Snow Cover Dynamics and Snowmelt Runoff Products & Services - Indian Himalayan River Basins under NHP

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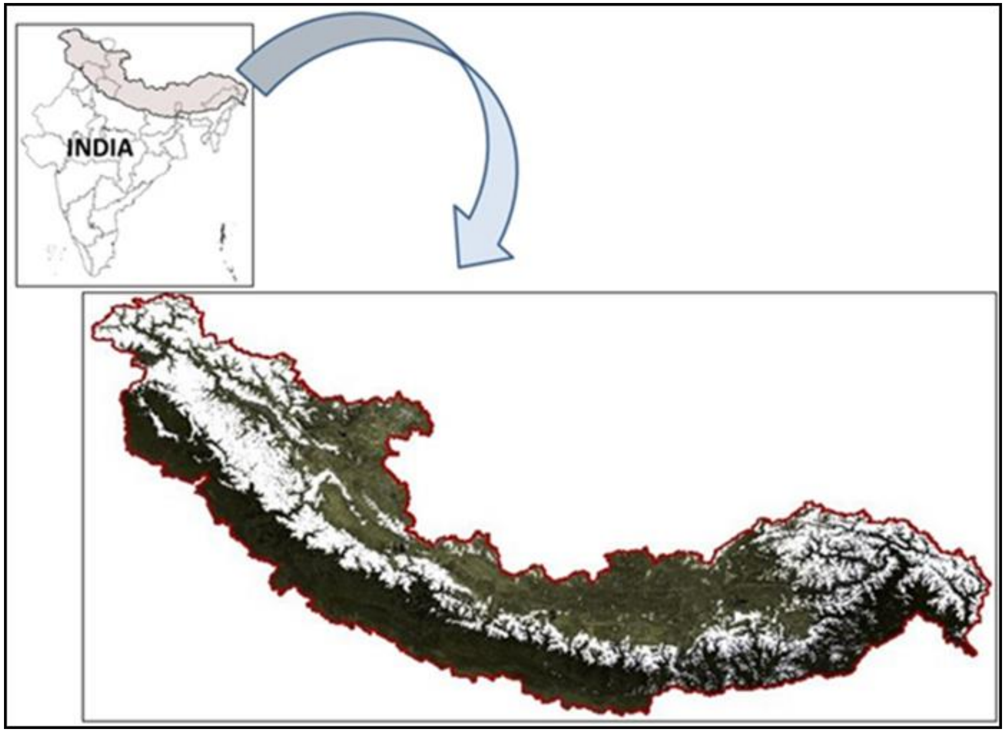
Snow Cover Dynamics and Snowmelt Runoff Products & Services

Study Objectives

- To develop a short-term snowmelt runoff forecasting model using satellite derived products and field data
- To generate a spatial daily gridded snowmelt product
- To generate a spatial 3-day snowmelt forecast gridded product
- To provide short term snowmelt runoff forecast at selected basin outlets during snowmelt season

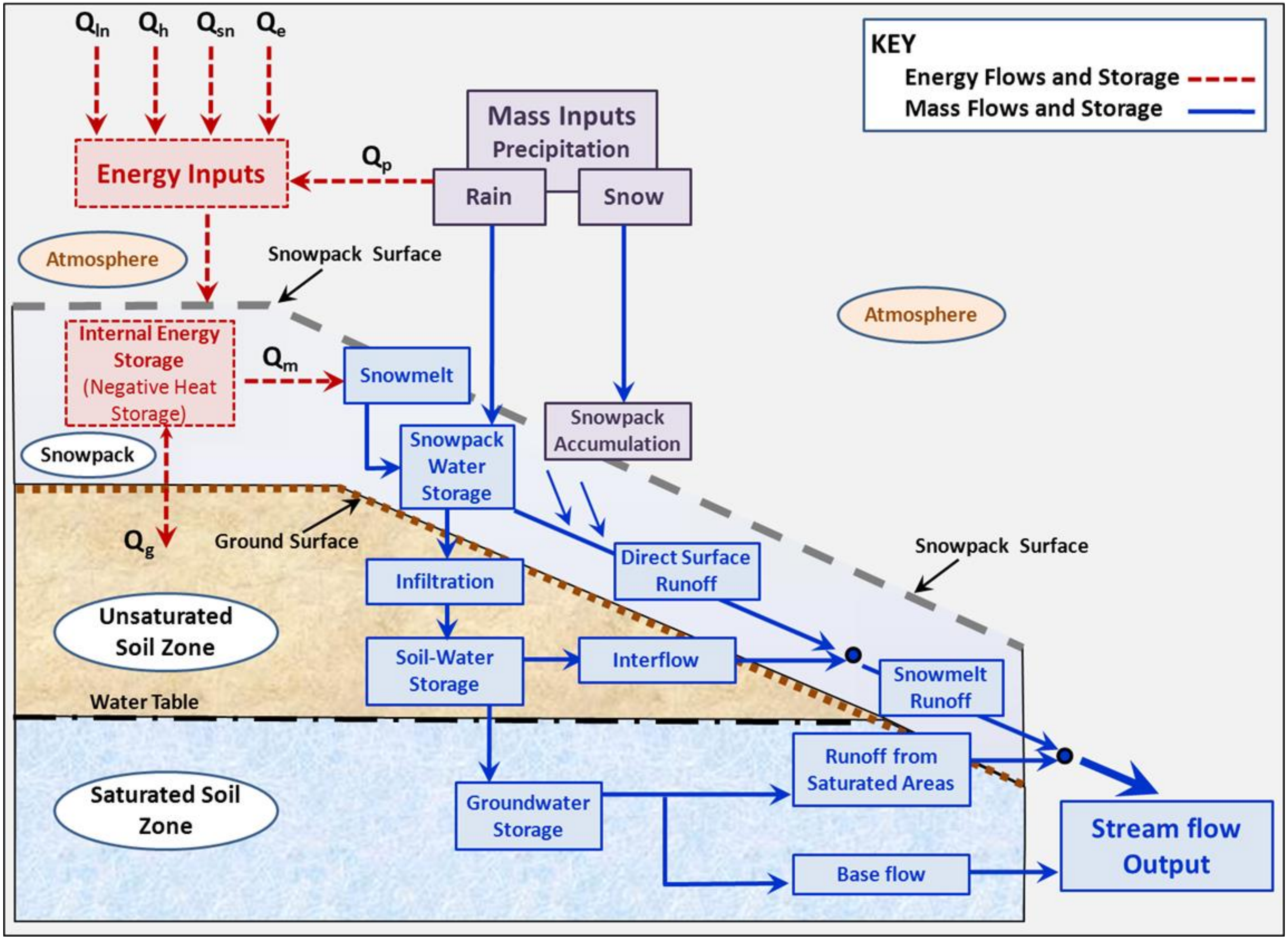
Study Area

- Indian Himalayas covering Major river systems (Indus, Ganga and Brahmaputra) including outside Indian boundary covering 9.89 Lakh sq.km.



Snow Cover Dynamics and Snowmelt Runoff Products & Services

Schematic of the Snowmelt Process



Source: Price, Hendrie, and Dunne (1979)

Snowmelt Runoff Estimation

- ❑ Temperature Index method
- ❑ Energy Budget method

Energy Budget for Snowmelt

The energy available for snowmelt

$$Q_m = Q_{sn} + Q_{ln} + Q_h + Q_e + Q_g + Q_p + Q_i$$

Q_{sn} = Shortwave net radiation
Q_{ln} = Longwave net radiation
Q_h = Sensible heat flux
Q_e = Latent heat flux
Q_g = Ground heat conduction
Q_p = Energy contained in the rainfall
Q_i = Change in internal energy

The amount of snowmelt

$$M = \frac{Q_m}{L_f \rho_w B}$$

M = Snowmelt, m
Q_m = flux density of melt energy, $J/m^{-2}day$
L_f = latent heat of fusion, Jkg^{-1} $0.334X10^6\ Jkg^{-1}$ at 0^0 C
ρ_w = density of liquid water, Kgm^{-3}
B = Thermal quality of snowpack

Energy Components for Snowmelt

Shortwave net radiation

$$Q_{sn} = (1-\alpha) R_s$$

α snow albedo

R_s Incoming solar radiation

Longwave net radiation

$$Q_{ln} = L\downarrow - L\uparrow$$

$$= L\downarrow - \{\varepsilon_s \sigma T_s^4 + (1-\varepsilon) L\downarrow\}$$

$$L\downarrow = \varepsilon_a \sigma T_a^4$$

$L\downarrow$ Incoming longwave radiation

T_s Snow surface temperature

ε_s Emissivity of snow surface

ε_a Emissivity of atmosphere

T_a Air temperature

Sensible heat flux

$$Q_h = \rho_a c_p C_h u_a (T_a - T_s)$$

ρ_a Density of air

c_p Specific heat of air

C_h Bulk transfer coefficient for sensible heat

u_a Wind speed

Latent heat flux

$$Q_e = [\rho_a 0.622 L / P_a] C_e u_a (e_a - e_s)$$

L Latent heat of vaporisation

P_a Atmospheric pressure

C_e Bulk transfer coefficient for latent heat

e_a Atmospheric vapour pressure

e_s Vapour pressure at the snowpack surface

Energy Components for Snowmelt

Ground heat conduction

$$Q_g = k_g(T_g - T_{sb})/(z_2 - z_1)$$

- K_g Thermal conductivity of soil
- z Soil depth
- T_g Soil temperature at depth z_2
- T_{sb} Temperature at base of snowpack depth z_2

Energy contained in rainfall

$$Q_p = P_r \rho_w c_w (T_r - T_s)$$

- P_r Rainfall intensity
- ρ_w Density of liquid water
- c_w Specific heat of liquid water
- T_r Temperature of rain (assumed as T_a)

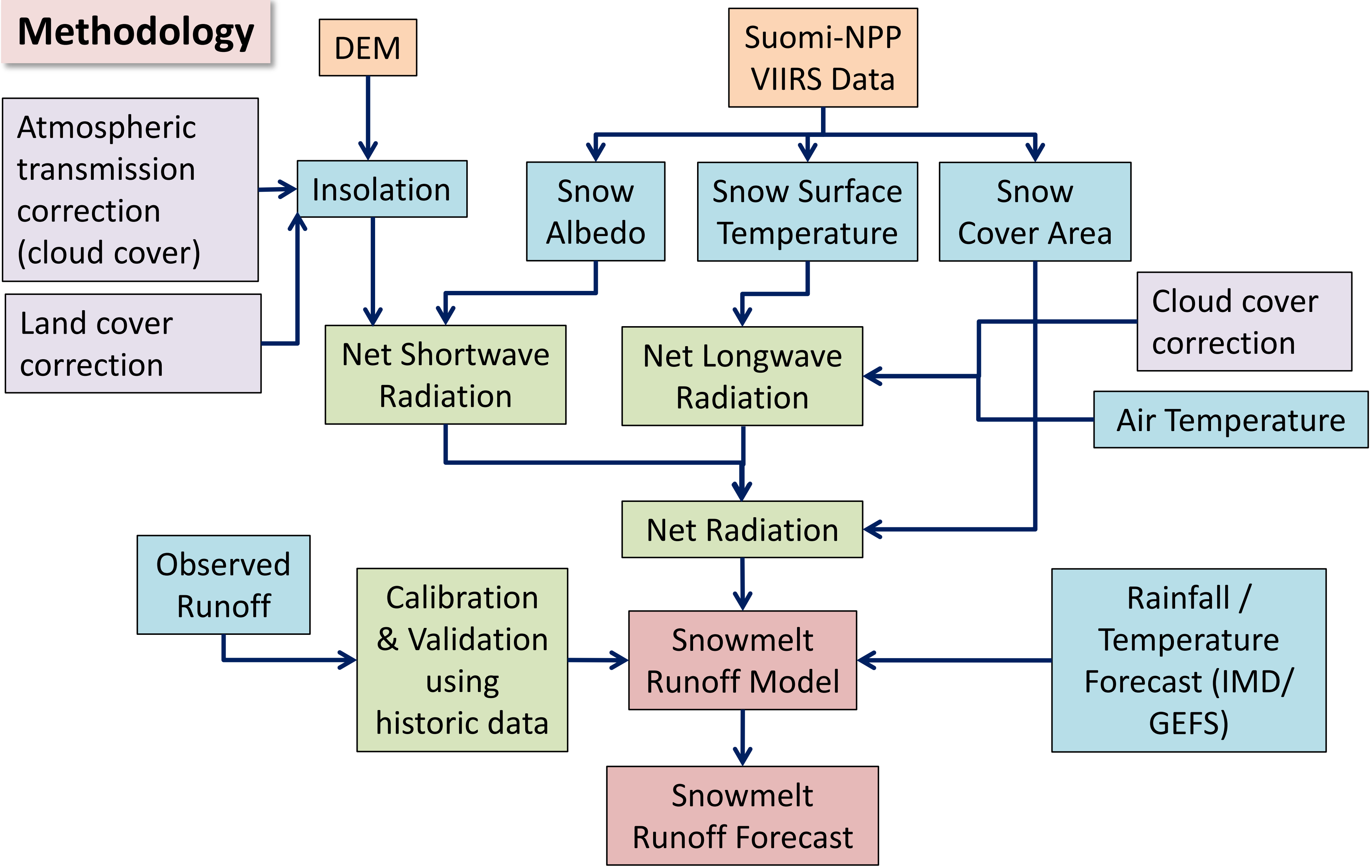
Change in internal energy

$$Q_h = [\rho_s c_i](\Delta T_s/\Delta t)\Delta z$$

- ρ_s Density of snowpack
- c_i Specific heat of ice
- t time
- z Height above ground (z=0 at ground; z=d at snowpack surface)
- d Snowpack depth

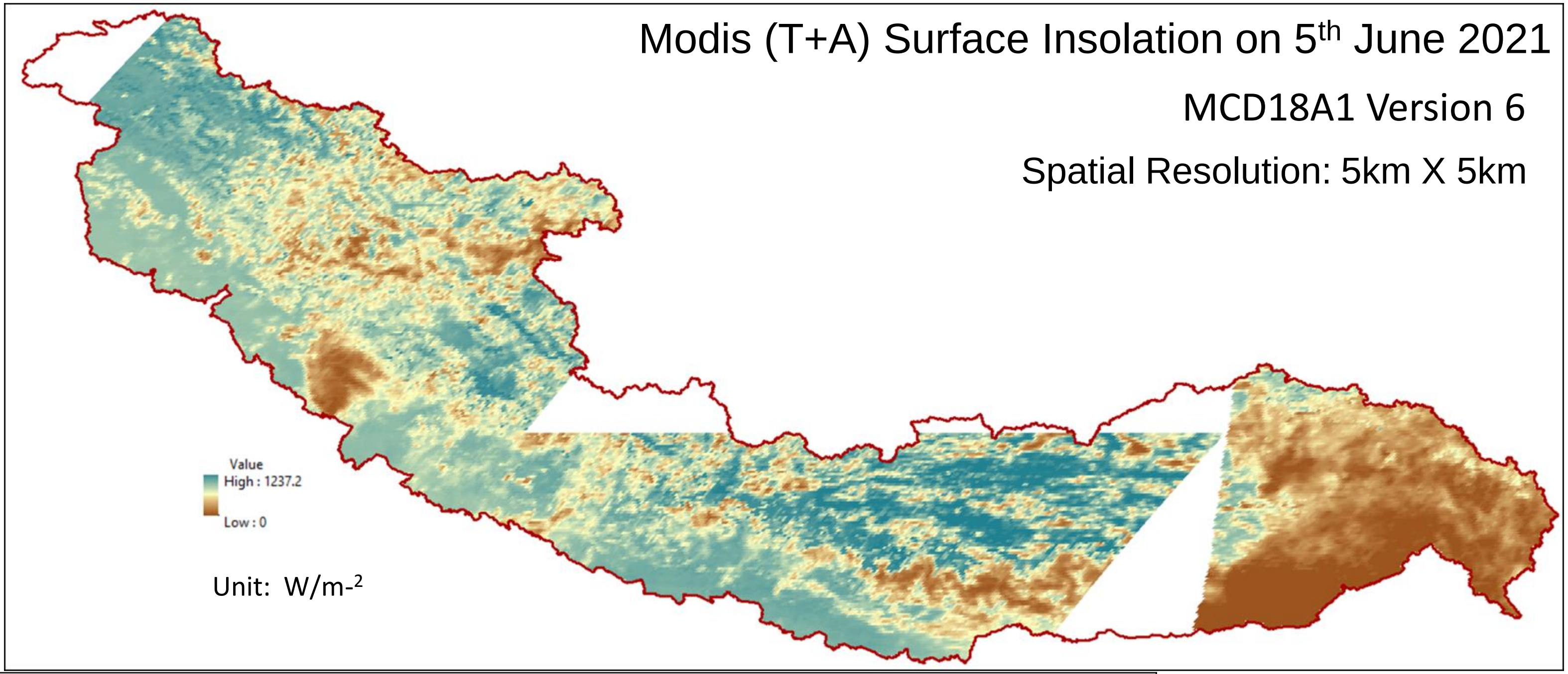
Snow Cover Dynamics and Snowmelt Runoff Products & Services

