Astronomy and the Atmosphere – the influence of meteorology

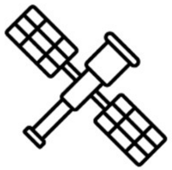
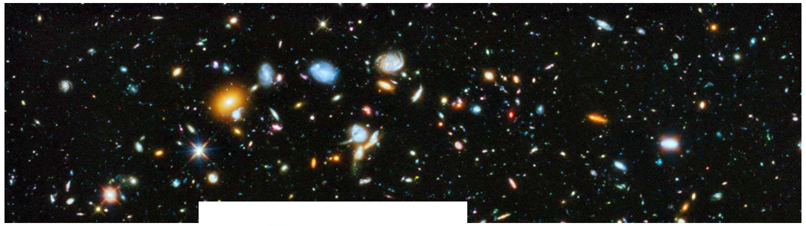
Edward Graham (University of the Highlands & Islands Scotland)

What’s the best place for astronomical viewing?

From Space? **or within the atmosphere on Earth?**





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What’s the costliest? Space versus ground-based telescopes

- Hubble: **$16 billion** ($16,000,000,000)
- James Webb Telescope: **$10 billion** ($10,000,000,000)
- ELT: **€1.45 billion** (baseline; $1,450,000,000)
- TMT: $2.65 billion ($2,650,000,000)
- GTS: €130 million ($130,000,000)
- SALT: **$36 million** ($36,000,000)

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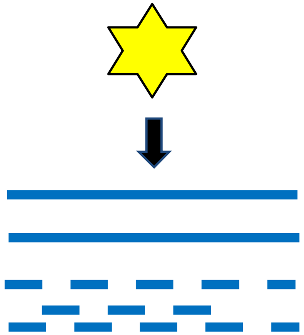
Twinkling stars and the refraction of light

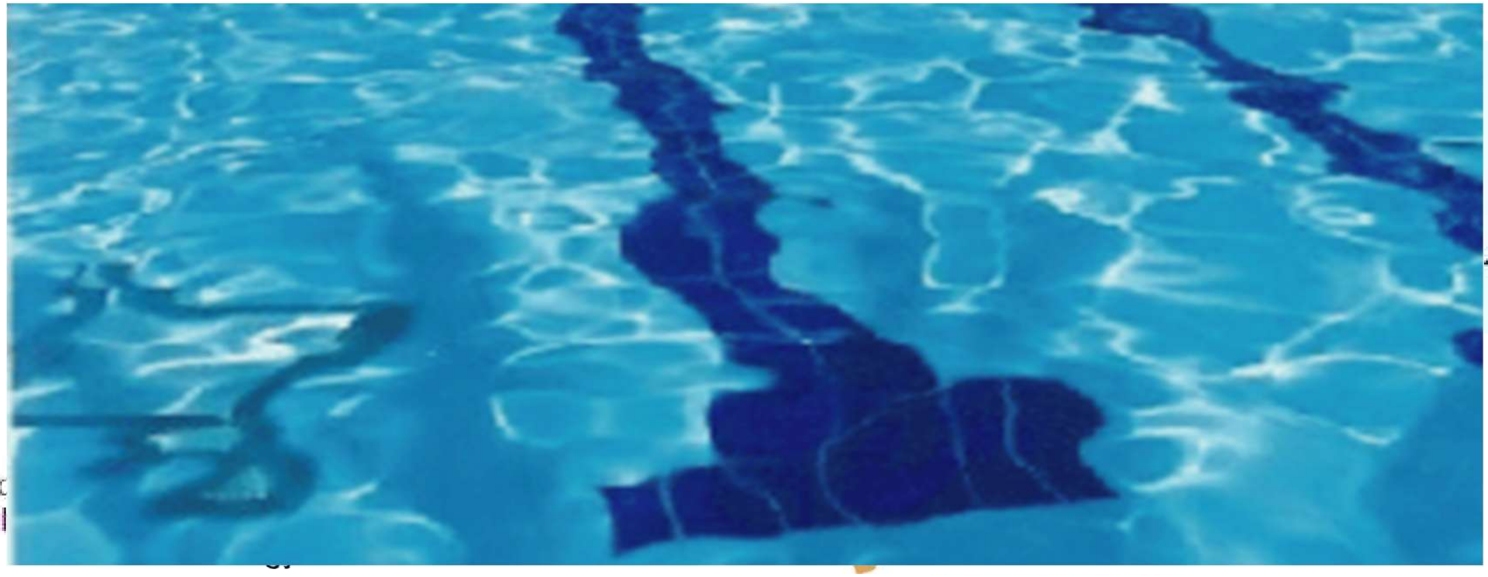

NASA ISS

Space



Atmosphere

Parallel wave front of stellar image gets distorted by atmosphere


(Denis, 2005)

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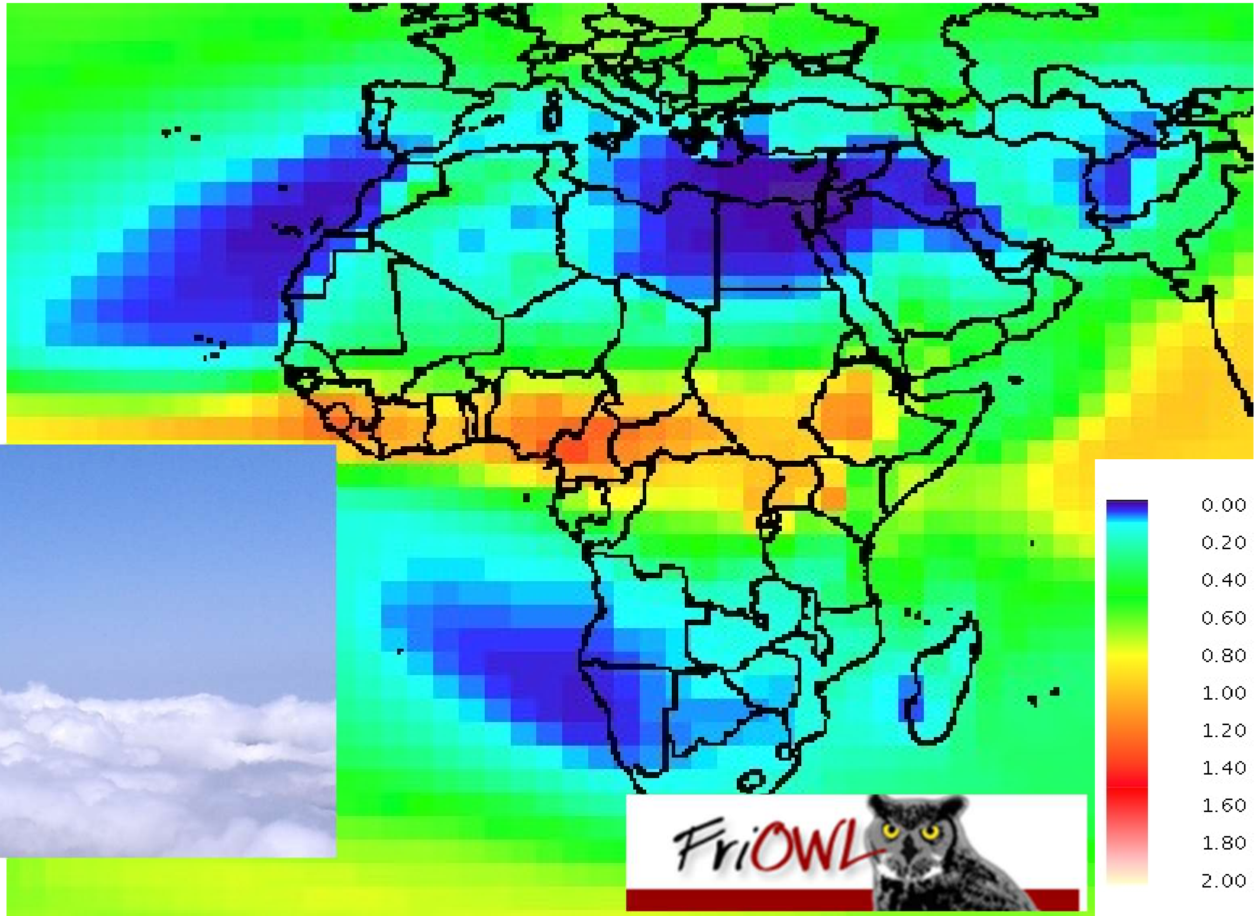
Atmospheric constraints on optical astronomy

