Distributed Hydrological Modeling in Cold Regions

2014.09.17

WEB-DHM-S model – physical and technical details, applicability discussion

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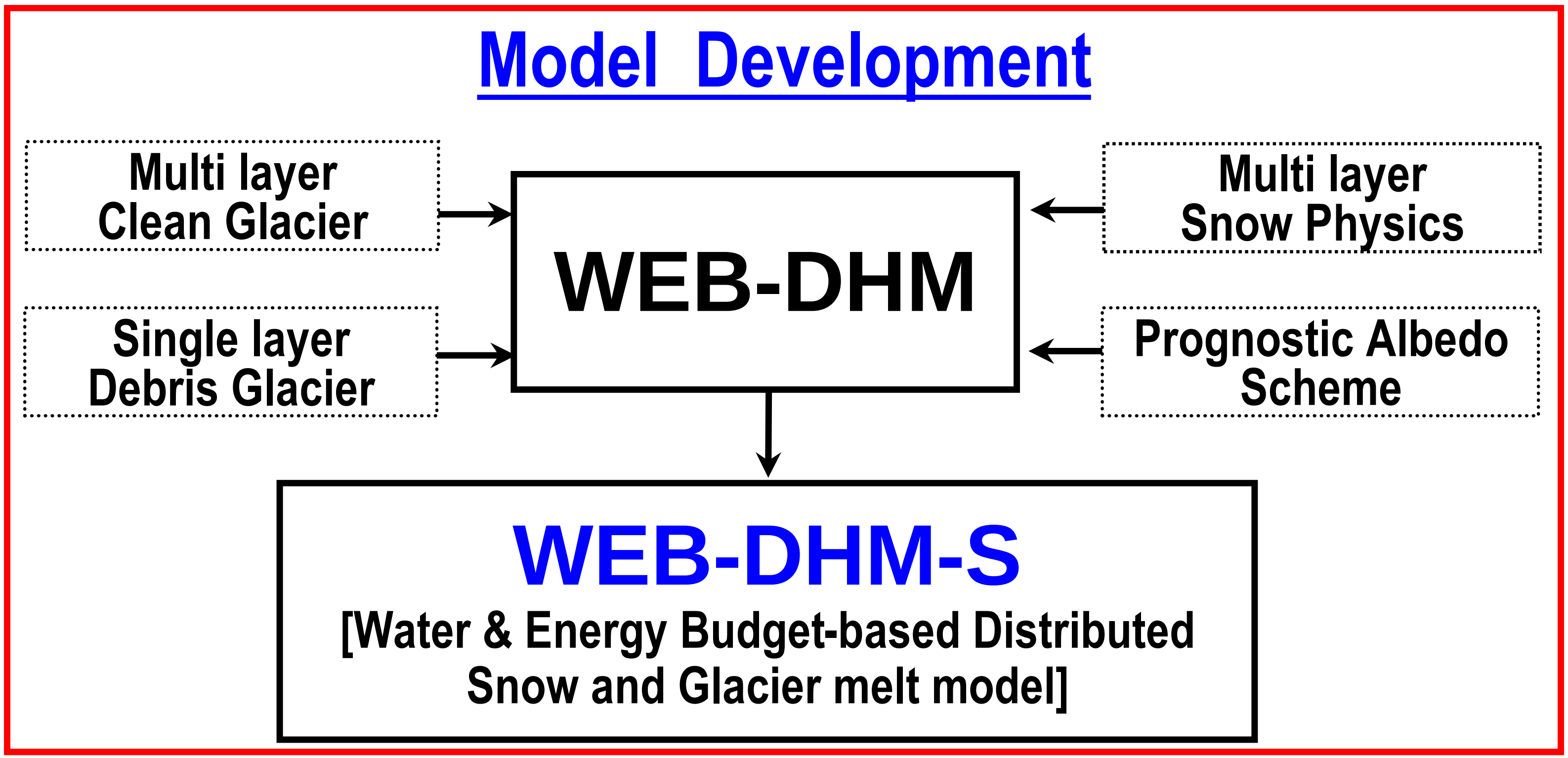
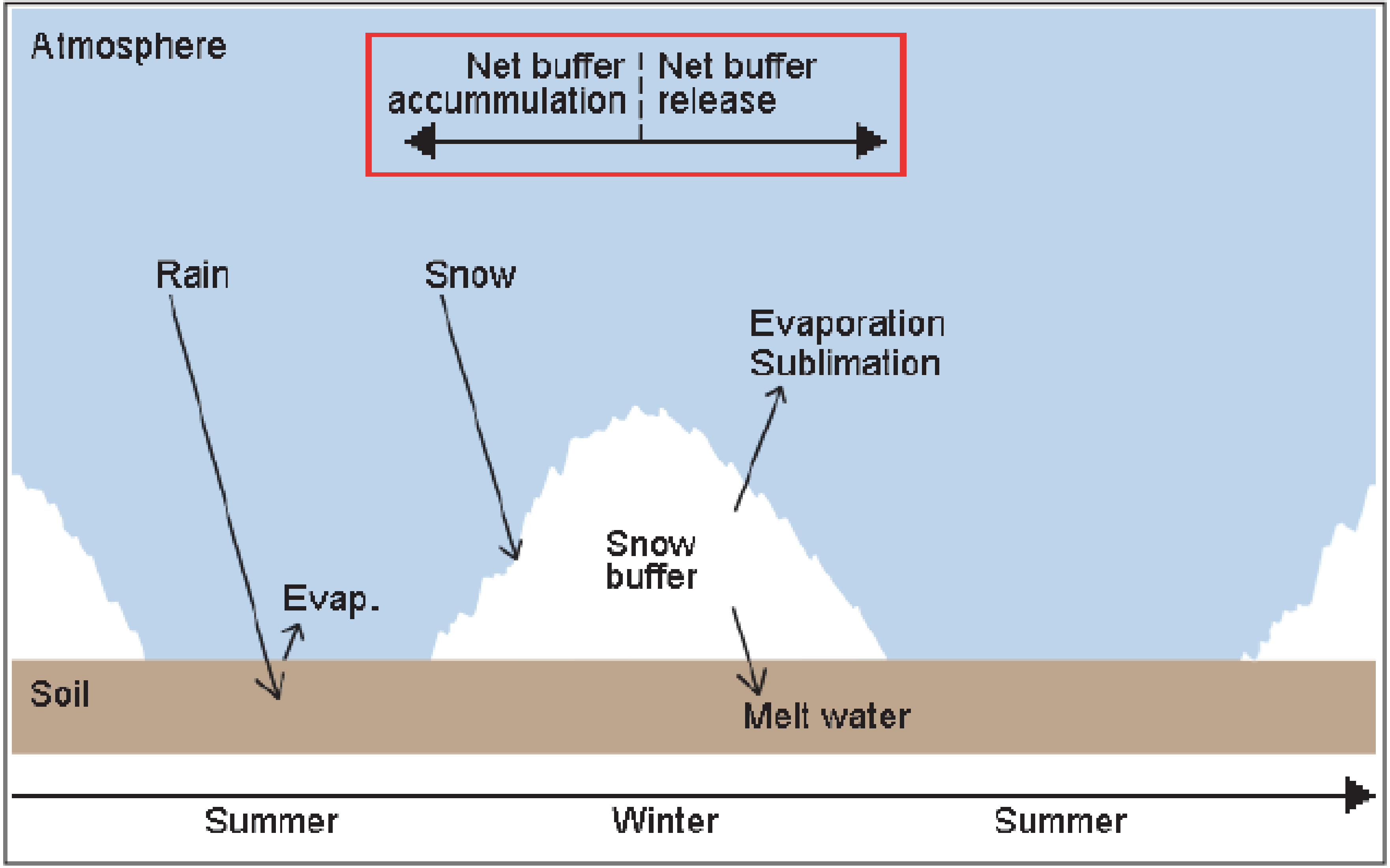
WEB-DHM-S Model



Seasonal snow – temporary buffer for precipitation



source: ETH Lecture

Snowdepth measurement

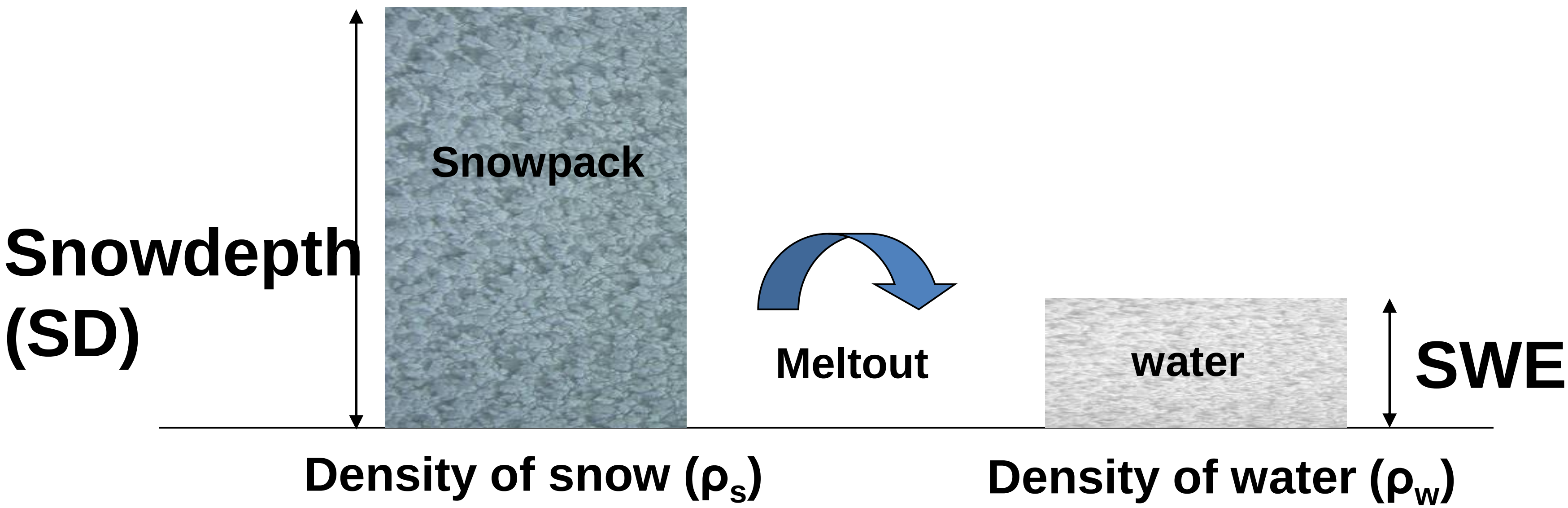
Using snowboard

Ultrasonic sounder

Other: Laser mapping

Snow water equivalent (SWE)

- SWE is the water balance parameter in hydrological models.
- SWE is the amount of water contained within the snowpack.
- It can be thought of as the depth of water that would theoretically result if the entire snowpack was melted out instantaneously.



$$SD \times \rho_s = SWE \times \rho_w$$

Snow Density

$$SD \times \rho_s = SWE \times \rho_w$$

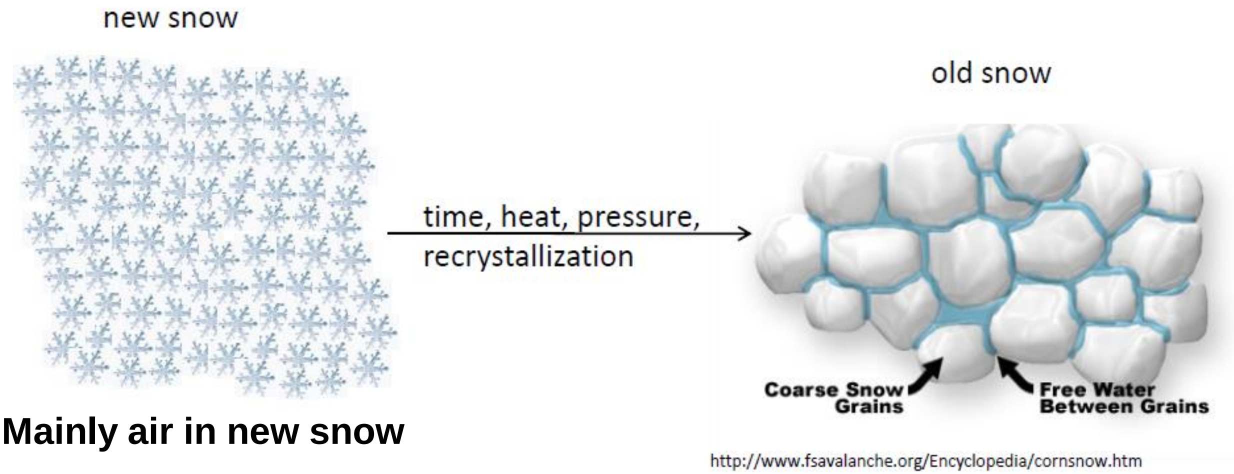
Density varies from 50 to 500 kg/m3

New snow is light – low density
Old snow is heavy – high density

<u>Why old snow is heavy ?</u>

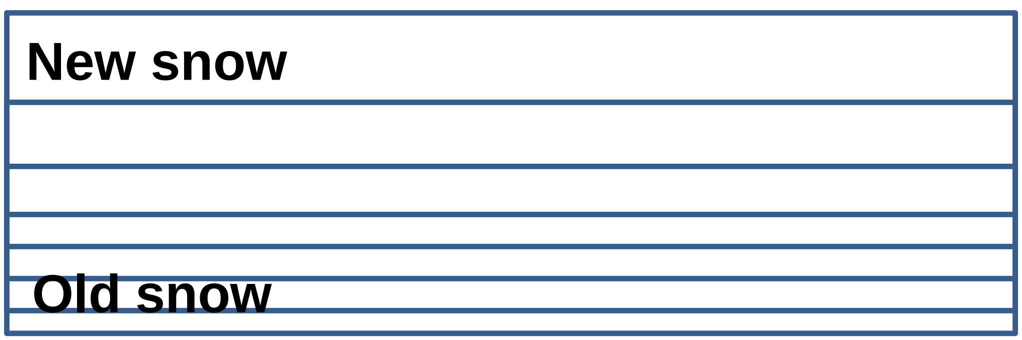
Snow Metamorphism
Water from snow melt
Overburden compaction