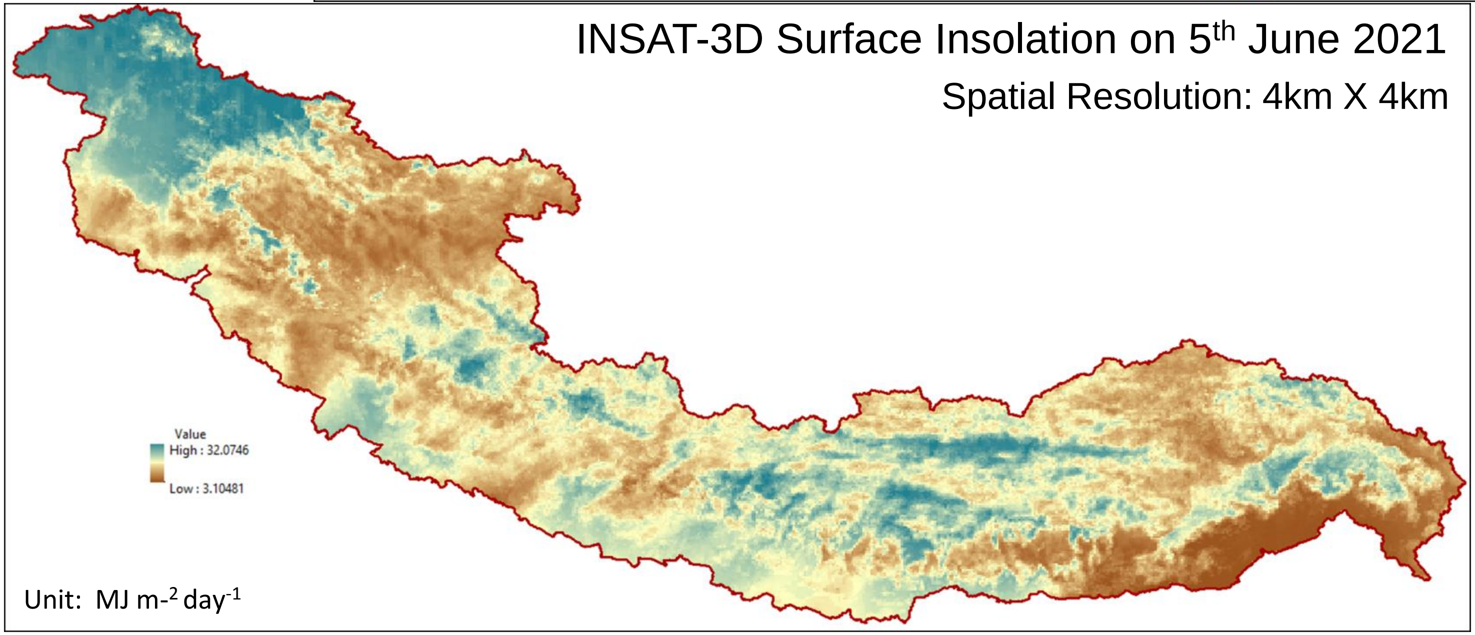
Methodology



Snow Cover Dynamics and Snowmelt Runoff Products & Services

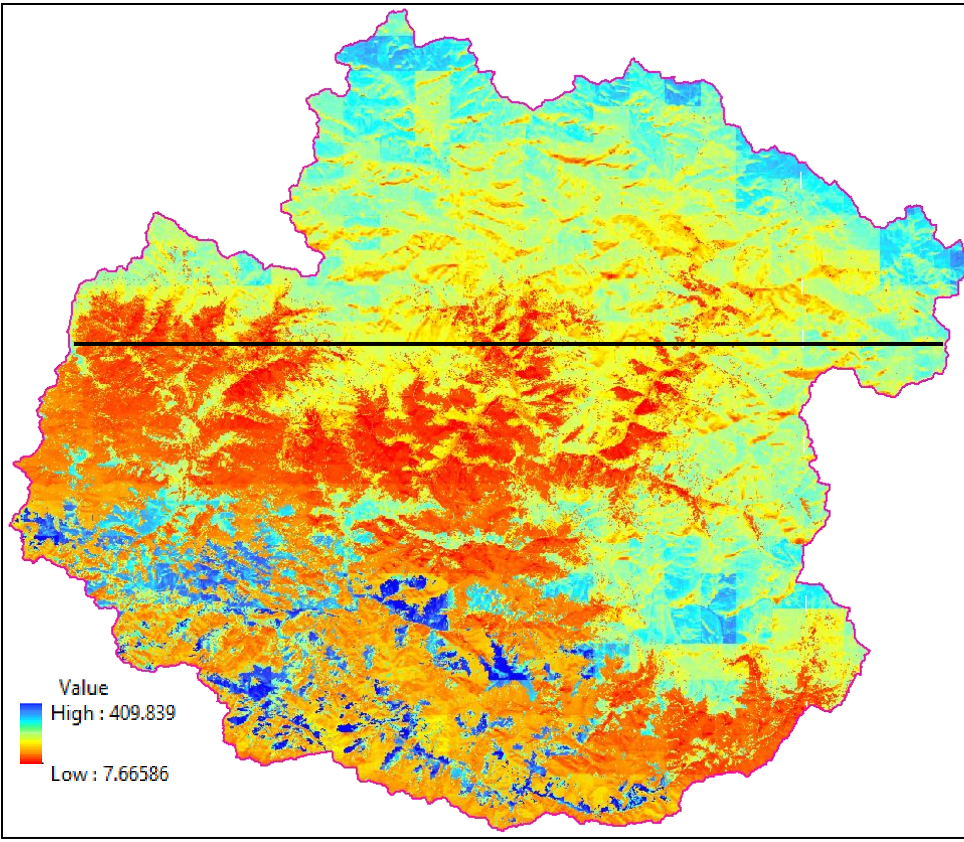
Satellite derived Insolation Products



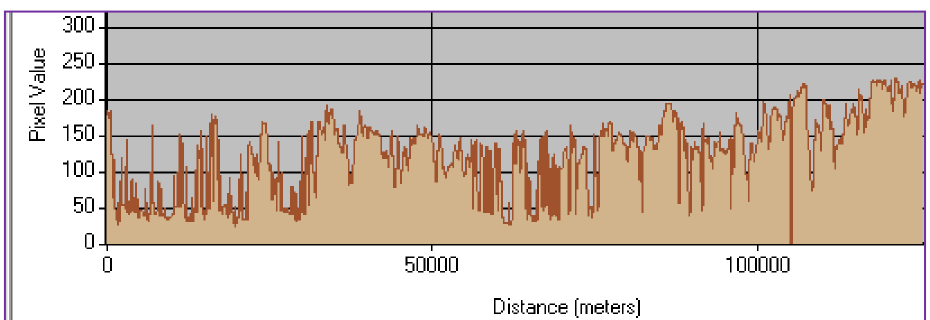


Snow Cover Dynamics and Snowmelt Runoff Products & Services

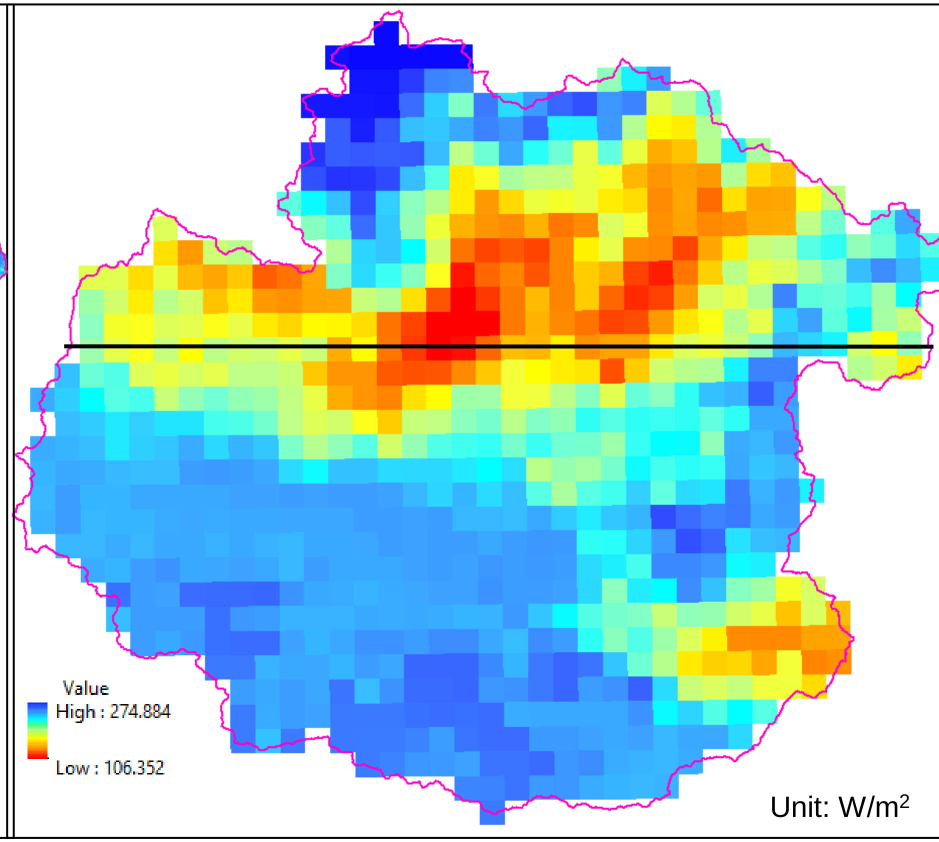
Surface Insolation using SRTM DEM 01-Apr-2021



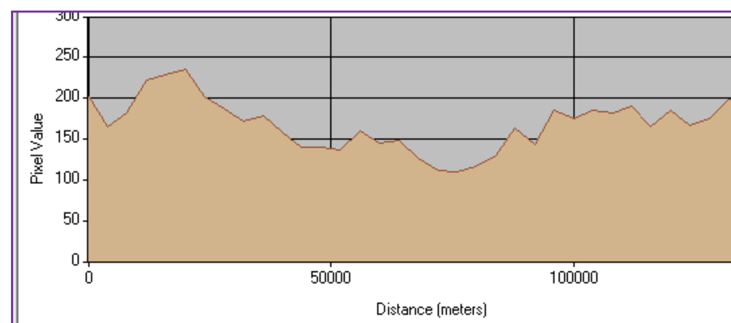
Spatial Resolution:90m



Surface Insolation product from INSAT-3D 01-Apr-2021

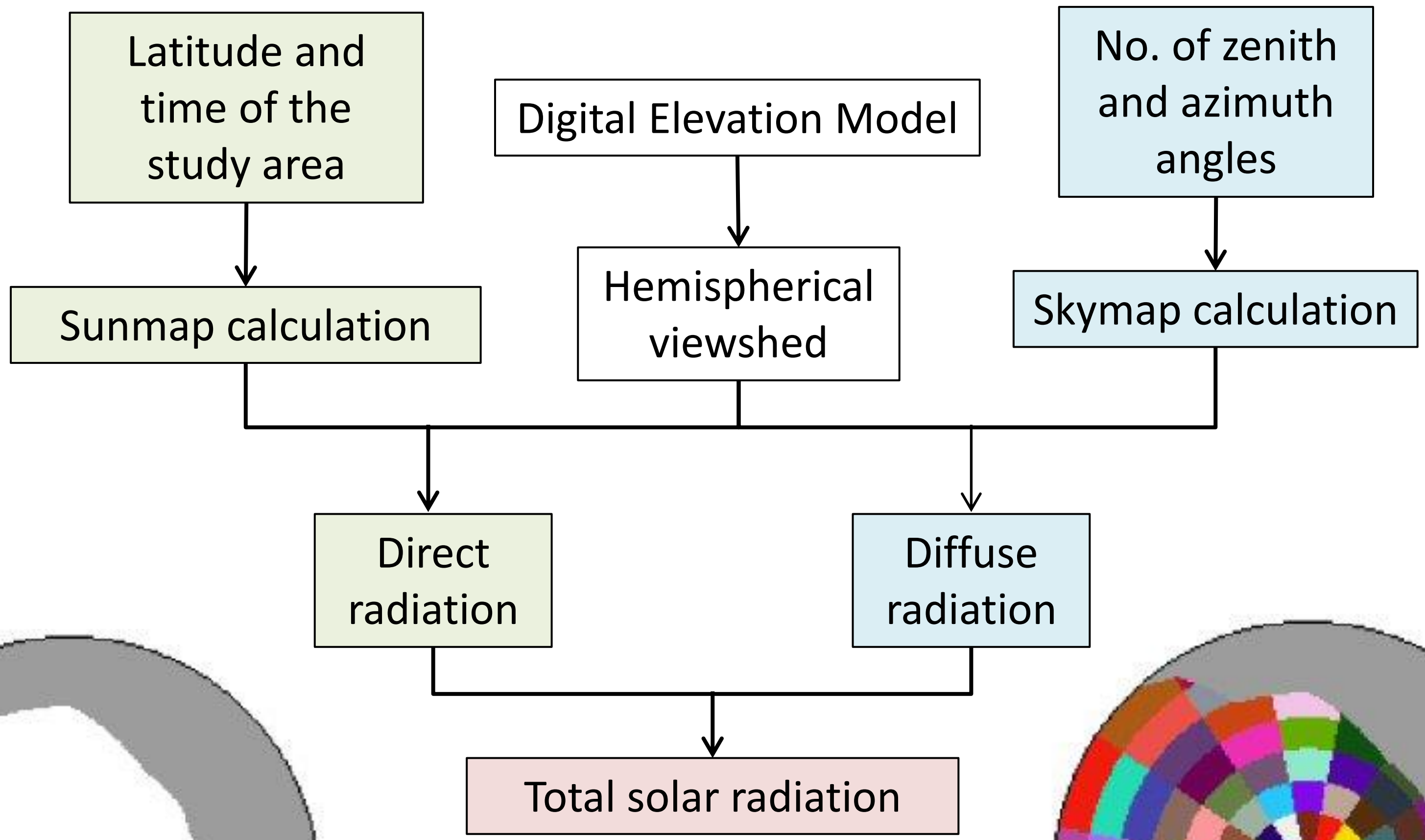


Spatial Resolution: 4 km

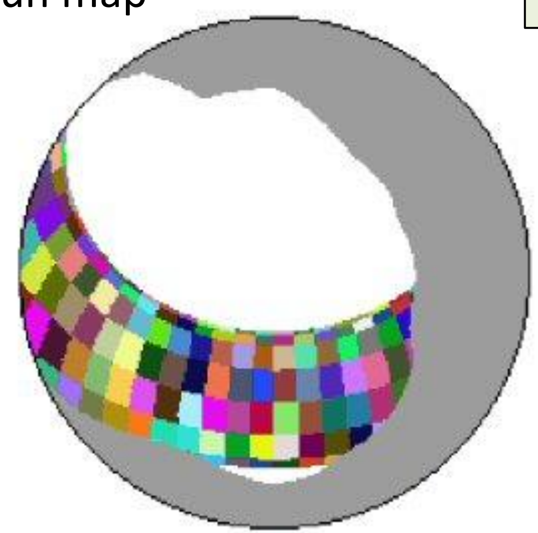


Snow Cover Dynamics and Snowmelt Runoff Products & Services

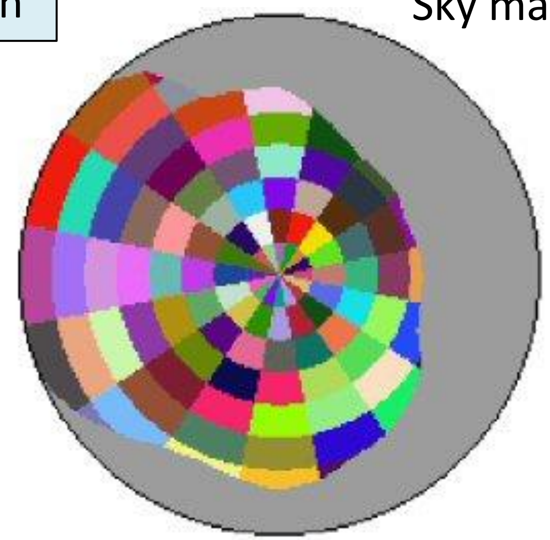
Computation of Insolation



Sun map



Sky map



Computation of Insolation

Methodology

- Direct radiation is estimated by overlaying viewshed on direct sunmap

$$R_{dir} = S_{const} * \beta^{m(\theta)} * SunDur * SunGap * \cos(AngIn)$$

Where
S_{const} = Solar constant; β = transmissivity of the atmosphere; m(θ) = relative optical path length; θ=solar zenith angle
SunDur = time duration represented by the sky sector; SunGap = gap fraction for the sunmap factor
AngIn = angle of incidence between the centroid of the sky sector and axis normal to the surface