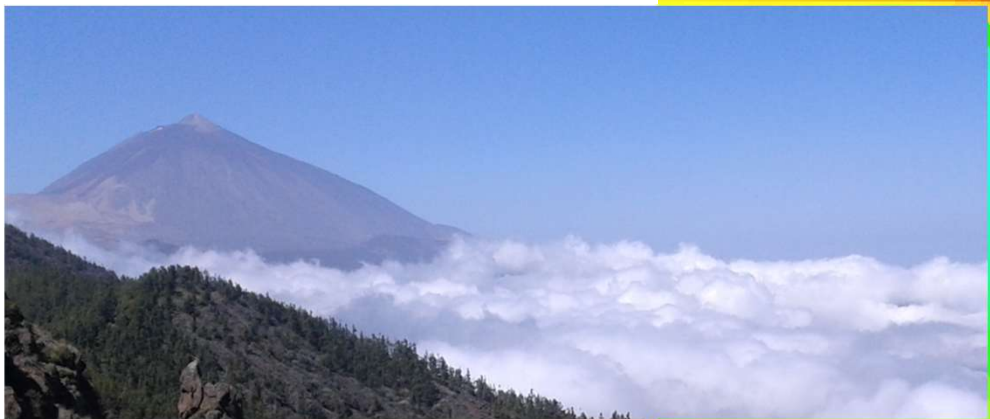
- Clear Skies
- Stable Atmosphere
- Low PWV/IWV
- Low RH%
- Gentle winds
- Mod air temps
- Low dust
- No light pollution
- **No ExWx**
- **No wildfires**

For summaries, please see:

- Sarazin (1997)
- Graham (2008)

Cloud cover: Altitude is most important





ERA40 reanalyses July total cloud cover (above 2,000m only)

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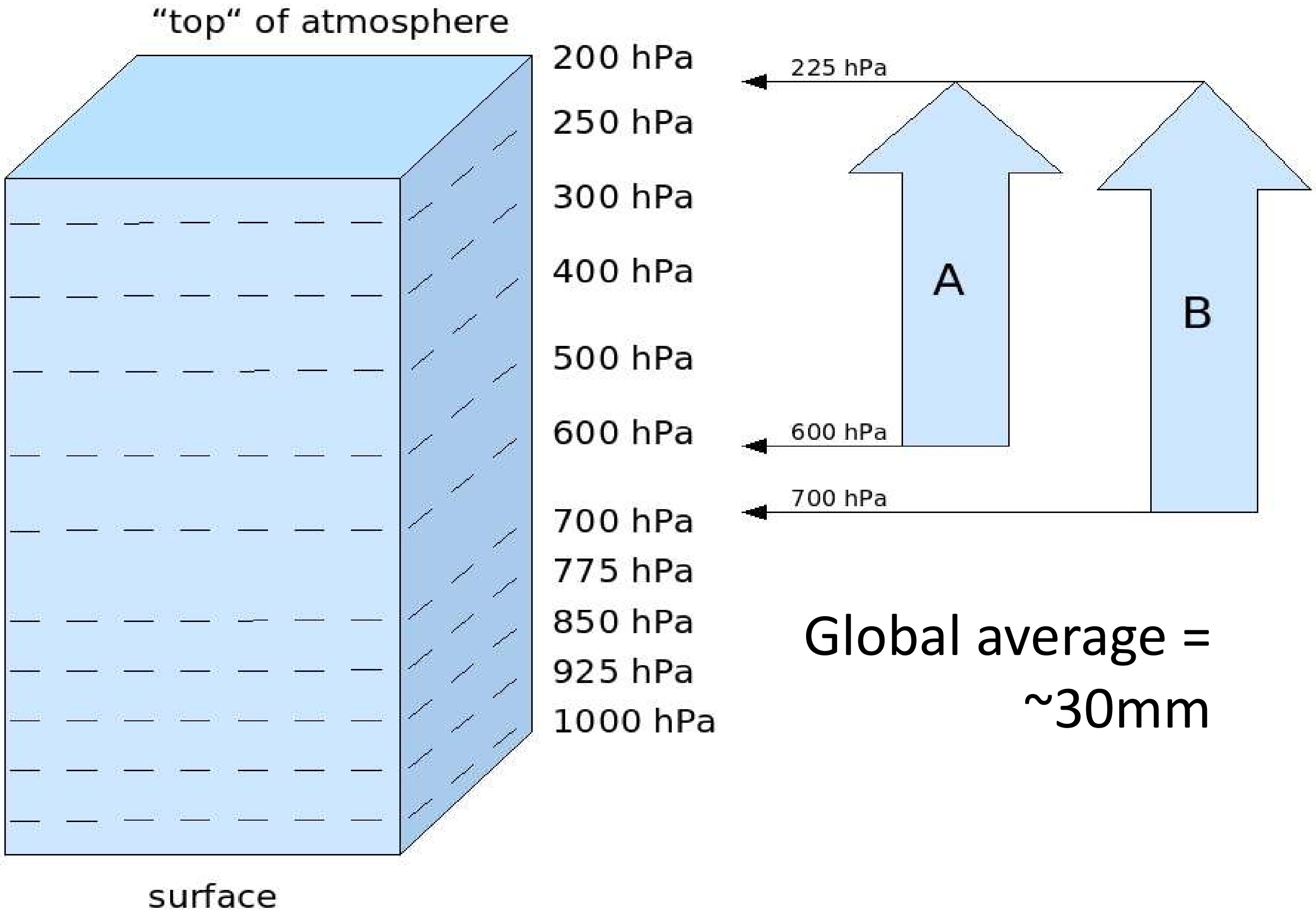
Integrated Water Vapour (IWV) / Precipitable Water Vapour (PWV)

Water vapour absorbs strongly in infrared; very strongly in microwave part of the spectrum. Need IWV < 4mm



Global average = ~30mm

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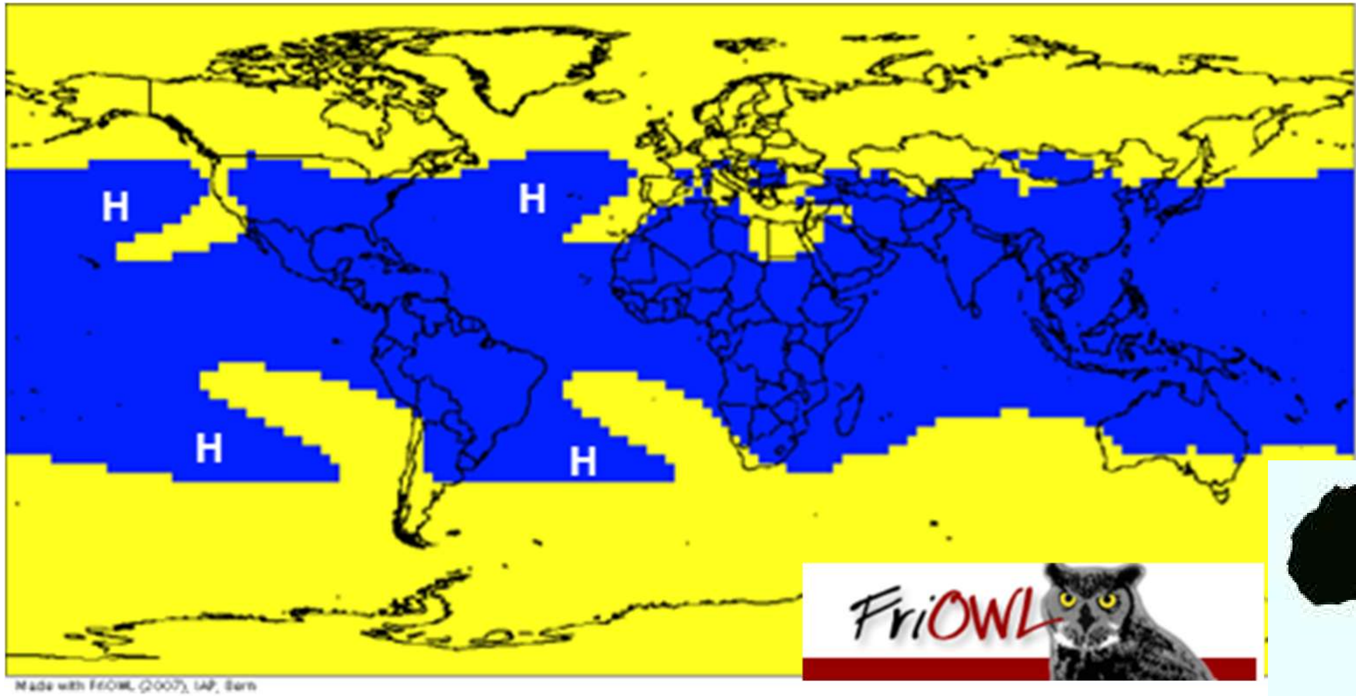
Integrated Water Vapour IWV (PWV) 4mm at ~3000m)

