedo



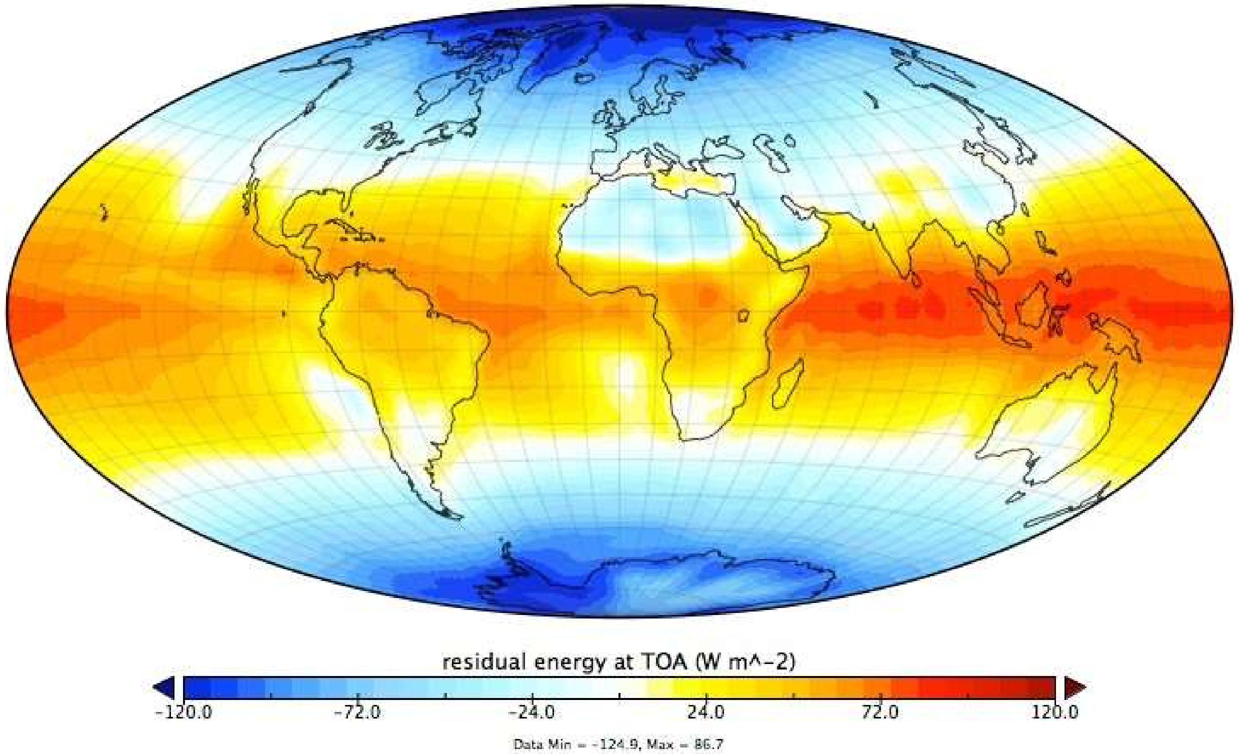

Earth: $T_e = 255K = -18°C$

Observed average surface temperature $= 288K = 15°C$

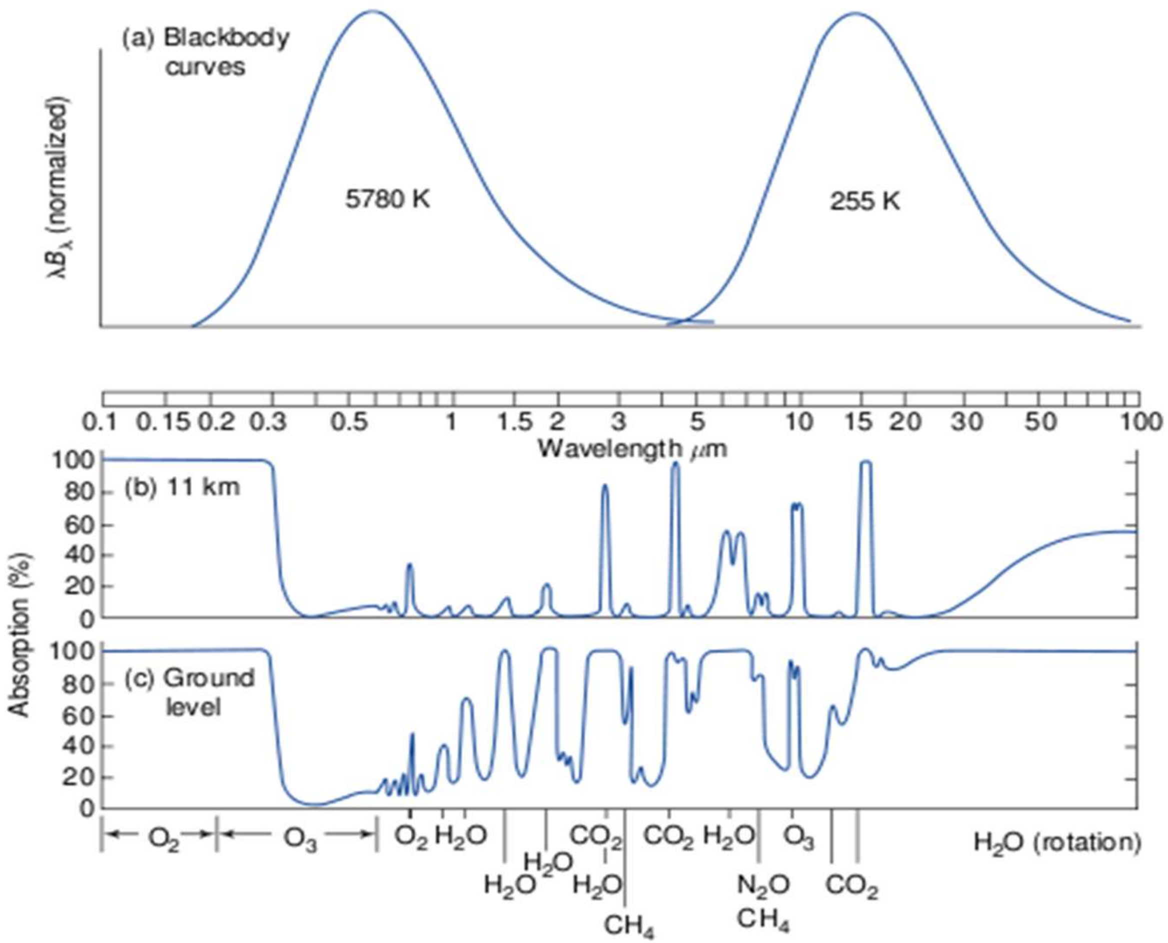
The Tropics get far more sun energy than they can get rid off locally.
Hence the excess is exported from Tropics to higher latitudes
where it is radiated out to space.

## That drives the atmospheric and oceanic circulations (weather)

Annual net radiative flux at the top-of-atmosphere (TOA; ERBE)

