The Secrets of the Best Rainbows on Earth

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Outline

i) Cultural and historical significance of rainbows in Hawai'i
ii) The science behind rainbow phenomena
iii) Why is Hawaii the Rainbow Capitol of the World?
iv) Chasing rainbows

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Ānuenue in Hawaiian Culture

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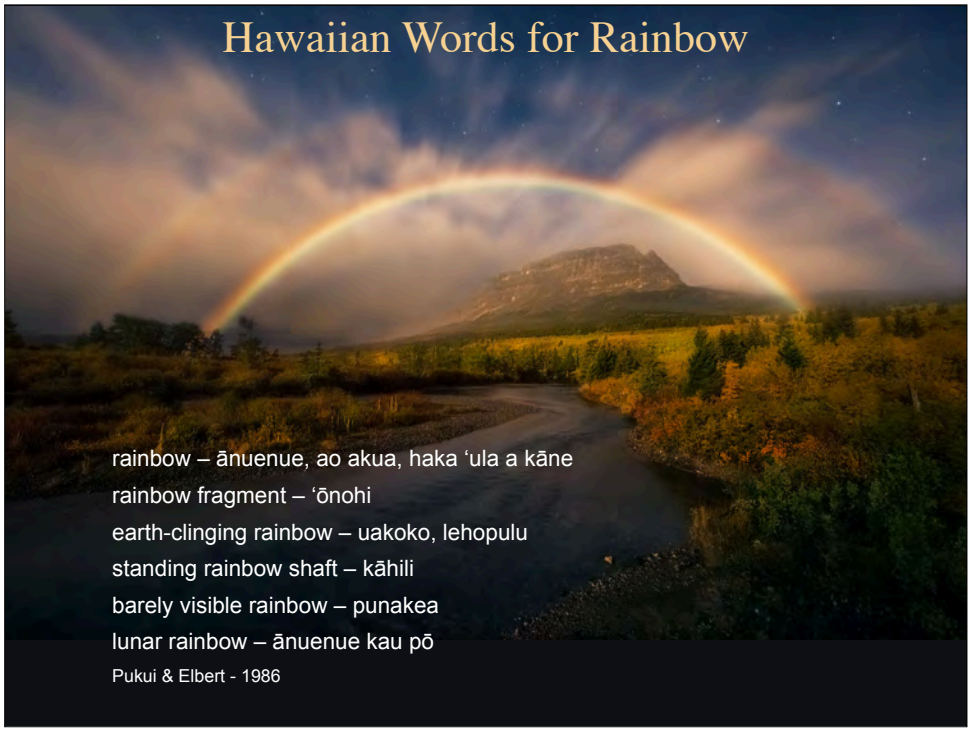
Hawaiian Words for Rainbow



rainbow – ānuenue, ao akua, haka 'ula a kāne
rainbow fragment – 'ōnohi
earth-clinging rainbow – uakoko, lehopulu
standing rainbow shaft – kāhili
barely visible rainbow – punakea
lunar rainbow – ānuenue kau pō
Pukui & Elbert - 1986

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The rainbow is a symbol of transformation. In Hawaiian mythology rainbows are a pathway between dimensions, between Earthly and Heavenly realms.

5

Kahalaopuna – Princess of Mānoa Valley

According to Hawaiian legend, these heavenly arcs embody the presence of Kahalaopuna, the daughter of a chief and chiefess who mourned her death at the hands of a jealous suitor by transforming themselves into their spirit forms, the Mānoa wind and misty rain. When these divine spirits blow through the valley, Kahalaopuna appears as a rainbow.

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"Mōhala i ke Ānuenue ka maka o ka pua"
Unfolded by Rainbows are the faces of the flowers.

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Outline

i) Cultural and historical significance of rainbows in Hawai'i
ii) Highlights of science behind rainbow phenomenon
iii) Why is Hawaii the Rainbow Capitol of the World?
iv) Chasing rainbows

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Early Observations of Rainbow Phenomena

Aristotle (384–322 BC) noted that rainbows have a specific shape and postulated that the appearance of the rainbow was a reflection of sunlight from distant clouds.

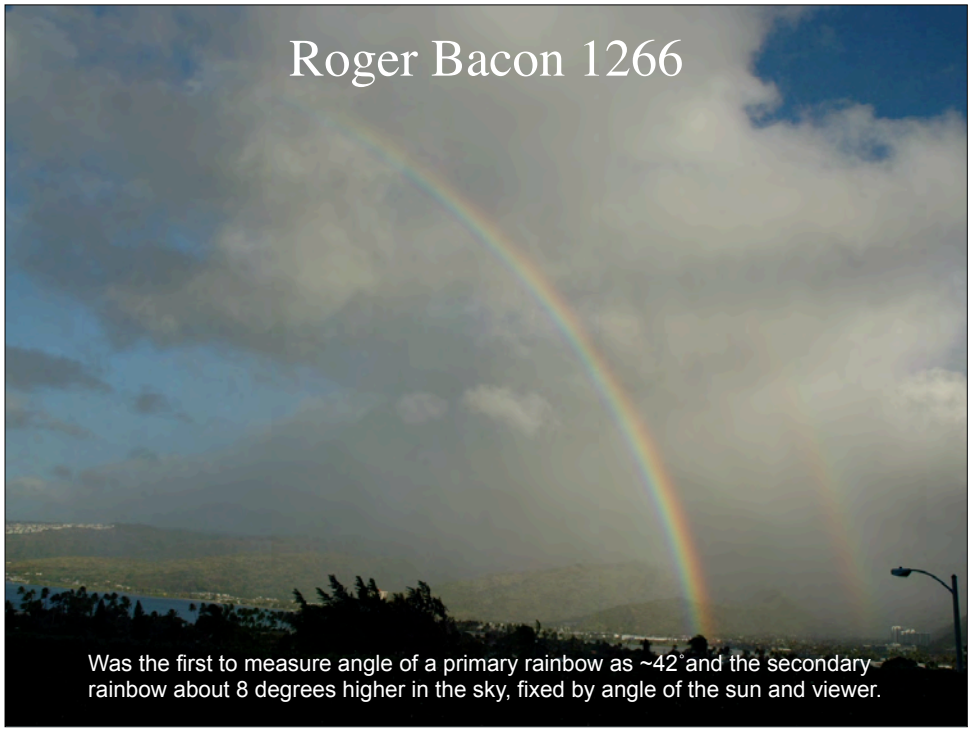
The Arab scientist Avicenna (980–1037) was aware of the necessity of sunlit water drops.

Iris is the Greek Goddess of the Rainbow

Alexander's Dark Band

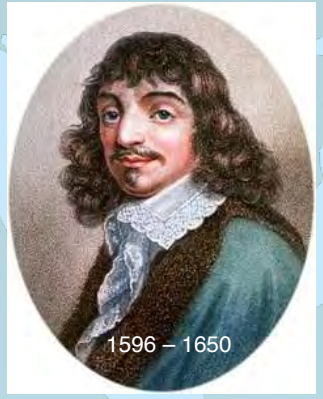
There is a darker band between the primary and secondary rainbows, known as "Alexander's dark band" after Alexander of Aphrodisias, who observed it around 200 C.E.

Roger Bacon 1266

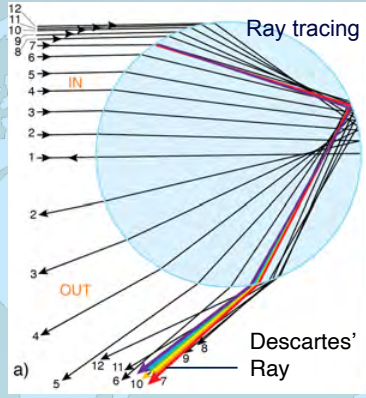


Was the first to measure angle of a primary rainbow as ~42˚and the secondary rainbow about 8 degrees higher in the sky, fixed by angle of the sun and viewer.

Rene Descartes 1637



1596 – 1650



Published rainbow theory as a chapter in his Discours de la méthode in 1637, in which he describes similar experiments with water filled glass spheres as was done by Theodoric of Freiberg in 1304.

But Descartes also performed quantitative ray tracing for parallel sunlight using the law of refraction that he derived. His analysis correctly predicted high concentrations of rays emerging from the spherical drop at the rainbow scattering angles of 42˚ for one and 51˚ for two internal reflections, respectively.

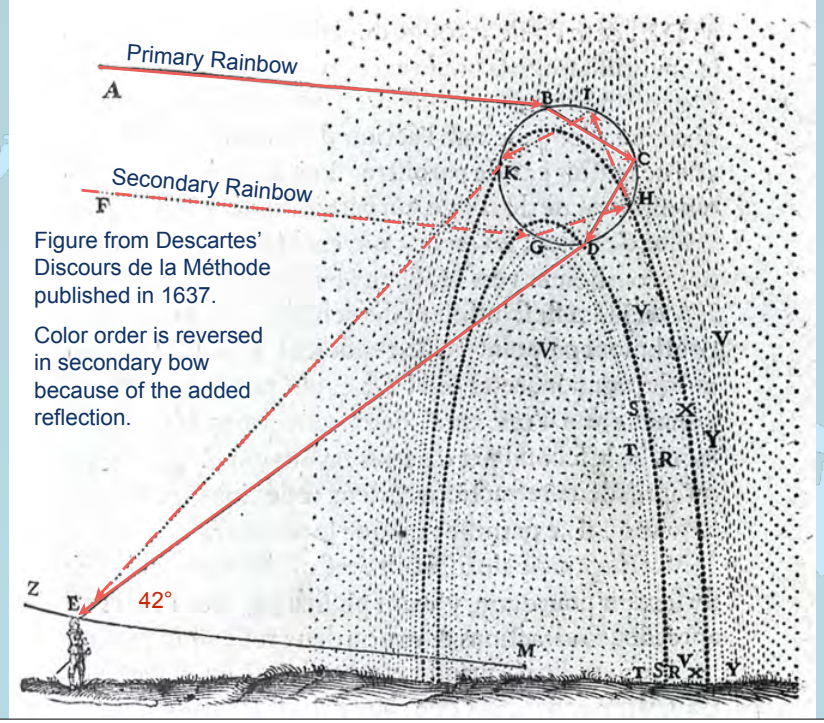


Figure from Descartes' Discours de la Méthode published in 1637.

