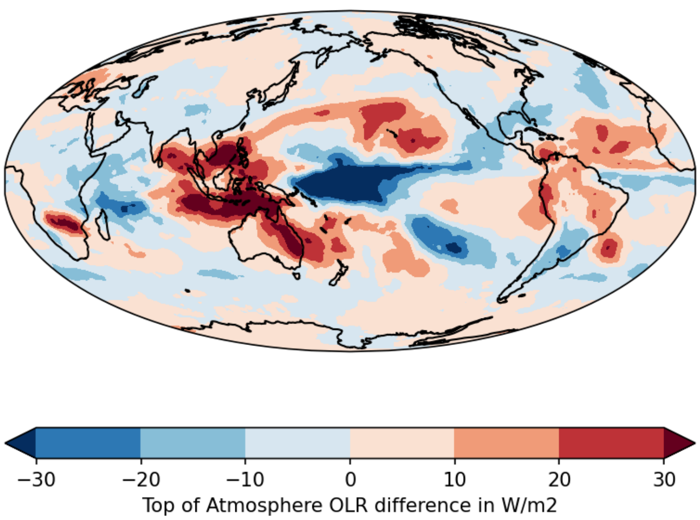
1. This is common to everyone. Identify years with El-Ninos and La Ninas in the dataset and compare and contrast the TOA, SFC and CLD datasets for the Decembers of these years. Based on your understanding and reading of ENSO, try and interpret the differences you observe. (To contrast two different years, you can use simple subtraction).

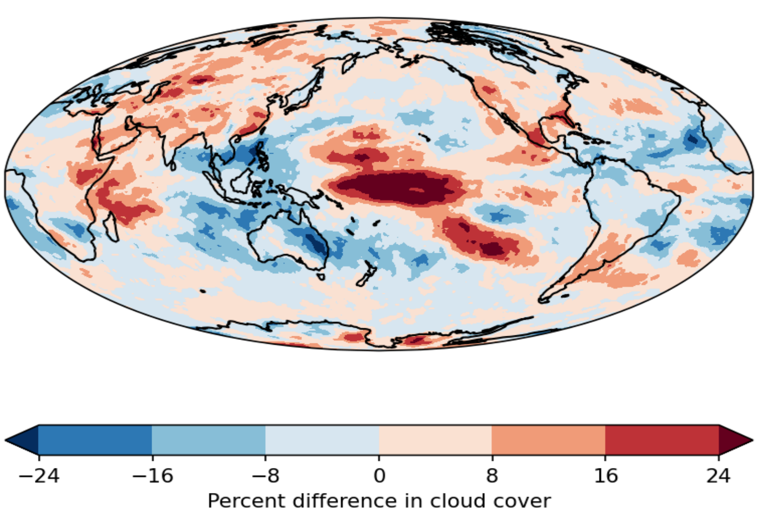
Using the SST anomaly chart:
<u>El-Nino December:</u> Decembers of 2015, 2018 and 2019

<u>La-Nina December:</u> Decembers of 2010,2011,2017 and 2020



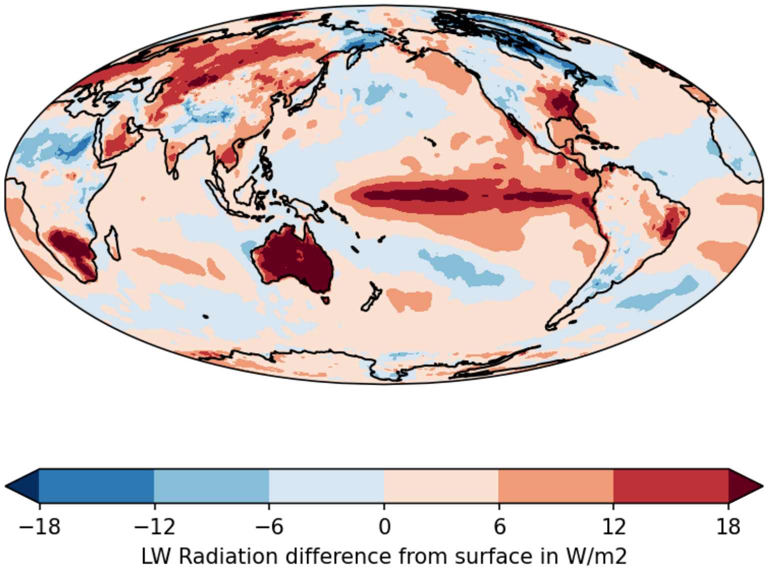
Difference of average El-Nino Decembers (Decembers of 2015, 2018 and 2019) from average La-Nina Decembers(Decembers of 2010,2011,2017 and 2020).

The plot shows that the average OLR is higher near South American Coast and significantly lesser near Papua New Guinea Islands. This shows that Elnino pushes hot water to the South-American coast, whereas La Nina pushes hot water to the Australasian coast of the Pacific Ocean.



This shows cloud cover difference percent from El Nino to La Nina.