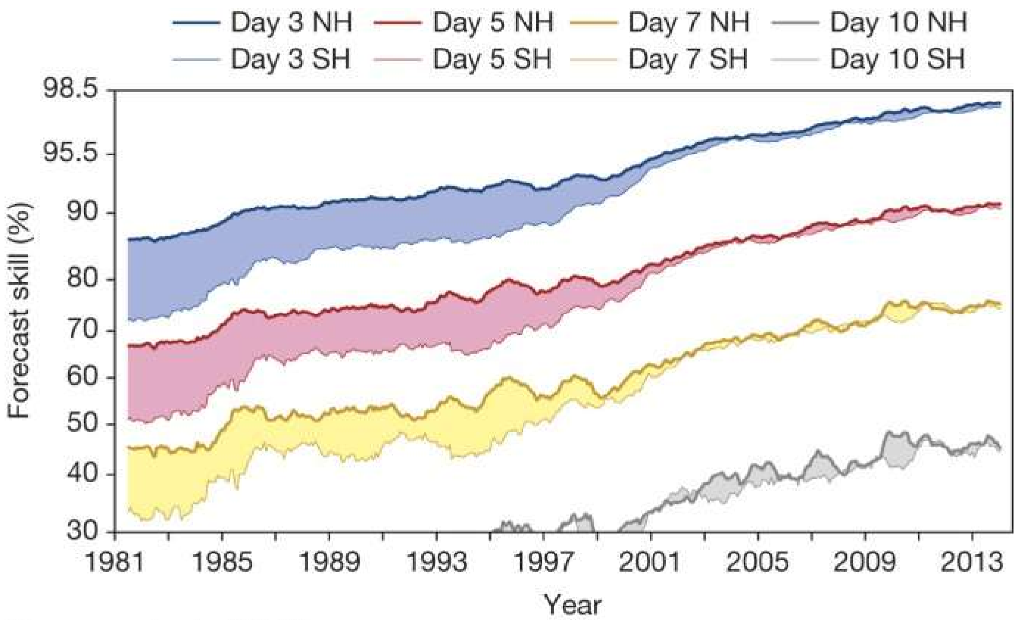


# Wien displacement law

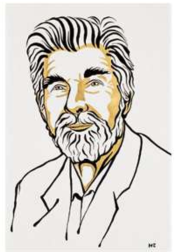


# Cambiamenti climatici: un pò di storia

## *The quiet revolution of Numerical Weather Prediction*




Bauer et al. 2015

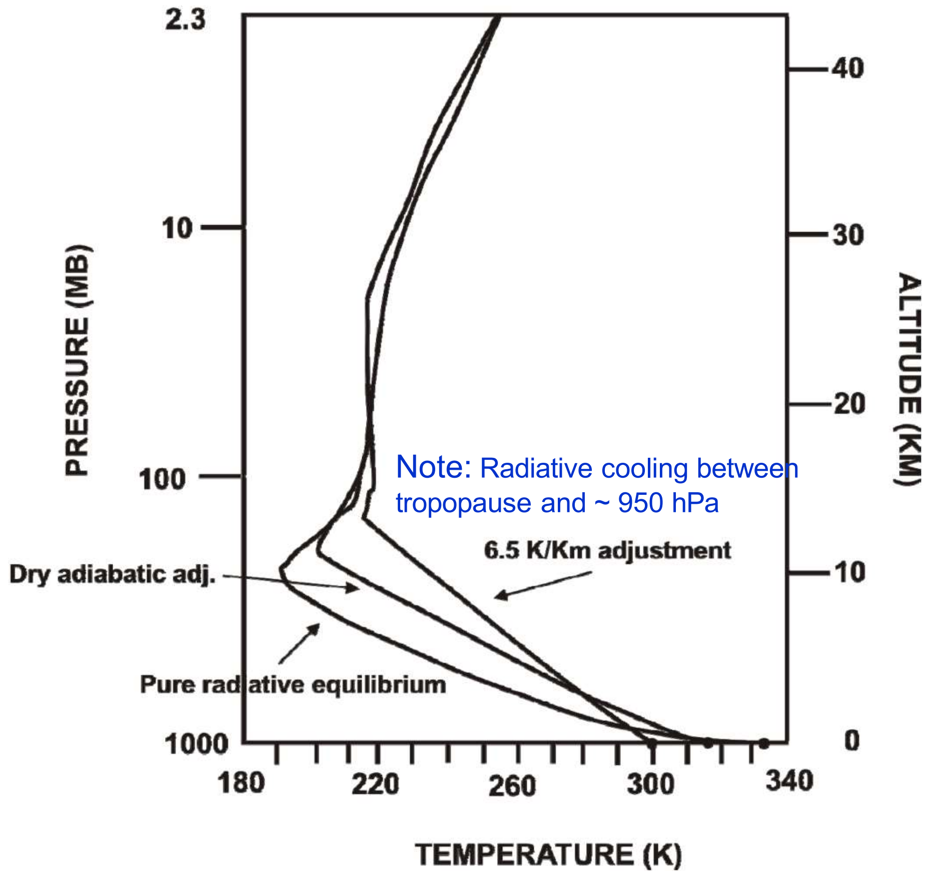


Klaus Hasselmann

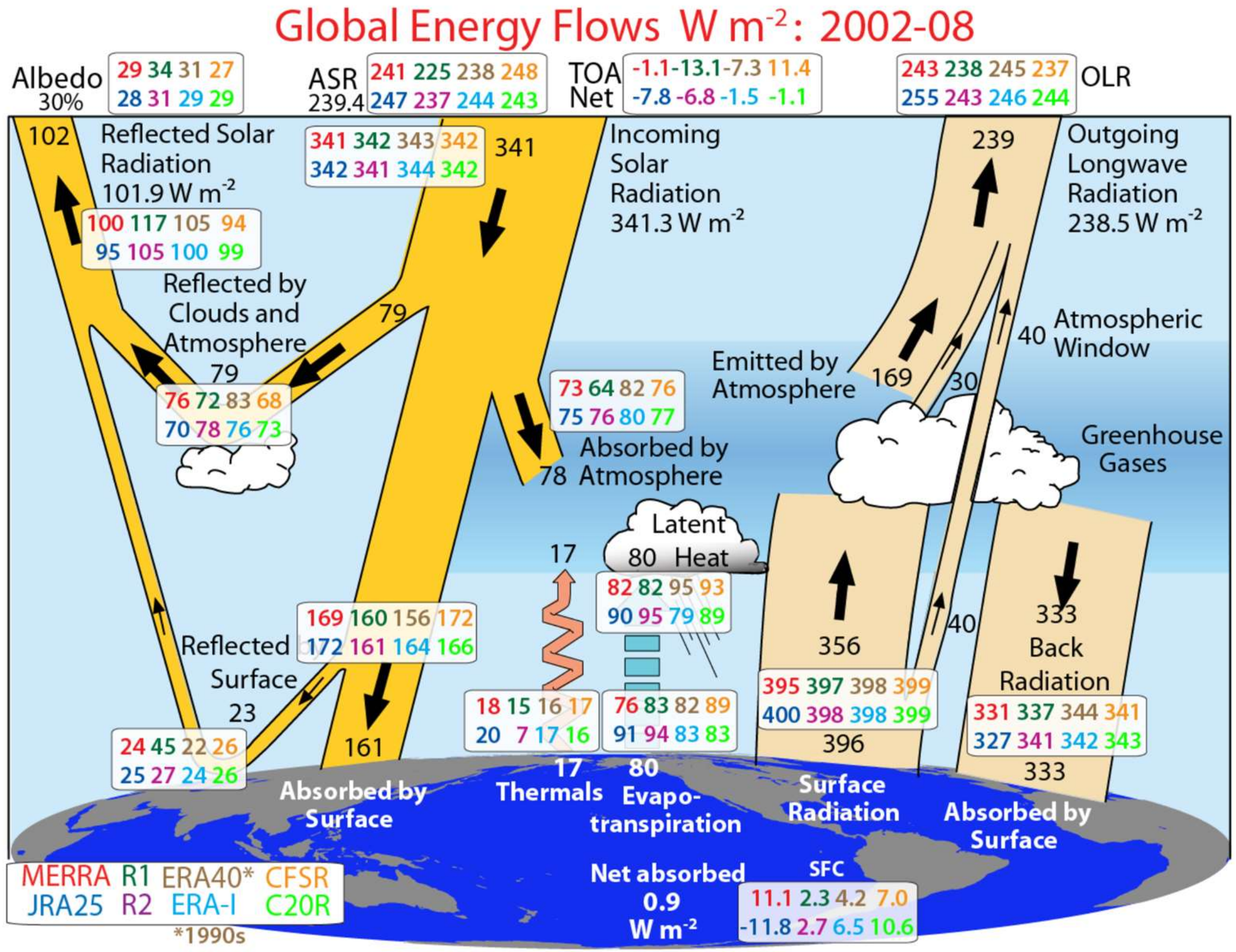
Syukuro Manabe

**"for the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming."**

# Manabe and Strickler 1964 calculation

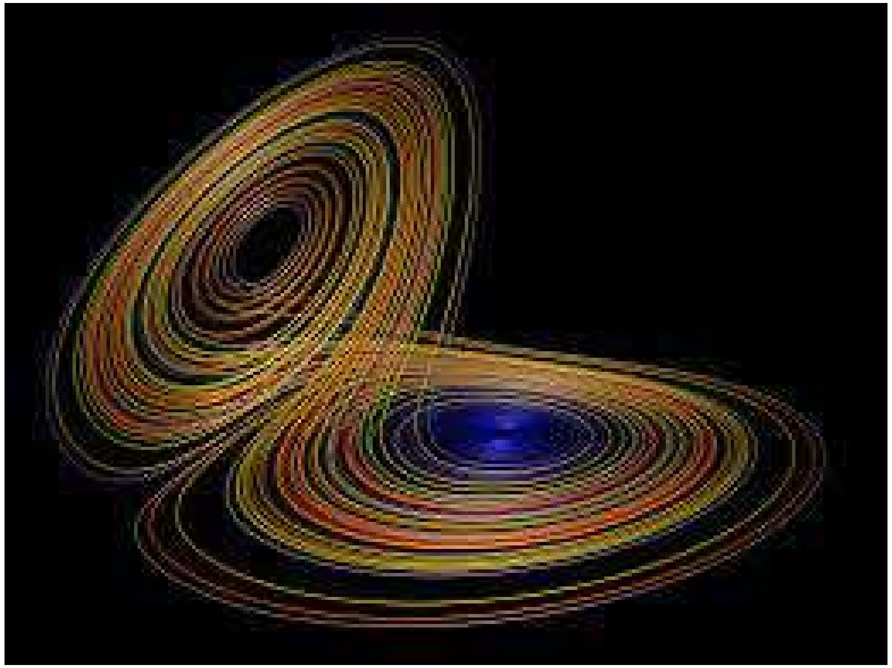


# Il sistema climatico



# Deterministic Chaos

$$\dot{X} = -\sigma X + \sigma Y$$
$$\dot{Y} = -XZ + rX - Y$$
$$\dot{Z} = XY - bZ$$



Edward N. Lorenz (1963). "Deterministic Nonperiodic Flow",
*Journal of Atmospheric Science*

Mathematica 14 WOLFRAM ALPHA Notebook Edition

# Deterministic Chaos

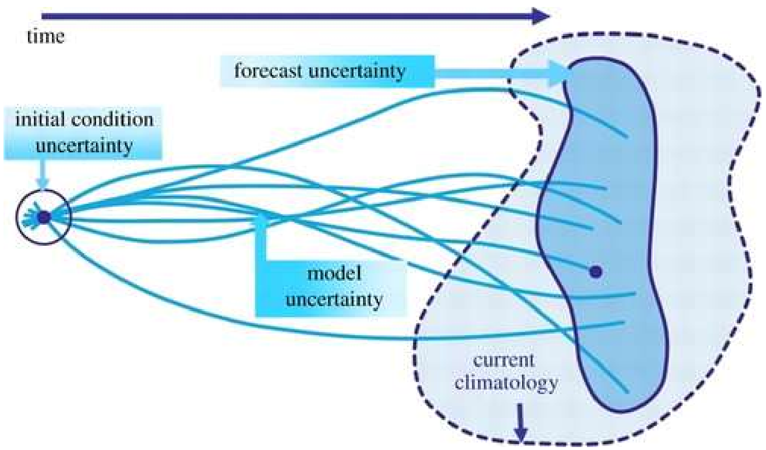
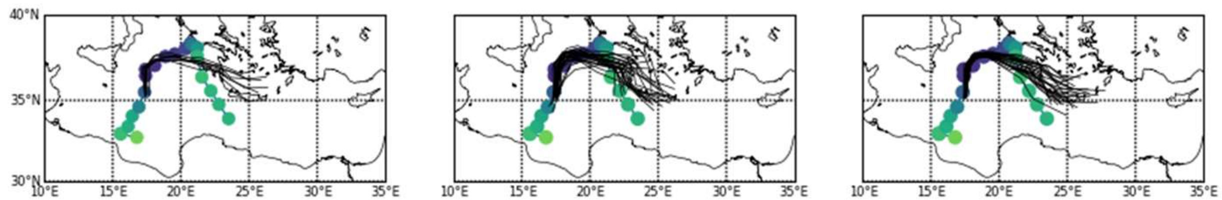
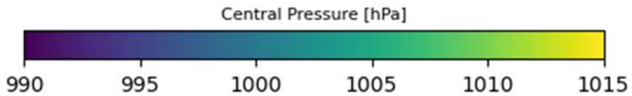



Figure 2 of Slingo, J., & Palmer, T. (2011). Uncertainty in weather and climate prediction.