Color order is reversed in secondary bow because of the added reflection.

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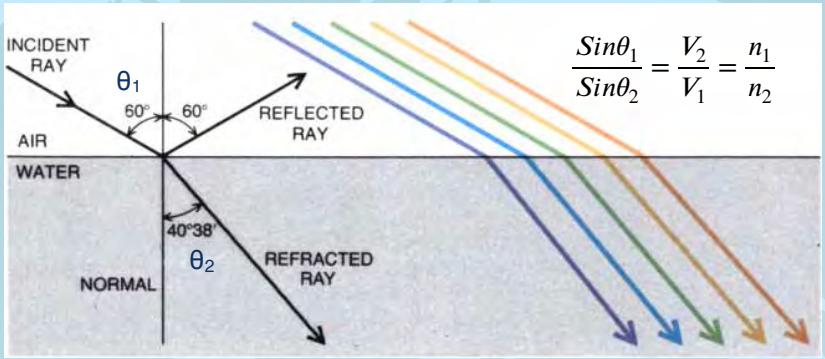
Willebrord Snell's Law, 1621



Known as Descartes' law in France – A ray of light passing from air into water is slowed at the boundary. If the ray strikes the surface obliquely, the change in speed results in a change in direction toward the slower medium. The sines of the angles of incidence and refraction are always in constant ratio to each other, and the ratio is equal to the ratio of the refractive indexes for the two materials.

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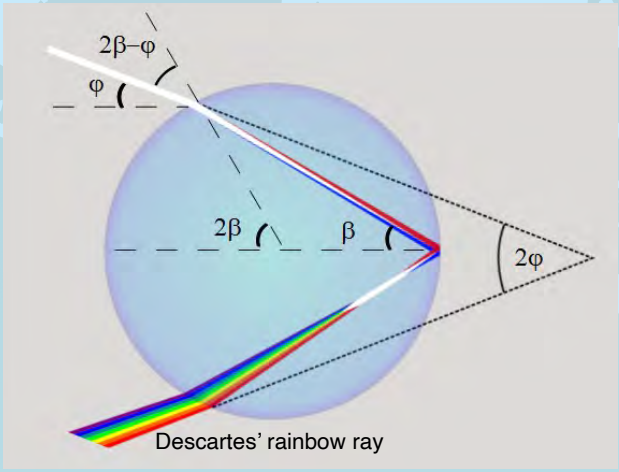
Applying Snell's Law

Given a spherical raindrop, and defining the perceived angle of the rainbow as 2φ, and the angle of the internal reflection as 2β, then the angle of incidence of the sun's rays with respect to the drop's surface normal is $2\beta - \varphi$.



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Mathematical Derivation

Since the angle of refraction is β, Snell's law gives us

Incident angle = n•refracted angle or $\sin(2\beta - \phi) = n \sin \beta$,

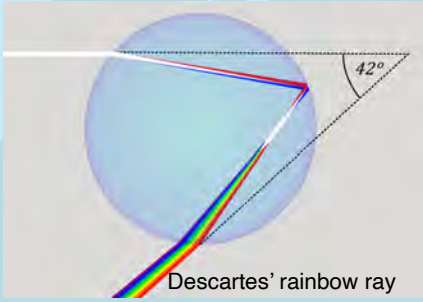
where $n = 1.333$ is the refractive index of water. Solving for ϕ, we get

$\phi = 2\beta - \arcsin(n \sin \beta)$.

The rainbow will occur where the angle ϕ is maximum with respect to the angle β. Therefore, from calculus, we can set $d\phi/d\beta = 0$, and solve for β, which yields

$$\beta_{\max} = \cos^{-1}\left(\frac{2\sqrt{-1+n^2}}{\sqrt{3}n}\right)$$

Substituting back into the earlier equation for ϕ yields $2\phi_{\max} \approx 42°$ as the radius angle of the top of the rainbow.



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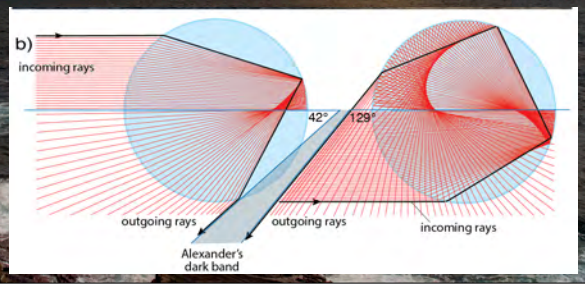
Alexander's Dark Band



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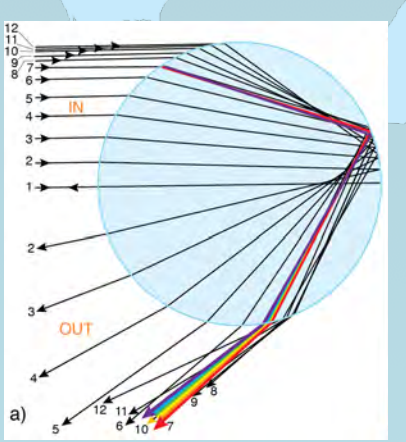
Rainbow Cones

Refraction cone cast by a single polished quartz crystal sphere, n = 1.54

Every sunlit raindrop casts a cone of light with a rainbow at the outer edge.



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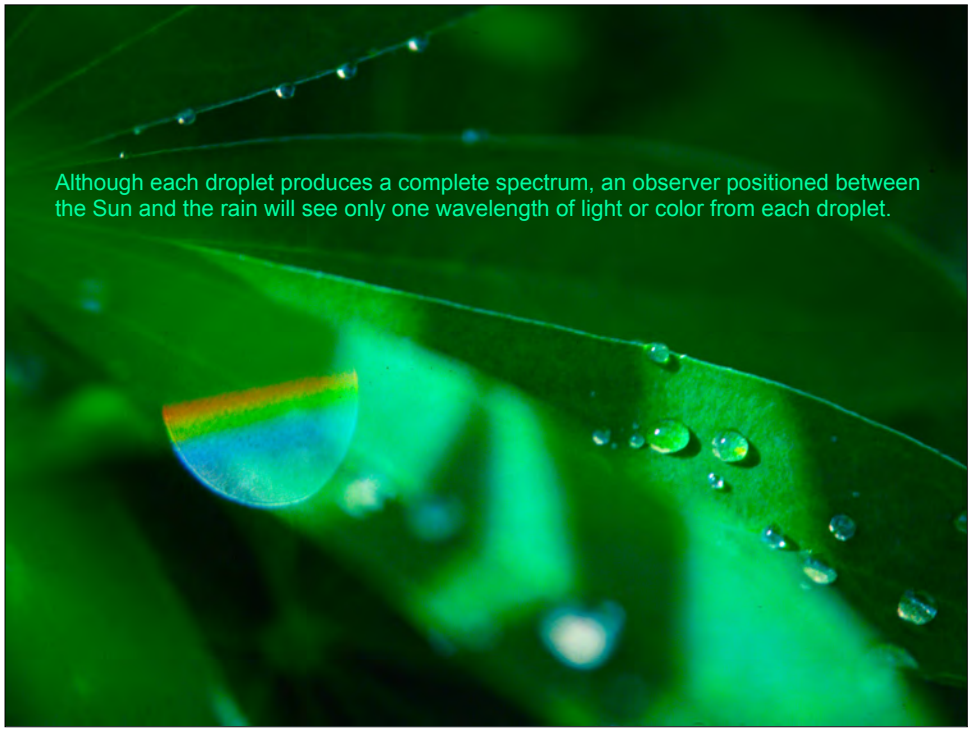

Although each droplet produces a complete spectrum, an observer positioned between the Sun and the rain will see only one wavelength of light or color from each droplet.

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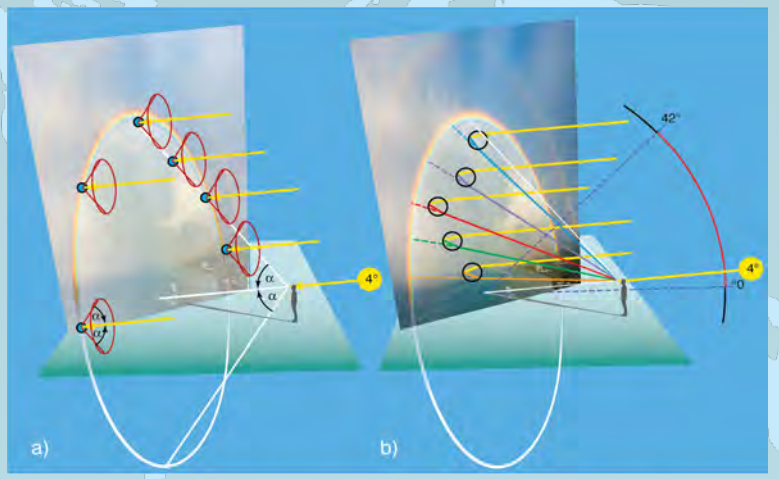
Millions of Rainbow Cones



Since each droplet produces a rainbow cone, two observers see two rainbows produced by two set of droplets located at angle = 42° from the individual shadows of their heads.

