Permafrost in Rock Walls

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Losanne(CH), December 18, 2012
Faculté des géosciences et de l'environnement

INTRODUCTION

Hypothesis:
The climate-induced
Permafrost degradation of steep bedrock areas
(changes in the thermal and hydrological regime)
CAN
directly affect man-made infrastructure,
cause increased **rockfall activity** or
trigger **natural disaster** via complex process chains (e.g. rock-ice avalanches,...)

Factors: space-time interactions

Climate

Is changed fast during the last decades (since 1850.)

- **Global**: last 10 years ranked in the top 11 hottest
- **Europe** +1.2°C
- **Alps** +1.6°C

Time interval: decades!

Rock faces

Has predisposing factors to instability rather constant over decades:

- lithology
- structure
- topography

Permafrost, Glaciers and Ice-faces

Extremely sensitive to climate change (geoindicators).

- Fast changes directly affecting the hydrothermal conditions of rock faces, thus their stability.

Time Interval: years!!

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- **In the next future**, the instability can affect areas historically mapped as safety.

- Implications for **Natural Hazard** mapping and **Risk management**

Factors: space-time interactions

Figure: Matterhorn - Cheminée - Aug.2003

What do we know on such interactions?

Evidence from field

- Correlation between rockfall activity and warmer decades in the past centuries
- The exceptional rockfall activity of 2003 in the Alps
- The frequent presence of perennial/massive ice in the failure surfaces

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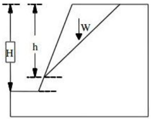

Figure: Geometry of centrifuge model

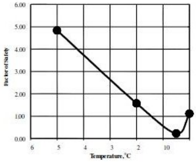

Figure: Predicted change in factor of safety with the temperature of ice in the joint

What do we know on such interactions?

Evidence from research (Davies et al. [2001])

Ice-filled discontinuities:
Factor of safety < 1 at -1.5°C ...
before melting!

Factors: space-time interactions

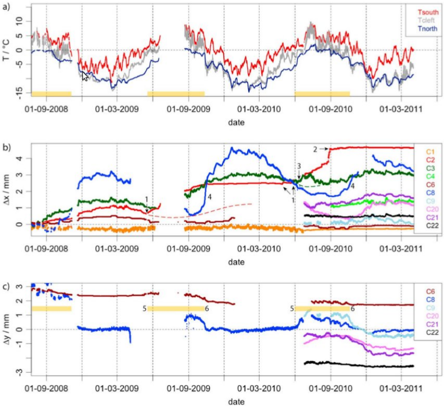

Figure: Overview of thermal conditions and cleft movements at the Matterhorn Hörnligrat

What do we know on such interactions?

Evidence from research (Hasler et al. [2012])

kinematics of steep bedrock:

- a cold-induced cleft dilatation due to a combined effect of thermomechanical and cryogenic forcing
- a warming-induced cleft movement due to (shear-) strength reduction caused by water percolation and infill-ice melting

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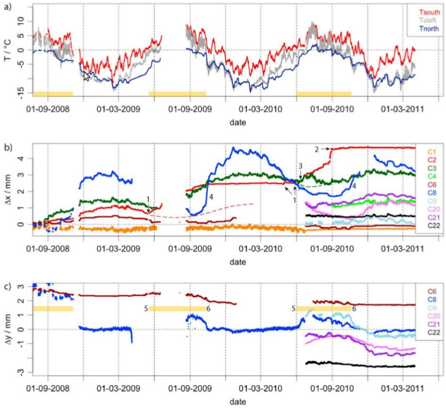

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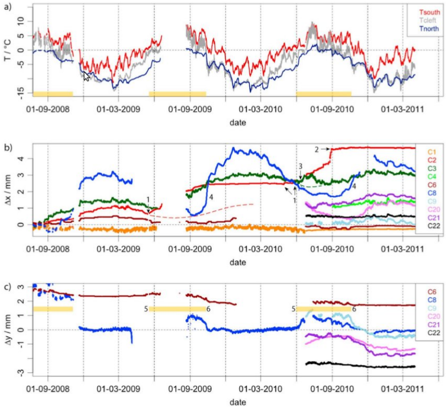

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In practice

Ultimate goal of research activities

Setting-up a collection of operative-tools
(maps, guidelines, models,...)
addressed to professionals and policy makers
for dealing with permafrost related risks in the Alps.

To be done, at alpine level, to achieve the goal

- Share data for building a large homogenized dataset for analysis
- Increase the number of case-studies (monitoring)
- Homogenize data and processing (data analysis)
- Modeling distribution and physical processes (validation, calibration...)

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Today we will focus on
THERMAL
monitoring, data analysis and modeling

MONITORING

Why... scope of the monitoring

What... surface or deep temperatures?