Ensemble weather forecasting at ECMWF




Cyclone Tracking with the ECMWF model



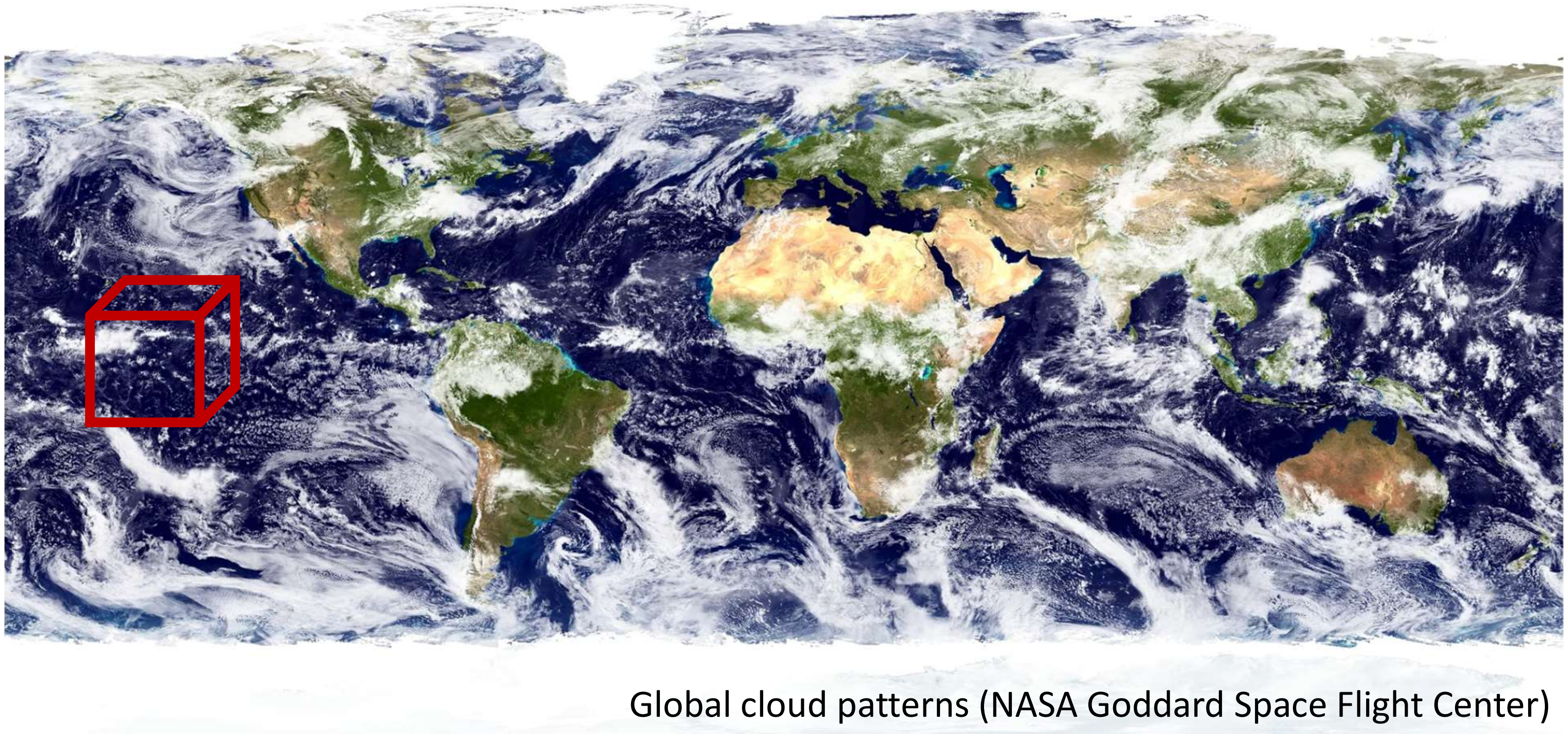
Argomenti di ricerca

1)The physics of the Mediterranean Tropical-like Cyclones

2)Weather ensemble for mapping predictability of extreme events

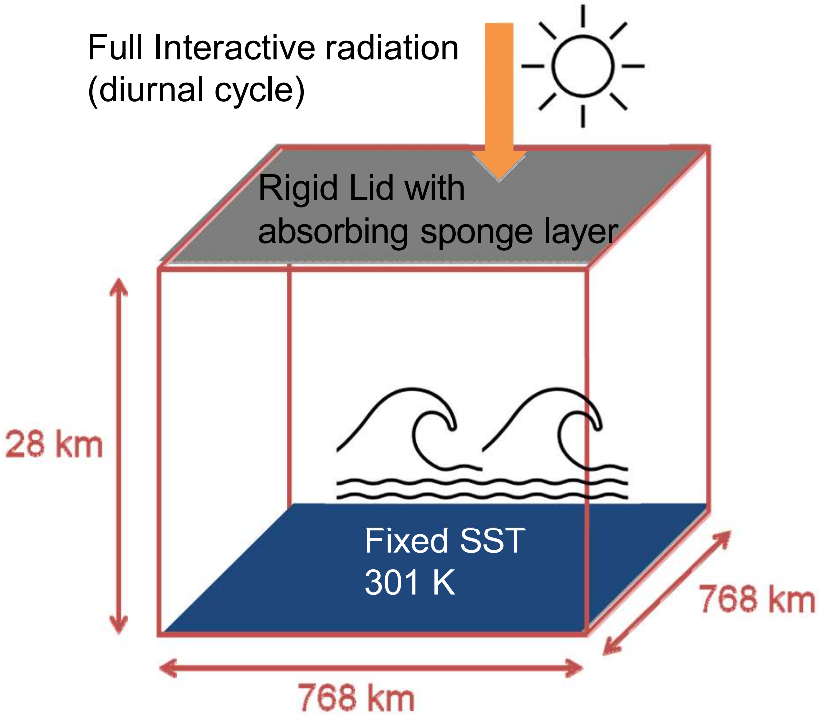
3)Weather extreme forecasting with HPCF (ATOS)

# Explicit Simulation of
# Radiative- Convective Equilibrium



Global cloud patterns (NASA Goddard Space Flight Center)

# Explicit Simulation of Radiative- Convective Equilibrium




$$\frac{\partial u^*}{\partial t} = -\left(u^*\frac{\partial u}{\partial x} + v^*\frac{\partial u}{\partial y} + w^*\frac{\partial u}{\partial z}\right) - \frac{\partial}{\partial x}(p' - \alpha \mathrm{Div}^*) + D_u,$$

$$\frac{\partial v^*}{\partial t} = -\left(u^*\frac{\partial v}{\partial x} + v^*\frac{\partial v}{\partial y} + w^*\frac{\partial v}{\partial z}\right) - \frac{\partial}{\partial y}(p' - \alpha \mathrm{Div}^*) + D_v,$$

$$\frac{\partial w^*}{\partial t} = -\left(u^*\frac{\partial w}{\partial x} + v^*\frac{\partial w}{\partial y} + w^*\frac{\partial w}{\partial z}\right) - \frac{\partial}{\partial z}(p' - \alpha \mathrm{Div}^*) + B + D_w,$$

$$\frac{\partial(\overline{\rho}\theta')}{\partial t} = -\left(u^*\frac{\partial \theta'}{\partial x} + v^*\frac{\partial \theta'}{\partial y} + w^*\frac{\partial \theta'}{\partial z}\right) - w^*\frac{\partial \overline{\theta}}{\partial z} + D_\theta + S_\theta, \quad \text{and}$$

$$\frac{\partial p'}{\partial t} = -\left(u\frac{\partial p'}{\partial x} + v\frac{\partial p'}{\partial y} + w\frac{\partial p'}{\partial z}\right) + gw^* - \overline{\rho}c_s^2\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right) + \overline{\rho}c_s^2\left(\frac{1}{\theta}\frac{d\theta}{dt}\right), \qquad (7)$$

Allison Wing, NE Tropical, May 29th 2013

## Equations

For simplicity of interpretation we will view the flow in Cartesian coordinates and neglect the Coriolis effect. With these restrictions, the WRF model can be configured to solve the following equations:

$$p = \rho R_d T;$$

Equation of state

$$\frac{\partial \rho}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z} = 0;$$