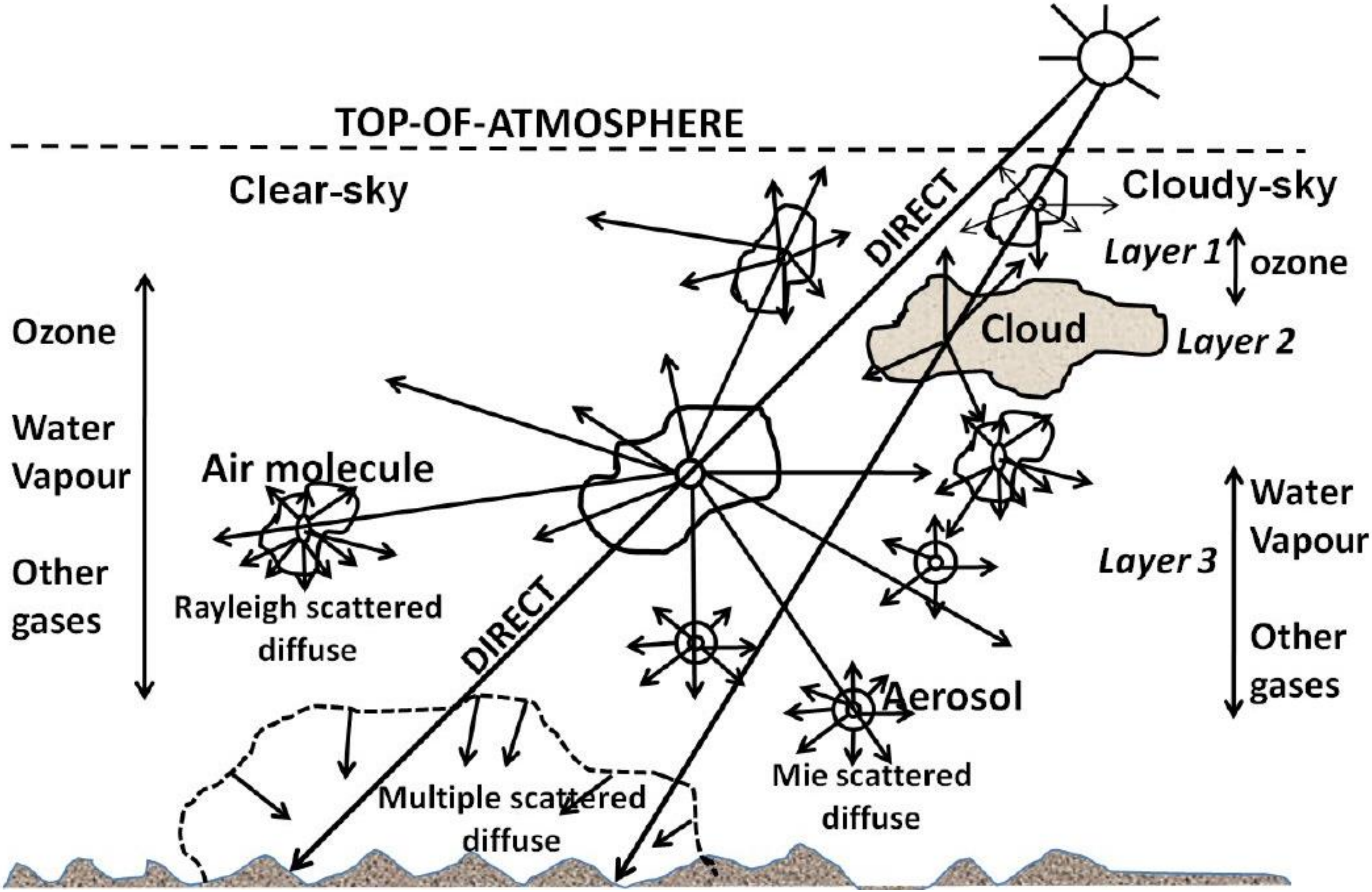
- Diffuse radiation is estimated by overlaying viewshed on diffuse map

$$R_{dif} = R_{glb} * P_{dif} * Dur * SunGap * Weight * \cos(AngIn)$$

Where
R_{glb} = global normal radiation; P_{dif} = proportion of global normal radiation that is diffused; Dur = time interval for analysis
Weight= proportion of diffuse radiation originating in a given sky sector and the intercepting surface

- The total solar radiation is estimated by addition of direct and diffuse radiation

$$R_{global} = R_{dir} + R_{dif}$$



Source: INSAT ATBD document(2015)

Snow Cover Dynamics and Snowmelt Runoff Products & Services

Shortwave Radiation

Insolation (without Atmospheric effects)

↓

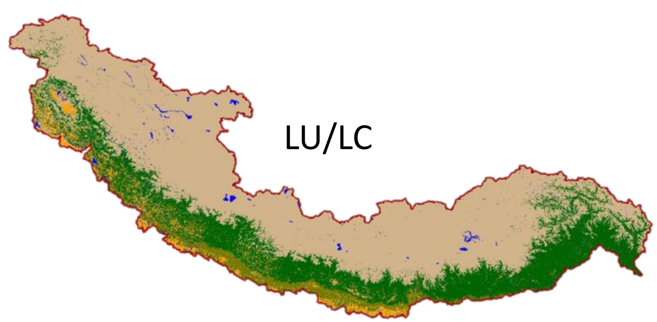
Insolation (with Atmospheric effects)

↓

Insolation (with cloud cover effects)

↓

Insolation (with land cover effects)



Longwave Radiation

Long wave Radiation (without cloud and land cover effects)

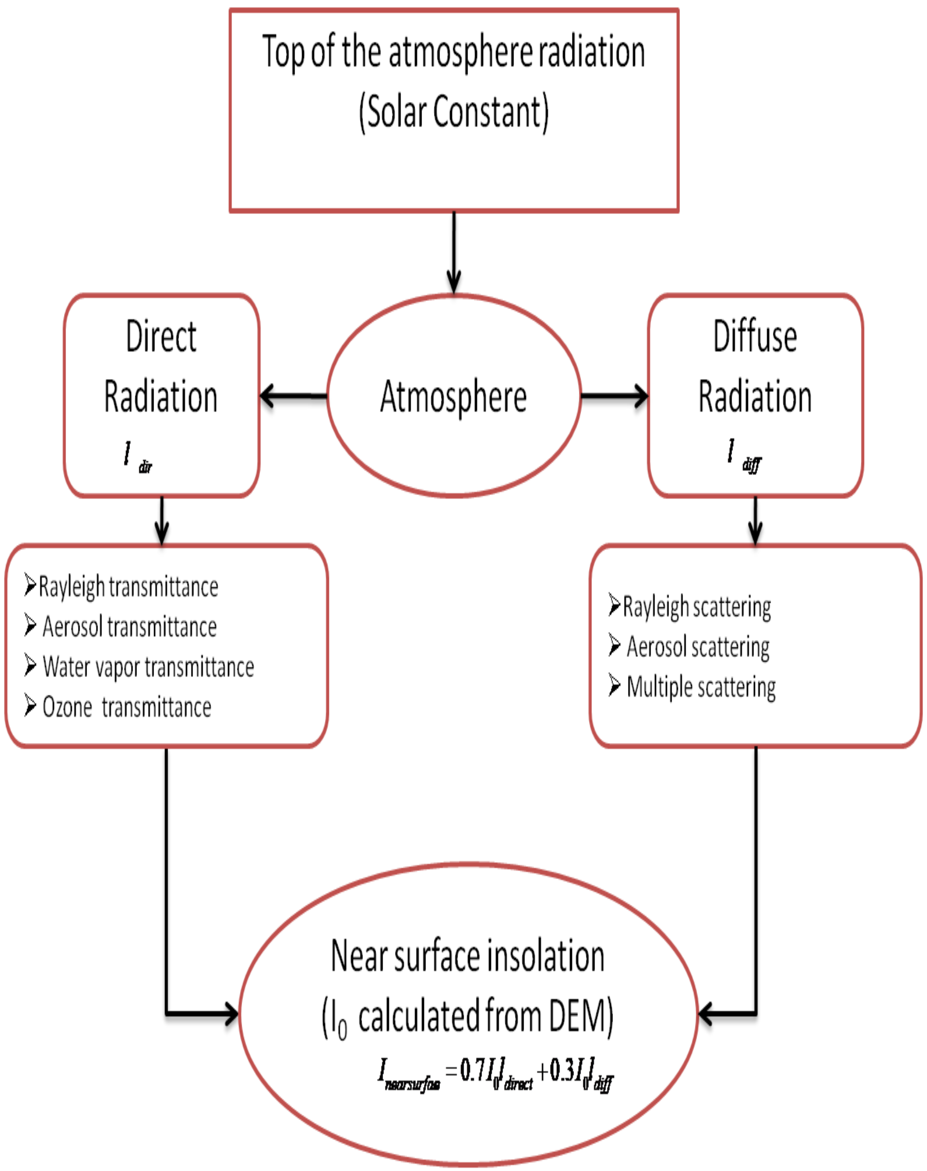
↓

Long wave Radiation (with cloud cover effects)

↓

Long wave Radiation (with land cover effects)

Shortwave Radiation



Insolation

$$I_0 = E_0 * \beta^{m(\theta)} * t_{\theta,a} * sungap_{\theta,\alpha} * \cos(AngIn_{\theta,\alpha})$$

$E_0 =$ Solar constant 1367 W/m^2

$\beta =$ atmospheric transmissivity

$m(\theta) =$ relative optical length of atmosphere

$m(\theta) = \exp(-0.000118 * elevation - 1.638 * 10^{-9} * elevation)$

$t =$ time duration

$Sungap =$ The gap fraction for the sun map sector

$AngIn =$ The angle of incidence between the centroid of the sky sector and the axis normal to the surface

Direct Radiation Losses

$$I_{dir} = \tau_R \times \tau_{oz} \times \tau_w \times \tau_g \times \tau_A$$

τ_R Rayleigh Transmittance

τ_{oz} Ozone Transmittance

τ_w Water vapor Transmittance

τ_g Gas Transmittance

τ_A Aerosol Transmittance

Diffuse Radiation Losses

$$I_{diff} = S_R + S_A + S_M$$

S_R Rayleigh Scattering

S_A Aerosol Scattering

S_M Multiple Scattering

Transmission Losses Through Direct and Diffuse Radiation

➢Water vapor, Ozone, Aerosol Transmittance

$$\tau(x) = \exp[-x(a + bx + cx^d)]$$

Component	x	Variables
For ozone	x=ml	l is ozone content in atmosphere in cm
For water vapor	x=mw	W is atmospheric perceptible water or columnar water vapor in gcm-2
For aerosol	x=mb	Atmospheric visibility of haziness based on given aerosol type and size distribution
For Other Gases	x=m	Relative optical air mass value

Atmospheric variable	Ozone (*l*)	Water vapor (*w*)	Aerosol (*b*)	Other gases
a	0.0184	0.002	1.053	-5.4×10^(-5)
b	0.0004	1.67 × 10^(-5)	0.083	-3.8×10^(-6)
c	0.022	0.094	0.3345	0.0099
d	-0.66	-0.693	-0.668	-0.62

Source: Paulescu and Schlett (2003)

Diffuse Radiation $I_{diff} = S_R + S_A + S_M$

1. S_R Rayleigh Scattering
2. S_A Aerosol scattering
3. S_M Multiple scattering

- **Rayleigh Scattering**

$$S_R = 0.79 I_0 \tau_{oz} \tau_g \tau_w (1-(1-w_0)(1-m+m^{1.06})(1-\tau_A)) \frac{0.5(1-\tau_R)}{1-m+m^{1.06}}$$

- **Aerosol scattering**

$$S_A = 0.79 s_0 \tau_{oz} \tau_g \tau_w \left(\frac{\tau_A}{1-(1-w_0)(1-m+m^{1.06})(1-\tau_A)}\right) \times \frac{f_c}{1-m+m^{10.6}} \left(1 - \frac{\tau_A}{(1-(1-w_0)(1-m+m^{1.06})(1-\tau_A)\tau_R)}\right)$$

- **Multiple scattering**

$$S_M = (S_{dir} + S_R + S_A) \frac{\rho_g \rho_a}{1-\rho_g \rho_a}$$

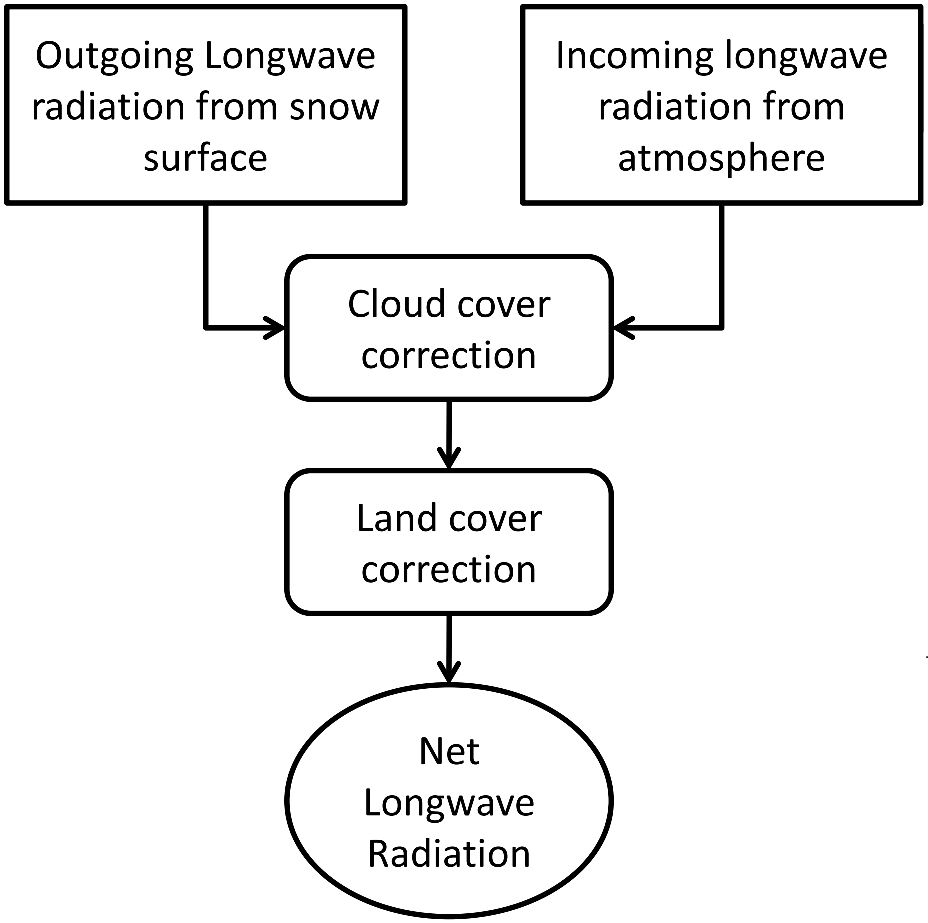
ρ_g is ground albedo and ρ_a atmospheric albedo respectively

$$\rho_a = 0.0685 + (1-f_c)\left(1 - \frac{\tau_A}{1-(1-w_0)(1-m+m^{1.06})}\right)$$

w_0 *is single scattering albedo assumed as 1*

f_c *is ratio of forward to backward scattering calculated as* $f_c = 0.9302 \cos(\theta_s)^2$

Longwave Radiation



Incoming Longwave Radiation

$$LW_{in} = \sigma * \varepsilon_{air} * T_{air}^{4}$$

σ Stefan Boltzmann Constant ($5.67\times10^{-8}\,\mathrm{Wm^{-2}K^{-4}}$)

ε_{air} Emissivity of air

T_{air} Air Temperature

Outgoing Longwave Radiation

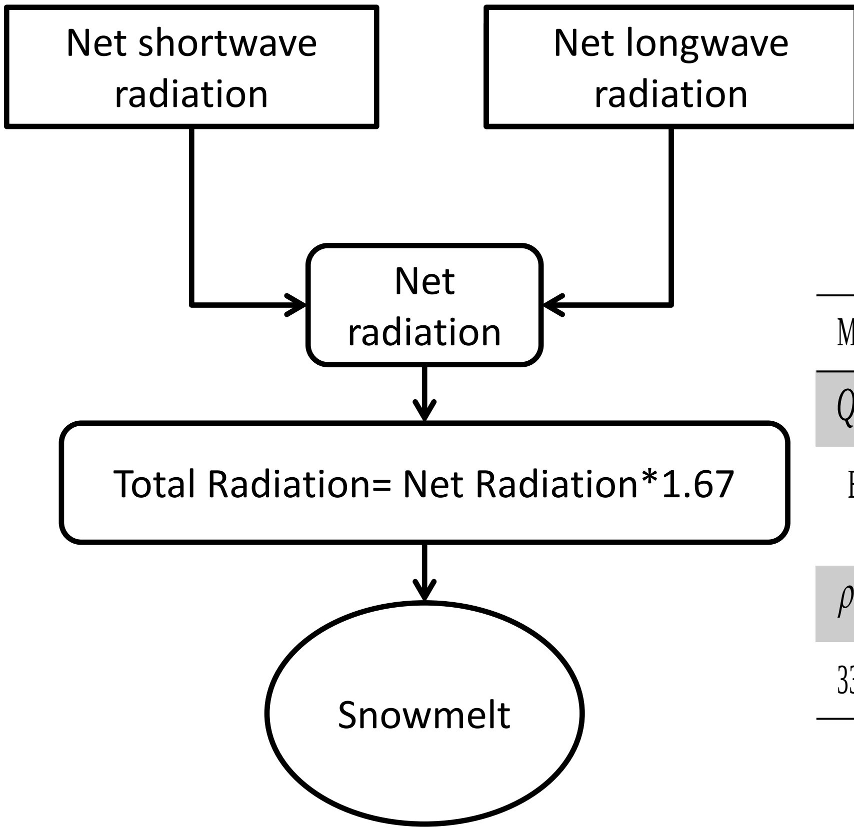
$$LW_{out} = \sigma * \varepsilon_{snow} * T_{lst}^{4} + LW_{in}(1 - \varepsilon_{snow})$$

σ Stefan Boltzmann Constant ($5.67\times10^{-8}\,\mathrm{Wm^{-2}K^{-4}}$)

ε_{snow} Emissivity of snow

T_{lst} Snow Surface Temperature

Methodology for Snowmelt Calculation



$$M = \frac{Q_m}{334.9 * \rho_w * B}$$

M	Depth of Snowmelt (mm)
Q_m	Total Energy available at snowpack for snowmelt (kJ/m2)
B	thermal quality of the snow (ratio of heat required to melt a unit weight of the snow to that of ice at 0 degree Celsius).
ρ_w	Density of water kg/m3.
334.9	Latent heat of fusion of ice kJ/Kg