Where... ele,slp,asp?... scar?...

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Constrains

- Safety of workers
- Accessibility
- Budget

Mini-dataloggers

- Small and light to handle
- Easy and fast to install
- One or more sensors/depths
- With or without GPRS
- Quite cheap
- 3/4 years batteries

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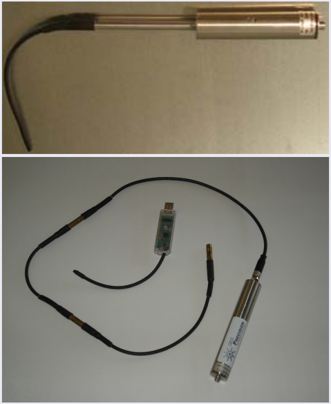

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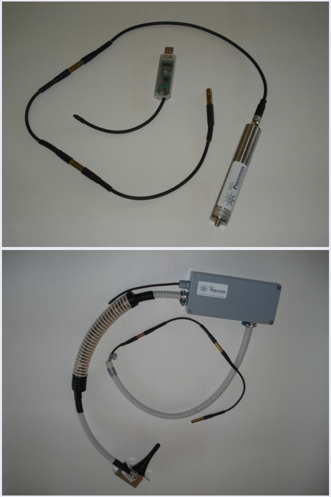

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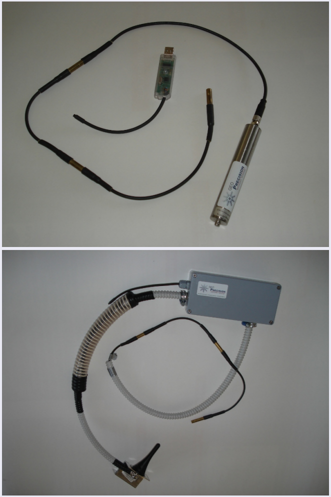

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- Limited depth (10-20 m)
- Instruments
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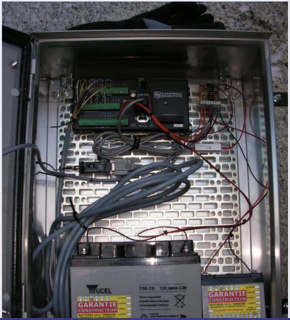

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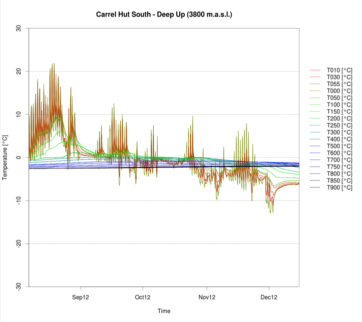

Workflow on raw data

- **Download**:
  on-field or automatic.
- Check missing records
- Check no-sense, spikes
- Gap-filling
- **Storing** (backup)
- Scripting (R, bash, mysql, ...)

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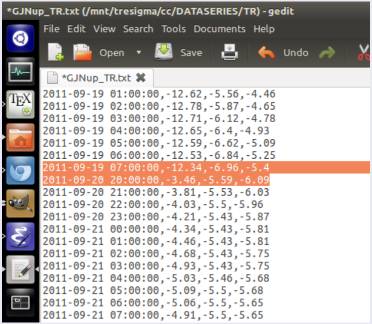

```
2011-09-19 01:00:00,-12.62,-5.56,-4.46
2011-09-19 02:00:00,-12.78,-5.87,-4.65
2011-09-19 03:00:00,-12.71,-6.12,-4.78
2011-09-19 04:00:00,-12.65,-6.4,-4.93
2011-09-19 05:00:00,-12.59,-6.62,-5.09
2011-09-19 06:00:00,-12.53,-6.84,-5.25
2011-09-19 07:00:00,-12.34,-6.96,-5.4
2011-09-20 20:00:00,-3.46,-5.59,-6.09
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2011-09-21 02:00:00,-4.68,-5.43,-5.75
2011-09-21 03:00:00,-4.93,-5.43,-5.75
2011-09-21 04:00:00,-5.03,-5.46,-5.68
2011-09-21 05:00:00,-5.09,-5.5,-5.68
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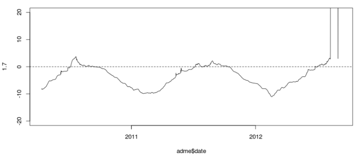

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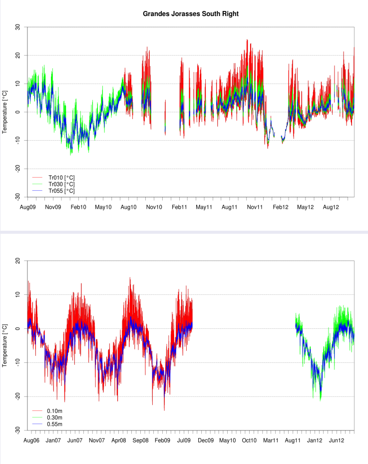

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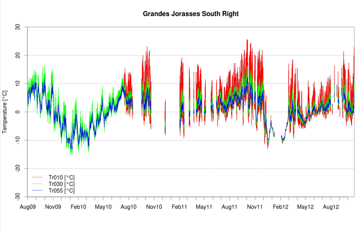

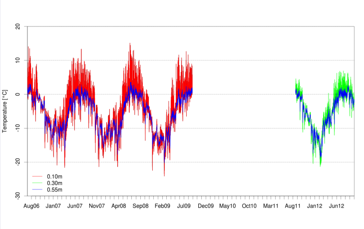

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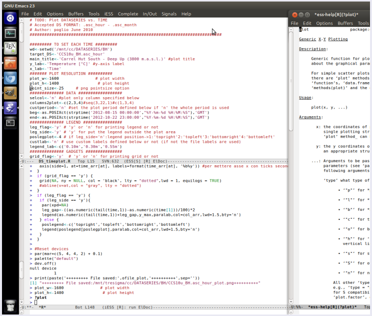


