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A comparison of the Lower Underworlds on the northern and southern hemisphere

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Abstract

Every winter a big bubble of potentially cold air arises on the North Pole. This bubble of air is called the Underworld. The coldest part of this Underworld is what we will call the Lower Underworld in this thesis. The total mass of the Lower Underworld on the northern hemisphere has decreased over the past 37 years. This is in line with the widely known phenomenon of global warming. However on the southern hemisphere the trend of the mass of the Lower Underworld is opposite. The mass of the Lower Underworld on the southern hemisphere is showing increase over the past 37 years. In this thesis we investigate the differences between the two Lower Underworlds. Several differences are found; the Lower Underworlds on the northern and southern hemisphere differ greatly in size, meridional profile, seasonal cycle, sea ice cover, snow cover and the topographic distribution of the poleward mass flux. The decrease in sea ice cover and snow cover on the northern hemisphere is a probable reason for the difference in trend in the mass of the Lower Underworld.

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1 Introduction

1.1 Climate Change

Global warming has its clear effects on the temperature in both the polar zones. The IPCC (Intergovernmental Panel on Climate Change), that has been set up in 1988, is studying global warming. [4] As a part of this study, the IPCC runs a Coupled Model Intercomparison Project (CMIP), which combines several major climate models in order to predict the climate of the future. This CMIP and the specific temperature trends for both the polar zones is described by Walsh [2]. This article shows increase in temperature for both the polar zones in the period 1900-2100. There is a difference between the temperature trends in both the polar zones though. Walsh compares the trends for the A1B scenario. Several scenario's were used for the models, each scenario had different values for e.g. greenhouse gas concentrations. These scenario's are described in detail by Nakicenovic et al. [19]. The A1B scenario is called a "middle-of-the-road" scenario and indicates a warming of 1-4 $^{\circ}C$ for the southern polar cap $(60-90^{\circ}S)$ by 2100. This is a firm increase but not as strong as the warming which the same scenario indicates for the northern polar cap (60-90°N). On the northern polar cap the A1B scenario predicts a warming of 3-7 °C by 2100. It gets even more interesting if we look at the past decades. This same article shows the annual observations on the Northern polar cap from the NASA Goddard Institute for Space Studies in the period of 1957-2006.



Figure 1: "Linear trends of annual mean surface air temperature for 1957-2006 based on a. observational data (from NASA Goddard Institute for Space Studies), and b. the CMIP3 models used in the IPCC Fourth Assessment Report (AR4)."[2].

Fig. 1, adopted from [2], shows that the trend of annual surface air temperature on the northern polar cap is positive everywhere around the North Pole, varying between 0-3 °C. On the midlatitudes there is some slight cooling visible of around 1 °C. Again in this article [2] Walsh shows this figure for the southern polar cap with the observational data from Chapman & Walsh 2007a [18] for the period 1958-2002, see fig. 2. This figure does not show such a clear trend, there are several areas that show cooling as well as areas that show warming. Though the warming areas seem bigger it is interesting that in the heart of the Antarctic continent it has gotten colder in this period.



Figure 2: "Linear trends of annual mean surface air temperature for 1958-2002 based on a. observational data (Chapman & Walsh 2007a), and b. the CMIP3 models used in the IPCC Fourth Assessment Report (AR4)."[2].

Comparable trends are found and illustrated by Nghiem et. al. [1]. This article is focused on the sea ice extent in the Arctic and Antarctic. The sea ice in the Arctic and Antarctic is governed by the same trends as the annual surface air temperature. Since the 1970s the sea ice in the Antarctic has increased slightly, this is in stark contrast with the drastic reduction of sea ice in the Arctic.

This research will investigate the temperature trends in the Arctic and Antarctic. It will not focus on sea ice cover or surface temperatures but on the temperature of the atmosphere around the North and South Pole.

1.2 The atmosphere

The atmosphere of the earth can be divided into five layers. Going outwards from the surface of the earth, you have respectively; troposphere, stratosphere, mesosphere, thermosphere and exosphere, see fig.1. As mentioned earlier this research will focus on the troposphere and its temperature. Roughly speaking the temperature in the troposphere decreases with height.