El Nino involves more cloud cover near Papua New Guinea Islands as warm water near the South American coast evaporates and then down wells near the Australasian coast(cool water) to form clouds. In contrast, the intensity of this phenomenon becomes lesser during La Nina.



Long-wave radiation difference at surface. The difference is between the average El-Nino December and the average La-Nina December. This clearly shows that El Nino involves warmer water near South-American Coast as compared to La-Nina, and colder water is pushed to the Australasian coast of the Pacific Ocean

<u>Conclusion:</u>

01.

La Nina involves the upwelling of cold water from Pacific depths near the South American Coast and the spread of warm ocean water near the Papua New Guinea Islands.

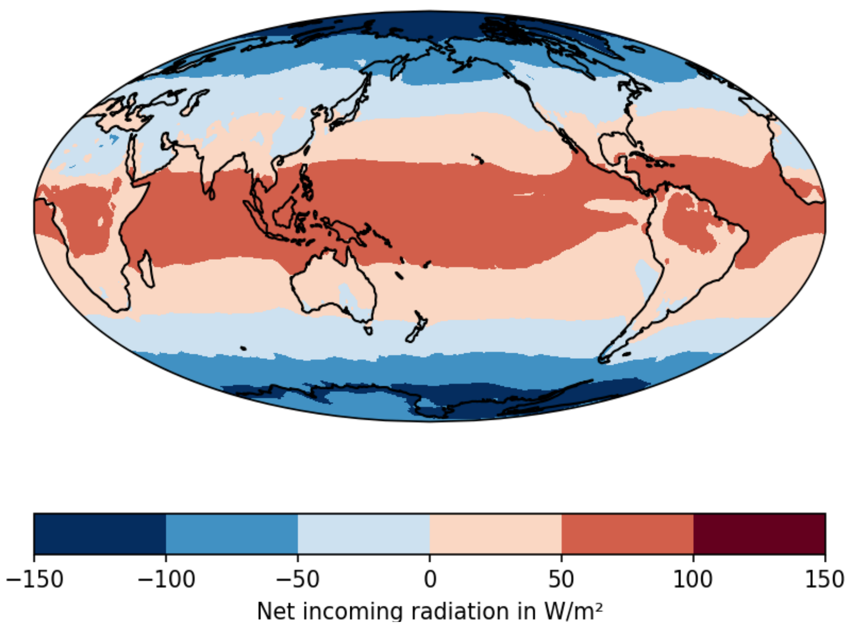
El Nino involves the transport of hot surface water of the Pacific from the coast of the Australasia to the South American Coast. This leads to hot surface sea water near the South American Coast and the accumulation of colder Pacific water near the Papua New Guinea islands.

2. Compute net radiation and its mean over the entire duration of the dataset.

We take the TOA data base and calculate the net radiation as follows:

$$Net\ incoming\ radiation = Incoming\ short\ wave\ radiation - (Outgoing\ long\ wave\ radiation + Outgoing\ Shortwave\ Radiation)$$

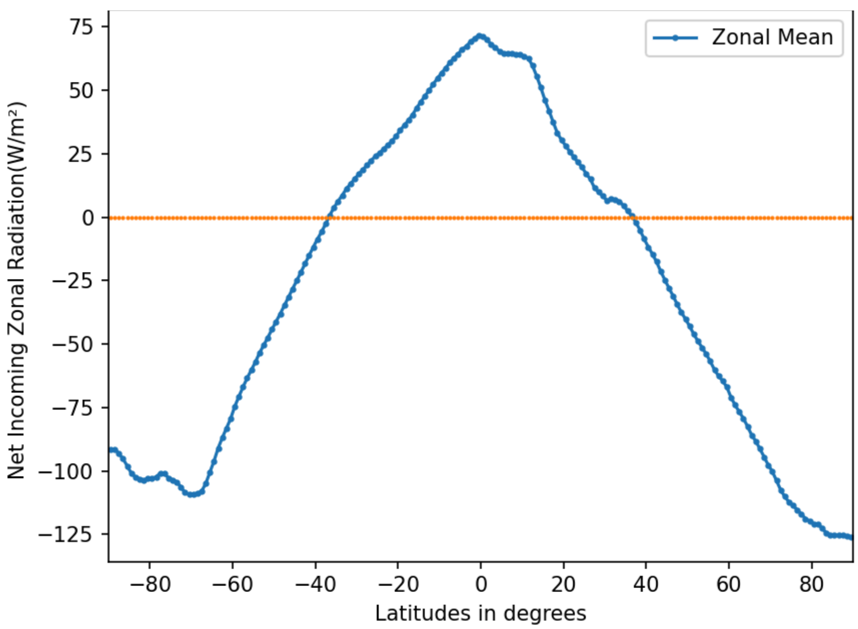
We then average this net incoming radiation over the whole time and make a contour plot that shows the time-averaged net incoming radiation for the whole globe.



This shows that the equatorial regions and sub-tropical regions are net receivers of energy, whereas the polar and sub-polar regions are net emitters of energy to space so that the net incoming radiation over the whole Earth is approximately zero.