```
# TODO: Plot DATASERIES vs. TIME
# Accepted DS FORMAT: .asc_hour - .asc_month
# Author: poglio June 2010
################################################################################

######### TO SET EACH TIME #########
wd<-setwd('/mnt/cc/DATASERIES/BH')
target_DS<-'CCS10u_BH.asc_hour'
main_title<-'Carrel Hut South - Deep Up (3800 m.a.s.l.)' #plot title
y_lab<-'Temperature [°C]' #y-axis label
x_lab<-'Time'
####### PLOT RESOLUTION ##########
plot_w<-1600               # plot width
plot_h<-1400                # plot height
point_size<-25     # png pointsize option
############## DATA ##################
selcol<-'n' #plot only column specified below
columns2plot<-c(2,3,4)#seq(3,22,1)#c(1,3,4)
custperiod<-'n' #set the plot period defined below if 'n' the whole period is used
beg<-as.POSIXct(strptime('2012-08-15 00:00:00',"%Y-%m-%d %H:%M:%S"),'GMT')
end<-as.POSIXct(strptime('2012-10-22 23:00:00',"%Y-%m-%d %H:%M:%S"),'GMT')
############### LEGEND #################
leg_flag<-'y' # 'y' or 'n' for printing legend or not
leg_side<-'y' # 'y' for put the legend outside the plot area
poslegplot<-4 # if leg_side='n':legend position->1:'topright'2:'topleft'3:'bottomright'4:'bottomleft'
custlab<-'n' # use custom labels defined below or not (if not the file labels are used)
legend_lab<-c('0.10m','0.30m','0.55m')
############## GADGETS ###############
grid_flag<-'y'  # 'y' or 'n' for printing grid or not
-U:---  DS_timeplot.R   Top L15   SVN:632  (ESS[S] [R] ElDoc)-----------------------------
+   axis(side=1, at=time_arr[at], labels=format(time_arr[at], '%b%y')) #per mettere asse x con ticks secon
+  }
>  if (grid_flag == 'y') {
+   grid(NA, ny = NULL, col = 'black', lty = "dotted",lwd = 1, equilogs = TRUE)
+   #abline(v=at,col = "gray", lty = "dotted")
+  }
>  if (leg_flag == 'y') {
+   if (leg_side == 'y'){
+    par(xpd=NA)
+    leg_gap<-((as.numeric(tail(time,1))-as.numeric(time[1]))/100)*2
+    legend(as.numeric(tail(time,1))+leg_gap,y_max,paralab,col=col_arr,lwd=1.5,bty='n')
+   } else {
+    poslegend<-c('topright','topleft','bottomright','bottomleft')
+    legend(poslegend[poslegplot],paralab,col=col_arr,lwd=1.5,bty='n')
+   }
+  }
>
> #Reset devices
> par(mar=c(5, 4, 4, 2) + 0.1)
> palette("default")
> dev.off()
null device
          1
> print(paste('+++++++++ File saved:',ofile_plot,'++++++++++',sep=''))
[1] "+++++++++ File saved:/mnt/tresigma/cc/DATASERIES/BH/CCS10u_BH.asc_hour_plot.png++++++++++"
> plot_w<-1600              # plot width
> plot_h<-1400               # plot height
> ?plot
>
-U:**-  *R*         Bot L148   (iESS [R]: run ElDoc)------------------------------------------
```

```
plot                      package:

Generic X-Y Plotting

Description:

     Generic function for plo
     about the graphical para

     For simple scatter plots
     there are 'plot' methods
     'function's, 'data.frame
     'methods(plot)' and the

Usage:

     plot(x, y, ...)