Input Data

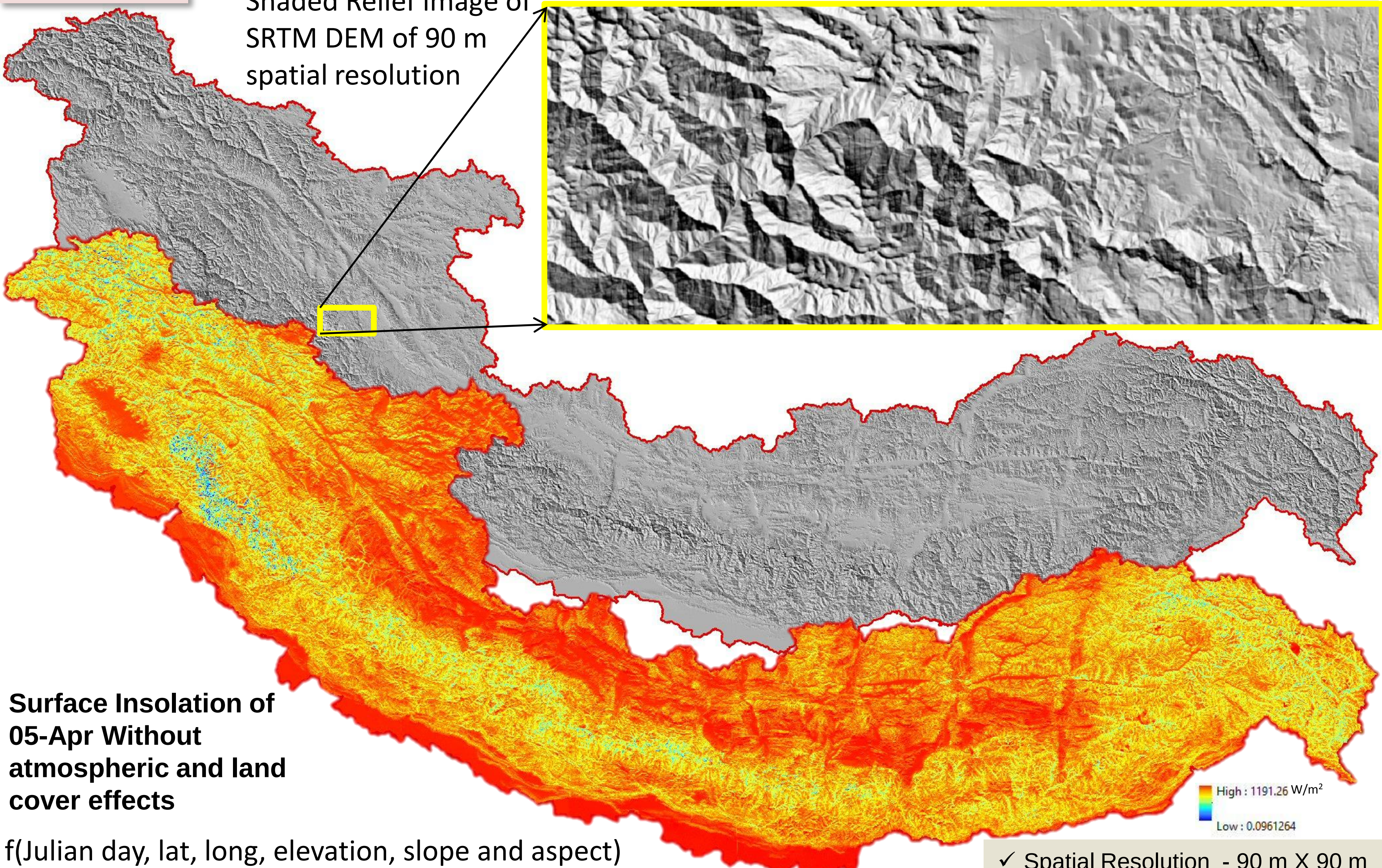
Input Data	Spatial Resolution	Source
Insolation – f(Julian day, lat, long, elevation, slope and aspect)	90 m	SRTM DEM
Snow Cover Area, Snow Albedo, LST	1 km	Suomi-NPP VIIRS satellite data - daily
AOD	11 km	INSAT-3D/3DR Imager – Half hourly
Water Vapour	11 km	INSAT-3D/3DR Sounder– Hourly
Ozone	11 km	INSAT-3D/3DR Sounder– Hourly
Cloud Mask	4 km	INSAT-3D/3DR Imager – Half hourly
GEFS - Rainfall and Air Temperature forecast	48 km	Daily
Land Use /Land Cover Map	56 m	Resourcesat-2 AWiFS satellite data
Soil Map		NBSS&LUP and HWSD
Glacier Map		Prepared from GLIMS, ICIMOD, and RGI Glacier Maps

Snow Cover Dynamics and Snowmelt Runoff Products & Services

Input Data

Surface Insolation

Shaded Relief image of SRTM DEM of 90 m spatial resolution



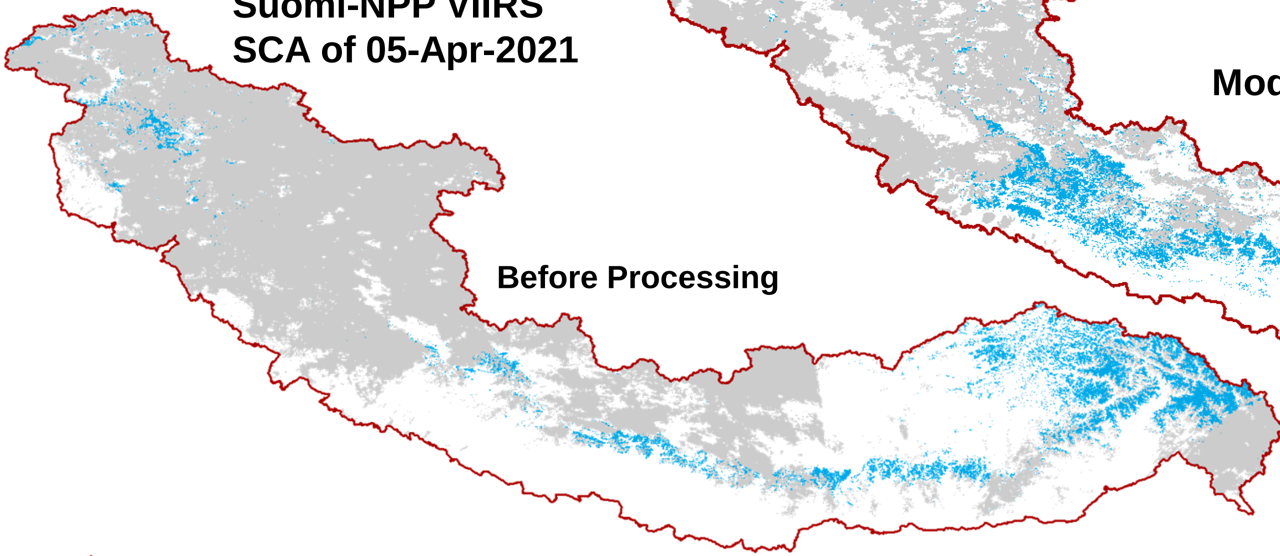
Surface Insolation of 05-Apr Without atmospheric and land cover effects

f(Julian day, lat, long, elevation, slope and aspect)

✓ Spatial Resolution - 90 m X 90 m

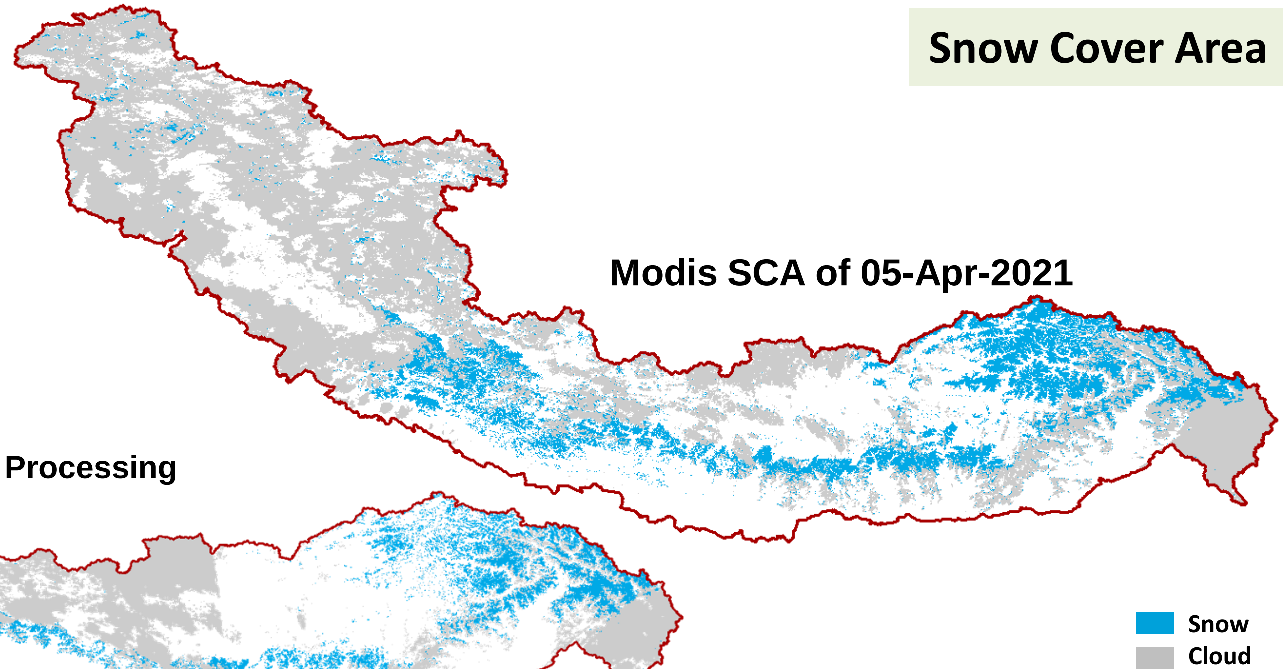
Snow Cover Dynamics and Snowmelt Runoff Products & Services

Input Data

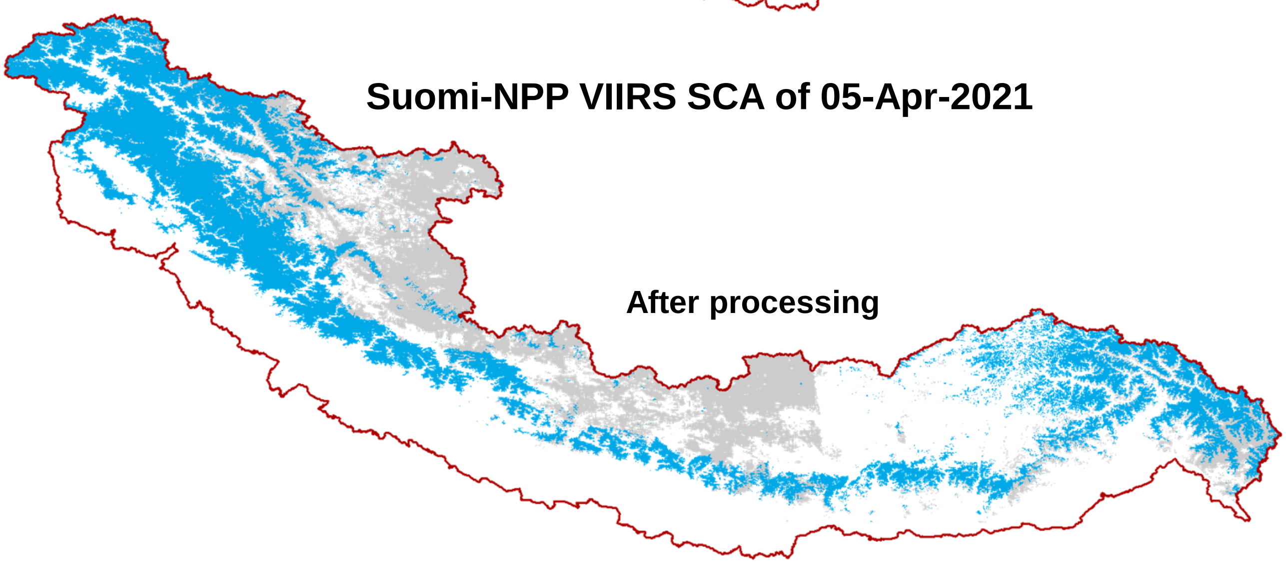


Suomi-NPP VIIRS SCA of 05-Apr-2021

Snow Cover Area



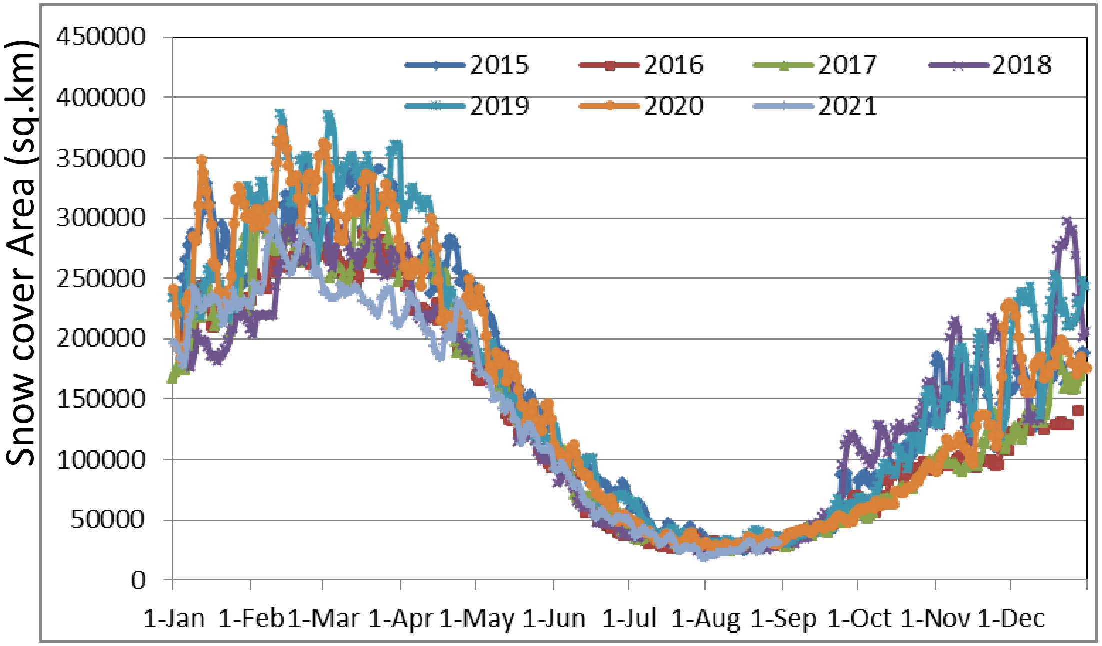
Modis SCA of 05-Apr-2021



Suomi-NPP VIIRS SCA of 05-Apr-2021

- ✓ Previous 3 day snow cover map
- ✓ Historic Modis snow cover

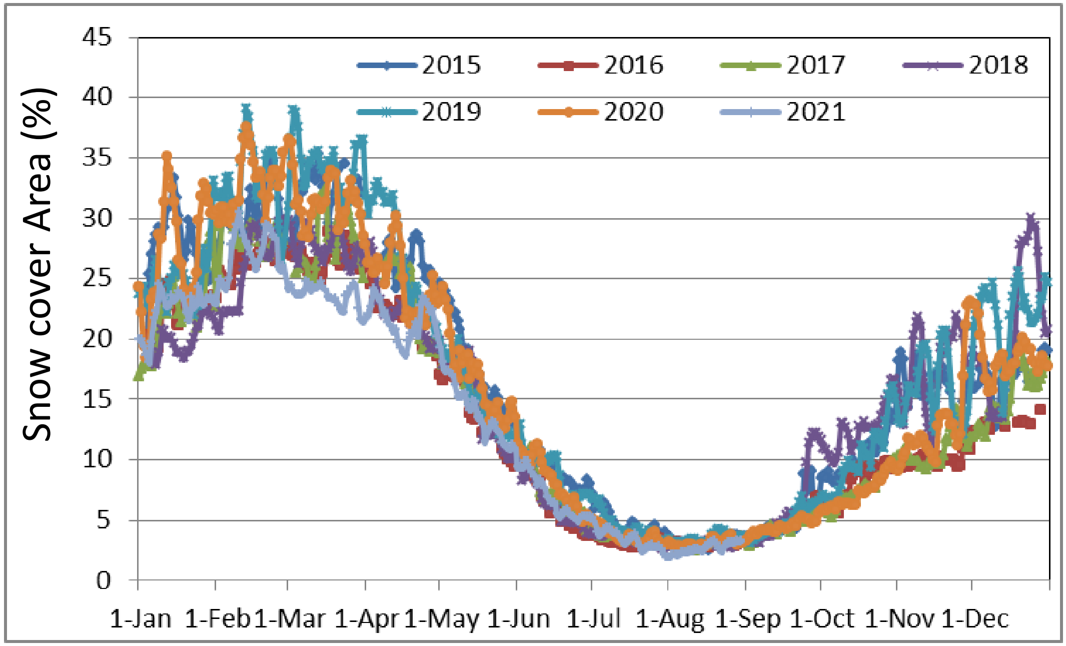
Snow Cover Dynamics and Snowmelt Runoff Products & Services