Figure 3: The layers of the atmosphere, adopted from [6]

1.3 Potential temperature

In this thesis we will not look at the temperature (T) but at the potential temperature (θ) of the troposphere. The potential temperature of a given volume of a fluid is the temperature this volume would have when it is adiabatically (no heat is added or extracted from the fluid) brought to a standard pressure level (P_{ref}). A pressure of 1000 hPa is chosen as standard reference pressure. Note that potential temperature is a conserved quantity in adiabatic conditions. The potential temperature, denoted by θ , is defined as:

$$\theta = T \left(\frac{P_{ref}}{P}\right)^{\kappa} \tag{1}$$

where κ is the ratio $R/c_p = (c_p - c_v)/c_p$ [6]. R is here the gas constant of air, c_p is the specific heat capacity of dry air at constant pressure and c_v the specific heat capacity of dry air at constant volume.

1.4 Dividing the atmosphere

Unlike temperature, potential temperature increases with height except for sometimes near the surface of the Earth. Potential temperature also increases from the Poles to the equator. "This led Sir Napier Shaw to construct a simplified picture of the potential temperature distribution in which isentropic surfaces (isentropes, i.e. iso-surfaces of potential temperature) form caps over the pole". See fig. 4 adopted from [7].

The Atmosphere has been divided into three zones by Brian J. Hoskins. [8] "The "Overworld" is the region encompassed by isentropic surfaces that are everywhere above the tropopause. In the "Middleworld", the region with isentropes crossing



Figure 4: "Nineteenth century (after Helmholtz, Brillouin and Shaw) depiction of isentropes in the atmosphere encircling the Earth. Only one hemisphere is shown. PN indicates North Pole. The 300 K isentrope usually grazes the Earths surface in the tropics." [7].



Figure 5: "The zonal mean and monthly mean potential temperature in the COSPAR International reference atmosphere as a function of latitude and pressure. Labels are in K. The isentropes in the Underworld are blue; the isentropes in the Overworld are red. Cyan isentropes belong to the Middleworld (defined in section 1.26). The isolated mass of very cold air over the north pole grows between September and December. Source: Fleming, E. L., Chandra, S., Barnett, J. J. and Corney, M. 1990. Zonal Mean Temperature, Pressure, Zonal Wind, and Geopotential Height as Functions of Latitude. Advances in Space Research, 10, No. 12, 11-59" [7].

the tropopause but not striking the Earth's surface" and "The "Underworld", in wich isentropic surfaces intercept the surface of the Earth" (the tropopause is the borderline between the troposphere and the stratosphere). In fig. 5 the Overworld, the Middleworld and the Underworld are illustrated. A very neat property of these isentropes of potential temperature is that "If conditions are adiabatic, i.e. heat is not added to or extracted from air parcels, air below specific isentropes within the Underworld is trapped by the Earths surface. An isolated reservoir of potentially very cold air exists over the poles in winter." [7]. So even though temperature may vary in an air parcel, if no heat is added or subtracted, it's potential temperature will stay the same. This means no air parcel will cross an isentrope if conditions are adiabatic.

1.5 The Underworld

In this thesis we will investigate the Underworld of the atmosphere, more specific the air below the 275 K isentrope wich we will refer to as the "Lower Underworld". The total mass of the Lower Underworld is strongly seasonal dependent, each winter it grows to it's maximum size only to decrease drastically in the summer. The increase and decrease of the Underworld is regulated by the so called Brewer-Dobson circulation. "This circulation consists of a poleward flux of mass in the upper troposphere and stratosphere and an equatoward mass flux near the earth's surface, by cold air outbreaks" [9]. Fig. 6, adopted from [11], shows the Brewer-Dobson circulation in the stratosphere and mesosphere, the surface sector of the Brewer-Dobson circulation is not visible here.