Arguments:

       x: the coordinates of
          single plotting str
          'plot' method_ can

       y: the y coordinates o
          an appropriate stru

     ...: Arguments to be pas
          parameters (see 'pa
          following arguments

          'type' what type of

                • '"p"' for "

                • '"l"' for "

                • '"b"' for "

                • '"c"' for t

                • '"o"' for b

                • '"h"' for '
                  vertical li

                • '"s"' for s

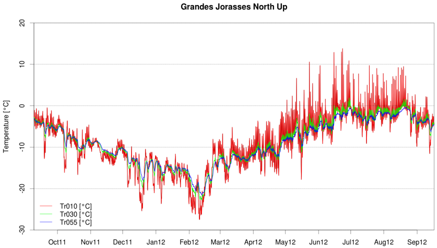
                • '"S"' for o

                • '"n"' for n

              All other 'type
              e.g., 'type = "
              for S compatibi
              'plot.factor',
-U:%%-  *ess-help[R](?plot)*   To
```

DATA ANALYSIS

Single monitoring site



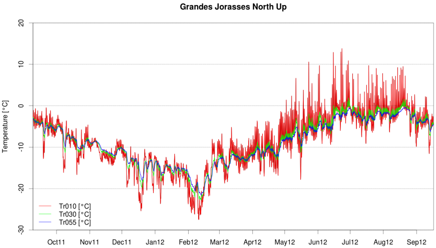
iLog - Grandes Jorasses North face (4100 m a.s.l.)

One Year of Data

- Permafrost Yes/No (Low accuracy)
- Stupid statistics (MAGST,Min,Max,Freezing-Days,...)

Depth	MART	MaxAbs	MinAbs	dTmax	ZCD	DBZ
0.10	-9.03	13.8	-27.5	19.02	88	333
0.30	-9.04	1.9	-22.75	4.62	16	347
0.55	-9.14	-0.37	-21.56	2.15	0	352

Single monitoring site



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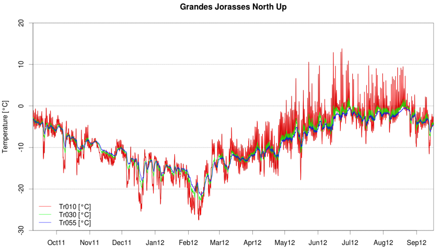

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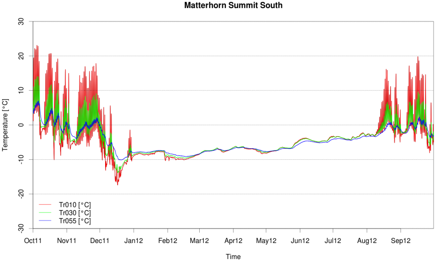

iLog - Matterhorn Summit South face (4400 m a.s.l.)

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- Stupid statistics (MAGST,Min,Max,Freezing-Days,...)