IWV is height dependent; There's a clear relationship between IWV and gently descending air masses



ERA49 IWV at 700 hPa < 4mm (yellow colours)

FriOWL

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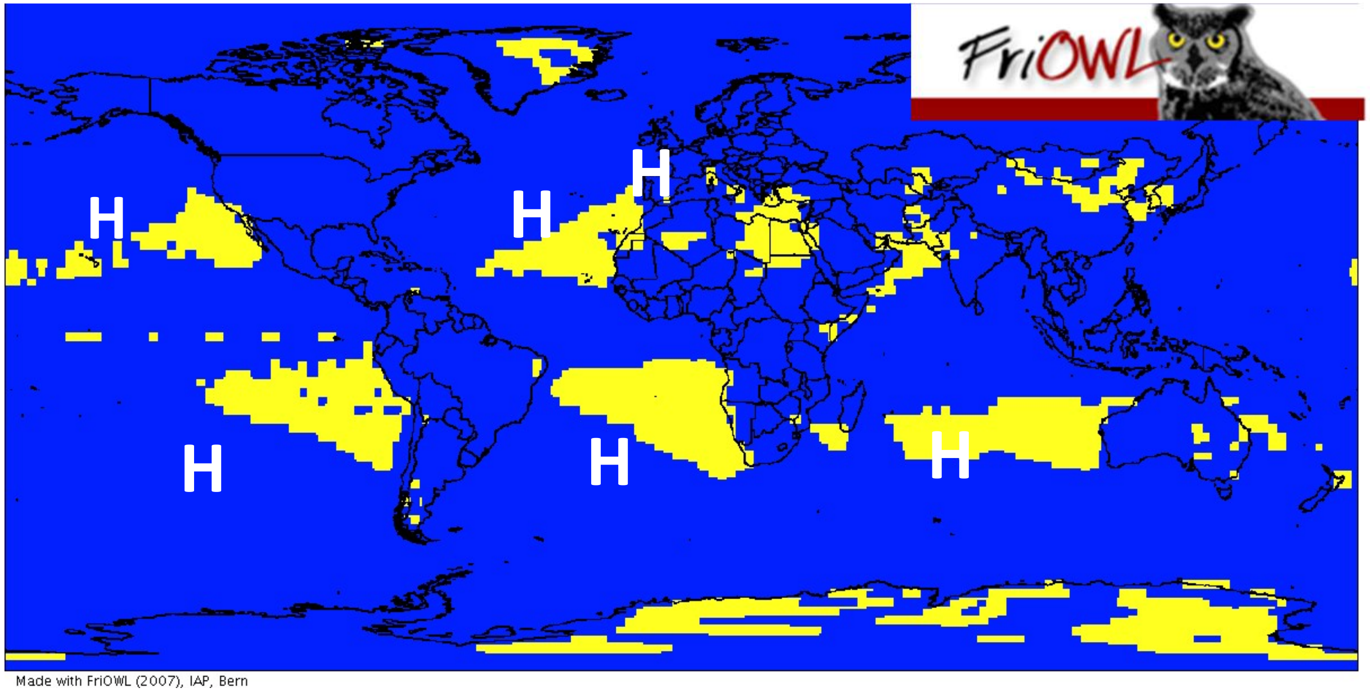
Atmospheric stability: Global zones of gently descending air

Certain weather types cascade across scales (*FriOWL)*.



Preferential zones of gently descending air, which warm adiabatically, creating stability

ERA40 775 to 200 hPa vertical velocities in range 0.025 < > 0.050 Pa/sec; [~2-5mm/sec)

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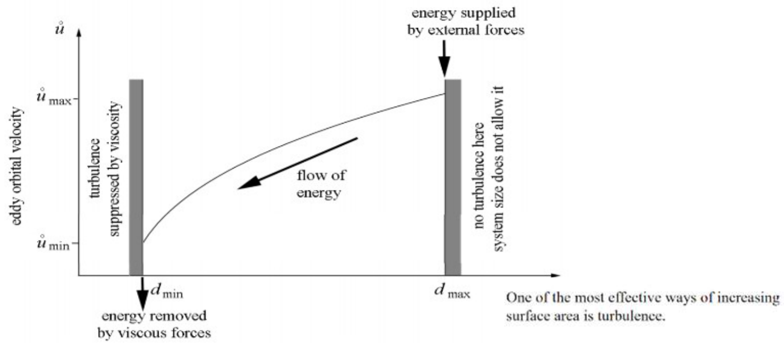
Kolmogorov (1941): The Turbulence Cascade

Kolmogorov showed that turbulence (in the “inertial” range, from millimetres to a ~few tens of metres) is determined only by conversion of **kinetic energy to heat** by viscosity.

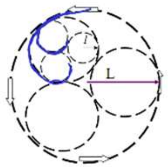
“Big whorls have little whorls, That feed on their velocity;

And little whorls have lesser whorls, And so on to viscosity”

Turbulence changes the refractive index of air.



Cushman-Roisin and Beckers (2011)



https://slideplayer.com/slide/8234023/

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Low night-time Relative Humidity (RH %)

- **RH** is just ratio (%) of how much water vapour is in the air ÷ how much it *could* hold if it was saturated at that same air temperature
- It's **inconvenient for astronomers** that **RH usually reaches a maximum during the night**
- Ground / surface /object temperatures are often **below** air temps
- Risk of dew / frost on optics if air > 80%

S. Burt

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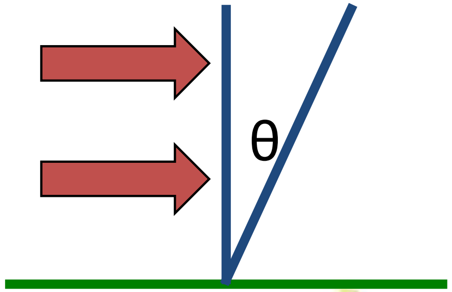
Gentle windspeeds at surface and in atmosphere