3. Compute zonal mean (i.e., mean along longitudes) of net radiation averaged over time.

This chart of zonal mean shows us that areas from 0°-40° latitude are net receivers, whereas 40°-90° latitudes are net emitters of heat energy.



The asymmetric distribution of net radiation on either side of the equator is due to the asymmetric distribution of landmasses on either side of the equator. Northern hemisphere has most of the landmasses. Whereas the south pole is surrounded by land(Antarctica), while the north pole is surrounded by Ocean(sea-ice). This leads to asymmetric distribution of energy too.

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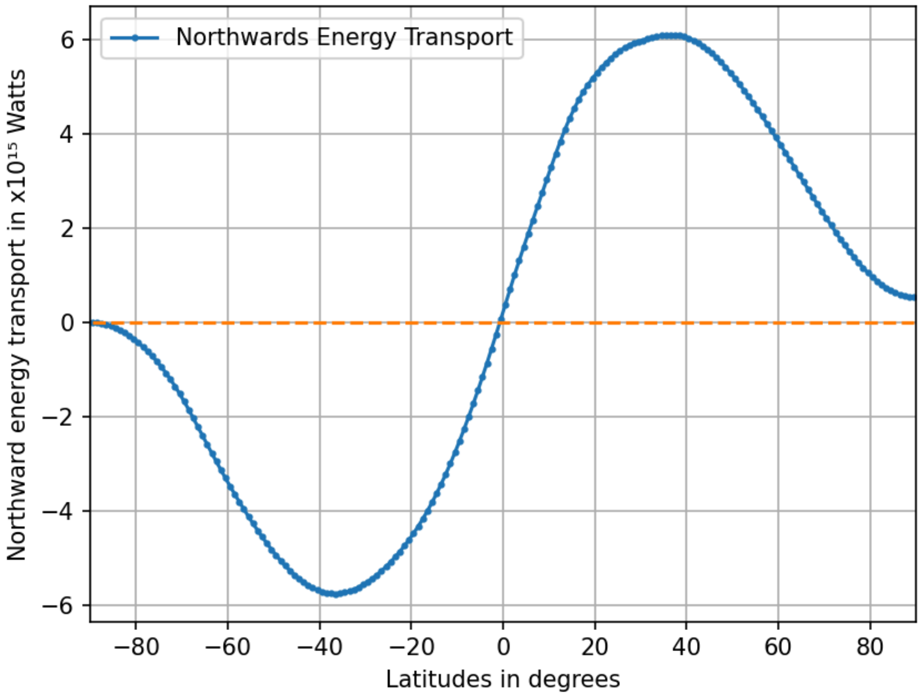
4. Compute the integral discussed in class for all latitude values available in the data.



Soln.: This graph shows the Northward energy transport at each latitude. Negative values on the y-axis indicate Southward energy transport.

From our graph it is seen that the energy transport is Southward in the Southern hemisphere and Northwards in the Northern hemisphere.

This is in-line with the intuition of poleward heat transport from the equator to the poles. The energy transport is seen to peak at around 40° latitude. This is the latitude at which the Earth turns from net receiver to net emitter of energy. The energy transport depends on the gradient of power received with respect to latitude, and this gradient is maximised at around 40° latitudes. At the poles and the equator, the gradient of power received with respect to latitude is the least, and therefore the energy transport to surrounding latitudes is lesser.

I have used the cumtrapz() function which computes the integral of heat transport using the limit of sum method and therefore the integral is not exact. This can be seen from the non-zero value of northward energy transport at the North Pole.

5.How much energy(percentage) is reflected(albedo) by the South-Asia during July. And compare this with the albedo in January.

For this question, I will be analysing the region:

Longitude	Latitude:
60.5°E to 97.5°E	0.5°S to 35.5°N

All the analysis will be done with a special focus on the Indian Sub-continent, particularly India. As the question states, we will analyse the months of July and January by taking the mean of all quantities used for the months of July and January respectively.

$$Albedo \ = Outgoing\ short\ wave\ TOA\ /\ Incoming\ short\ wave\ TOA$$

The average albedo of July and January is calculated by taking the mean of Outgoing short wave TOA and Incoming shortwave TOA for the respective months and then using the albedo formula.