Depth	MART	MaxAbs	MinAbs	dTmax	ZCD	DBZ
0.10	-4.16	23.09	-17.4	22.83	85	293
0.30	-4.24	14.06	-13.87	10.03	57	296
0.55	-4.58	7.02	-10.12	3.25	28	315

Single monitoring site

Many Years of Data

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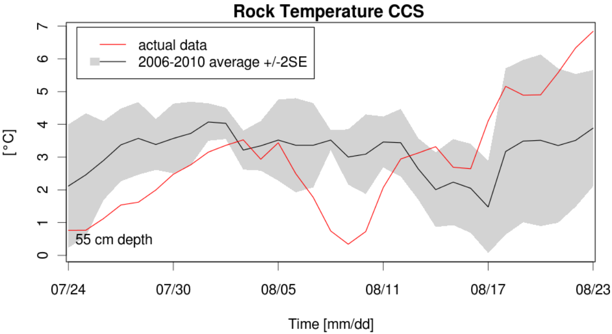
- Anomalies
- Trends (...maaany years!)



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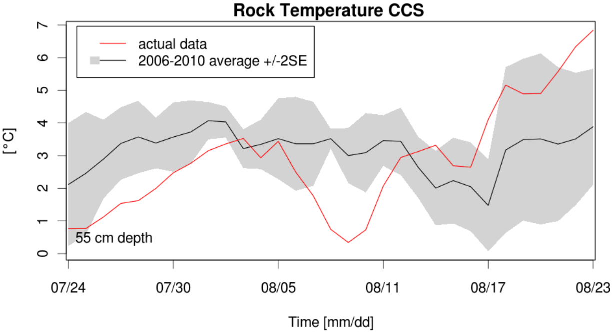

Single monitoring site

Many Years of Data

- Permafrost Yes/No (Higher accuracy)
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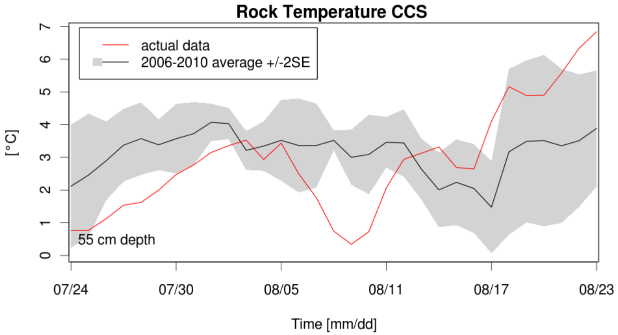

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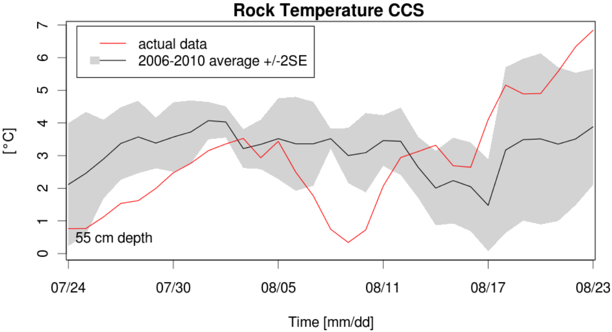

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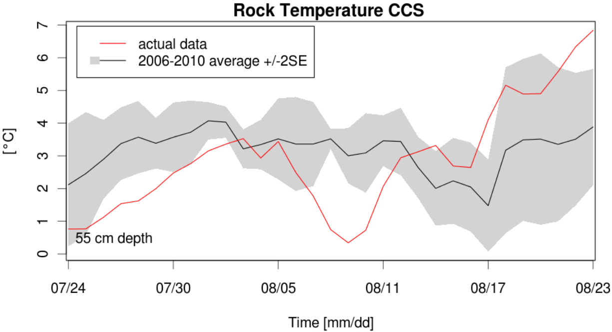
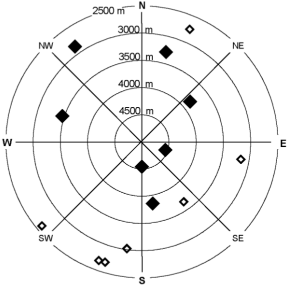
...these are 'only' **temporal analysis!**.

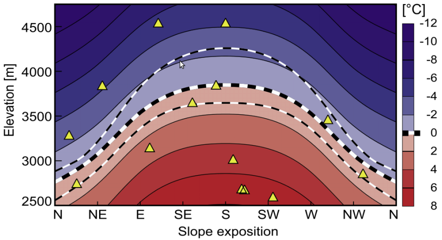


Many monitoring site

Spatial Variability

Statistics on the variability of measured temperatures with topography.





Gruber et al. [2003, 2004a]

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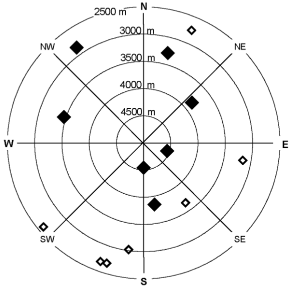
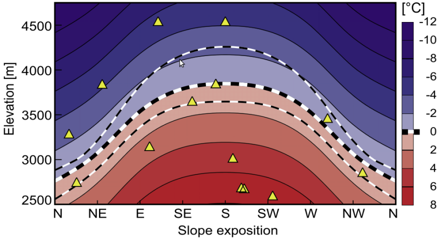




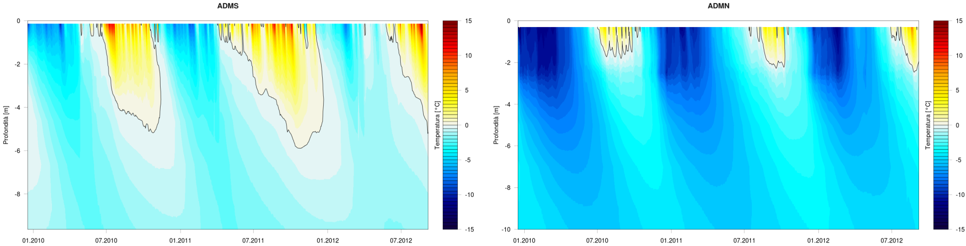
This is the base of the empirical modeling
of permafrost distribution over complex topographies (next section.)

Gruber et al. [2003, 2004a]

Active Layer Thickness (ALT)

Aiguille du Midì - Boreholes depth 10m.

Maximum depth reached by the 0°C isotherm



Contour Plots: Left - south face, Right - north face