Surface windspeeds

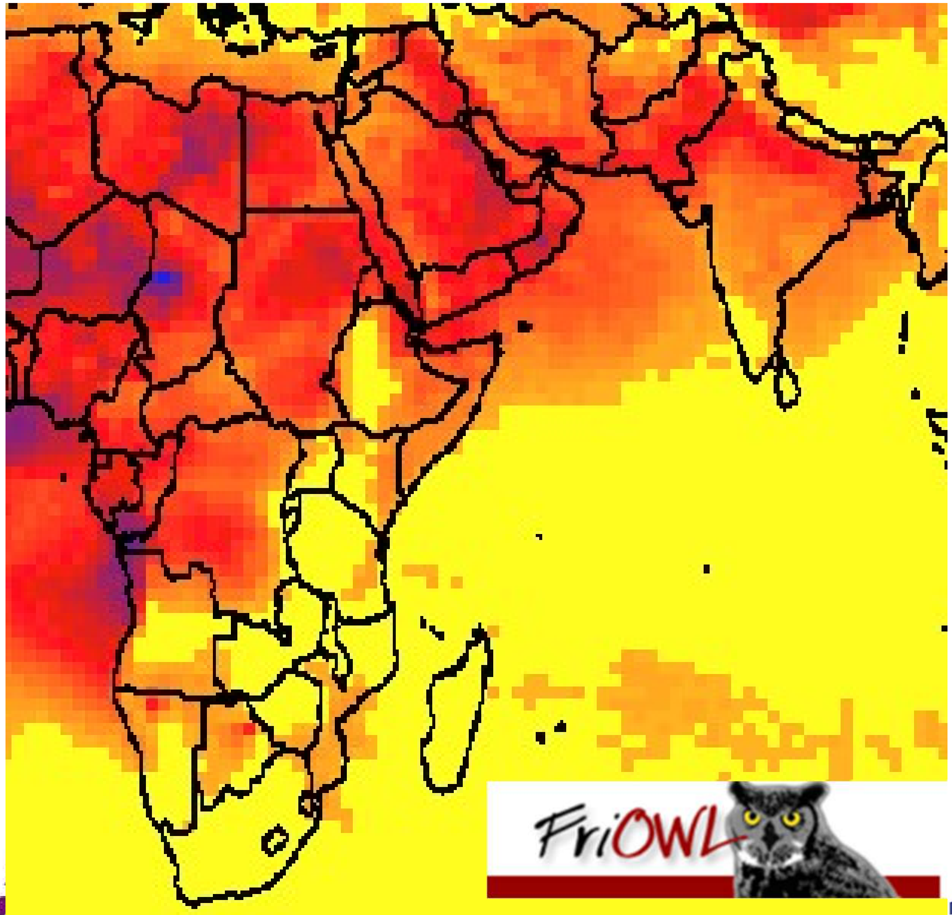
- **2-> 9m/sec** (~4-17kn) are ideal surface windspeeds for *the* VLT
- **< 2m/sec** (below ~4kn) -> no flushing of dome
- **> 9-14 m/sec** (~17-27kn) -> above this, risk of shake!

Winds at altitude

- Isoplanatic angle (θ) subtended to telescope becomes smaller as height increases & as windspeed at jetstream 200hPa level increase



Aerosols (fine dust / particulates)



TOMS aerosols 22yr dataset (Graham, 2004)

- **Aerosols** (lofted desert dust, smoke from biomass burning) both contribute to **atmospheric extinction**
- On-site **wind-blown dust** is a hazard, **degrades mirrors** & **contaminates optics**
- 22-years of TOMS aerosol data made available on FriOWL (Graham *et al.* 2004)
- Many aerosols become **hygroscopic** (attract water vapour condensation) at relative humidities below 100%)

mission

Ambient air temperatures

- Big differences between dome temperature and outside air temperature can lead to "**dome seeing**"
- Domes are ventilated to keep *dT/dx* differences small
- Not surprisingly, extreme cold or heat can put a strain on instrumentation, equipment and personnel!

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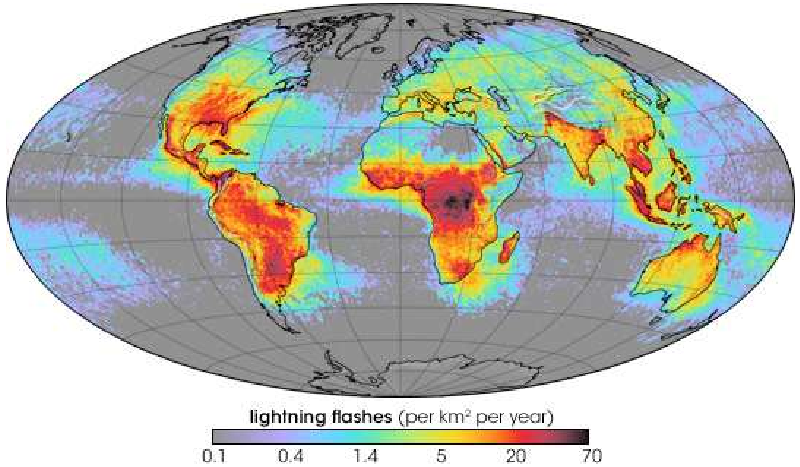
Infrequent Severe Weather



http://thunder.nsstc.nasa.gov/data/query/distributions.html

- Much greater exposure to lightning at the top of a mountain…
- But a dry desert with few storms mitigates against chance of a lightning hit..
- Engineering needs to allow for specific loadings of snow at coldest sites
- Extreme wx is becoming more frequent globally due to Climate Change

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Astronomical viewing indices controlled by weather & climate

Photometric Night %

$C_n^{\,2}$

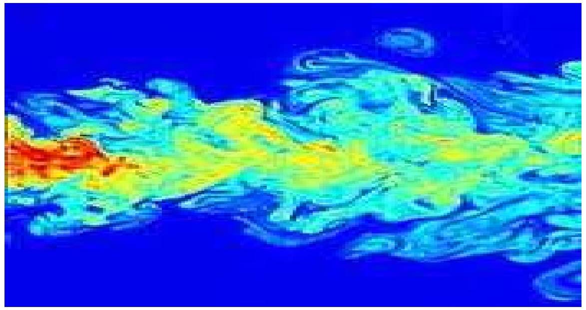
Coherence Length r0

Coherence Time τ_0

Isoplanatic Angle θ_0

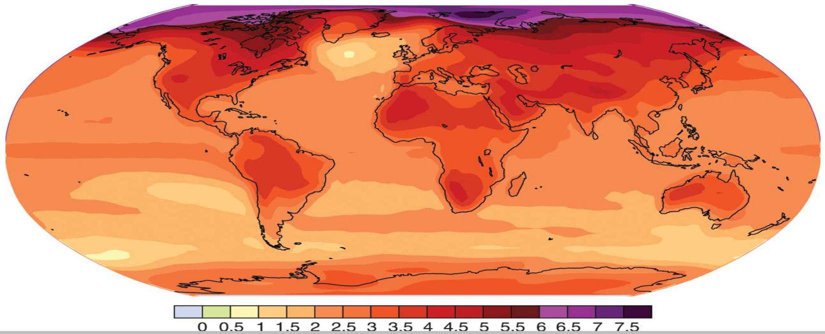
Seeing (FWHM)

e.g. wind tunnel (mm)



10^{11} difference in scales

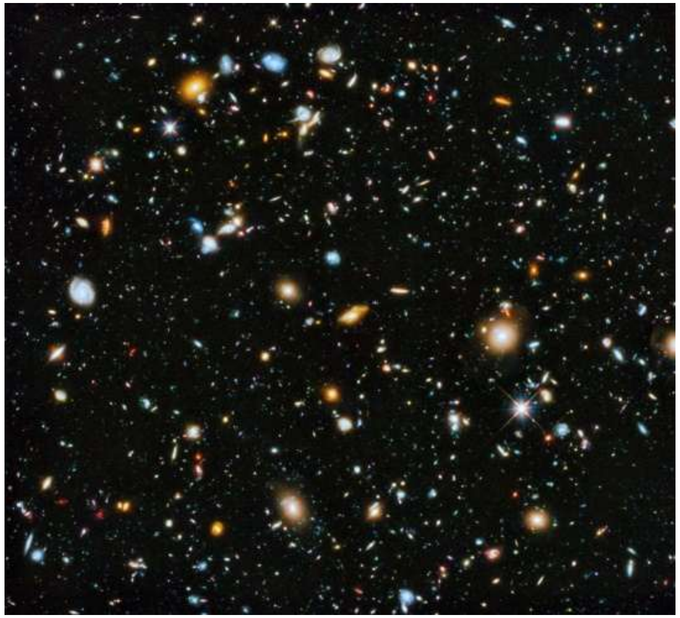
Impossible to represent in a single model



From micrometeorological to decadal & global climate scales!