Snow Compaction – Snow Density



Mainly air in new snow

Metamorphism



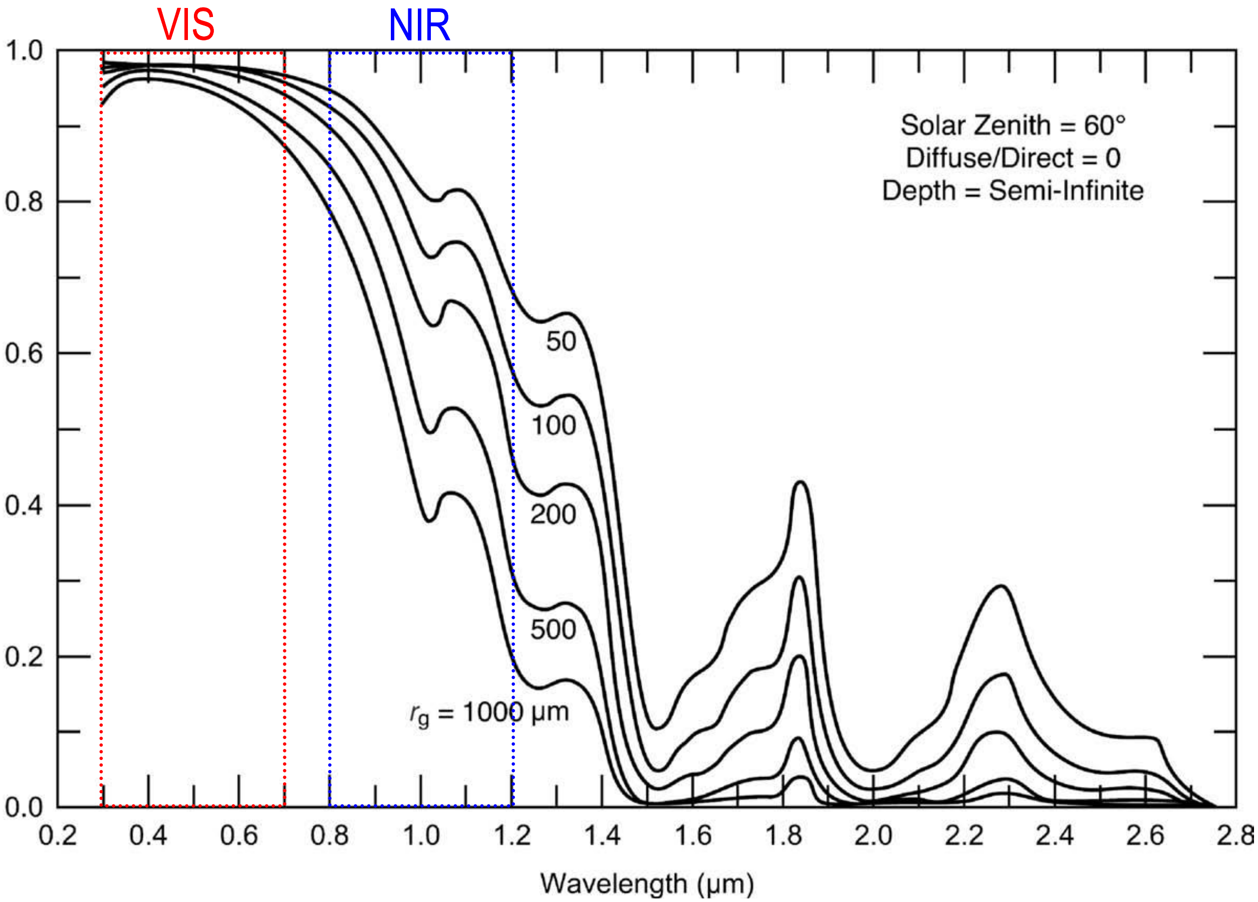
Overburden

Amount of water increases in snow and density increases

Melt

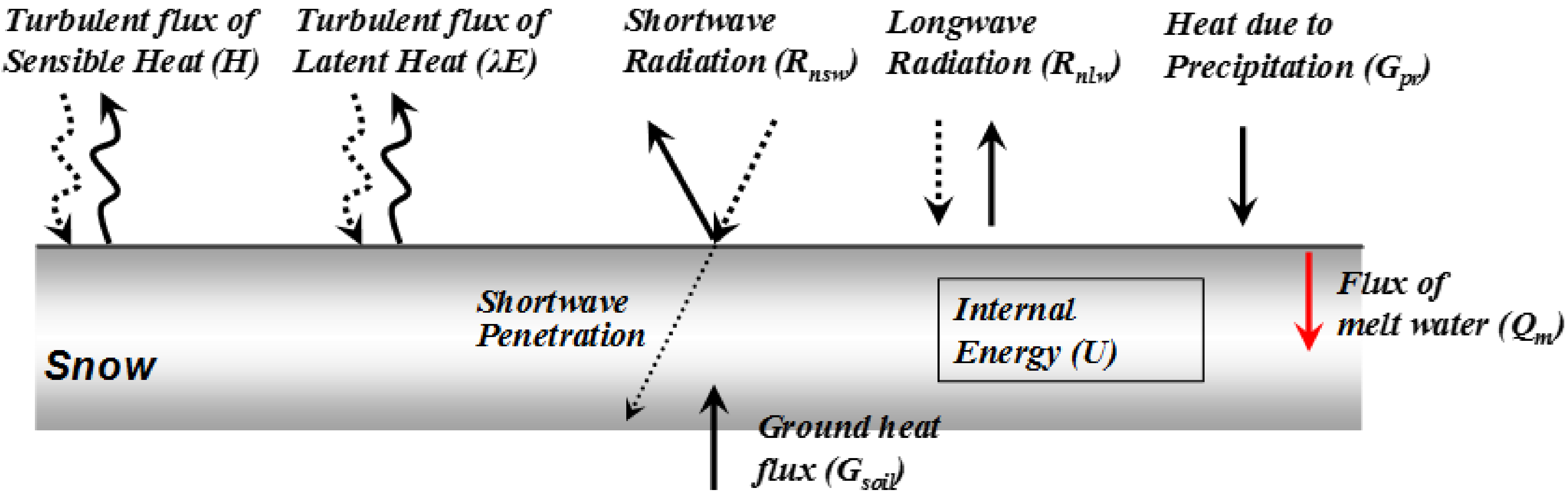
Snow Albedo

Albedo = Reflectance



Why snow is white?

Snow Energy Balance



$$Q_m = R_n - H_{sn} - \lambda E_{sn} + G_{pr} - G_{soil} - \frac{\partial U}{\partial t}$$

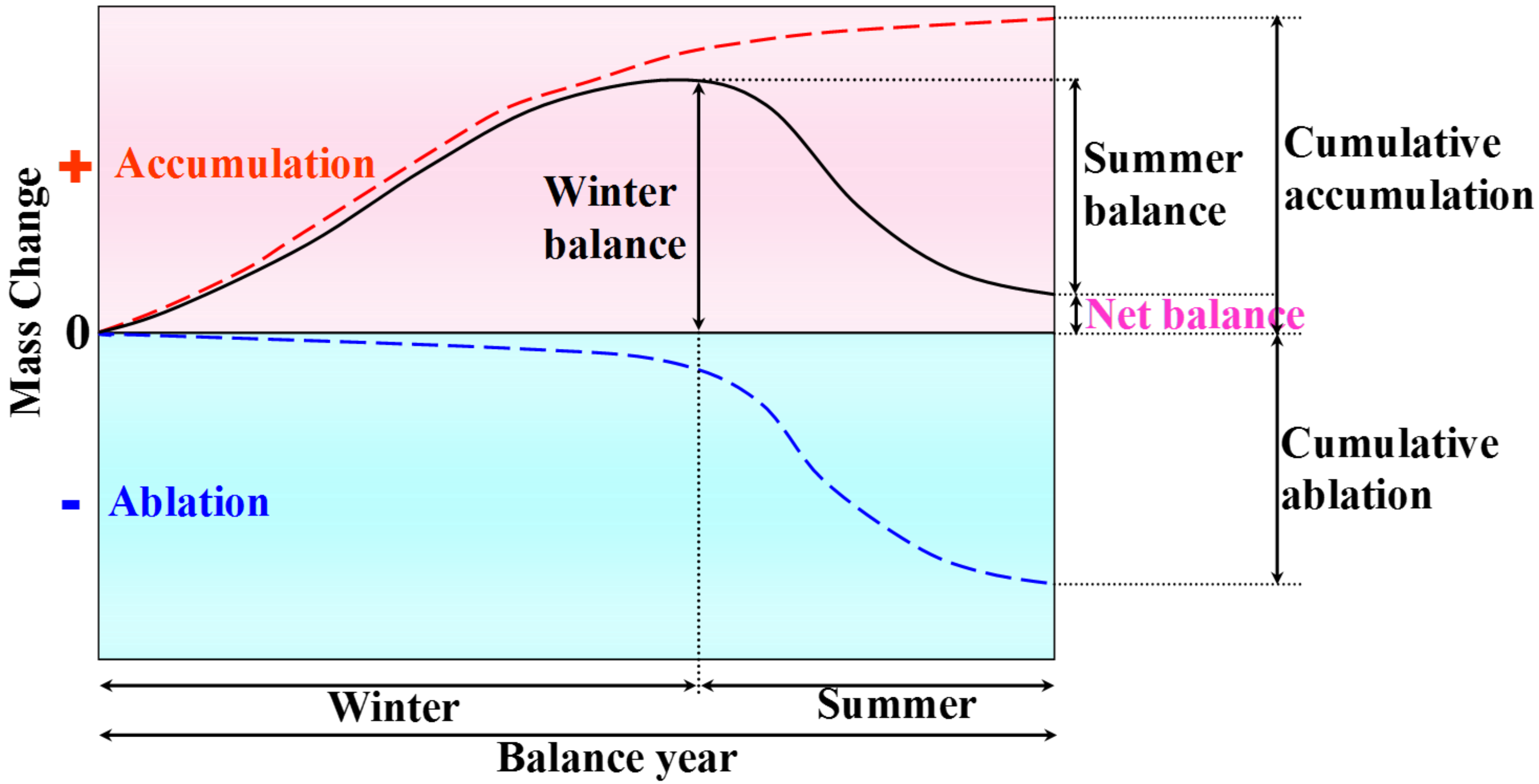
Permanent snow(firn)/Glacier

If the snow cover is not completely melted away in the summer season and persists until the following accumulation period, it is referred to as permanent snow cover/firn. Firn can be defined as wetted snow that has survived one summer without being transformed to ice [Paterson, 1994].

As metamorphism proceeds, the interconnecting air passages between the grains are closed off, and a state of glacier ice is reached which visibly moves under its own weight in response to gravitational force [Paterson 1994; Singh and Singh, 2001]

Types
Temperature – Temperate (0 degree) and cold region
Surface characteristics - Clean and Debris covered

Glacier Mass Balance



Idealized seasonal cycle of glacier mass balance [after Paterson, 1994].

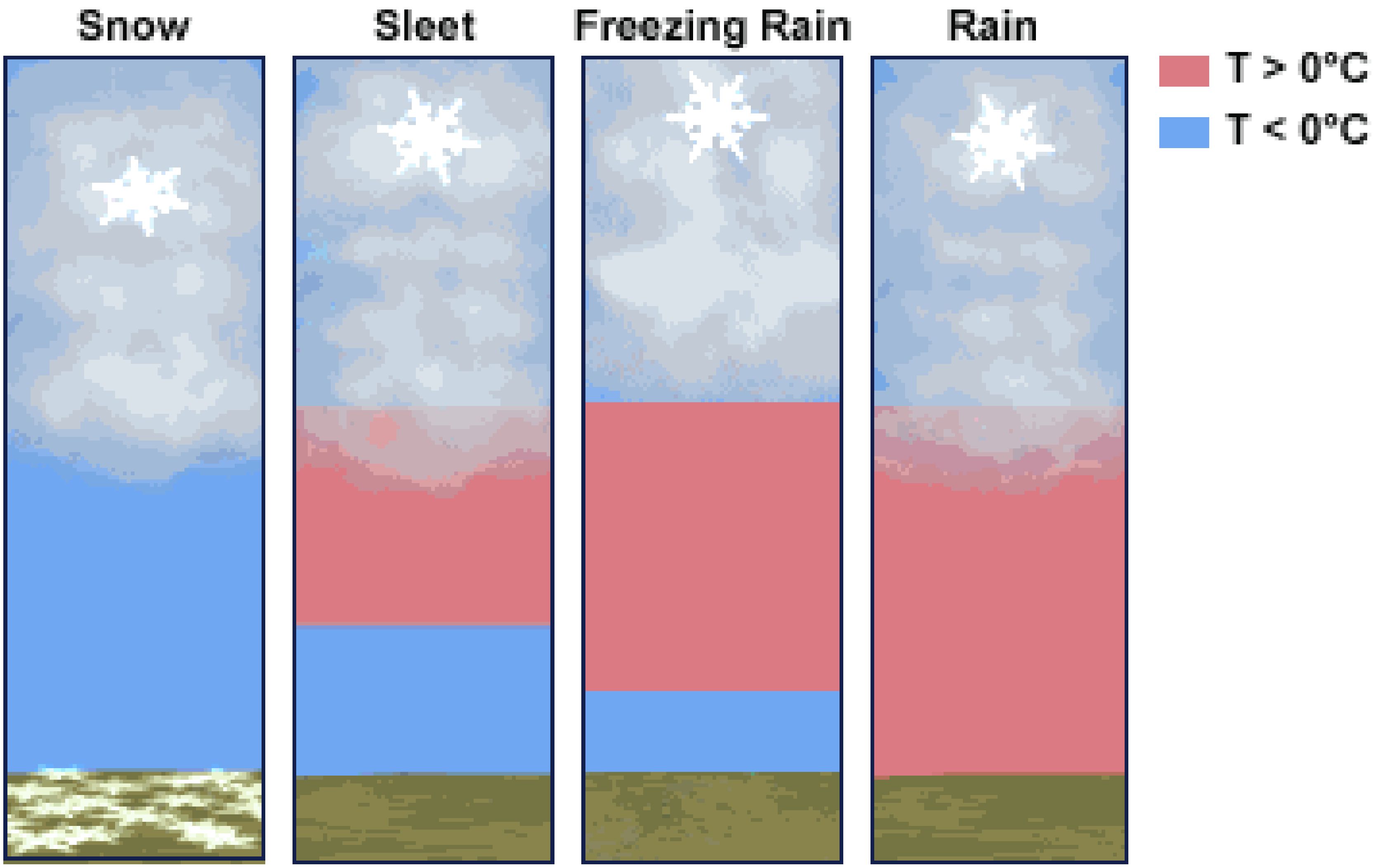
Albedo Values

Surface Type	Albedo range	Mean value
Dry snow	0.80 – 0.97	0.84
Melting snow	0.66 – 0.88	0.74
Firn	0.43 – 0.69	0.53
Clean ice	0.34 – 0.51	0.40
Slightly dirty Ice	0.26 – 0.33	0.29
Dirty ice	0.15 – 0.25	0.21
Debris covered Ice	0.10 – 0.15	0.12

[after Paterson, 1994]

Snow/Glacier state evolution

Snow/Rain Threshold



The COMET Program

Snow/Rain Threshold

Tair > Tcr , Rainfall
Tair ≤ Tcr, Snowfall
Tcr = -1 to 2, normally 0°C

Advanced parameterization (Kienzel, 2008; Sugaya, 1991)

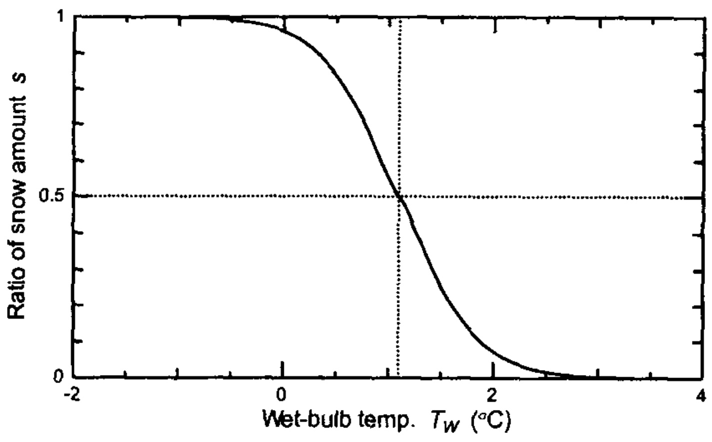


Fig. 2. Relationship between the ratio of snowfall amount and wet-bulb temperature.