Figure 6: "Zonal mean circulation in the middle atmosphere during solstice (W indicates winter; S indicates summer), according to Timothy Dunkerton (1978) (On the Mean Meridional Mass Motions of the Stratosphere and Mesosphere. J.Atmos.Sci., 35, 2325-2333). This circulation is now known as the "Brewer-Dobson circulation"." [11].

The air that is transported from the equator towards the poles will decrease in potential temperature due to particle energy radiation and decreased radiation from the sun. In this manner, air will enter the Underworld from the top, so it is crossing isentropes. This is how the Underworld grows. The Underworld shrinks due to cold air outbreaks. These happen at the surface of the earth. See fig. 7, adopted from [17].



Figure 7: "The zonal mean position of selected isentropes at t=2 days (thin contours), at t=3 days (thicker contours) and at t=4 days (thick contours) during the simulation of the adiabatic life cycle of an unstable baroclinic wave. The initial state is shown in figure 10.6. Each arrow indicates the change in vertical position of the 290 K isentrope during 1 day." [17] The units of the labels are potential temperature (θ) .

We speak of a cold air outbreak when the winds at the surface of the earth transport a big amount of potentially cold air towards the equator. When this happens the potentially cold air will increase in potential temperature due to increased radiation from the sun and latent heat release: "When water (in any of the three phases) moves from gas to liquid or from liquid to ice, the air surrounding the H2O will have energy added to it. This is called a release of latent heat" [10]. This results in a loss of mass for the Underworld. A schematic view of a polar air outbreak is shown in fig. 7. Fig. 7 shows that a part of the Underworld is transported towards the equator, as is visible in the figure this happens at the surface of the Earth. However, in fig. 7 no mass escapes the Underworld since it is an adiabatic simulation. In the real world the part of the Underworld that is transported towards the equator will increase in potential temperature and this mass will eventually escape the Underworld.

1.6 Research question

In this thesis we will investigate the Lower Underworld on the North and South Pole. Obviously the northern and southern hemisphere differ a lot in topography. This leads to differences between the Lower Underworlds. We will investigate these differences between the two Lower Underworlds, focusing on the influence of the winds.

2 Data or Model description

2.1 ECMWF

All the data used in this thesis comes from the ECMWF. This is the European Centre for Medium-Range Weather Forecasts, which was established in 1975 and is "an independent intergovernmental organisation supported by 34 states." [12] The ECMWF is "both a research institute and a 24/7 operational service, producing and disseminating numerical weather predictions to its Member States." [12]

2.2 Data used

Besides weather forecasting, the ECMWF also "periodically uses its forecast models and data assimilation systems to 'reanalyse' archived observations, creating global data sets describing the recent history of the atmosphere, land surface, and oceans. Reanalysis data are used for monitoring climate change, for research and education" [13]. One of these data sets, the ERA-Interm, is used in this thesis. This is the successor of the ERA-40 data set which Walsh et. al. [2] describes as "The ERA40 provides one of the most consistent gridded representations of surface air temperature and it therefore serves as a useful benchmark against which the model simulations of the late 20th century may be compared.". "ERA-Interim is a global atmospheric reanalysis from 1979, continuously updated in real time." [14]. The data set is available in a spatial resolution of up to 0.125 x 0.125 degree, though we will mostly use a spatial resolution of 1x1 degree. In the vertical it has 60 levels from the surface up to 0.1 hPa.

A neat feature of the ERA-Interim is that it has been interpolated on to potential temperature levels by the ECMWF in levels ranging from 265 up to 850 K.

3 Results

3.1 General shape of the Lower Underworld

To get an idea of the shape of the Lower Underworlds we plotted the meridional profile of the Lower Underworlds in the winter on the northern hemisphere as well as the winter on the southern hemisphere.

The Lower Underworlds on the northern hemisphere and southern hemisphere have a very different profile. The profile of both the Lower Underworlds in DJF (December, January and February) is shown in fig. 8. Fig. 9 shows the same profiles but now for JJA (June, July and August). These plots show a more flat profile for the Lower Underworld in the Antarctic compared to the one in the Arctic. Another notable feature is difference in size in the summer. Where the northern Lower Underworld almost disappears in JJA, the southern Lower Underworld retains about one third of its size in DJF. Besides a difference in shape these plots also show the difference in size between both the Lower Underworlds.



