How is temperature forecast at ECMWF?

Annelize van Niekerk

… and the Physical Processes Team

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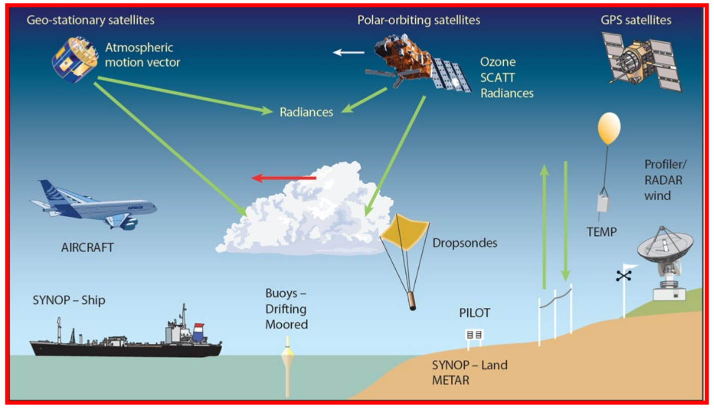
The ECMWF physical model

125 km

40 km

25 km 25 km

Data assimilation



Large-scale resolved dynamics

$$\frac{\partial T}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial T}{\partial \lambda} + V\cos\theta\frac{\partial T}{\partial \theta}\right\} + \dot{\eta}\frac{\partial T}{\partial \eta} - \frac{\kappa T_v \omega}{(1+(\delta-1)q)p} = \boxed{P_T} + K_T$$

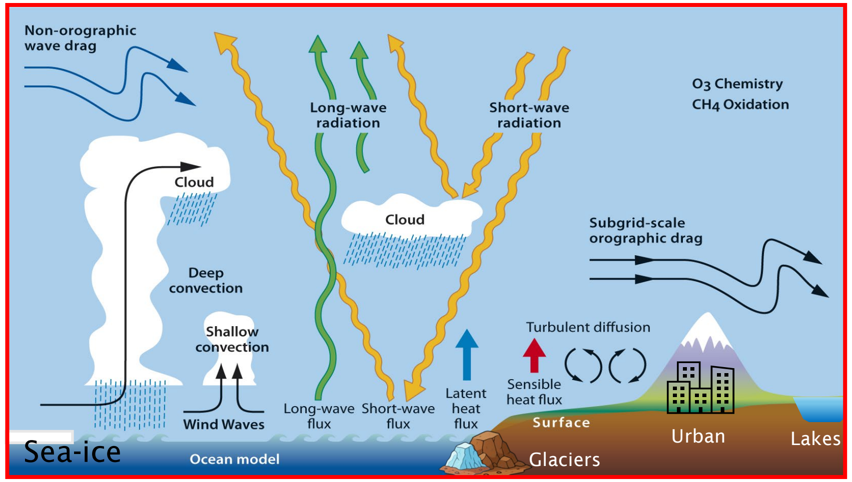
$$\frac{\partial q}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial q}{\partial \lambda} + V\cos\theta\frac{\partial q}{\partial \theta}\right\} + \dot{\eta}\frac{\partial q}{\partial \eta} = \boxed{P_q} + K_q$$

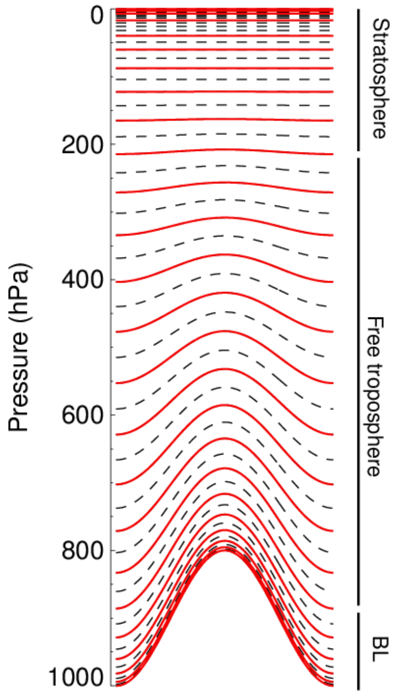
$$\frac{\partial}{\partial t}\left(\frac{\partial p}{\partial \eta}\right) + \nabla\cdot\left(\mathbf{v}_H\frac{\partial p}{\partial \eta}\right) + \frac{\partial}{\partial \eta}\left(\dot{\eta}\frac{\partial p}{\partial \eta}\right) = 0$$

$$\frac{\partial U}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial U}{\partial \lambda} + V\cos\theta\frac{\partial U}{\partial \theta}\right\} + \dot{\eta}\frac{\partial U}{\partial \eta} - fV + \frac{1}{a}\left\{\frac{\partial \phi}{\partial \lambda} + R_{dry}T_v\frac{\partial}{\partial \lambda}(\ln p)\right\} = \boxed{P_U} + K_U$$

$$\frac{\partial V}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial V}{\partial \lambda} + V\cos\theta\frac{\partial V}{\partial \theta} + \sin\theta(U^2+V^2)\right\} + \dot{\eta}\frac{\partial V}{\partial \eta} + fU + \frac{\cos\theta}{a}\left\{\frac{\partial \phi}{\partial \theta} + R_{dry}T_v\frac{\partial}{\partial \theta}(\ln p)\right\} = \boxed{P_V} + K_V$$

Parameterized sub-grid processes





We live on the surface of Earth…

…2m temperatures are, therefore, the most important forecast variable for what we ‘feel’

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Why then do we forecast from ‘soil-to-space’?

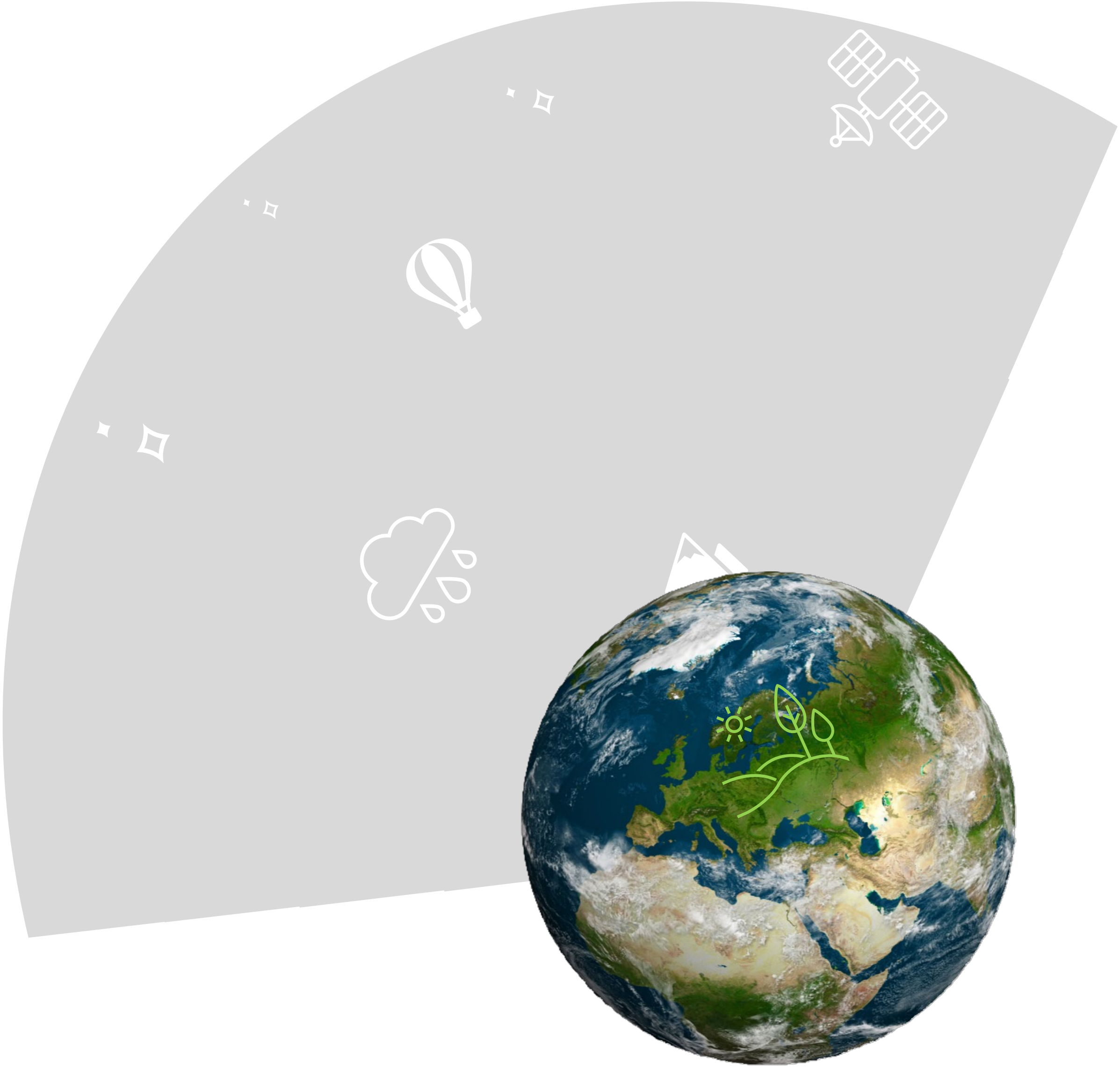
We live on the surface of Earth…

…2m temperatures are, therefore, the most important forecast variable for what we ‘feel’

Why then do we forecast from ‘soil-to-space’?

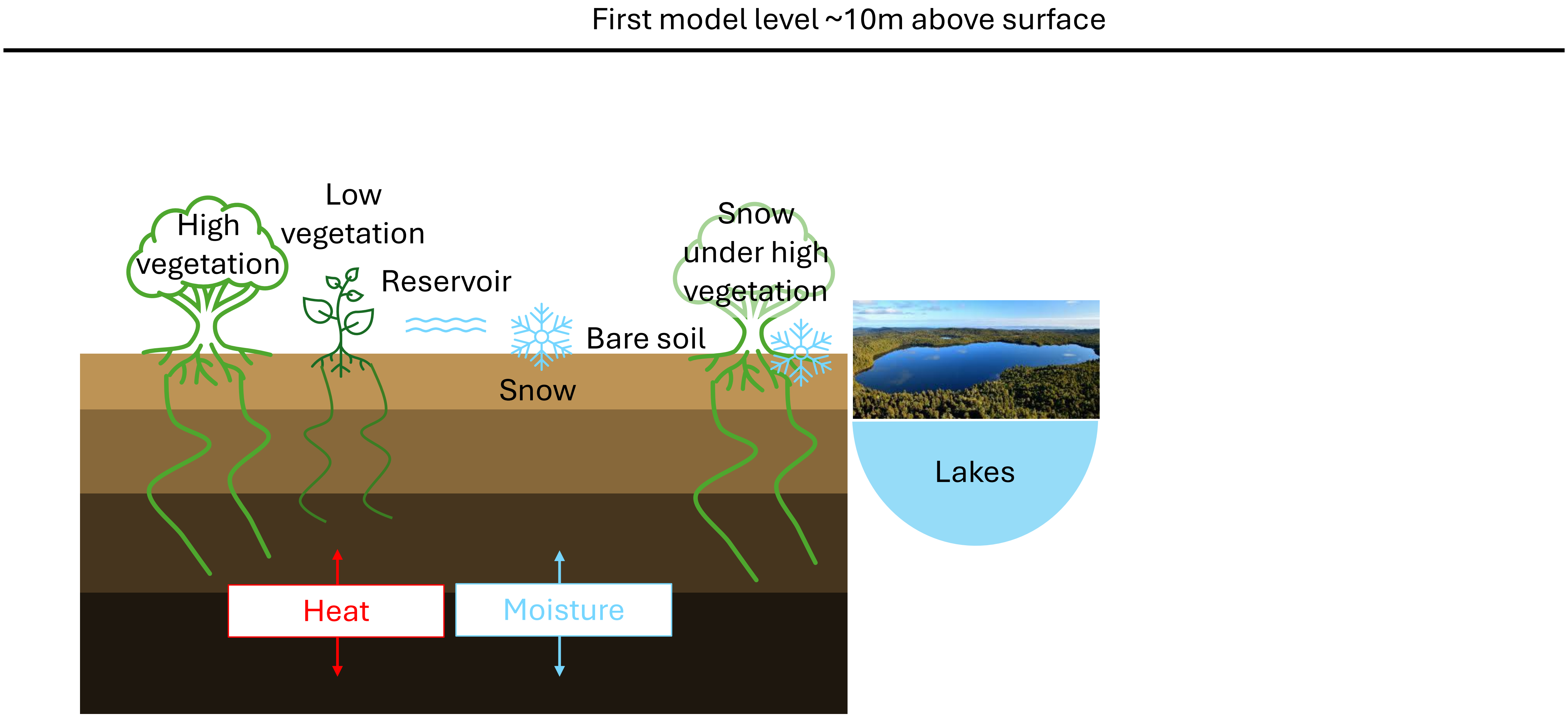
There many processes throughout the atmosphere that impact surface temperatures

Processes that impact forecast temperature

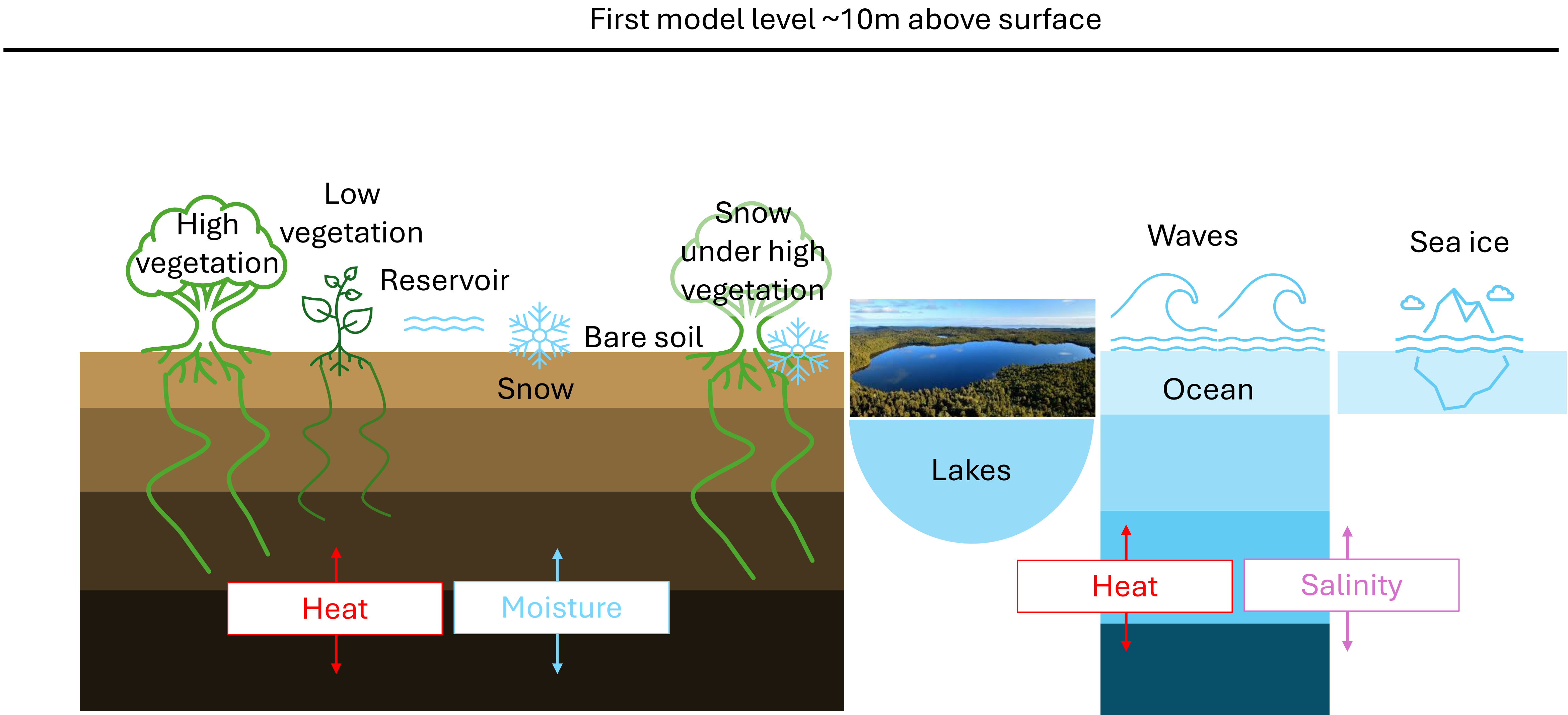


Land surface and ocean

Land surface, waves and ocean



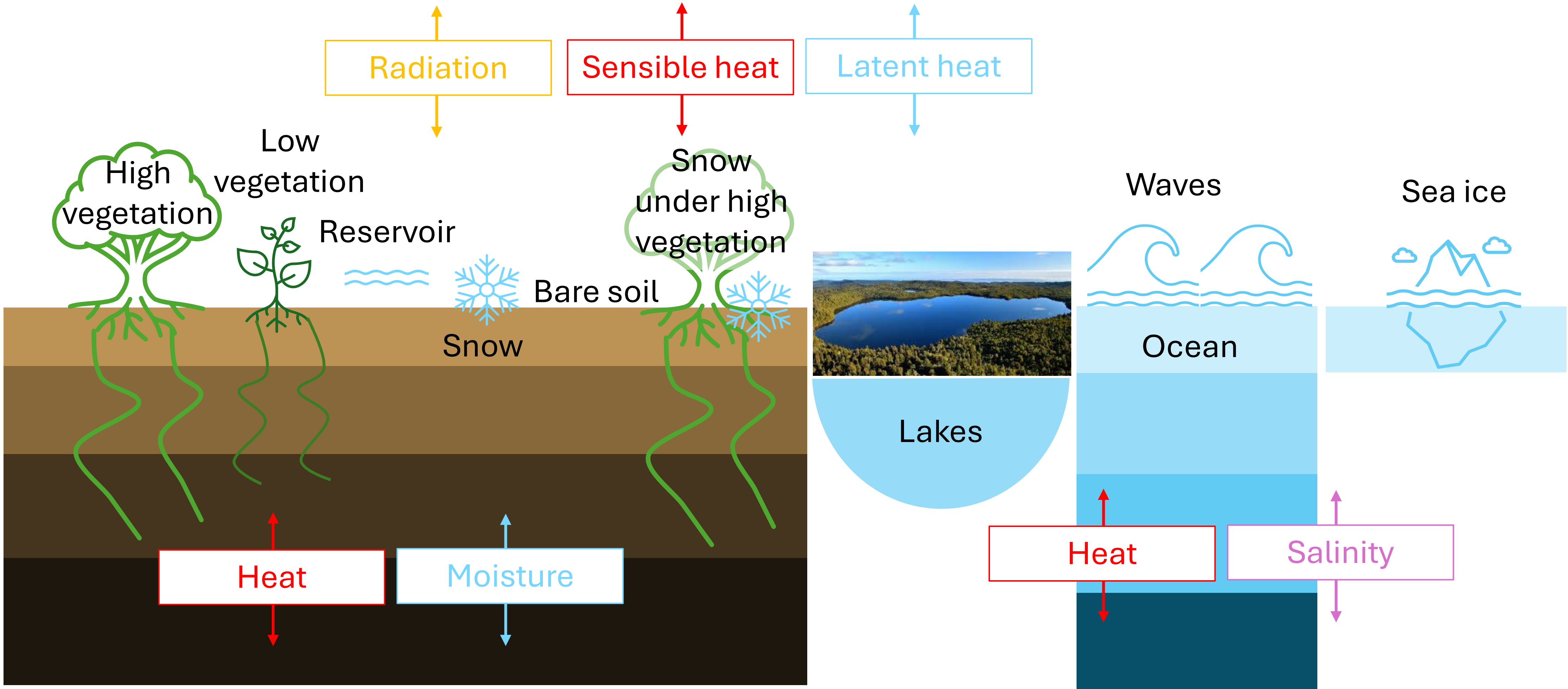
Land surface, waves and ocean



Land surface, waves and ocean

$$R_{LW} + R_{SW} + SH + LH = \Lambda(T_{10m} - T_{surf})$$

First model level ~10m above surface



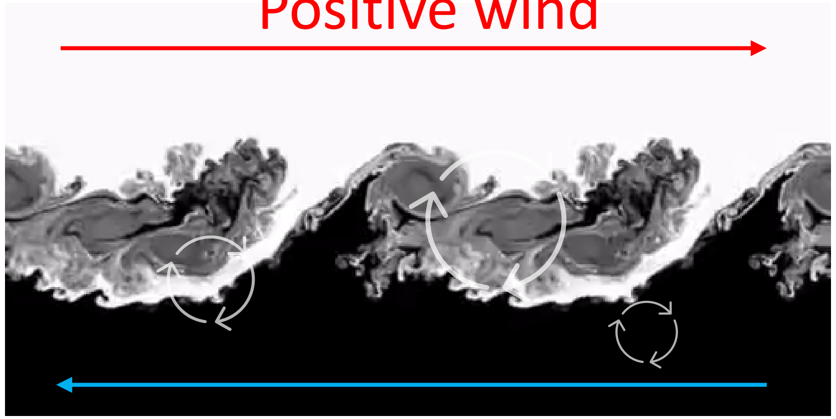
Processes that impact forecast temperature

Boundary layer turbulence

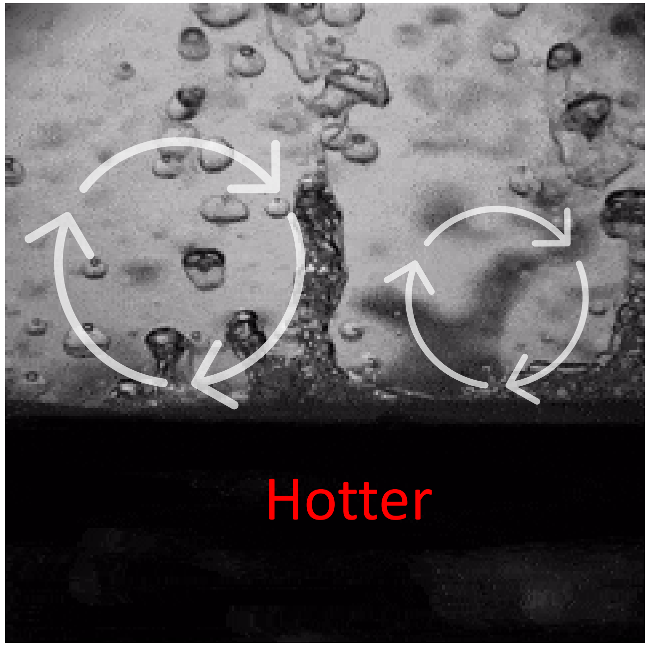
Land surface and ocean

Types of turbulence

Shear turbulence:

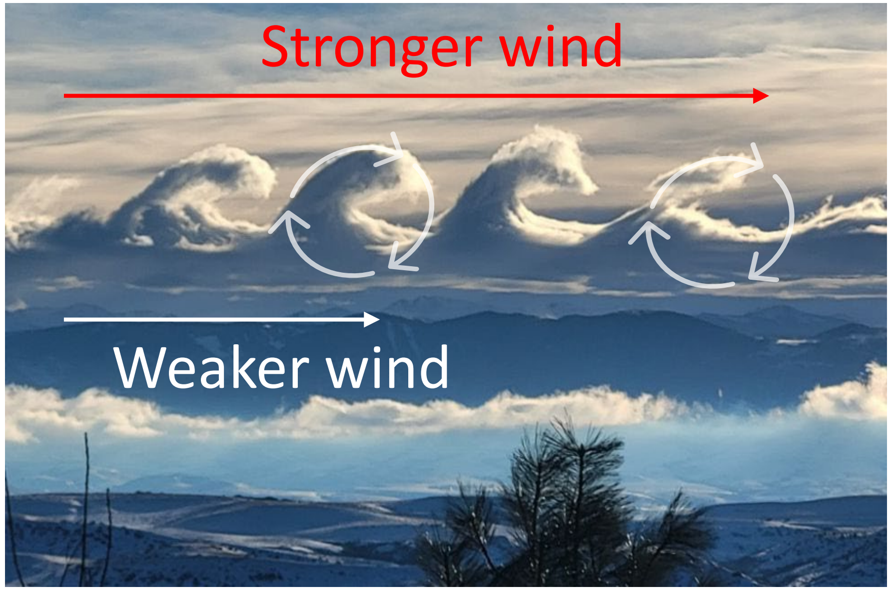


Convective turbulence:

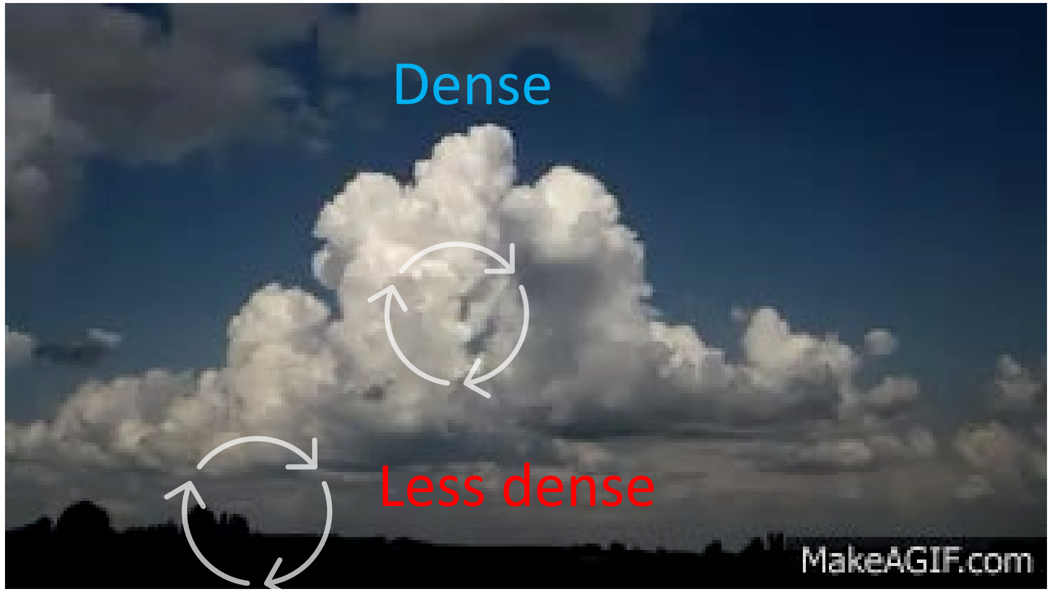


Types of turbulence

Shear turbulence:



Convective turbulence:



Turbulence acts to homogenise the fluid by mixing: momentum, heat, moisture, tracers and clouds

ECMWF

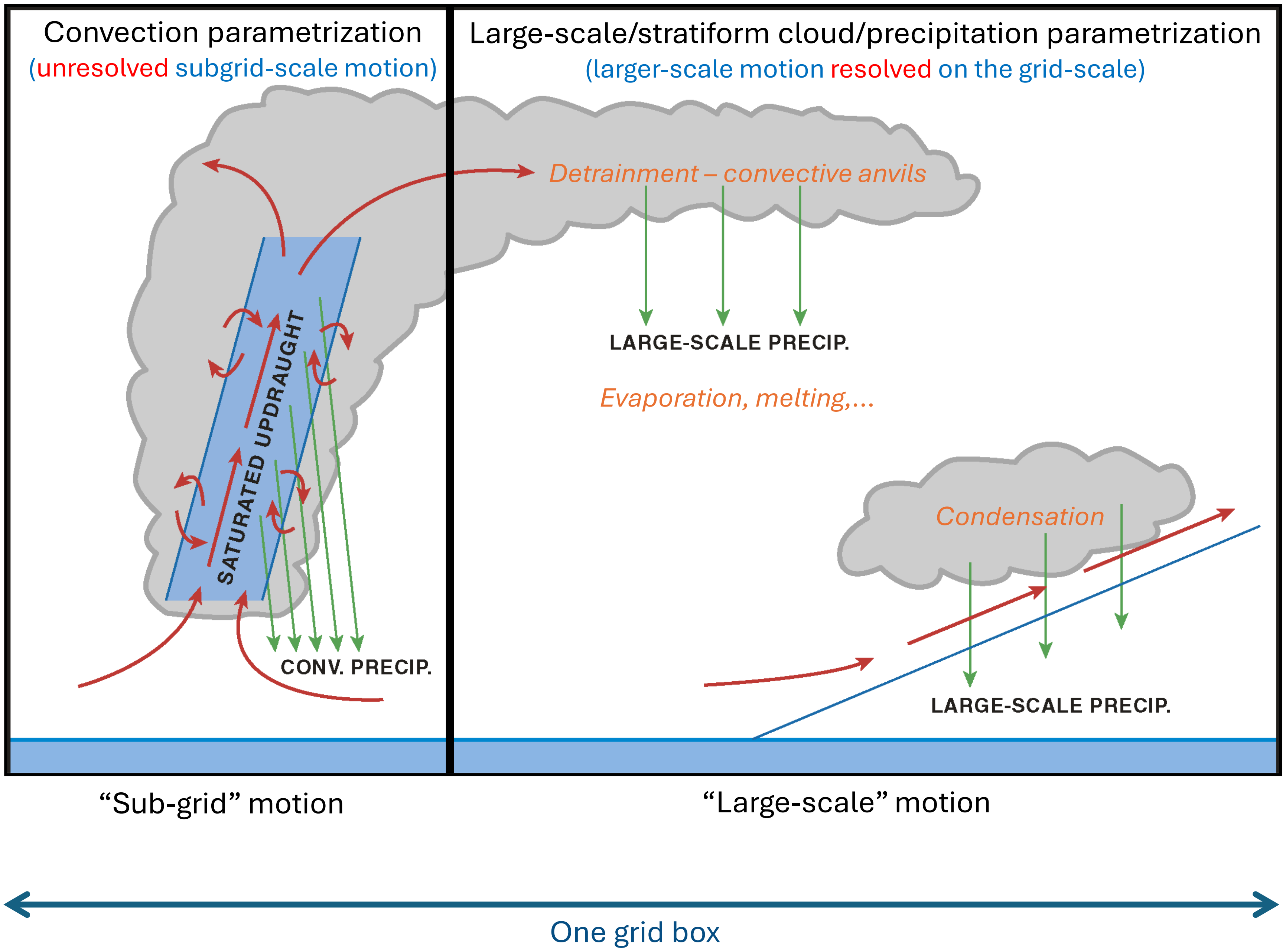
Processes that impact forecast temperature