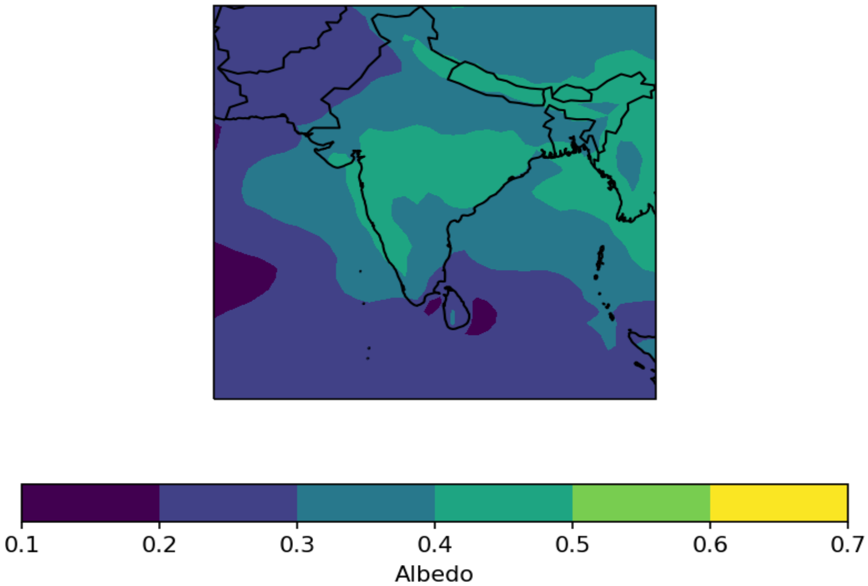
Code:

```
only_july= olr_data['time.month']==7
only_jan = olr_data['time.month']==1

out_swdatajuly=out_sw_data.groupby(only_july==True).mean(dim='time')[1]
in_swdatajuly=in_sw_data.groupby(only_july==True).mean(dim='time')[1]

out_swdatajan=out_sw_data.groupby(only_jan==True).mean(dim='time')[1]
in_swdatajan=in_sw_data.groupby(only_jan==True).mean(dim='time')[1]

albedo_jan_avg= out_swdatajan/in_swdatajan

albedo_july_avg= out_swdatajuly/in_swdatajuly

albedo_july_south_asia=albedo_july_avg.loc[dict(lon=slice(60.5, 97.5), lat=slice(-0.5, 35.5))]

albedo_jan_south_asia=albedo_jan_avg.loc[dict(lon=slice(60.5, 97.5), lat=slice(-0.5, 35.5))]
```

Hypothesis:

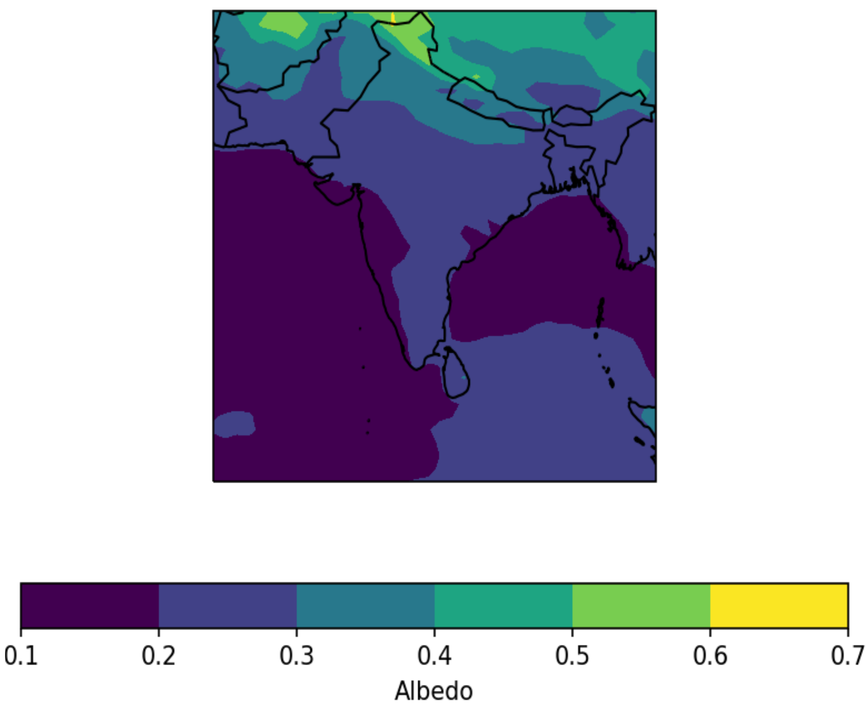
As the Indian subcontinent has heavy cloud cover during July due to the monsoon, I would expect the albedo over land to be higher for July than for January with minor anomalies in various places, these anomalies could be due to the geography of the region.

Data:



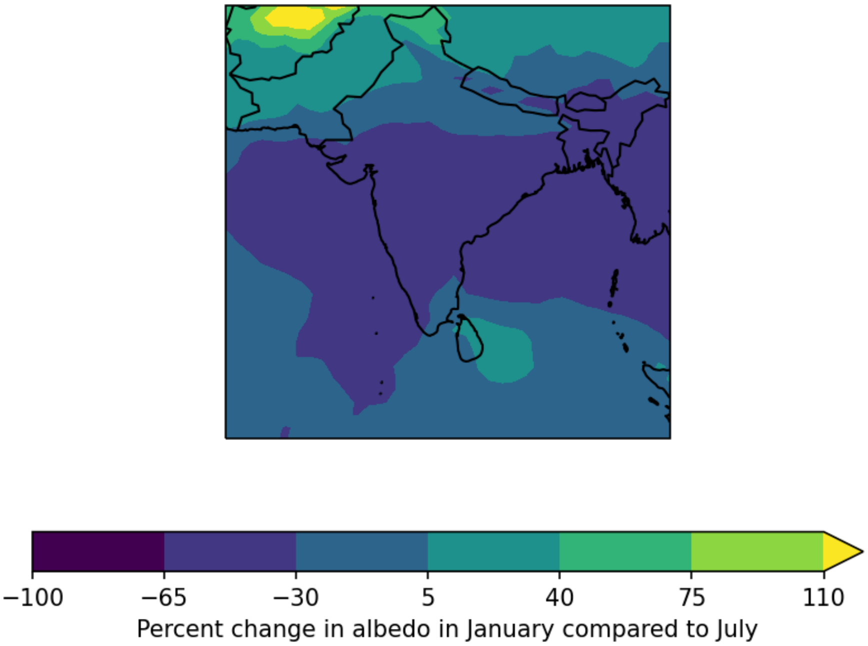
Albedo of the region for July

From this map it is seen that high albedo prevails in central India where moisture-laden monsoon clouds cover the land. Albedo keeps on decreasing as the clouds lose moisture and move northwards. Albedo again peaks at the foothills of the Himalayas, probably due to the trapping of these clouds, which are then forced to shed the remaining moisture.



Albedo of the region for January

This shows that low albedo conditions prevail over the oceans and mainland as the winds reverse their direction and the monsoon clouds have long lost their moisture. However, the western disturbances coming in from the north-west aid in slightly increasing the albedo in these regions'. The snow-covered mountain peaks of Afghanistan, Pakistan and Northern India in winter lead to an increase in albedo in these regions.



<u>The parameter in the above map is calculated as follows</u>:

$$percent\_change\_in\_january\_compared\_to\_july = 100 \times \frac{(albedo\_jan\_south\_asia - albedo\_july\_south\_asia)}{albedo\_july\_south\_asia}$$

The percent change in January compared to July shows that albedo almost uniformly decreases all over the Indian sub-continent other than parts of Southernmost India and the Northern plains.

Albedo decrease is not as drastic in the Northern plains of India due to the formation of foggy conditions. The foggy conditions prevail as cold moisture-laden air is trapped in the Northern Plains by the Himalayas in North and the Plateaus of Central India in the South. Furthermore, western disturbances also lead to cloudy conditions.

At the same time, parts of Tamil Nadu and Sri Lanka experience cloudy conditions due to the North-East Monsoon in January.

This, in fact even leads to an increase in albedo in certain parts of Sri Lanka and adjoining ocean regions and helps reduce the change in albedo in these regions

Furthermore, the mountainous regions of Northern India and Afghanistan show an increase in albedo. This is likely due to the accumulation of snow on the mountain tops increasing the albedo.

6. Try finding the average albedo of clouds over a certain location at a given time and then generalise the method for the entire globe.

I have chosen oceanic to find the albedo of clouds over an oceanic region as the albedo of oceanic regions remain more or less constant as they are free from influence of physical and biotic processes that alter albedo on land on similar latitudes. These clouds, would eventually move on to cause rain on land so can be considered to be albedo of 'fully-laden' monsoon clouds. Loss of water on land from clouds in form of rain can also effect the albedo.

I have used SFC short wave data to find the albedo of the surface, and then used the TOA data to find the albedo at the top of atmosphere for given Location and time. And then use the cloud cover area dataset to find the albedo of clouds

$$Net\_albedo = Outgoing\ Shortwave_{TOA} / Incoming\ Shortwave_{TOA}$$

$$albedo\_surface = Outgoing\ Shortwave_{SFC} / Incoming\ Shortwave_{SFC}$$

This method is pretty accurate and easily generalisable to most of the dataset, but depends on the accuracy of SFC data. Furthermore, this cannot be used for times and places where/when incoming short wave is 0 and/or refracted shortwave makes for a large part of TOA readings.(Example: Polar regions)

This should give a rough approximation of the albedo of clouds in the year of interest. However, I am not sure how the error percentages would work out as monsoon cloud formation is dependent on many factors like the ENSO cycle, the past climate states and so on....

We shall solve and try finding the albedo for at least one case.

72.5 E, 18.5 N(off coast of Mahrashtra(south of Mumbai) 2013 July. The location and time are arbitrarily chosen.

<u>Note</u>: All the quantities used in the various formulae are time-averaged for July

<u>Data obtained from the dataset</u>:

<u>Cloud cover percent</u> at: 72.5E, 18.5N on 2013 July is 98.576622%

<u>Net Albedo </u>at: 72.5E, 18.5N on 2013 July is 0.4769744

<u>Albedo of Ocean</u> (using SFC SW data)at : 72.5E, 18.5N on 2013 July is 0.07608606

Average cloud cover over all the years in July and same location = 95.58018%

Net albedo (using TOA SW data) at the same location and month = 0.42029706

We have albedo of the surface and the net albedo.

$$Net\_albedo \ =$$

$$\{(cloud\_cover\_percent \div 100) \times albedo\_cloud\} + [\{(1 - (cloud\_cover\_percent \div 100)\} \times albedo\_surface]$$

$$\Rightarrow albedo\_cloud =$$

$$[\,Net\_albedo - (\frac{\{1-(cloud\_cover\_percent/100)\} * albedo\_surface)}{(cloud\_cover\_percent/100)})]$$