(Sugaya, 1991)

$$s(T_W) = 1 - 0.5\exp(-2.2(1.1 - T_W)^{1.3}) \quad (T_W < 1.1°\mathrm{C})$$
$$s(T_W) = 0.5\exp(-2.2(T_W - 1.1)^{1.3}) \quad (T_W \geq 1.1°\mathrm{C}),$$

$$T_W = 0.584T_a + 0.875e - 5.32,$$

Modeling works

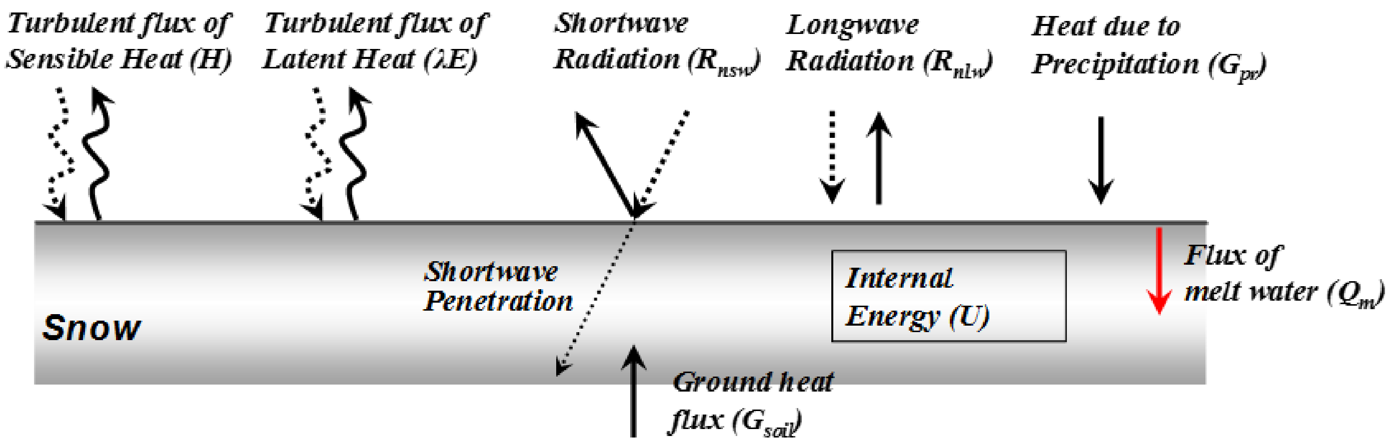
Degree Day Model

Just a function of temperature
Simple, Empirical
Degree day factor parameter
MELT = DDF * Tair

DDFsnow, DDFice, DDFdebris
Region specific
Needs to be calibrated

Lumped model: SRM, HBV
Distributed hydrological model
SWAT, MIKE-SHE, GBHM ….

Energy Balance Model



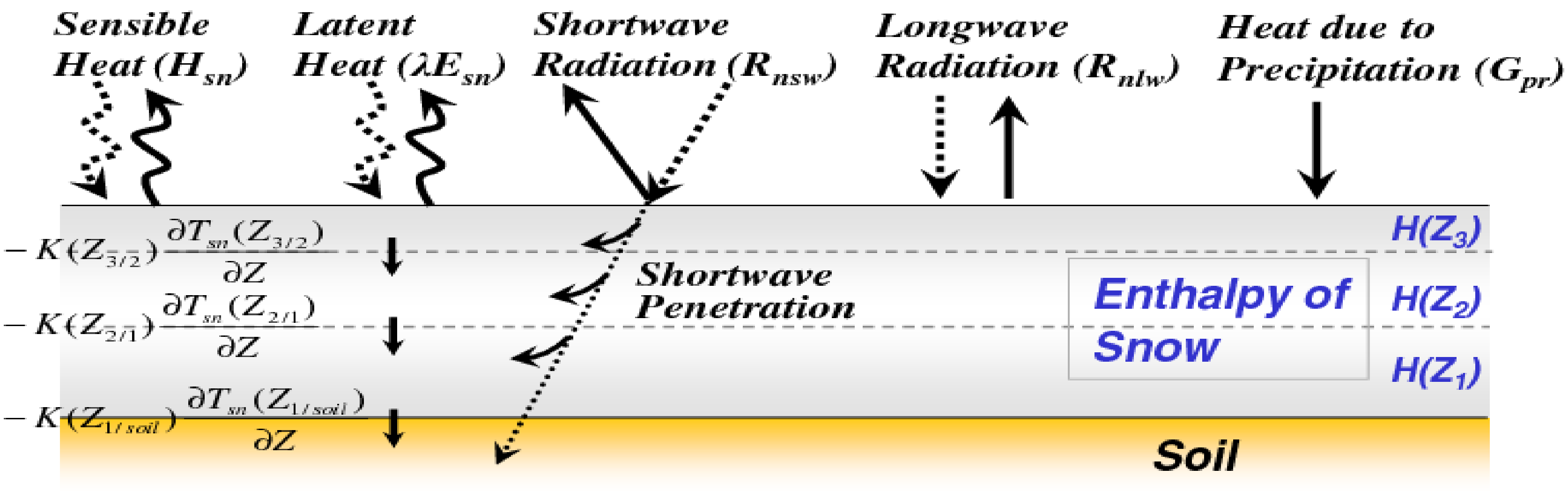
$$Q_m = R_n - H_{sn} - \lambda E_{sn} + G_{pr} - G_{soil} - \frac{\partial U}{\partial t}$$

$$Melt = \frac{Q_m}{\rho_w h_v}$$

Where hv is the latent heat of fusion

Single to Multi-layered model

In WEB-DHM-S



$$H(Z_j) = C_v(Z_j).[T_{sn}(Z_j) - 273.16] - f_{ice}(Z_j).h_v.\rho_s(Z_j)$$

$$\frac{\partial H(Z_j)}{\partial t} = -\frac{\partial G_{sn}(Z_j)}{\partial Z}$$

$$G_{sn}(Z_j) = \begin{cases} R_{nsn} - H_{sn} - \lambda E_{sn} + G_{pr} & (j = 3) \\ K(Z_j)\dfrac{\partial T_{sn}(Z_j)}{\partial Z} + SW_{sn}(Z_j) & (j = 2,1) \end{cases}$$

Albedo in WEB-DHM-S (Dickinson et al., 1993)

$$\text{Fresh snow albedo (VIS)},\ \alpha_{vis0} = 0.95$$

$$\text{Fresh snow albedo (NIR)},\ \alpha_{nir0} = 0.65$$

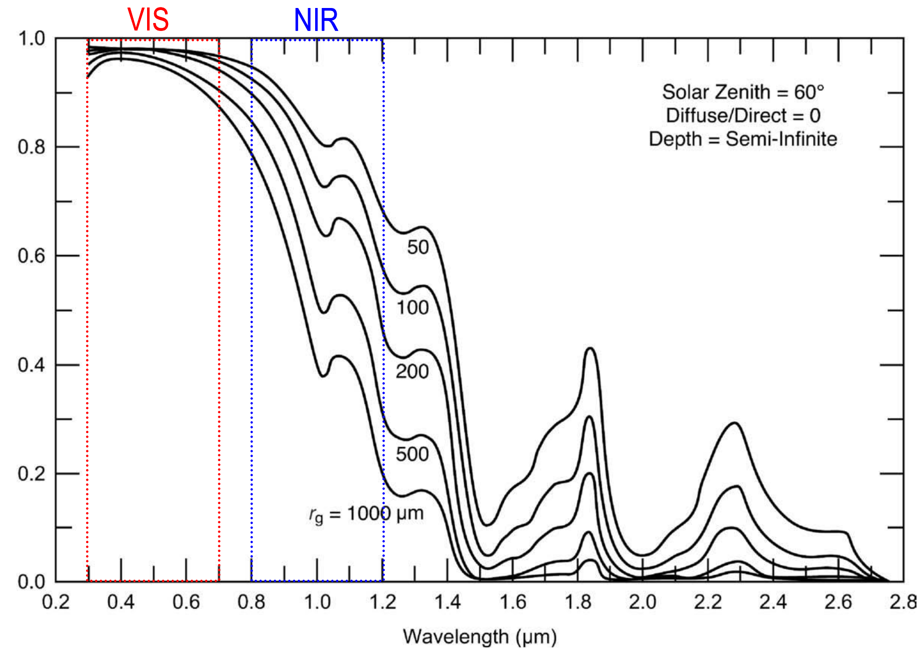
$$\alpha_{vd} = \alpha_{vis0} \times (1 - 0.2 \times f_{age})$$

$$\alpha_{nird} = \alpha_{nir0} \times (1 - 0.5 \times f_{age})$$

$$\alpha_{vis} = \alpha_{vd} + 0.4 \times f_{zen} \times (1 - \alpha_{vd})$$

$$\alpha_{nir} = \alpha_{nird} + 0.4 \times f_{zen} \times (1 - \alpha_{nird})$$

$$f_{zen} = \frac{1}{2}\left[\frac{3}{1 + 4Cos\theta_z} - 1\right] \qquad \begin{array}{l} Cos\theta_z \geq 0.5,\ f_{zen} = 0 \\ Cos\theta_z = 0,\ f_{zen} = 1 \end{array}$$



Snow aging factor (f_{age})

$$f_{age} = \frac{\tau_s}{(1 + \tau_s)}, \qquad \tau_s^{t+\Delta t} = (\tau_s^{t} + \Delta\tau_s)[1 - 1000P_s]$$

$$\Delta\tau_s = \frac{(r_1 + r_2 + r_3)\Delta t}{\tau_0} \qquad \begin{array}{|l} \tau_0 = 1 \times 10^6 s \\ r_1 = \exp\left[5000\left(\frac{1}{273.16} - \frac{1}{T_{sn}}\right)\right] \\ r_2 = (r_1)^{10} \leq 1 \\ r_3 = 0.3 \end{array}$$

Effect of grain growth due to vapor diffusion (r1)
Effect due to freezing of melt water (r2)
Effect of dirt and soot (r3)

Compaction in WEB-DHM-S (Jordan et al., 1991)

$$\rho_s = \max\left\{ \left\lfloor 109 + 6 \times (T_{air} - 273.16) + 26 \times \sqrt{u_m} \right\rfloor, 50 \right\}$$ *(Brun et al., 1992)*

Density of Fresh snow ~ function of air temperature & wind speed

$$\left[\frac{1}{\Delta z}\frac{\partial \Delta z}{\partial t}\right]_{metamorphism} = -2.778 \times 10^{-6} \times C_3 \times C_4 \times \exp\left[-0.04 \times (273.16 - T_{sn})\right]$$

$$C_3 = \begin{cases} \exp\left[-0.046 \times (\gamma_i - 150)\right] & \gamma_i > 150 \\ 1 & \gamma_i \le 150 \end{cases}$$

$$C_4 = \begin{cases} 1 & \gamma_l = 0 \\ 2 & \gamma_l > 0 \end{cases}$$

$$\left[\frac{1}{\Delta z}\frac{\partial \Delta z}{\partial t}\right]_{overburden} = -\frac{W_s \times \exp\left[-C_5 \times (273.16 - T_{sn}) - C_6 \times \rho_i\right]}{\eta_o}$$

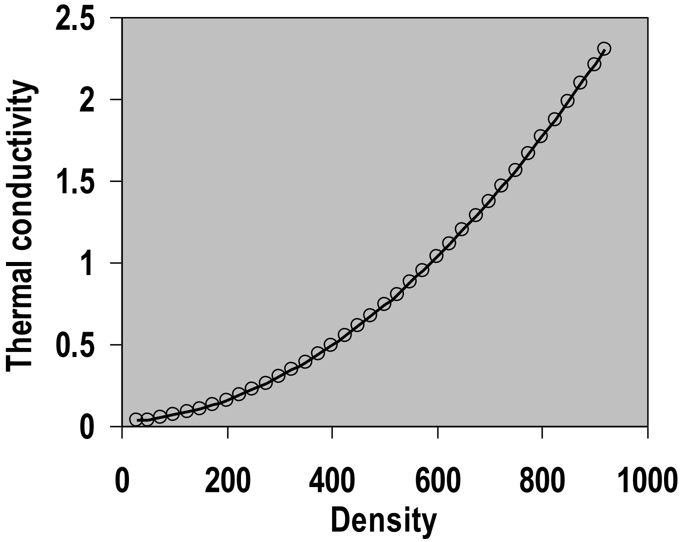
$$\left[\frac{1}{\Delta z}\frac{\partial \Delta z}{\partial t}\right]_{melt} = -\frac{dh_s}{h_s}$$

Thermal conductivity

$$K = K_a + \left(7.75\times10^{-5}\rho_s + 1.105\times10^{-6}\rho_s^{\,2}\right)\times\left(K_i - K_a\right)$$

where K_i (2.29 $Wm^{-1}K^{-1}$) and K_a (0.023 $Wm^{-1}K^{-1}$)

Dense snow, snow that is compacted or wet, loses much of its insulation value because it loses a lot of its trapped air.



Radiation penetration

$$SW_{sn}(Z_j) = \begin{cases} SW_{nsn}\times\left[1-\exp(-\beta_{vis}.Z_j - 0.002.\beta_{nir})\right] & \text{top layer} \\ SW_{nsn}\times\left[1-\exp(-\beta_{vis}.Z_j)\right]\times\exp(-\beta_{vis}.Z_{j+1} - 0.002.\beta_{nir}) & \text{middle layer} \\ SW_{nsn}\times\exp(-\beta_{vis}.Z_{j+1})\times\exp(-\beta_{vis}.Z_{j+2} - 0.002.\beta_{nir}) & \text{bottom layer} \end{cases}$$

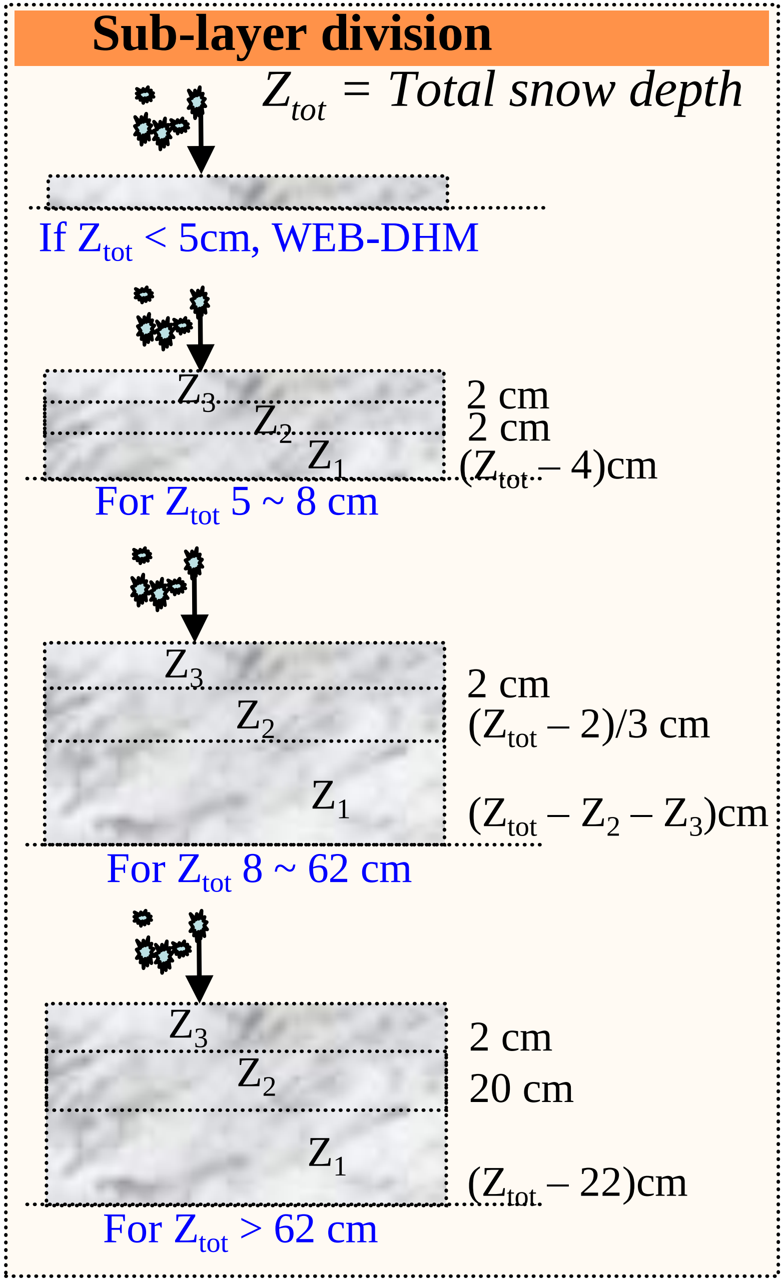
(Jordan, 1991)