Variations of Snow Cover Extent

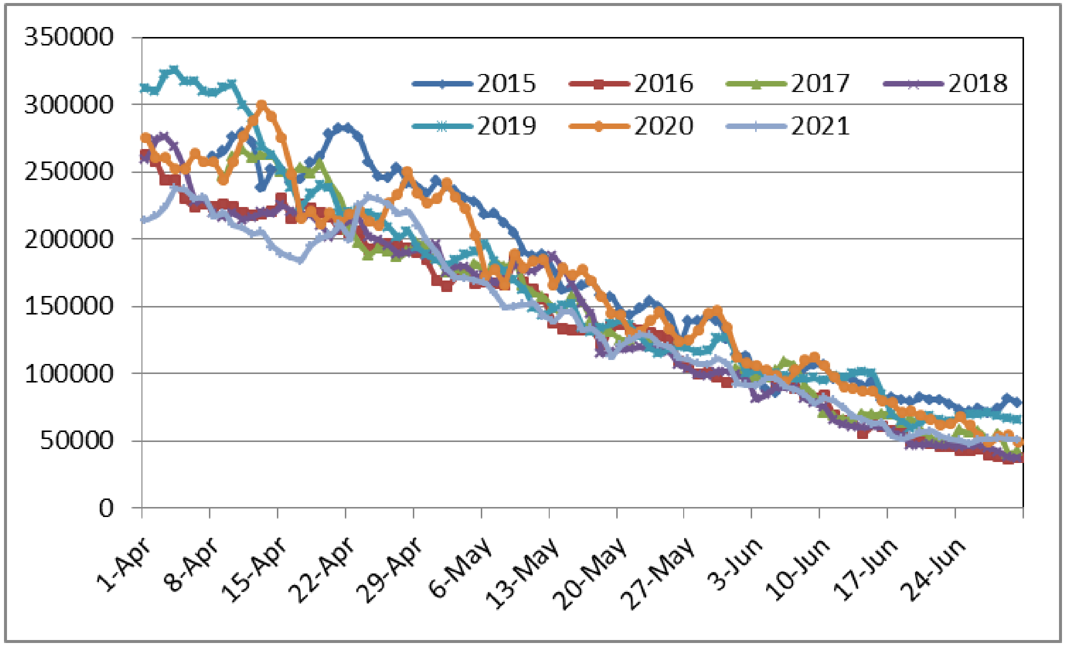
Snow Cover Area Information

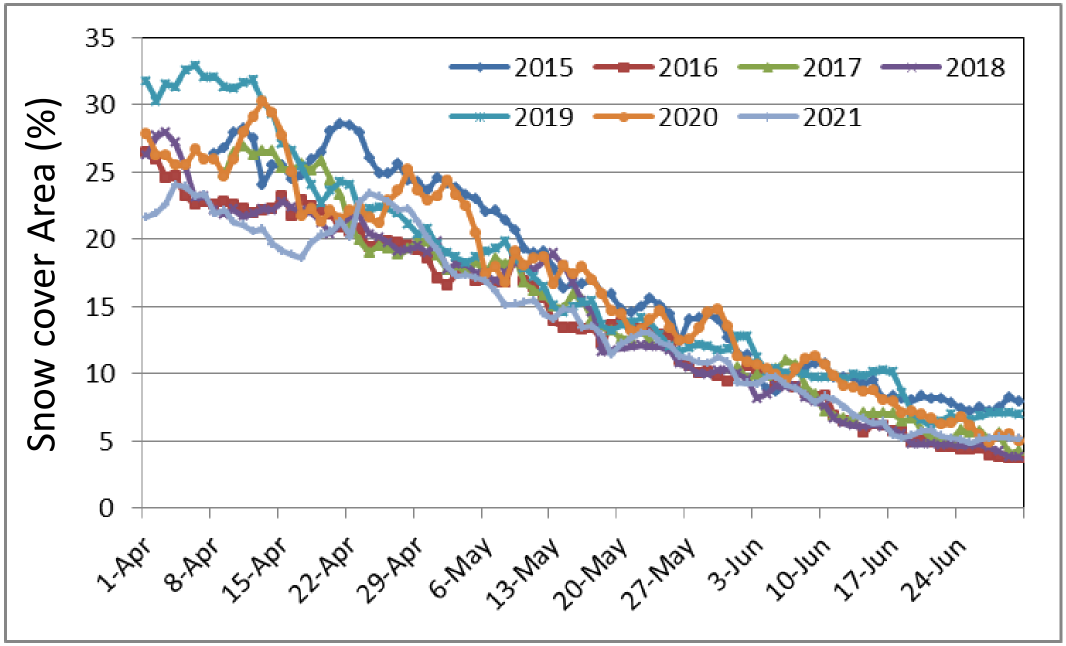
Year	Max	Min	Max	Min
2015	3,48,713	71,156	35.23	7.19
2016	2,86,035	26,728	28.90	2.70
2017	3,19,363	40,465	32.27	4.09
2018	2,96,539	24,451	29.96	2.47
2019	3,86,127	59,613	39.02	6.02
2020	3,72,313	26,425	37.62	2.67
2021	3,00,625	18,720	30.38	1.85



Snow Cover Dynamics and Snowmelt Runoff Products & Services

Variations of Snow Cover Extent



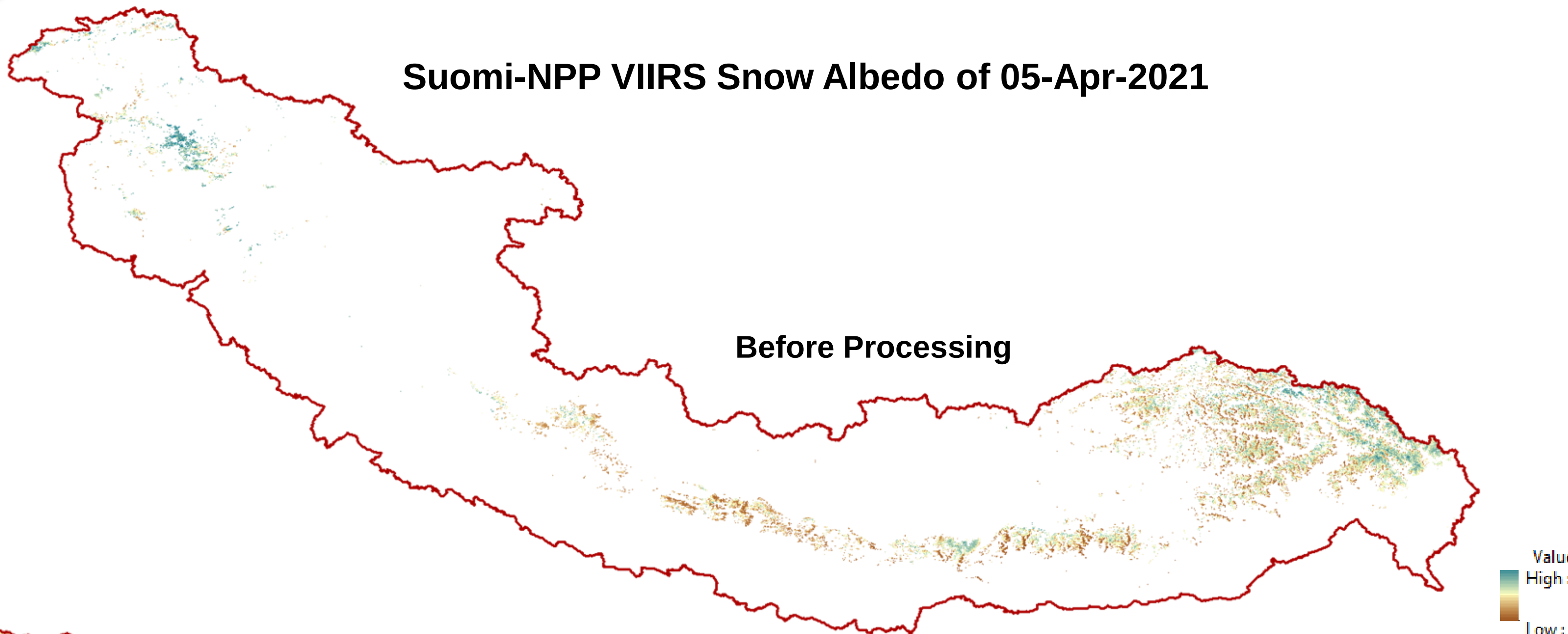


Snow Cover Dynamics and Snowmelt Runoff Products & Services

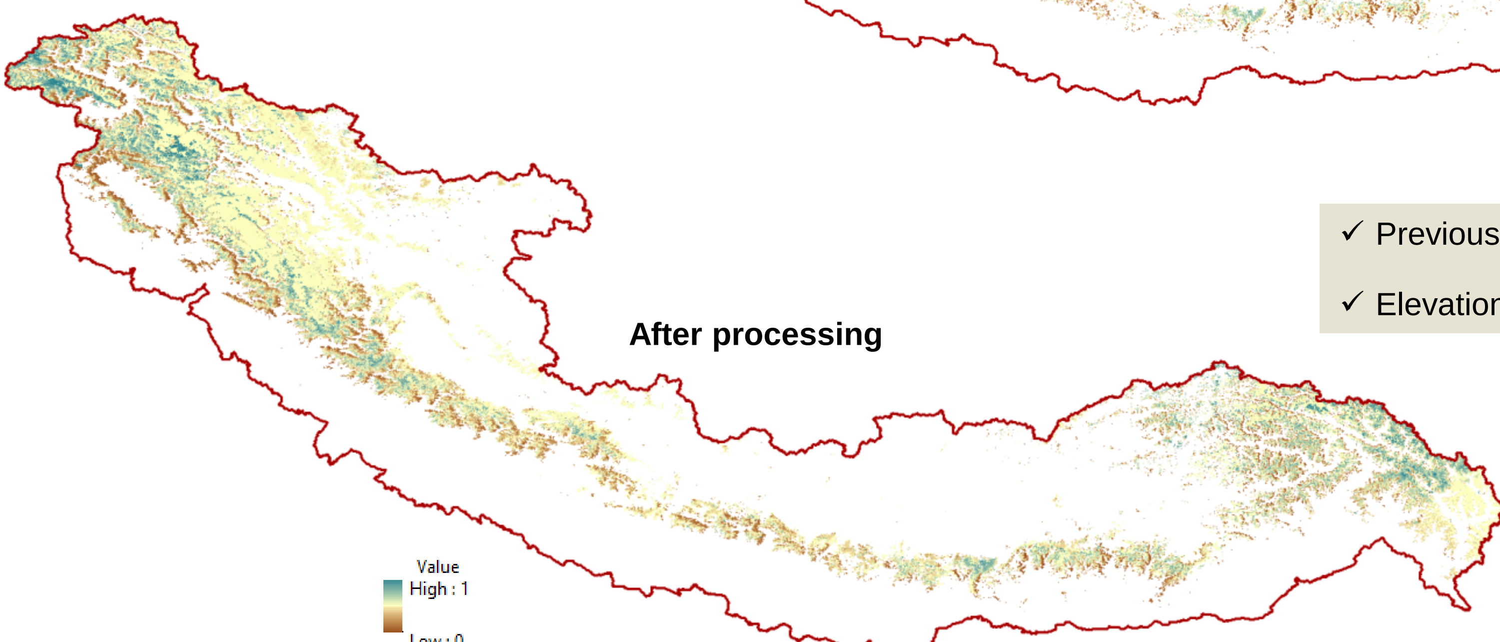
Input Data

Snow Albedo

Suomi-NPP VIIRS Snow Albedo of 05-Apr-2021



Before Processing



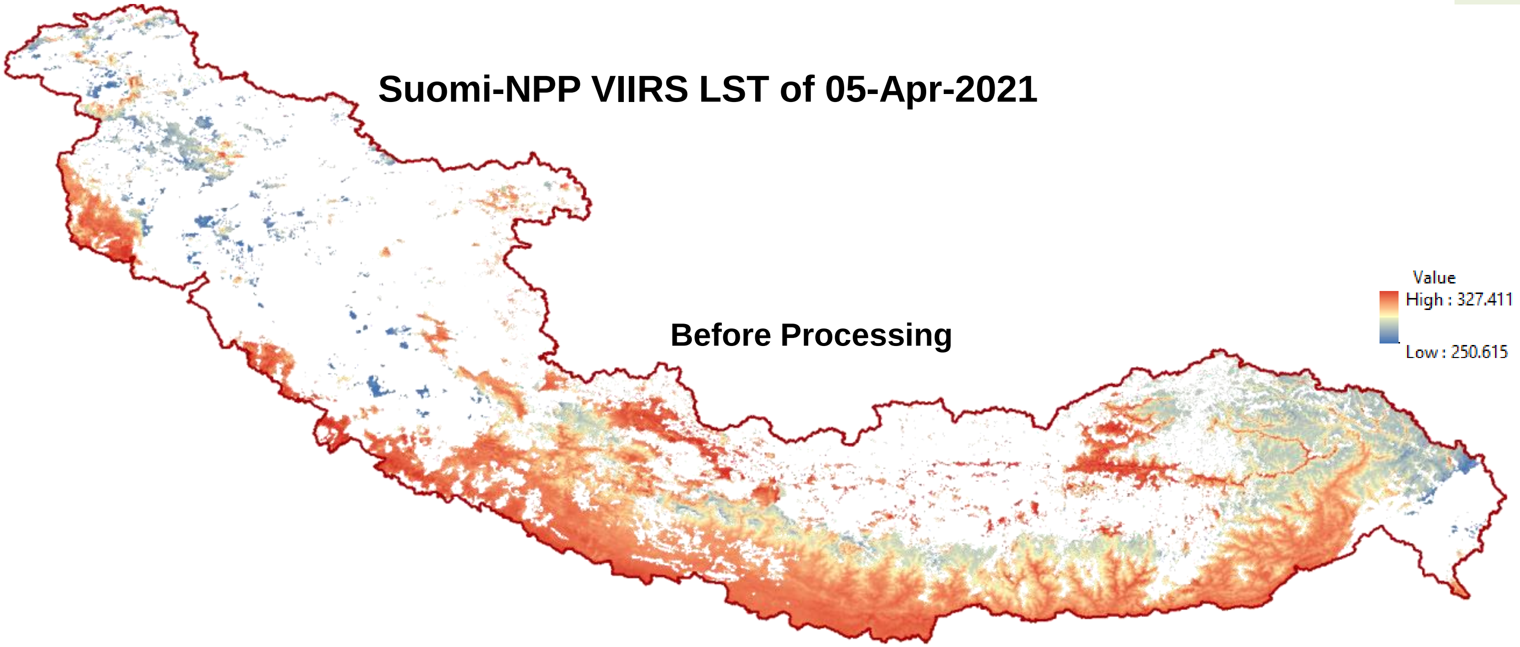
After processing

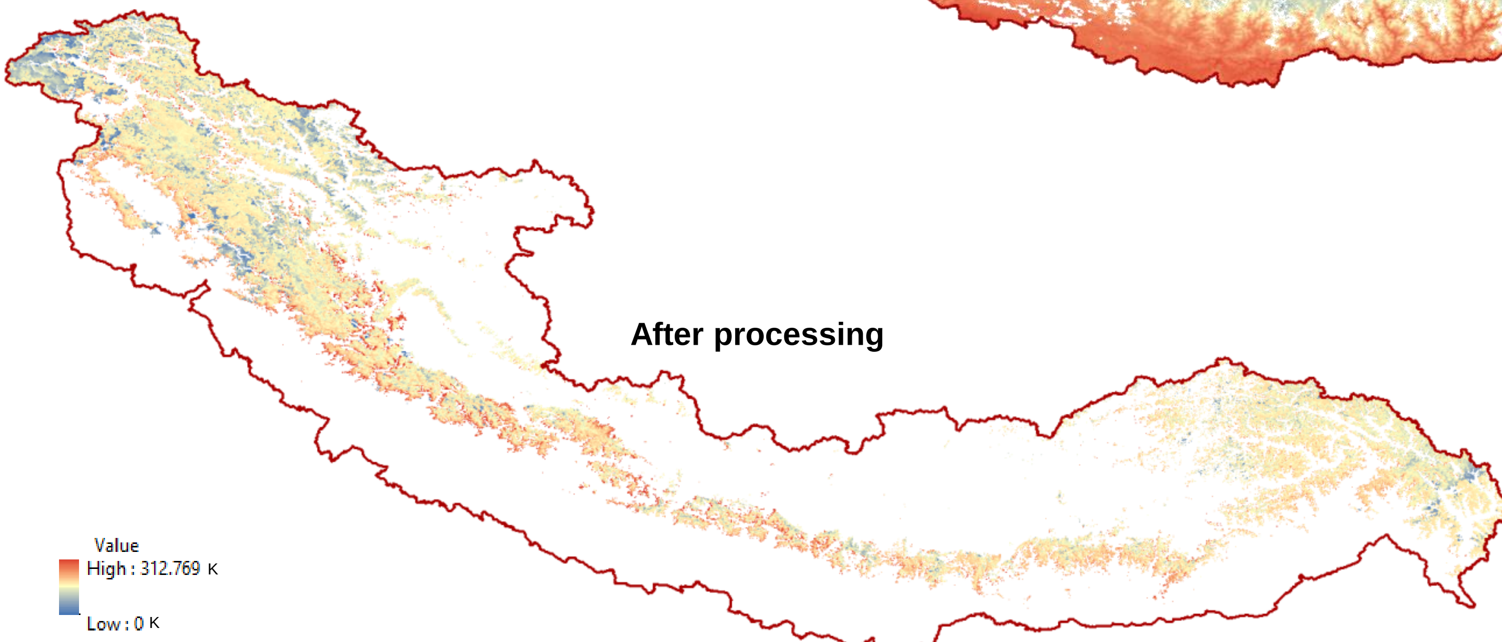
- ✓ Previous 3 day snow albedo
- ✓ Elevation band based snow albedo