From our data we plug in values to get approximate albedo of clouds as:

albedo_cloud for given location and time = {0.4769744 - (1- 0.98576622)* 0.07608606}/ 0.98576622

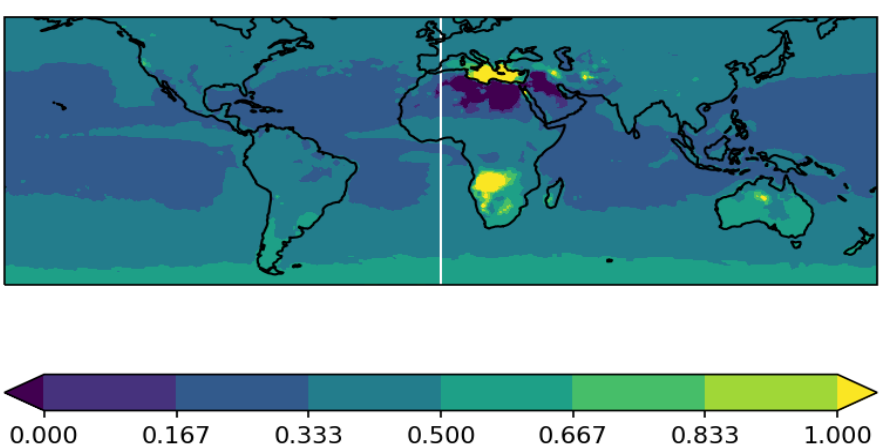
= 0.48276295

Therefore the albedo of the cloud at the given location and time is: 0.48276295

<u>Note</u>:

- *This albedo is for monsoon clouds covering the region.*
- *The net albedo formula used assumes that there are 2 sources that contribute to the albedo, the surface and the clouds. This is largely a reasonable argument except for places with exceptional geographies (Example: Deserts)*

We shall now use the net albedo and try to find the albedo of clouds for most of the Earth. This will not give accurate values for Polar regions as well as desert regions.



Map of the calculated albedo of clouds in July (all quantities used in the formula are time-averaged for July)

The above cloud albedo map is not accurate for polar regions and it's error range increases as we move polewards(due to increasing component of refracted shortwave radiation measured at TOA for higher latitudes)

It is also not very accurate for very low values of cloud cover and for places where there is net outgoing radiation from earth, as it leads to very high senstivity to errors in our original data and other sources of error in original data.

It is not accurate for deserts and surrounding regions also because it can lead to the inclusion of albedo of suspended dust particles from dust storms rather than albedo of clouds. This could lead to inflated/deflated values depending on the place and time.

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7. See the net effect of clouds on the surface energy balance by comparing energy exchanged at the surface with energy exchanged at top of the atmosphere.

I will answer this question in general for the whole of Earth, but I will focus particularly on the Indian monsoon clouds in July. The latitude and longitude range for this is also the same as given above in the previous question.

Longitude	Latitude:
60.5°E to 97.5°E	0.5°S to 35.5°N

All the parameters used in this solution will be time-averaged for July.

The parameters used in the below maps are calculated by using the SFC database and TOA database and averaging for the month of July.

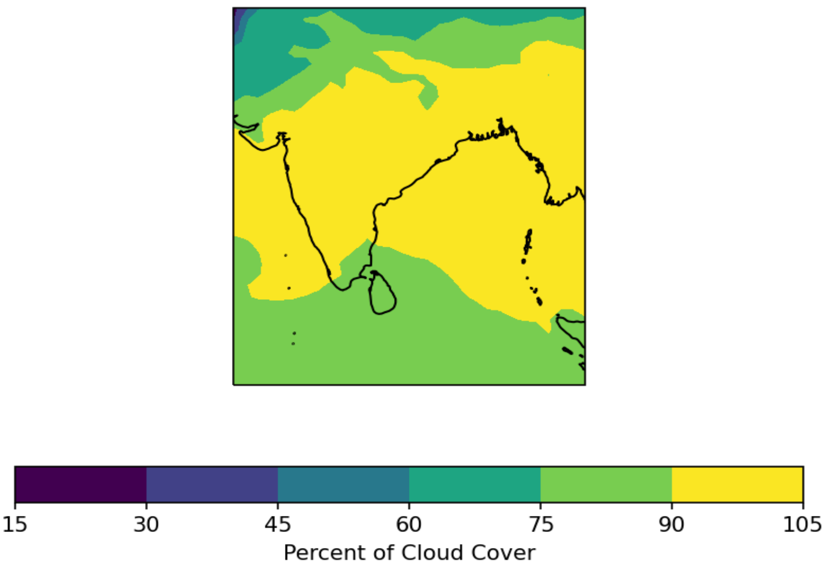
- Excess incoming energy on land =
  Net incoming energy on land - Net incoming energy on TOA

- Net incoming energy on land = Incoming shortwave radiation$_{SFC}$ - (Outgoing longwave$_{SFC}$ + Incoming shortwave$_{SFC}$)