Clouds and convection

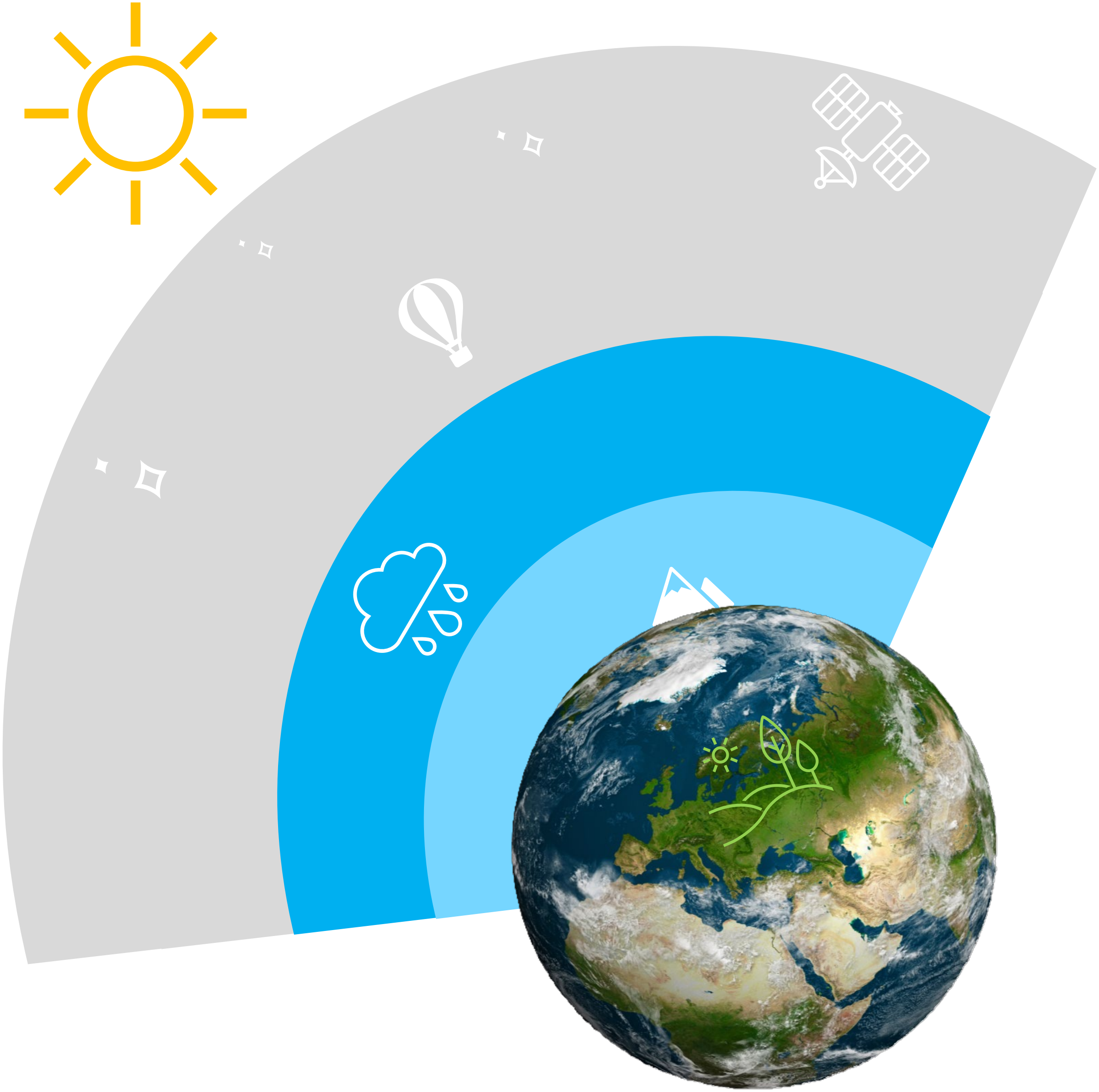
Boundary layer turbulence

Land surface and ocean

Large-scale and sub-grid convection



Processes that impact forecast temperature

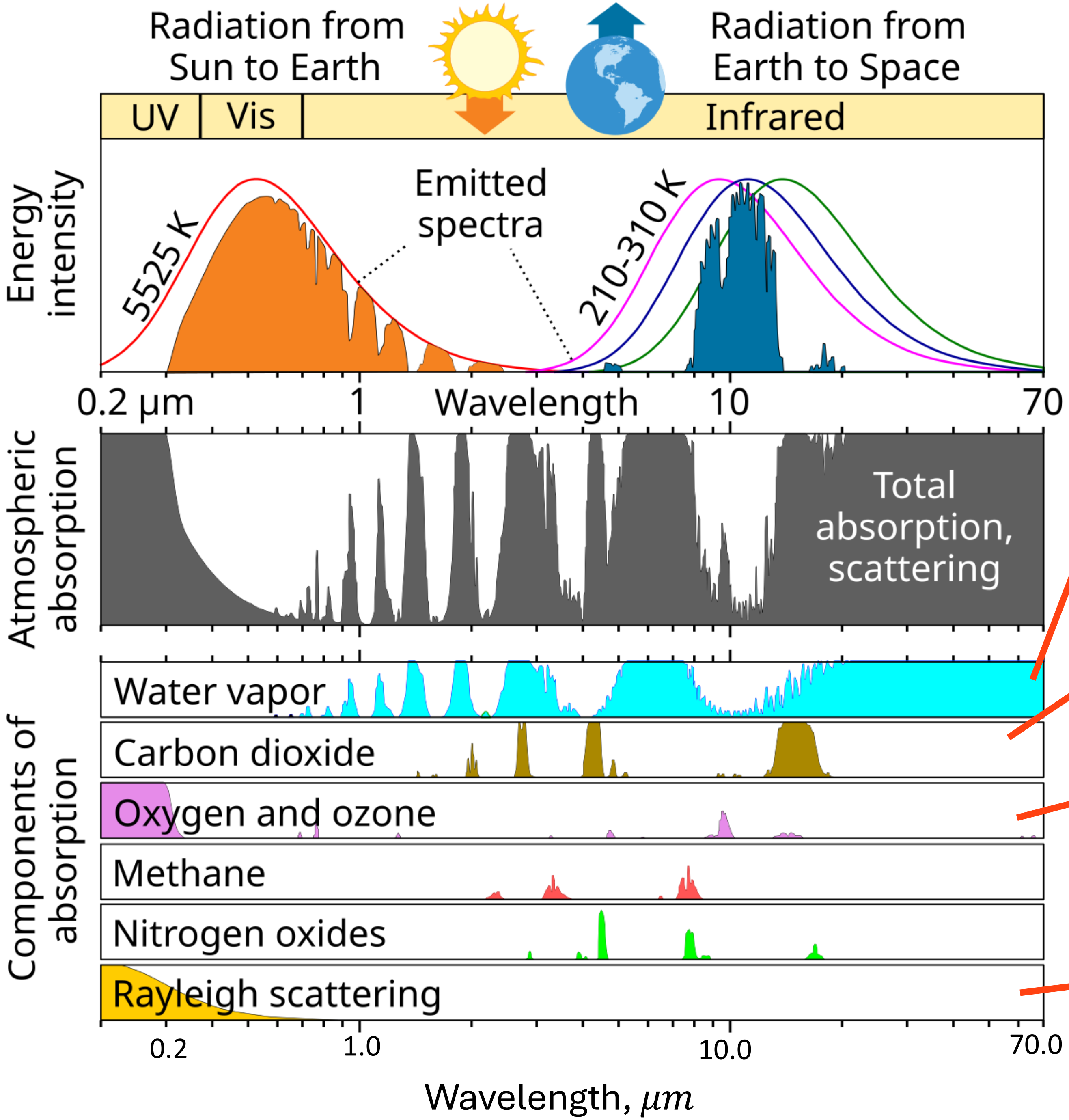


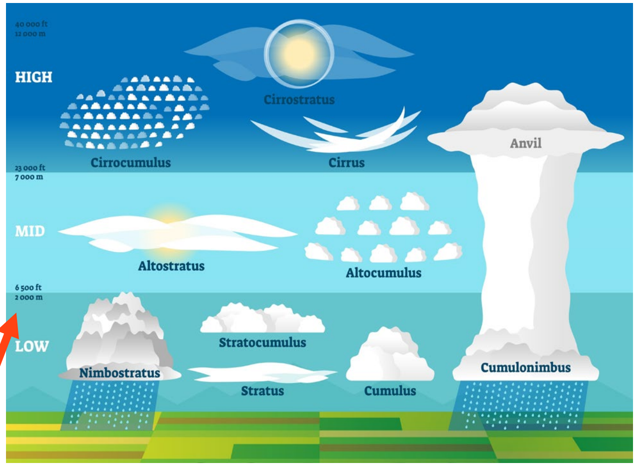
Clouds and convection

Boundary layer turbulence

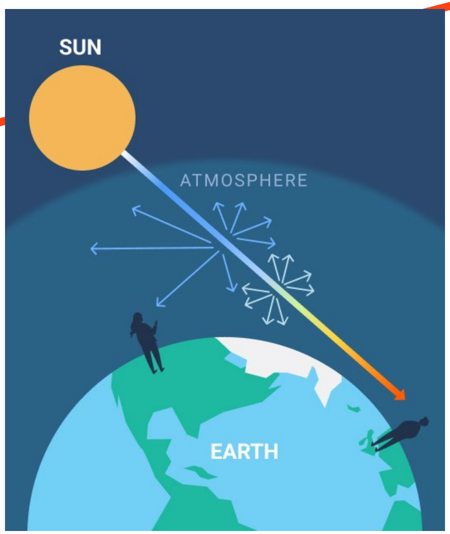
Land surface and ocean

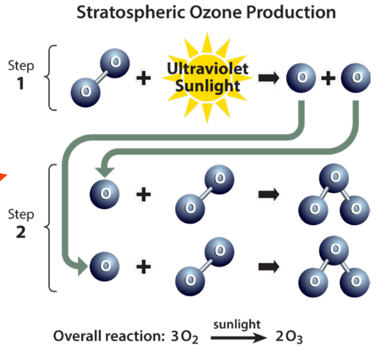
Radiation


Radiation from Sun to Earth
Radiation from Earth to Space
UV
Vis
Infrared
Energy intensity
5525 K
Emitted spectra
210-310 K
0.2 µm
1
Wavelength
10
70
Atmospheric absorption
Total absorption, scattering
Components of absorption
Water vapor
Carbon dioxide
Oxygen and ozone
Methane
Nitrogen oxides
Rayleigh scattering
0.2
1.0
10.0
70.0
Wavelength, µm

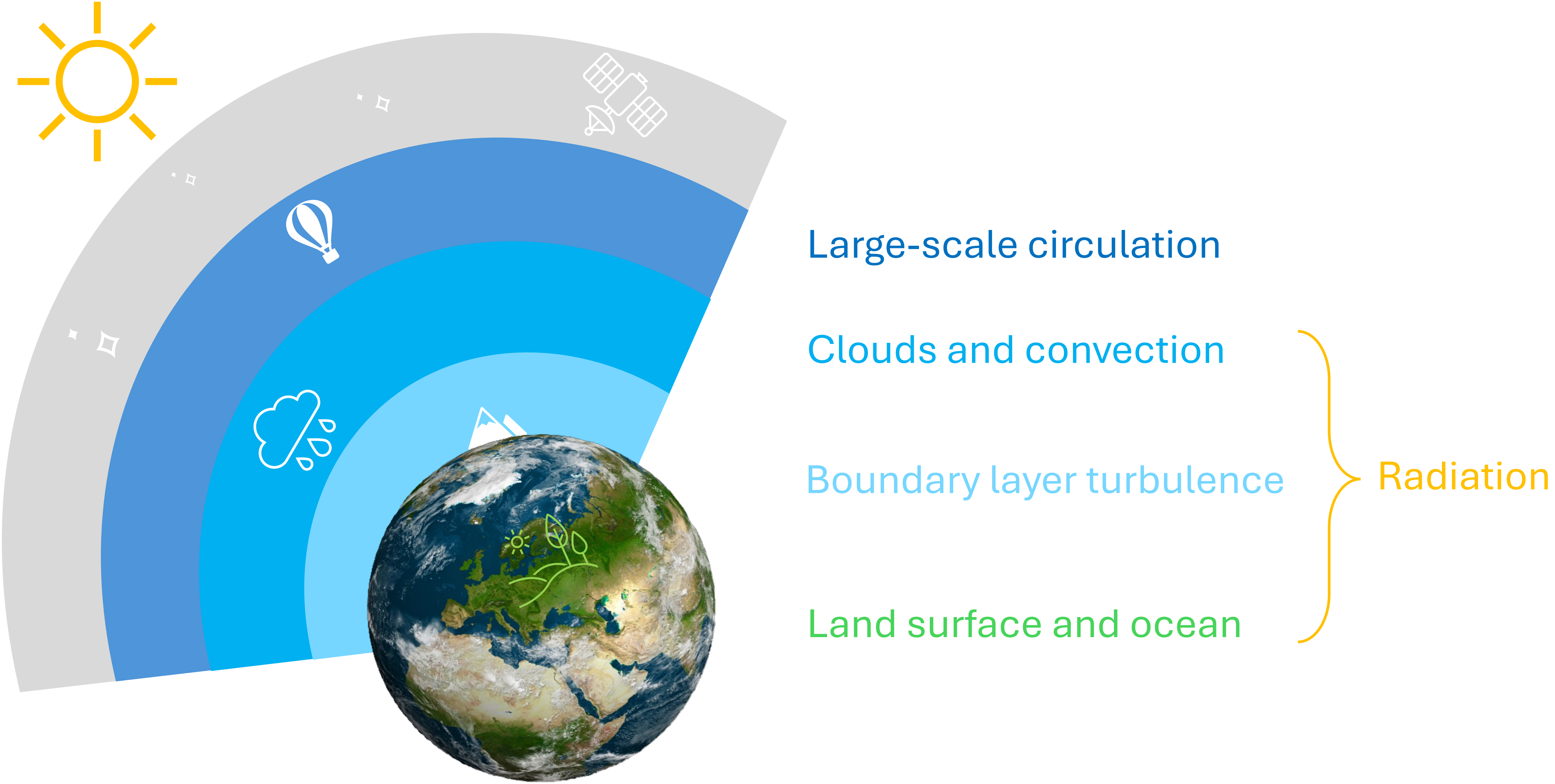

HIGH
Cirrostratus
Anvil
Cirrocumulus
Cirrus
MID
Altostratus
Altocumulus
LOW
Stratocumulus
Nimbostratus
Stratus
Cumulus
Cumulonimbus


CO2

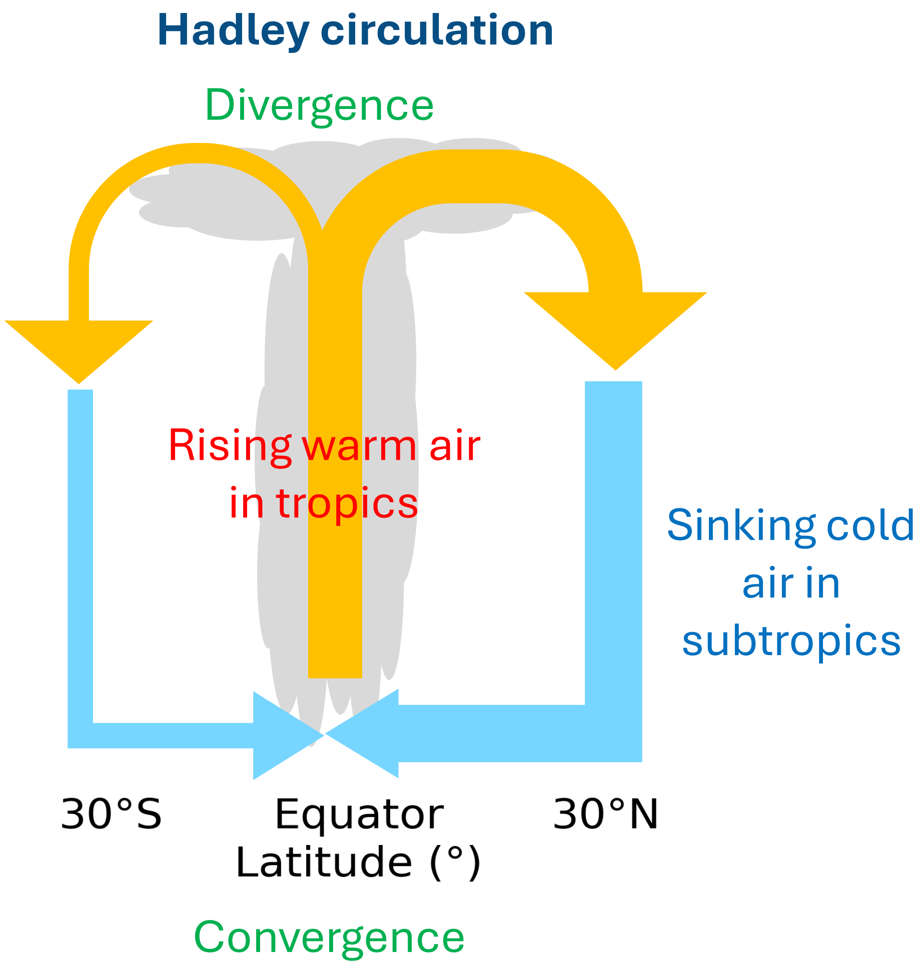

SUN
ATMOSPHERE
EARTH


Stratospheric Ozone Production
Step 1
Ultraviolet Sunlight
Step 2
Overall reaction: 3O2 sunlight → 2O3

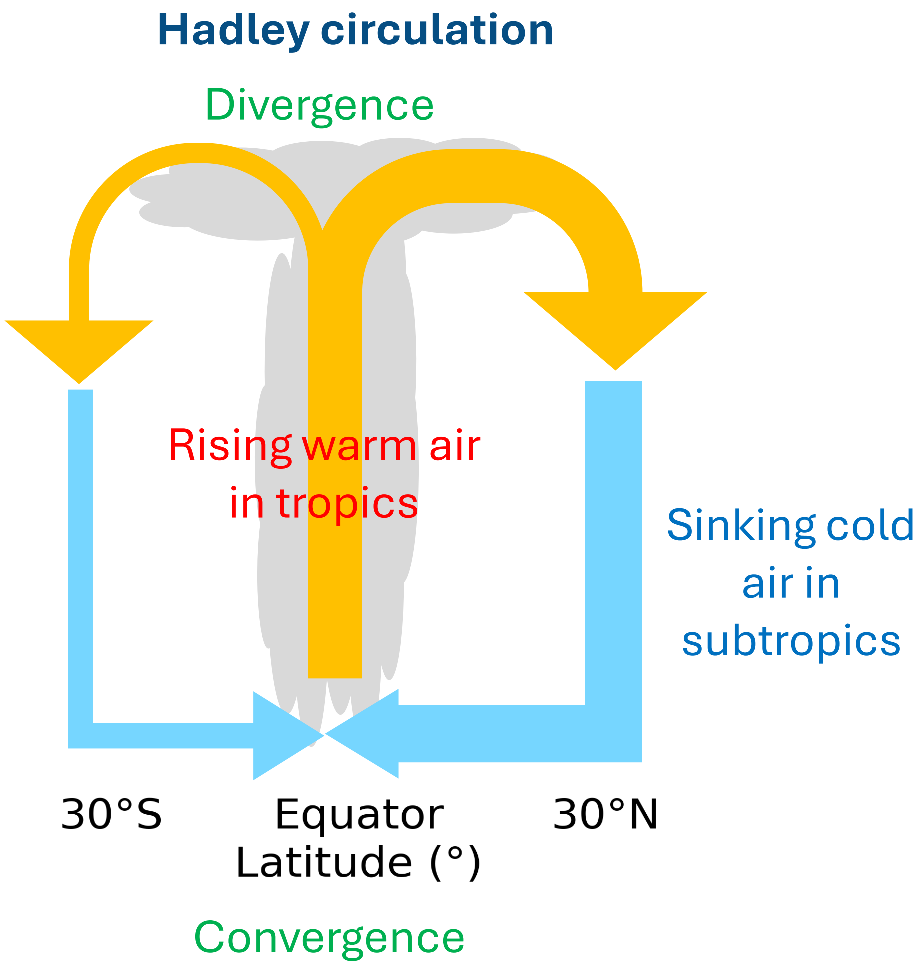
Processes that impact forecast temperature

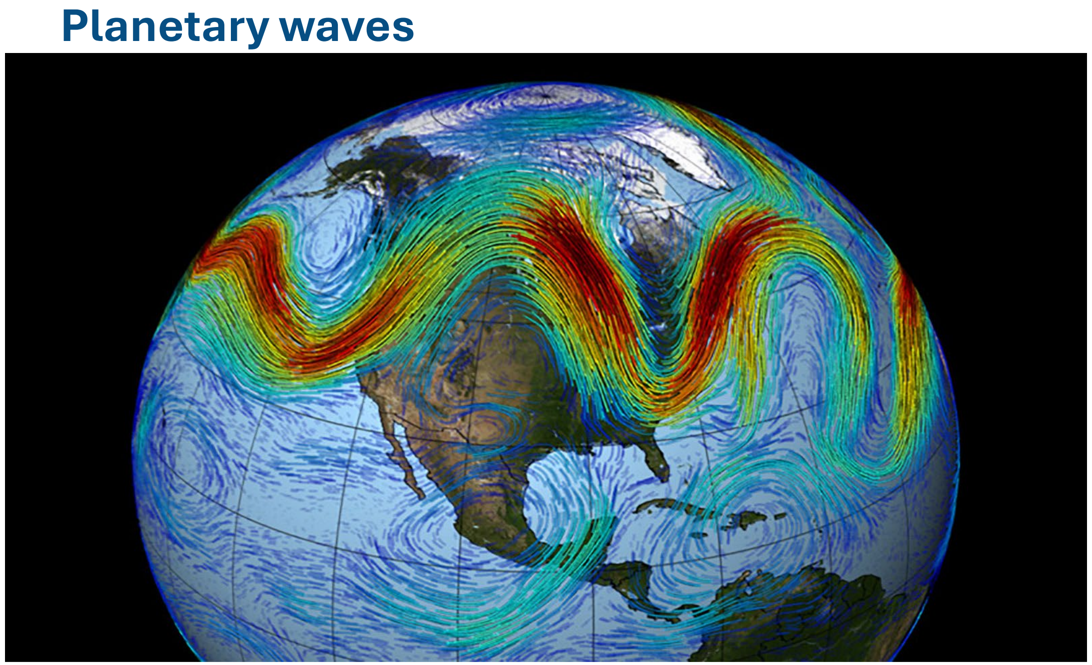


Large-scale circulation



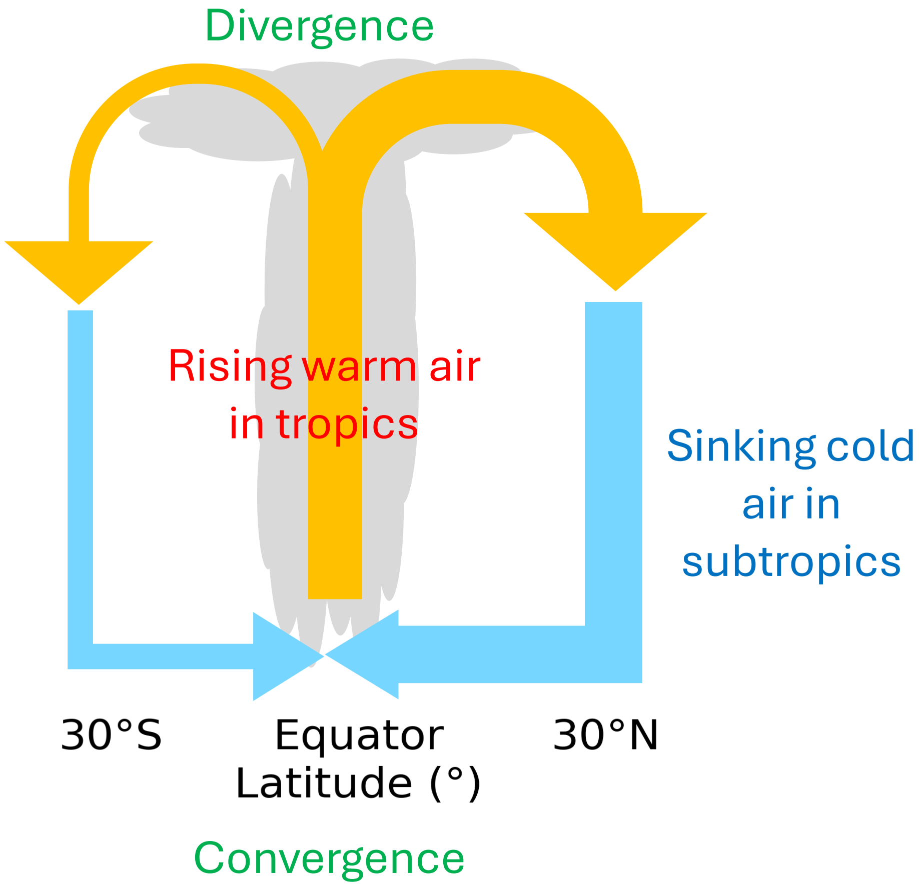
Large-scale circulation





Large-scale circulation

Hadley circulation



Large-scale resolved dynamics

$$\frac{\partial T}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial T}{\partial \lambda} + V\cos\theta\frac{\partial T}{\partial \theta}\right\} + \dot{\eta}\frac{\partial T}{\partial \eta} - \frac{\kappa T_v \omega}{(1+(\delta-1)q)p} = \boxed{P_T} + K_T$$

$$\frac{\partial q}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial q}{\partial \lambda} + V\cos\theta\frac{\partial q}{\partial \theta}\right\} + \dot{\eta}\frac{\partial q}{\partial \eta} = \boxed{P_q} + K_q$$

$$\frac{\partial}{\partial t}\left(\frac{\partial p}{\partial \eta}\right) + \nabla\cdot\left(\mathbf{v}_H\frac{\partial p}{\partial \eta}\right) + \frac{\partial}{\partial \eta}\left(\dot{\eta}\frac{\partial p}{\partial \eta}\right) = 0$$