data ownership: Laboratoire EDYTEM - Université de Savoie

Temperature profiles

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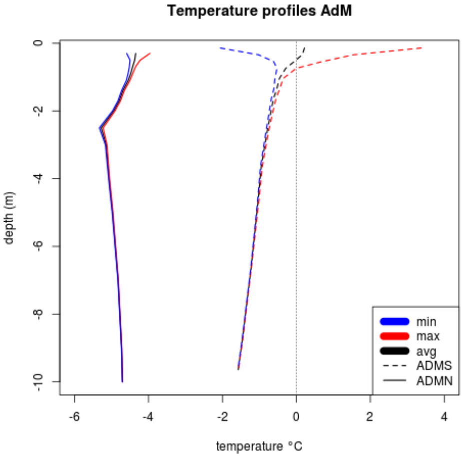

MODELING

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Statistical distribution of
Mean Annual Rock Surface Temperatures (MARST)
over a DEM

Ingredients

- MARST measured in many points
- Some weather stations around
- A digital elevation model of the area

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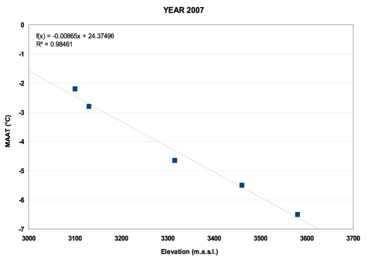
Is function of elevation



Map of MAAT derived from DEM

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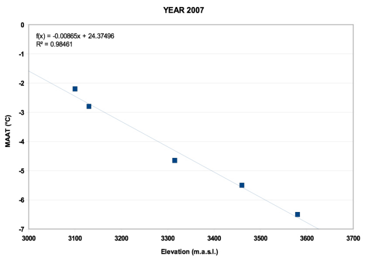
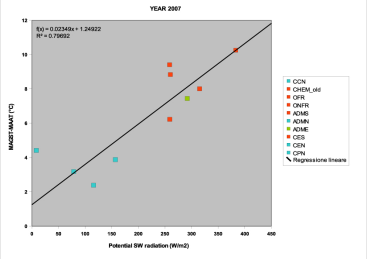


Map of MAAT derived from DEM

ΔT

Is function of PSWR (slp,asp)



Map of ΔT derived from PSWR

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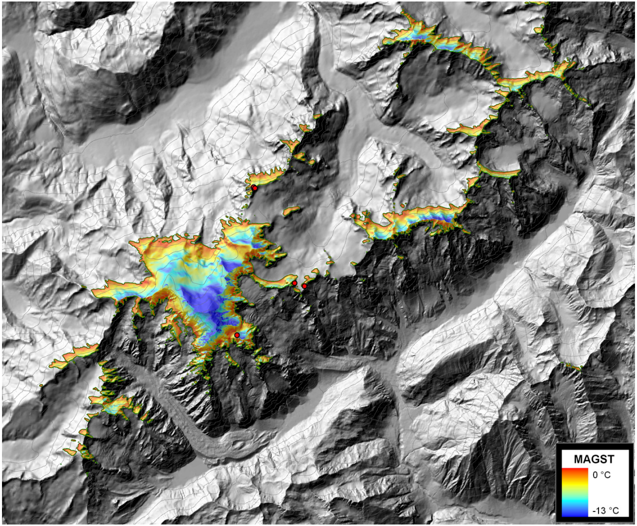

Example: Alpine Permafrost Map

Integrated approach: **Debris Model + Rock Model**

Debris covered area (*slope* $< 37^\circ$)

- Rock glaciers inventories (3580 points)
- **GLMM** - predict P(intact/relict)
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Combination based on a land cover map...

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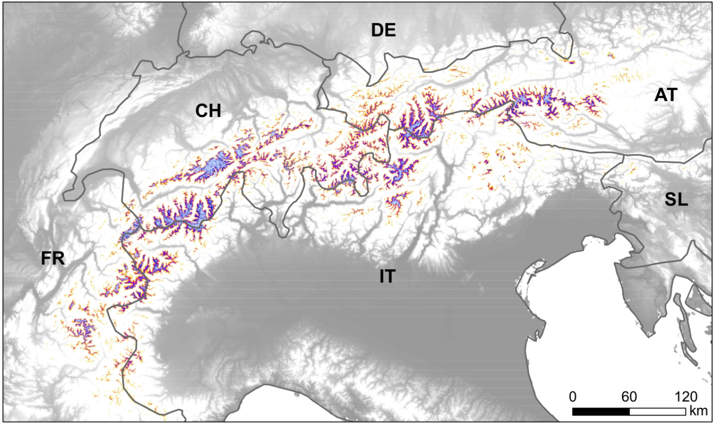

Boeckli et al. [2012a,b], Cremonese et al. [2011]

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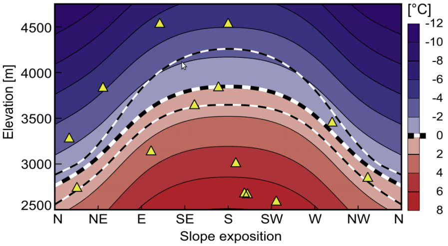
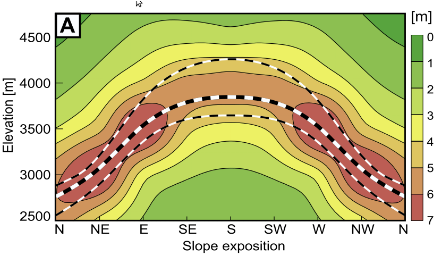
