INTERNSHIP REPORT

British Antarctic Survey

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I) Introduction

During a 3-months internship from June to August 2020, we tried to analyze some temperature datasets measured inside the George VI ice shelf. This ice shelf is situated between two blocks of continental bed, in Antarctica.

Several references will be made to the Jupyter files hosted on this Git. Run those files to visualize the figures.

II) Moorepoint data analysis

We had, first, a dataset containing the temperature at one location on the George VI ice shelf. The measures contain 15 different altitudes, over an ice column, and were done every two hours for approximately two years. The measures were done by Keith Nichols in 1988.

The thermistors were melted in the ice. In consequence, the points are lagrangian, because they moved with the ice because of vertical and horizontal advection.

The Z array indicates the original altitudes of the points, but we do not have the exact altitude of the thermistors with time. As said previously, those points are not stationary: they go down because of vertical advection, caused by the melting of the base of the ice shelf.

1) First observations

a) Time series

We first look at the time series, over altitude (see Figure 1 of jupyter_moorepoint)

The 5 first altitudes are in the ocean, because their altitude is negative. For those altitudes, there is strong oscillations in the time series, with an amplitude of approximately 0.1°C: the temperature in the ocean fluctuates a lot.

For the altitudes strictly superior to 0m, we can see an increase of temperature over time, which seems quite linear. There are no visible oscillations, excepted for the point near the surface (the glacier is 140m thick, the higher point is at 118m). This indicates that there are probably some oscillations at the surface, which can be seen if we look near the surface.

For the point at altitude 0m: we see, at the beginning of the time series, some low amplitude oscillations. Around 180 days, the oscillations start to be stronger, and are quite similar to the other oscillations in the ocean. This indicates that the point at altitude 0m was first in the ice, near the base of the glacier, and oscillated with low amplitudes due to the oscillations of temperature in the ocean. Then, at approximately 180 days, it melted, and the point was then inside the ocean.

b) Vertical profile

If we look at the temperature over altitude at a fixed time (see Figure 2 of jupyter_moorepoint), we can see that the vertical profile is not linear (which would be the case for the simplest situation, where the border temperatures would be constant, where the ice properties wouldn't depend on the temperature, and where the only source of heat propagation would be the diffusion). Here, the vertical profile even seems quadratic, which is curious.

We observe that there is a minimum for temperature, of -6.6°C, at 73m (for the first measure on the time series, but the vertical profile keeps globally the same shape over time).

2) Oscillations of temperature

a) First observations

Following the code on jupyter_moorepoint, we look at the time series and remove the slope (just the mean, for the points in the ocean) of every time series. We have isolated the oscillations. When we look at the normalized oscillations (see Figure 3 of jupyter_moorepoint), we see oscillations for the points inside the ocean, and for the points at altitude 0m and 8m, which are inside the ice. If we look at the not normalized oscillations, we see that the amplitude of the oscillations decreases quickly as we go deeper in the ice. Sadly, we also see that the oscillations at altitude 8m have approximately the same amplitude than the temperature resolution of the measures. In consequence, we choose to focus only on the oscillations inside the ocean (we pick altitude -1.96m), and at the altitude 0m, near the base of the glacier, where the point melted.

We filter those signals, by applying a Tukey window (which proved itself to be the best for this dataset, but you can still change the window in the code) and a lowpass filter to reduce the noise (see Figure 4 of jupyter_moorepoint).

b) Ocean and Ice cross-correlation

We use cross correlation: this method correlates two curves, but also shifts one of the curves and gives a value of the correlation for each value of the shift. We then search the shift for which the correlation is maximal, and we obtain the correlation of the two curves, but also the lag between those two curves. This lag, between the time series inside the ocean and inside the ice, exists because the temperature oscillations do not propagate instantaneously inside the ice.

We first do a cross-correlation for all altitudes (see Figure 5 of jupyter_moorepoint), but as the oscillations only exist, inside the ice, for the first altitude (at 0m), this correlation matrix is quite not significant. In facts, the lag, which sould be monotonous with the altitude, is clearly not appropriated (see Figure 6 of jupyter_moorepoint).

We now focus on altitudes -2m and 0m (as we said previously). We look at a truncated time series which stops before the melting of altitude 0m. You can see the temperature series, filtered and unfiltered oscillations for those altitudes on Figures 7, 8 and 9 of jupyer_moorepoint.