Where, $\beta_{vis} = 0.003795 d^{-1/2}\rho_s(Z_j)$, $\beta_{nir} = 400$, d = grain size diameter

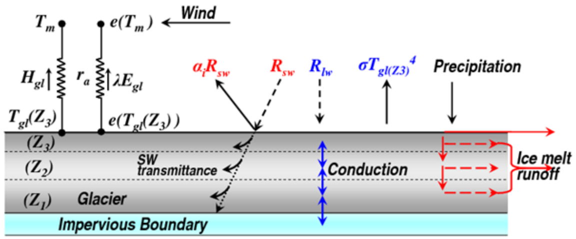
$$d = \begin{cases} 2.796\,mm & 400 \le \gamma_i \le 920 \\ 0.16 + 0.11(\gamma_i/1000)^4 & \gamma_i < 400 \end{cases}$$

High density = large grain size = radiation is more scattered in forward direction (into the snowpack), increasing absorption of radiation

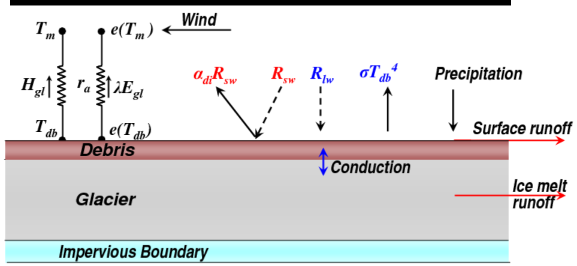
Layer Division



Integrated modeling System : WEB-DHM-S



Clean Glacier



Debris covered glacier

&
Seasonal Snow over these glaciers

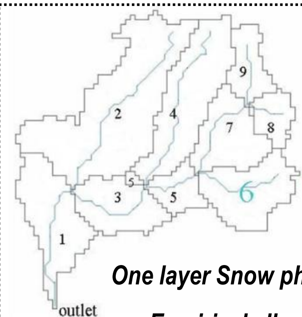
Shrestha et al., 2010, 2012, 2014

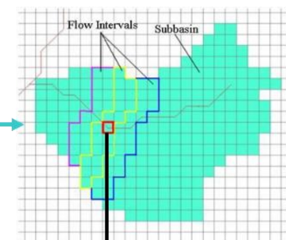
MODEL DEVELOPMENT

- Multi layer Clean Glacier
- Single layer Debris Glacier
- Multi layer Snow Physics
- Prognostic Albedo Scheme

→ **WEB-DHM** *(Wang et al, 2007)*

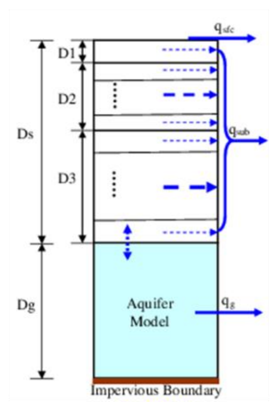
→ **WEB-DHM-S**
[Water & Energy Budget-based Distributed Snow and Glacier melt model]



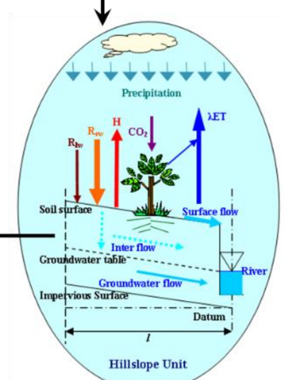


One layer Snow physics

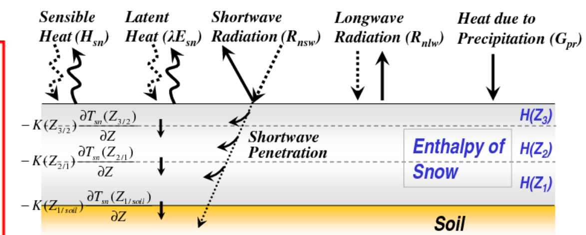
Empirical albedo



Soil Model



WEB-DHM (Wang et al, 2009)



Snow over Bare Land

Snow over forest

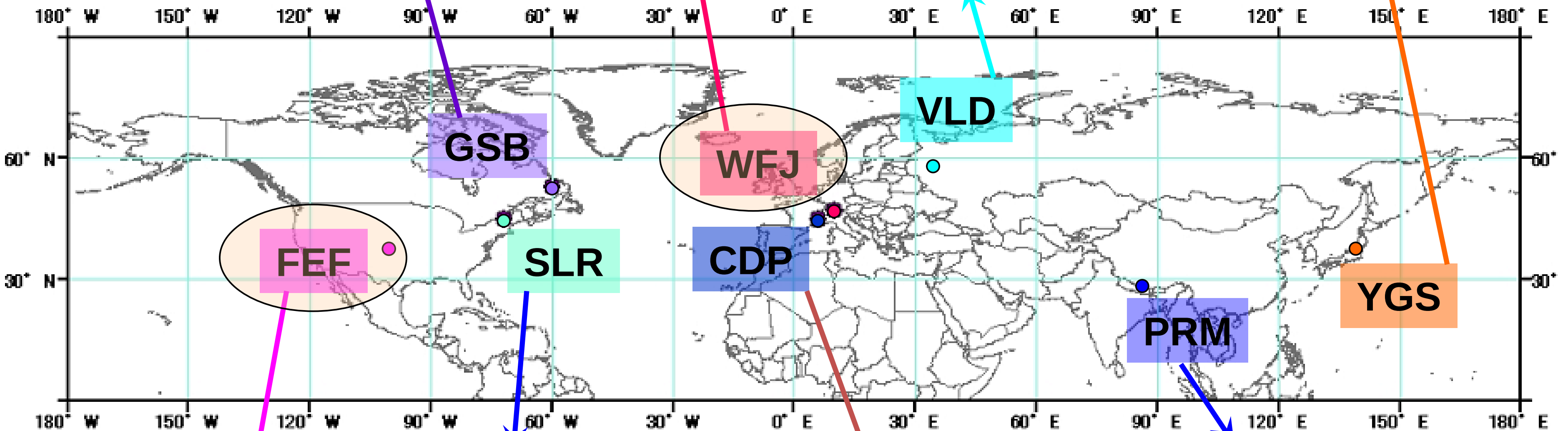
Point-scale Evaluation

Weissfluhjoch (1992-93)
Switzerland, Elev.: 2540m

Yagisawa (2000-04)
Japan, Elev.: 740m

Goose Bay (1969-83)
Canada, Elev.: 46m

Valdai (1966-83)
Russia, Elev.: 212m



Sleepers river (1996-97)
USA, Elev.: 552m

Pyramid (2002-2003)
Nepal, Elev.:5030m

Fraser Forest (2003-05)
USA, Elev.: 2820m

Col de Porte (1996-98)
France, Elev.:1340m

8 Sites

Open Swiss site: Snow Depth and SWE

WEB-DHM (Control Run)

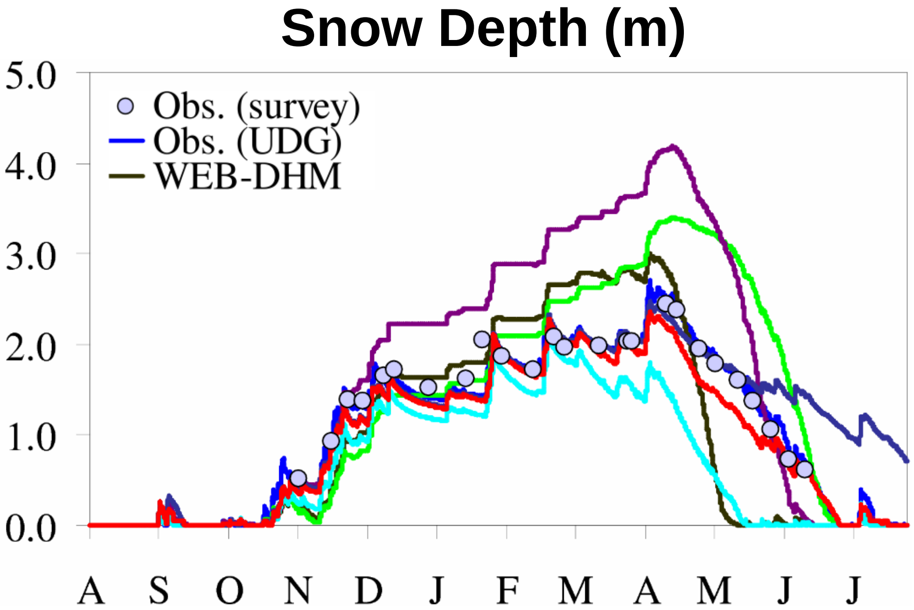
WEB-DHM + Realistic Constant Albedo (VIS: 0.85/NIR:0.65) -- Not Improved

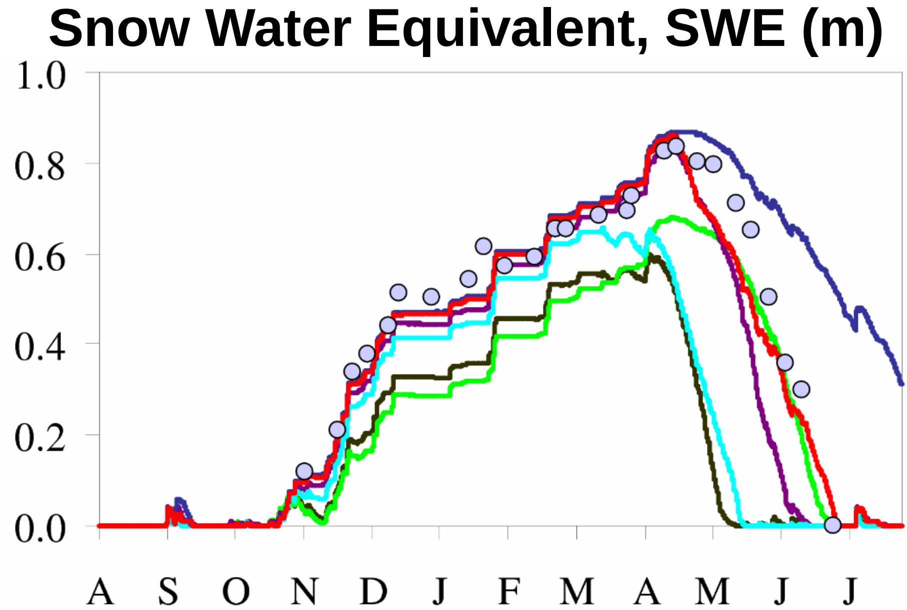
WEB-DHM + BATS Albedo scheme -- Only SWE Improved

WEB-DHM + 3 layer snow scheme -- Depth/SWE Improved but still early melt

WEB-DHM + 3 layer snow scheme + Realistic constant albedo -- Depth/SWE prolonged/overestimated

WEB-DHM + 3 layer snow scheme + BATS albedo = WEB-DHM-S -- Both SWE/depth Improved

