DOCTOR OF PHILOSOPHY

Utilisation of remote sensing for the study of debris-covered glaciers: development and testing of techniques on Miage Glacier, Italian Alps

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TERMINOLOGY

A

A = Dimensionless transfer coefficient

A' = Aspect of the slope (degrees)

Ab = Ablation (m)

Ac = Linear coefficient

$\frac{\partial T_t}{\partial t}$ = Average rate of temperature change (K s^{-1})

α = Stability correction constant

$*\alpha$ = Surface albedo

$*\alpha_m$ = Mean albedo of the snowpack

$\partial STOR$ = change in heat store (W m^{-2} or M J m^{-2})

ASTER = Advanced Spacebourne Thermal Emission and Reflectance radiometer

AVP = Air vapour pressure (kPa)

AWS = automatic weather station

B

β = Coefficient of heat transfer (4.89 J m^{-3} deg $^{-1}$)

C

c = Specific heat capacity of air at constant pressure (1.0 J kg^{-1} deg $^{-1}$)

COND = Conductive heat flux (W m $^{-2}$)

C_{pw} = Specific heat capacity of water (4200 J kg^{-1} deg $^{-1}$)

c_t = density of material (Kg m^{-3})

D

d = Debris thickness (m)

D = Bulk exchange/transfer coefficient (J m^{-3} K^{-1})

D_f = Diffuse fraction of total incoming shortwave radiation (Wm^{-2})

E

$\varepsilon*$ = Effective emissivity of the sky

e_a = Vapour pressure in the air (Pa)

ep = empirical constant (stability correction constant)

e_s = Vapour pressure at debris surface (Pa)

ε_0 = Clear sky emissivity (8.733 x 10^{-3} Ta 0.788)

F

F = Radiation heat flux (Wm^{-2})

G

g = Acceleration due to gravity (9.8 m^{-1} s^{-2})

G = Global radiation flux (W m^{-2})

K

k = von Karmans constant (0.40; Oke 1987)

kc = Constant depending upon cloud type (0.26 = mean value for altostratus, altocumulus, stratocumulus, stratus, and cumulus)

K = Thermal conductivity (Wm^{-1} K^{-1})

L

L = Monin-Obukhov stability length scale

L_e = Latent heat of evaporation of water (2.49 x 10^{6} J kg^{-1})

L_i = latent heat fusion of ice (3.34 10^5 J Kg^{-1})

LHF = Latent heat flux (W m^{-2})

LPDAAC = Land Processes Distributed Active Archive Centre

$LWR\downarrow$ = Incoming long wave radiation (W m^{-2})

$LWR\uparrow$ = Out going long wave radiation (W m^{-2})

LWR = Longwave radiation flux (W m^{-2})

LWS = Lower weather station

M

M = Total radiance from the surface of a material W m^{-2}

$MELT$ = Sub-tephra ice melt rate over unit of time (mm w.e. per hour)

N

n = Cloud cover (value ranging 0.0-1.0, where 1 complete cloud cover, 0 no cloud cover)

P

P = Air pressure at the site (Pa)

ρ_a = Air density (kg m^{-3})

Po = Standard air pressure at sea level (1.0.13 x 10^5 Pa)

ρo = Density of the air at standard sea-level pressure (1.29 kgm $^{-3}$)

PRE = Energy from precipitation

ρw = Density of water (1000 kg/m^{-3})

ρt = Density of a material (Kg m^{-3})

R

r = Rainfall rate (mm hr^{-1})

R = Thermal resistance (K m^2 W^{-1})

Rb = Richardson number

RH = Relative humidity (%)

S

SA = Solar azimuth (degrees)

SHF = Sensible heat flux (W m^{-2})

$Sh1$ = Stake height in the first month (m)

$Sh2$ = Stake height in the second month (m)

σ = Stefan-Boltzmann constant 5.6697 x 10^{-8} Wm^{-2} K^{-4}

$SWR\downarrow$ = Incoming short wave radiation (W m^{-2})

$SWR\uparrow$ = Out going short wave radiation (W m^{-2})

SWR = Radiation flux (W m^{-2})

$SWR'n$ = Equivalent radiation received by a surface (Wm^{-2})

SWR$\downarrow$ dif = Diffuse component of incoming shortwave radiation (Wm^{-2})

$SWR\downarrow$ dir = Direct component of incoming shortwave radiation (Wm^{-2})

SWR_f = Diffuse fraction of total incoming shortwave radiation (Wm^{-2})

SWR' = Incoming shortwave radiation measured in a horizontal plane (Wm^{-2})

T

T = Absolute temperature (K)