- Net incoming energy at TOA = Incoming shortwave radiation$_{TOA}$ - (Outgoing shortwave$_{TOA}$ + Outgoing longwave$_{TOA}$)

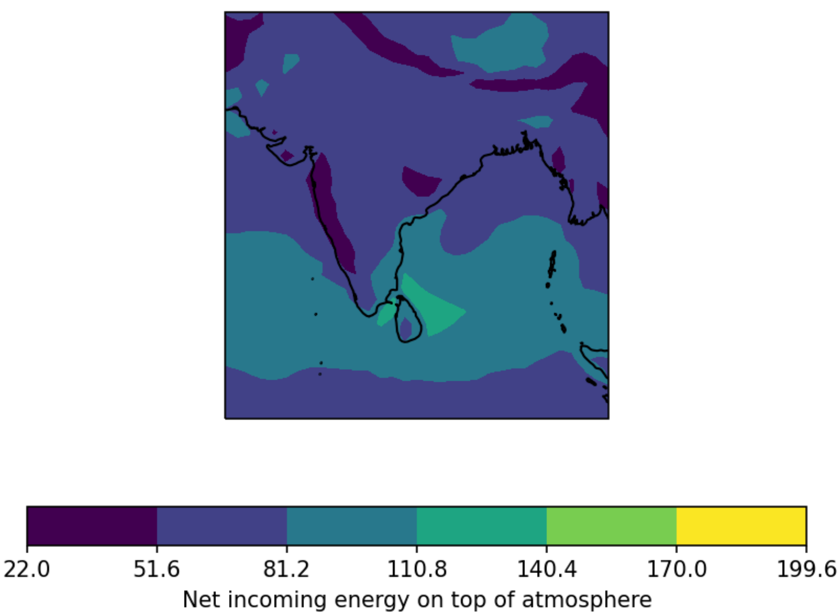
Here the word ‘land’ used in the parameters refers to surface.

We shall now talk about the Indian Monsoon clouds initially and then move on to the global scale.



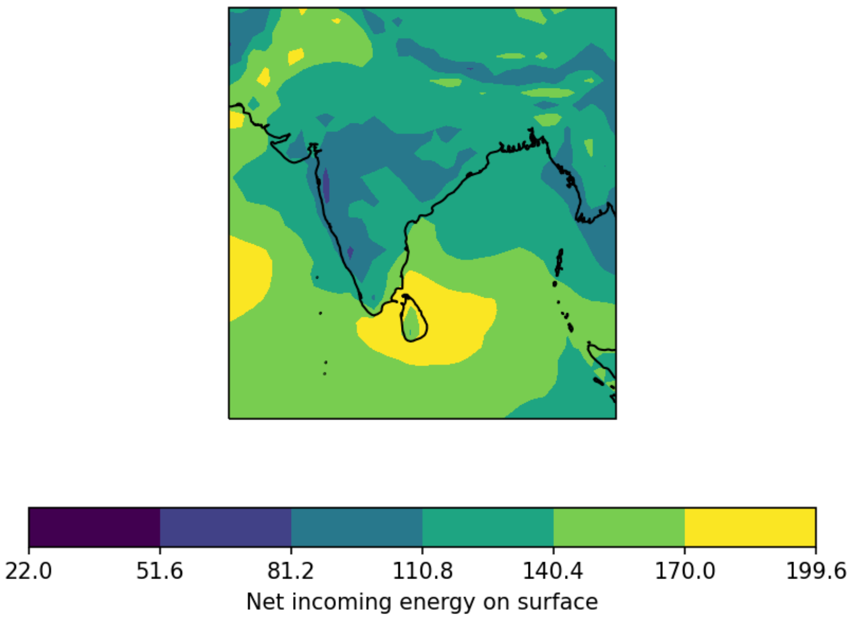
This is map of percent cloud cover time-averaged for the month of July.

This shows the high cloud-cover over the Indian subcontinent during the monsoons



This map is of the net incoming energy at the top of the atmosphere.

Here, it is seen that the net incoming energy at TOA drops significantly at all the place where the monsoon clouds can get trapped by highlands, like the foothills of the various mountain and hill ranges of India, such as the Western Ghats, Himalayas and so on. This could be because the clouds are forced upwards into the atmosphere and also forced close together, increasing their albedo and Also reducing their emission temperature.



This map shows that the reduced incoming energy on TOA at foothills is also transferred vertically downwards but gets diffused in the process. All the regions which had a lower incoming energy at TOA also seem to have a reduced incoming energy t the surface level. In contrast, the not-so-densely clouded regions around Sri Lanka have a comparatively high surface incoming energy.

This would suggest that monsoon clouds have a major role in preventing the heating up of the atmosphere as they reflect off most of the incoming radiation. Furthermore, this property of monsoon clouds would allow for the ground to receive lesser thermal energy, even after accounting for the cloud's energy-trapping ability.

All this reduction in energy received is despite the fact that the monsoon clouds carry energy from the oceans in the form of latent heat and release it into the atmosphere over the land when it rains.