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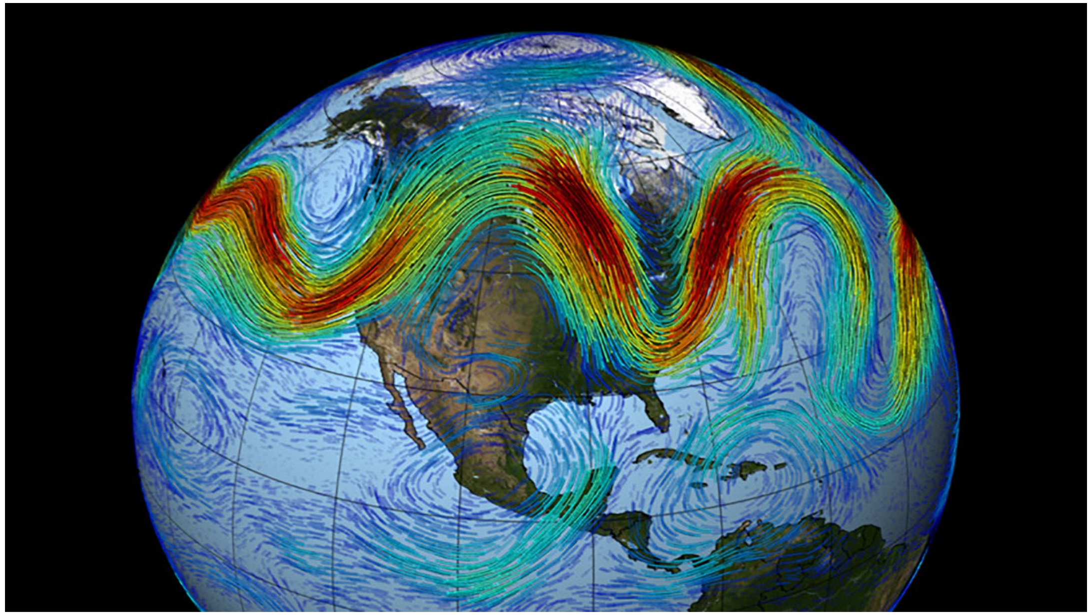
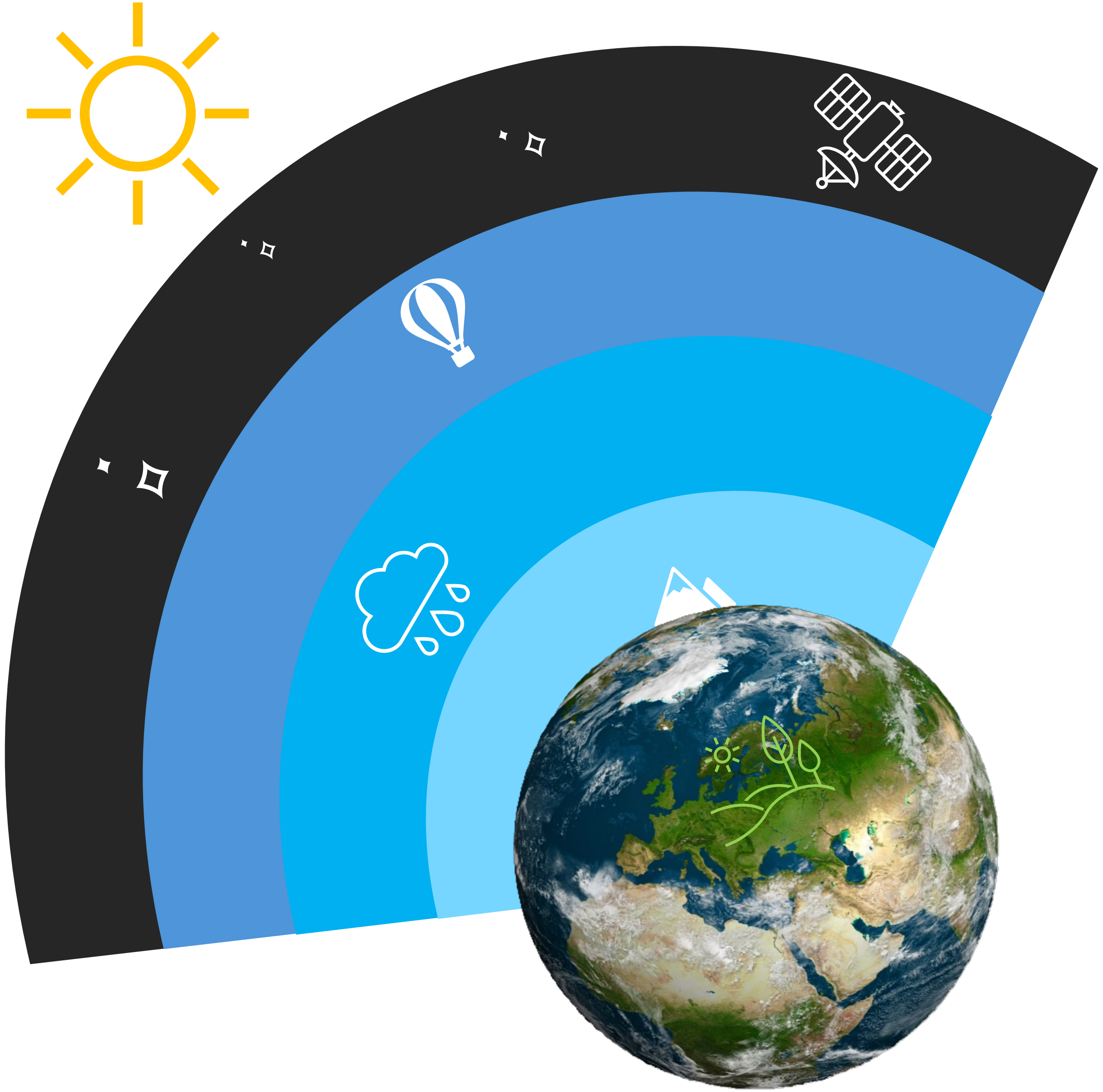
$$\frac{\partial V}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial V}{\partial \lambda} + V\cos\theta\frac{\partial V}{\partial \theta} + \sin\theta(U^2+V^2)\right\} + \dot{\eta}\frac{\partial V}{\partial \eta} + fU + \frac{\cos\theta}{a}\left\{\frac{\partial \phi}{\partial \theta} + R_{dry}T_v\frac{\partial}{\partial \theta}(\ln p)\right\} = \boxed{P_V} + K_V$$

Planetary waves



Processes that impact forecast temperature



Observations (remote and in-situ)

Large-scale circulation

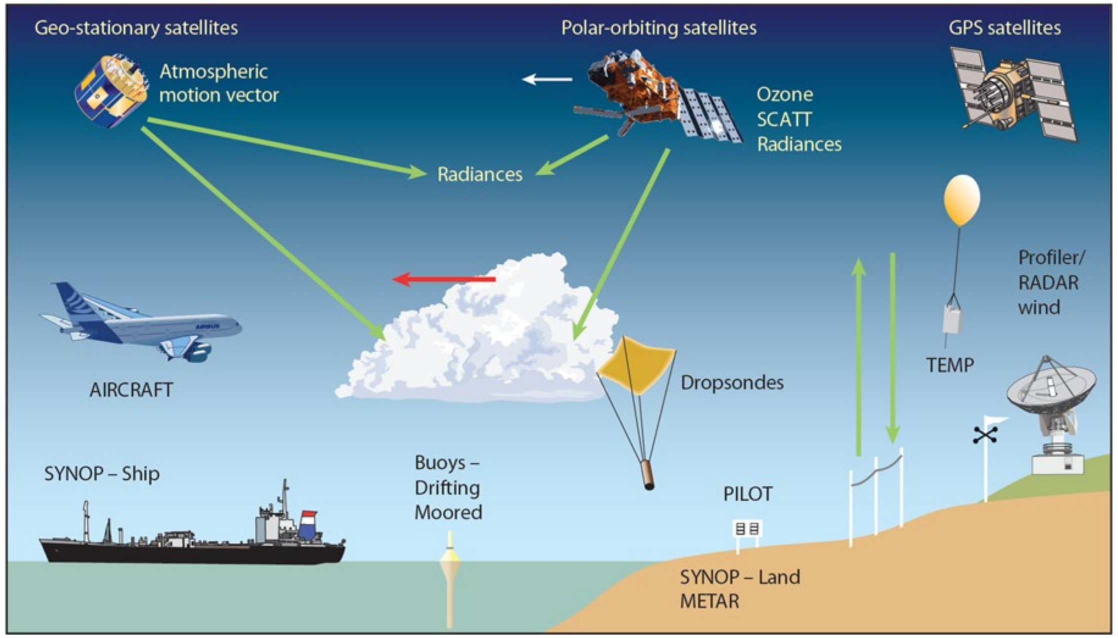
Clouds and convection

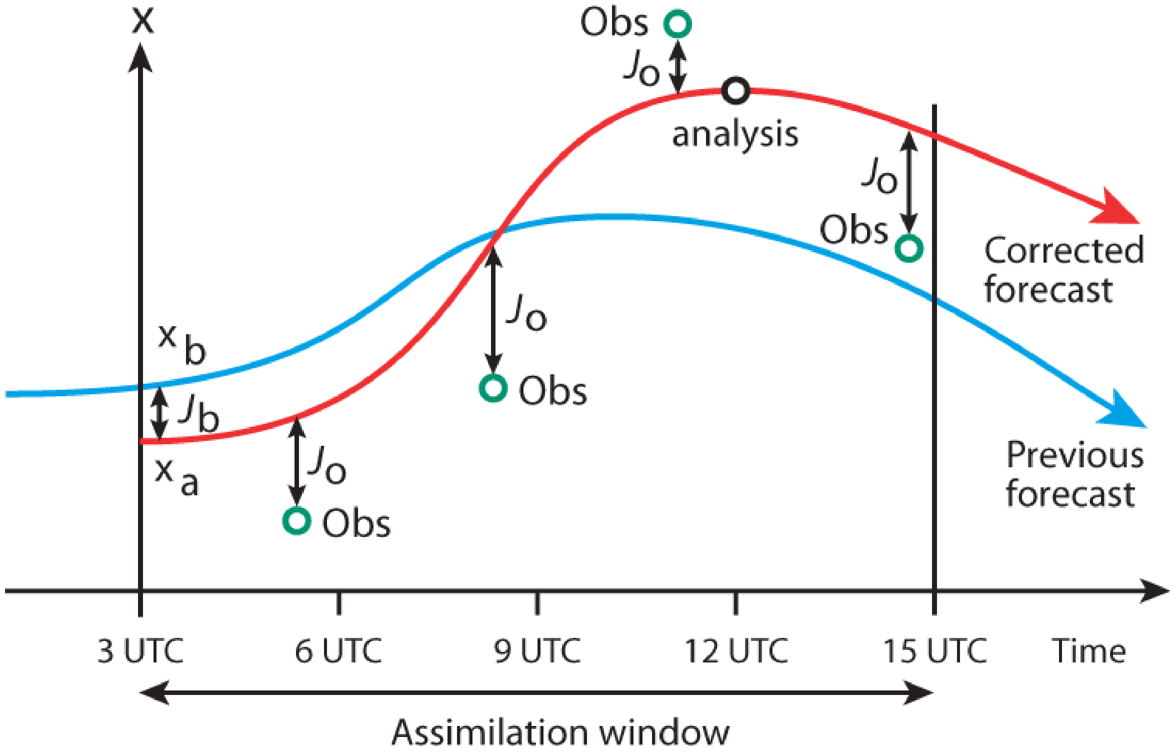
Boundary layer turbulence

Land surface and ocean

Radiation

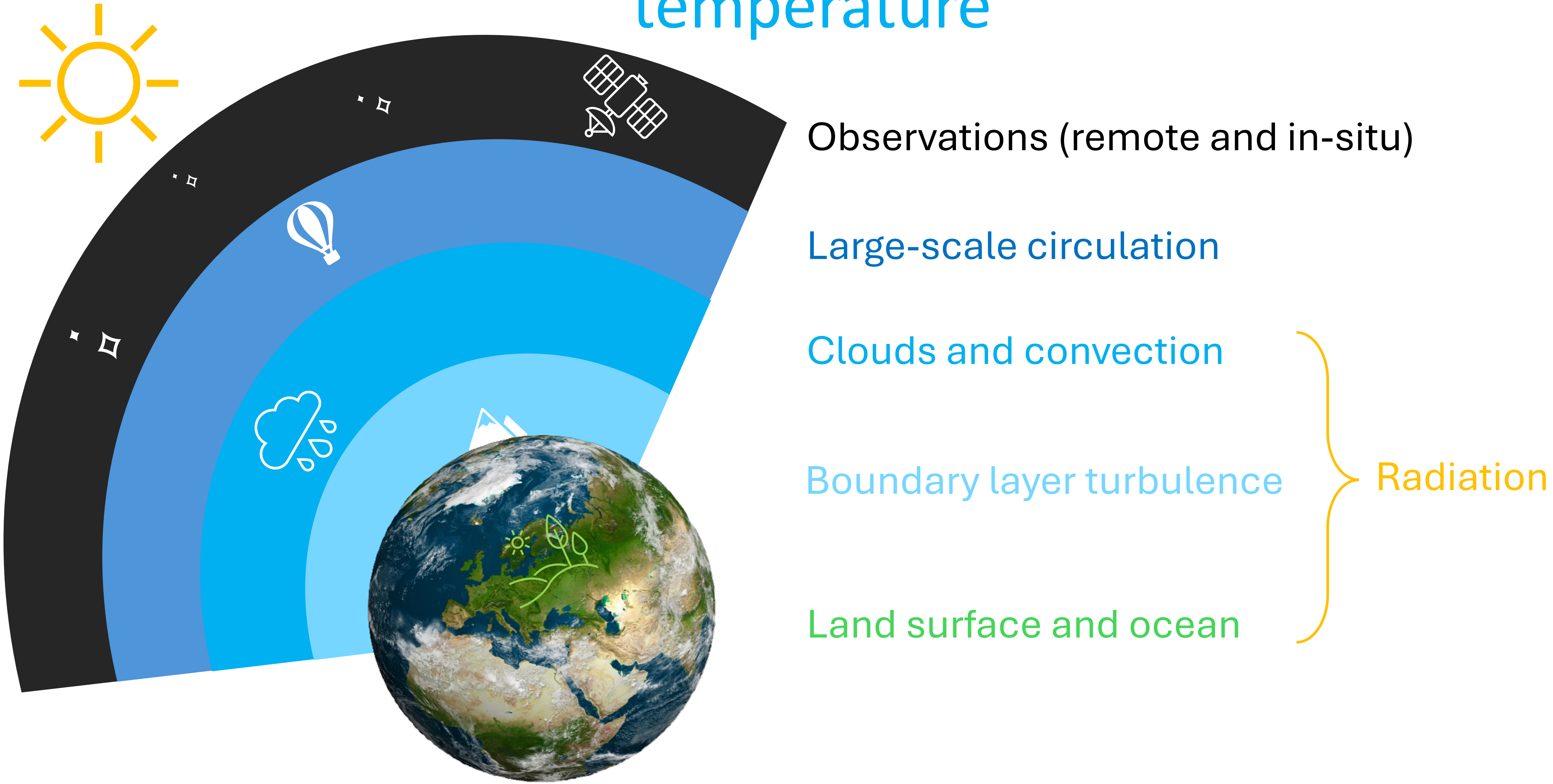
4D-Variational data assimilation



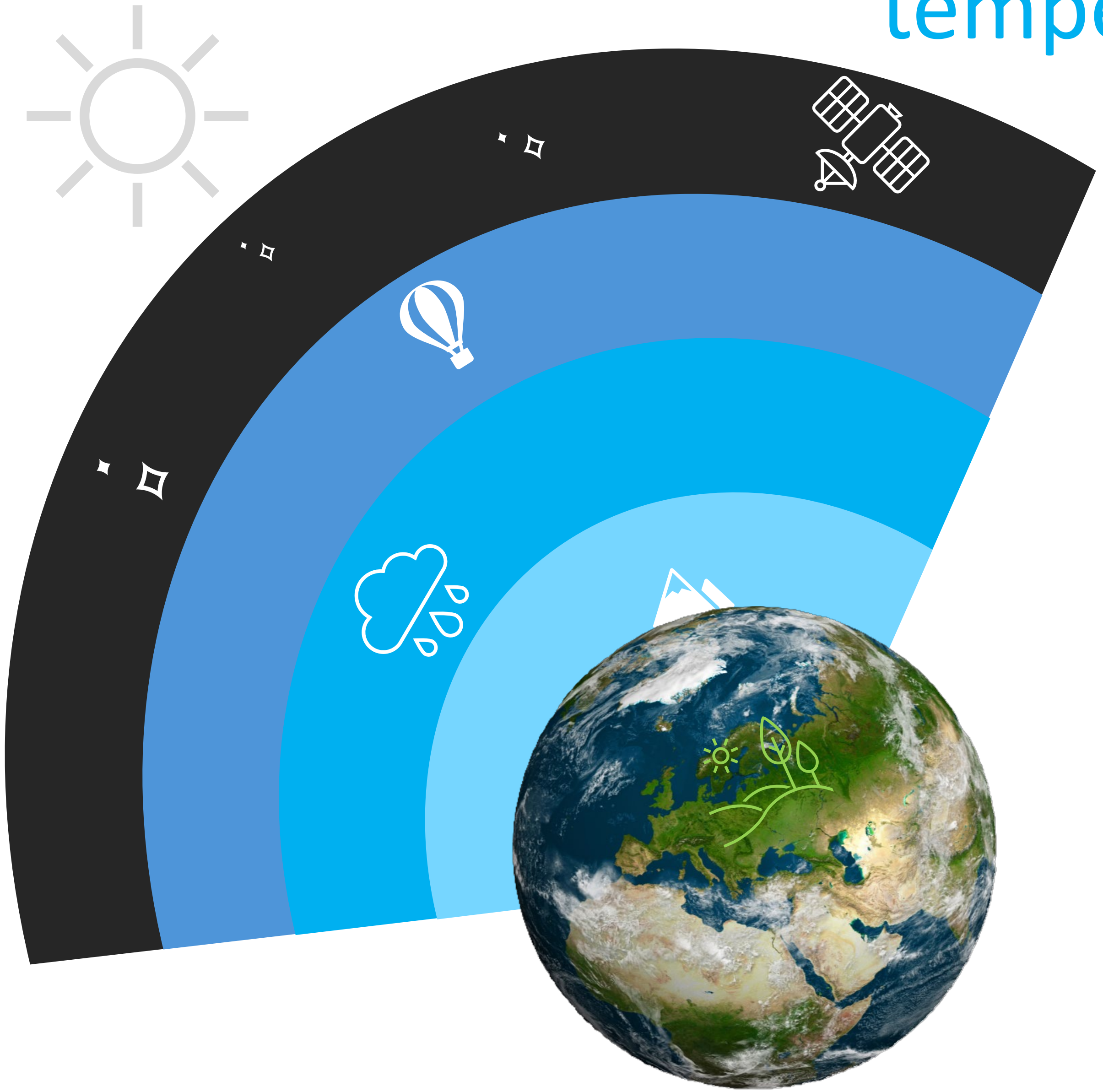


Many (millions) of observations are assimilated to get an accurate initial condition for the model, including many temperature observsations

Interaction of processes that impact forecast temperature



Interaction of processes that impact forecast temperature



Observations (remote and in-situ)

Large-scale circulation

Clouds and convection

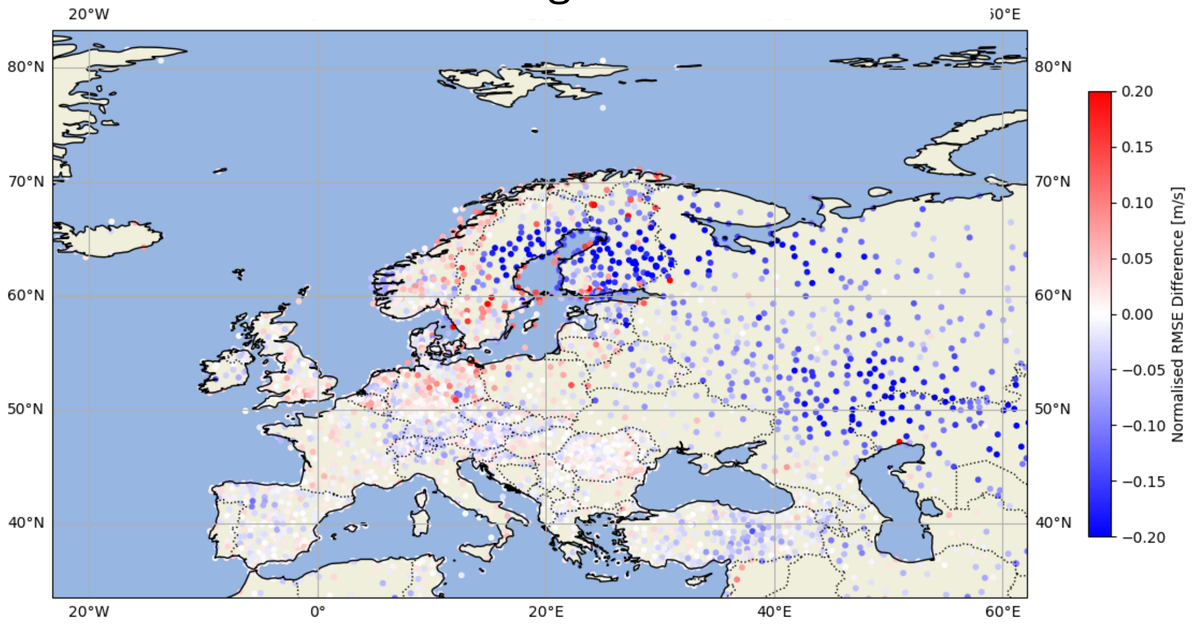
Boundary layer turbulence

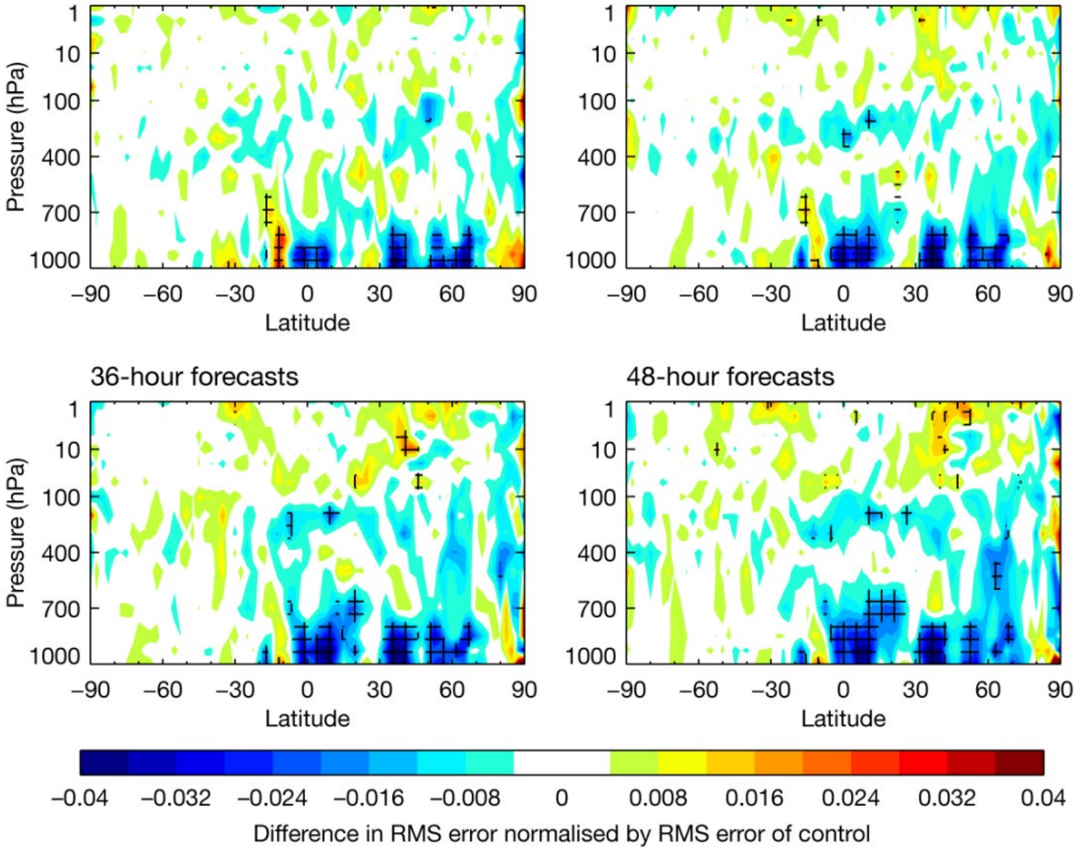
Land surface and ocean

Radiation

Impact of assimilating in-situ 2m temperature observations

Normalised change in RMSE +24h

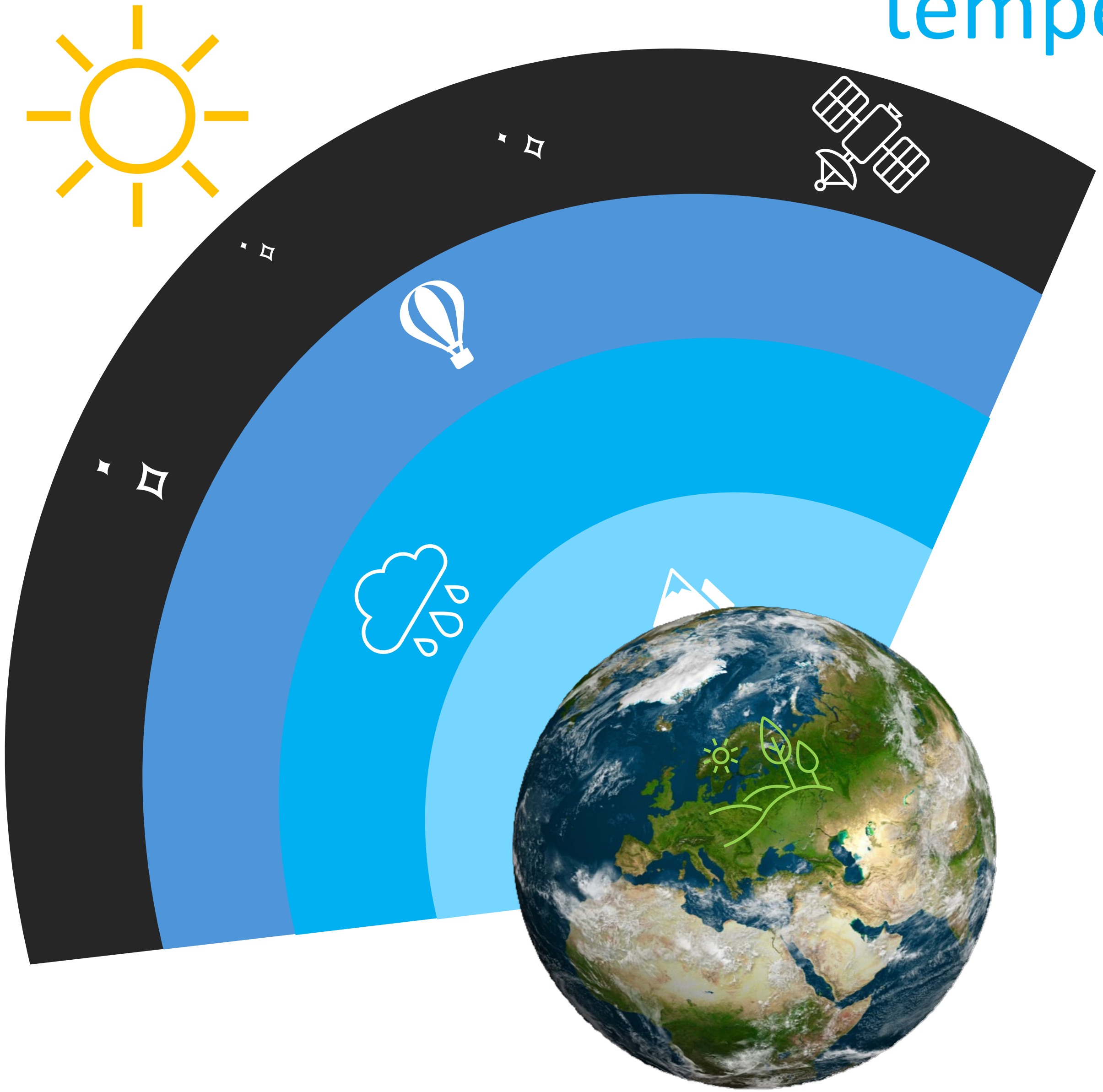




Assimilation of 2m temperatures over land has a lasting impact (+48 hours) on the temperature throughout the troposphere

Ingleby et al, ECMWF newsletter, Winter 2024

Interaction of processes that impact forecast temperature



Observations (remote and in-situ)

Large-scale circulation

Clouds and convection

Boundary layer turbulence

Land surface and ocean

Radiation

Soil moisture analysis

For each grid point, analysed soil moisture state vector $\boldsymbol{x}_a$:

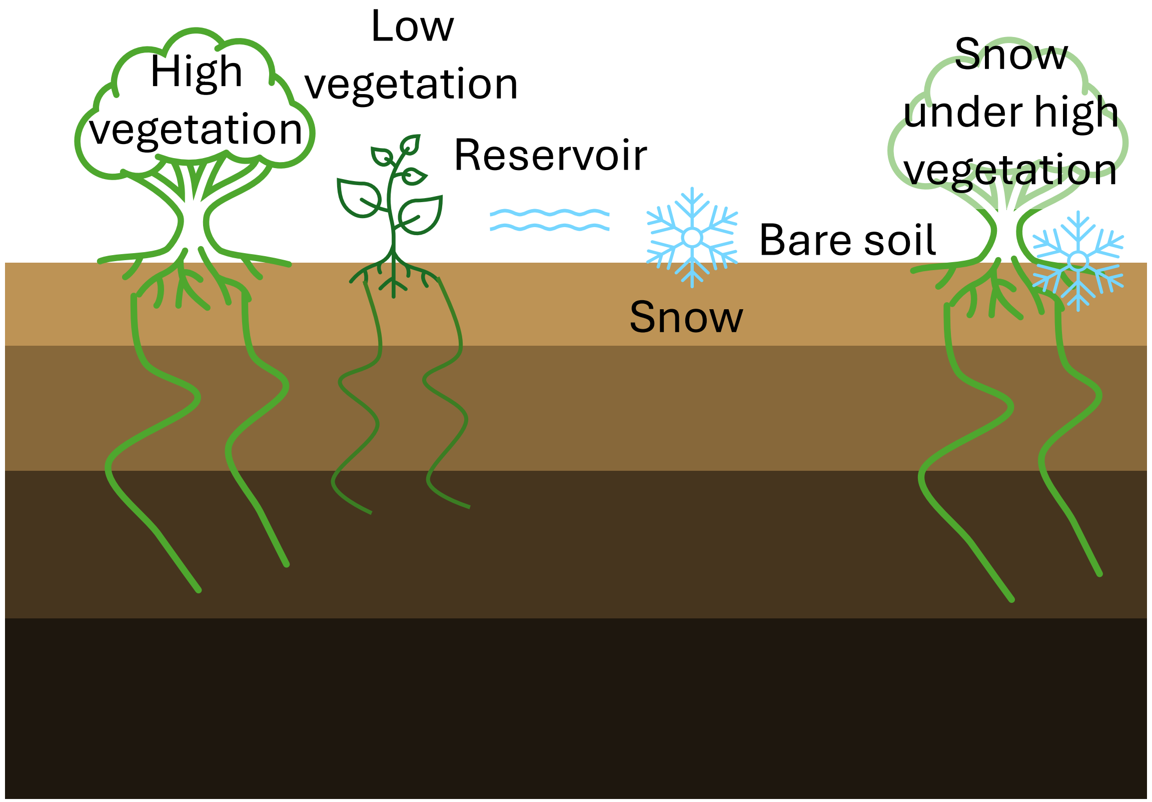
$$\boldsymbol{x}_a = \boldsymbol{x}_b + \boldsymbol{K}\,(\boldsymbol{y} - \mathcal{H}[\boldsymbol{x}_b])$$

x background soil moisture state vector,
$\mathcal{H}$ non linear observation operator
y observation vector
K Kalman gain matrix, function of
H (linearsation of $\mathcal{H}$), **P** and **R** (covariance matrices of background and observation errors).