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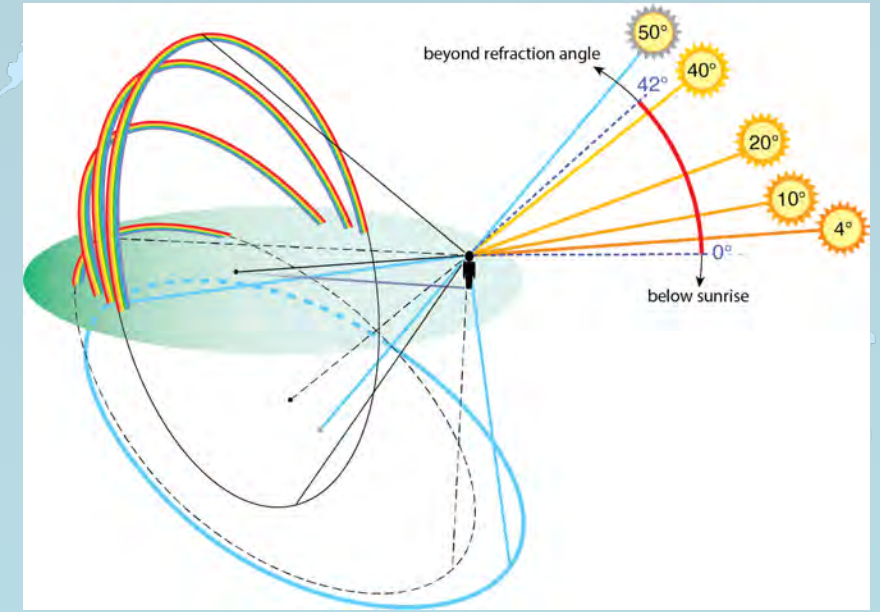
Rainbow Morning



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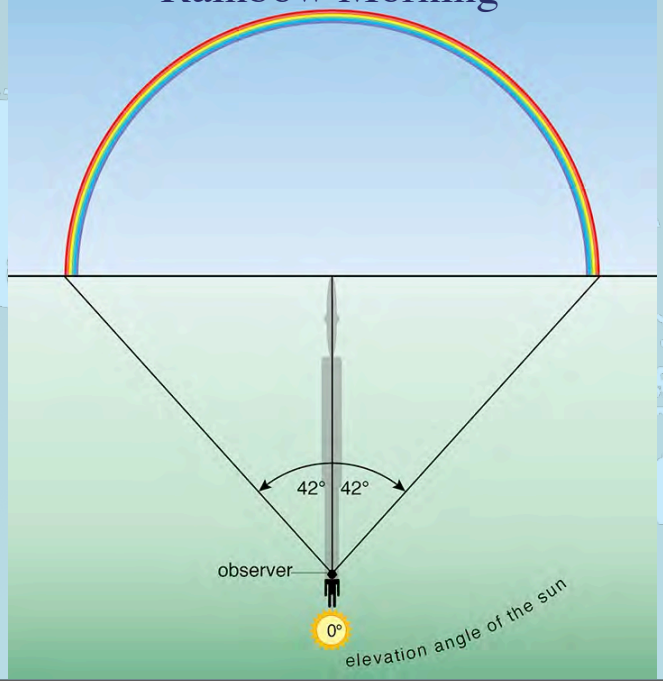
Rainbow Morning



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Low Sun High Bow

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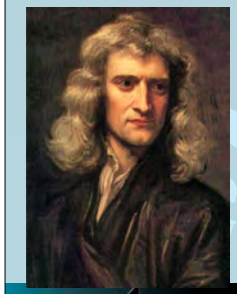
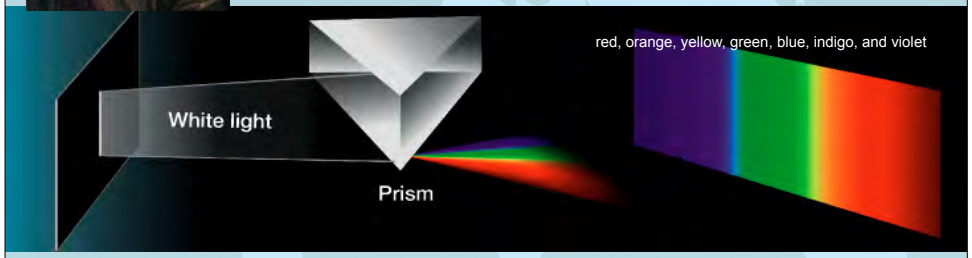


Isaac Newton 1666

Interested in light and colors. Newton showed that color is a property of light, and he coined the term *spectrum*.



The separation of white light into a spectrum of colors is called dispersion.

Newton chose to divide the visible spectrum into seven colors informed by the beliefs of the ancient Greeks, who thought there was a connection between the colors, the musical notes, the known objects in the Solar System, and the days of the week.

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Rainbows in Ocean Spray

Ocean water has a slightly larger index of refraction than fresh water, thus a salt spray rainbow has an angular diameter that is smaller than normal (freshwater) rainbow.

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Reflected Rainbow

Is the reflected bow in the water a true reflection of the rainbow we see above? Ray tracing suggests that it is created by a different set of raindrops.

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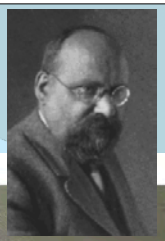
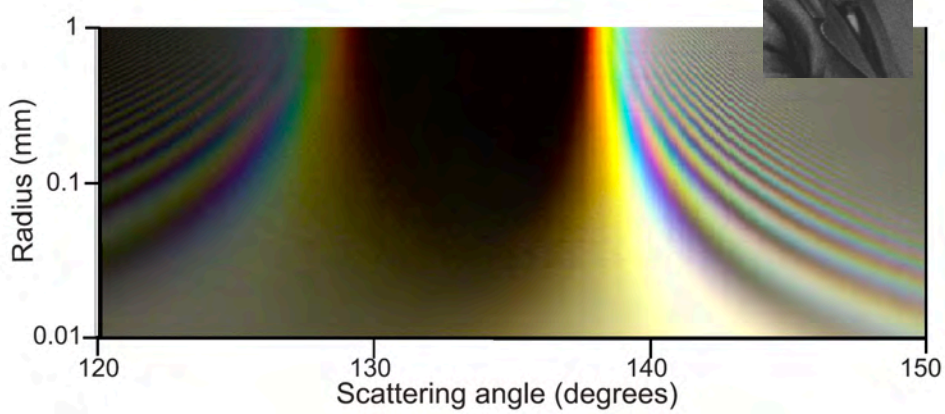
Gustav Mie – Theory (1908)





Lee diagram shows the variation in appearance of primary and secondary rainbows caused by scattering of sunlight by a spherical water drop as a function of radius (Lorenz-Mie theory calculations). Note that larger drops produce brighter bows and very small raindrops no longer produce dispersion.

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Larger Raindrops are not Spherical

Raindrop shape changes with increasing radii because of a combination of surface tension, hydrostatic forces, and aerodynamic pressure (Beard and Chuang 1987).

Large drops usually make up a small fraction of a rain shower, but when they do contribute, their oblateness leads to a change in the position of the top of the rainbow, while leaving the base unaffected. This is why the base of a rainbow often appears brighter than the top of the bow: all drop sizes contribute at the base, whereas near the top, light from the large, hamburger-bun drops is dispersed.

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Twinned Rainbow

Twinned rainbow results from a mixture of large non-spherical water drops and smaller spherical ones.

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Diffraction and Reflection

Thomas **Young** in 1803 linked color with wavelength and provided the first explanation of the spurious 'supernumerary arcs' that are occasionally visible inside the primary rainbow and very rarely outside the secondary bow. Supernumerary Bows were important in providing early observational evidence of the wave nature of light.

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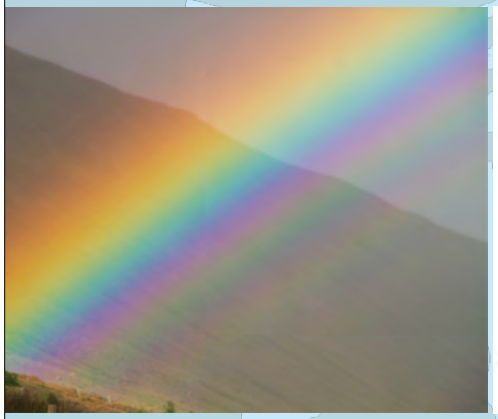
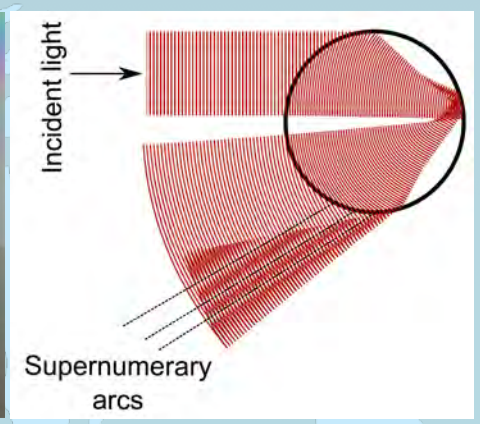
Supernumerary Bows





The faint bows in the inside of the primary rainbow are caused by interference or diffraction in reflected rays from uniform small rain droplets. On right, a moire' pattern mimics the constructive and destructive interference pattern of sunlight refracted, reflected, and dispersed within a raindrop.

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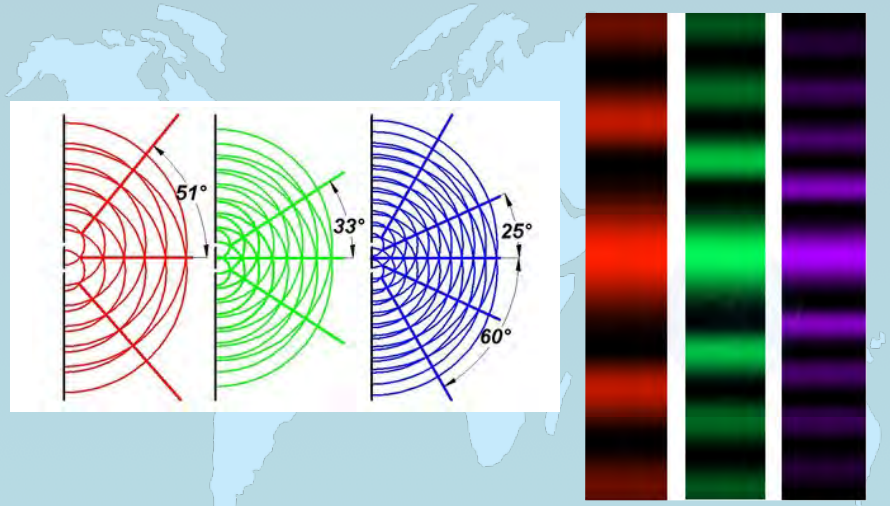
Diffraction causes Interference



The angle of constructive interference is color dependent.