We re-compute a cross correlation for those two isolated altitudes. The figure 10, containing the correlation over the shift, indicates that the calculus seems ok, because the values are between -1 and 1, oscillate with the shift (because the original curves are also oscillating), and contains a maximum for a shift near 0 days. We obtain a shift of 1 day, between the first point in the ice, and the ocean.

Of you look at Figure 8 of jupyter_moorepoint, you'll see that there is, in facts, a visible shift between those two altitudes. You'll also see that this shift goes down to 0 with time, which is logical because the point finally melted into the ocean. The previous shift we calculated is, in reality, a mean value for the shift, over time. We divide the time series of the ice into segments, and we do a cross-correlation for each of these segments. By doing this, we obtain a value for the shift for each segment, and thus a shift, over time (see Figure 13 of jupyter_moorepoint). The shift seems to decrease linearly with time. This is caused by the fact that the entire column of ice goes down, because of vertical advection : there is snow accumulation on the surface, and basal melting at the bottom of the glacier, and in consequence, the ice moves vertically, with speeds equaling the surface accumulation rate and the basal melt rate, respectfully for the surface and the base of the ice shelf. The fact that the shift seems linear with time near the base indicates that the vertical advection stays approximately constant over the altitude travelled by the point at the initial altitude of 0m. In facts, this point moved only of a few meters (maximum) over this period of time, and if the accumulation rate is of the same order of magnitude than the melting rate, if we assume that the vertical advection has a linear profile over altitude (from the accumulation rate at the top to the melting rate at the bottom), we will not see significant variations of the advection on the last meters of a 140m thick ice column.

c) Spectral analysis

Using the previous oscillations, we apply on them a Fourier transform in order to have the spectra of those curves. We try different methods (a Welch method, a simple fft transform, and a manual Welch method with modifiable parameters, see figures 14, 15 and 16 of jupyter_moorepoint). We finally see that there is strong amplitudes for monthly oscillations. We also see tidal oscillations, which are the daily oscillations, with frequencies of 1 per day, 2 per day, 3 per day, etc. Those privileged frequencies are quite visible inside the ocean, less visible inside the ice (but still present).

3) Melt rate of the ice shelf

With the data we have, we can calculate a meltrate. We consider that on the given dataset, dT/dt (partial derivative) equals 0, i.e. that the eulerian curves are stationnary, and do not depend on time. This approximation is correct if we look only at the base of the glacier, where the temperature profile is not impacted by the warming of the atmosphere (not like the upper part of the vertical profile). This is why we will focus on the temperatures near the base in this calculus.

If we look at a point, descending a linear vertical slope at a given speed w over time, the correct formula for the meltrate (the speed) is the ratio of the lagrangian time derivative, with the eulerian z derivative. But, here, we only have lagrangian curves so we cannot calculate the eulerian z derivative. The meltrate we calculate is an approximated meltrate, for which we neglect the difference between eulerian and lagrangian derivatives for the calculus of the spatial derivative, which is OK because of the slow values of the vertical advection (the order of magnitude is 1m/y).

a) First calculus

We do a first meltrate calculus by doing :

- a global linear regression over all the time series, at altitude 8m, for DT/Dt,
- a linear regression over 2 points, at altitudes 8m and 18m, over time, for DT/Dz.

We use only 2 points for the spatial regression, because we ideally want to have a very local derivative, but we do not have a lot of points over the altitude, and because those points seem to give the good slope at the base of the glacier (see Figure 2 of jupyter_moorepoint : the 3 first altitudes in the ice seem well aligned). We do not use the altitude 0m because of the oscillations which can produce a biased calculus.

This calculus gives us a meltrate depending on time. The mean meltrate is 1.68m/y. This calculus is not good, because choosing to calculate a global time derivative is not a good option (as the simulations will indicate later). A mean time derivative will not accord well with a local z derivative, because DT/dt changes with time: the lagrangian point changes in altitude with time, because of the vertical advection, and as you can see on Figure 2 of jupyter_moorepoint, the slopes of the time series are clearly not constant with the altitude. In consequence, the advection causes DT/Dt to be not constant, and we have here a biased meltrate.

The meltrate is here decreasing with time, but this is caused only by the fact that we use a global time slope, as the simulations will show.