Conservation of mass

$$\frac{\partial U}{\partial t} + c_p \Theta \frac{\partial \pi}{\partial x} = -\frac{\partial Uu}{\partial x} - \frac{\partial Vu}{\partial y} - \frac{\partial Wu}{\partial z} + F_x,$$

$$\frac{\partial V}{\partial t} + c_p \Theta \frac{\partial \pi}{\partial y} = -\frac{\partial Uv}{\partial x} - \frac{\partial Vv}{\partial y} - \frac{\partial Wv}{\partial z} + F_y,$$

and

$$\frac{\partial W}{\partial t} + c_p \Theta \frac{\partial \pi}{\partial z} + g\rho = -\frac{\partial Uw}{\partial x} - \frac{\partial Vw}{\partial y} - \frac{\partial Ww}{\partial z} + F_z;$$

Conservation of momentum

$$\frac{\partial \Theta}{\partial t} + \frac{\partial U\theta}{\partial x} + \frac{\partial V\theta}{\partial y} + \frac{\partial W\theta}{\partial z} = \rho Q.$$

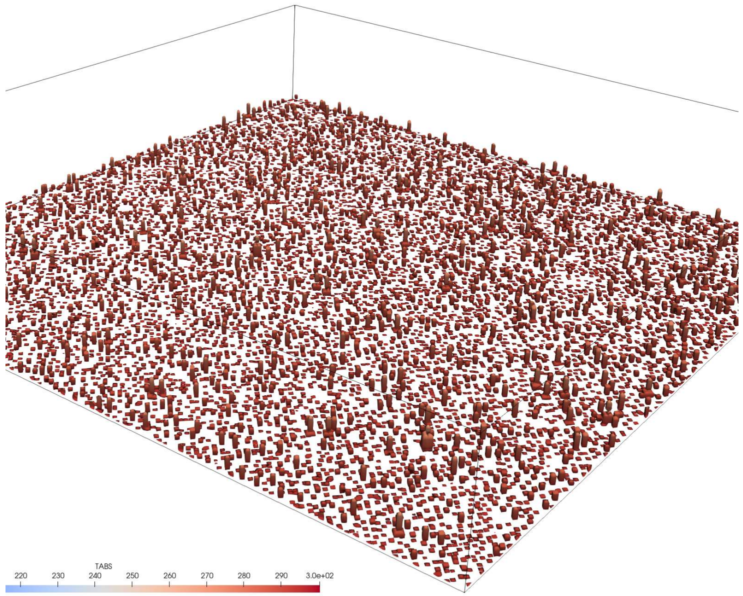
Conservation of energy

and

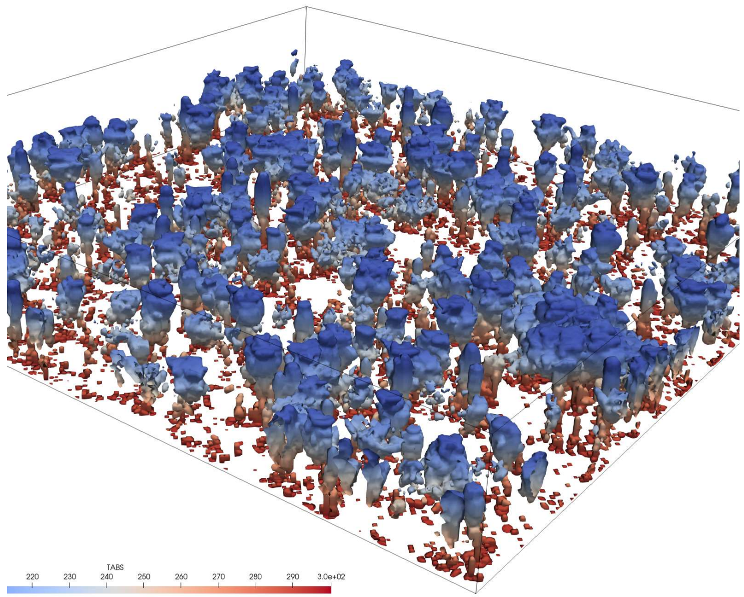
$$U = \rho u, \quad V = \rho v, \quad W = \rho w, \quad \Theta = \rho\theta,$$

**where ($u$, v, $w$) are the velocity components in the ($x$, $y$, $z$) directions, $\theta$ is the potential temperature, and $\rho$ is the air density. The other variables appearing above are the absolute temperature $T$ and the Exner function $\pi$= ($p$/$p_0$)^($R_d$/$c_p$) , where $p$ is the pressure and $p_0$ = 1000 hPa is a reference value. The specific heat at constant pressure for dry air is given by $c_p$ = 1004.5 JK^(-1) kg^(-1), and $R_d$ = (2/7)$c_p$ is the gas constant for dry air; $F_x$ , $F_y$ , and $F_z$ are friction terms.**

# Explicit Simulation of
# Radiative- Convective Equilibrium:
# CLOUDS

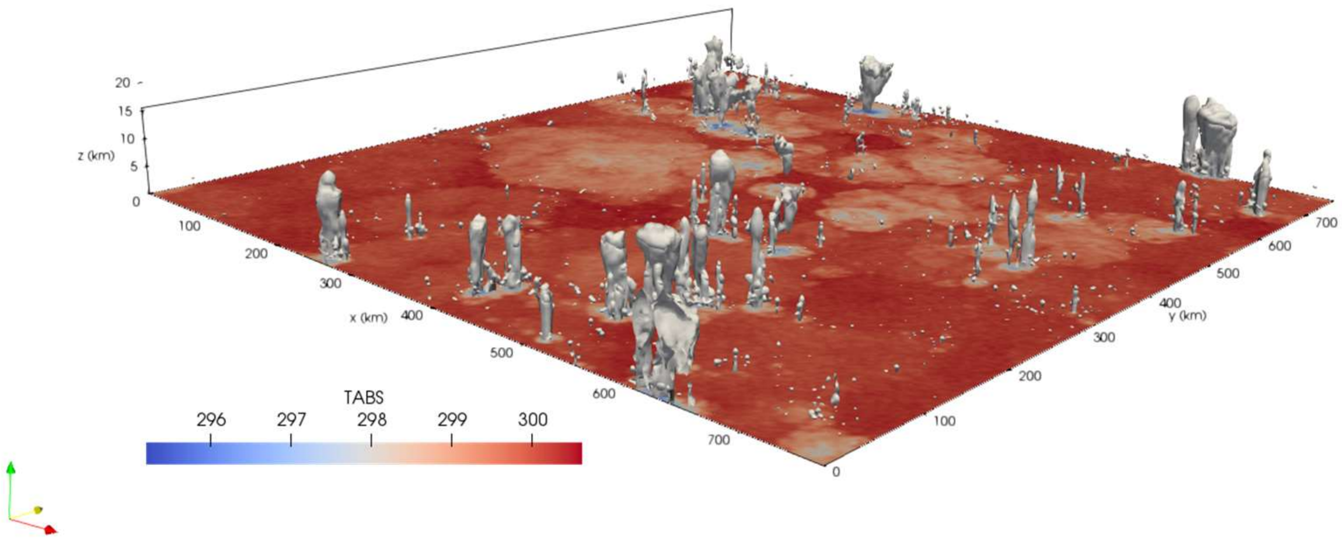



After 2 hours



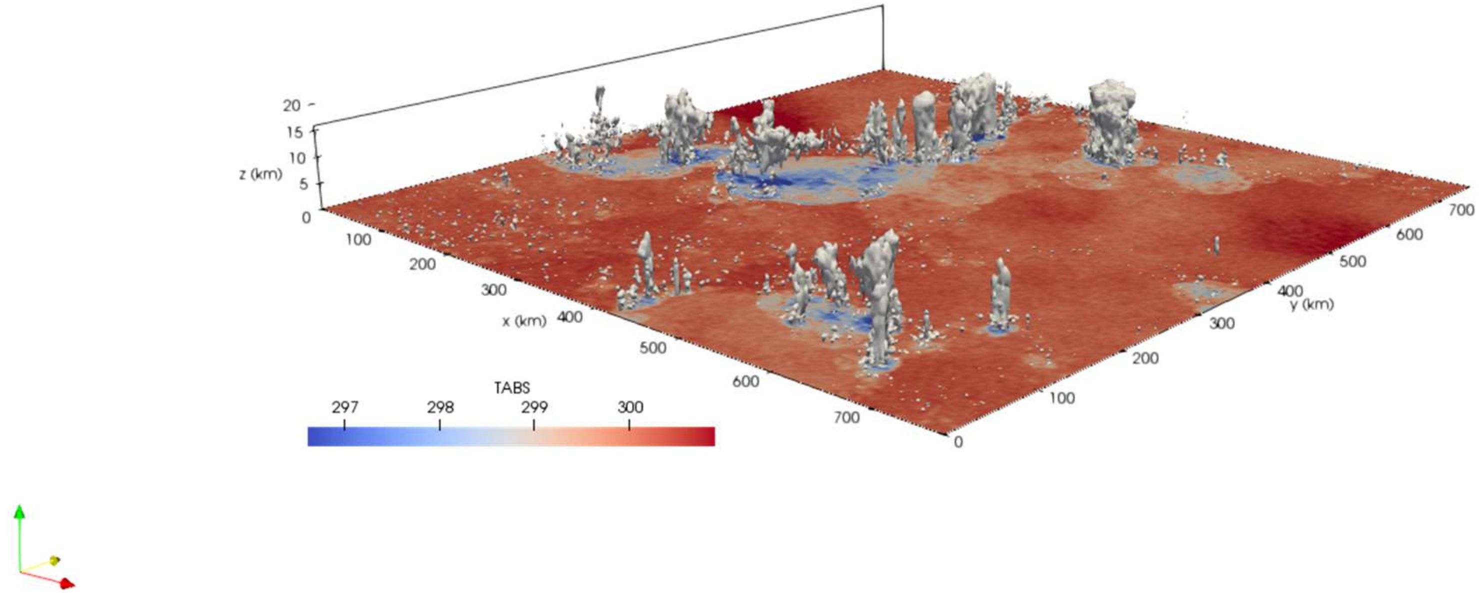

After 6 hours

## Convection in RCE




In SAM after convection develops uniformly for about 20/30 : here Tsfc and cloud water plus cloud ice and rain and snow.