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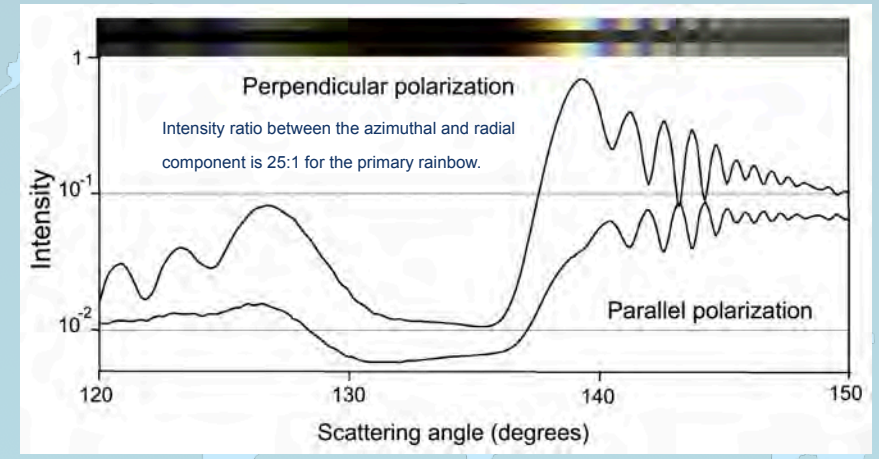
Rainbow Light is Circularly Polarized



Graph of intensity as a function of scattering angle for the primary rainbow caused by scattering of sunlight by a spherical drop of water of radius 0.1 mm. The color stripes on top represent, from top to bottom, the phase function for perpendicular polarization, parallel polarization, and unpolarized light, respectively.

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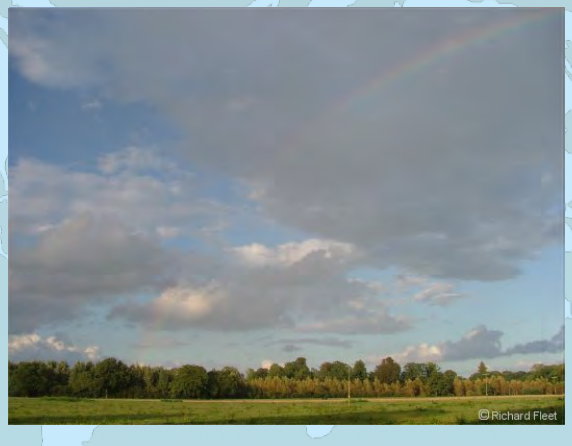
Rainbow Light is Polarized



Each picture was taken through a polarizing filter which was rotated 90 degrees between the two photographs. Since the sunlight resulting in a rainbow reflects off the back of a drop over a small range of angles, rainbows are not 100% polarized, rather ~96% polarization is typical.

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Reflection Rainbow

The reflection bow above is created by the sunlight that is reflected by still water.

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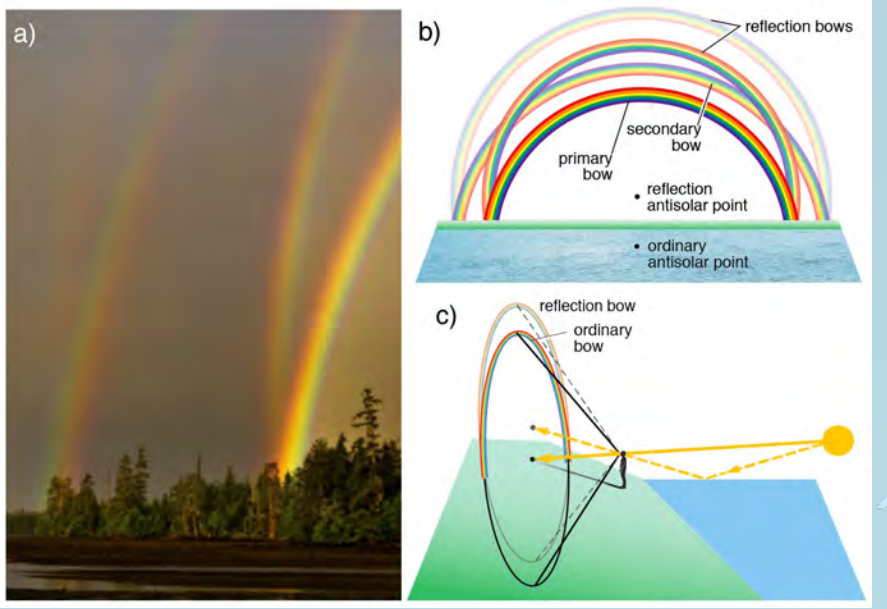
Schematic of Reflected Sun Rainbow



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Red Rainbow

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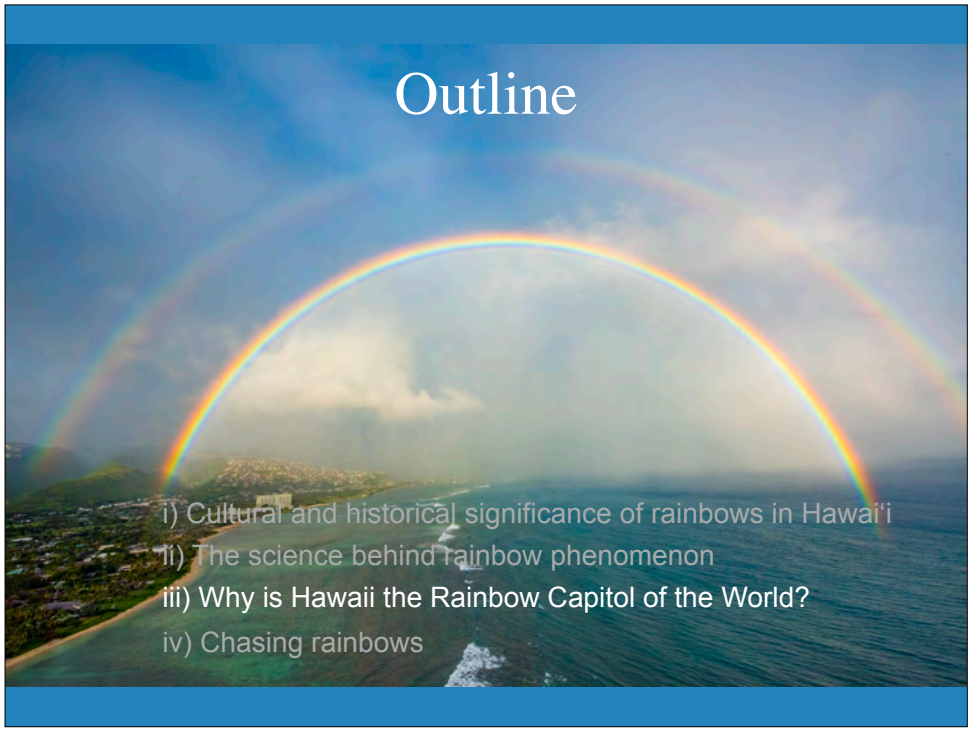
Outline



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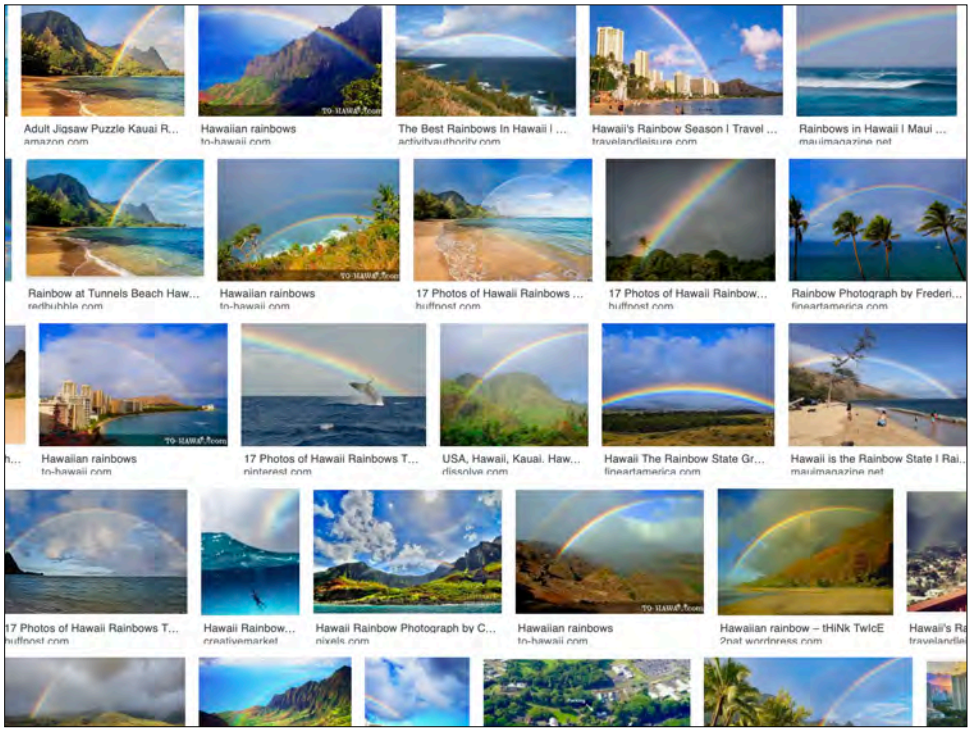

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Why is Hawaii the Rainbow Capital?

Bright sunshine - Ka lā

Rain showers - Waiʻi

Geometry

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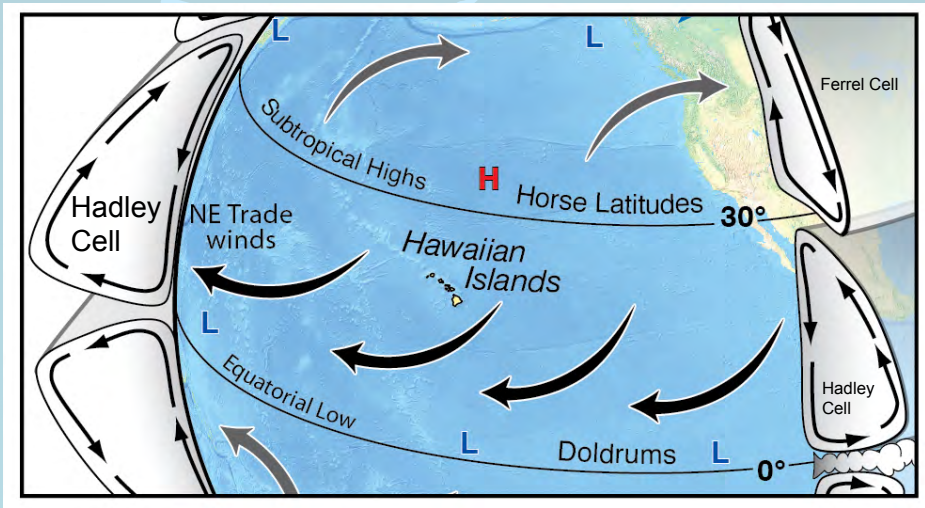
Hadley Cell



The Hadley cell results in sinking air, clear skies, and NE trade winds over Hawaii. Without our mountains Hawaii would be a desert.