Snow Cover Dynamics and Snowmelt Runoff Products & Services

Input Data

LST





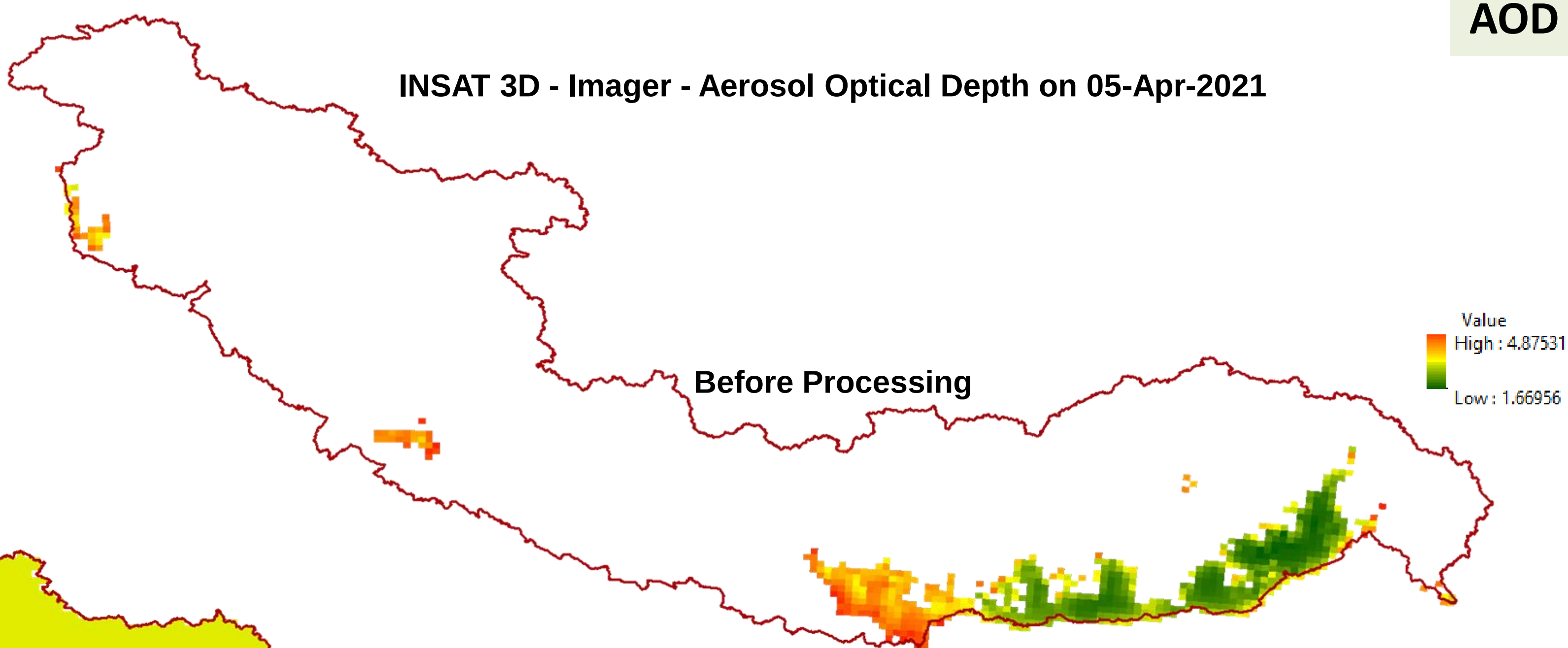
- ✓ Previous 3 day
- ✓ Elevation based
- ✓ Historic Modis LST

Snow Cover Dynamics and Snowmelt Runoff Products & Services

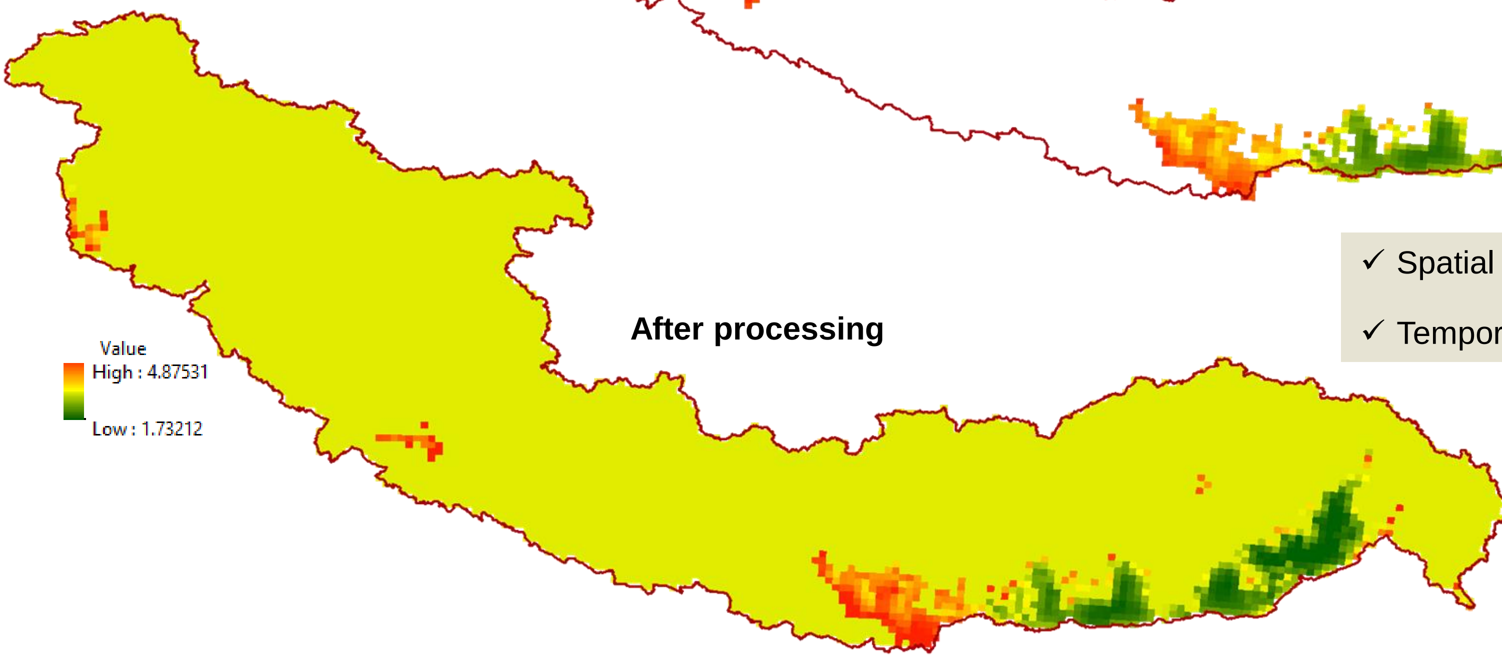
Input Data

AOD

INSAT 3D - Imager - Aerosol Optical Depth on 05-Apr-2021



Before Processing



After processing

- ✓ Spatial Resolution - 11 km X 11 km
- ✓ Temporal Resolution – Half hourly

$$\tau_{a}(\lambda) = \beta\lambda^{-\alpha}$$

$\tau_{a}(\lambda)$ = aerosol optical depth or thickness at wavelength λ (in µm)

β = Angstrom turbidity coefficient is related to aerosols content

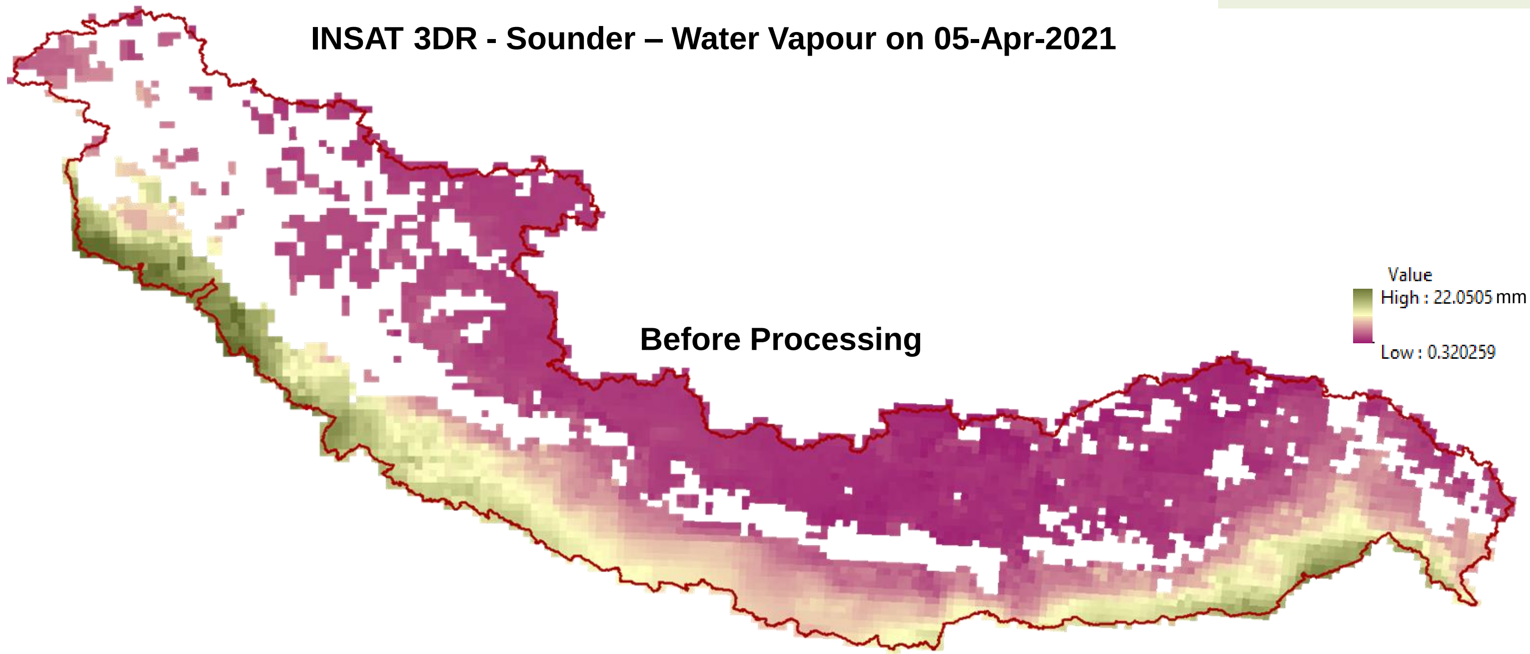
α = Angstrom wavelength exponent is related to the size distribution of particles

Snow Cover Dynamics and Snowmelt Runoff Products & Services

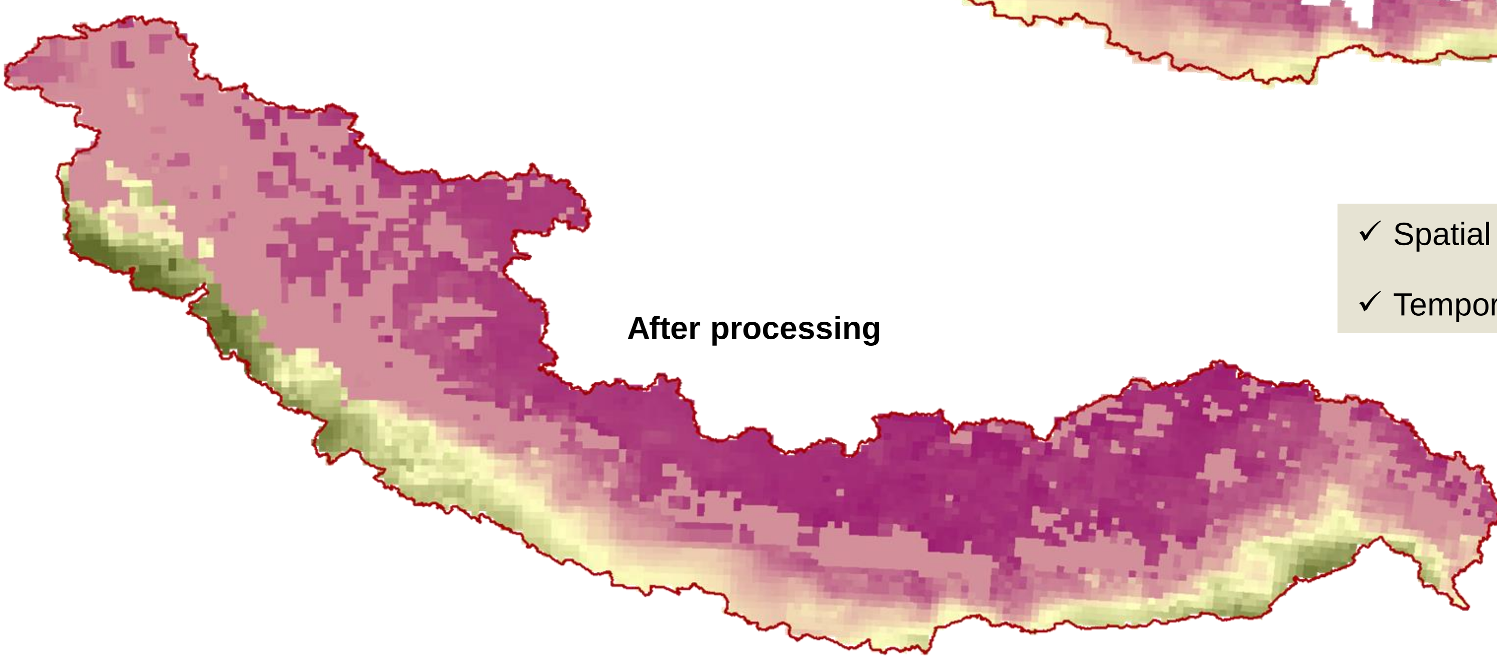
Input Data

Water Vapour

INSAT 3DR - Sounder – Water Vapour on 05-Apr-2021



Before Processing



After processing

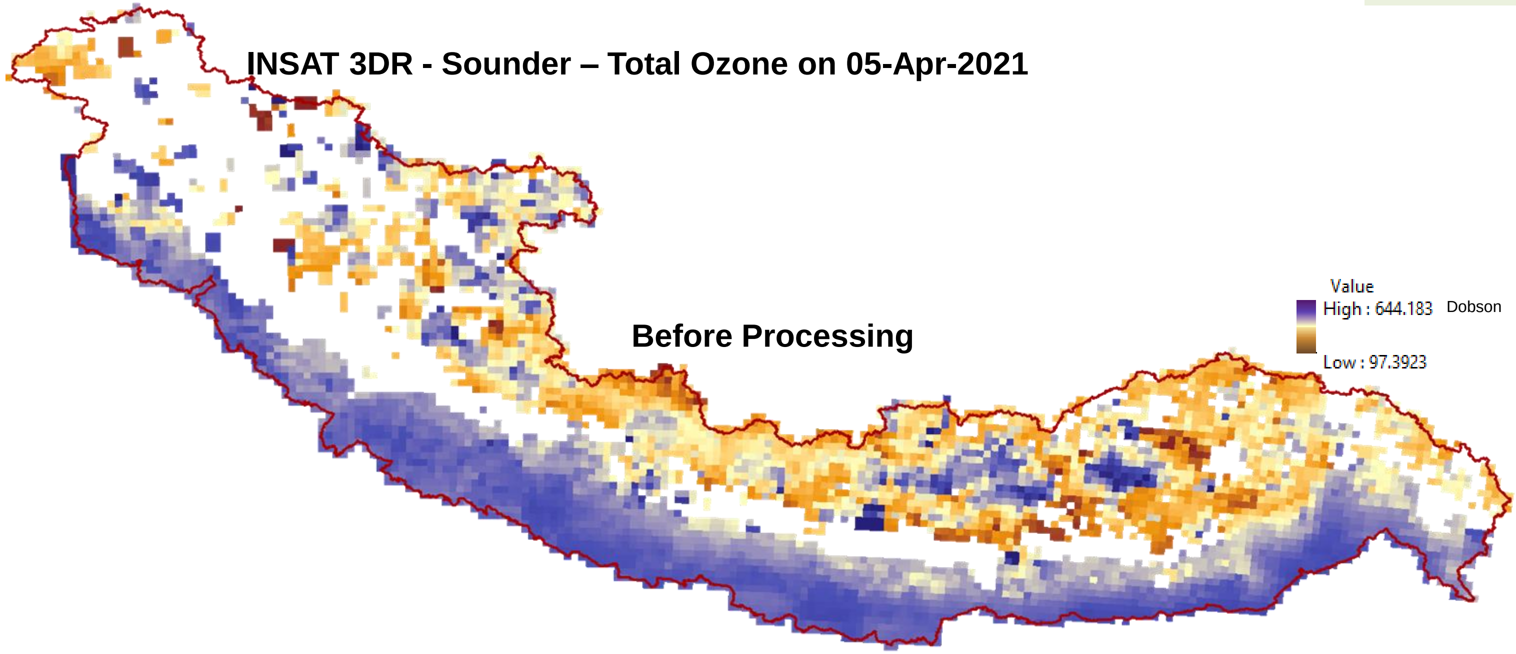
- ✓ Spatial Resolution - 11 km X 11 km
- ✓ Temporal Resolution – Hourly