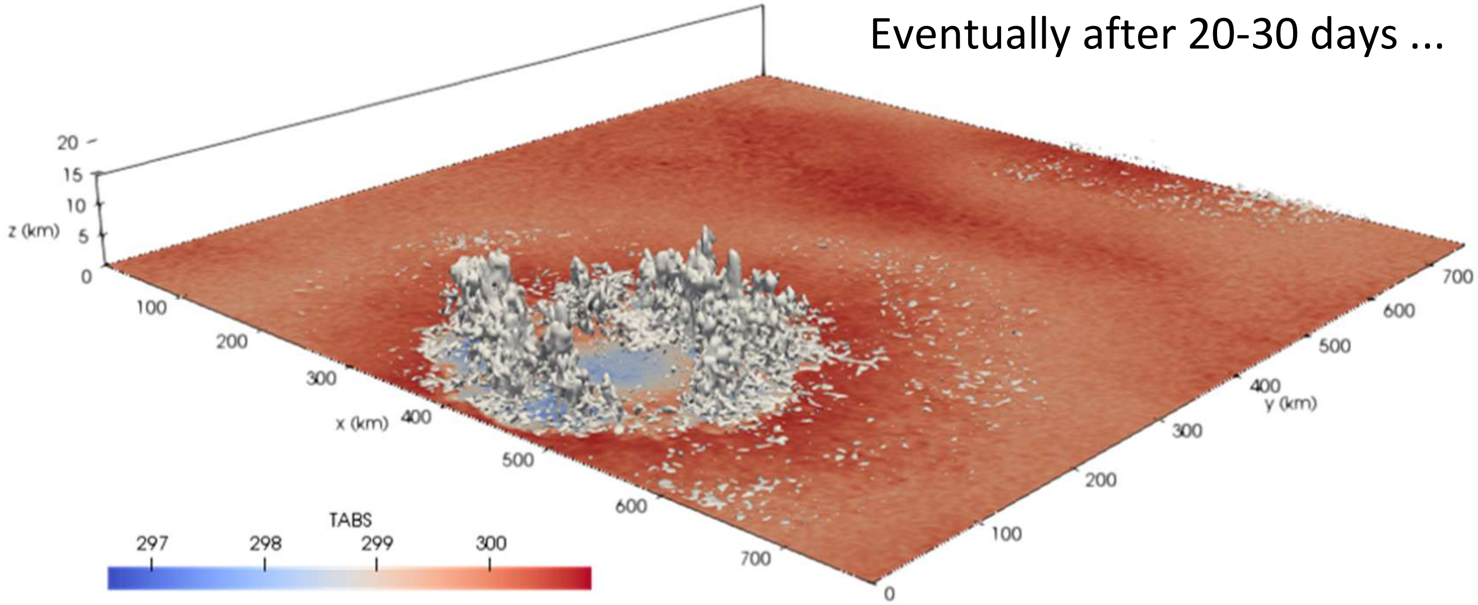
## Self-aggregation in RCE




In SAM after about 60 days self-aggregation of clouds and related variables appears: same variables as previous slide

# Explicit Simulation of
# Radiative- Convective Equilibrium:
# Self-Aggregation of clouds

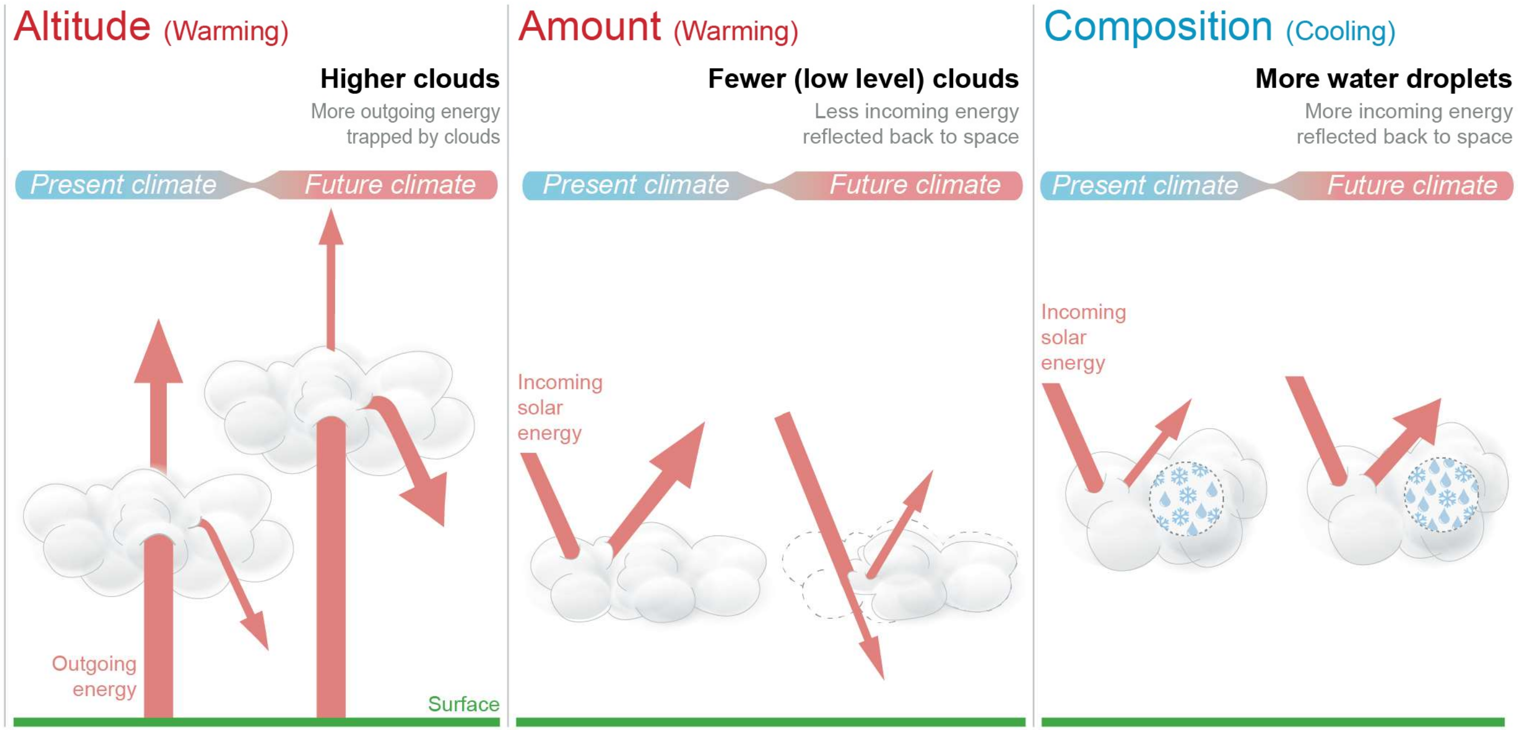
Eventually after 20-30 days ...




This phenomenon is found to occur across a wide variety of models (different equations formulation and parametrizations) and its strength increases with SST.

# The importance of clouds in a changing climate

FAQ 7.2: **What is the role of clouds in a warming climate?**
Clouds affect and are affected by climate change. Overall, scientists expect clouds to **amplify future warming**.




FAQ 7.2 Figure 1 in IPCC, 2021: Chapter 7. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In Climate Change 2021*