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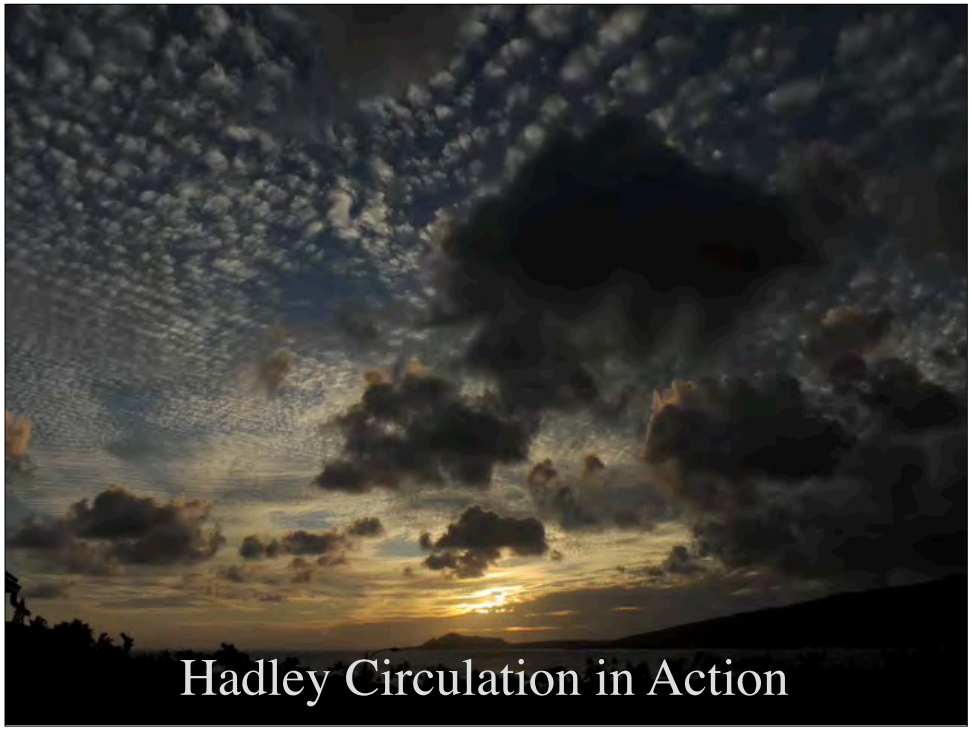

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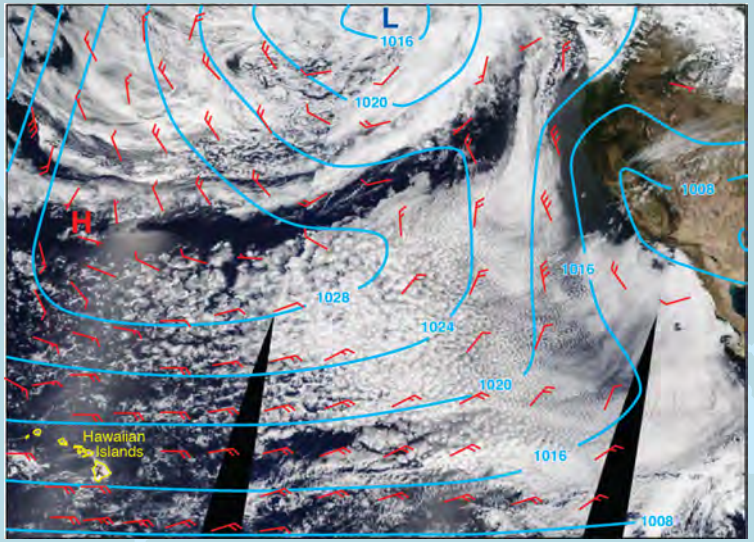
Marine Cloud Evolution



Stratus off the coast of California changes to closed cell convection and then to open cell convention near Hawaii. This transition occurs as the marine boundary layer deepens in response to sea-surface fluxes and entrainment and mixing from above.

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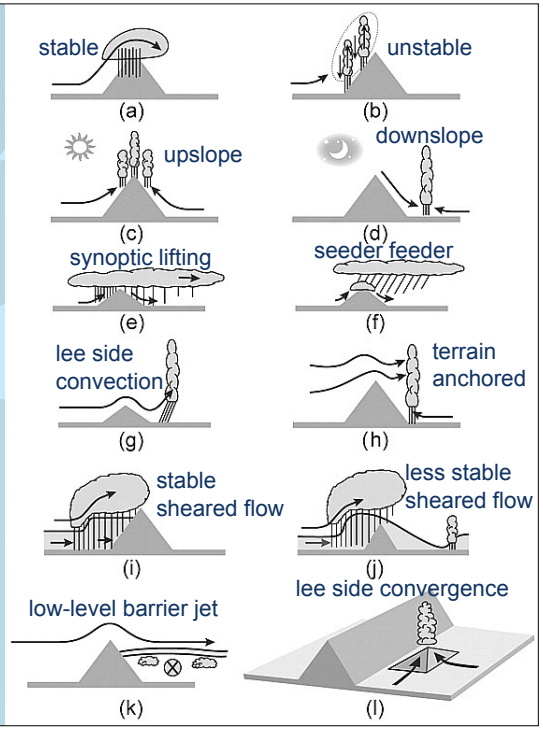
Types of Orographic Forcing

Houze 2012

a) stable flow over mountain
b) unstable flow
c) daytime upslope
d) nighttime downslope flow
e) stratiform cloud from synoptics
f) seeder feeder precipitation
g) lee side convection
h) sheared flow and terrain anchoring
i) stable sheared flow
j) less stable sheared flow
k) sheared flow with low-level barrier jet
l) lee side convergence



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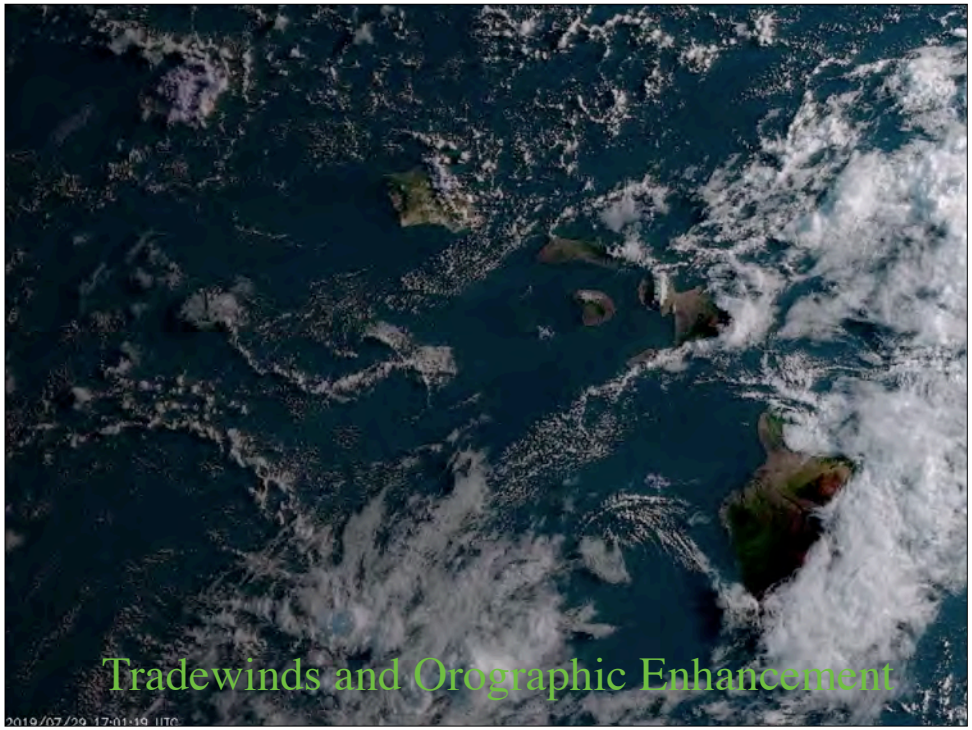

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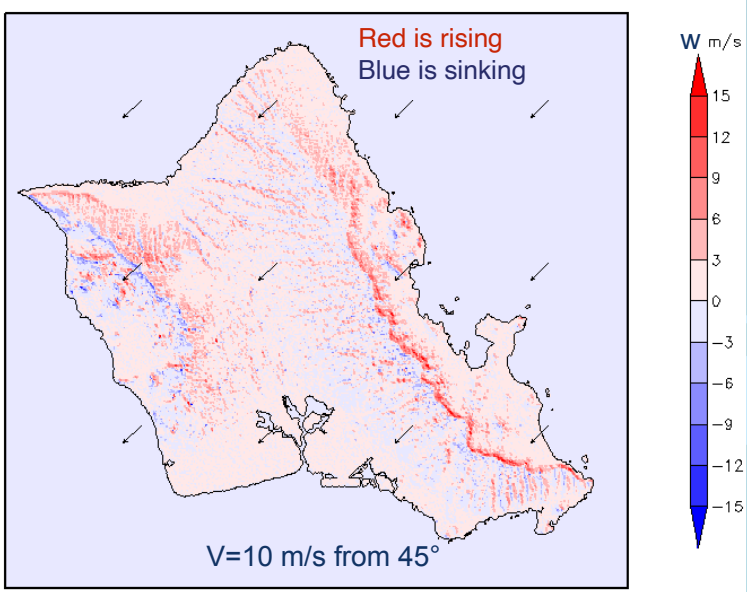
Orographic Lift from Prevailing NE Tradewinds