TEBAL: impact of summer 2003 on permafrost in rock wall

Energy-balance model coupled to an heat conduction scheme.
Simulation of RST based on meteorological observations.



MARST and elevation of isotherm 0°C



Variability of Active Layer Thickness

Simulated daily rock temperatures from 01/1982 to 12/2003 (Jungfraujoch).
Fixed slope: 70°
classes elev:2000-5000 by 500
classes asp: step 45°N

Gruber et al. [2004a,b]

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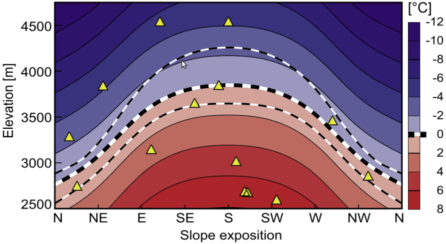

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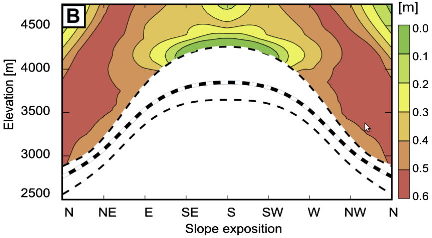

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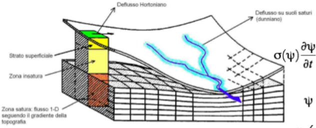
GEOtop, Rigon et al. [2006]



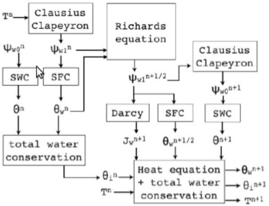
$$\sigma(\psi)\frac{\partial\psi}{\partial t} = \nabla\cdot(K(\psi)\nabla(\psi+\eta_z))+q_s$$

$$\psi = \frac{1}{\alpha}\left(\left(\frac{\theta_r-\theta_s}{\theta_s-\theta_r}\right)^{1/m}-1\right)^{1/n}$$

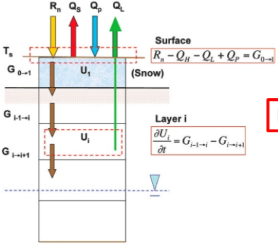
$$K(\theta) = K_S\left(\frac{\theta_r-\theta_s}{\theta_s-\theta_r}\right)^{\nu}\left(1-\left(1-\left(\frac{\theta_r-\theta_s}{\theta_s-\theta_r}\right)^{1/m}\right)^{m}\right)^{2}$$

Mass Balance (Tamanini, 2003)

Freezing-soil (Dall'Amico, 2010)



Snow-Cover (Zanotti, 2004)

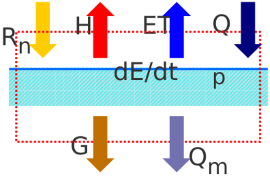


Energy Balance (Bertoldi, 2000)

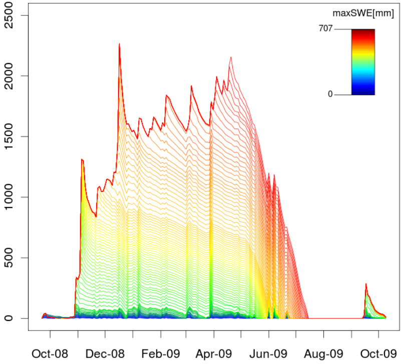
$$\frac{dE}{dt} = C_p\frac{dT_s}{dt} = R_n - H - ET + Q_p - G - Q_m$$

$$H = \rho\, c_p C_H\, \hat{u}\,(Ts - T_a)$$

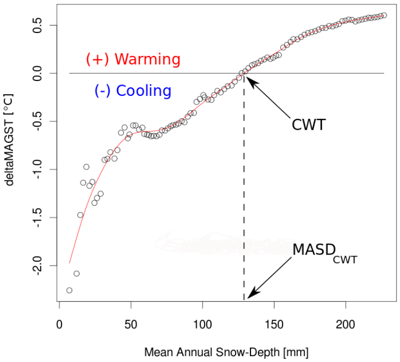