There could be an incertitude due to the fact that the vertical advection is not constant over altitude, and thus changes the value of Dz in the calculus of Dt/Dz. But, the thermistors are fixed on a solid cable, and are at constant distance between them.

b) Second calculus

We use the same method than before, but we do local linear regressions on the time series, in order to have a more accurate value for the meltrate. We can’t use a very local linear regression, because at altitude 8m, the slope is quite low, and the values of the temperature are the same for like 10 to 50 successive points: the slope is too low and the resolution for the measures of the temperature cause the data to be locally constant. To avoid this issue, we choose to calculate DT/Dt over each month (with linear regressions for every month).

We obtain a meltrate quite constant with time (or at least not clearly decreasing), with a mean value of 1.74m/y. This value is coherent with other melting rates calculated by some papers on George VI ice shelf, or on other ice shelf, which have the same order of magnitude.

III) Site3 data analysis

Here, we analyze a similar dataset, but measured on another site on George VI, at the same period approximately.

On this dataset, we have 3 points inside the ocean, and 12 within the ice. We observe similar phenomenon than on the previous dataset: we see, in particular, some oscillations for the altitude 2.88m, which are correlated with the oscillations in the ocean below.

On this dataset, we observe also similar privileged frequencies for the oscillations in the ice and in the ocean, very similar to the Moorepoint dataset. But, in the ice, the high frequencies are less visible because the point is at 3m above the ocean, instead of the 0m deep we had before.

We also observe that the time series in the ocean and in the ice are correlated, and when we do a new local cross correlation on the oscillations of temperature at those altitudes, we still see that there is a privileged lag, decreasing with time.

We execute the same meltrate calculus than the one used for the Moorepoint dataset, with the local DT/Dt (not biaised), and we obtain a mean (over time) value of 1.14 m/y.

For this dataset, we also plotted the eulerian curves, deduced from the lagrangian curves by using the meltrate obtained before. You can see on figure 11 of jupyter_site3 that the points seem more stationary than before, suggesting that the dT/dt (eulerian) approximation would be OK. We can nonetheless observe that the curves are still evolving with time. This can be caused by an error in the calculus off the meltrate (for example, caused by the fact that we have to use a local DT/Dt, but that we can't use a too local DT/Dt because the data is locally constant), or by the fact that we supposed the meltrate constant with time and altitude for this plot.

This eulerian plot has to be stationnary only for the pat of the curve where we supposed that the eulerian time derivative is null, i.e. the base of the glacier, the lower part of the vertical profile.

IV) Simulation of the glacier

We try here to explain the quadratic profile on the George VI ice shelf. We will isolate the phenomena responsible for this vertical profile and for the warming of the glacier.

All the parameters and border conditions for this simulation are defined in jupyter_simul_glacier. You can run the simulations coded on jupyter_simul_glacier, change the parameters etc.

We find that the main two factors responsible for this profile are the warming of the atmosphere and the vertical advection. In those simulations, we put the properties of the glacier George VI, and we consider the temperature over time and altitude. We consider the advection-diffusion heat equation, with a non-zero vertical advection. The horizontal advection is neglected. The fact that the ice thermal conductivity may depend on the temperature is negligible as you can see on figures 2 and 3 of jupyter_simul_glacier.

1) Warming atmosphere

Here, we do a first simulation where the atmosphere warms up, over a long period of time. We then do a second simulation starting from the previous simulation, with the same parameters, but with the same duration than the Moorepoint dataset we have. By doing this, we can compare the results of the simulation with the Moorepoint dataset.

If we start from a linear temperature profile and do a warming of the atmosphere, we obtain a curve similar to the dataset. If we try to optimize the simulation, by changing the duration of the warming, in order to have a minimum temperature situated at 73m (just like the dataset), we obtain a profile (for a 35-years warming) quite similar to the dataset, with a minimum over altitude of -6°C (dataset: 6.64°C), and a slope over time of 0.35°C, over the duration of the dataset, at 18m (0.38°C, over the duration of the dataset, for the dataset), and of 0.20°C, over the duration of the dataset at 33m (0.26°C, over the duration of the dataset, for the dataset).

If we do the same warming, but starting from a spinup profile, a profile which is stationary (this profile is not linear because of the vertical advection), the duration of the warming is now of only 18 years (in order to have a minimum over altitude at 73m), and we obtain a minimum of -5.8°C, and gradients over time of 0.42°C and 0.29°C, over the duration of the dataset, for respectively 18m and 33m. The glacier warms faster if we use an initial spinup profile.