Photometric Night

A photometric night is defined as:
A night with « *six hours or more of consecutive photometric night-time, where photometric night-time is time without any clouds more than 5° above the horizon, for hours when the sun is more than 18° below the horizon* » (Sarazin, 1995).



ESO Paranal, Chile: 75%
ESO La Silla, Chile: 62%
Northern Kenya up to 50%?

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C_N^2: An optical refractive index structure parameter

- **C_n^2 Temperature Structure Parameter** (refractive index)

According to the theories developed by Kolmogorov and Tatarskii, for well-developed turbulence there exists a temperature structure function:

A fundamental principle

$$C_T^2 = \frac{\langle (T(\rho) - T(\rho + \Delta\rho))^2 \rangle}{\Delta\rho^{2/3}}$$

where T is temperature (K), ρ is a point in space, Δρ is the distance to the next point, and the < .... > brackets refer to an ensemble mean. A corresponding optical refractive index structure parameter can also be described:

$$C_N^2 = \left(80\,X\,10^{-6}\frac{P}{T^2}\right)^2 C_T^2$$

where P is pressure (Pa). Here, humidity fluctuations at visible wavelengths may be neglected. Typical values of C_N^2 range from 10^{-13} (turbulent atmosphere) to 10^{-17} (stable atmosphere).

see
Sarazin (1997)
Graham (2008)

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“Seeing”

Seeing: Full width at half maximum of the stellar disc, when viewed at the zenith at 0.5µm wavelength, using a telescope without optical alterations, over a long exposure time (~20-30 minutes) and is measured in arcseconds. Essentially, it is a measure of the amount of blurring of the stellar image, much like the way « flying shadows » at the bottom of a swimming pool.

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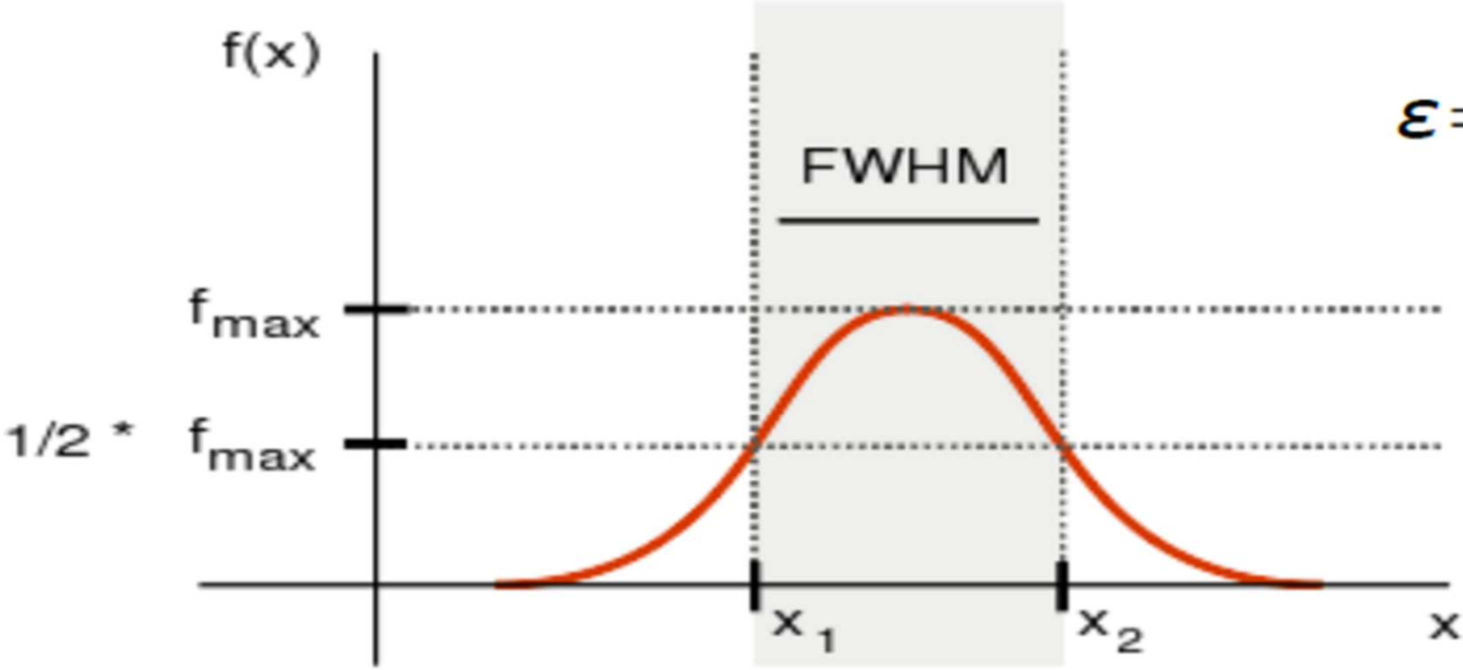
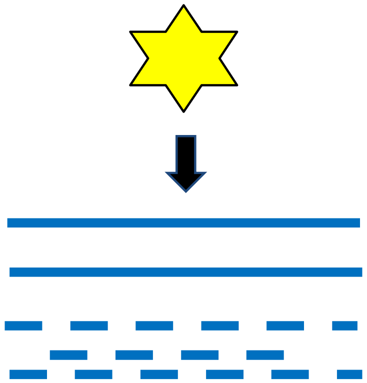
6. Seeing, ε



$$\varepsilon = 0.976 \frac{\lambda}{r_0}$$

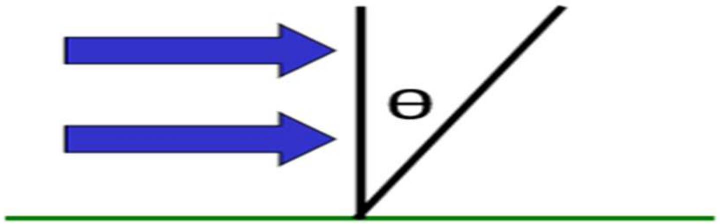
Seeing: Seeing depends only on the wavelength (λ) of the radiation and the Coherence Length (r0). Typical mean seeing values at the world's best observatories are in the range 0.5 to 1.0''

Coherence Length (r_0) / Coherence time τ_0 / Isoplanatic Angle θ_0



Coherence Length **r0** (horizontal distance over which the stellar wavefront is coherent). In other words, it is the distance over which one considers the considered photons to be in phase.

Coherence Time τ_0 (the time over which the stellar wavefront is coherent).



Isoplanatic Angle θ_0 (the angle over which the stellar wavefront is coherent).