Extra Part:

We shall now discuss the monsoon clouds from a global perspective to see what differentiates Indian Monsoon clouds from the rest.

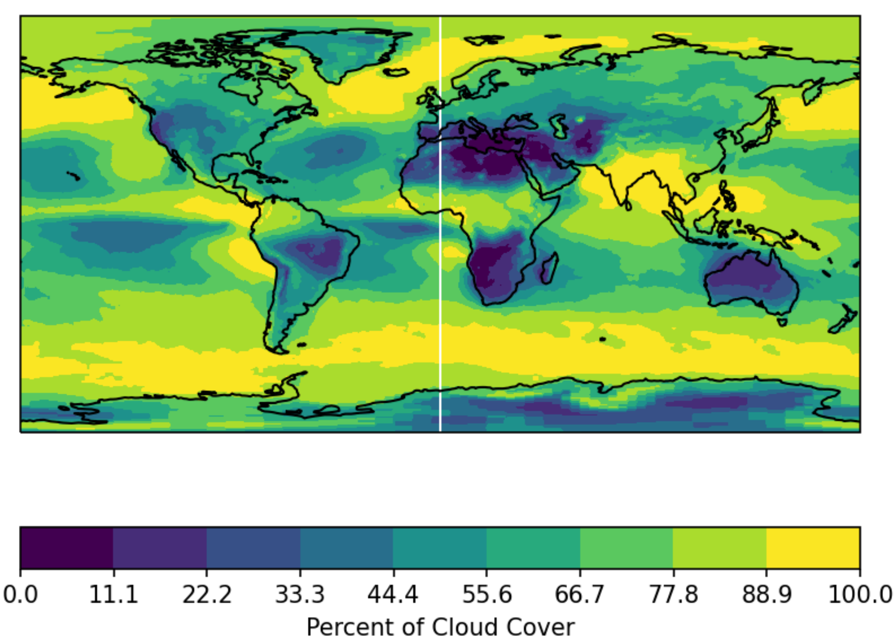
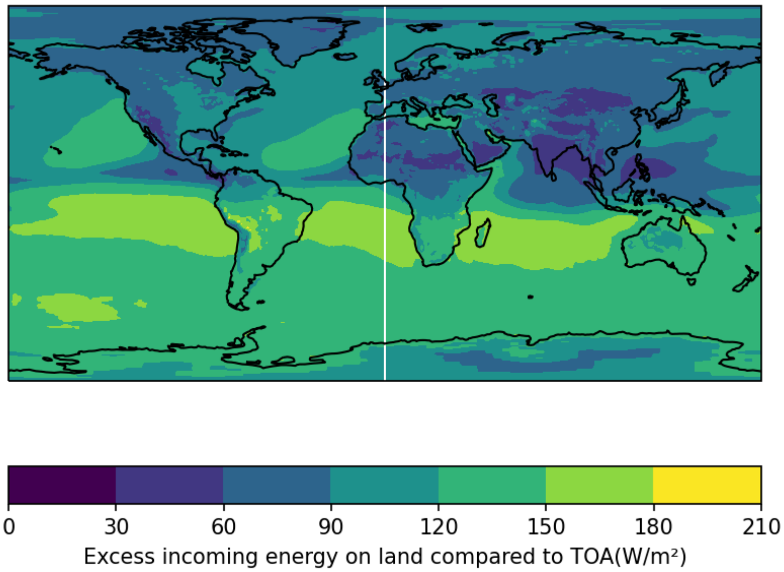


Chart of global cloud cover time-averaged for the month of July.

This shows heavy cloud cover over India and simultaneously the heavy cloud cover associated with the ITCZ in July over Northern South America and the adjoining Atlantic Ocean and Africa.

We shall focus on these regions as we see the map of for a parameter called “Excess incoming energy on land”



Excess incoming energy on land is the excess energy at the surface level as compared to TOA

This shows a very less value for all places lying on ITCZ with high cloud cover.

Having seen the energy transport graph, this parameter seems to have some connection with thermal energy transport in the atmosphere.

This parameter is probably related to radiative energy transfer through conduction, convection and radiation. In contrast, the areas of moisture-covered clouds have energy transport largely in the form of latent heat transfer.

The excess land energy and clouds seem to occur simultaneously at the equator. However, we cannot determine if they happen due to the same underlying reason or if one causes the other. This will require a more detailed data analysis to determine the relationship.

However, a rough look at the overall global regions shows that there seems to be some sort of correlation between the cloud cover and the excess energy parameter.

The monsoon clouds seem to lead to a sort of levelling effect by reducing the excess “thermal” energy received on the ground when compared to TOA. This could mean that the clouds lead to increase in “energy” carried by the atmosphere at a given temperature by carrying a larger part of it as latent heat.

As seen from the global excess energy graph. The location of ITCZ can be approximated by the cloud coverage percent graph. It is the area of relatively high cloud cover north of the equator.

When this graph is superimposed on the excess energy graph, an area of high cloud cover(ITCZ) appears to coincide with areas of low difference in surface incoming energies with respect to TOA.

This could be due to the nature of clouds formed around the ITCZ.