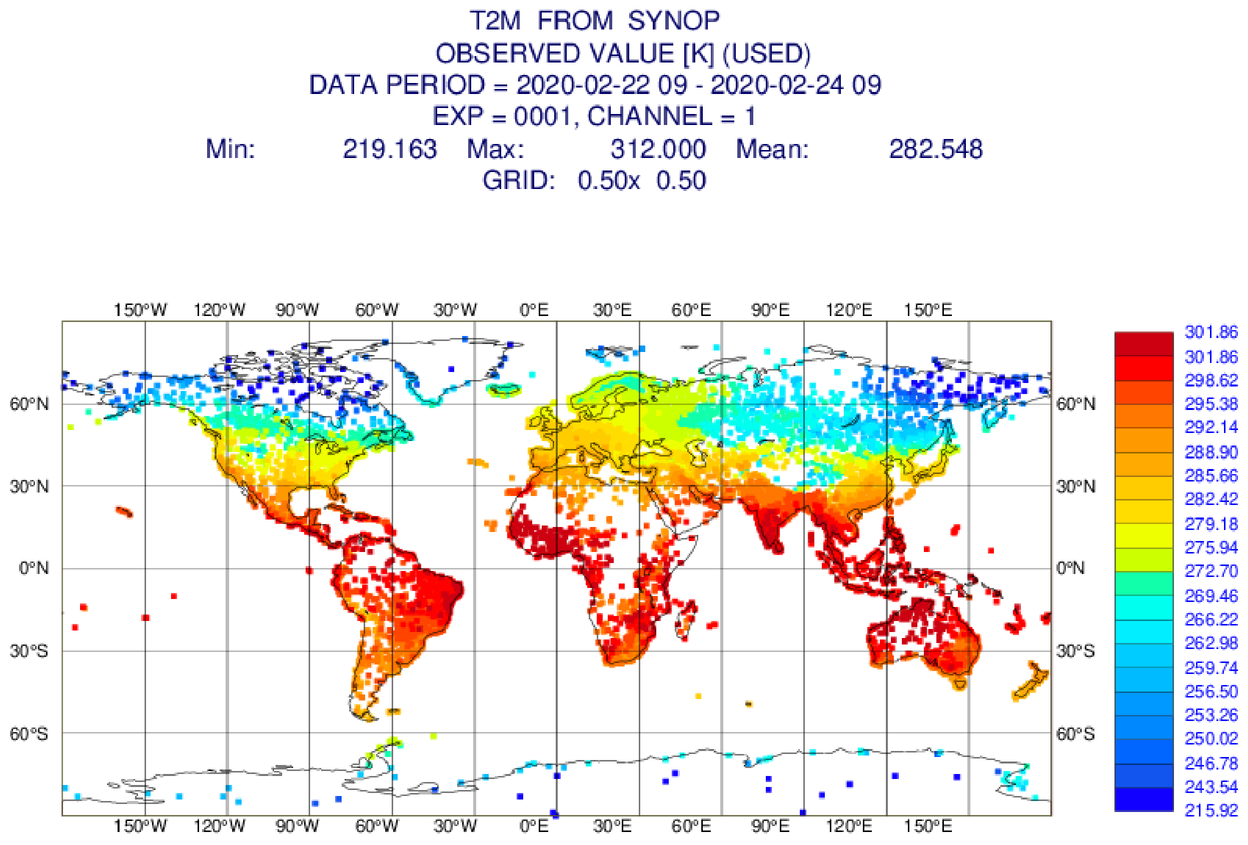
Used at ECMWF (NWP, ERA5, ERA6), DWD, UKMO

Drusch et al., GRL, 2009
de Rosnay et al., QJRMS, 2013
Fairbairn et al., JHM 2019
Munoz-Sabater et al QJRMS, 2019
Rodriguez-Fernandez et al, RS 2019

Assimilation of temperatures and humidity is used to corrects the soil moisture trajectory of Land Surface Model



SYNOP T2m, RH2m in situ data assimilated in land data assimilation



Screen level observations are:

- T2m, two meter temperature

- RH2m, relative humidity (RH2m)

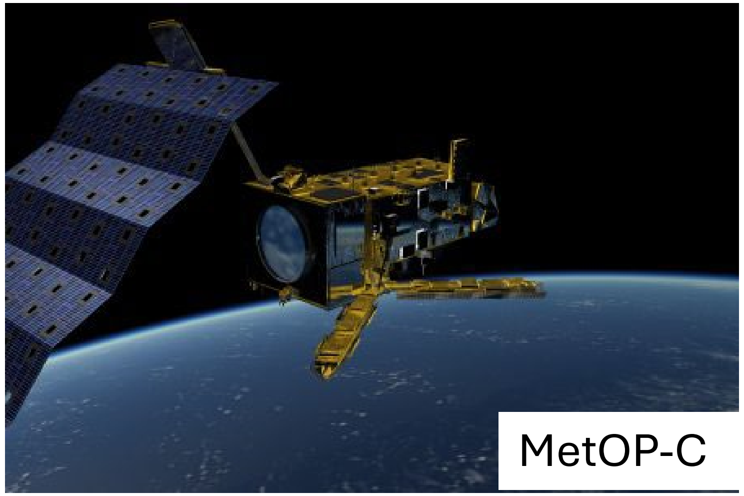
Diversity of Report types:

Automatic and manual SYNOP stations, METAR (METeorological Airport Reports), etc...

c/o Patricia de Rosnay

Soil moisture satellite observations assimilated operationally

Active microwave data:
ASCAT: Advanced Scatterometer
On MetOP-A (2006-2021),
MetOP-B (2012-), MetOP-C (2018-)
C-band (5.6GHz) backscattering coefficient
EUMETSAT Operational mission



Scatterometer soil moisture also used in ERA5
(ERS-SCAT, Metop/ASCAT)

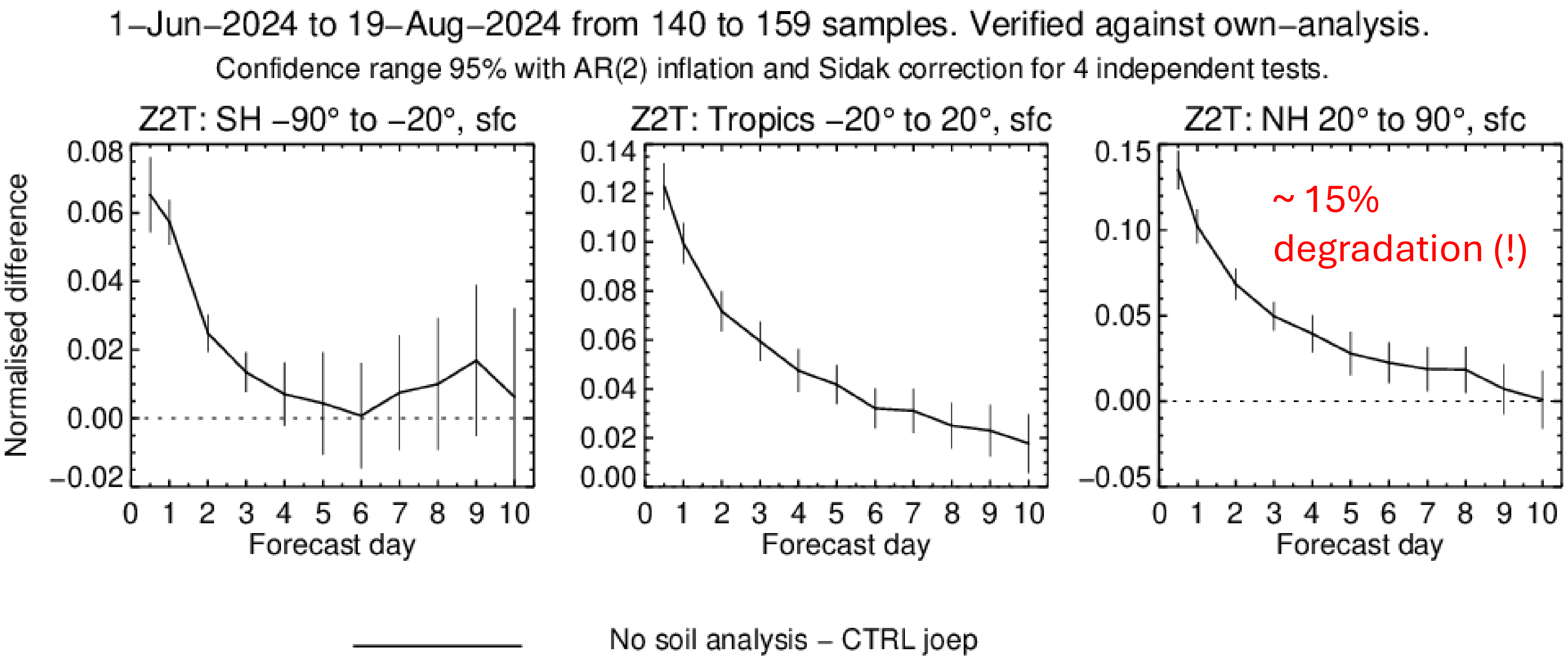
Passive microwave data:
SMOS: Soil Moisture & Ocean Salinity (2009-)
L-band (1.4 GHz) Brightness Temperature
ESA Earth Explorer, dedicated soil moisture mission
(Munoz-Sabater et al., 2020, Rodriguez-Fernandez et al., 2019)

c/o Patricia de Rosnay

Soil analysis: impact on the atmospheric forecast

Impact of **removing** soil moisture and temperature analysis on 2m T RMSE

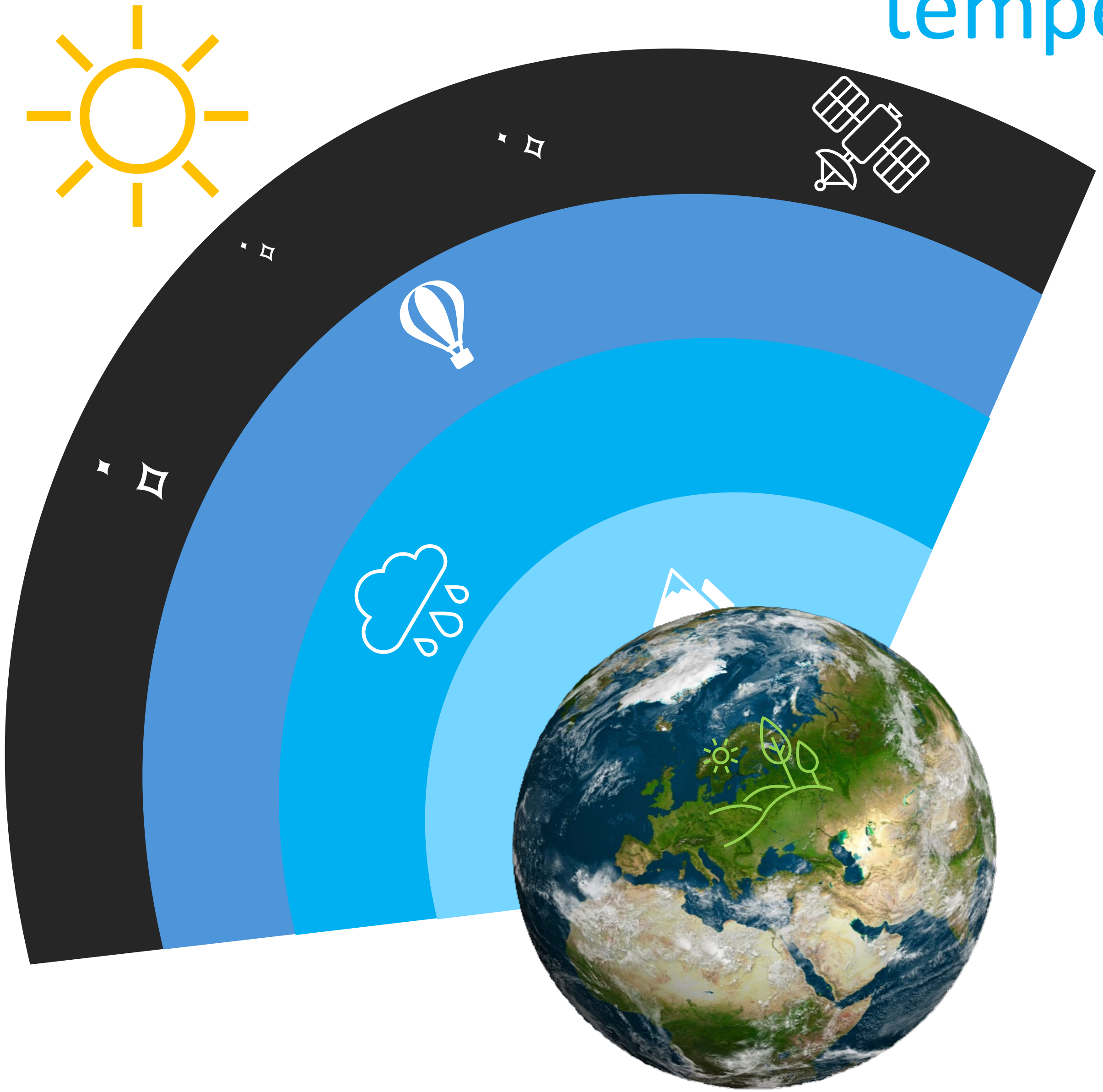
JJA 2024
IFS cycle 50r1



Significant positive impact of soil DA on low level atmospheric temperature forecasts

c/o Patricia de Rosnay

Interaction of processes that impact forecast temperature



Observations (remote and in-situ)

Large-scale circulation and stratosphere

Clouds and convection

Boundary layer turbulence

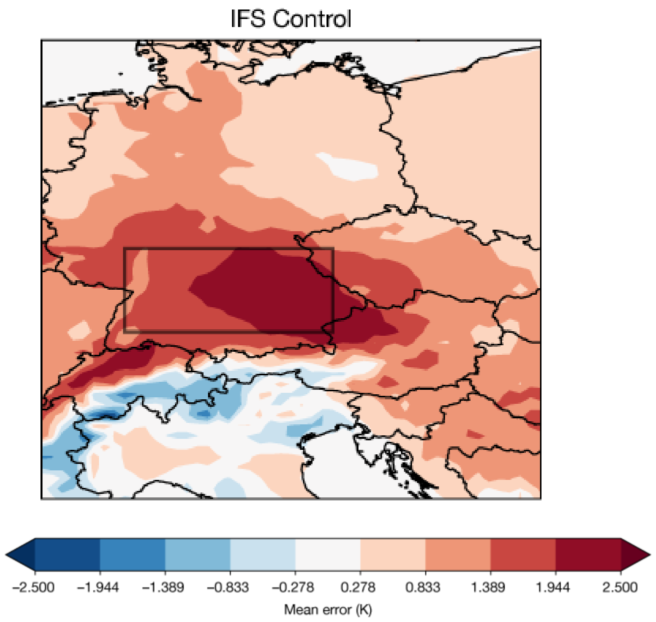
Land surface and ocean

Radiation

Example: Low cloud cover and temperature errors

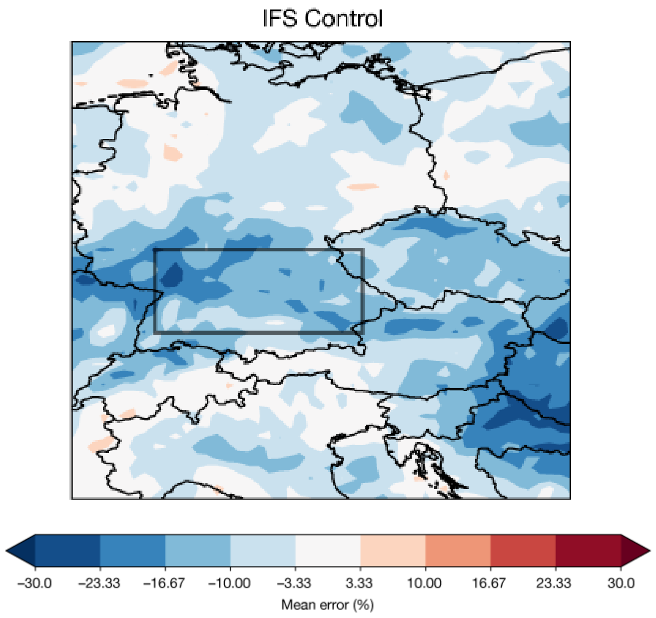
Errors in anticyclonic conditions

2m T error



Too warm 2m temperatures

Low cloud cover error



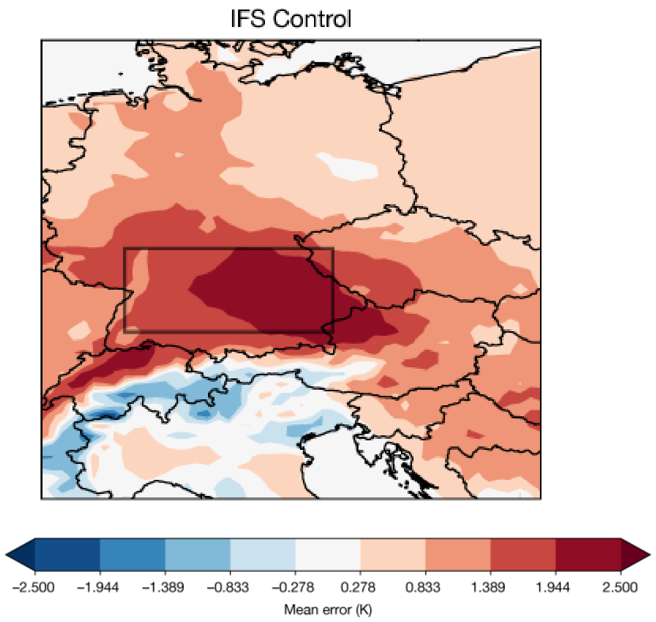
...because of too little low cloud

Soufiane Karmouche,
ECMWF Newsletter May 2025

Example: Low cloud cover and temperature errors

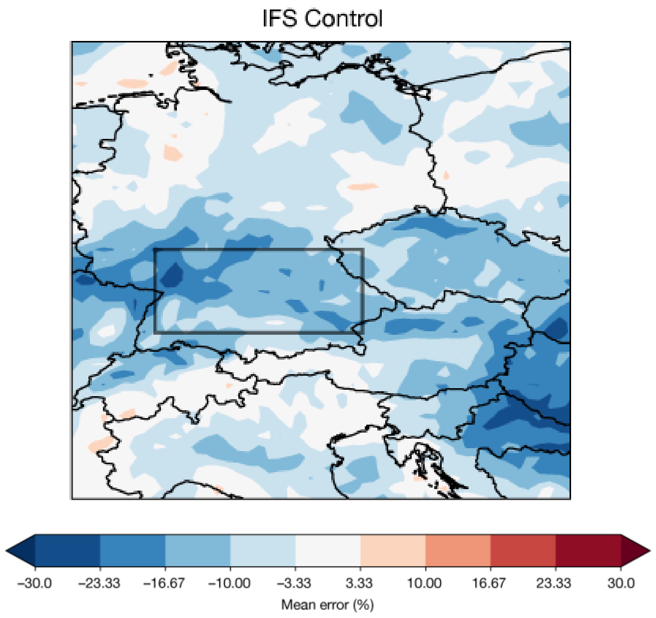
Errors in anticyclonic conditions

2m T error



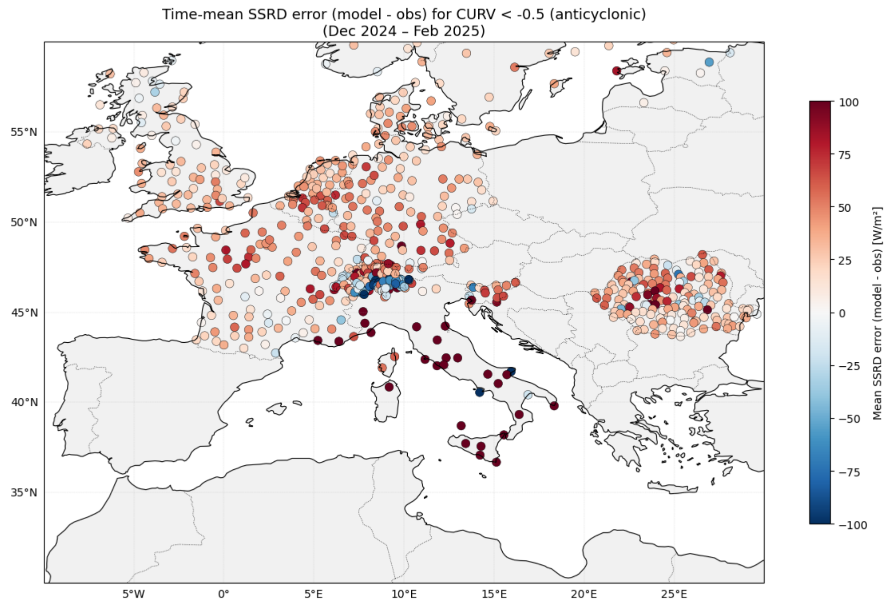
Too warm 2m temperatures

Low cloud cover error



...because of too little low cloud

Surface SW radiation error

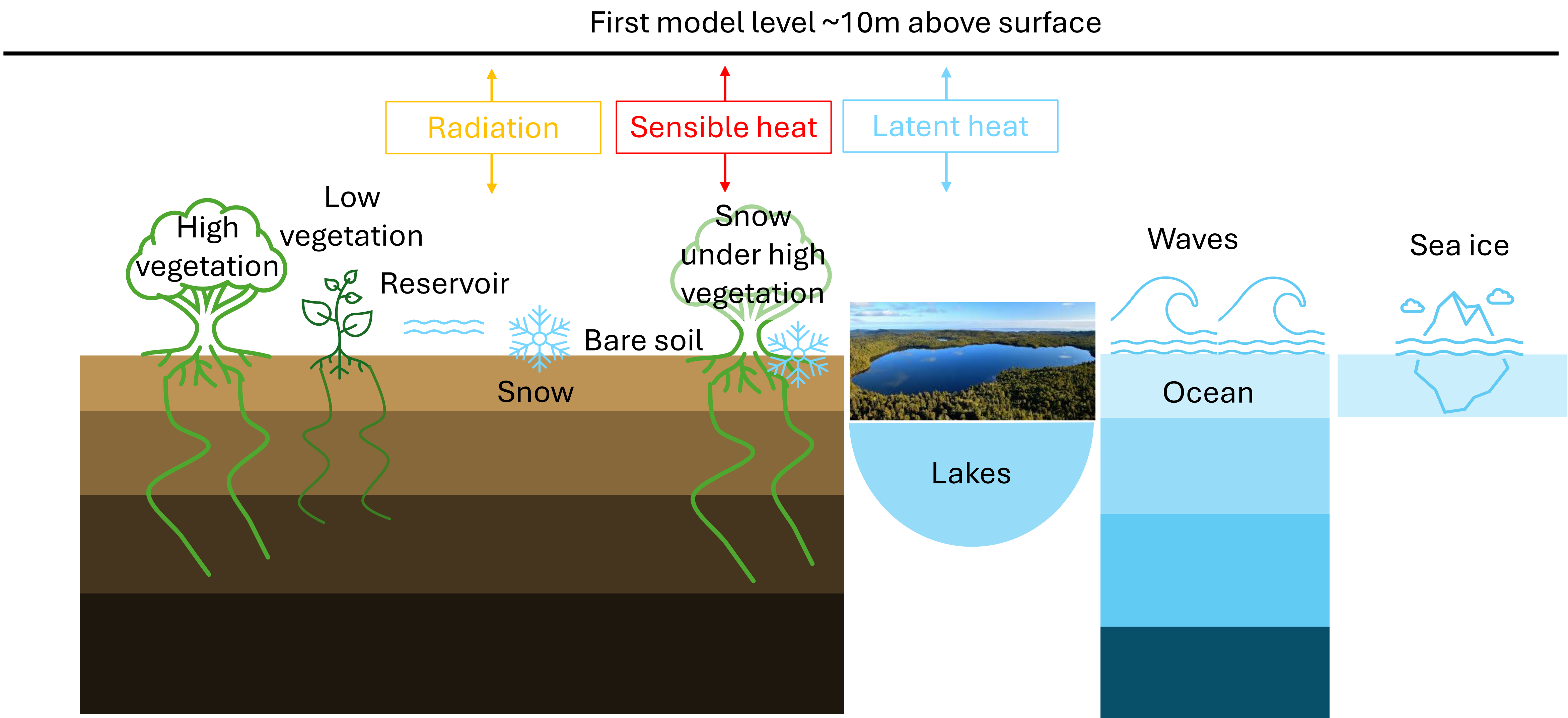


Too much SW radiation reaching the surface, heating the surface and increasing fluxes

Soufiane Karmouche,
ECMWF Newsletter May 2025

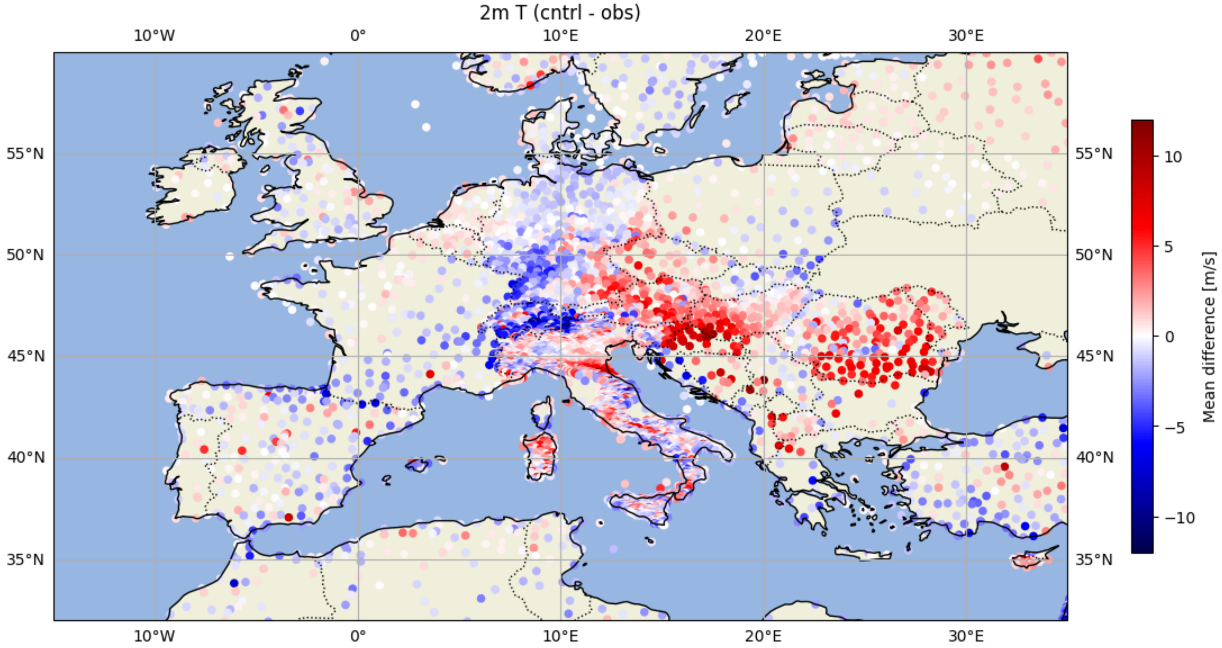
Land surface, waves and ocean

$$R_{LW} + R_{SW} + SH + LH = \Lambda(T_{10m} - T_{surf})$$



Example: case of 2m T errors in anticyclonic condition

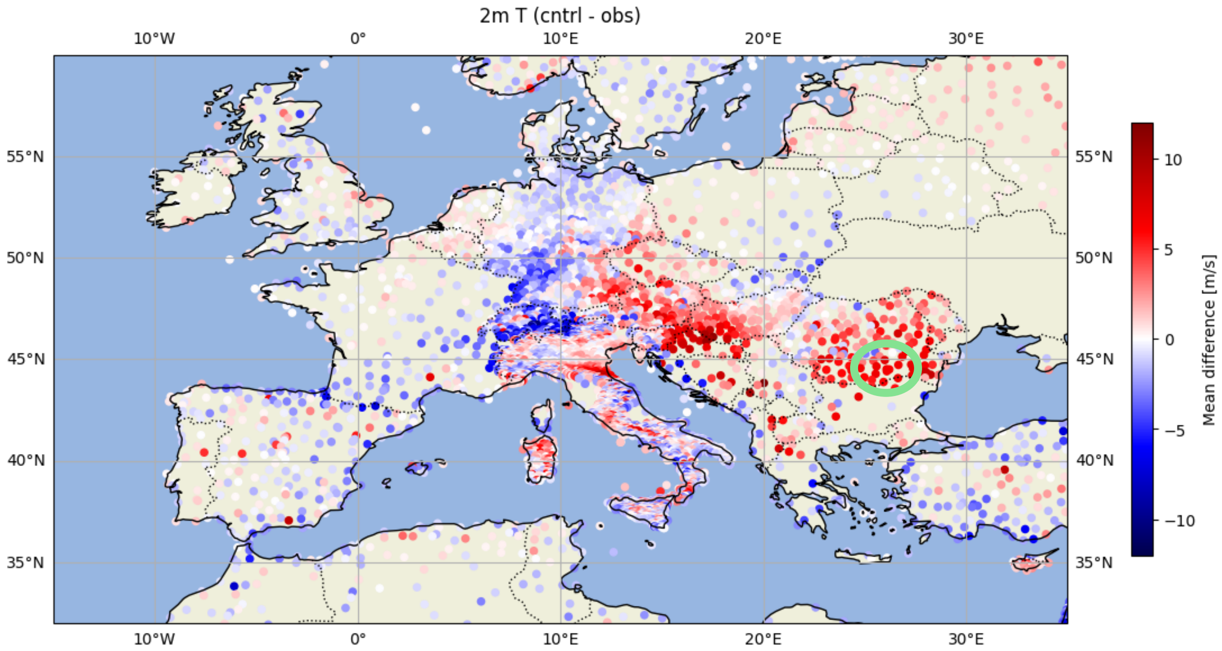
Model 2m temperature error T+72 h
21 Dec 2022