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NRF National Research Foundation

AfAS African Astronomical Society

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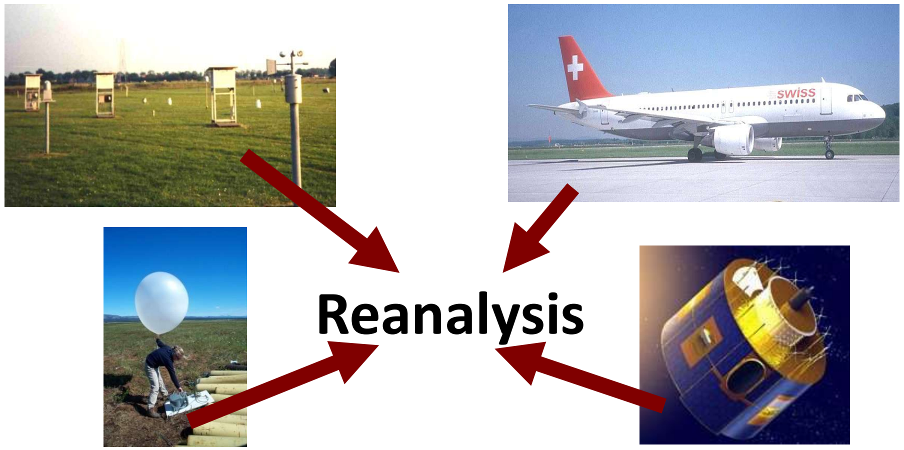
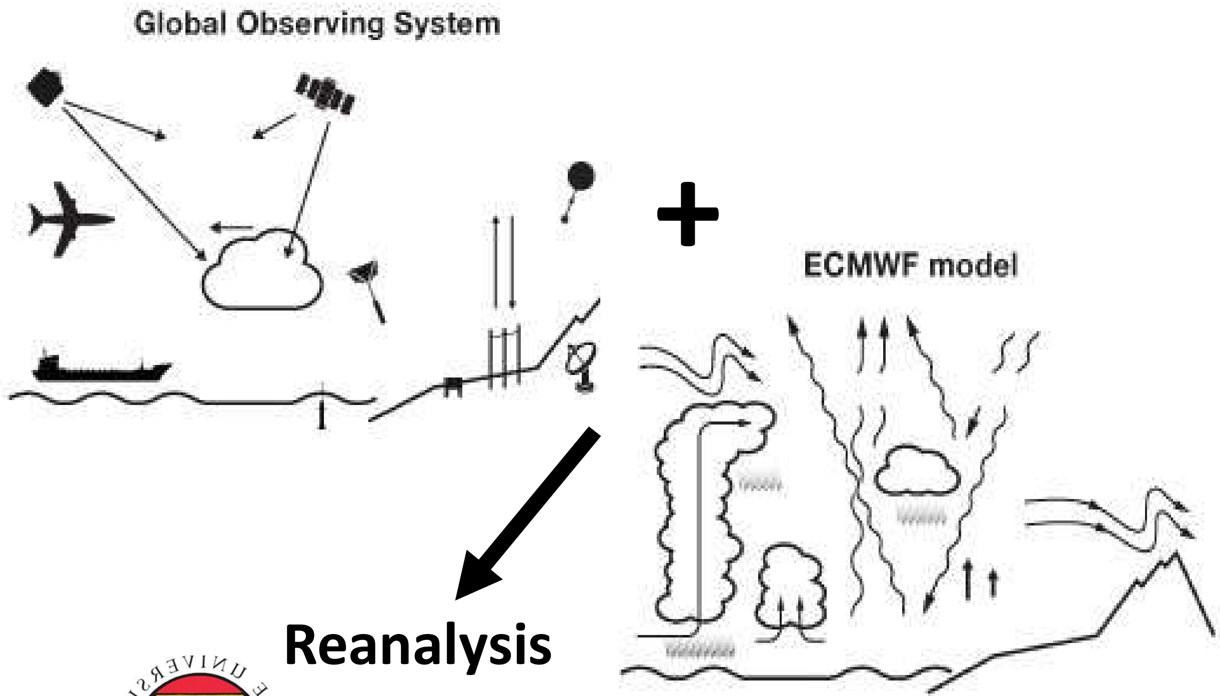
How are met observations & met model data used in astronomy?

From 1990s, using global climate models called **reanalyses** = historic weather data (~1950s->) is used to initialise an **accurate numerical met model of today** to re-simulate weather in the past.





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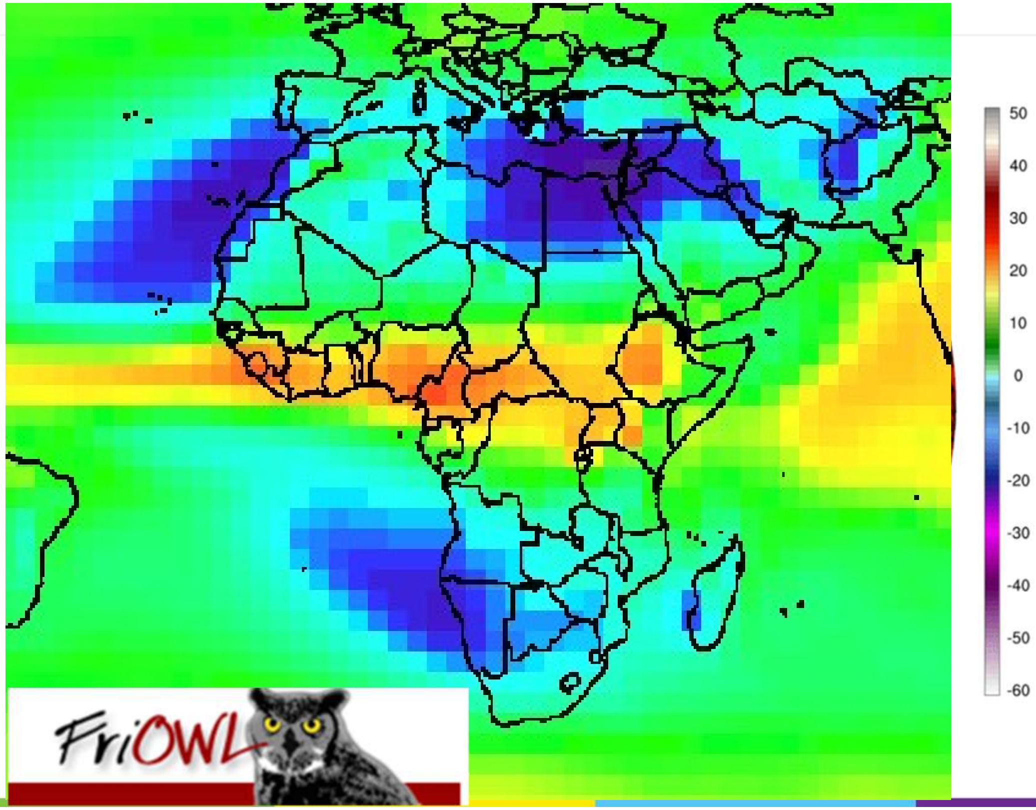
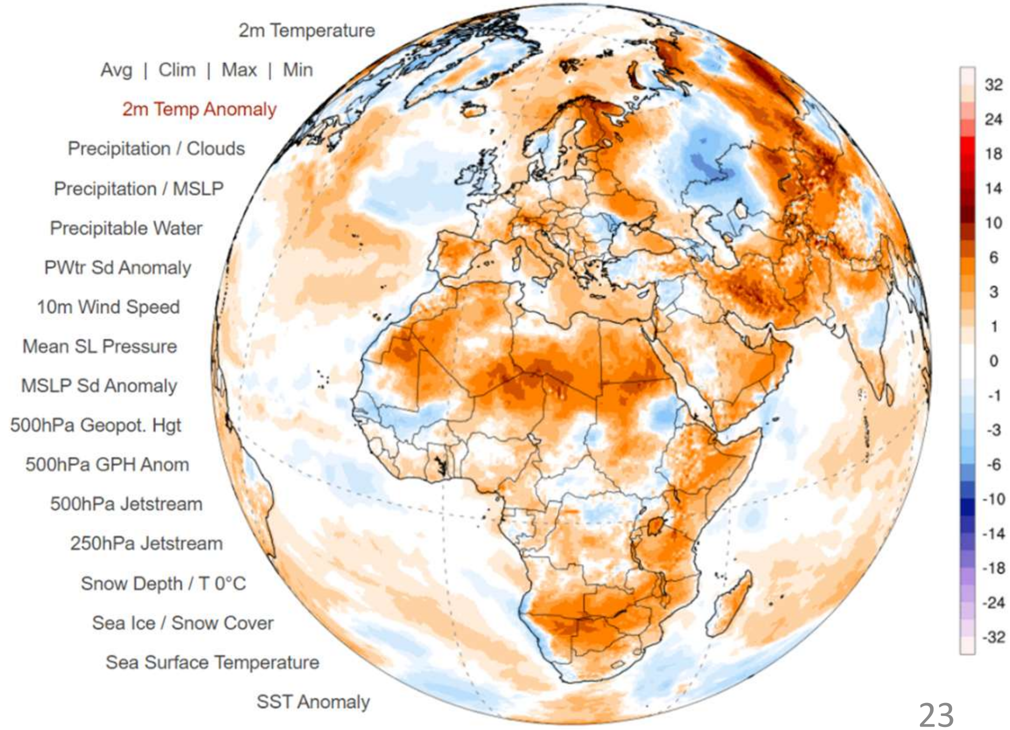
Atmospheric & Climate Science - *Reanalyses*