# Argomenti di ricerca

4) Cloud feedback in a warming climate

5) The spontaneous Aggregation of Convective Storms

# The uncertainty in tropical anvil high-cloud feedback and the IRIS effect

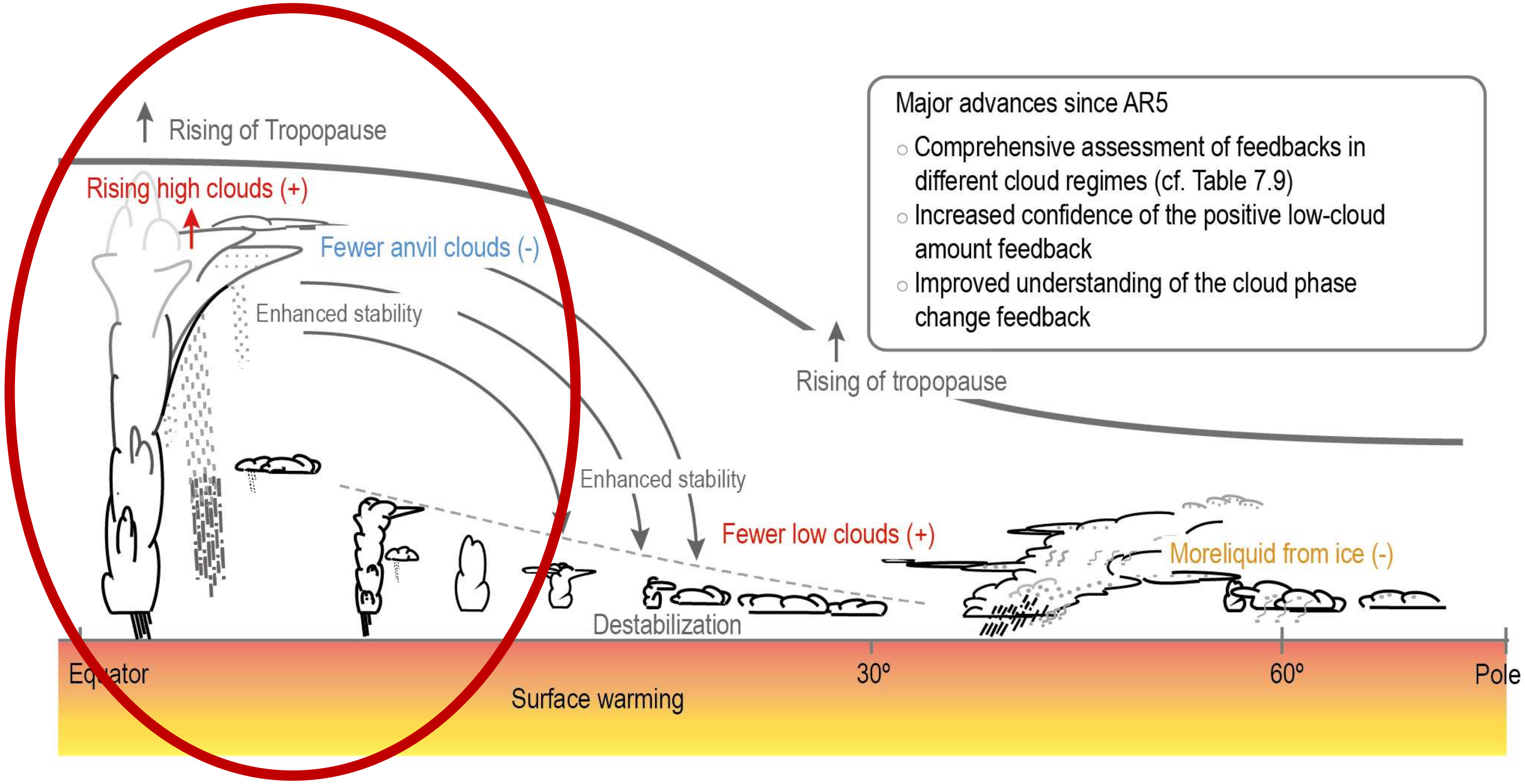
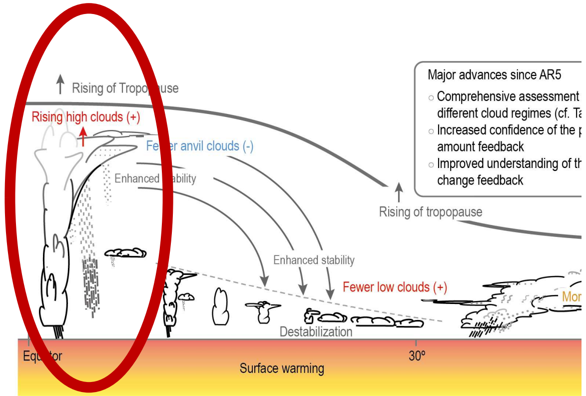
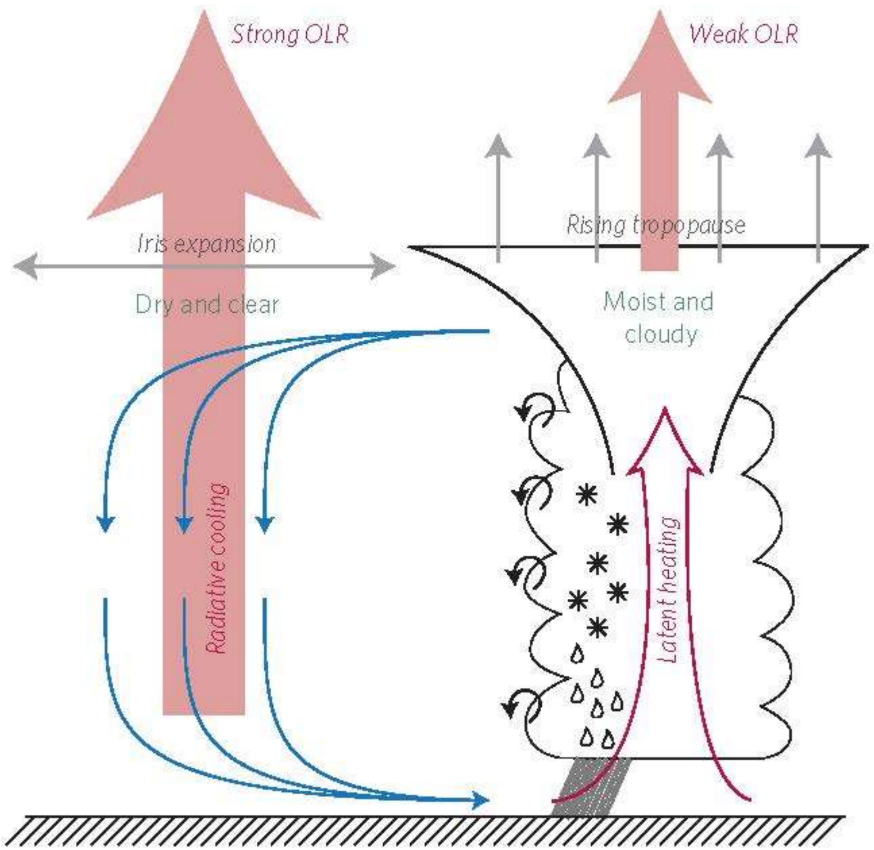



Figure 7.9 in IPCC, 2021: Chapter 7. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Forster, P., T. Storelvmo, K. Armour, W. Collins, J.-L. Dufresne, D. Frame, D.J. Lunt, T. Mauritsen, M.D. Palmer, M. Watanabe, M. Wild, and H. Zhang, 2021: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity.*

# The uncertainty in tropical anvil high-cloud feedback and the IRIS effect




Processes that may change the balance in favour of dry and clear regions in warmer climates have been proposed to constitute **a possible negative feedback not represented by climate models**. This potential feedback has been termed the iris effect, in analogy to the enlargement of the eye's iris as its pupil contracts under the influence of more light.




Mauritsen, T., Stevens, B. Nature Geosci 8, 346–351 (2015).

# Argomenti di ricerca

6) IRIS Effect in global models

# Sensitivity of Self-Aggregation: turbulence

Different models with **different turbulence parametrizations** can lead to different final equilibrium states.

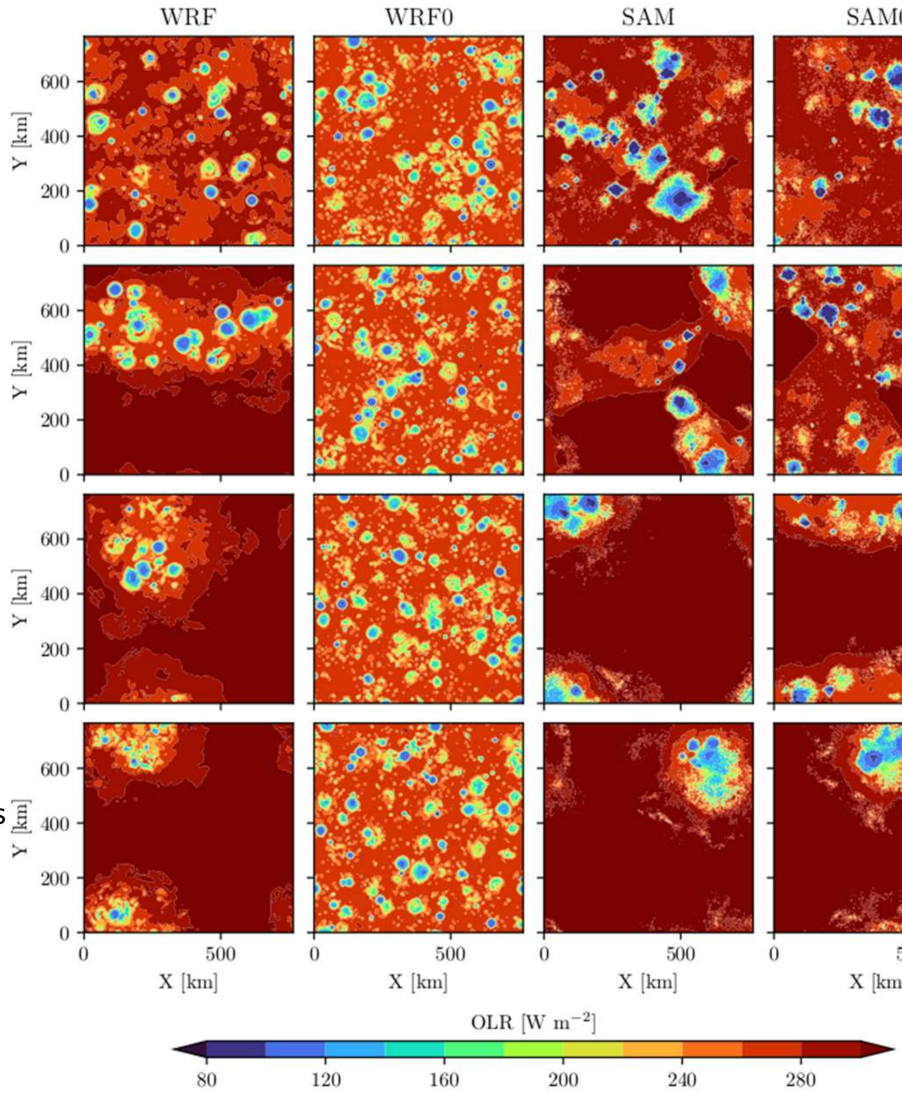
**different clouds feedback on climate**

after 5 days

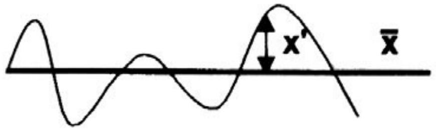
after 25 days

after 50 days

after 100 days

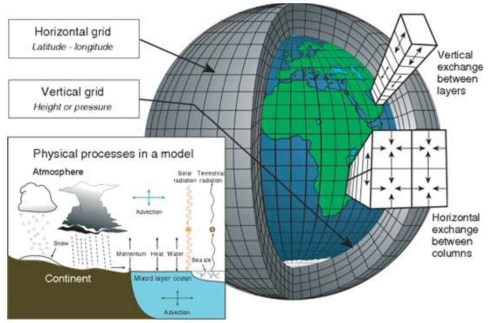


# Sensitivity of self-aggregation: the turbulence closure problem




Reynolds decomposition

$$\tilde{u}_i = U_i + u_i, \quad \tilde{p} = P + p, \quad \tilde{\rho} = \overline{\rho} + \rho', \quad \text{and} \quad \tilde{T} = \overline{T} + T'$$