Figure 8: The, zonal mean, meridional profile of both the Lower Underworlds in DJF, averaged over the period 1981-1990.



Figure 9: The, zonal mean, meridional profile of both the Lower Underworlds in JJA, averaged over the period 1981-1990.

More on the difference in size is visible in fig. 10. Fig. 10 shows the yearly averaged total mass in the Lower Underworld between 1979 and 2015. Here you can see a firm decrease in the mass of the Lower Underworld on the northern hemisphere. The mass of the Lower Underworld on the southern hemisphere shows a slight increase over the years. This plot also shows that the Lower Underworld on the northern hemisphere is a lot bigger than the one on the southern hemisphere.

Based on this plot we investigated two periods in the history of the Lower Underworlds. These two periods are 1981-1990 and 2001-2010. The first period represents the "former" situation of the Lower Underworlds, the second period represents the changed situation.



Figure 10: The yearly averaged total amount of mass in the Lower Underworld for the northern hemisphere (blue), southern hemisphere (red) and the two averaged (black) since 1979. Linear fits are made for all three lines, these are shown in respectively dark blue, dark red and gray. Linear fit: $y = a \cdot x + b$, with $a = -5.2933 \cdot 10^{14}$ and $b = 1.2303 \cdot 10^{18}$ for the northern hemisphere. For the southern hemisphere linear fit $a = 2.8686 \cdot 10^{14}$ and $b = -4.5622 \cdot 10^{17}$

3.2 Mass in the Lower Underworld

Fig. 8 and fig. 9 show that the Lower Underworlds on the northern hemisphere and southern hemisphere differ in size in the winter as well as in the summer. This difference in "summer size" is also visible in fig. 11 which shows the seasonal cycle for both the Lower Underworlds. This plot reveals the strong variance in the size of the northern Lower Underworld. In the summer on the northern hemisphere, the Lower Underworld decreases to less than one sixth of its winter size. Whereas the oscillation of the southern Lower Underworld is not that strong. In the summer on the southern hemisphere the Lower Underworld only decreases to one third of its winter size.



Figure 11: The seasonal cycle of the Lower Underworld on the northern hemisphere (blue), the southern hemisphere (red) and the two averaged (black).

Fig. 12 and fig. 13 show the geographic distribution of the Lower Underworlds in DJF for the earlier mentioned two periods. The same is plotted in fig. 14 and fig. 15 but here it is done for JJA.

Both the Lower Underworlds are changing in size as seen in fig. 10. To further investigate these mass differences in the Lower Underworld we plotted the difference in mass in the Lower Underworld between the periods 1981-1990 and 2001-2010. We did this for DJF as well as for JJA, the results are shown in respectively fig. 16 and fig. 17.

Fig. 16 shows that in DJF from -140 to 80 degrees longitude the Lower Underworld on the northern hemisphere has shrunken in size and from 80 to 180 degrees longitude (eastern Siberia) it has increased in size, except for one "island" around 130 degrees longitude (Japan). The Lower Underworld on the southern hemisphere has only increased in size in DJF. Comparable differences are found for JJA, though less strong. Fig. 17 shows that in JJA the Lower Underworld on the northern hemisphere has shrunken in size across all longitudes. The Lower Underworld on the southern hemisphere has increased in size around -30 degrees longitudes as shown in fig. 17.



Figure 12: The mass in the Lower Underworld in DJF averaged over the period 1981-1990.



Figure 13: The mass in the Lower Underworld in DJF averaged over the period 2001-2010.



Figure 14: The mass in the Lower Underworld in JJA averaged over the period 1981-1990.



Figure 15: The mass in the Lower Underworld in JJA averaged over the period 2001-2010.



Figure 16: The mass difference in the Lower Underworld in DJF between the periods 1981-1990 and 2001-2010.



Figure 17: The mass difference in the Lower Underworld in JJA between the periods 1981-1990 and 2001-2010.