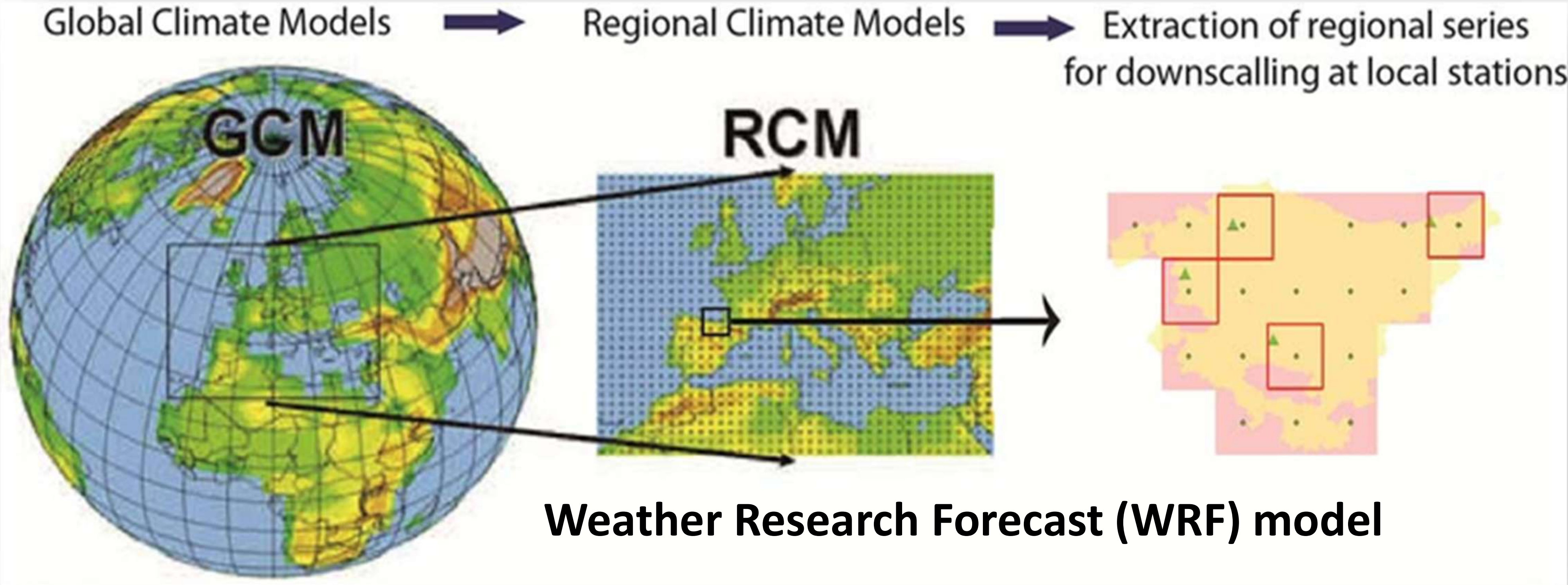
Climate Reanalyzer
Climate Change Institute | University of Maine

https://climatereanalyzer.org/
reanalyses.org/





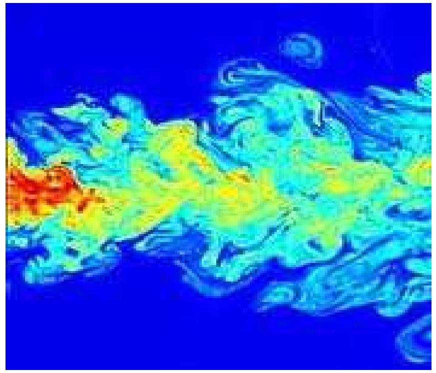
From global (GCM) to regional (RCM) to local (LES) models

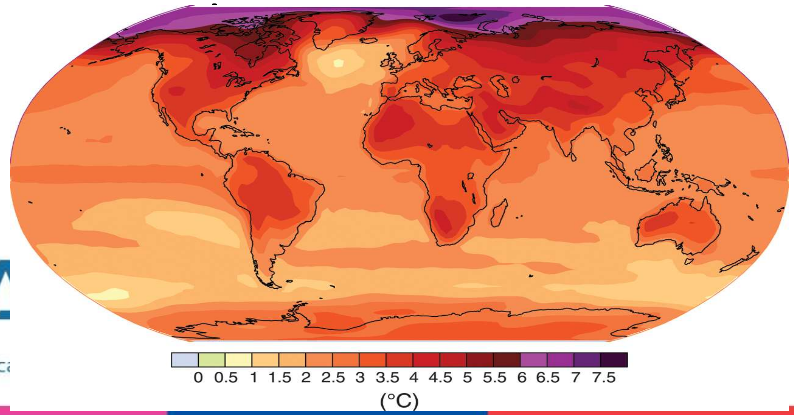


Weather Research Forecast (WRF) model

Attempts to model astroclimate indices

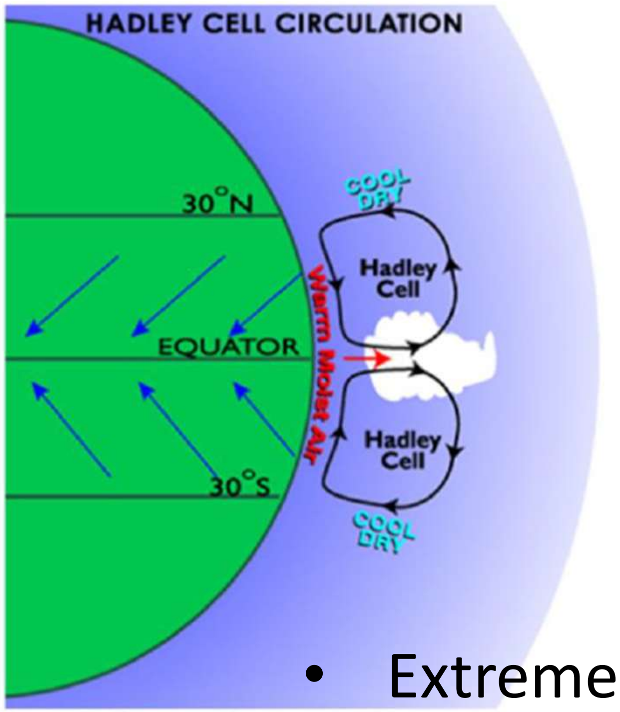
- In past decade, several attempts to model astronomical viewing parameters directly using both hi-res models and AI/ML e.g. **Osborn & Sarazin** (2018); **Cherubini et al.** (2022); **Turchi et al.** (2022), some with more success than others…
- **Main point**: Integration timestep of local met models is typically between tens of seconds to minutes, so that's still 3-4 orders of magnitude too high to resolve motion explicitly. So we will need to rely on statistical / empirical approximations for some time yet.
- **AI & ML** should be more promising in make linkages turbulent cascade
- **Local weather knowledge** is still vital!