$T_{a\,(K)}$ = Absolute air temperature (K)

T_a = Air temperature (^{o}C)

Td = Temperature difference (^{o}C)

Tdf = Thermal diffusivity (m^2 s^{-1} x10 $^{-6}$)

T_{di} = Temperature at debris-ice interface (^oC)

T_i = Ice temperature (^oC)

Tr = Thermal resistance (m^2 deg W^{-1})

T_r = Temperature of rainfall (^oC)

T_s = Surface temperature (^oC)

T_z = Air temperature (K) at height z (m)

U

u = Wind speed (m s^{-1})

u_z = Mean wind speed at height z (M^{s-1})

UWS = Upper weather station

W

λ_m = Wavelength of maximum spectral radiant exitance (μm)

Z

z_a = Measurement height (m)

z_o = Aerodynamic roughness length (m)

z_t = Roughness length for temperature (m)

Z' = Angle of slope from the horizontal (degrees)

Z = Angle of sun above horizon (degrees)

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DECLARATION

I declare that all of the work within this thesis is my own, also unless stated:

- All references cited have been consulted.
- The work of which the thesis is a record has been completed by myself.
- It has not been previously accepted for a higher degree.

Signed:…………………………..

ABSTRACT

Utilisation of remote sensing for the study of debris-covered glaciers: development and testing of techniques on Miage Glacier, Italian Alps

An increase in the number of debris-covered glaciers and expansion of debris cover across many glaciers has been documented in many of the world's major glacierised mountain ranges over the last 100 years. Debris cover has a profound impact on glacier mass balance with thick layers insulating the underlying ice and dramatically reducing ablation, while thin or patchy cover accelerates ablation through albedo reduction. Few debris-covered glaciers have been studied in comparison with 'clean' glaciers and their response to climatic change is uncertain. Remote sensing, integrated with field data, offers a powerful but as yet unrealised tool for studying and monitoring changes in debris-covered glaciers. Hence, this thesis focuses on two key aims: i) to test the utility of visible/near infrared satellite sensors, such as TERRA ASTER, for studying debris-covered glaciers; ii) to develop techniques to fully exploit the capability of these satellite sensors to extract useful information, and monitor changes over time.

Research was focused on four interrelated studies at the Miage Glacier, in the Italian Alps. First, a new method of extracting debris-thickness patterns from ASTER thermal-band imagery was developed, based on a physical energy-balance model for a debris surface. The method was found to be more accurate than previous empirical approaches, when compared with field thickness measurements, and has the potential advantage of transferability to other sites. The high spatial variability of 2 m air temperature, which does not conform to a standard lapse rate, presents a difficulty for this approach and was identified as an important area for future research. Secondly, ASTER and Landsat TM data are used to map debris-cover extent and its change over time using several different methods. A number of problems were encountered in mapping debris extent including cloud cover and snow confusion, spatial resolution, and identifying the boundary between continuous and sporadic debris. Analysis of two images in late summer 1990 and 2004 revealed only a small up glacier increase in debris cover has occurred, confirming other work's conclusions that the debris cover on Miage Glacier increased to its present extent prior to the 1990s.

A third area of research used ASTER DEMs to monitor surface elevation changes of the Miage Glacier over time to update previous studies. Surface velocities on the glacier tongue were also calculated between 2004-2005 using feature-tracking of ASTER orthorectified visible band imagery and ASTER DEMs. However, ASTER DEMs were found to be rather poor for both applications due to large elevation errors in topographically rough parts of the glacier, which prevented a full analysis and comparison of results to

previous surface elevation and velocity studies. Finally, the lithological units of the debris cover were mapped, based on the spectral differences of different rock types in the debris layer, providing information both on the location and concentration of different rock types on the surface. Therefore, the identification in the variation in emissivity throughout the glacier surface can be identified, which in turn has an impact upon calculated surface temperatures and ablation respectively.

Overall, this research presents a significant contribution to understanding the impact of a debris layer on an alpine glacier, which is an area of key interest and current focus of many present glaciological studies. Since future glacial monitoring will increasingly have to consider supraglacial debris cover as a common occurrence, due to climate warming impacts of glacial retreat and permafrost melting. This contribution is achieved through the successful application of methods which utilise ASTER data to estimate debris thickness and debris extent, and the lithological mapping of debris cover. Therefore, the potential for incorporating these remote sensing techniques for debris-covered glaciers into current global glacier monitoring programs has been highlighted. However the utility of ASTER derived DEMs for surface elevation change analysis and surface velocity estimations in a study site of steep and varied terrain has been identified as questionable, due to issues of ASTER DEM accuracy in these regions.