Large +ve errors ~8K

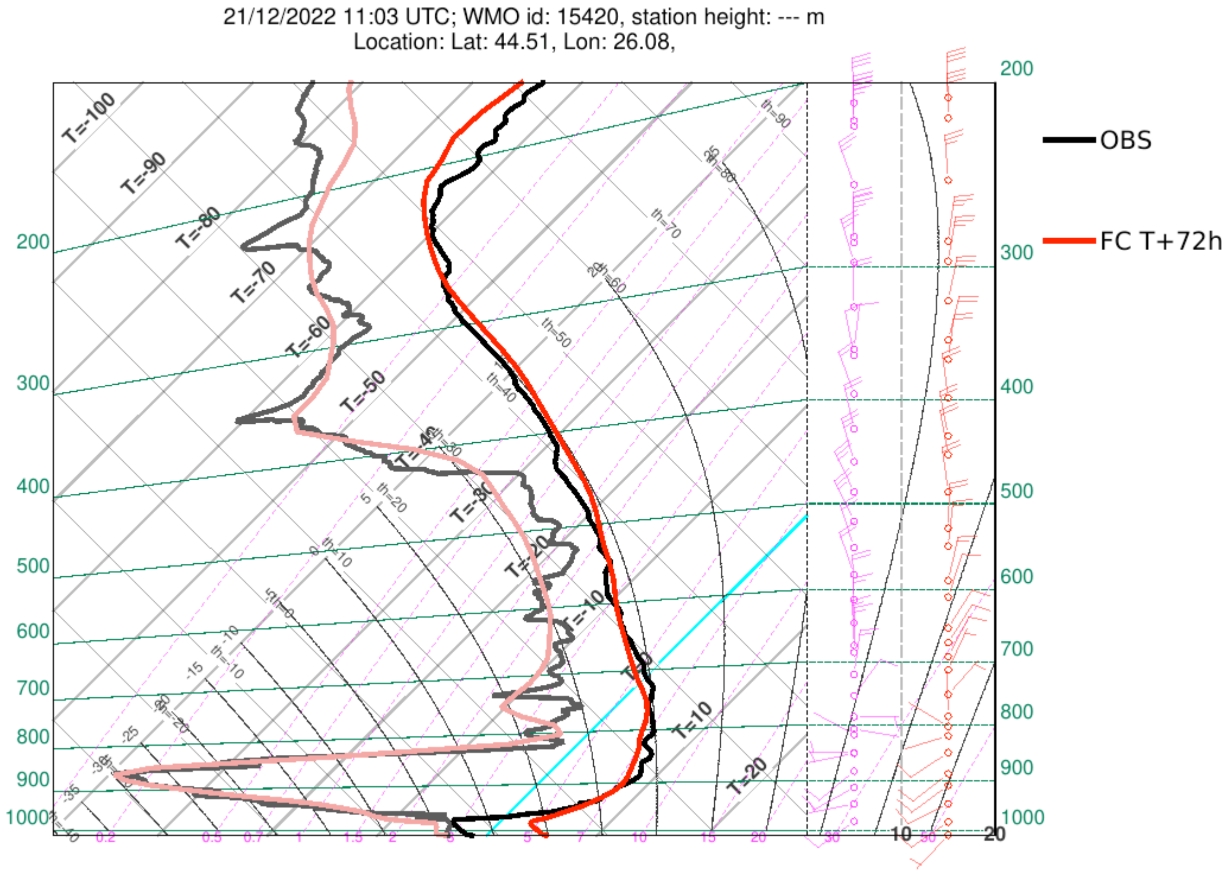
Example: case of 2m T errors in anticyclonic condition

Model 2m temperature error T+72 h
21 Dec 2022



Large +ve errors ~8K

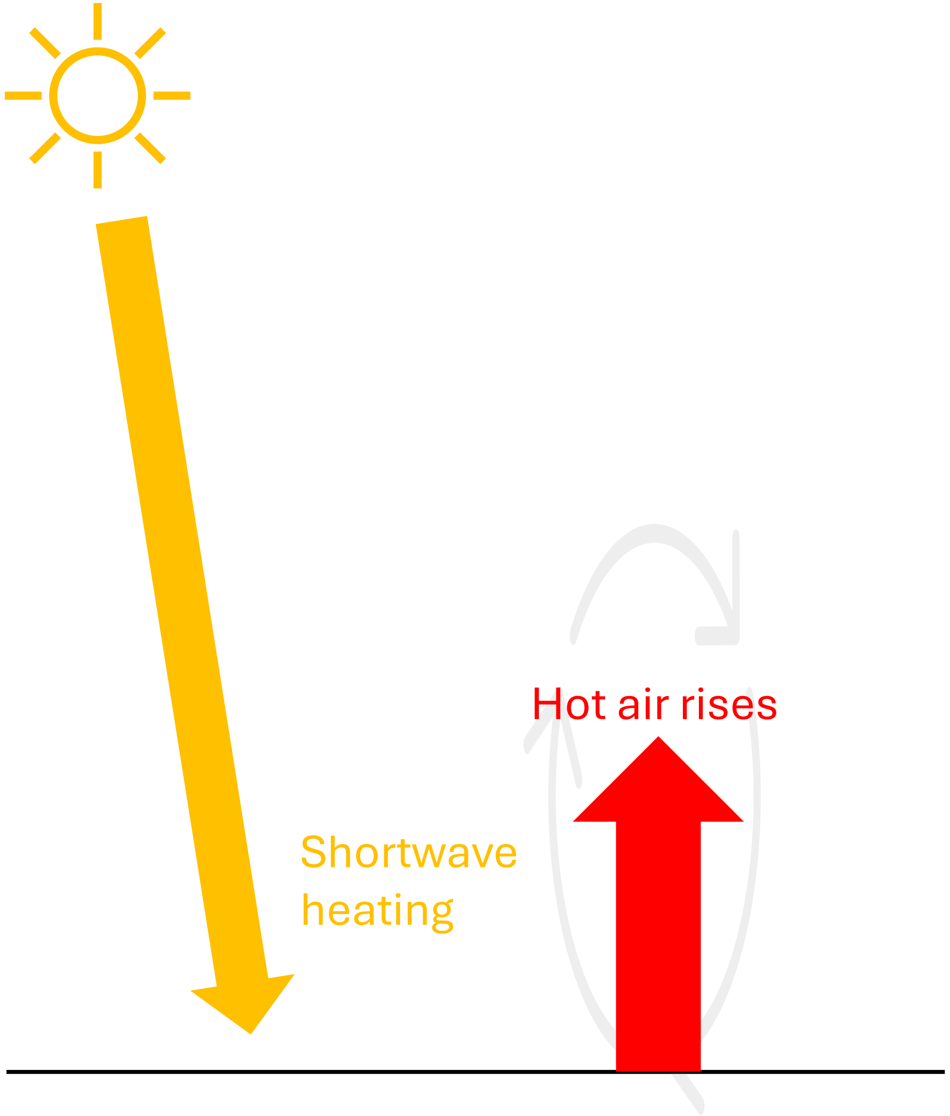
Radiosonde and model at
Bucharest



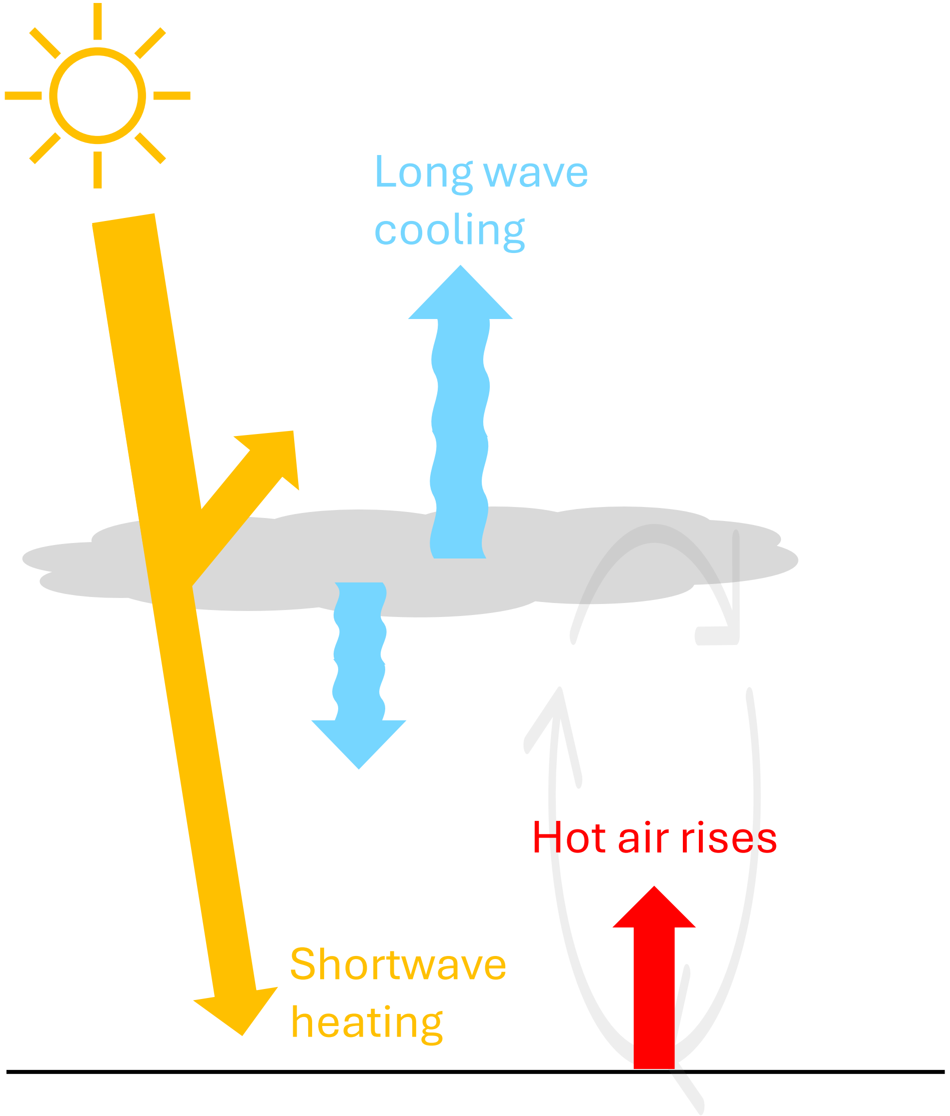
Strong inversion and low cloud
not capture in model

ECMWF

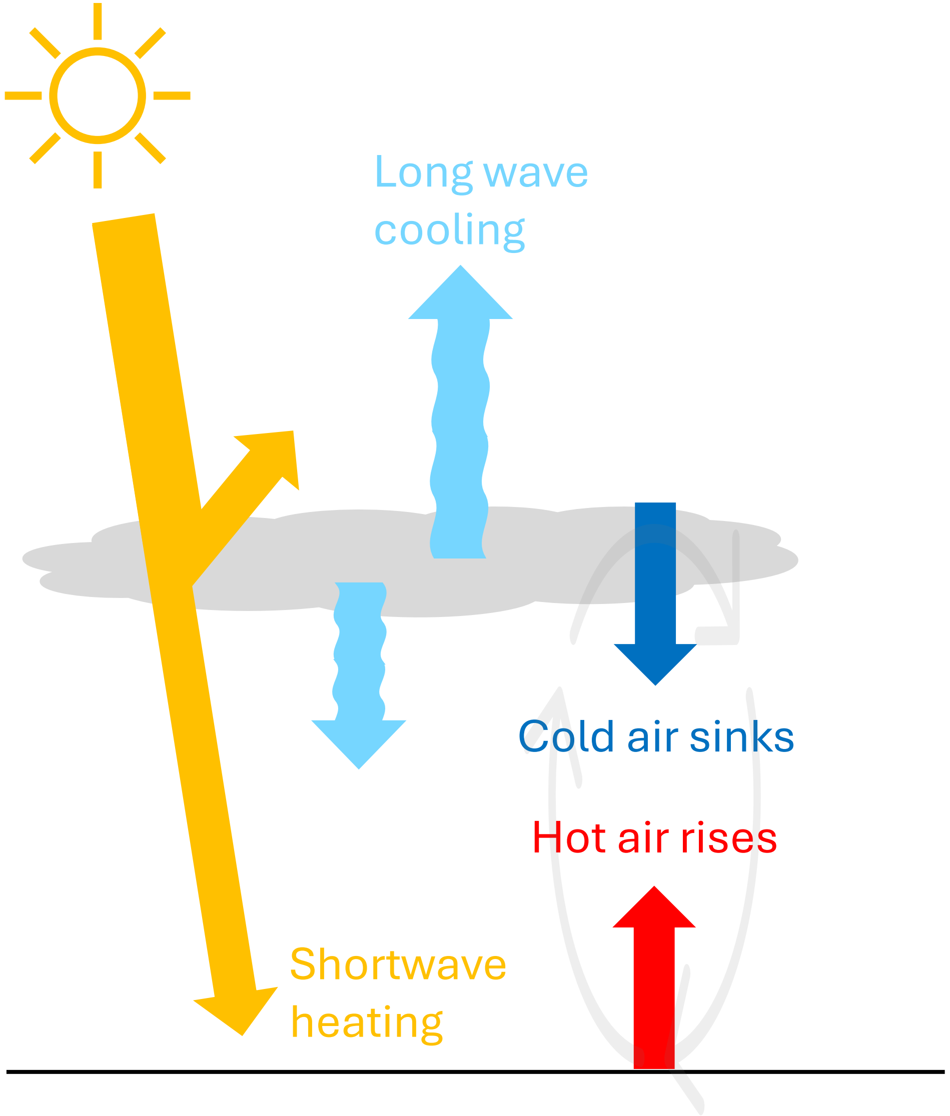
Example: Cloud-top driven mixing



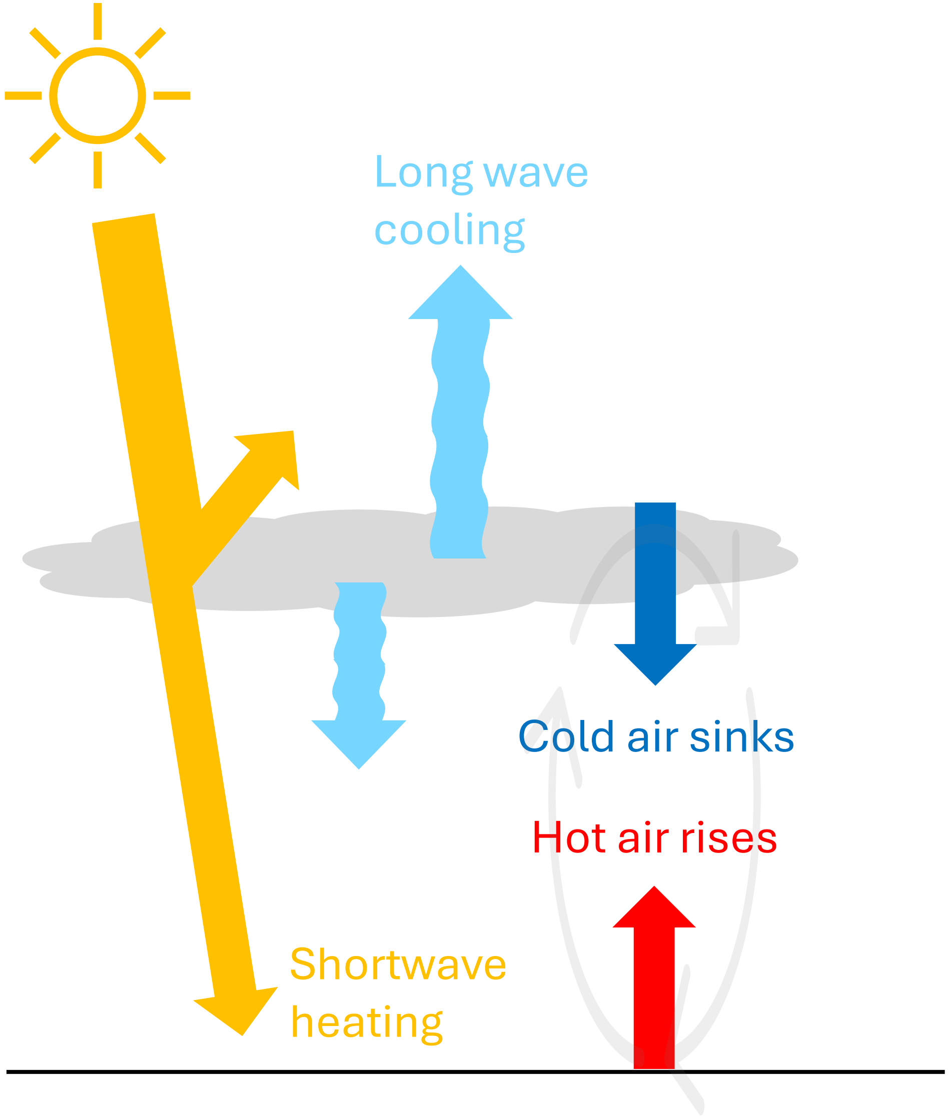
Example: Cloud-top driven mixing



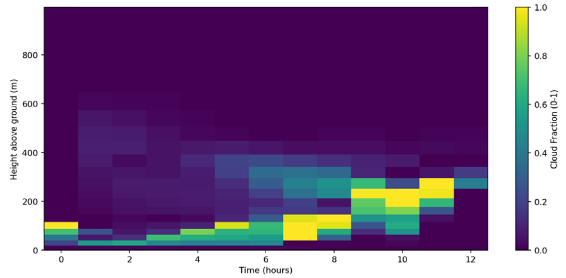
Example: Cloud-top driven mixing

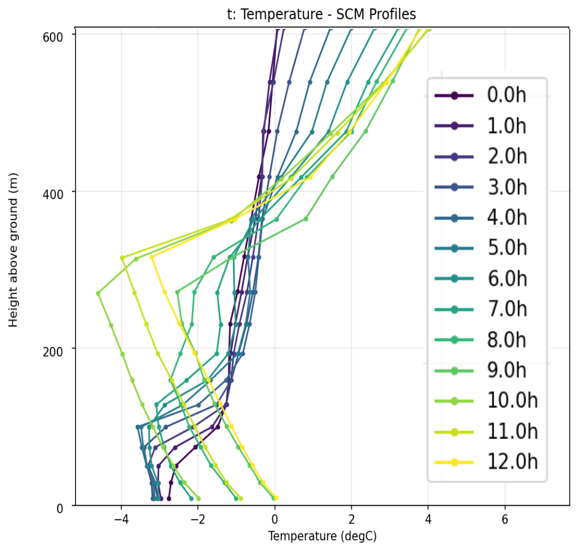


Example: Cloud-top driven mixing



Analysis
Cloud fraction





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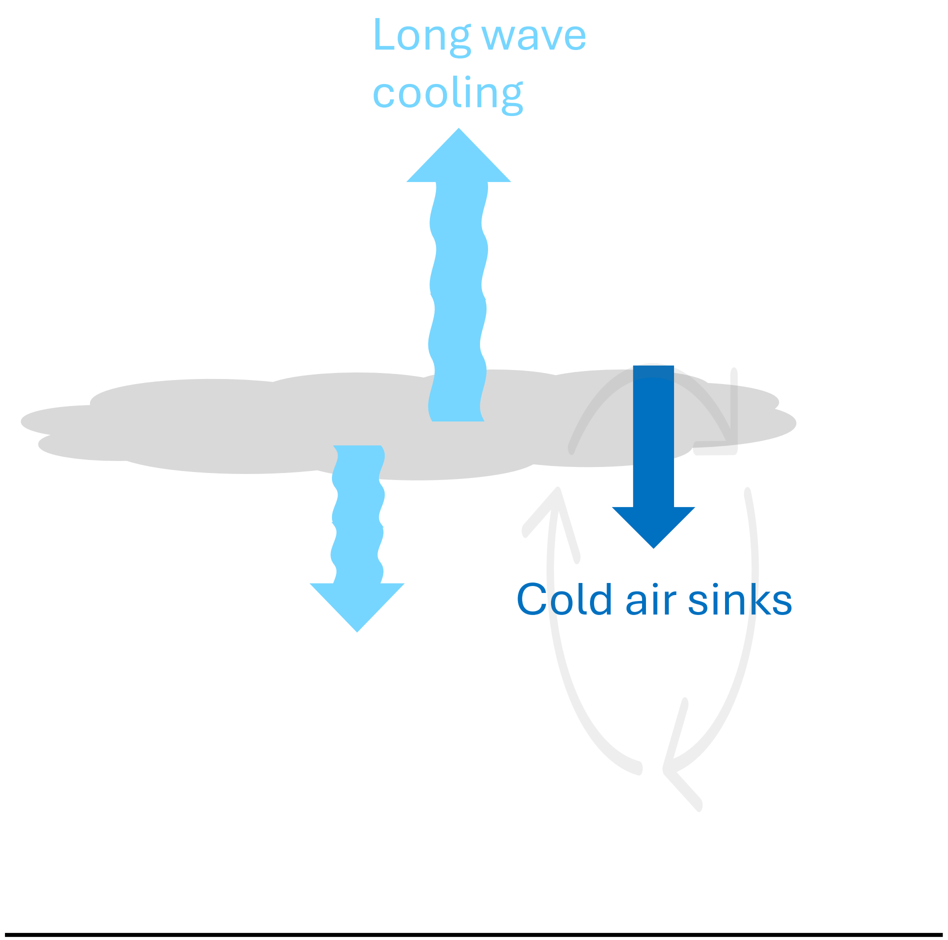

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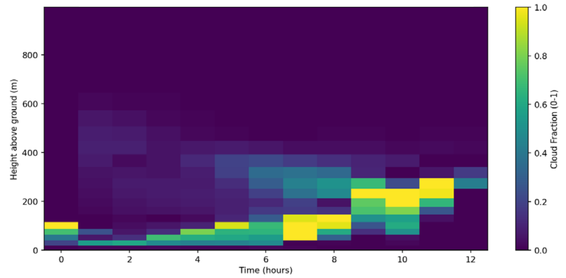

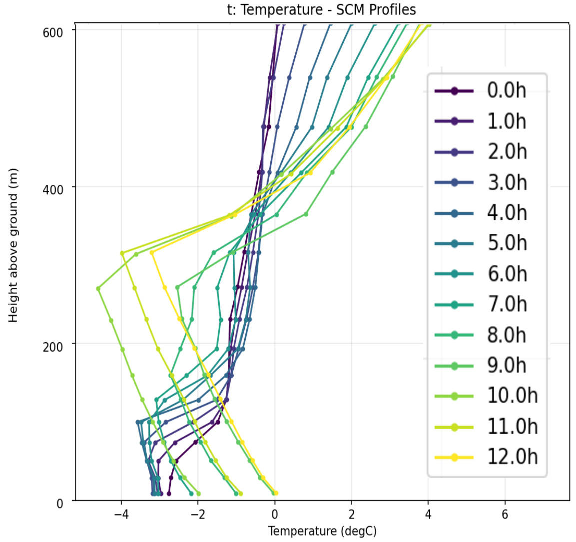

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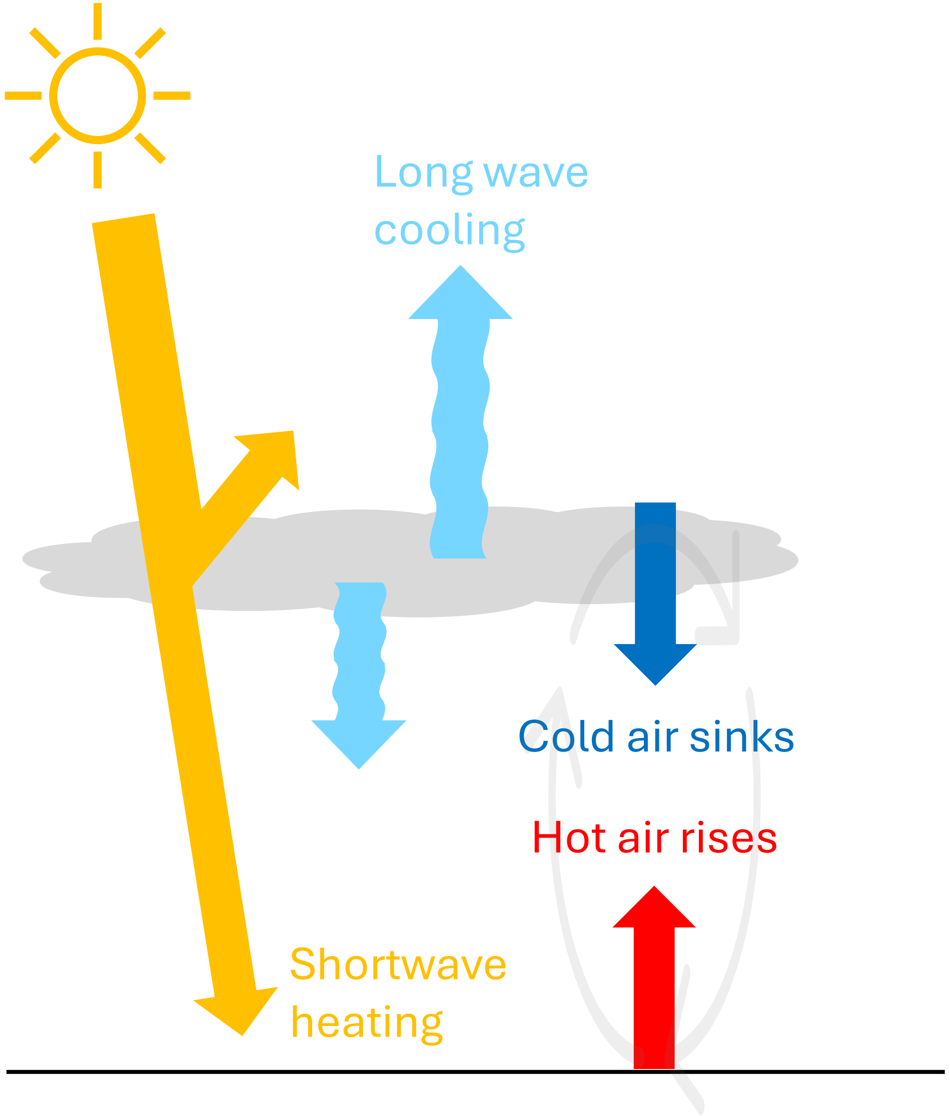

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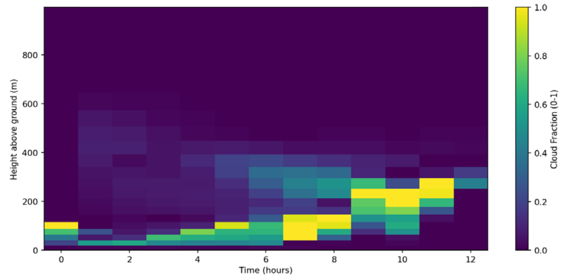
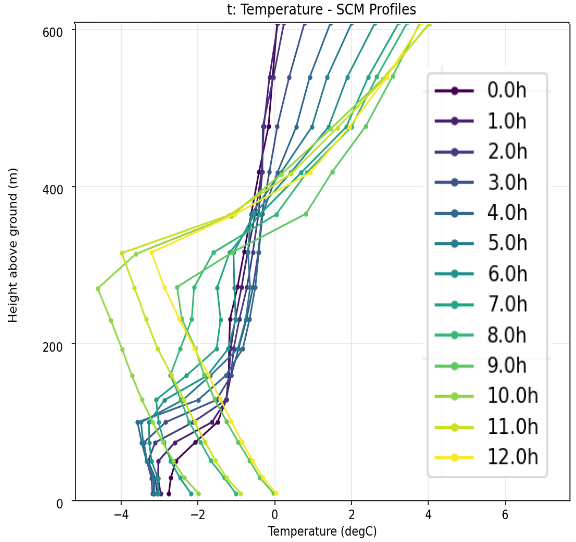
Cloud fraction