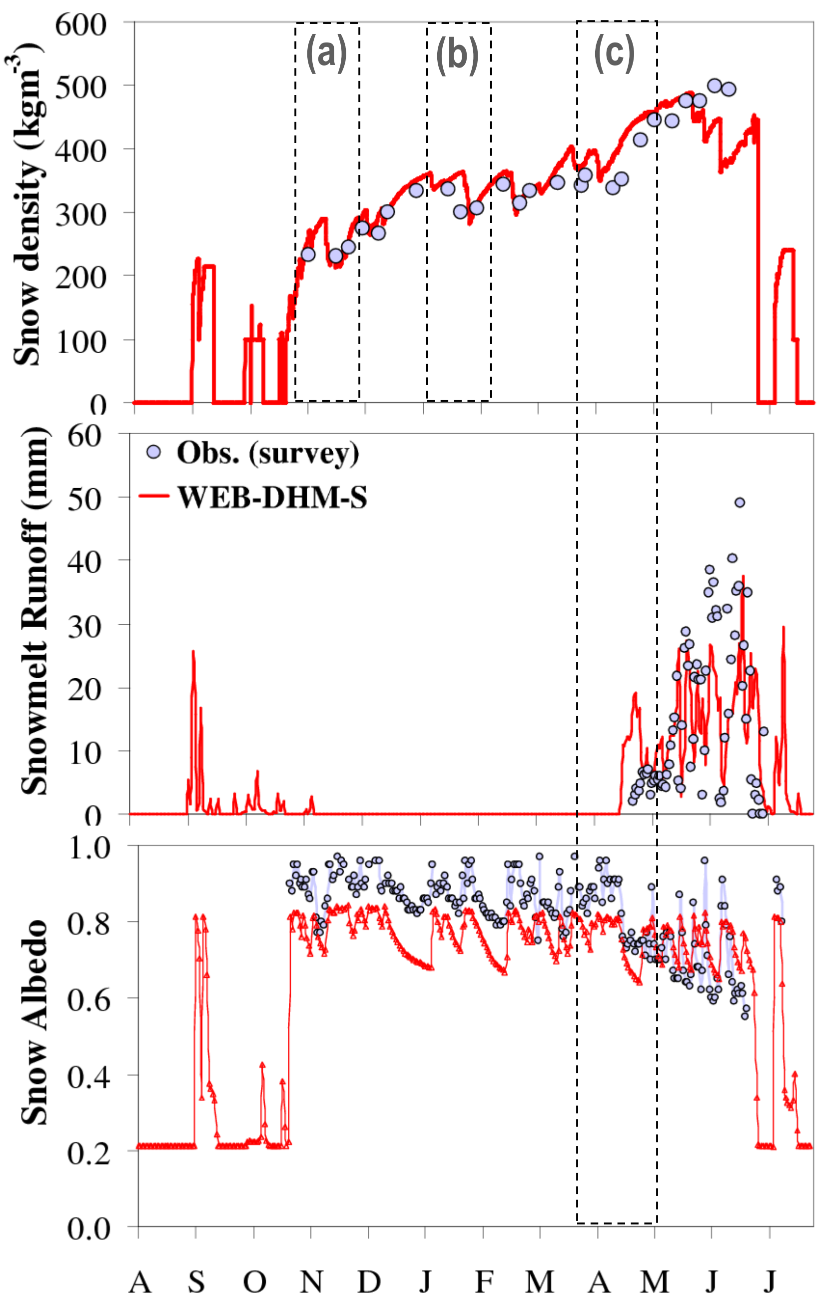


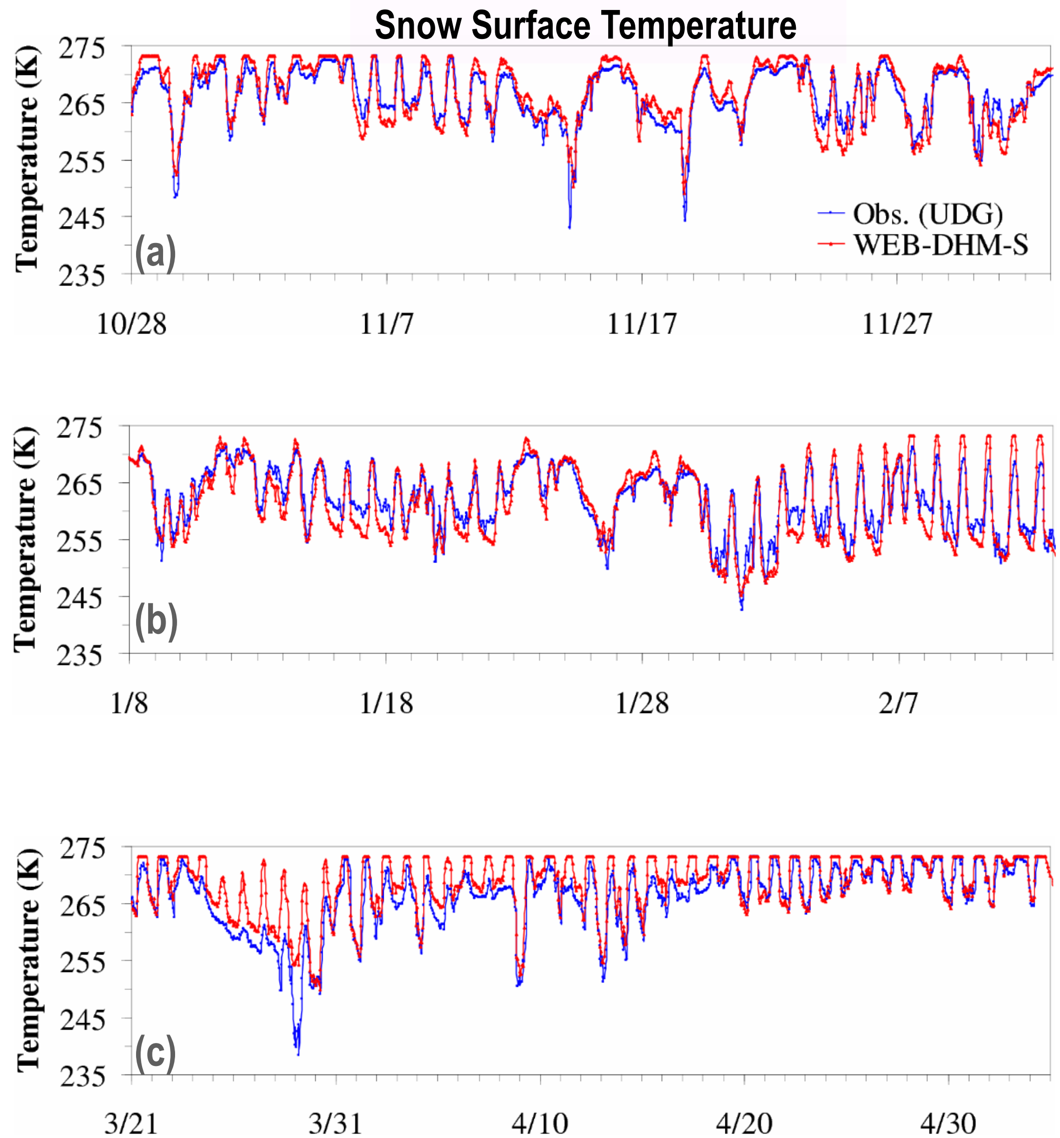


[Shrestha et al., 2010, HESS]

Albedo scheme and 3 layer snow scheme are equally

Density, Runoff, Albedo and Temperature

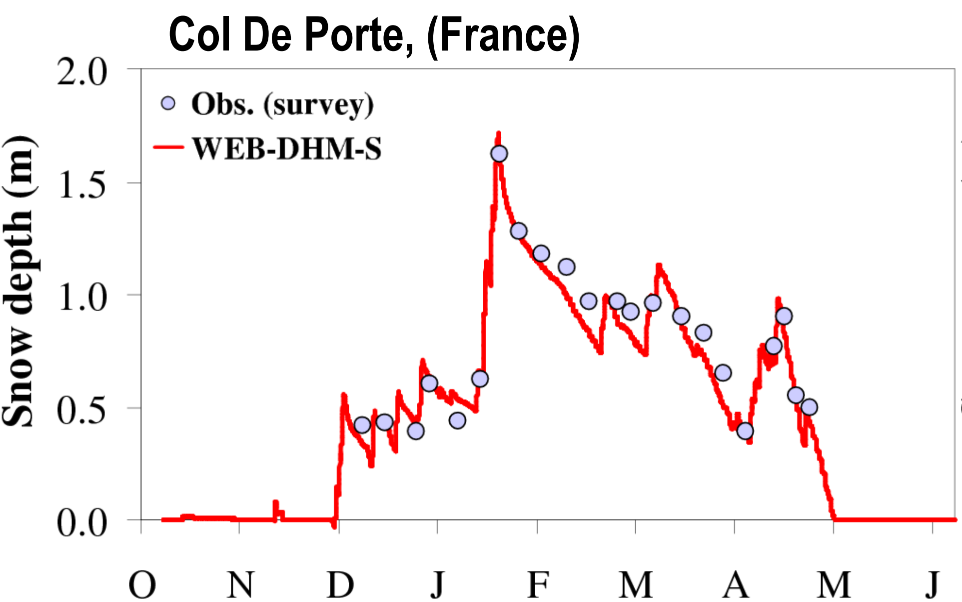


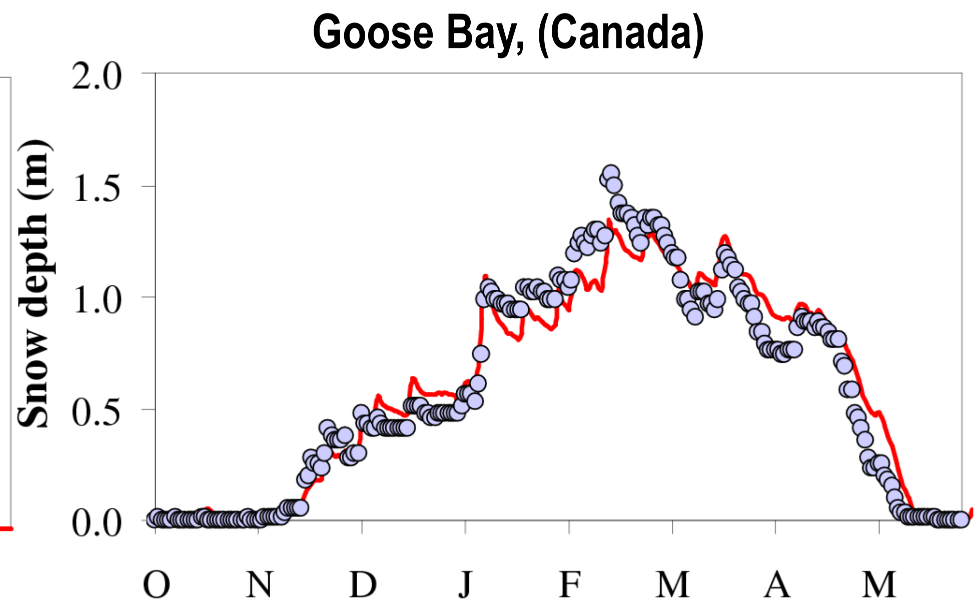


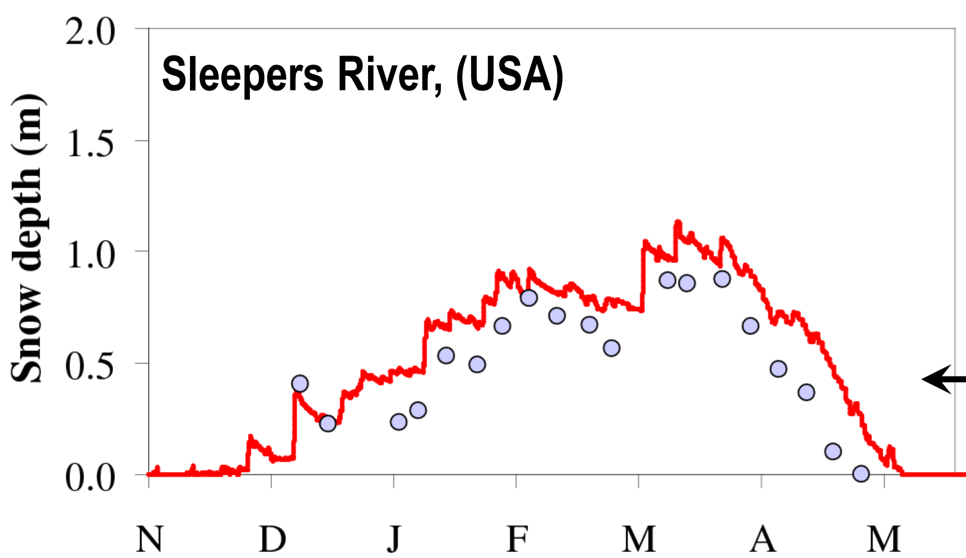
- Snow Depth, SWE, Density, Runoff,
- Albedo, Snow Surface Temperature

Snow depth Results@ SnowMIP open sites

SnowMIP: Snow Model Intercomparison Project



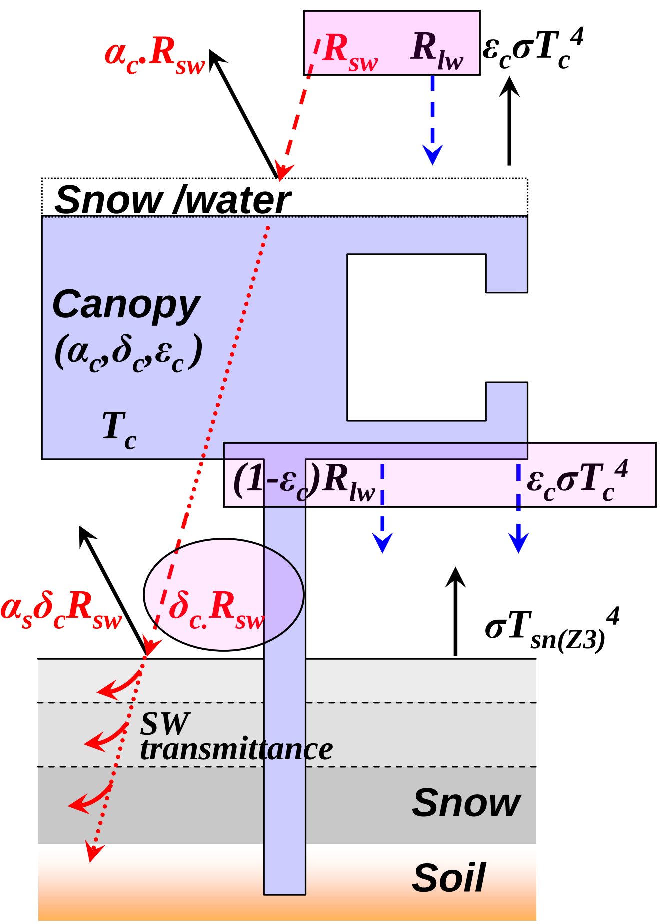




Uncertainty in Precipitation Phase

Forest Site: Vegetation Effect

[Shrestha et al., 2012, JSCE]



δ: Transmissivity

ε: Emissivity

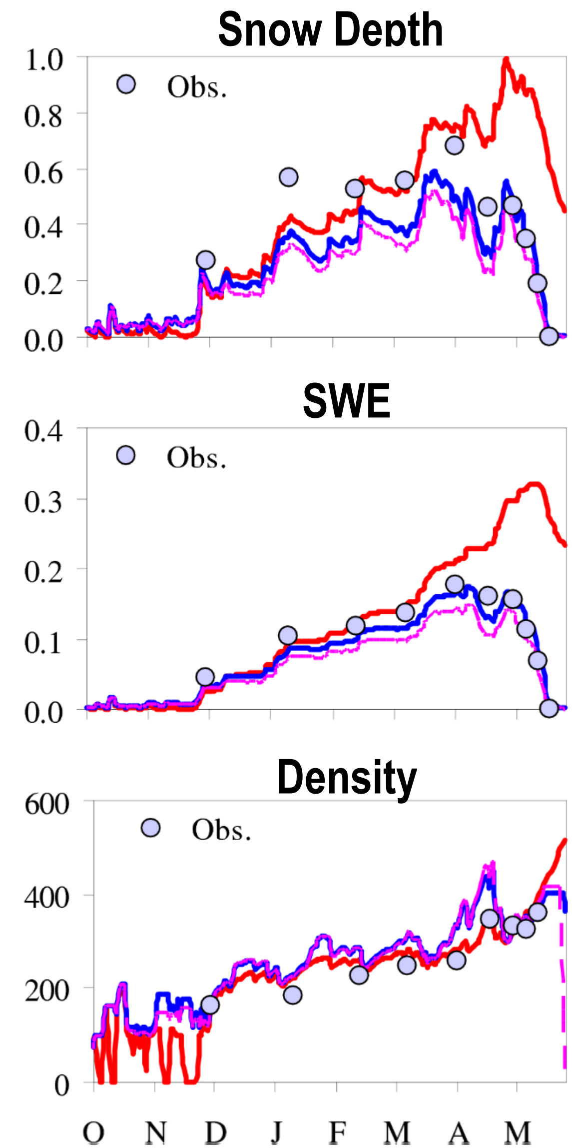
α: Reflectivity (albedo)

Fraser Experimental Forest (2004-2005)

Case 1:
Consider No vegetation:
➢ Overestimation

Case 2:
Vegetation
Interception capacity=0.3mm
(Default in SiB2)
➢ Simulated Well

Case 3:
Same as Case 2 with
Interception capacity
of canopy = 1 mm (3*Case2)
➢ Little underestimation