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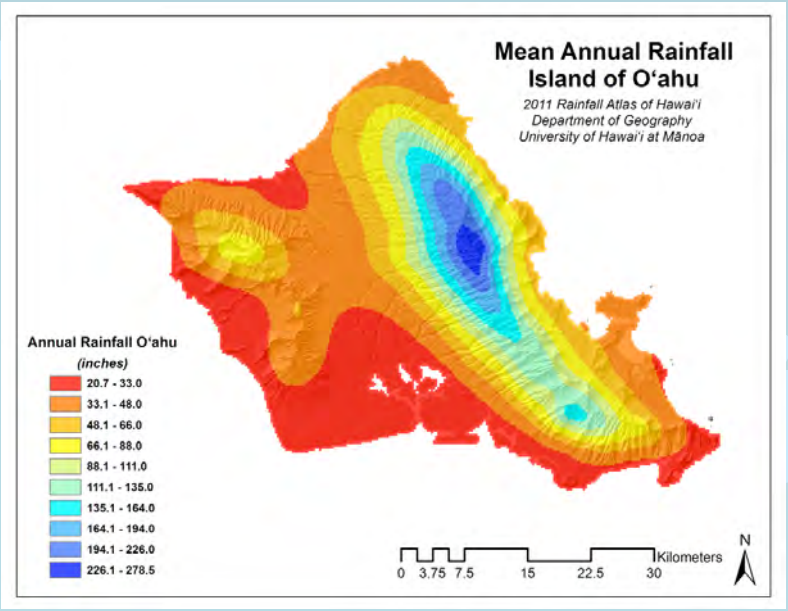
Annual Rainfall for Oahu



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Orographic Precipitation Enhancement

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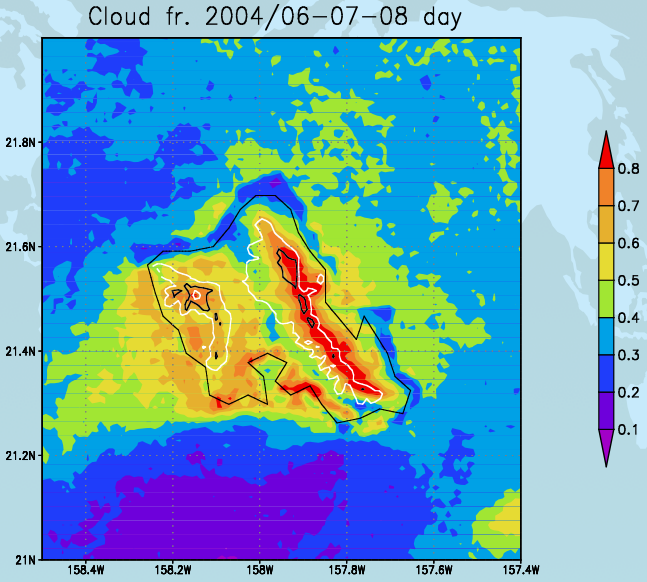
Daytime Heating

Ascending air flow caused by mountains occurs in two broad categories.

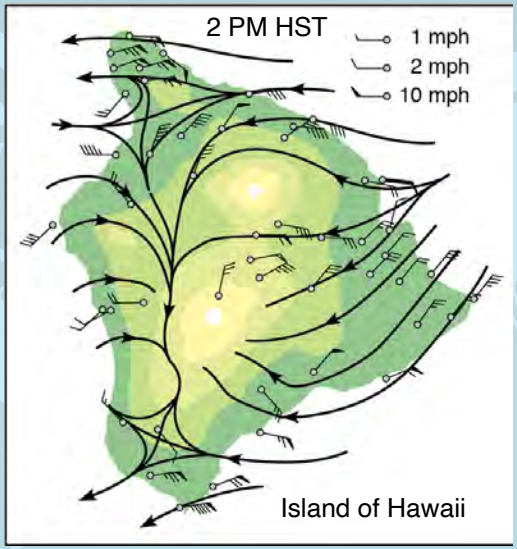
- Upward deflection of large scale flow by the orography acting as a barrier.
- Daytime heating causing anabatic flow up the mountain slopes causing updrafts near the peaks (sea-breeze and mountain valley circulations combined)..

Diurnal Sea and Land Breezes

Satellite Cloud Fraction Leaves Room For Sunlight



Flow Blocking & Sea Breeze Winds



Average afternoon (2 PM HST) winds (mph) during a six-week period during July and August, 1990. Elevation contours for Island of Hawaii plotted every 3000 ft.

Kona Sea-breeze Front

Kona sea breeze has insufficient kinetic energy to overcome the large altitude of the Big Island's volcanoes.

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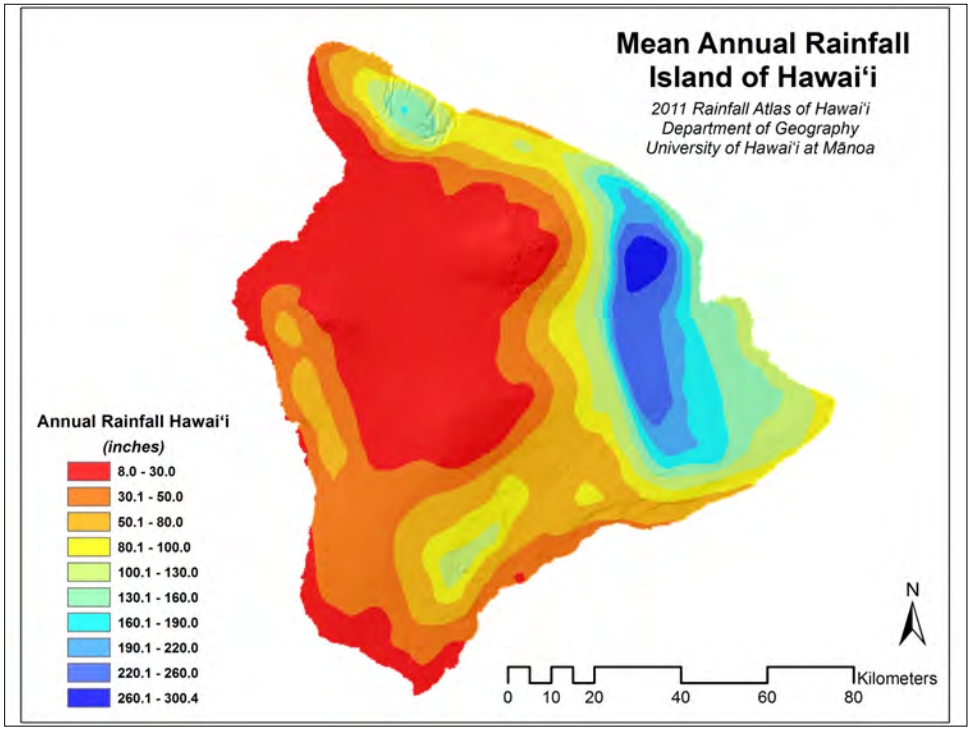

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Clean Air means Bight Sunlight

Very clean air in Hawaii mean less scattering of light leaving more light of all the colors at low sun angles for bright rainbows.

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LandSat Image of Hawaii

Note the contrasting vegetation, which is a proxy for sun and rain.

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Warm Rain

Clean air means fewer aerosols, which results in fewer but larger cloud droplets that are more likely to coalesce and result in “warm” rain from small cumulus clouds.

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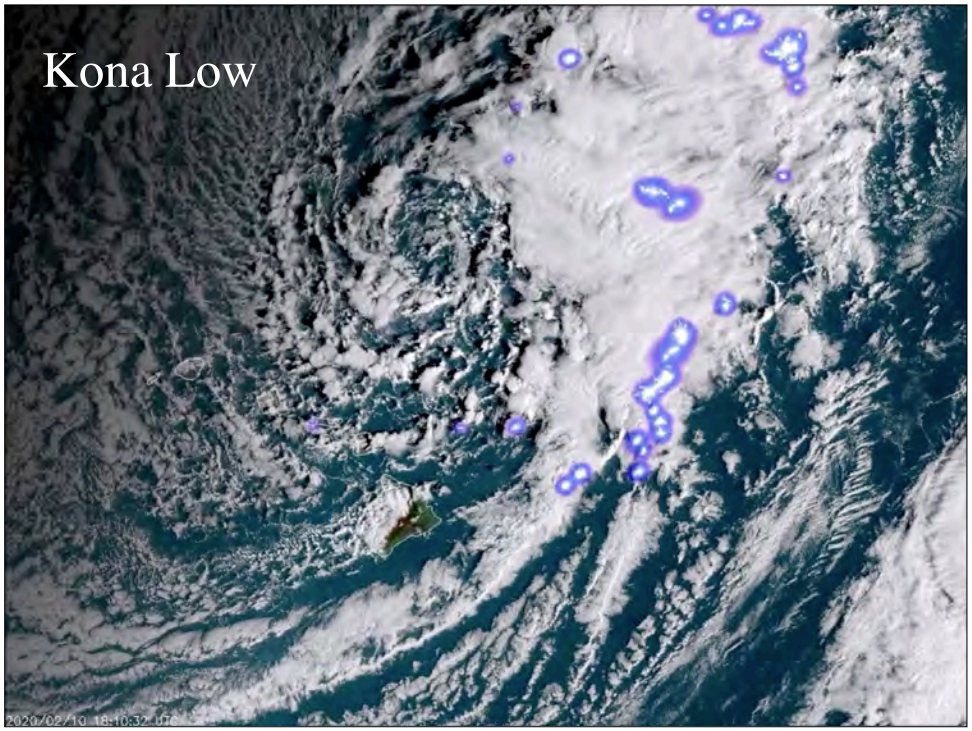

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Cold fronts dissipate as they approach Hawaii due to the warming of cold side of the front by ocean surface fluxes, resulting in more blue sky for rainbows.