In both cases, the warming of the atmosphere warms up only the upper part of the temperature vertical profile. The temperatures near the base (all the lower part, in facts), stay more stationary. The temperatures near the base evolve stronger on the lagrangian profiles, because of the effects of a point going down the curve.

2) Changing basal melt rate

We here analyze the effects of a changing basal melt rate, which changes all the vertical advection profile. This is how we change the vertical advection over time :

- the surface value is constant at 2m/y
- the basal value is initially at 2m/y and decreases of 0.1m/y every year
- at each time, the vertical advection inside the glacier is a linear function given by the surface and basal advection

The results of a changing basal melt rate on a stationary (spinup profile) are as it follows :

- If the surface temperature is lower than the basal temperature, the curve is shifted right, the glacier gets warmer.
- If the surface temperature is higher than the basal temperature, the curve is shifted left, the glacier gets cooler.

This is logical because reducing the basal melt rate also reduces all the vertical heat transfer from the top to the bottom. If the top is cooler than the bottom, reducing those transfers warms up the glacier.

3) Warming and changing basal melt rate

We run a simulation where both surface temperature and basal melt rate change with time. At a fixed time, if the surface temperature stops warming up, for a defined basal melt rate, the temperature evolves as it follows:

- If the vertical profile is warmer than the corresponding stationary state, the temperature goes cooler
- If the vertical profile is cooler than the corresponding stationary state, the temperature goes warmer

Considering that the basal melt rate actually creates a cooler temperature profile, and that reducing this meltrate, in consequence, warms up the glacier, decreasing the basal melt rate has thus for consequence to :

- Warm up the glacier if the actual vertical profile is cooler than the stationary one
- Reduce the cooling of the glacier, if the actual vertical profile is warmer than the stationary one (because decreasing the basal melt rate gets the stationary profile closer than before to the actual profile)

As a conclusion for this part, the warming of the atmosphere is mostly responsible for the warming of the upper part of the glacier, and the vertical advection and a potential decreasing basal melt rate are mostly responsible for the warming of the lower part of the glacier (and the upper part too).

V) 1D oscillations model

We now use another simulation, focused on the propagation of the oscillations of temperature of the ocean, inside the ice. The model used is as it follows :

- 3m depth
- Border condition at the base is defined as oscillations of temperature (for a given amplitude / period)
- Border condition at 3m is defined as a constant gradient
- We take only diffusion in consideration (for the beginning of this part at least), which is ok because the characteristic time for diffusion is 0.3y, and approximately 2years for advection

There are some limits to this model : the advection may not impact so much the eulerian curves, but our data is lagrangian, and the change eulerian/lagrangian may not be negligible. Furthermore, we approximate the temperature in the ice, at the interface ice/ocean, by saying that it's the same than the temperature of the ocean, which is not the case.

You can run all those simulations on jupyter_simul_oscill.

1) First observations

We first run some simulations, and we can see that:

- The temperature oscillates for all altitudes at the same frequency than the frequency of the basal border condition
- The amplitude (in the ice) decreases quickly with the altitude
- Changing the amplitude of the basal border condition will change the amplitude at all altitudes by the same factor, which is logical because the equation is linear
- The oscillations are less attenuated for high periods than for low periods
- For low periods (low in relation to the diffusion characteristic time), the vertical profile stays globally linear and stationary, excepted at the base of the glacier
- For high periods (high in relation to the diffusion characteristic time), the vertical profile is always linear, but is shifted with the time. In this case, in facts, we obtain the same result as if we solve for each time, for each basal temperature, the diffusion equation, as if the basal temperature is constant
- The phase seems to increase with the input basal period

You can see on figures 6, 7 and 8 of jupyer_simul_oscill some colormaps of the amplitude and the phase of the oscillations, over the altitude and over the input basal period of oscillations.

2) Oscillations with advection

Now, we add the advection on our model in order to check the impact of advection and to estimate an error in the calculus of the meltrate done on the lagrangian Moorepoint dataset.

The advection seems to have a limited impact when we look at the eulerian curves but has a clear impact on the lagrangian curves. Furthermore, if we run the simulations over a period of time which is not negligible in relation to the advection characteristic time, the advection starts to have a visible impact on the eulerian curves too.