Basin-wide Model development & Validation

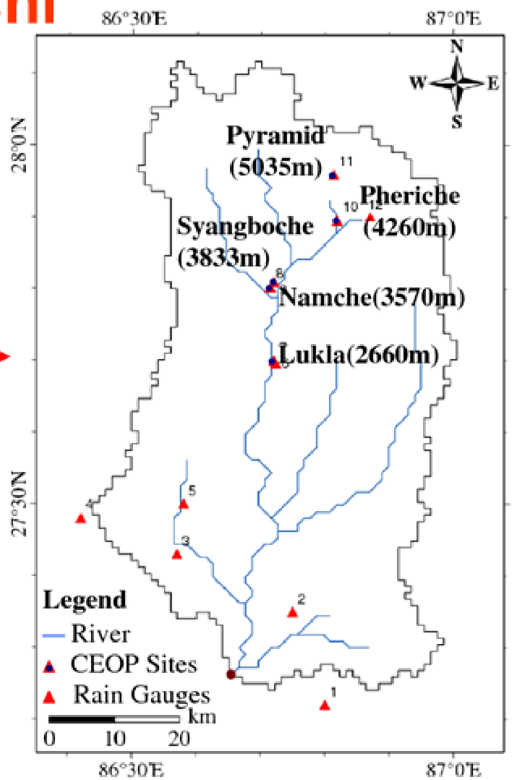
Snow & Glaciermelt Dominant

Snow+Glacier But Monsoon Dominant

Seasonal Snow cover

Basin-wide Model development & Validation

NEPAL (Dudhkoshi Basin)
(3700 km²)

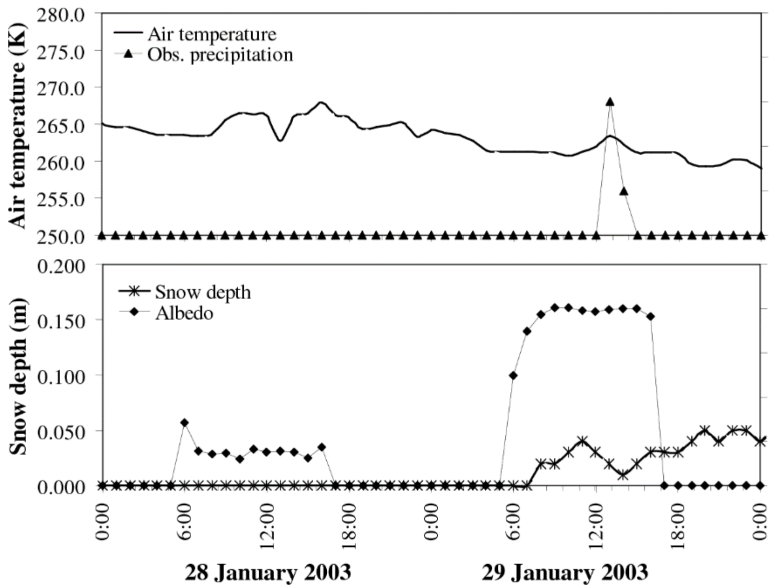


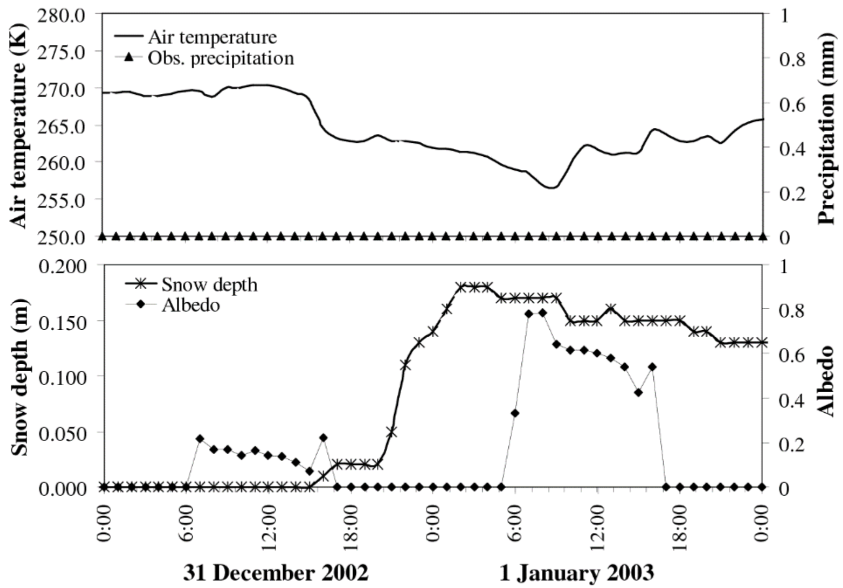
- Complex Topography (Himalaya)
- Elevation : 400 – 8848 m
- Climate: Tropical to Arctic
- Monsoon Dominant
- CEOP Reference Stations