$$ET = \lambda\rho\, C_e\, \hat{u}\,(q^*(Ta) - q^*(T_a)\, U_a)$$



GEOtop: thermal effect of snow cover on MAGST



Snow-depth scenarios



Net effect of MASD on MAGST

Simulation interval from 15/09/2008 to 15/10/2009

10 loops of model spin-up.

111 Sim. Points = Slp: 0°-90° - Ele:2000-4000 - Asp: step 90°N

Pogliotti [2011]

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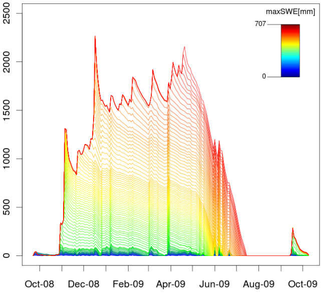

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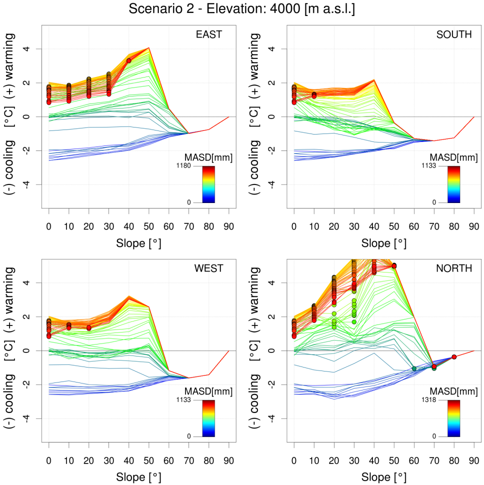
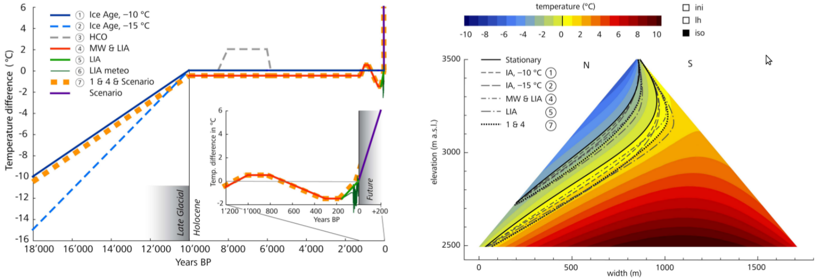


Net effect of MASD on MAGST - Synoptic View

TEBAL + COMSOL Multi-Physics

Surf.EB model + 3D heat conduction scheme
TEBAL: Corvatsch 1990-1999 (stationary conditions)
COMSOL: Initialized with differing temperature histories



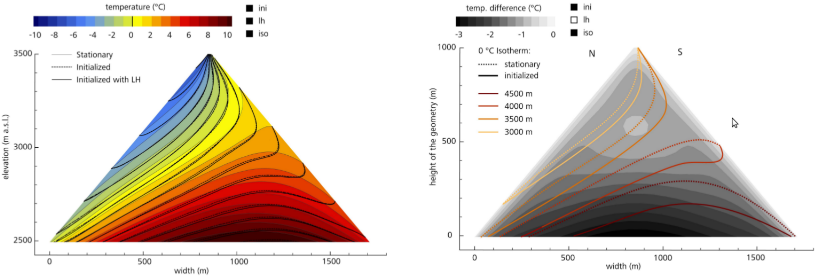
Left: **surf. temp. histories**

Right: **Sub. surf. temp. stationary vs. histories. Isotherms 0°C and -3°C.**

Noetzli and Gruber [2009]

TEBAL + COMSOL Multi-Physics

Effect of past climatic conditions and topography



Left: **Isotherms of a stationary temperature field compared to the init. (7)**
Right: **Temp. difference of the stationary solution to the init. (7) vs. elevation**

Isotherm 0°C

Noetzli and Gruber [2009]

TEBAL + COMSOL Multi-Physics

Effect of future warming at differing elevations

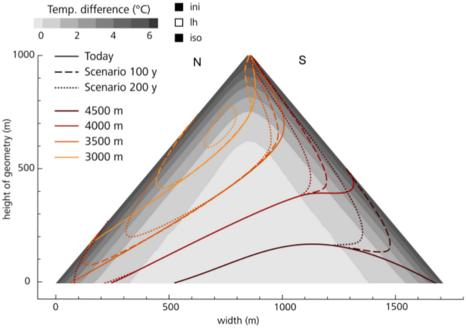


Fig: **Temp. difference between current transient temp. field and a 200-year scenario (+3°C). Isotherm 0°C**

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