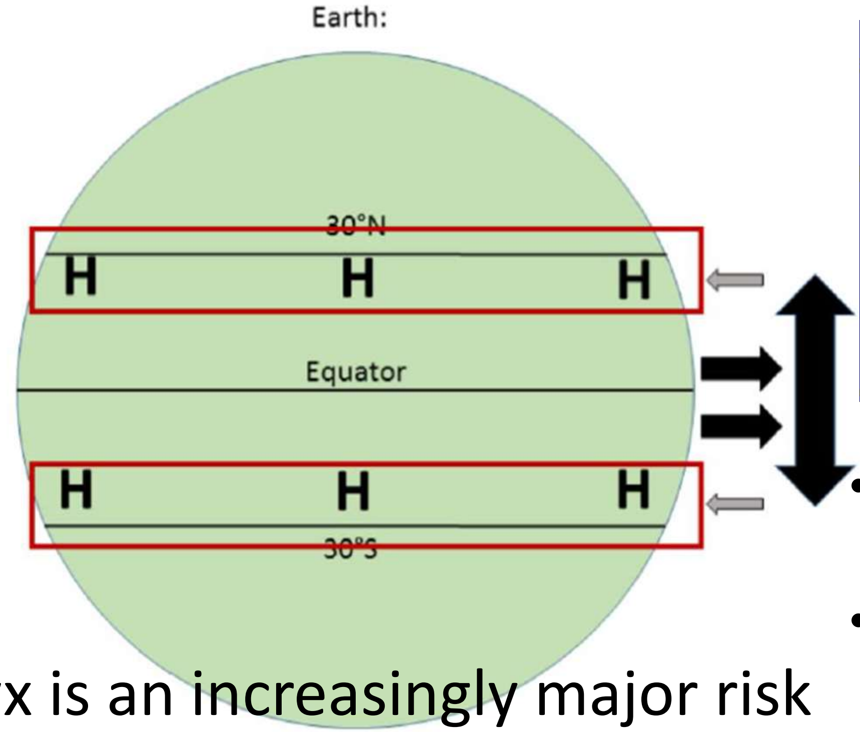


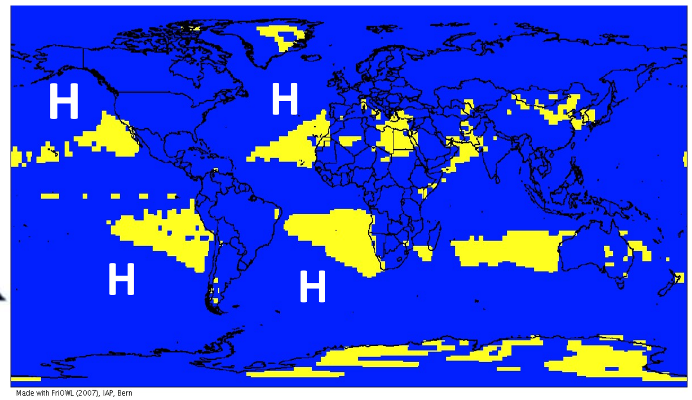
Elephant in the room: We are now the weather makers

Hadley Cell expansion is one of the most well-established atmospheric responses to global warming. The current rate of expansion is 0.1°–0.5° latitude poleward per decade. Hadley cell winds may be increasing too -> likely consequences for key astronomical sites.



Credit: https://warosu.org/



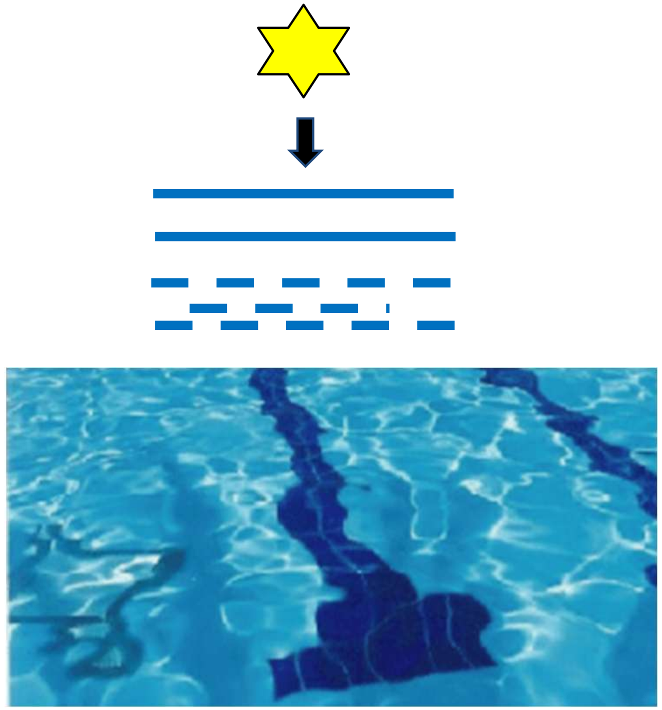


- Extreme wx is an increasingly major risk

- Graham (2017-18), Climate Study for TMT
- Sarazin (2025) Atmosphere / MPDI

Conclusions

- Atmosphere influences astronomical viewing across a huge range of scales $\sim 10^{11+}$
- It's impossible to represent all of these within a single model or framework, or even simulate certain individual scales (e.g. high frequency turbulence)
- However, the similarity of some weather & climate features occurs across range of scales ("fractal") especially in gentle, settled airflow
- These can be exploited by atmospheric models



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Development in Africa with Radio Astronomy

Spiral Galaxy, NGC 1232 21 Sep 1998, VLT Paranal (ESO)

Thank you!

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Appendix 1:

- **Coherence Length r0** (horizontal distance over which the stellar wavefront is coherent). In other words, it is the distance over which one considers the considered photons to be in phase.
- Typical values of **r0** at ESO Chilean sites are around 10 to 20 cm, but perhaps up to 40 cm in Antarctica.

$$r_0 = \left[0.423 k^2 \sec\gamma \int_{h_0}^{\infty} C_n^2(H)\, dH\right]^{-3/5}$$

where k is the wavenumber (reciprocal of wavelength), γ is the zenith angle H is height (m) and h0 is observing height. This means that the coherence length:

- decreases with increasing zenith angle (closer to horizon, longer path through atmosphere),
- decreases with increasing wavenumber (i.e. decreasing wavelength) and with an increasing CN^2 (greater sum of refractive indices)

Appendix 2:

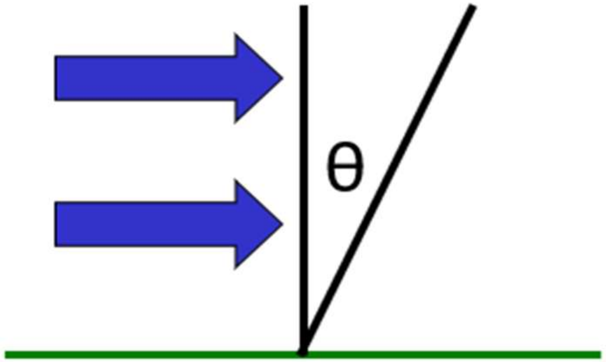
- **Coherence Time τ_0** (the time over which the stellar wavefront is coherent). Since time = distance ÷ speed:

$\tau_0 = \frac{r_0}{\bar{V}}$, where $\bar{V}$ is the mean horizontal velocity of the wavefront corrugations

- Advanced "Adaptive Optics" mechanisms of the very large telescopes can then use this information to correct the telescope image, by distorting the mirrors at a microscopic scale at a very high frequency. Mean values of τ0 at Paranal are about 4 milliseconds, but up to 8 milliseconds during the best viewing conditions.

- **Isoplanatic Angle θ_0** (the angle over which the stellar wavefront is coherent).

Adaptive Optics mechanisms of a telescope apply corrections to an image, but these are only valid to within a certain angle - this angle is called the isoplanatic angle (θ0).



Furthermore, the angle subtended by a given horizontal length is smaller at higher levels in the atmosphere than at lower levels -> turbulence at th upper levels reduces the isoplanatic angle to a greater degree than turbulence at lower levels.

Typical values for the isoplanatic angle at current large observatories range from 1 to 5 arcseconds

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