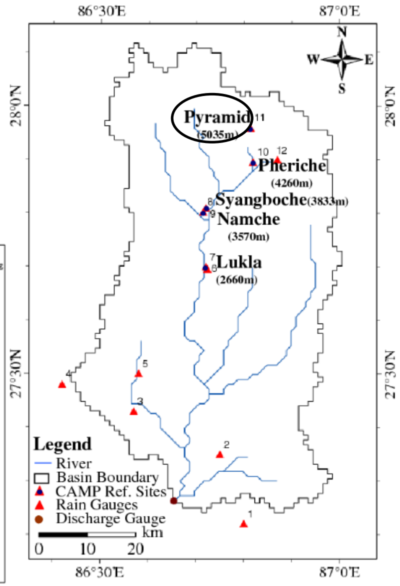
Point-scale snowfall correction

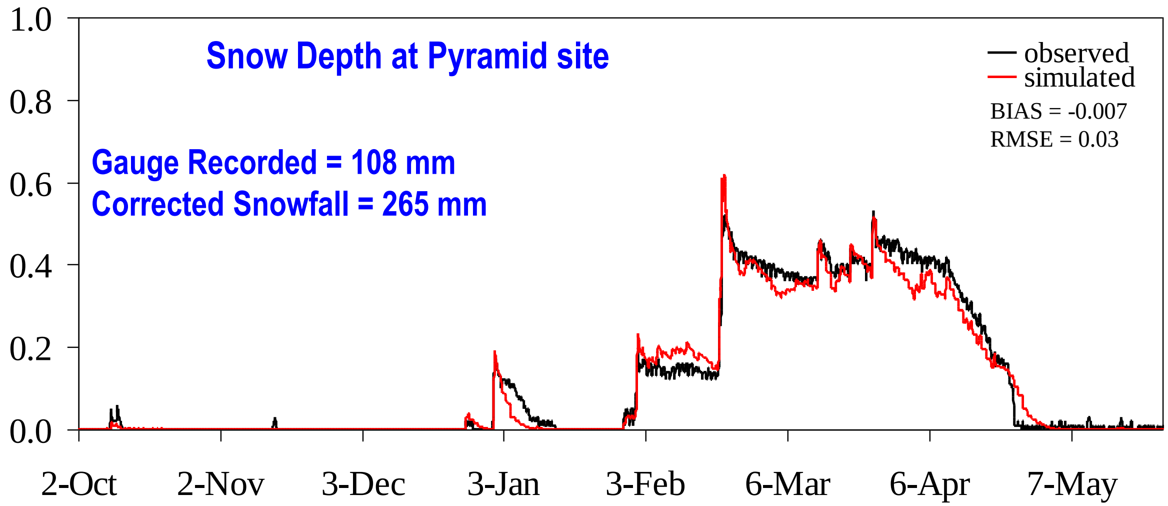
Rain gauges are not heated

Snowfall need to be corrected based on albedo/snow depth/temperature

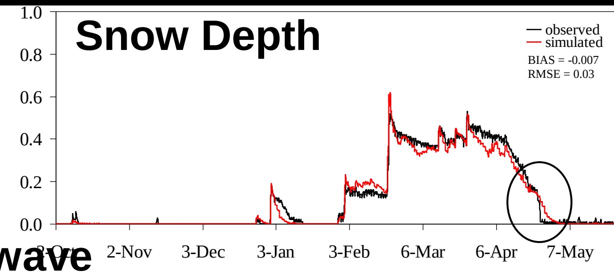




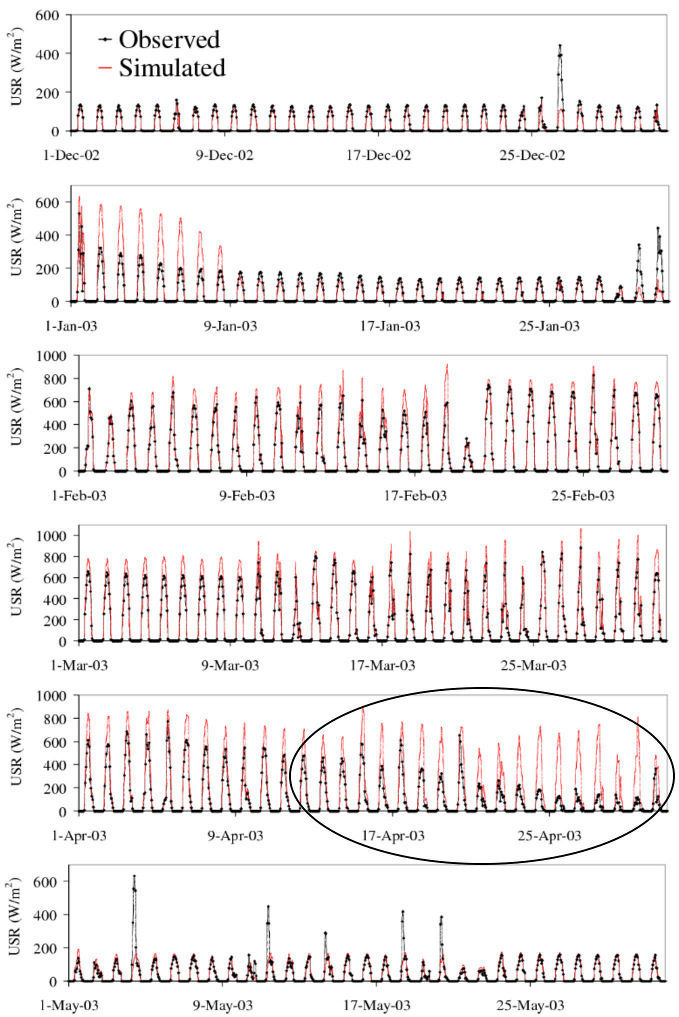




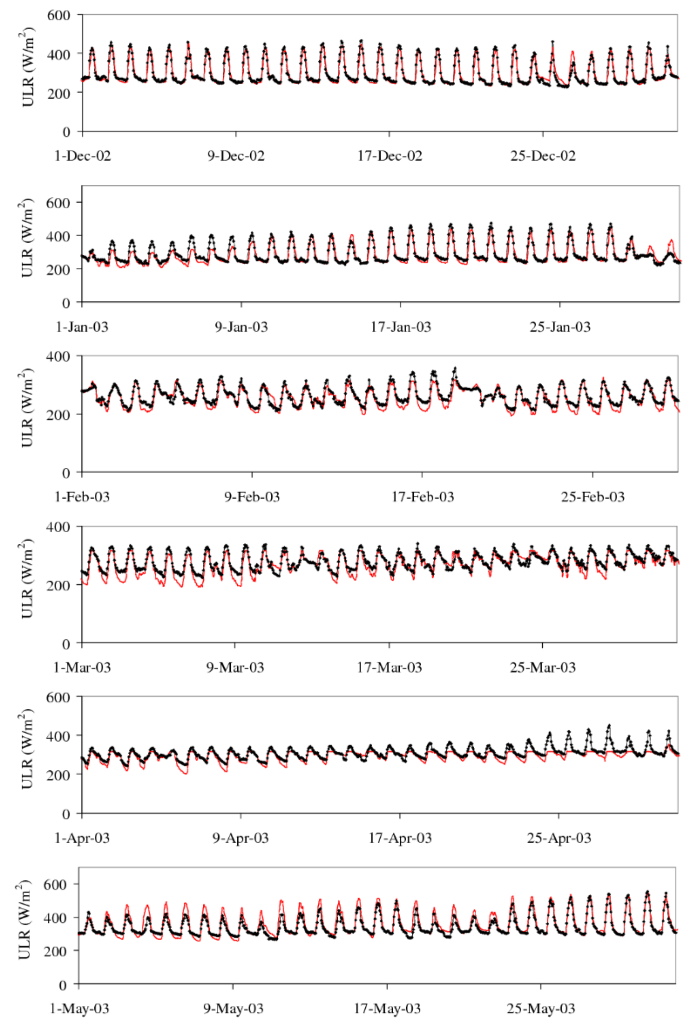
Pyramid: Dudhkoshi



Upward Shortwave

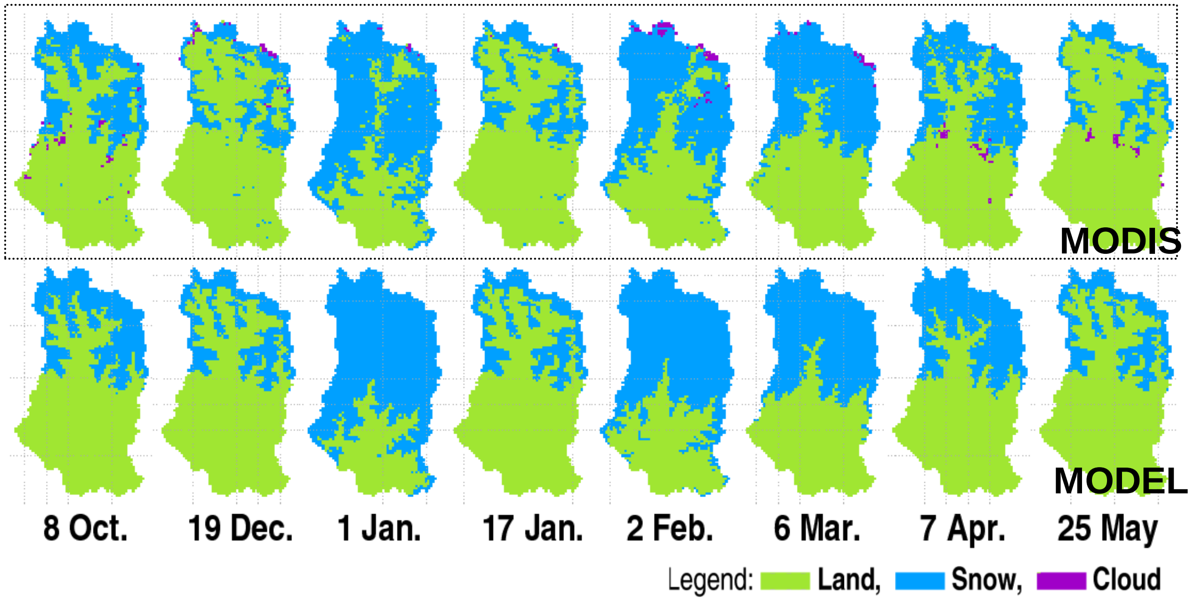


Upward Longwave



Dudhkoshi: Snow Cover

Spatial Distribution of Snow Cover

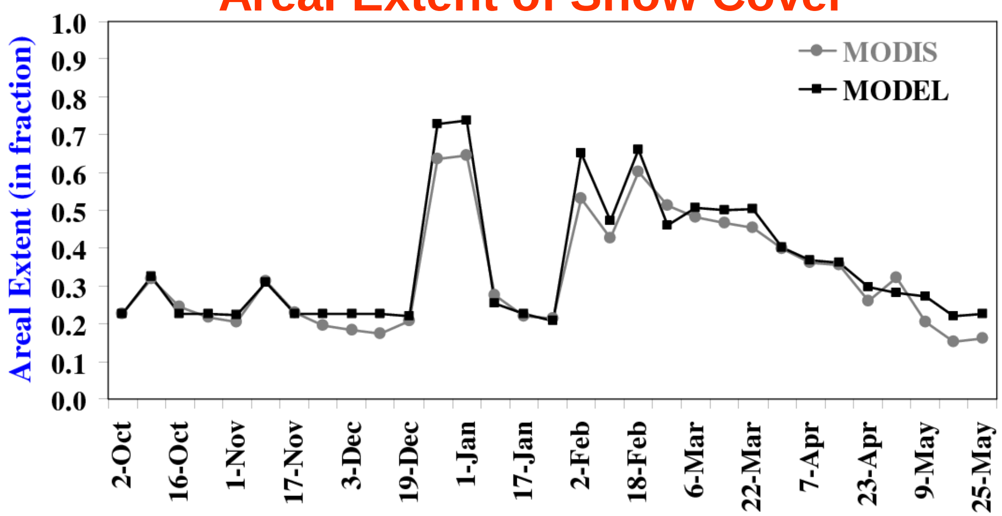


Pixel-by-Pixel Analysis

MODEL	MODIS Snow	MODIS No Snow
Snow	A	B
No Snow	C	D

N = Total basin pixels
A = Number of Pixels for MODIS = Snow, MODEL= Snow

Areal Extent of Snow Cover



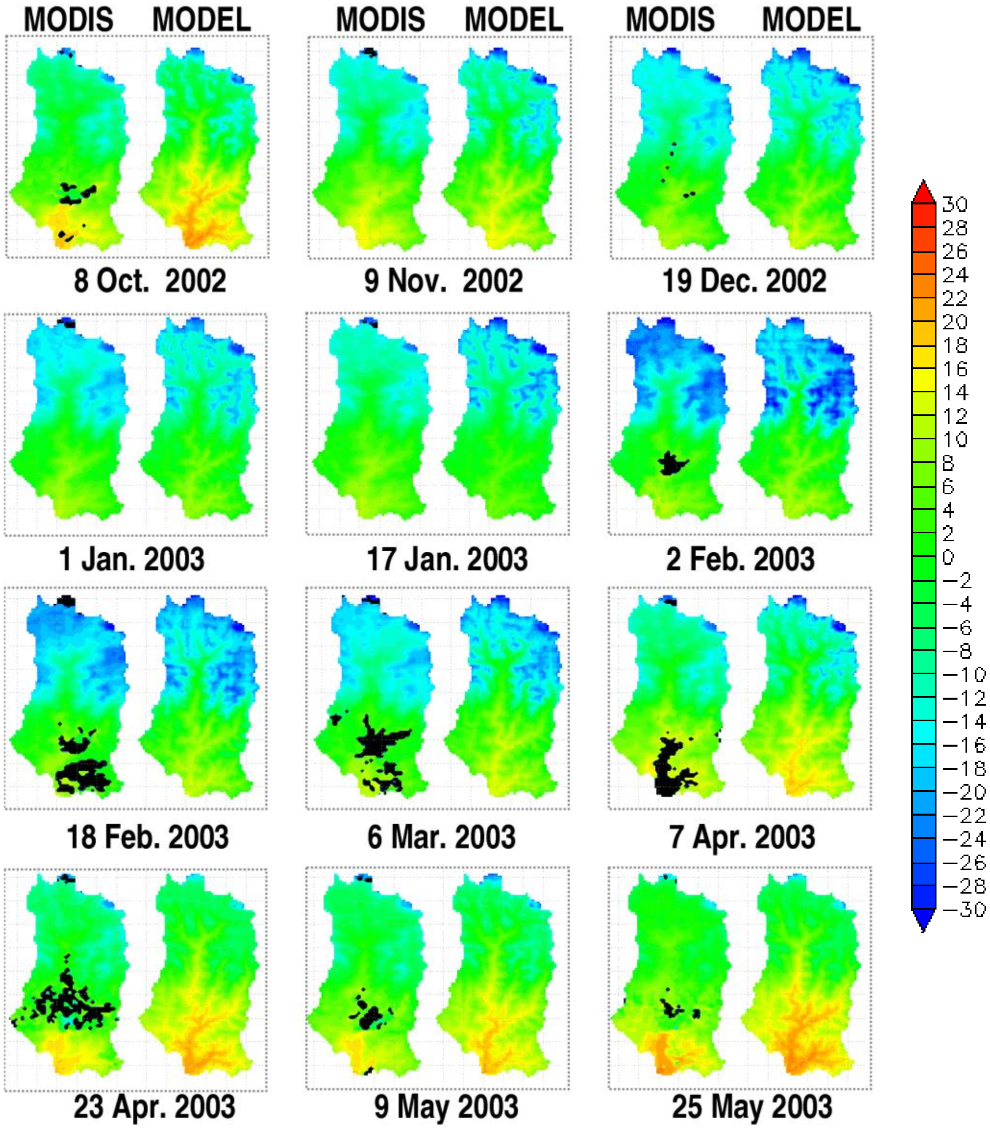
Evaluation Indices

Proportion Correct (PC)	(A+D)/N	0.90
Underprediction (PU)	C/N	0.10
Overprediction (PU)	B/N	0.10
Probability of Detection (POD)	A/(A+C)	0.90
False Alarm Ratio (FAR)	B/(B+D)	0.10
Bias Ratio Score (BRS)	$\frac{(A+B)}{(A+C)}$	1.10

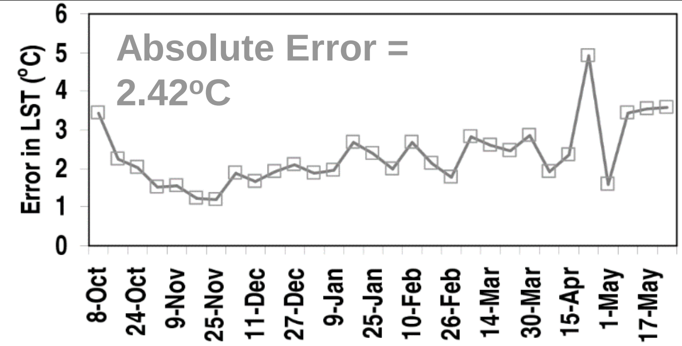
[Shrestha et al., 2011, JHM]

Dudhkoshi: Land surface temperature

Spatial Distribution of nighttime LST

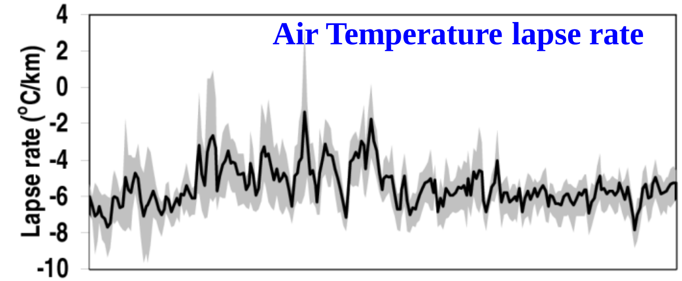


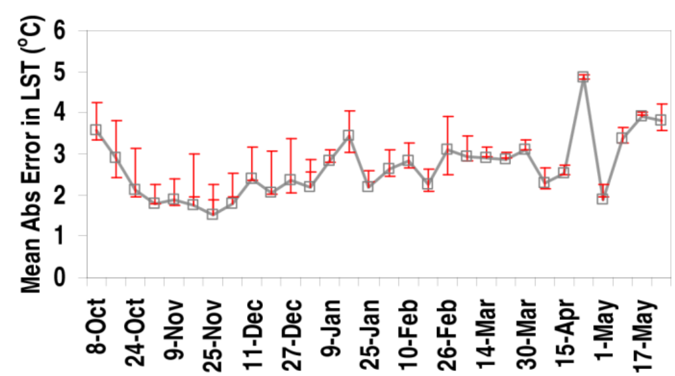
- ➢ **MODEL follows the MODIS in simulating the seasonal variation of LST**



LST Bias: 1. MODIS data
2. Air Temperature

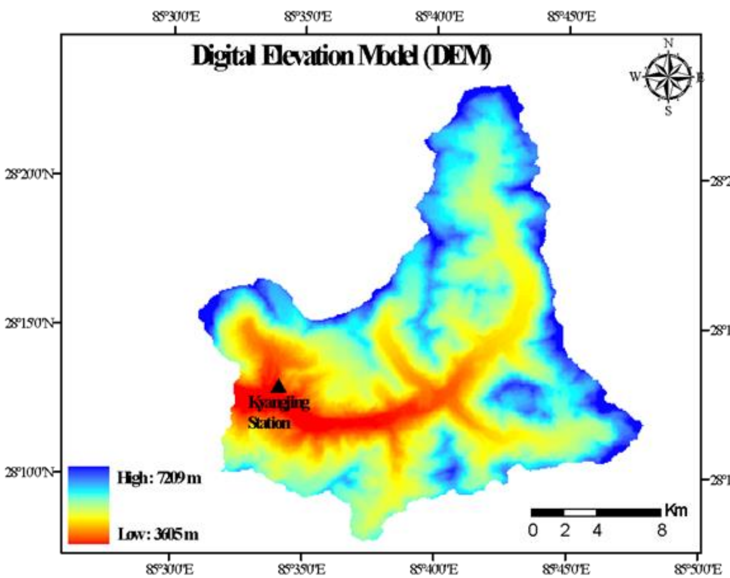
Sensitivity to Air Temperature



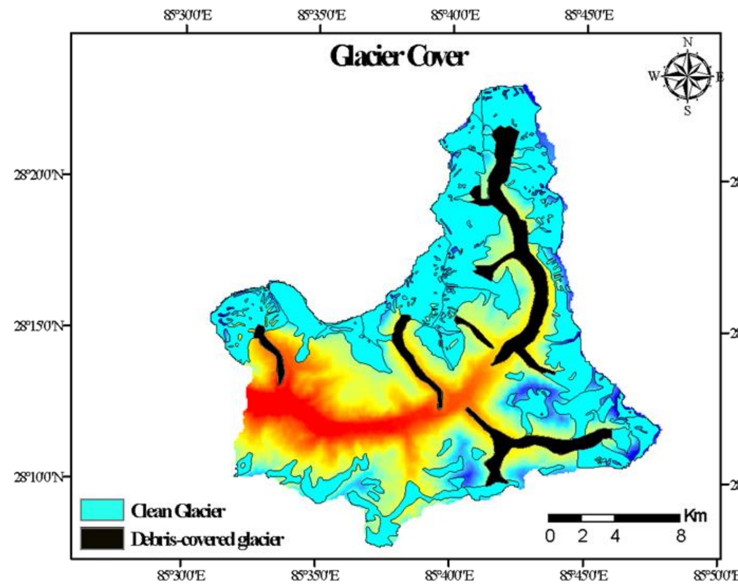


- ➢ **Variation in air temperature shows sensitivity to LST bias.**

Langtang Basin



Department of Survey, GoN



ICIMOD

Hydro-met data – only ONE station

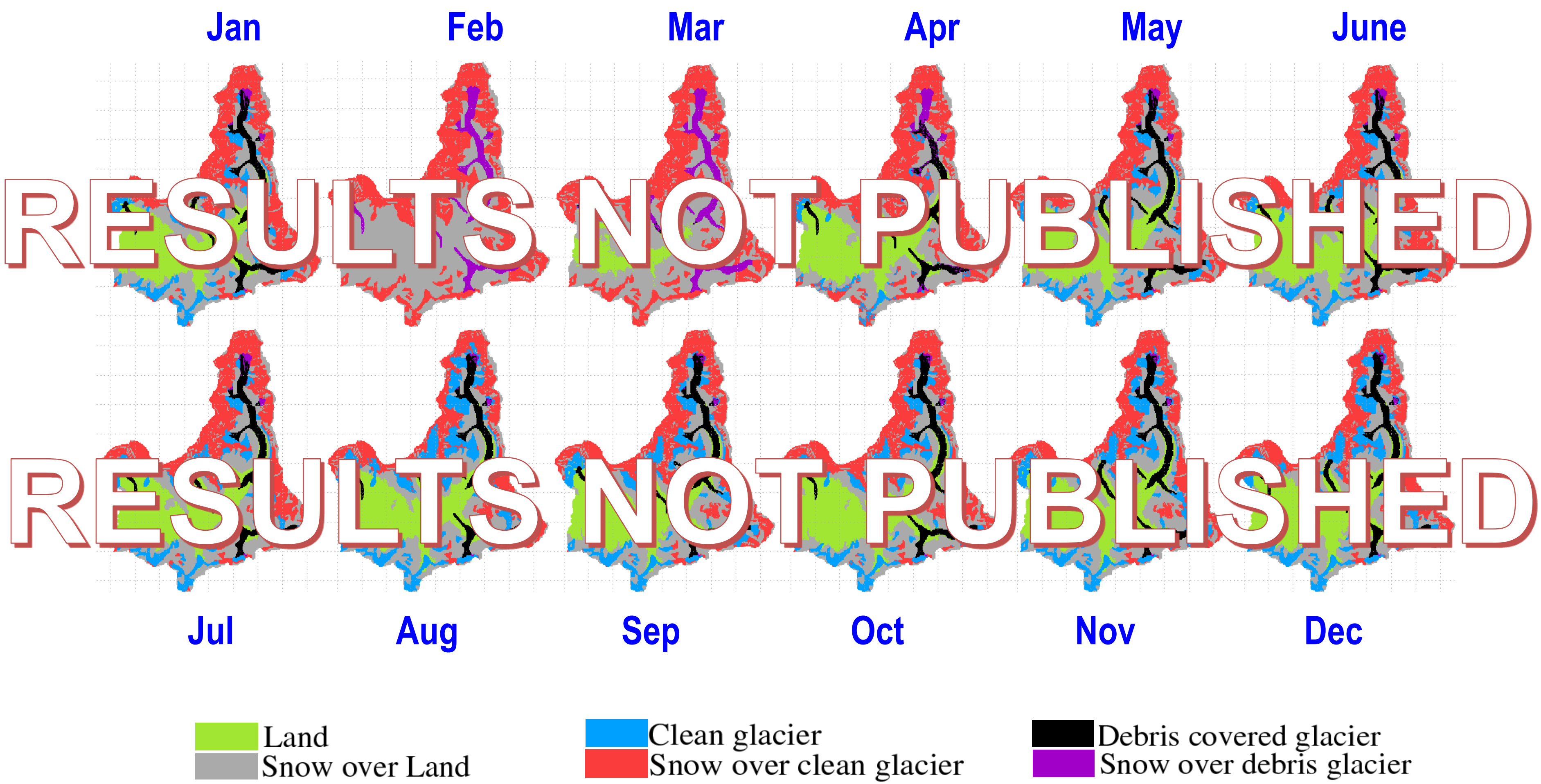
(Dept. of Hydrology & Meteorology, GoN)

- ***2 hourly wind speed***
- ***6 hourly air temperature***
- ***6 hourly relative humidity***
- ***2 hourly solar radiation***
- ***Daily (Manual) & hourly (AWS) precipitation***
- ***Daily Discharge***
- ***1988-2004***