N-S Equations (Simplified Boussinesq set)

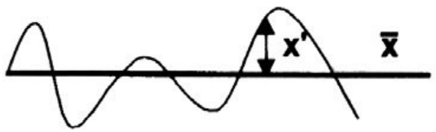
$$\frac{\partial \tilde{u}_i}{\partial x_i} = 0,$$ Mass conservation

$$\frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_j \frac{\partial \tilde{u}_i}{\partial x_j} = \frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial}{\partial x_j}(\tilde{u}_j \tilde{u}_i) = -\frac{1}{\rho_0}\frac{\partial \tilde{p}}{\partial x_i} - g\left[1 - \alpha(\tilde{T} - T_0)\right]\delta_{i3} + \nu \frac{\partial^2 \tilde{u}_i}{\partial x_j^2},$$ Momentum conservation

$$\frac{\partial \tilde{T}}{\partial t} + \tilde{u}_j \frac{\partial \tilde{T}}{\partial x_j} = \frac{\partial \tilde{T}}{\partial t} + \frac{\partial}{\partial x_j}(\tilde{u}_j \tilde{T}) = \kappa \frac{\partial^2 \tilde{T}}{\partial x_j^2},$$ Energy conservation

$$\frac{\partial}{\partial t}(\rho_m \tilde{Y}) + \frac{\partial}{\partial x_j}(\rho_m \tilde{Y} \tilde{u}_j) = \frac{\partial}{\partial x_j}\left(\rho_m \kappa_m \frac{\partial}{\partial x_j}\tilde{Y}\right),$$ Passive scalar conservation

# Sensitivity of self-aggregation: the turbulence closure problem




Reynolds averaged N-S Equations

**Turbulent fluxes: Arising from non-linear advective terms**

$$\frac{\partial U_i}{\partial x_i} = 0,$$

Mass conservation

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -g\left[1 - \alpha(\overline{T} - T_0)\right]\delta_{i3} + \frac{1}{\rho_0}\frac{\partial \overline{\tau}_{ij}}{\partial x_j}$$

$$= -g\left[1 - \alpha(\overline{T} - T_0)\right]\delta_{i3} + \frac{1}{\rho_0}\frac{\partial}{\partial x_j}\left(-P\delta_{ij} + 2\mu \overline{S}_{ij} - \rho_0 \overline{u_i u_j}\right),$$

Momentum conservation

$$\rho_0 c_p \left(\frac{\partial \overline{T}}{\partial t} + U_j \frac{\partial \overline{T}}{\partial x_j}\right) = -\frac{\partial Q_j}{\partial x_j} = -\frac{\partial}{\partial x_j}\left(-k\frac{\partial \overline{T}}{\partial x_j} + \rho_0 c_p \overline{u_j T'}\right),$$

Energy conservation

$$\frac{\partial \overline{Y}}{\partial t} + U_j \frac{\partial \overline{Y}}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\kappa_m \frac{\partial \overline{Y}}{\partial x_j} - \overline{u_j Y'}\right),$$

Passive scalar conservation

# Sensitivity of self-aggregation: the turbulence closure problem

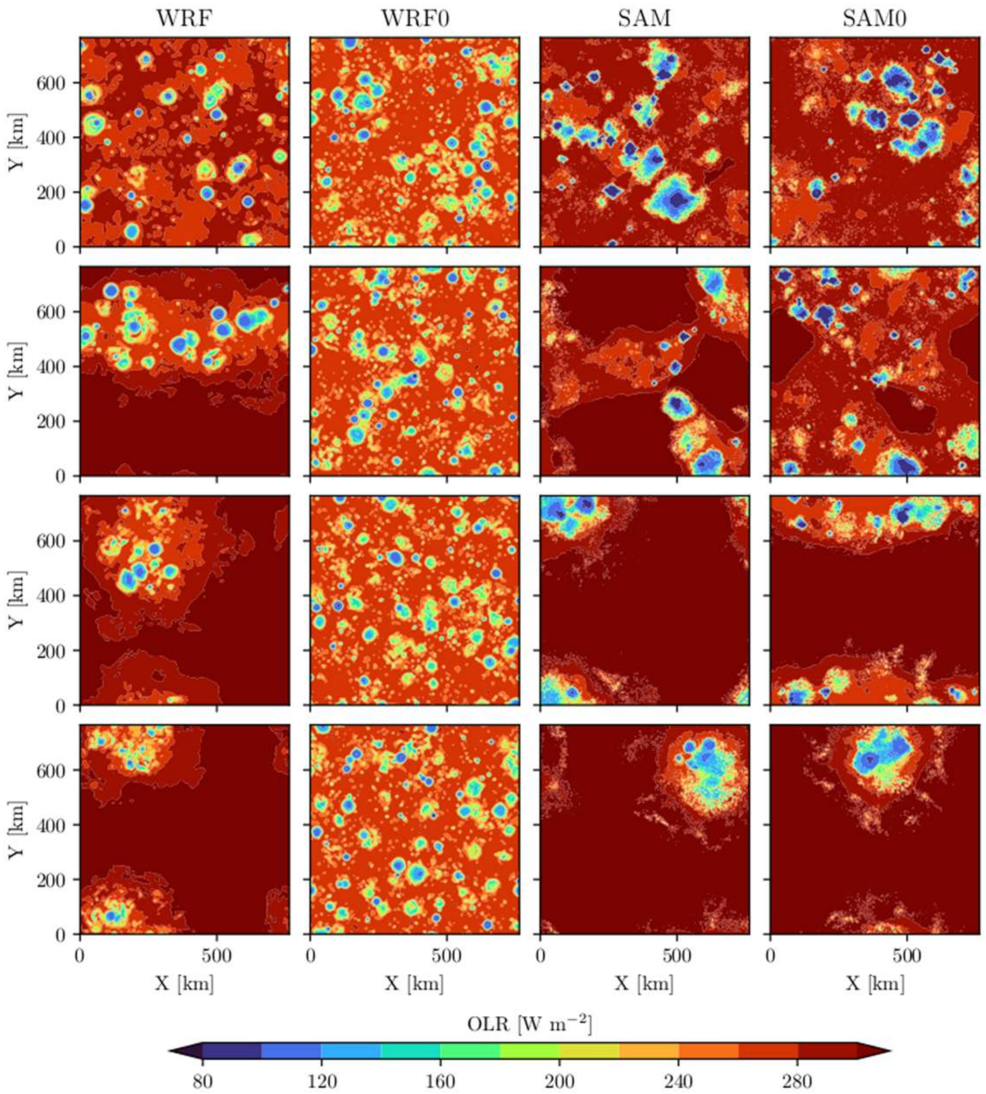
**INCLUDING OR NOT THESE TERMS …**

$$\rho_0 \overline{u_i u_j})$$

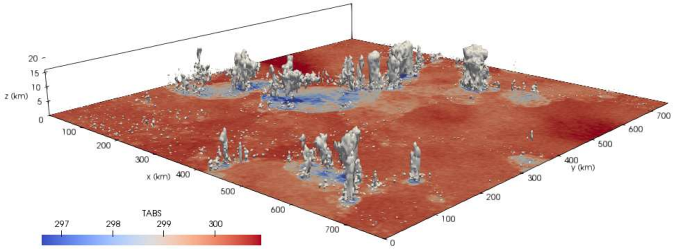
$$\rho_0 c_p \overline{u_j T'})$$

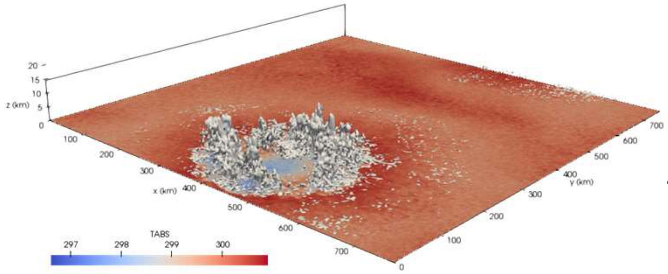
$$-\overline{u_j Y'})$$

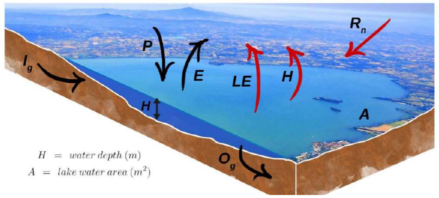
**MAKES THE DIFFERENCE FOR OUR CLIMATE …**