We now calculate the meltrate by using the lagrangian curves of the simulation (we should use the eulerian curve for the dT/dz part, but we want to see precisely what's the incertitude), and we compare this value with the input vertical advection defined at the base of the glacier in the simulation (they should have the same value).

As we saw in the dataset, we find that by using a global DT/Dt calculus, we obtain a meltrate decreasing with time, with an incertitude on consequence increasing with time if you have an initial value beyond the theorical value.

We also obtain that if we use the eulerian curve for the calculus of dT/dz, we obtain the right value for the meltrate.

We obtain that the calculus with lagrangian curves, lagrangian derivatives, and a local derivative for the dT/dt, gives a meltrate with a small error rate (despite the fact that we use DT/Dz instead of eulerian dT/dz).

Finally, as described more precisely in the jupyter file, we use a formula to obtain a value for the vertical gradient of temperature inside the ocean that should correspond to the observed amplitudes in the ice. We obtain a value of -33.5K/m, which is the good order of magnitude.

3) Estimation of the altitude of the thermistors

We also tried to use this simulation to get the altitude of the measure points, on the Moorepoint dataset. We put at the base the same oscillations than the oscillations in the ocean on the Moorepoint dataset. Then, we looked at the phase and amplitude for a given input frequency which dominated the Moorepoint dataset (we obtained this frequency with the spectral analysis of the Moorepoint dataset), and we looked, more precisely, the altitude that matched with the amplitude and phase we obtained by analysing the Moorepoint dataset. Then, we had and estimated altitude for the point labelled "0m" on the Moorepoint dataset, which was averaged over the time (before it melted) for technical reasons. Because we also know that around 170 days, the point melted in the ice (and was in consequence at 0m), we could thus divide this altitude by half the time it took for this altitude to melt, in order to have an estimated meltrate for the glacier (we divide by only half the time because we have an averaged value for the altitude, i.e. a value for the altitude at the middle of the time series). We obtained through this method good orders of magnitude for the meltrate, but those calculus suffer from some approximations:

- The veracity of the simulation is not demonstrated
- Using a single input frequency and supposing that we can neglect all the other frequencies and still match the dataset with the simulations is a bit ambitious
- The oscillations inside the ocean cannot be modelled by the same oscillations at the base of the glacier, in the ice (and for this reason, the altitudes we obtained by comparing the phases were more accurate than the altitudes obtained by using the amplitude, because if there is a transfer function between the ice and the ocean at altitude 0, we can suppose, I guess, that the lag is limited)
- The simulation is not working for some parameters because it can't fit the sinusoidal regressions of the oscillations are too small
- If we use the shift method, we can't isolate a shift for each frequency (we can do that for the amplitude through a spectral analysis)
- The dataset also contains a restricted number of oscillations

For a low input period, by matching the amplitudes, we obtained a meltrate of 1.72 m/y.
For a high input period, by matching the amplitudes, we obtained a meltrate of 4.52 m/y.
For a high input period, by matching the phases (in facts, we supposed that the phase was mainly due to the high period very visible in the spectrum), we obtained a meltrate of 1.36 m/y.

Those results confirm that this method is not appropriated to a precise calculus of the meltrate and will only give you a large estimation, estimation we can already guess by looking at orders of magnitude of other meltrates already calculated.

VI) Meteorological data

Here, we analyze some meteorological data to check if the atmosphere is warming on George VI. In facts, on the simulation, the warming of the atmosphere where the temperature is measured, contains 3 factors, because of the fact that there is horizontal advection which causes the ice to move to the sea : the warming of the lagrangian points can be explained by the fact that the glacier goes to the north, so to a warmer place, but also by the fact that the ice goes to lower altitudes, and finally by the global warming of the atmosphere.

This meteorological dataset is located also on George VI ice shelf and contains the temperature at the surface of George VI.

As you can see on the Figure 1 of jupyter_meteo_data, we need to plot the same temperature for a chosen month, over years, because of yearly oscillation.

On the figure 2 of jupyter_meteo_data, we filtered the temperature at the surface of the glacier, for two chosen months. One color corresponds to an average temperature, over the chosen month, for each year. We also filtered the data to have the measures taken into account always done at the same hour. Thus, for a lot of months, there is not enough data to conclude. But for January and February for example, we can see that there is a warming of 1°C to 2°C over 35 years.

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