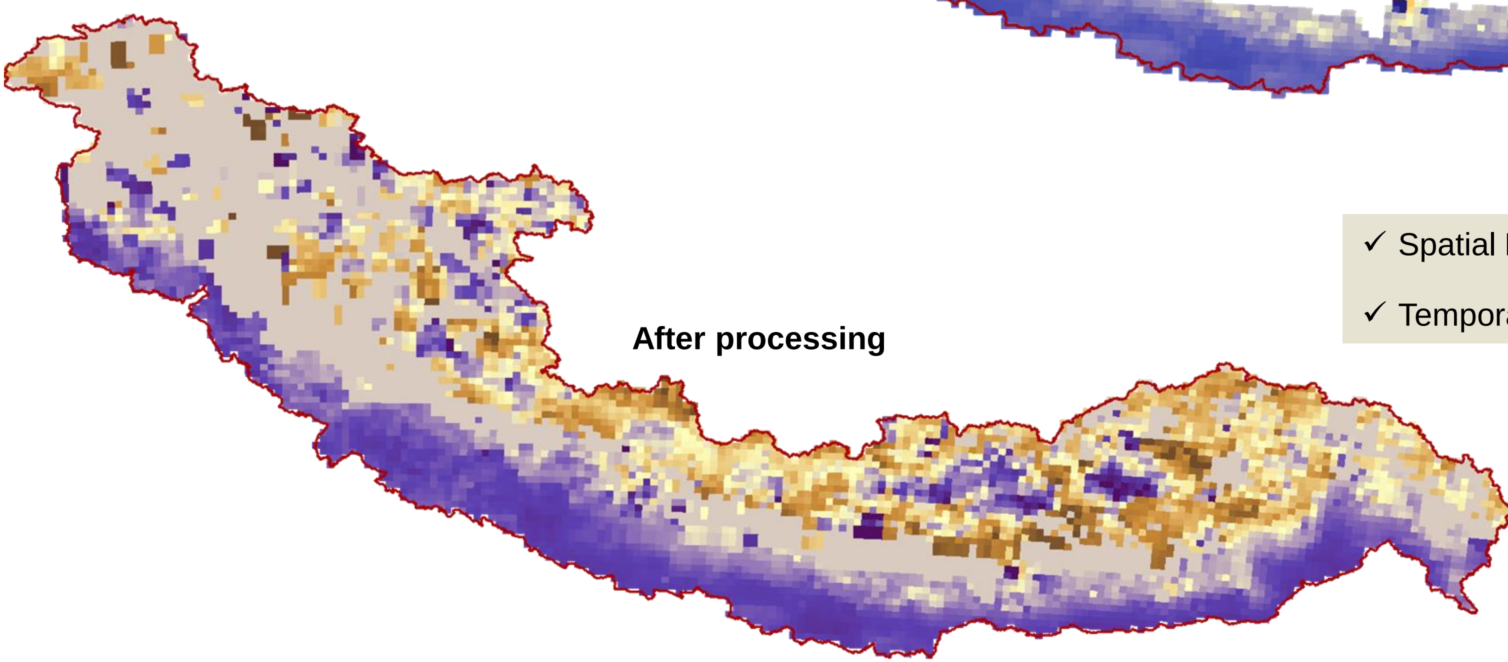
Snow Cover Dynamics and Snowmelt Runoff Products & Services

Input Data

Ozone

INSAT 3DR - Sounder – Total Ozone on 05-Apr-2021



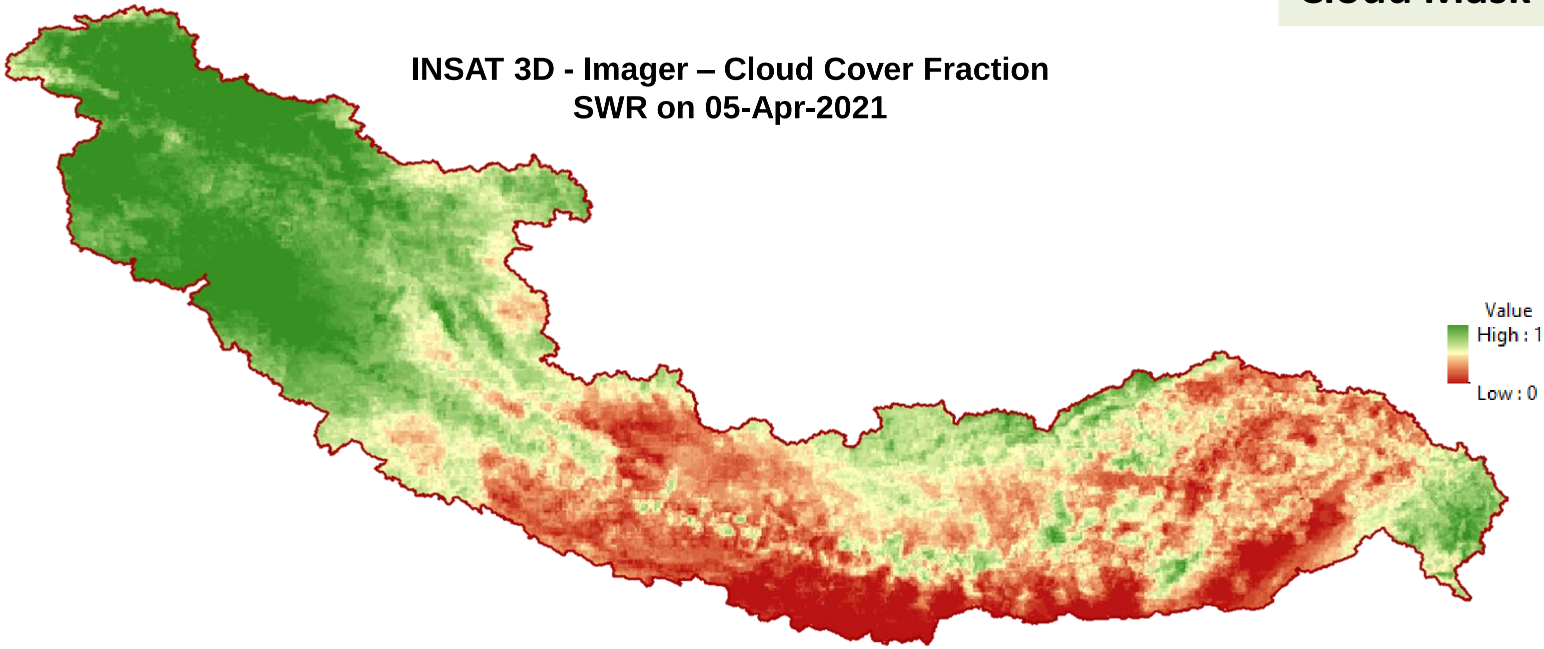


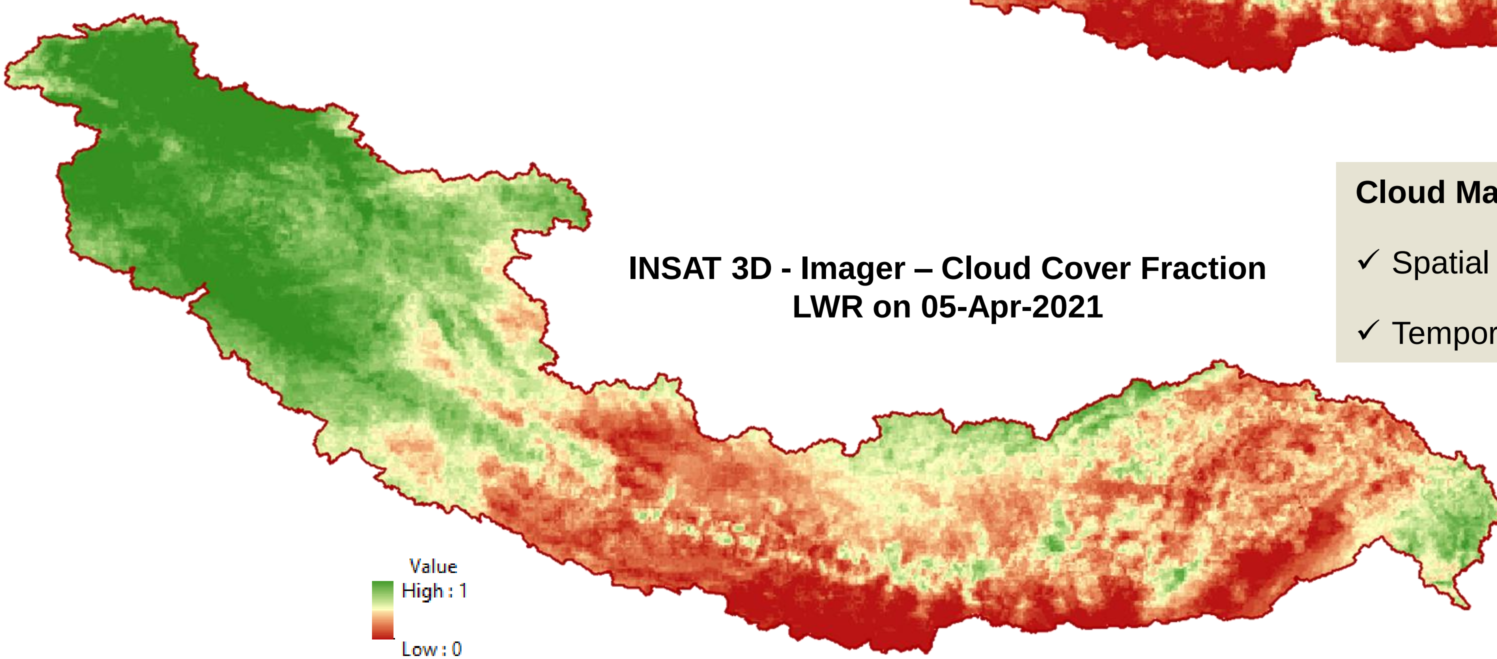
- ✓ Spatial Resolution - 11 km X 11 km
- ✓ Temporal Resolution – Hourly