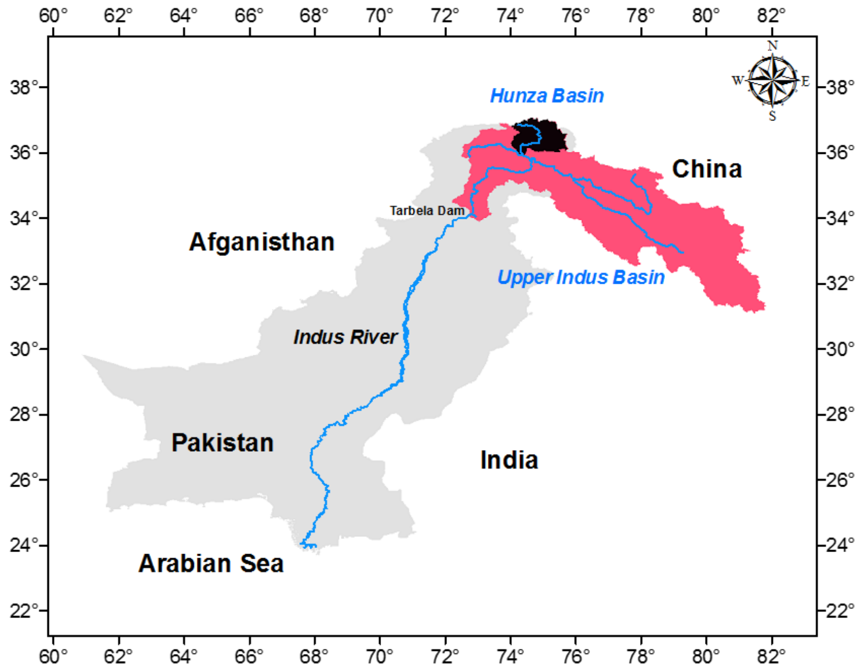
Downward Shortwave radiation	**Slope Aspect**
Cloud Amount *Gourdiann (1977)*	**Direct & diffuse** (Visible and near infrared)
Air Temperature *Environmental Lapse rate*	**Air Pressure** *(Based on Elevation)*
Downward longwave radiation *Crawford & Duchon (1999)*	**Wind Speed Precipitation** *Snowfall (Tair ≤ Tf)* *Rainfall (Tair > Tf)*

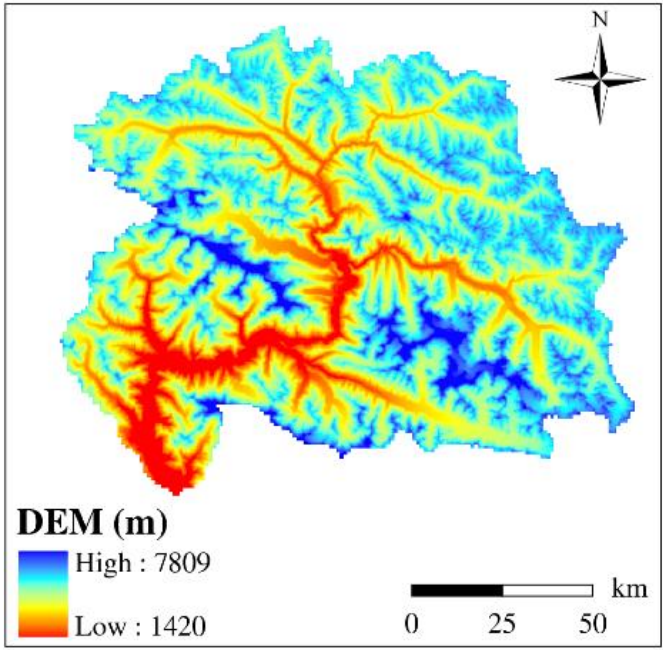
Langtang Basin

Spatial distribution of snow/glacier state



Hunza Basin (13700 km^2)





Gauge Data – Max/Min air temperature, relative humidity, precipitation, total solar radiation at daily time step

APHRODITE precipitation data

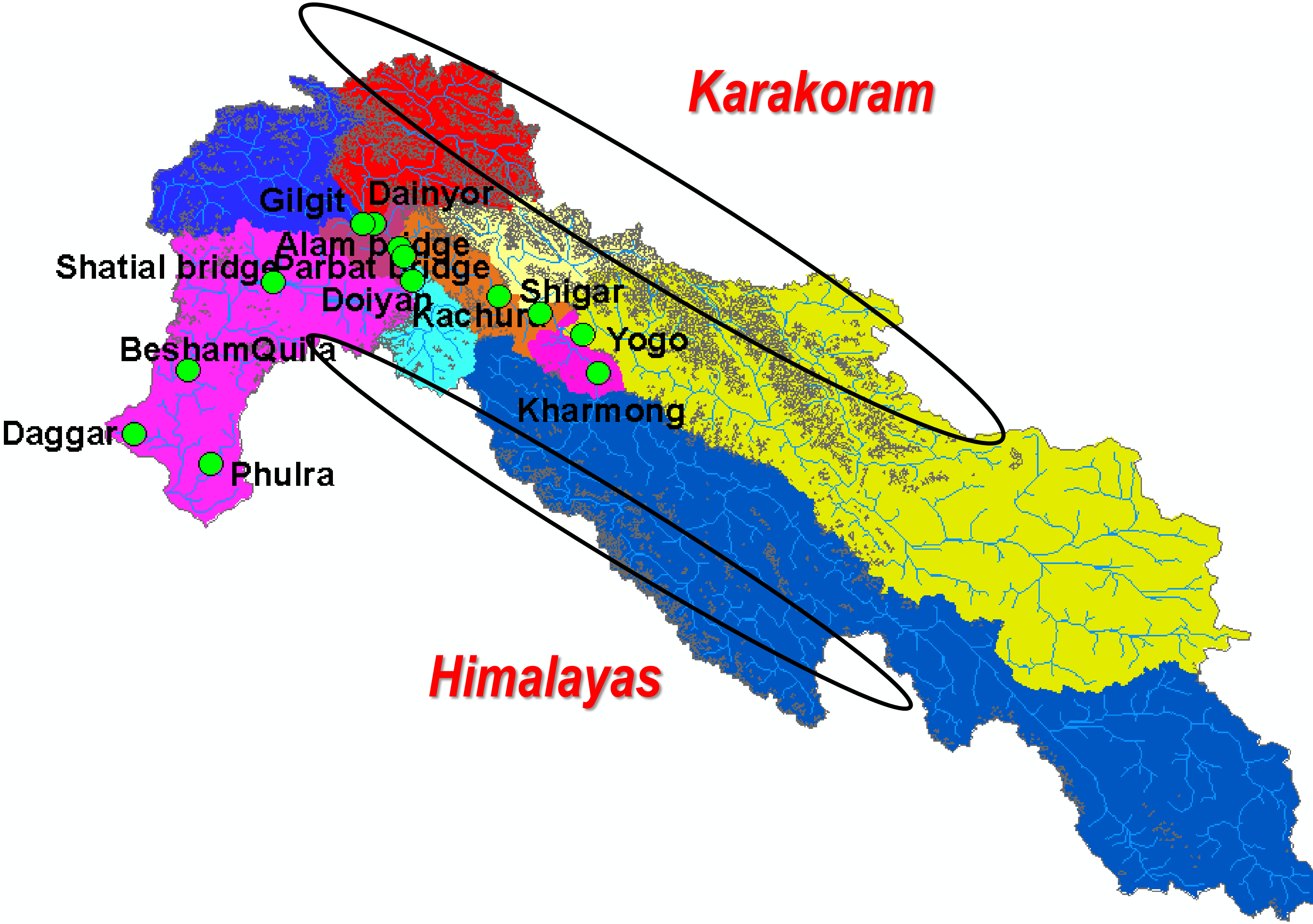
GLDAS data (Humidity, Shortwave, Wind speed)

Hunza Basin

RESULTS NOT PUBLISHED

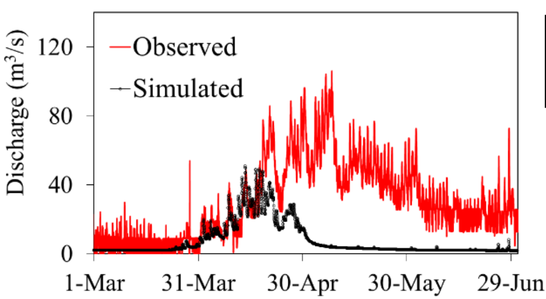
RESULTS NOT PUBLISHED

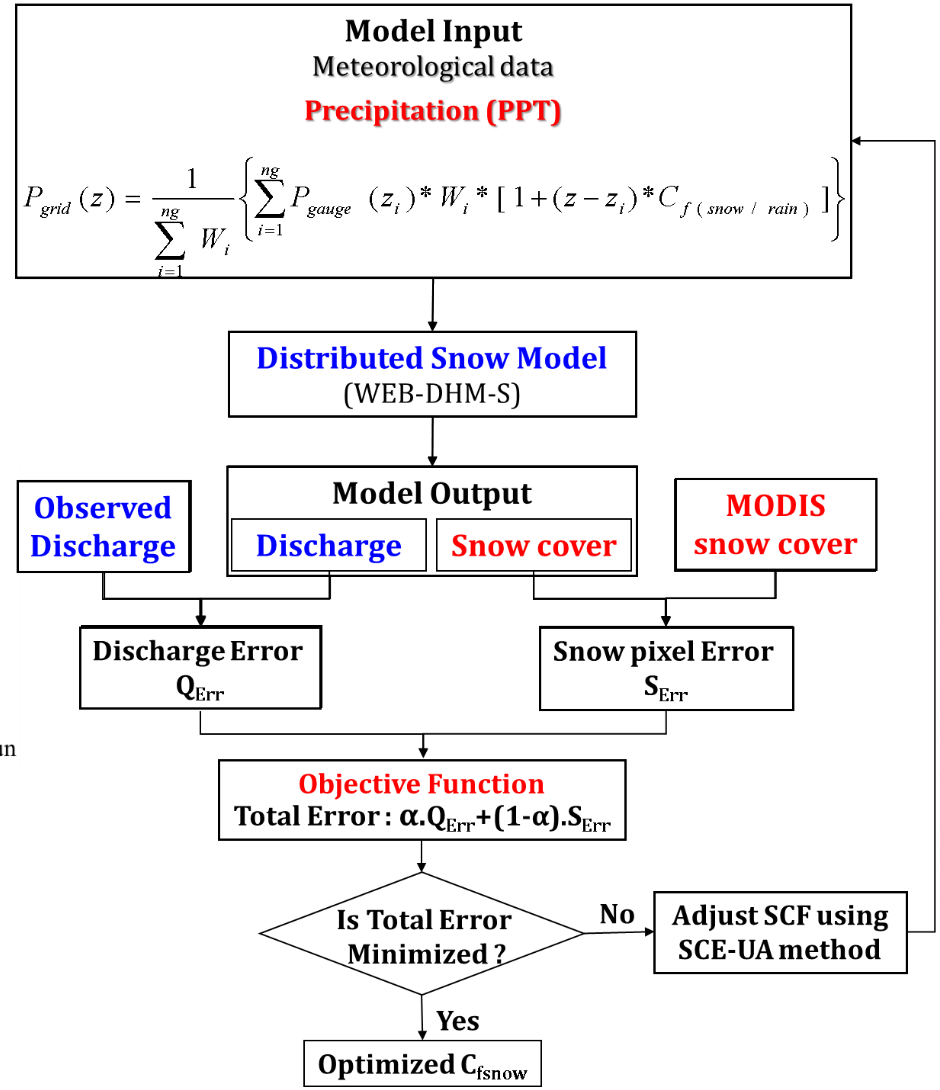
Upper Indus Basin

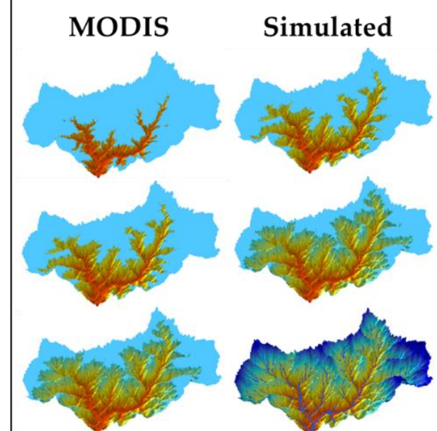


Correction of snowfall in basin scale

Shrestha, Wang, Koike 2014 (HESS)



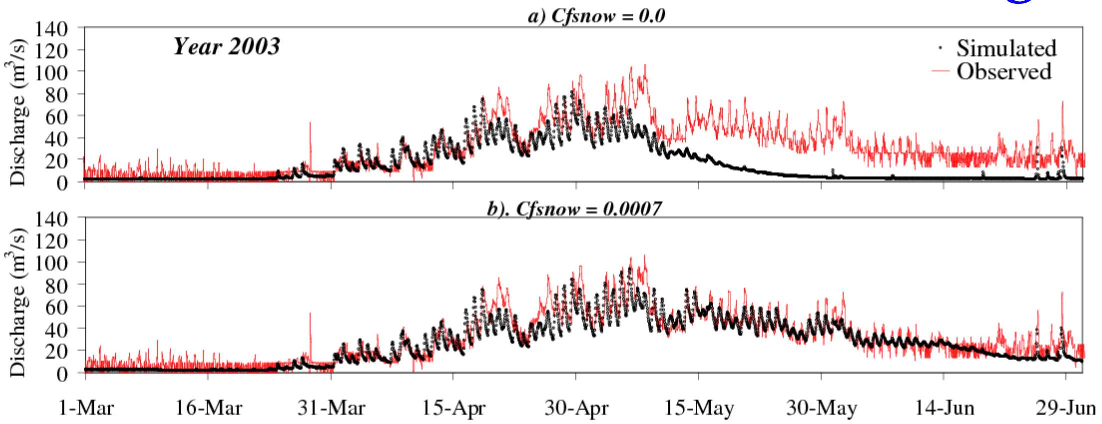




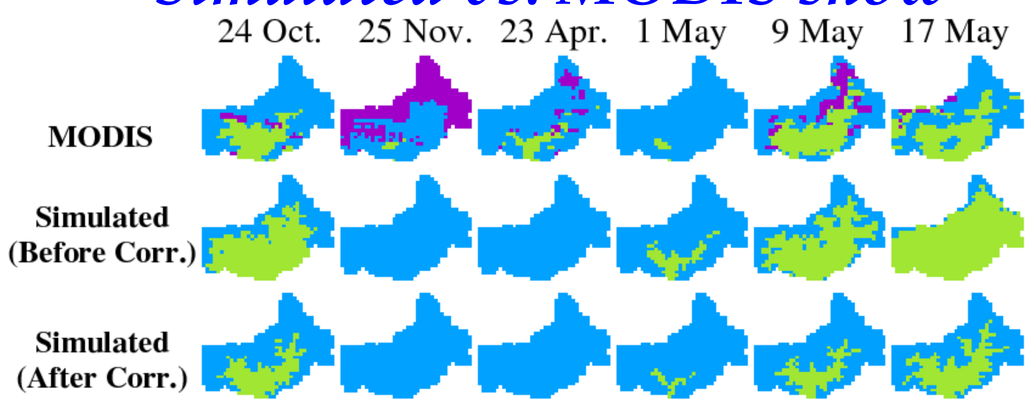
MODIS = Spectro-Radiometer onboard Terra Satellite

Correction of snowfall in basin scale

Simulated vs. Observed Discharge



Simulated vs. MODIS snow



Summary

1. **A Comprehensive Modeling system has been established which can simulate the Snow processes and Glacier processes and Forest snow processes simultaneously in a basin scale. Point and basin scale validation have been achieved at multiple sites.**

2. **Basin scale snowfall correction algorithm has been developed based on observed discharge and satellite snow cover and well tested in Upper Tone basin.**