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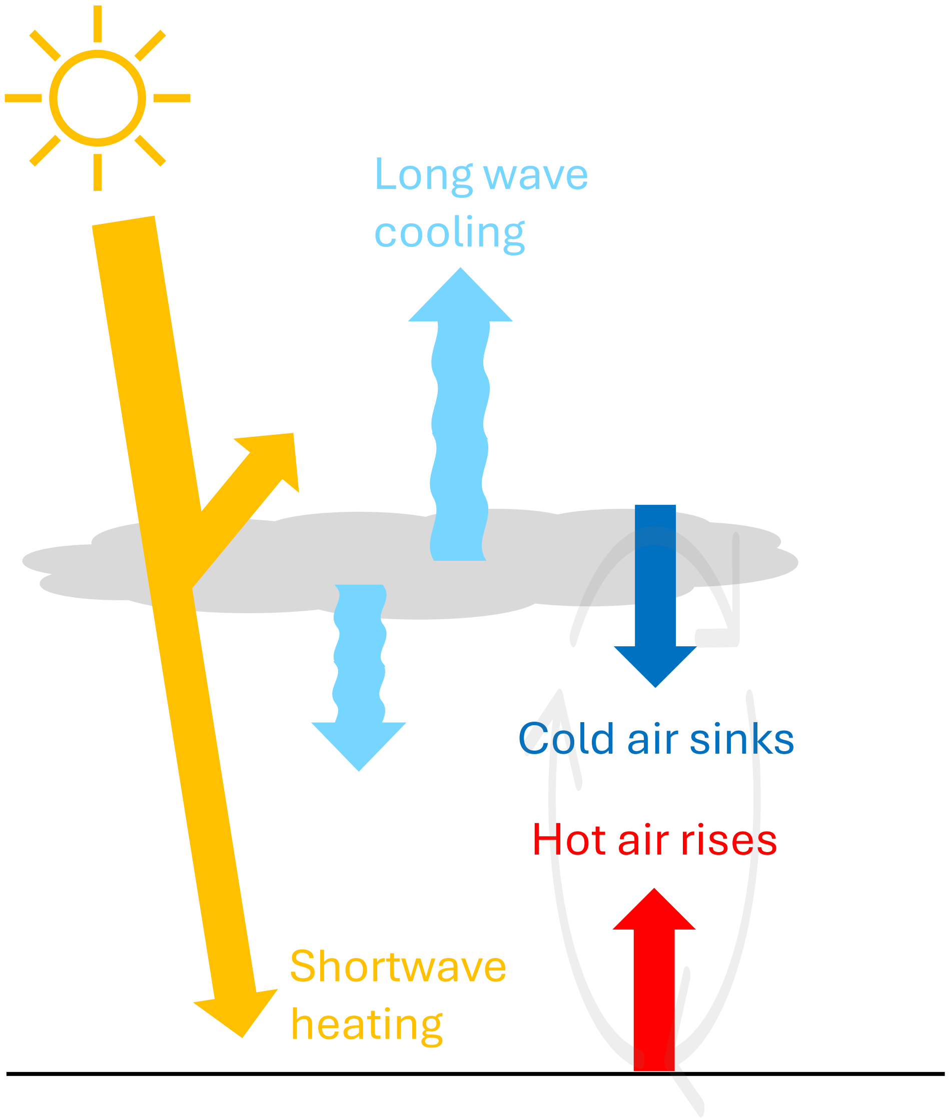
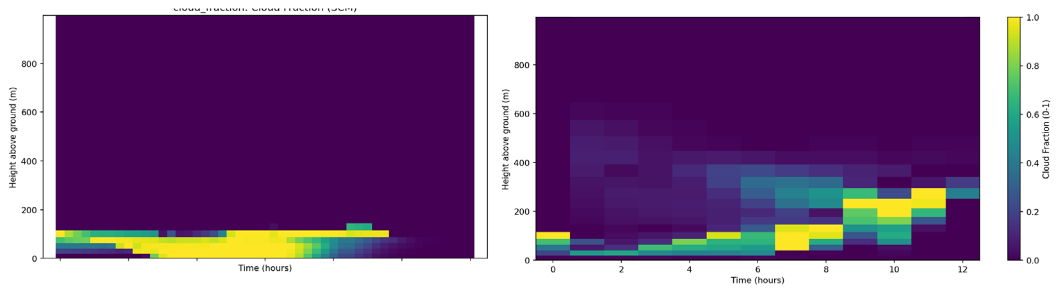
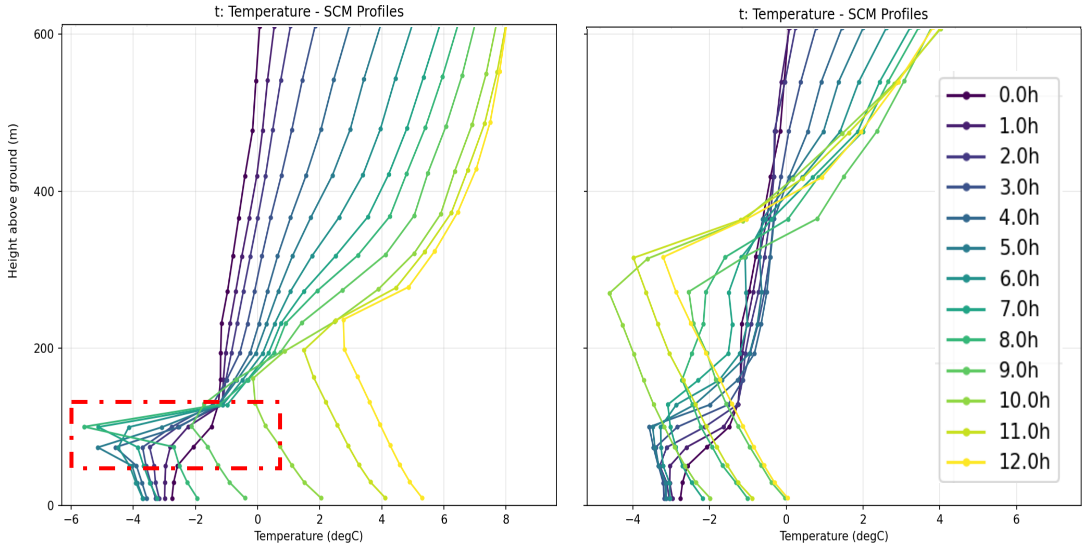


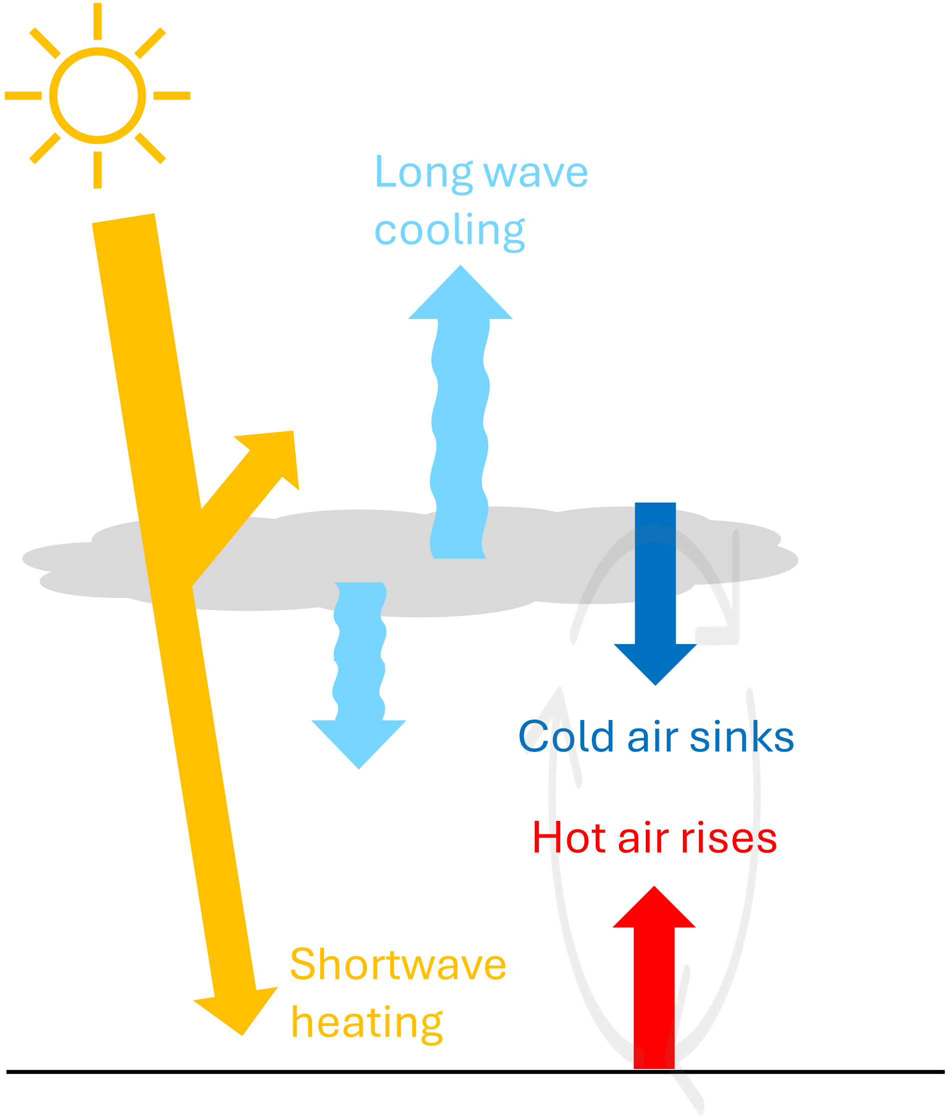
Control
Cloud fraction

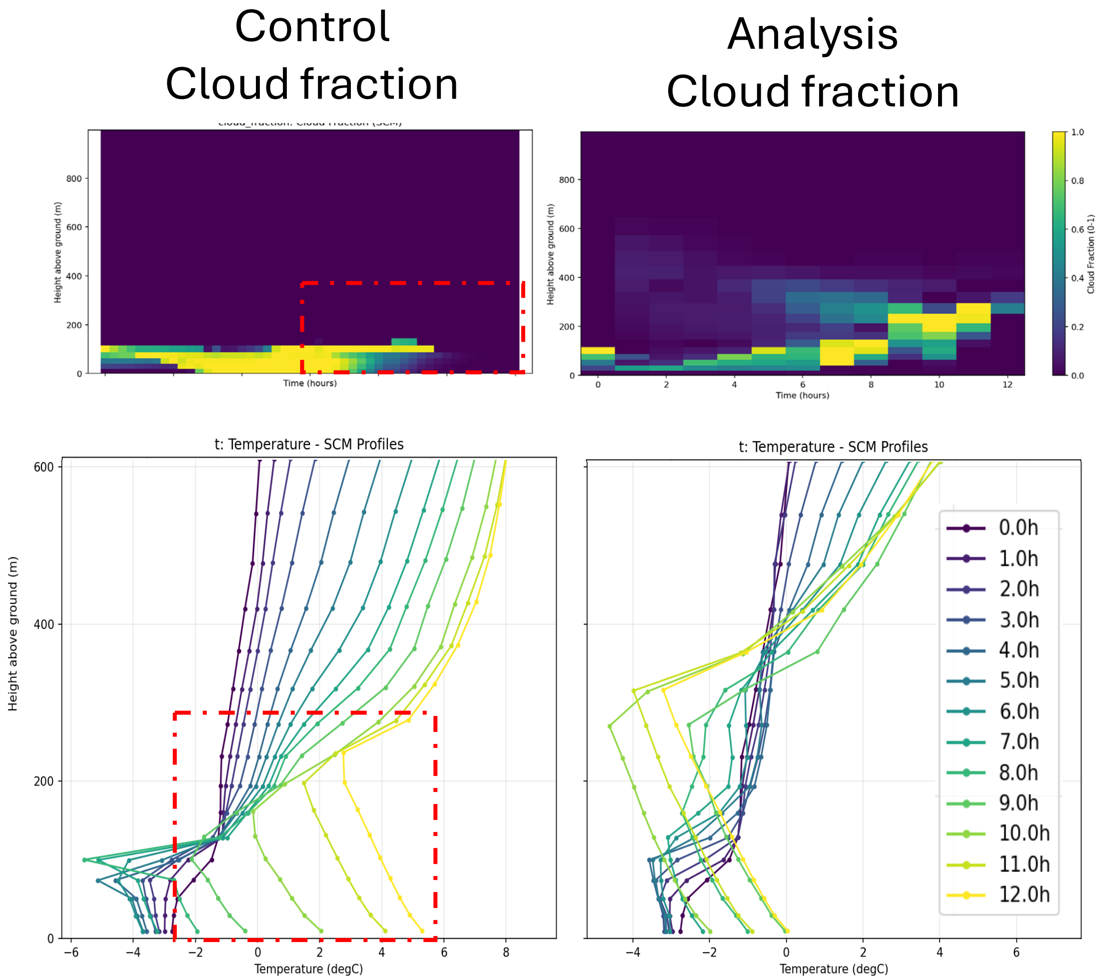
Analysis
Cloud fraction





Example: Cloud-top driven mixing





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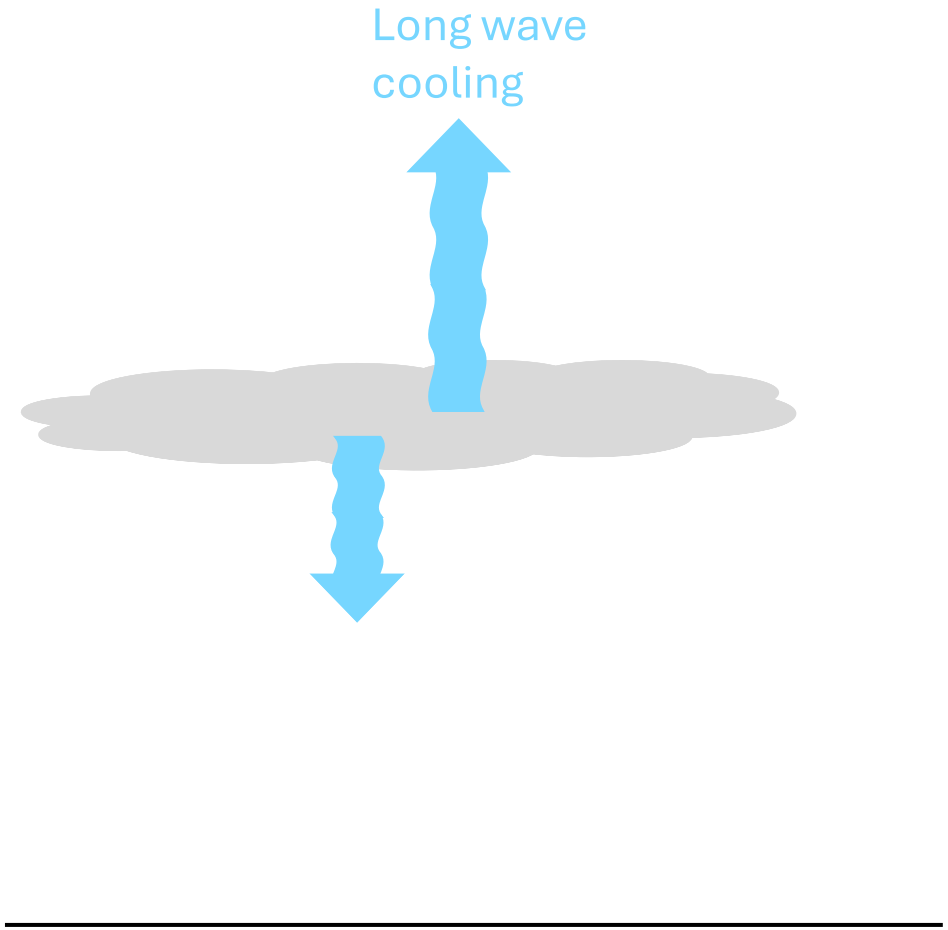

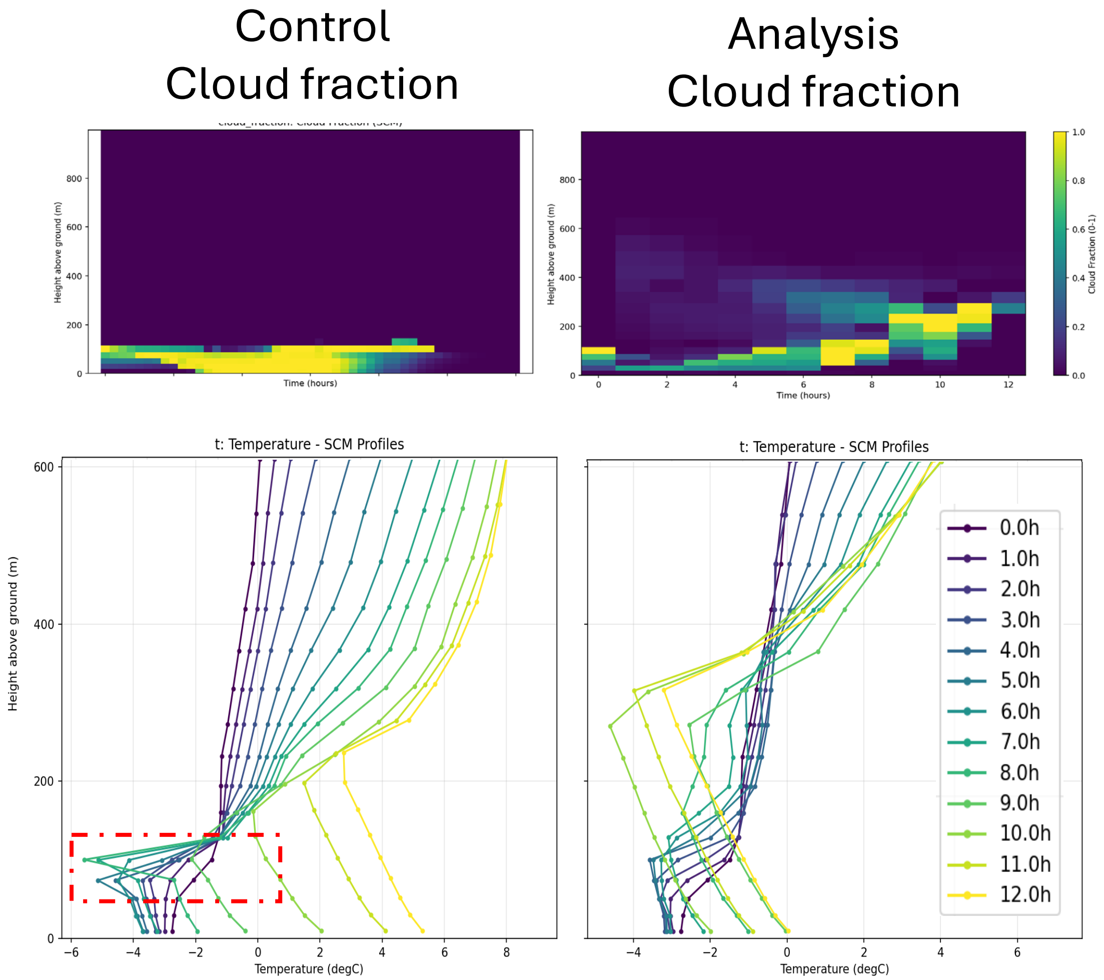

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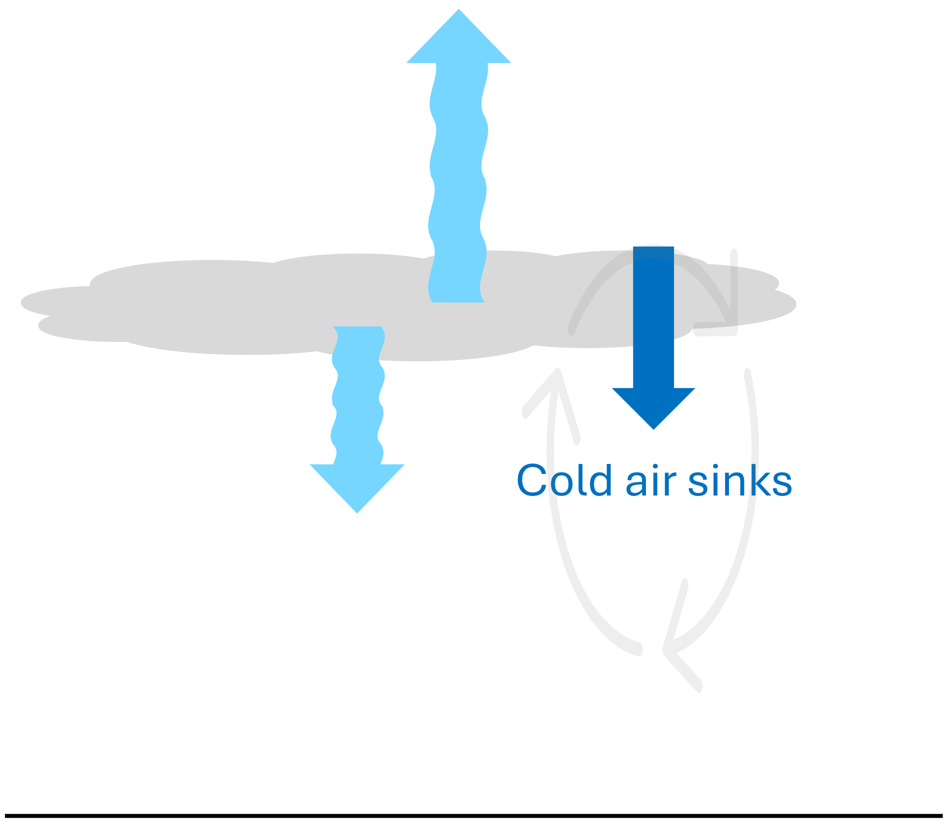