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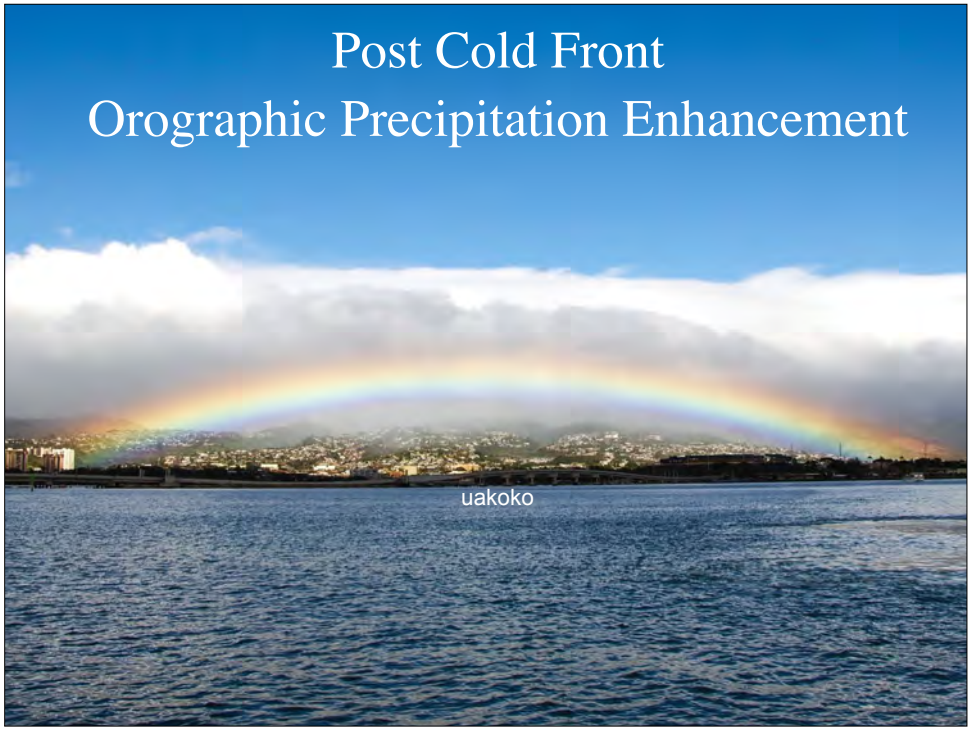

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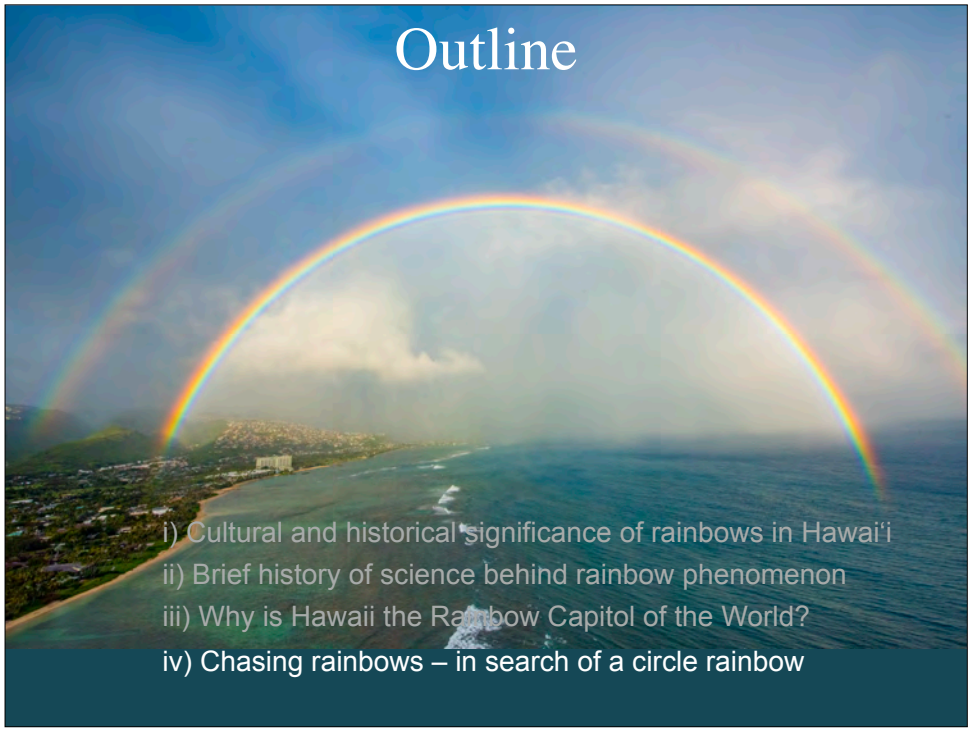

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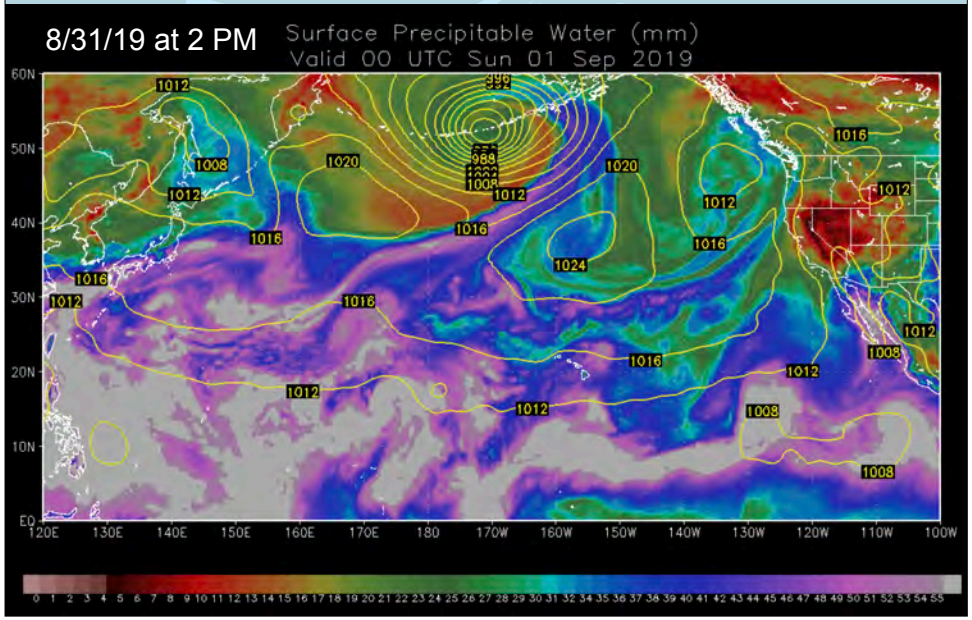
Check Weather Model Moisture Field



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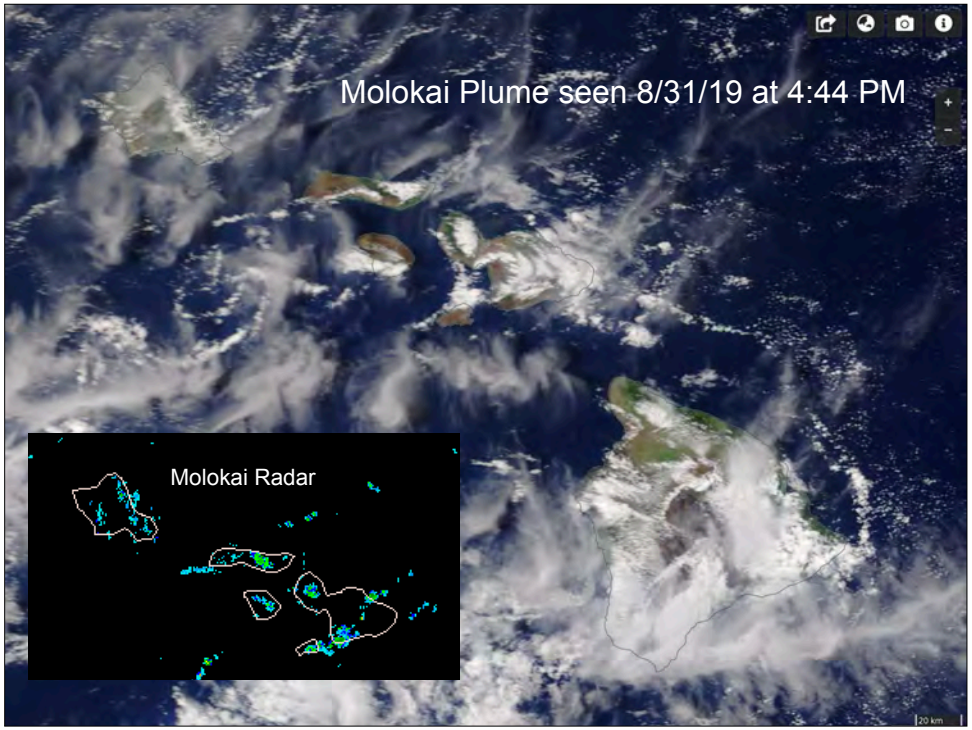
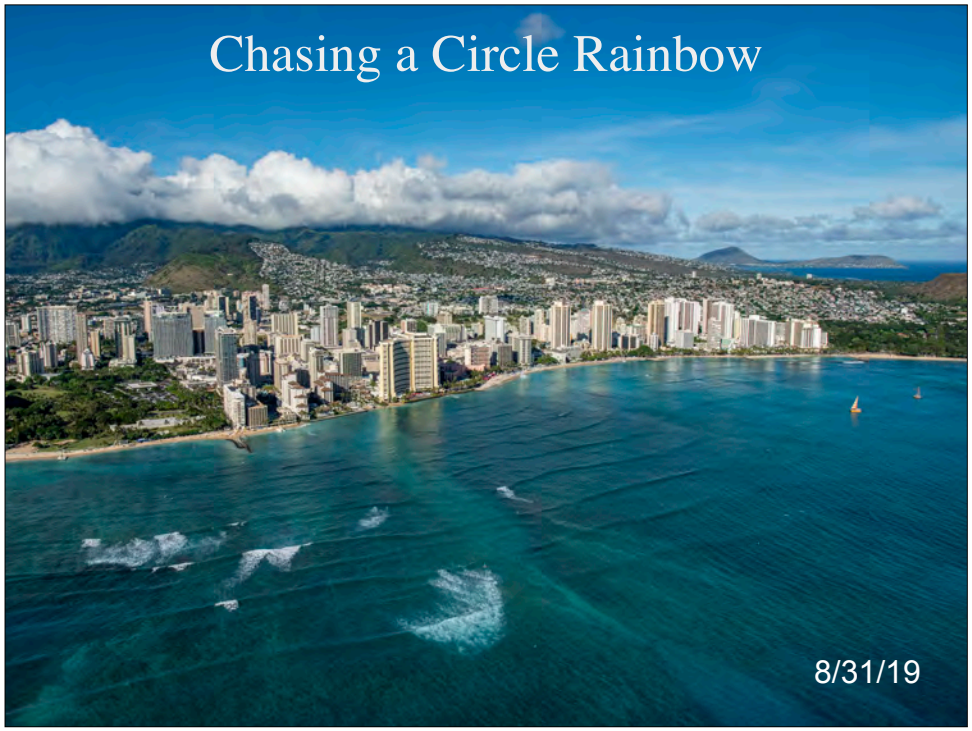
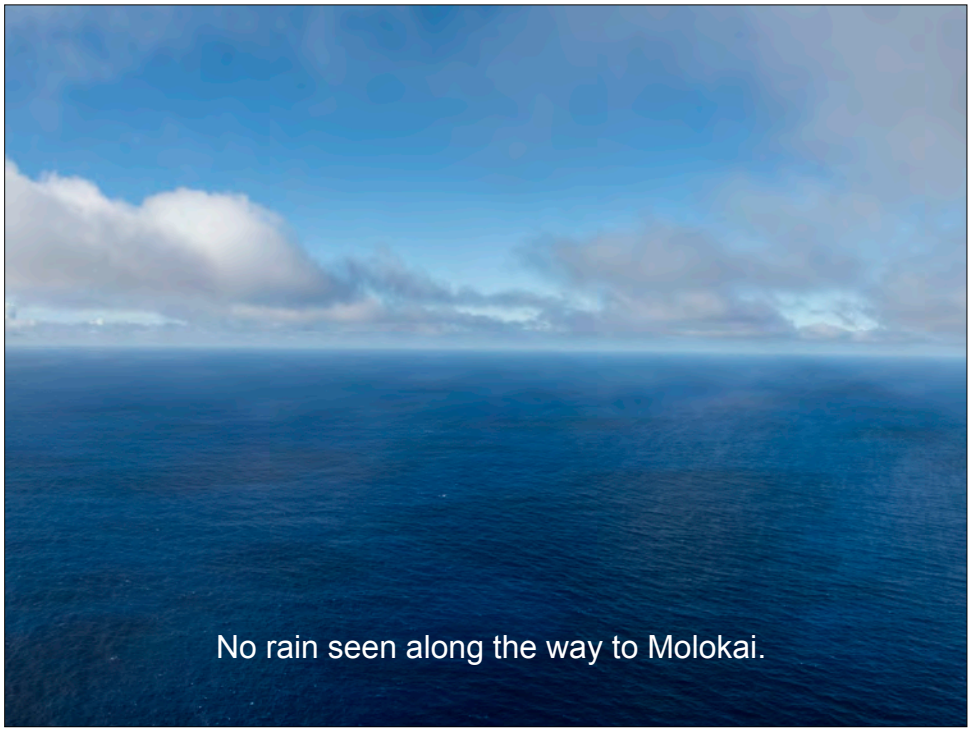