3.3 Mass flux in the Lower Underworld

As mentioned before, the Lower Underworld is strongly varying in size during a year. This is possible because there is a strong in and out flux of mass of the Lower Underworld. As explained in section 1.5, the Lower Underworld loses a lot of its mass due to "Polar air outbreaks". To investigate this phenomenon we plotted the poleward mass flux in the Lower Underworld in fig. 18, fig. 19, fig. 20 and fig. 21. Again this is done for two periods; 1981-1990 and 2001-2010. In these two periods plots are made for the Arctic as well as the Antarctic.

We calculated the poleward mass flux using the following equation.

$$PWMF[kg \cdot s^{-1} \cdot m^{-1}] \simeq \frac{1}{2 \cdot g} \{ (v_s + v_{265}) \cdot (p_s - p_{265}) + (v_{265} + v_{275}) \cdot (p_{265} - p_{275}) \}$$
(2)

Where g is the gravitational constant, v_s , v_{265} and v_{275} respectively the ycomponents of the wind on the surface, the $\theta = 265K$ and the $\theta = 275K$ isentropes. The same holds for p_s , p_{265} and p_{275} , which are the pressure values for respectively the $\theta = 265K$ and the $\theta = 275K$ isentropes.

We derived equation 2 using the hydrostatic balance:

$$\left(\frac{\partial p}{\partial z}\right) = -\rho \cdot g \tag{3}$$

Rewriting this gives:

$$-\rho \cdot \partial z = \frac{1}{g} \cdot \partial p \tag{4}$$

Equation 4 gives the mass of a layer of air with thickness ∂z above a surface element. Multiplying this by the wind speed gives the mass flux. We average the wind speeds of the layers using the wind speed at the top and the bottom of the layer.

When we look at the equatorward mass flux in the lower (higher) latitudes for the northern (southern) hemisphere we see a big difference between the northern and southern hemisphere. Between -50 and -70 degrees latitude on the southern hemisphere the mass flux is poleward almost everywhere. This is not the case on the northern hemisphere. On the northern hemisphere the equatorward mass flux on the mid and lower latitudes is mostly equatorward and happens mainly at the west side of the oceans. Another feature in fig. 18 and fig. 19 that stands out is the poleward mass flux between 50 and 180 degrees longitude on the higher latitudes (Siberia). The mass of cold air that flows towards the pole on these longitudes flows over the North Pole and then flows equatorward on -180 to -80 degrees longitude. The same phenomenon is found on the southern hemisphere. When we look at the lower latitudes in fig. 20 and fig. 21 we see an poleward mass flux on 100 to 180 degrees longitudes and on -180 to -150 degrees longitudes, after passing the South Pole this air moves equatorward on -50 to 50 degrees longitude. To investigate the difference in poleward mass flux between the periods 1981-1990 and 2001-2010 we plotted fig. 22 and fig. 23. Fig. 22 shows that the total mass flux has decreased on the northern hemisphere; on 100 to 180 degrees longitude the poleward mass flux has decreased and on -140 to 50 degrees longitude the equatorward mass flux has decreased. Fig. 23 does not show a strong difference in poleward mass flux between the periods 1981-1990 and 2001-2010, though it shows more increase than decrease in poleward mass flux.

In an attempt to explain why there are preferred longitudes in the Antarctic where the mass flux is equatorward instead of poleward, we plotted the surface pressure on the southern hemisphere, see fig. 24. When we compare fig. 20 and fig. 15 with fig. 24 we see that the equatorward mass flux takes place at the east side of the Wedell Sea and the Ross Sea.



Figure 18: The poleward mass flux in the Lower Underworld on the northern hemisphere. The flux shown is the total flux of DJF averaged over the period 1981-1990.



Figure 19: The poleward mass flux in the Lower Underworld on the northern hemisphere. The flux shown is the total flux of DJF averaged over the period 2001-2010.



Figure 20: The poleward mass flux in the Lower Underworld on the southern hemisphere. The flux shown is the total flux of JJA averaged over the period 1981-1990.