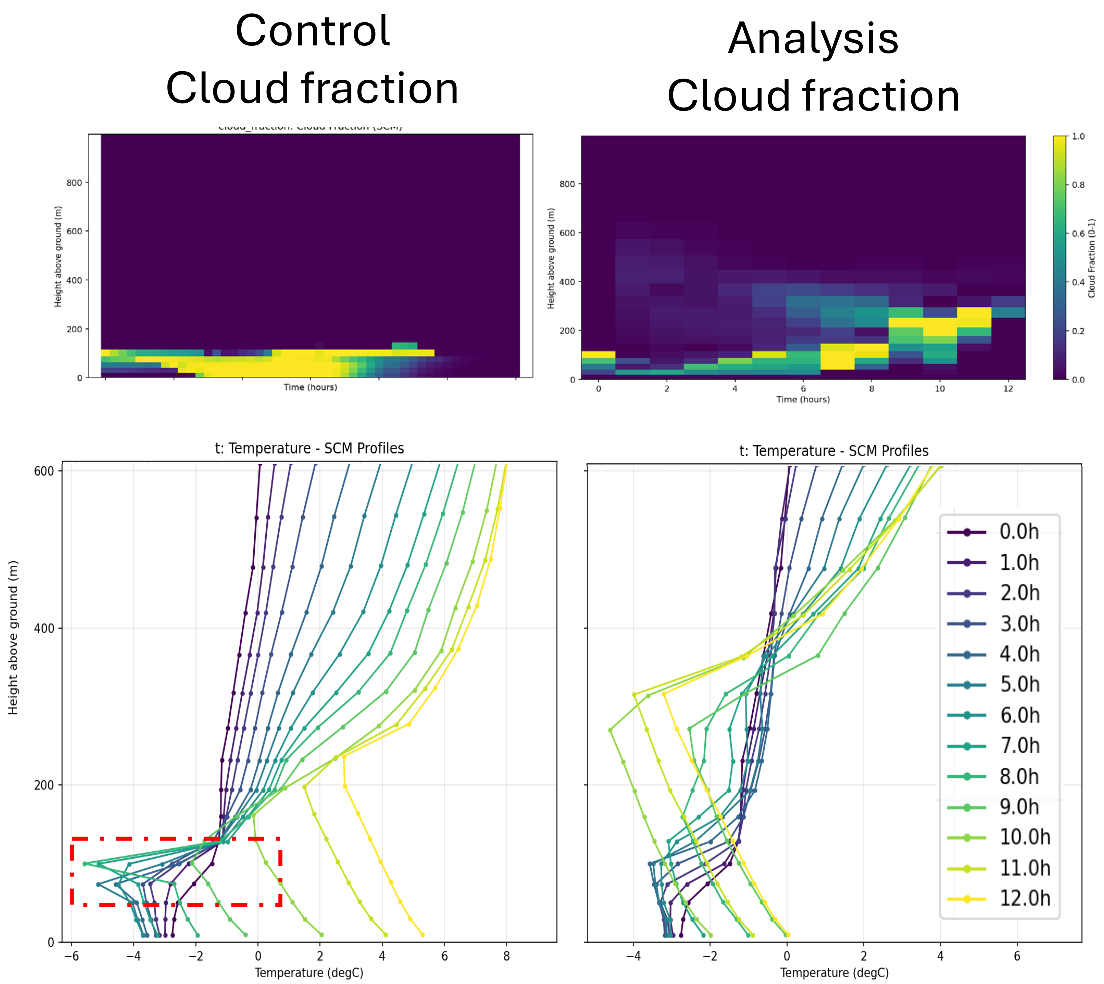

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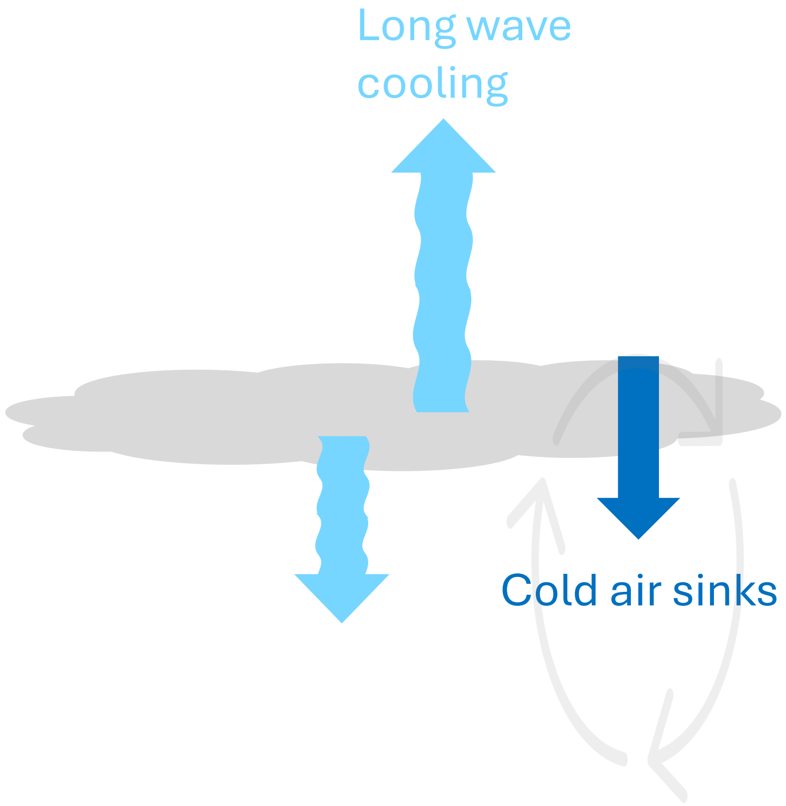
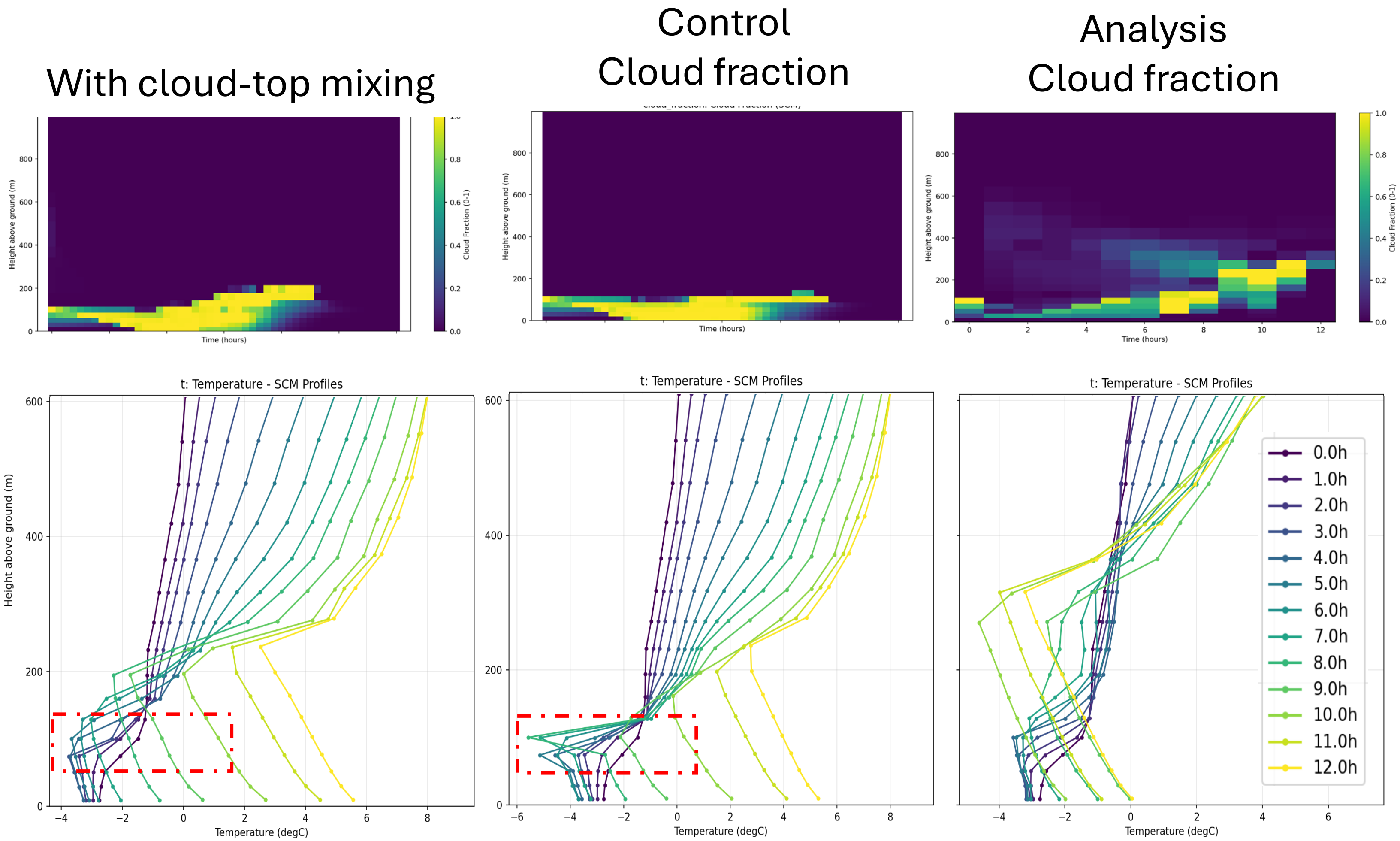
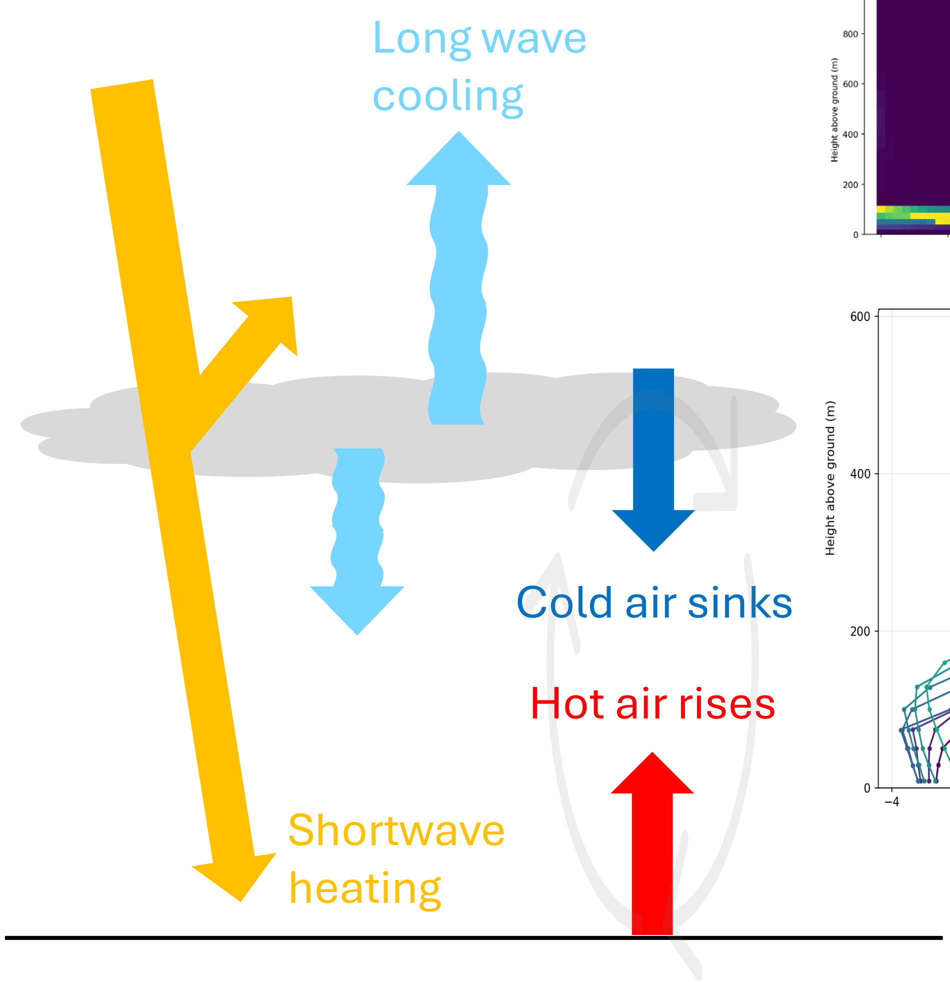
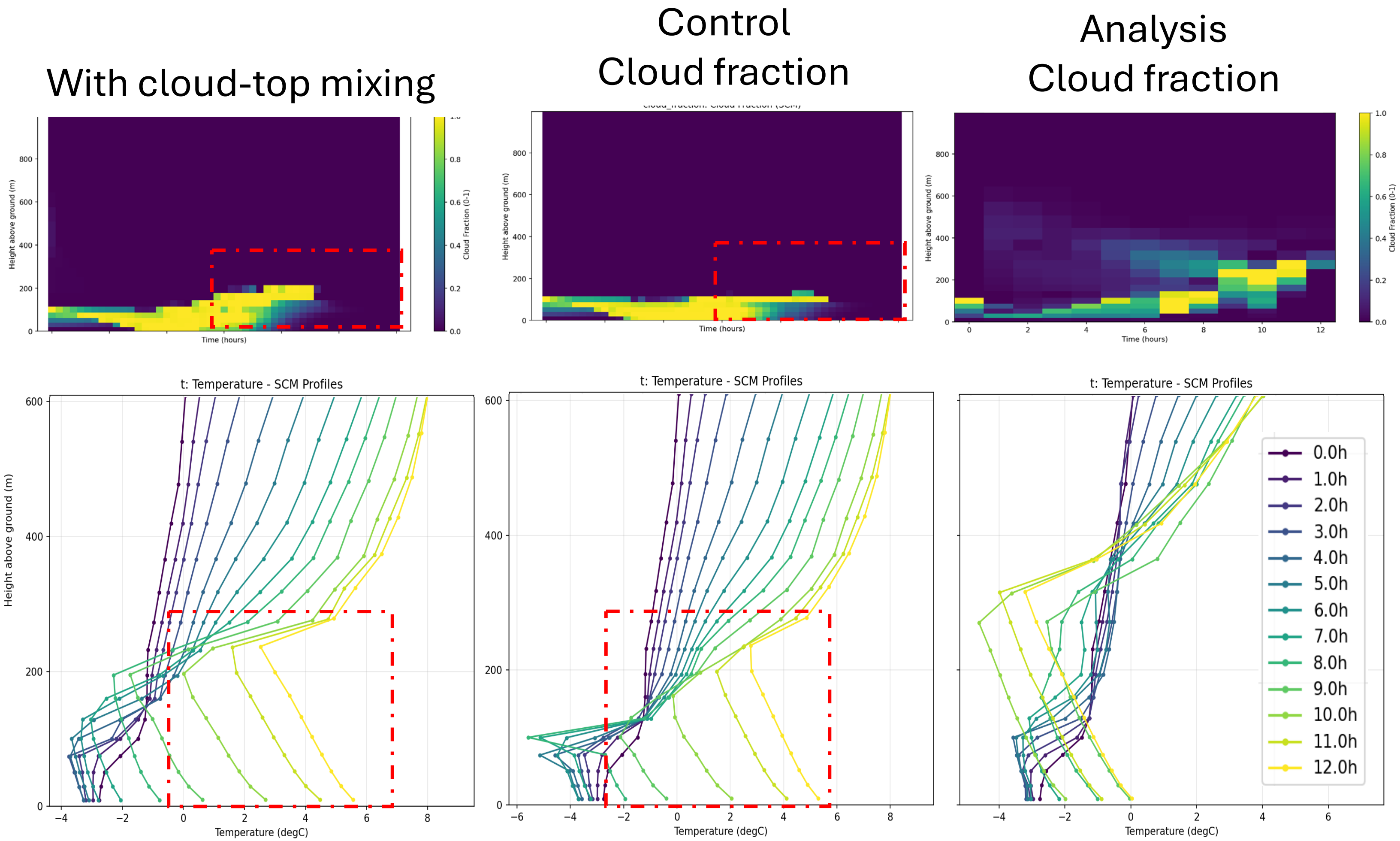




Example: Cloud-top driven mixing





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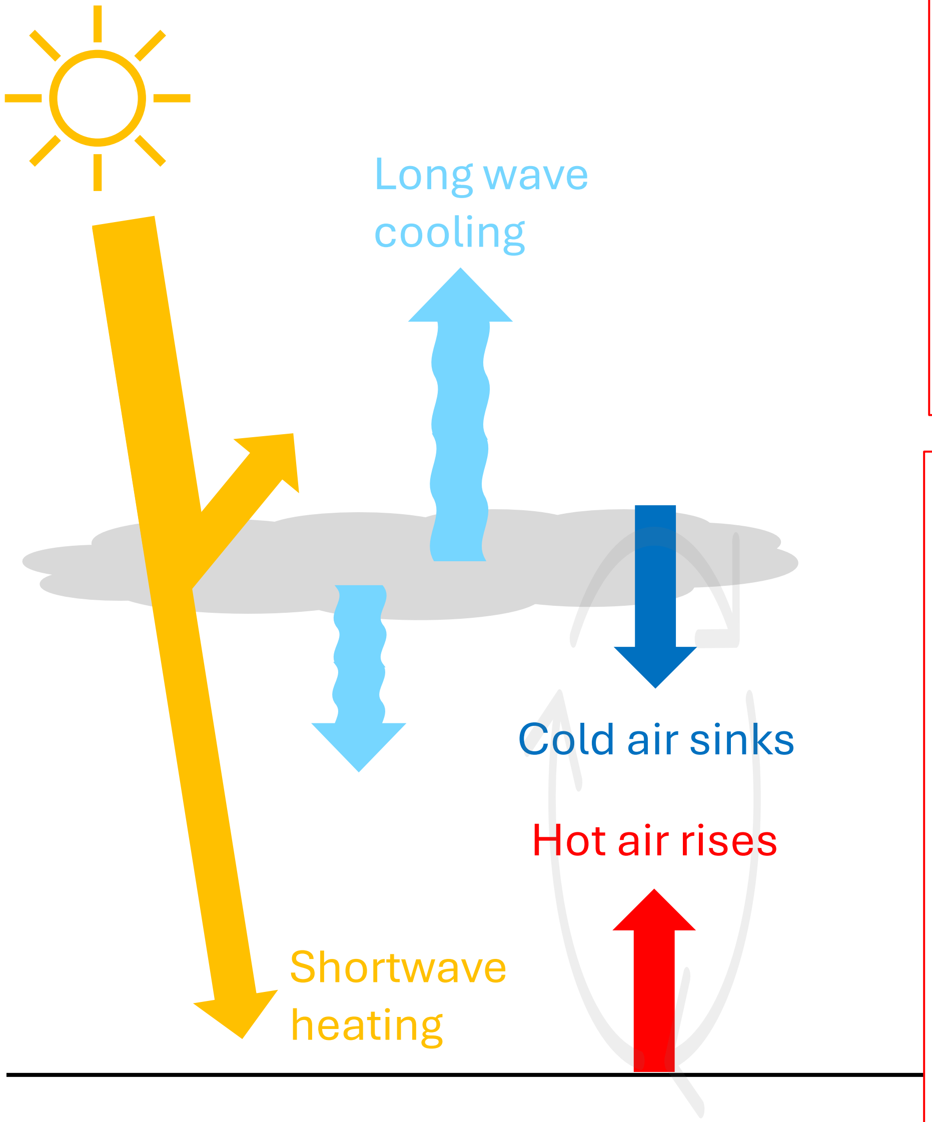
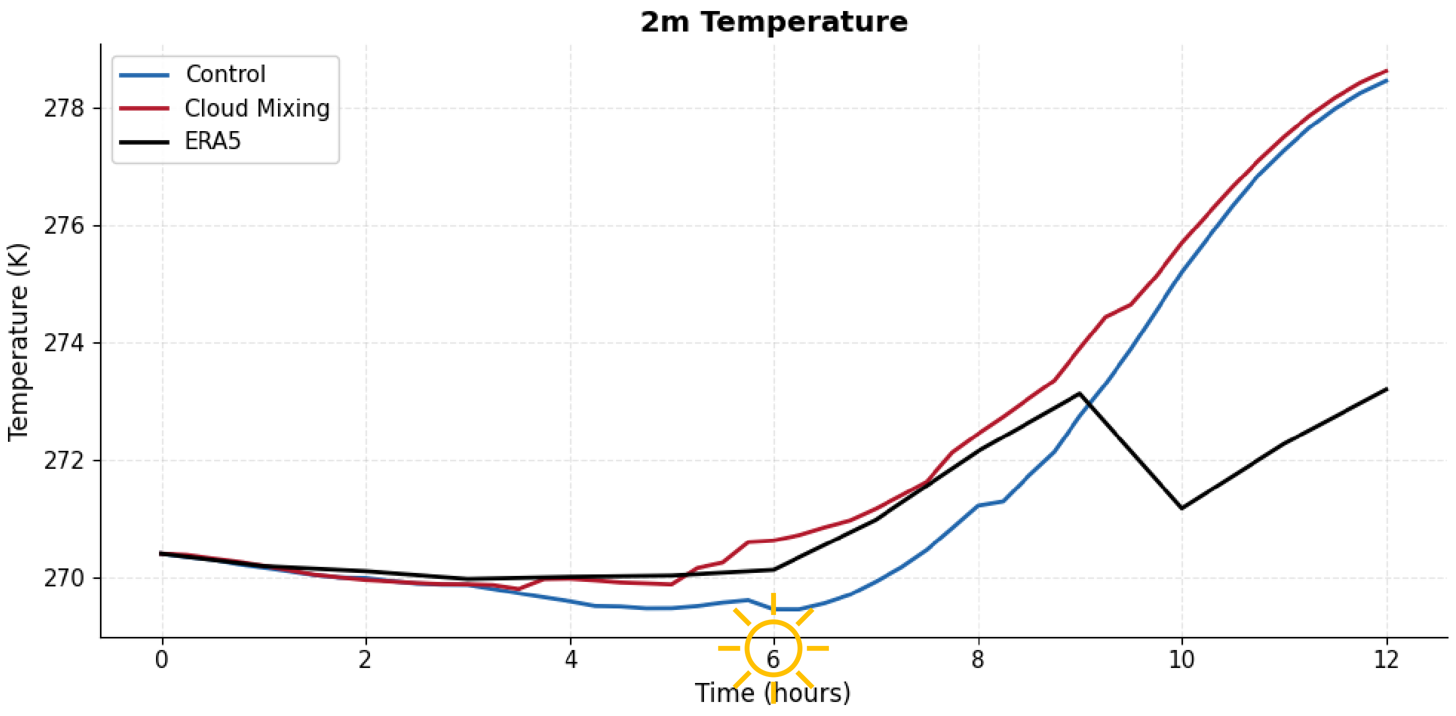
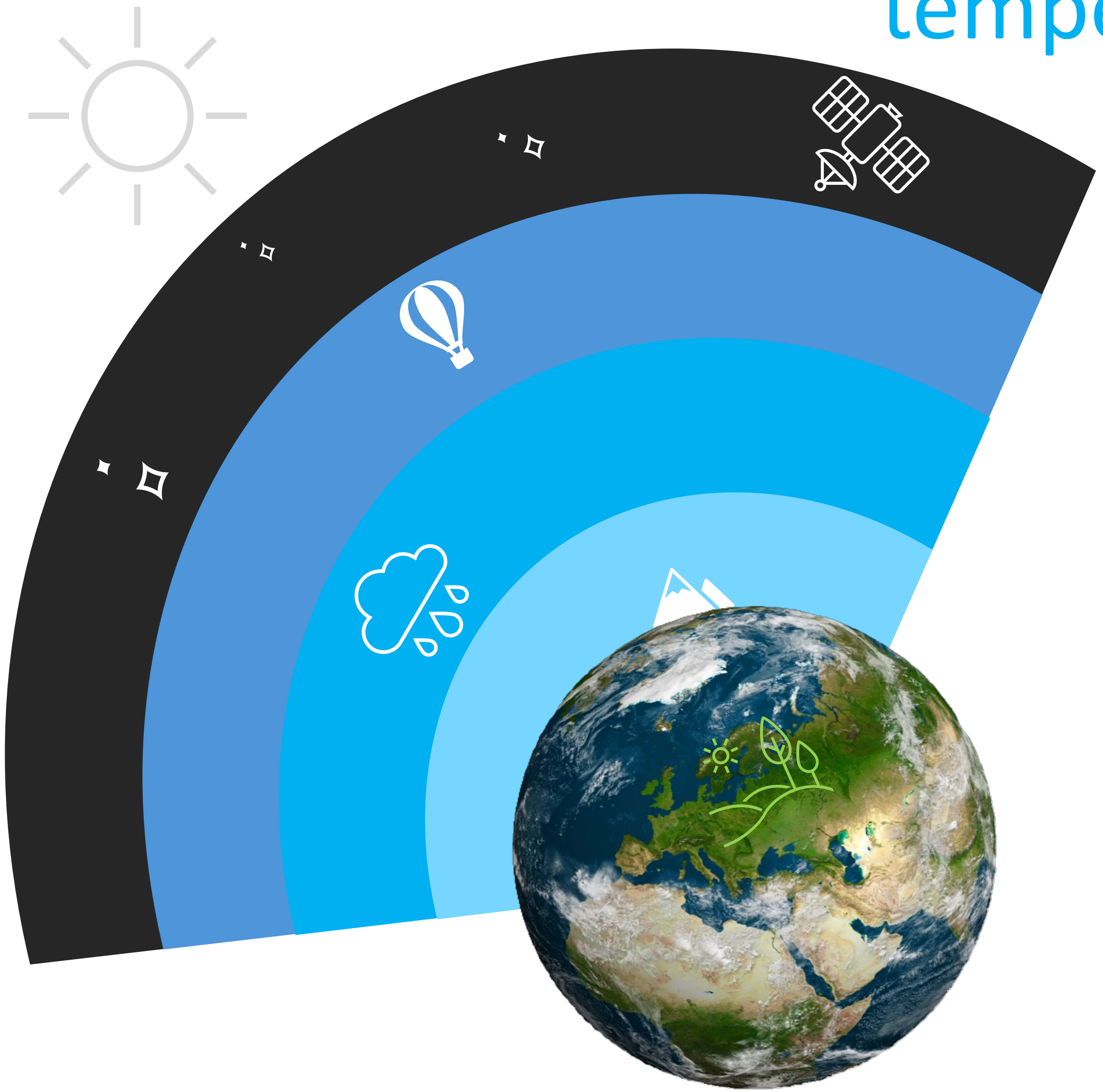


Possible causes:

Too much **turbulent diffusion** in daytime (removes cloud)
Incorrect subgrid **cloud** formation (e.g. too shallow a layer)
Insufficient surface moisture transport (e.g. not enough **moisture flux from surface**)
...others



Interaction of processes that impact forecast temperature



Observations (remote and in-situ)

Large-scale circulation

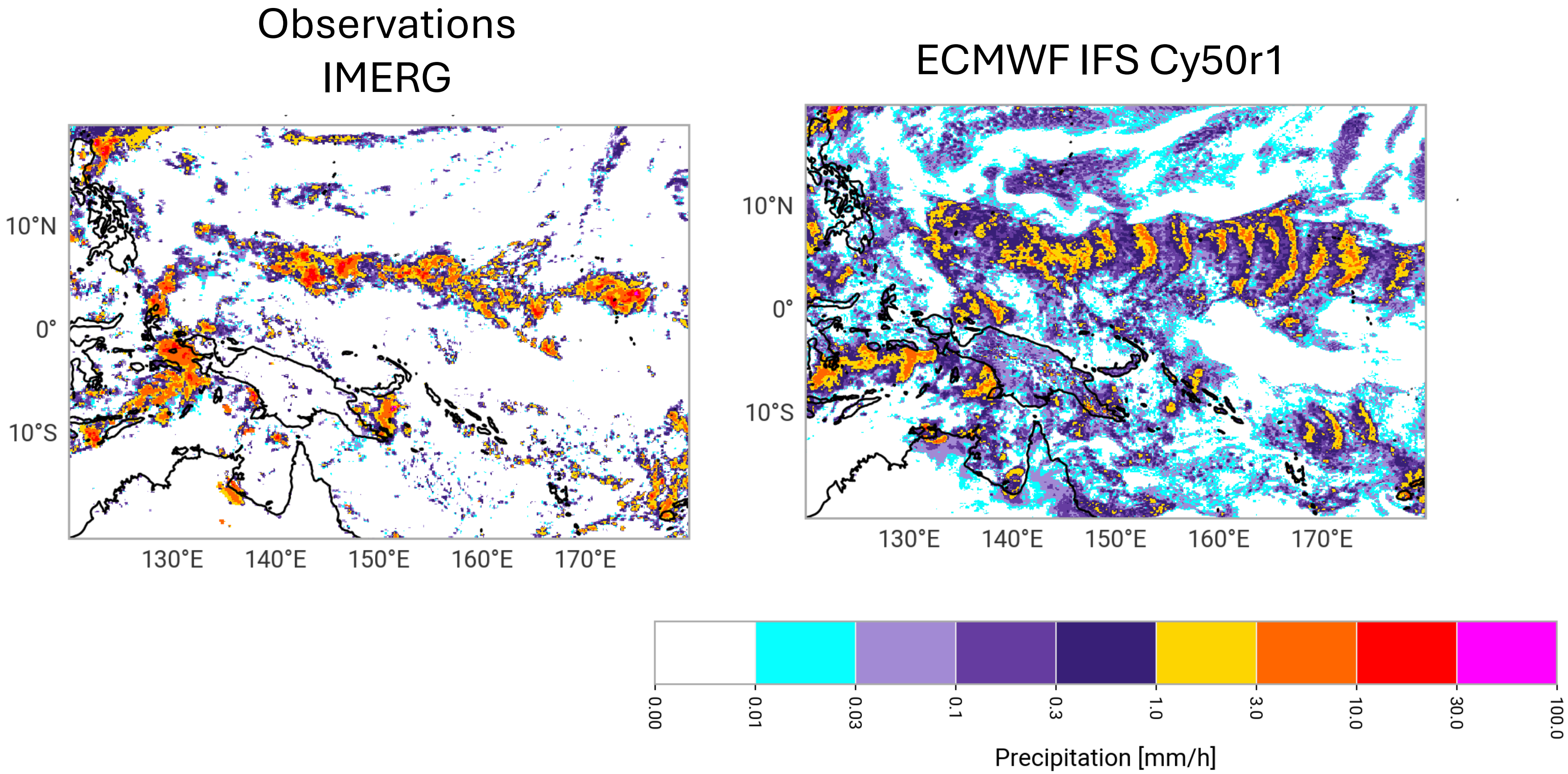
Clouds and convection

Boundary layer turbulence

Land surface and ocean

Radiation

Convective organization in tropics



IFS at 9 km resolutions does not exhibit enough convective organization

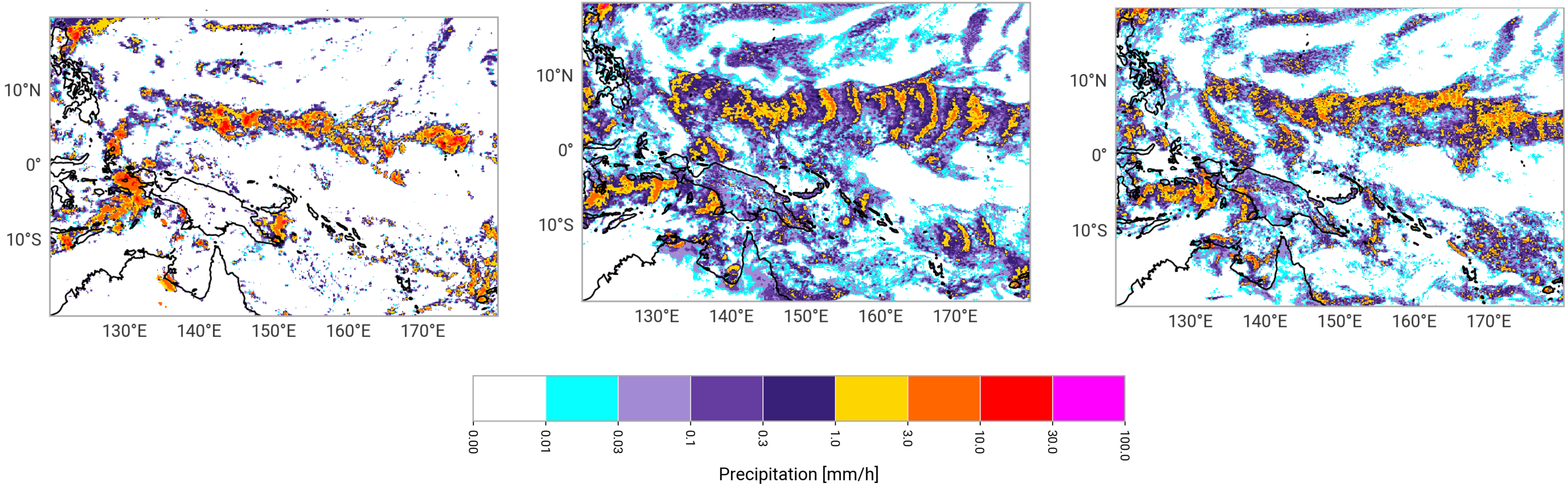
Tobias Becker, Benoit Vanniere

Convective organization in tropics

Observations
IMERG

ECMWF IFS Cy50r1

ECMWF IFS Cy50r1 +
improvements to organisation

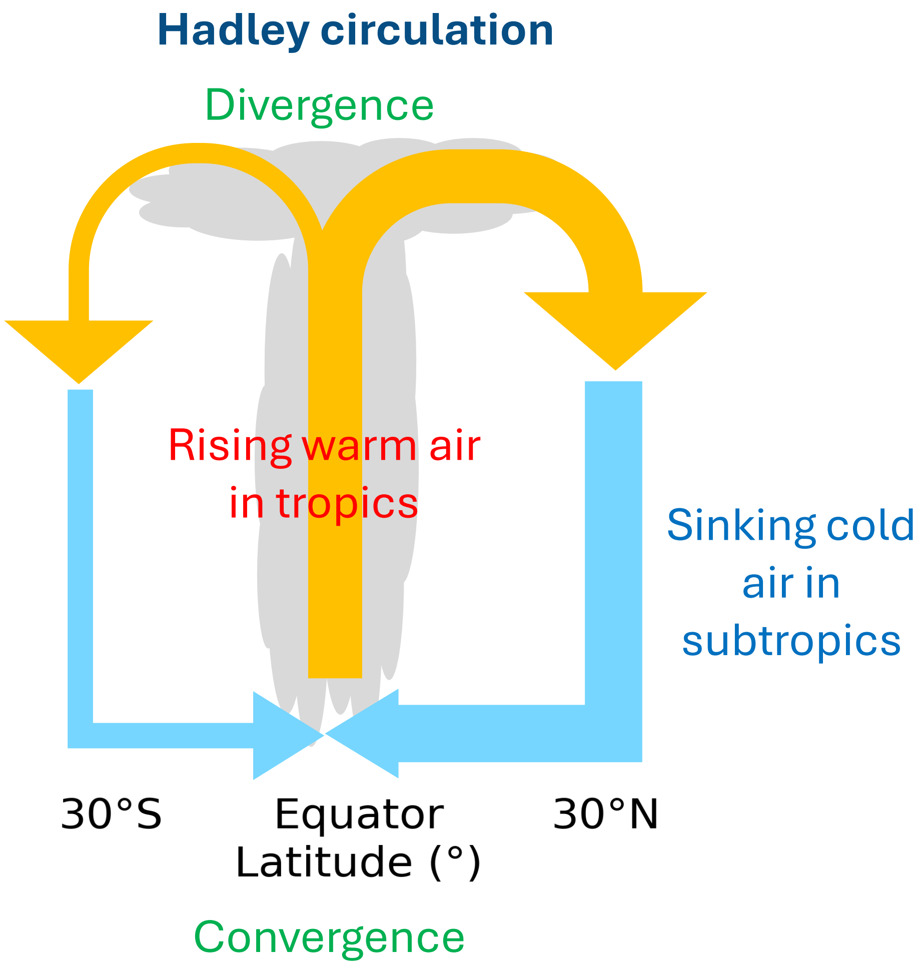


IFS at 9 km resolutions does not exhibit enough convective organization

Changes to convection parametrization (reducing downdrafts) improves convective organisation

Tobias Becker, Benoit Vanniere

Convection in the tropics and largescale transport



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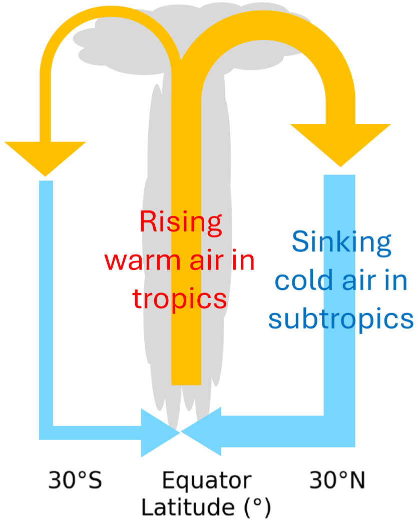