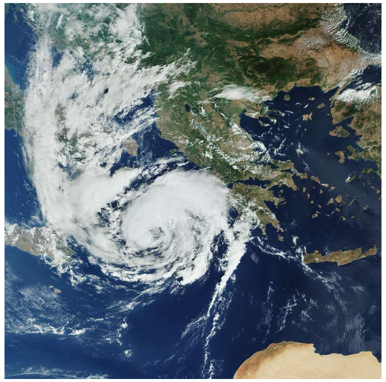
# La ricerca di UNIPG

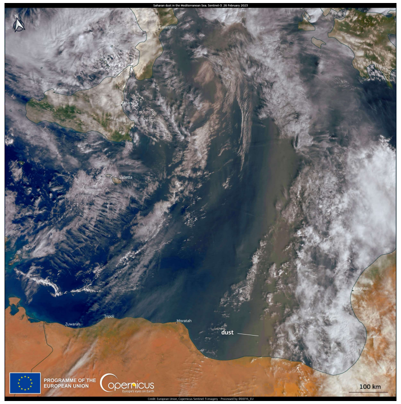


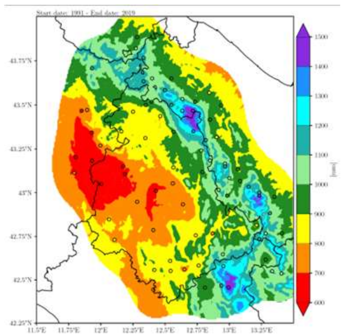



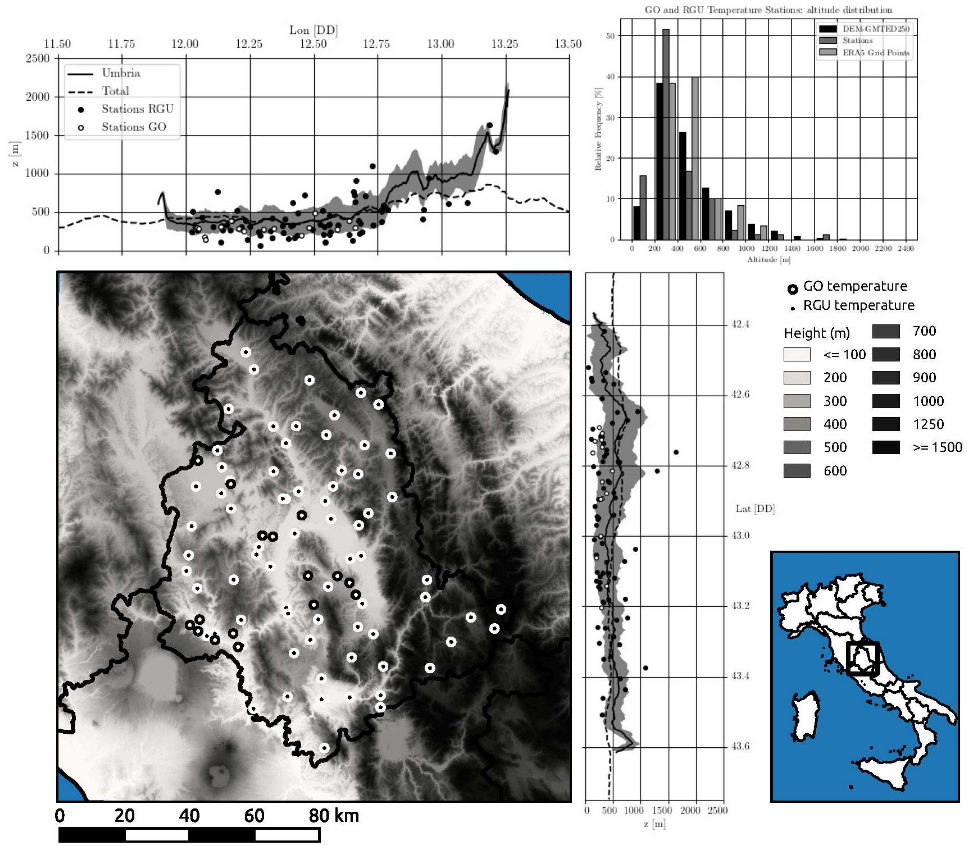




**Il clima:**
**interazioni complesse di fenomeni a tutte le scale**







Lon [DD]
z [m]
Umbria
Total
Stations RGU
Stations GO
GO and RGU Temperature Stations: altitude distribution
DEM-GMTED250
Stations
ERA5 Grid Points
Relative Frequency [%]
Altitude [m]
Lat [DD]
GO temperature
RGU temperature
Height (m)
<= 100
200
300
400
500
600
700
800
900
1000
1250
>= 1500
0 20 40 60 80 km

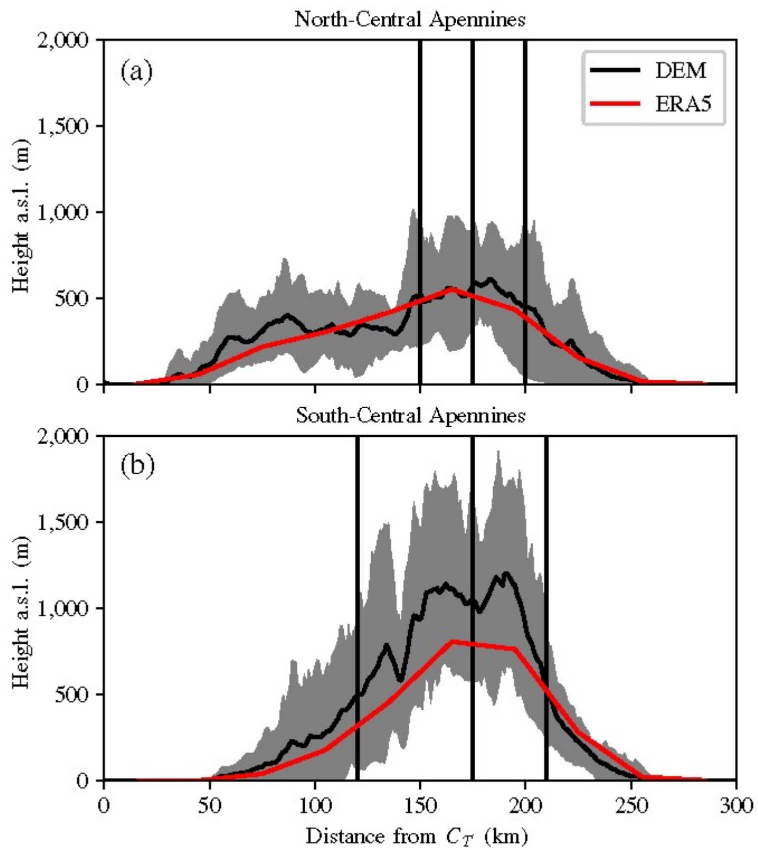



**FIGURE 2** Cross section of orography in the study domain for the north-central Apennines (top) and south-central Apennines (bottom). Black and red lines are the meridional average of height for the digital elevation model (DEM) and ERA5 reanalysis, respectively. Grey shading represents the area between 90th and 10th percentile of DEM height across all considered latitudes. Straight vertical lines indicates reference central line and width of the region occupied by central Apennines [Colour figure can be viewed at wileyonlinelibrary.com]

Argomenti di ricerca

7) Detecting climate change using reanalysis (ERA5) and observations from COPERNICUS CDS (RIMU)

8) The effect of climate change over the orography of Apennines

9) AI for the analysis of climate data.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# Argomenti di ricerca

1) The physics of the Mediterranean Tropical-like Cyclones

2) Weather ensemble for mapping predictability of extreme events

3) Weather extreme forecasting with HPCF (ATOS)

4) Cloud feedback in a warming climate

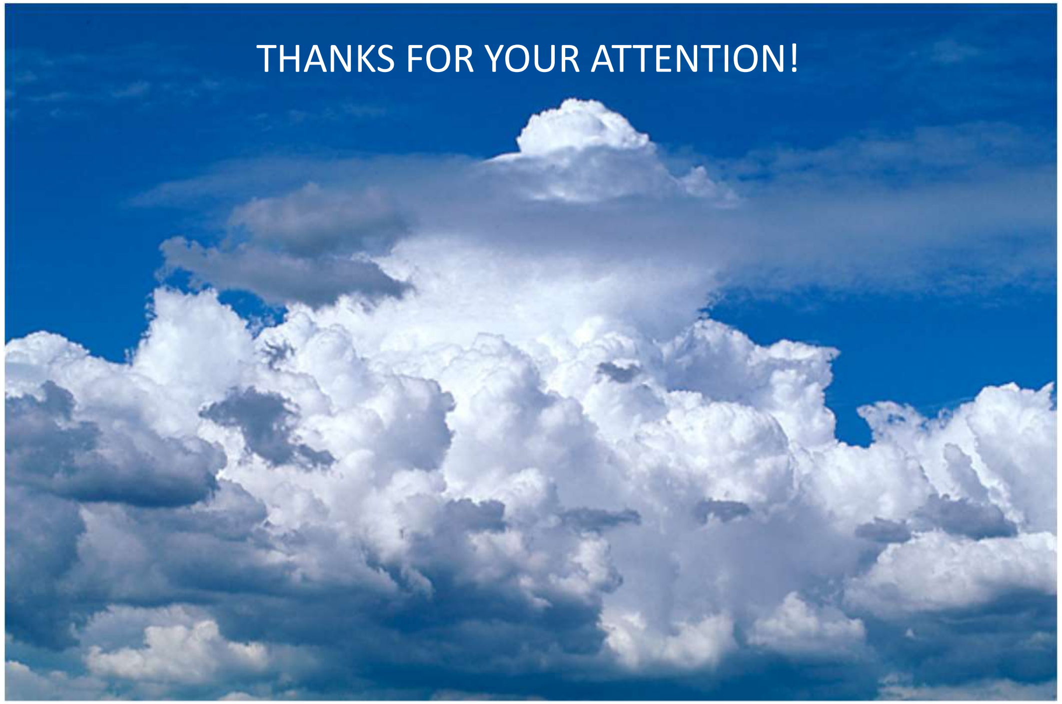
5) The spontaneous Aggregation of Convective Storms

6) IRIS Effect in global models

7) Detecting climate change using reanalysis (ERA5) and observations from COPERNICUS CDS

8) The effect of climate change over the orography of Apennines

9) AI for the analysis of climate data.

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