70

Chasing a Circle Rainbow



71



72

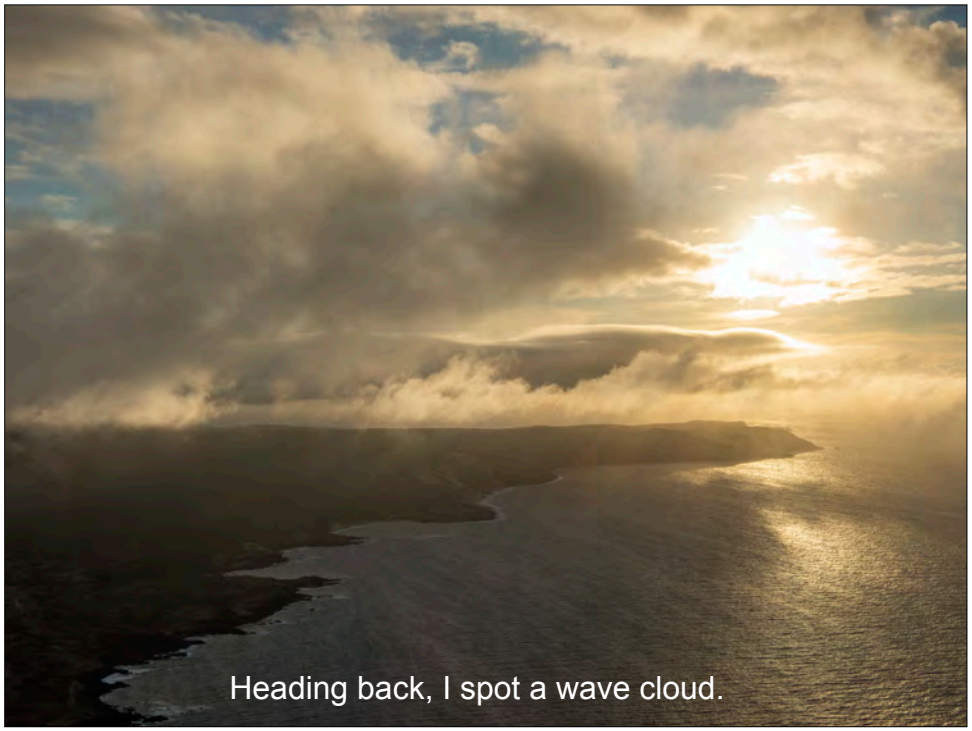

Yes, a shower in the lee of Molokai.

73

74


Too many clouds on the windward side of Molokai

75


Heading back, I spot a wave cloud.

76


A Cloud Bow and a Glory
Cloud Bow looks white because colors blend as light emerges from very small droplets.

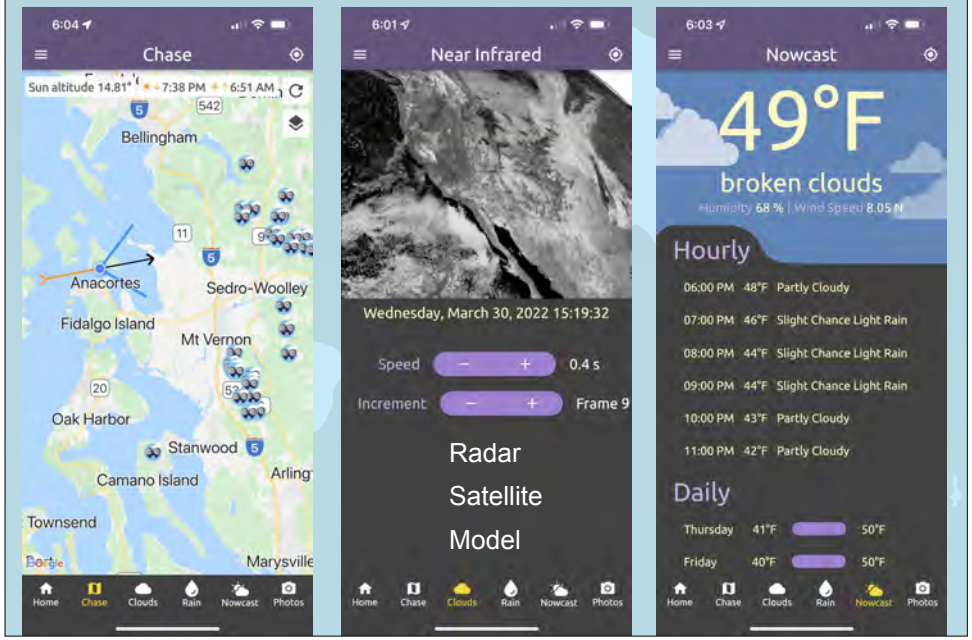
77

78

79

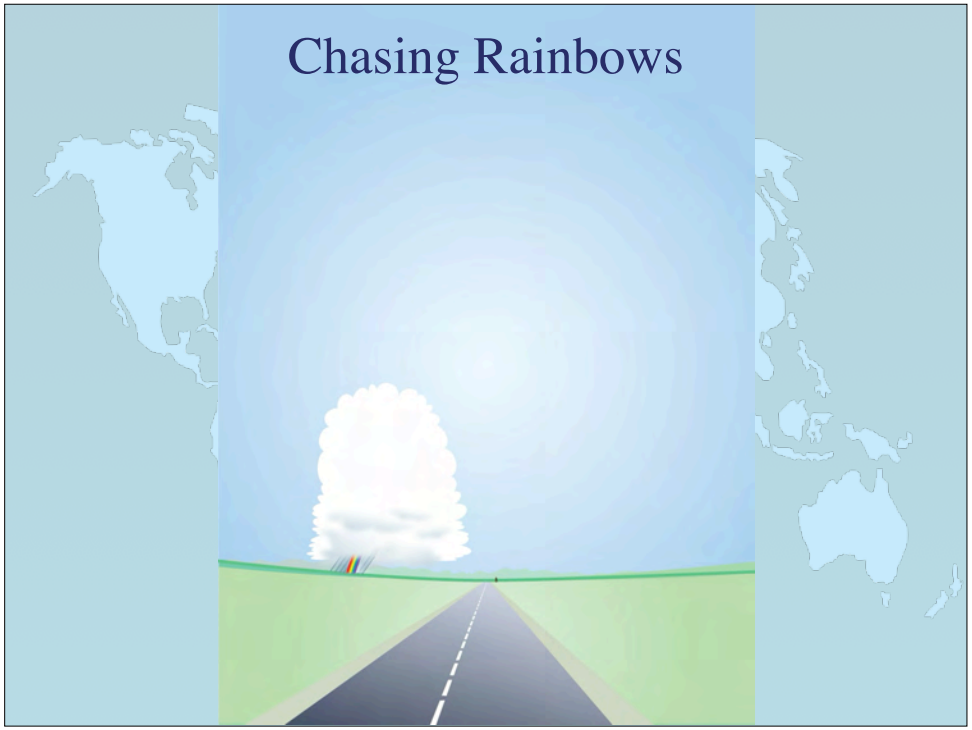
80

Rainbow Chase – Free Smartphone App



81

Chasing Rainbows



82

83

84

Questions?

See how many problems with this illustration you can identify.

1. Colors not reversed on secondary rainbow
2. 3rd bow should not exist in that location
3. Sun in wrong place.
4. Scattering should make the inside first bow bright and outside the secondary bow brighter as well, with a dark band between.
5. Secondary bow should be dimmer than the primary rainbow.

Questions?

Since the rainbow is in reality a full circle with no end, does the end of the rainbow exist?

For more on Chasing Rainbows see RainbowChase.com

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https://www.youtube.com/watch?v=OQSNhk5ICTI for a really emotional response to a rainbow!