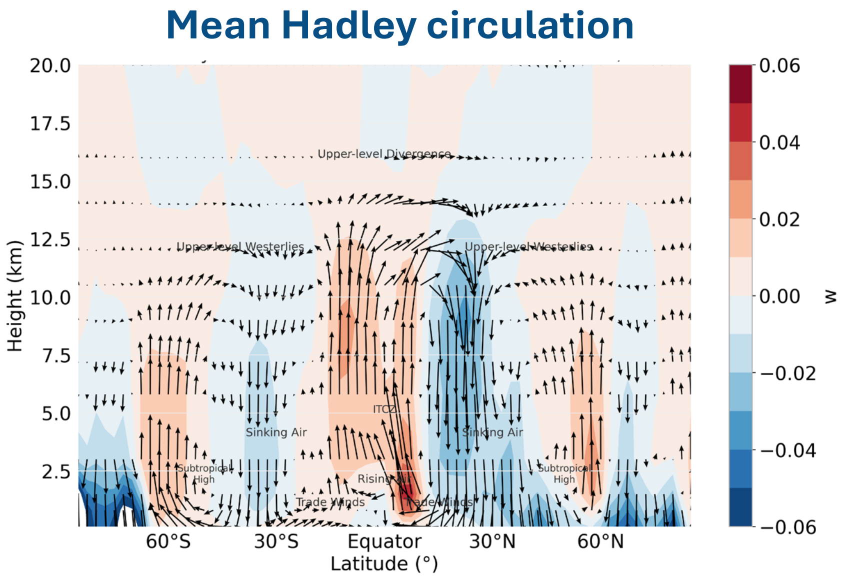

Tobias Becker, Benoit Vanniere

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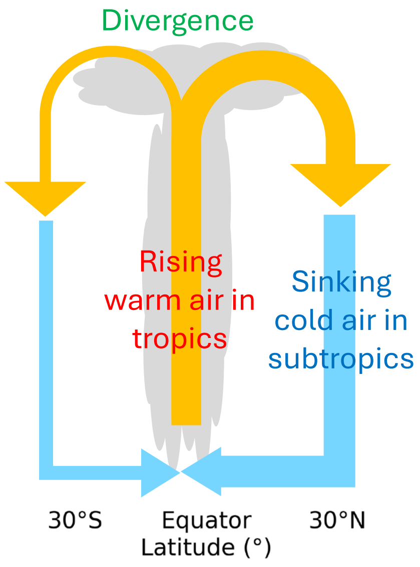
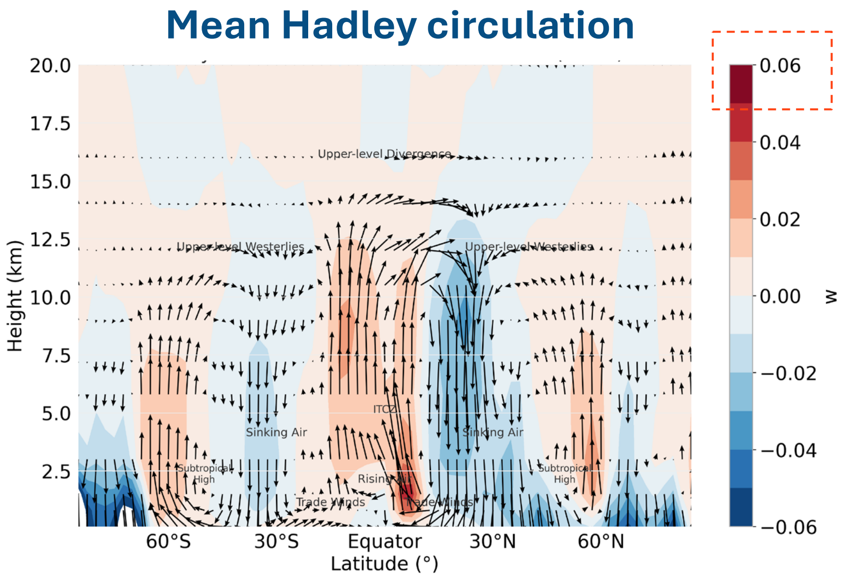
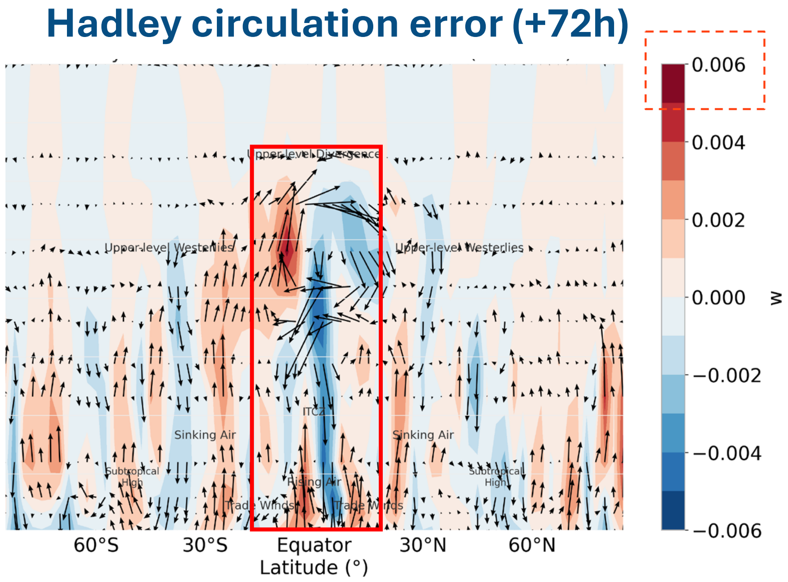


The model currently exhibits a too-weak Hadley circulation

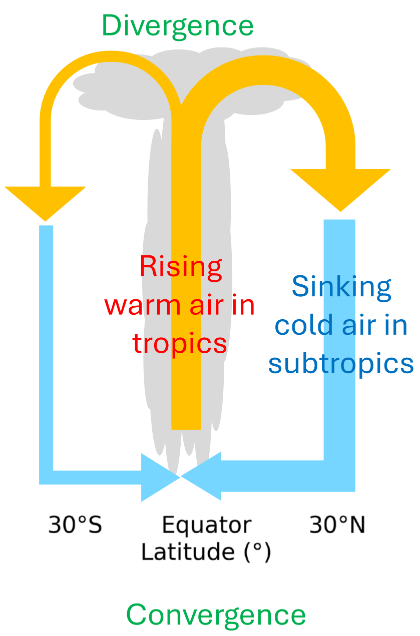




ECMWF

Tobias Becker, Benoit Vanniere

Convection in the tropics and largescale transport



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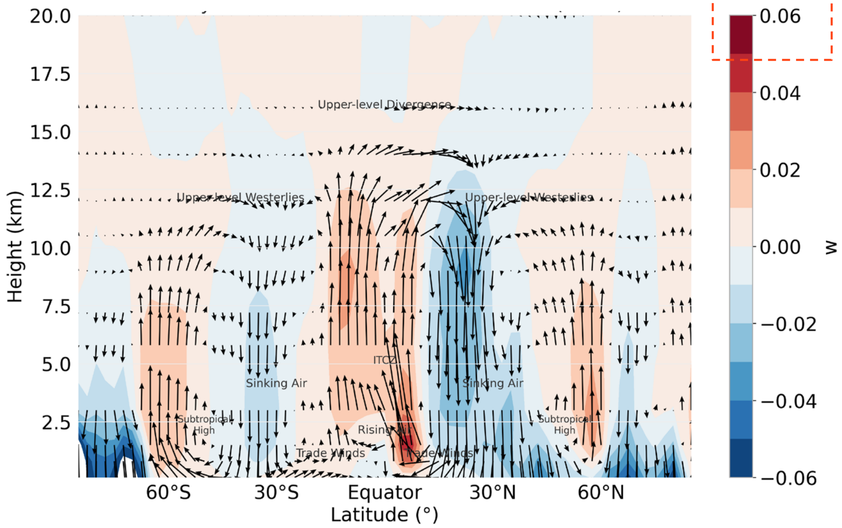
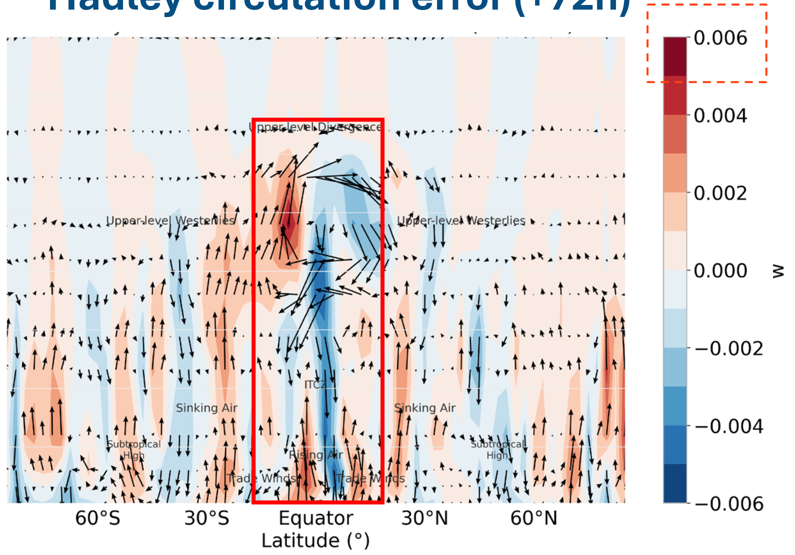
Mean Hadley circulation

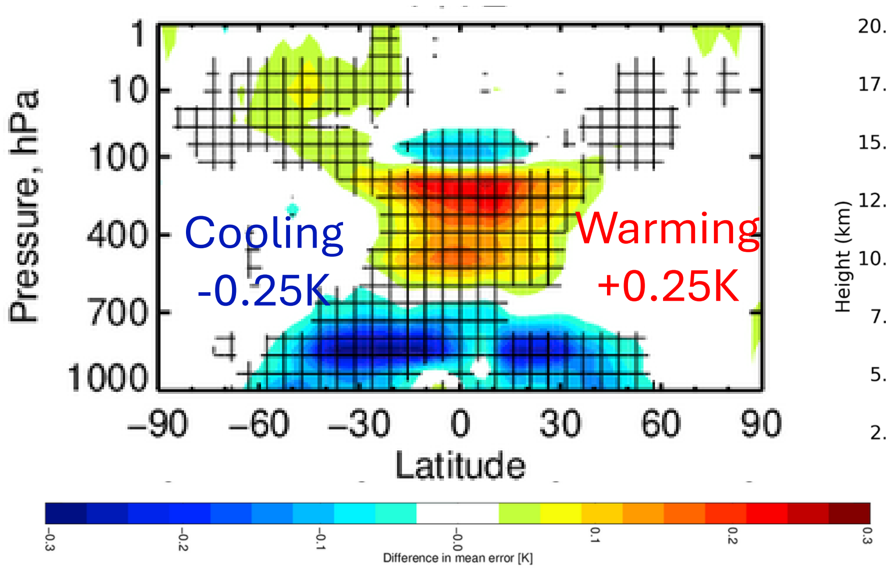


Hadley circulation error (+72h)

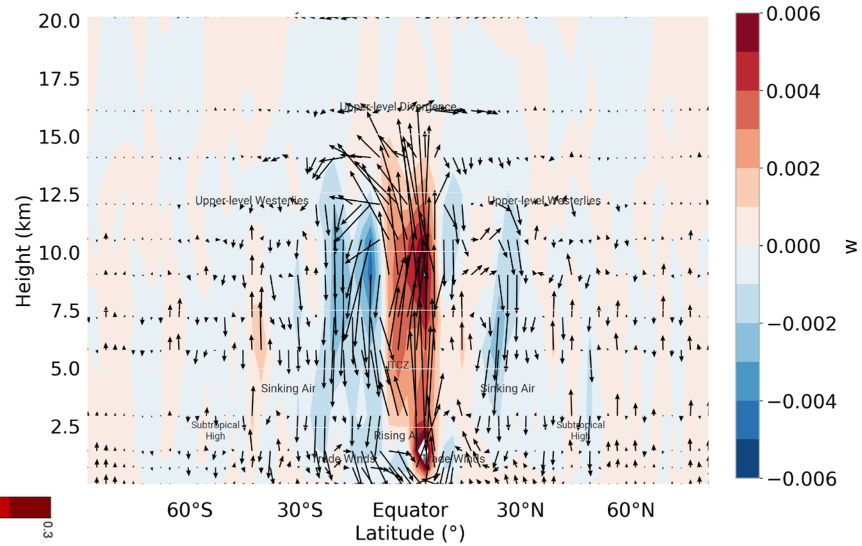


Impact of improving convective organization in the tropics

Mean temperature change (+72h)



Mean Hadley circulation change (+72h)



ECMWF

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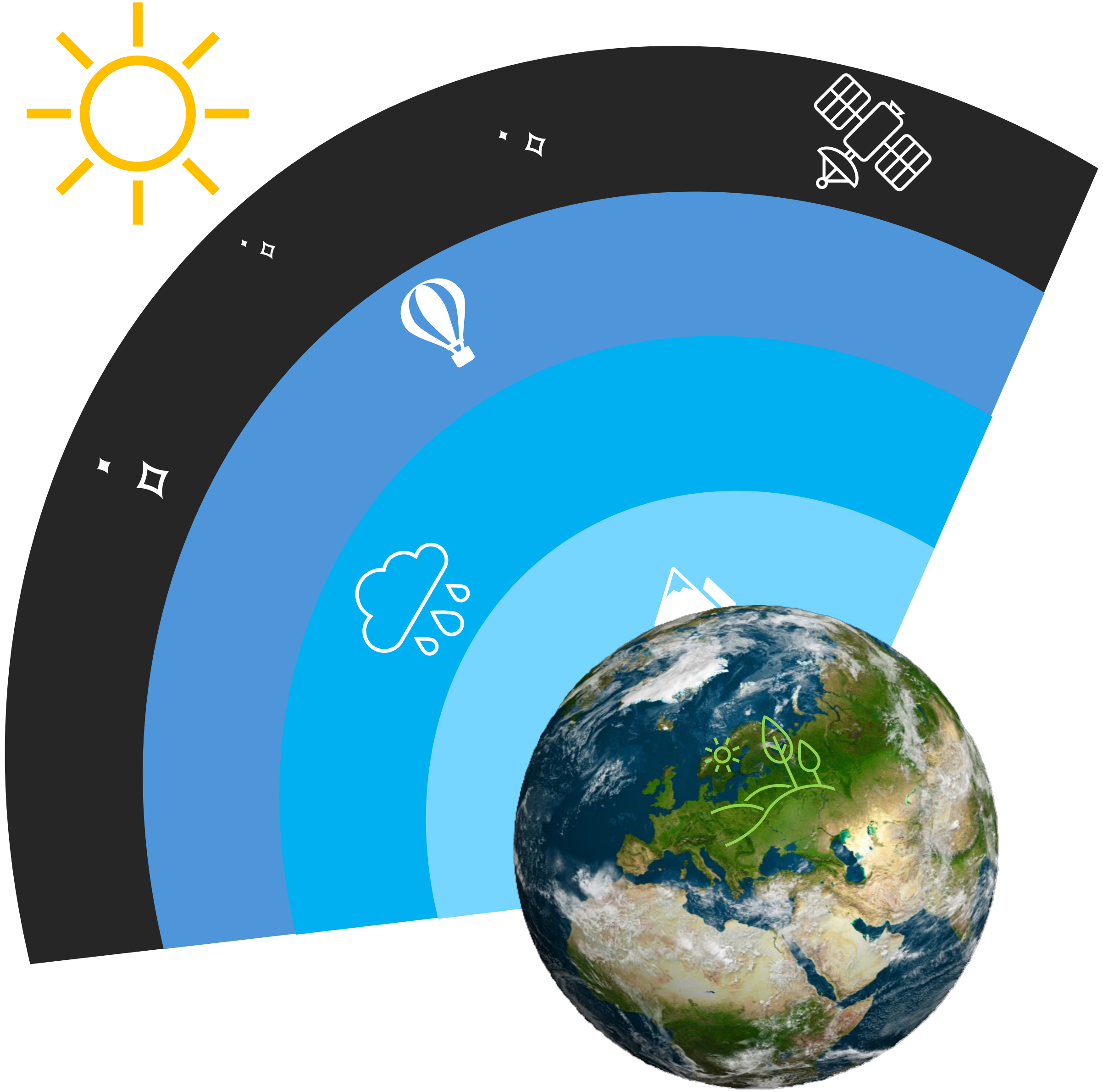
Perturbing processes that impact forecast temperature



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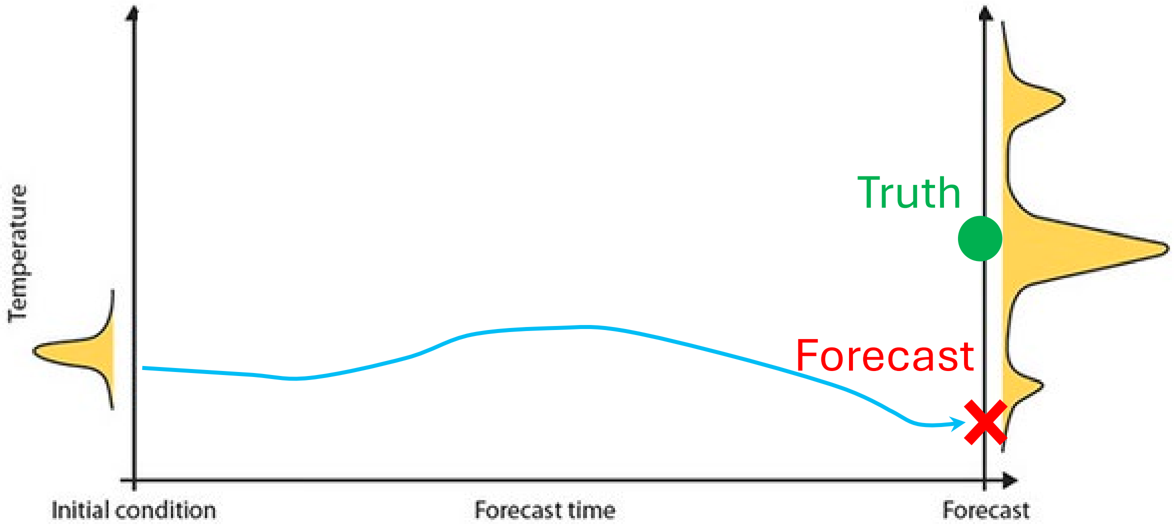
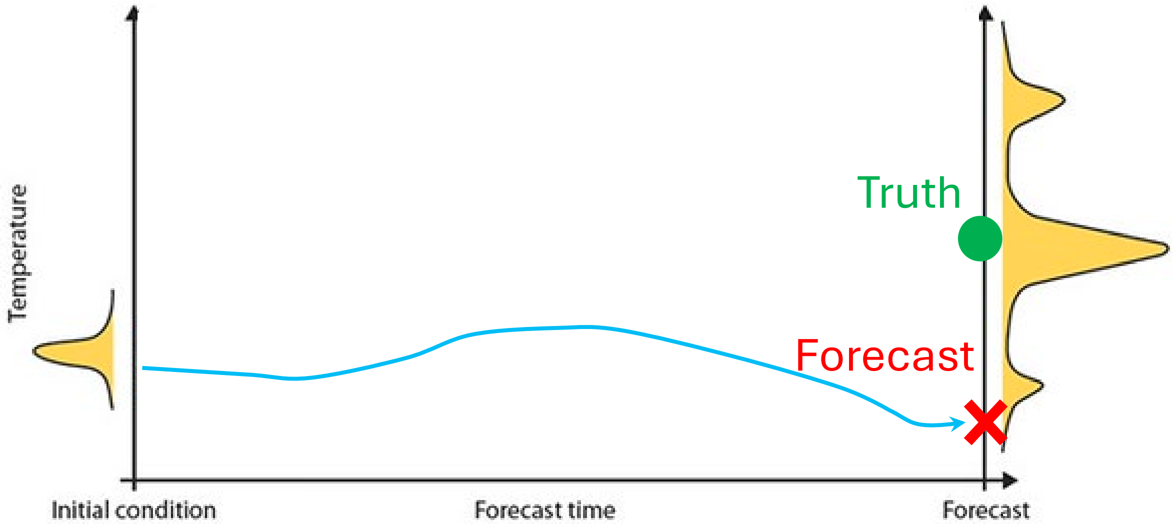
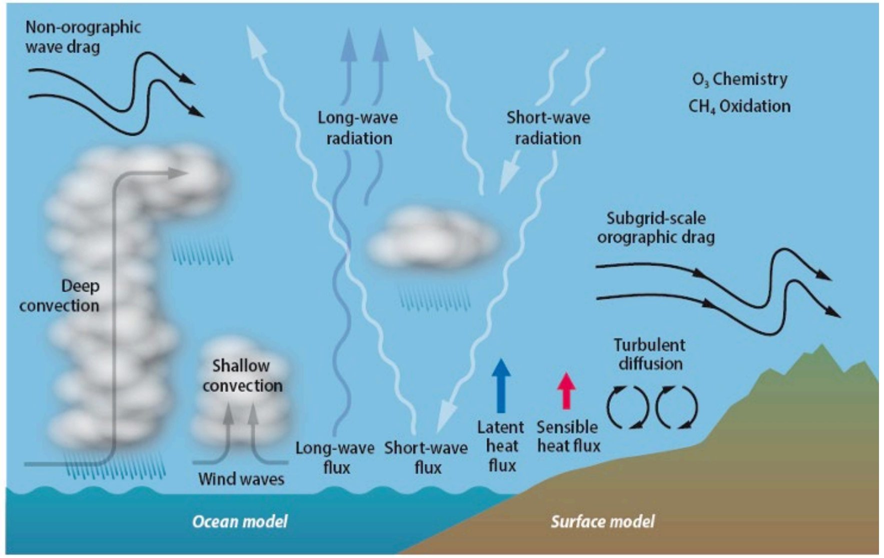
Ensemble forecasting as a means of accounting for process uncertainty

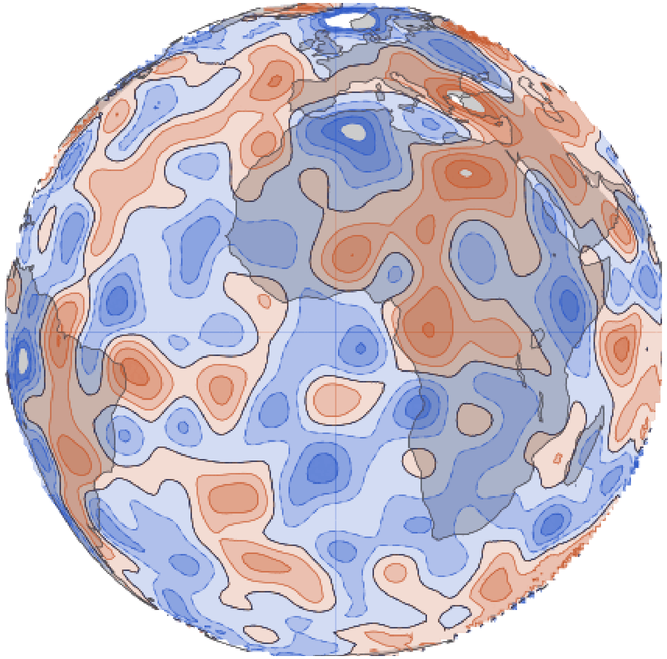


Ensemble forecasting as a means of accounting for process uncertainty





SPP perturbation pattern example



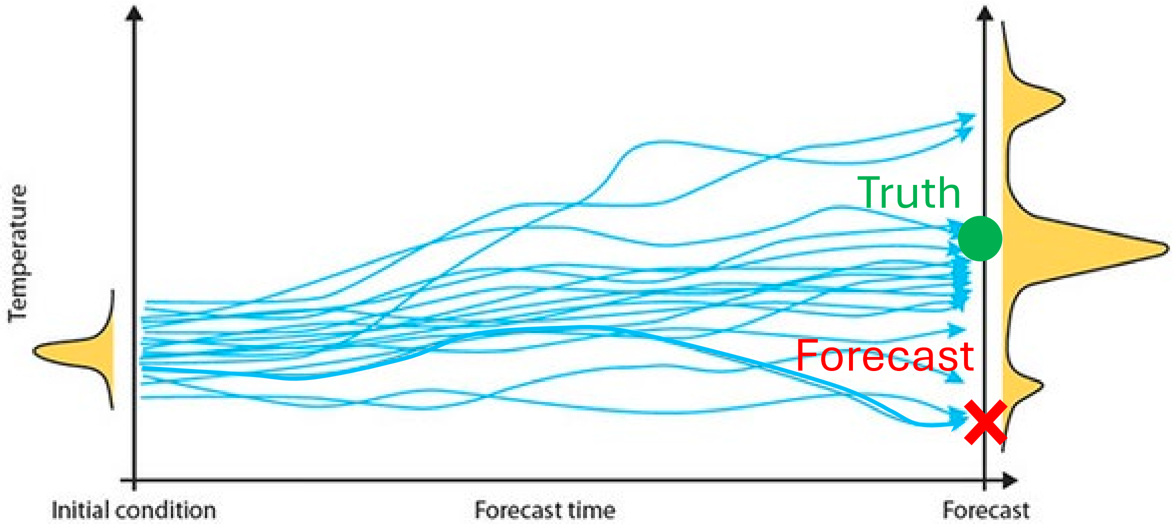
Red:
+0.5 perturbation

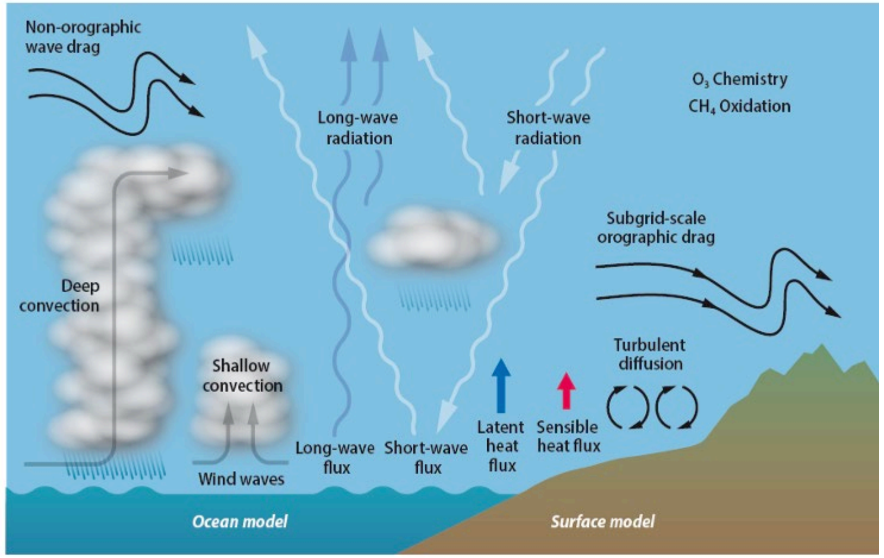
Blue:
-0.5 perturbation

A stochastically perturbed parametrisations scheme (SPP) is used to overcome uncertainties in the sub-grid physical processes (an their interactions)

This allows for a probability of outcomes to be produced...

Ensemble forecasting as a means of accounting for process uncertainty





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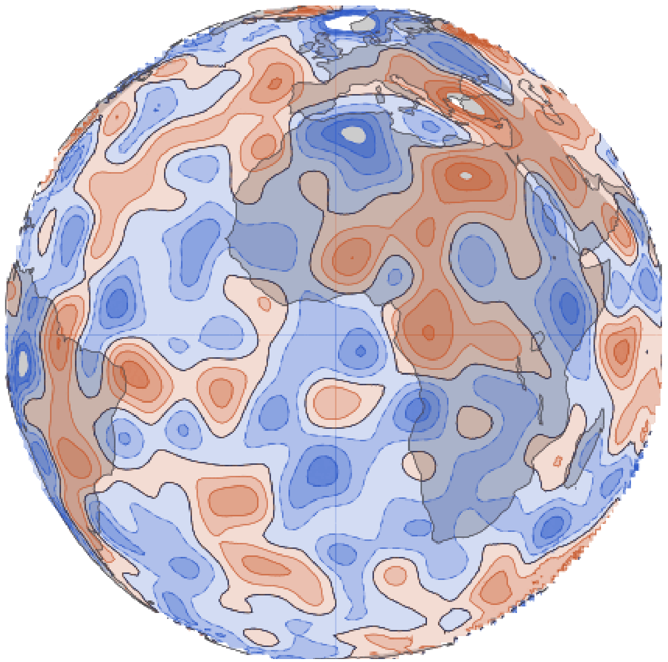

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This allows for a probability of outcomes to be produced...

Conclusions

- The ECMWF model represents may physical processes: from local to global scale
- Each process plays a role in the prediction of near surface temperature
- But, processes interact strongly and, in certain cases, a delicate balance between them is required to capture correct temperature
- Ensemble forecasting, namely SPP, helps to account for uncertainty in the processes and their interactions
- Continued understanding of the insufficiencies in the representation of processes is needed for accurate temperature forecasts