Snow Cover Dynamics and Snowmelt Runoff Products & Services

Input Data

Cloud Mask



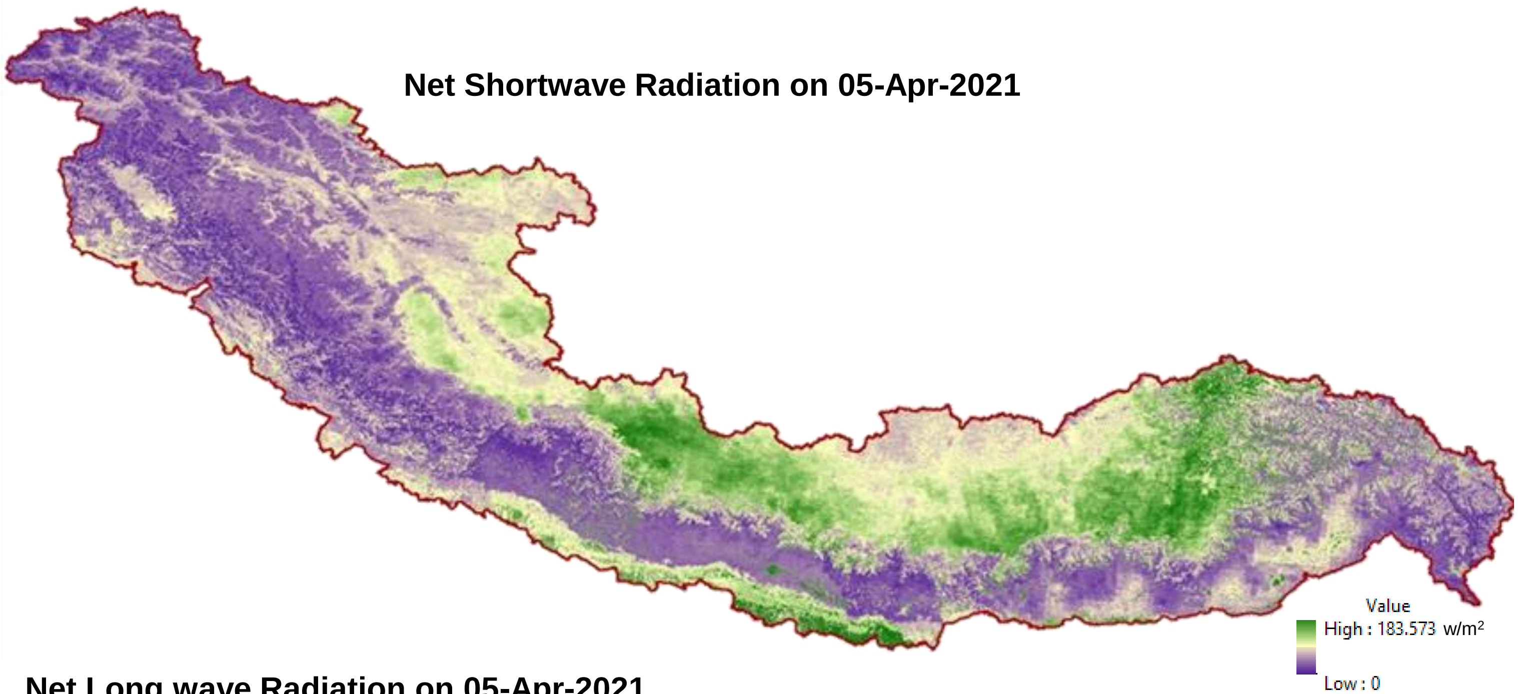


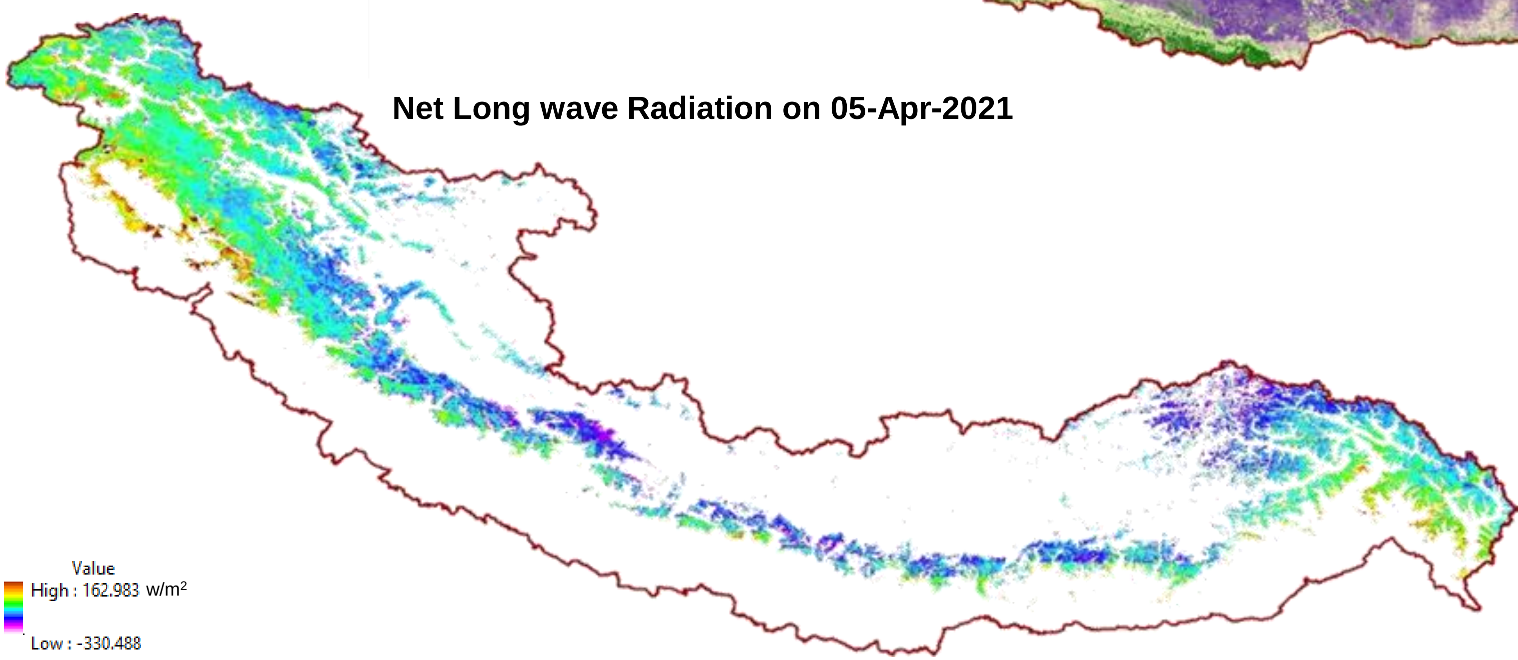
Cloud Mask

- ✓ Spatial Resolution - 4km X 4km
- ✓ Temporal Resolution – Hourly

Snow Cover Dynamics and Snowmelt Runoff Products & Services

Net Shortwave Radiation

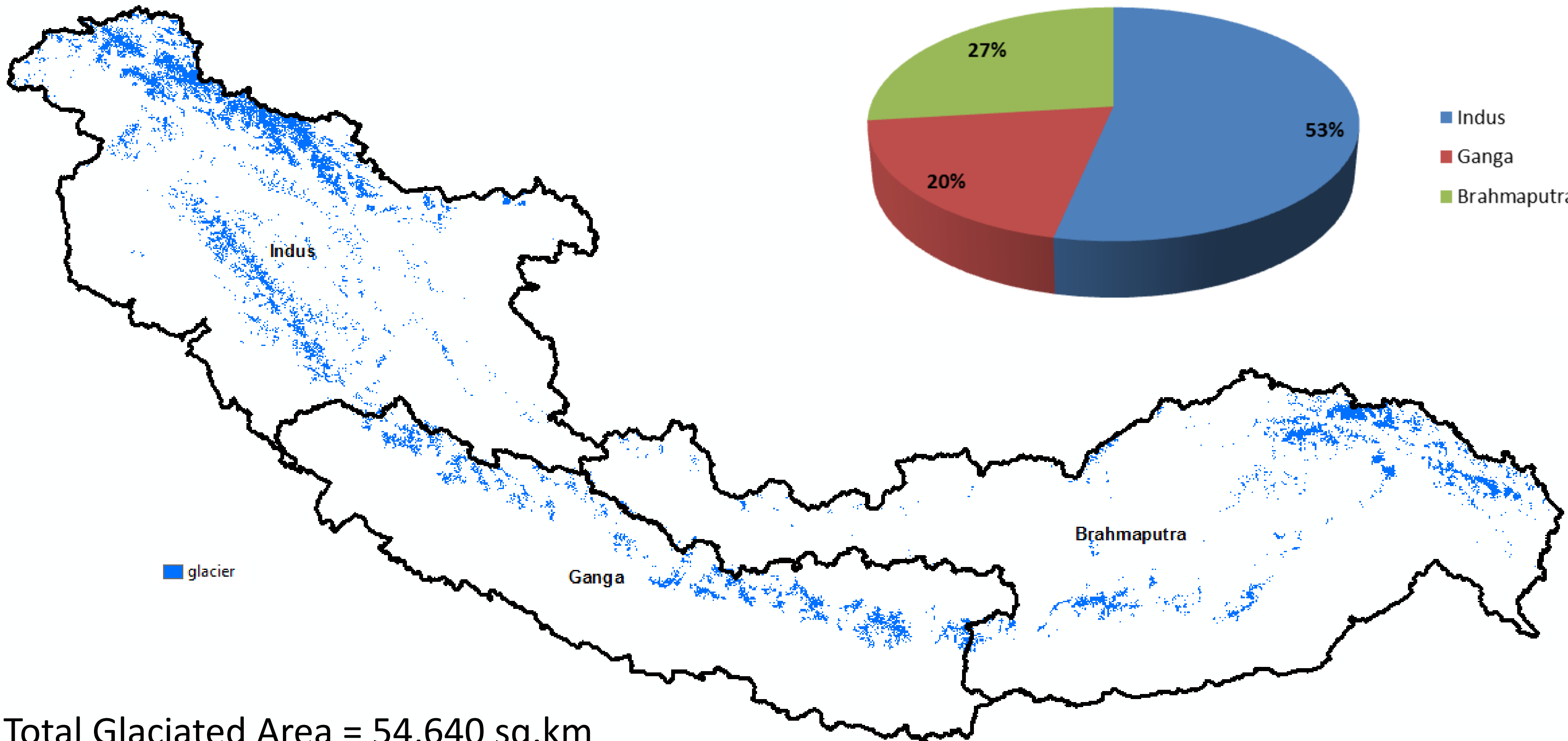




Net Longwave Radiation

Glaciers

Glaciers mapped from GLIMS , ICIMOD, and RGI for Indian Himalayas region



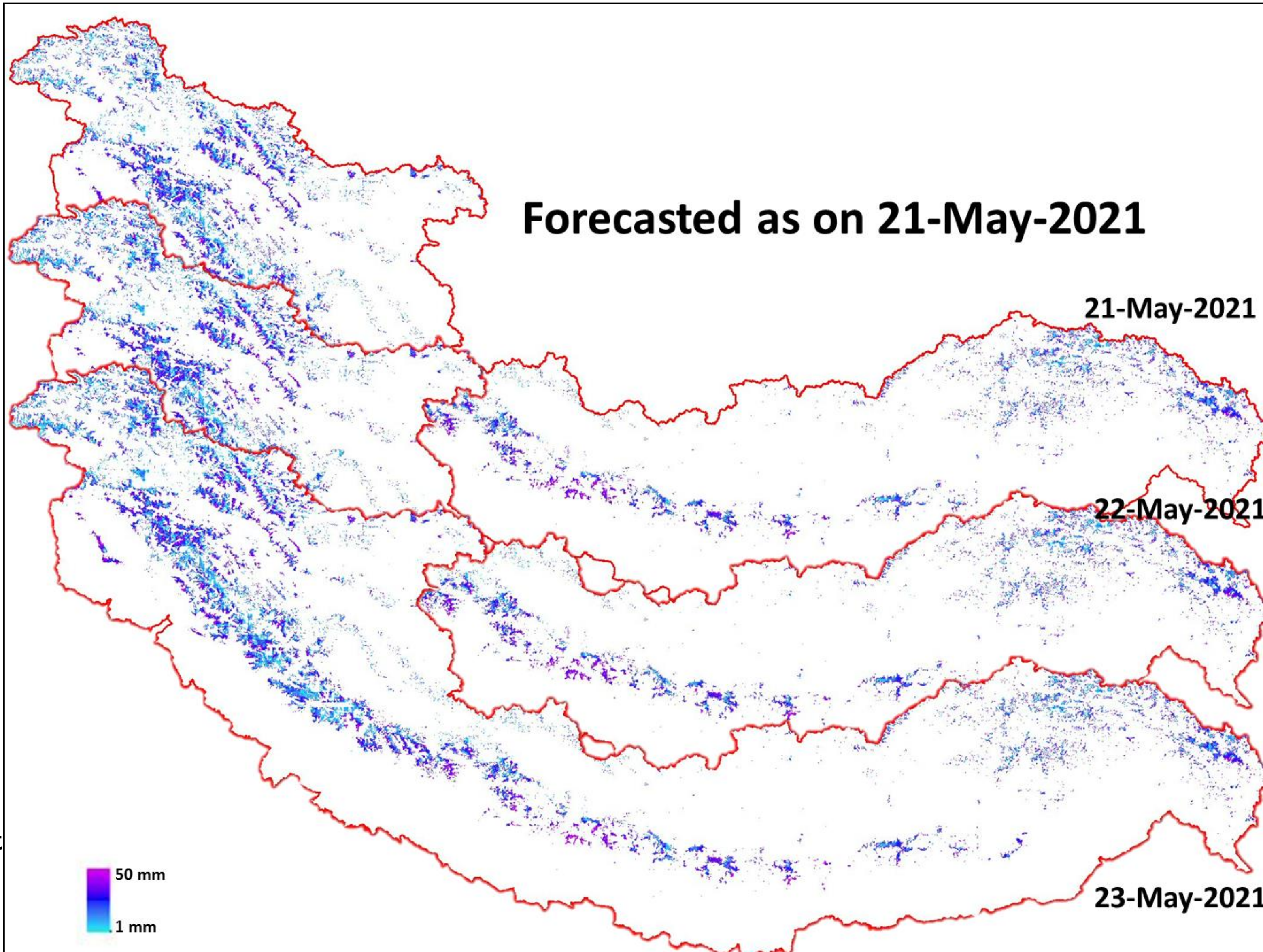
Total Glaciated Area = 54,640 sq.km

Global Land Ice Measurements from Space (GLIMS)
International Centre for Integrated Mountain Development (ICIMOD)
Randolph Glacier Inventory (RGI) version 6

- ✓ Glacier melt computed using empirical approach

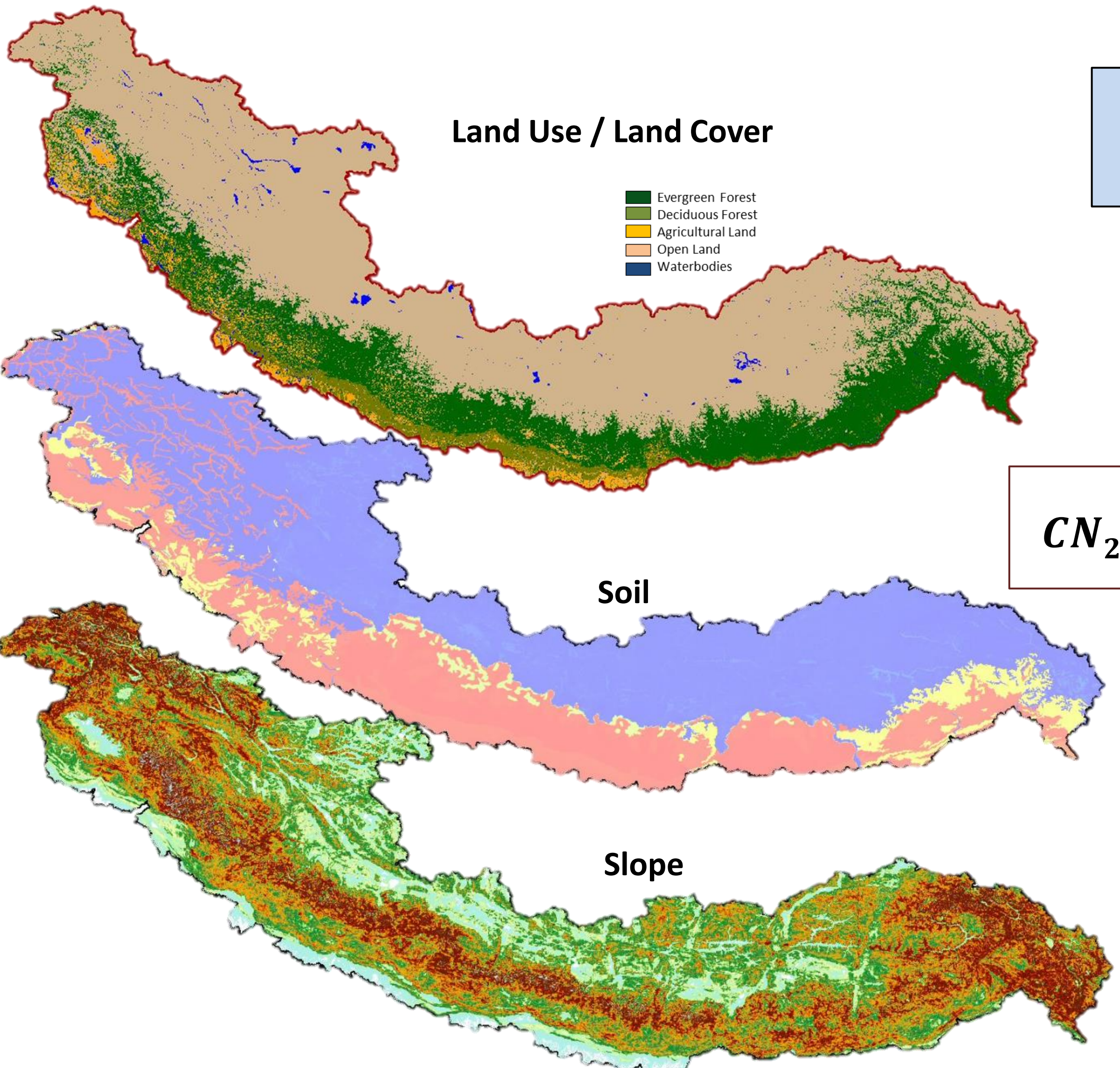
Snow Cover Dynamics and Snowmelt Runoff Products & Services

Snowmelt Runoff Forecast



Snowmelt Forecast (mm/day)

Rainfall-Runoff Modelling



Slope Corrected SCS Curve Number Method

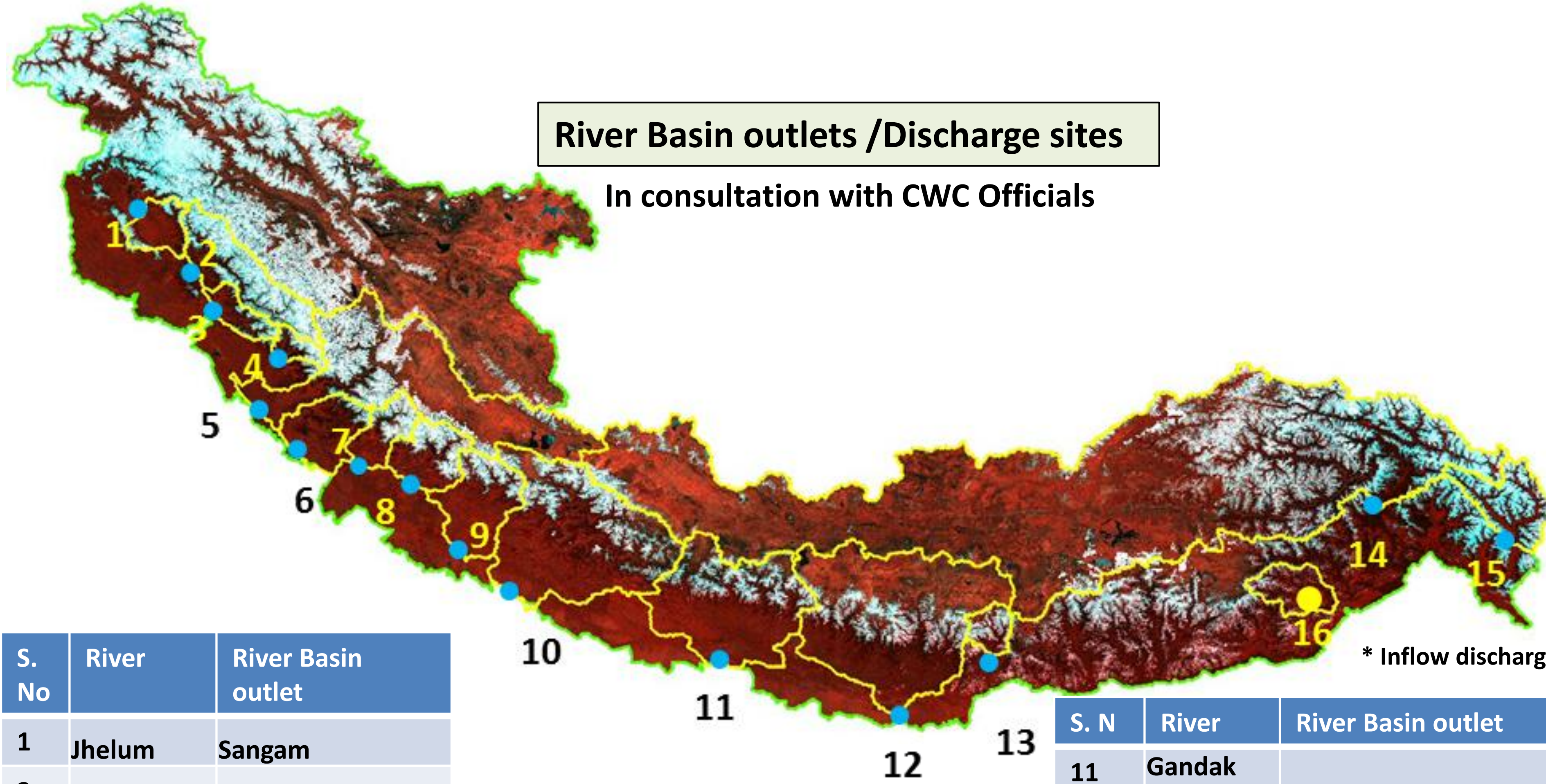
Huang et al 2006

$$CN_{2\alpha} = CN2 + \frac{322.79 + 15.63\,\alpha}{\alpha + 323.52}$$

Source: NBSS&LUP; HWSD soil database

✓ Rainfall occurrence assumed in regions < 4500m

Snow Cover Dynamics and Snowmelt Runoff Products & Services



River Basin outlets /Discharge sites

In consultation with CWC Officials

* Inflow discharge

S. No	River	River Basin outlet
1	Jhelum	Sangam
2	Chenab	Premnagar
3	Ravi	Chamera Dam*
4	Beas	Bhuntar
5	Satlej	Bakra*
6	Yamuna	Hatnikund*
7	Bhagarathi	Tehri Dam*

S. N	River	River Basin outlet
8	Alaknanda	Rudraprayag
9	Sarda	Banbasa barrage*
10	Ghaghara	Girija barrage*
11	Gandak barrage	Gandak barrage*

S. N	River	River Basin outlet
11	Gandak barrage	Gandak barrage*
12	Kosi	Kosi barrage*
13	Teesta	Teesta Lower Dam –III*
14	Dihang	Tuting
15	Lohit	Kibithu
16	Subansiri	Lemeking / Tamen

Approach for 3-day Forecasting

Adopted the following approach for inputs

1. All snow inputs (SCA, SA, LST, AOD, Ozone, WV) of previous day is considered as same for next 3days of forecast
2. Rainfall forecast for next 3 days
3. Air Temperature forecast for next 3 days

Daily Snow Product Generation Schedule

Suomi-NPP satellite products
- Snow Cover Area
- Snow Albedo
- Snow Surface Temperature

T-1
18:00

T
05:00

INSAT satellite products
- AOD
- Water Vapour
- Ozone
- Cloud Mask

GEFS forecast products
- Rainfall forecast
- Air Temperature forecast

T
11:00

Snow products
- SCA
- Snowmelt rate
- Snowmelt rate forecast

T
12:00

Assumptions and Limitations

- Net SW Radiation and net LW Radiation estimated, out of all (7) EB components. For other EB components, it is assumed that they constitute about 40% of total energy input – based on literature
- Empirical formula used for estimation of cloud cover effects on SW and LW radiation
- Suitable coefficients for Land cover classes are assumed for estimation of SW and LW radiation
- Empirical relationship was used to estimate air emissivity as a function of air temperature.
- It is assumed that rain fed area in Himalayan basins is generally below 4,500 m in elevation.
- Glacier melt is assumed to occur from middle of May. Glacier melt is estimated assuming suitable runoff coefficients considering the total glacier area within the basin. However, the level of exposure of glaciers may vary temporally and spatially. Year to year this exposure may differ.
- Even though cloud cover effect on net radiation, SCA, SA, LST is minimised, it may vary in actual conditions
- LST captured at 1030 Hrs is assumed to represent mean temperature of the day.
- Non-availability of snow depth and SWE data at fine resolution is major limitation
- Observed discharge at 0800 Hrs is assumed to represent that day's average discharge at that station. This assumption may not be valid as the discharge varies during the day.

Snow Cover Dynamics and Snowmelt Runoff Products & Services

Utility of Snow Products

- Irrigation, Hydropower & Drinking water allocations
- Planning and Management of Reservoir Operations
- Planning of new hydropower projects
- Essential Climate Variable (ECV) for climate change studies
- Planning of new transport network

THANK YOU