Figure 21: The poleward mass flux in the Lower Underworld on the southern hemisphere. The flux shown is the total flux of JJA averaged over the period 2001-2010.



Figure 22: The difference in poleward mass flux the Lower Underworld on the northern hemisphere in DJF between the periods 1981-1990 and 2001-2010.



Figure 23: The difference in poleward mass flux the Lower Underworld on the southern hemisphere in JJA between the periods 1981-1990 and 2001-2010.



Figure 24: A contour plot of the surface pressure on the southern hemisphere.

3.4 Additional points of research

The Lower Underworld is not an isolated segment of the atmosphere. Many phenomena could affect the Lower Underworld. To investigate the very likely relation between the size of the Lower Underworld and the amount of sea ice, we plotted the sea ice coverage over the years in fig. 25. From this figure it is evident that the sea ice coverage follows the same trend as the mass of the Lower Underworld, both on the northern and on the southern hemisphere. However, the trend seems weaker for the sea ice cover. Also the negative and positive trend for respectively the northern and southern hemisphere commences later for the sea ice coverage than for the total mass of the Lower Underworld.



Figure 25: Yearly averaged sea ice cover since 1979, plotted for the northern hemisphere (blue), the southern hemisphere (red) and the two averaged (black).

Another factor that could play a big role in the shrinking or growing in size of the Lower Underworld is snow cover. However, this is only interesting for the northern hemisphere since there is barely any land in the Antarctic apart from Antarctica, which is always covered in snow. On the northern hemisphere the snow cover in Eurasia and North America can greatly affect the size of the Lower Underworld. Fig. 26 shows the yearly average snow cover on the northern hemisphere. It is evident that the snow cover on the northern hemisphere has been decreasing since 1979.



Figure 26: Yearly averaged snow cover in square kilometers since 1979, plotted for the northern hemisphere (blue), with a linear fit (dark blue).

4 Discussion

When we take a look at the total trend of the Lower Underworlds on the northern and southern hemisphere (see fig. 10) we find similar trends as in the surface temperature trends [2]. This means a decrease in size for the Lower Underworld on the northern hemisphere and an increase in size of the Lower Underworld on the southern hemisphere.

This result is in line with the trend of the sea ice cover in both the Arctic and the Antarctic as discussed earlier. [1] In fig. 25 we looked into the trend of the sea ice cover and found the same trends as discussed by Nghiem et al..

These results also show that the data from the ECMWF agrees with other research, at least roughly speaking.

When we look at the results of this thesis several interesting subjects stand out. One of these subjects is snow cover throughout the winter. This applies mostly for the northern hemisphere since the Antarctic barely contains any land apart from Antarctica. The yearly snow cover on the northern hemisphere has decreased strongly since 1979 as seen in fig. 26. This decrease in snow cover is probably a component in a downward spiral in which a decreased snow cover causes temperatures to rise because of a changed radiation balance. Higher temperatures cause on their turn less snow to fall. Further research is still needed on the snow cover throughout the winter.

Another interesting point for further research is the mass flux in the Antarctic. When we look at the poleward mass flux in the lower latitudes of the southern hemisphere in fig. 20 and fig. 21 we see that there are roughly two large areas where the mass flux is equatorward. When we compare fig. 20 and fig. 15 with fig. 24 we see that these two areas with equatorward mass flux are located at the east side of both the Weddell Sea and the Ross Sea. This could be due to katabatic winds that drive the potentially cold air off shore. The east side of both the Weddell Sea and the Ross Sea could also be preferred areas for cyclogenesis. This is also a possible cause for the equatorward mass flux at the east side of both the Weddell Sea and the Ross Sea. However, further research is needed to fully understand why there are preferred longitudes where the mass flux is equatorward.

Another point for further research would be the use of data from other models. We solely used data from the ECMWF. Even though the ECMWF data sets are considered to be of high quality (see section 2), using several data sets always gives a more objective view.

We have seen the impact of the mass flux on the mass losses of the Lower Underworld. Mass fluxes can cause a polar air outbreak, which leads to great losses in mass for both the Lower Underworlds. These mass fluxes are regulated by the winds. On the southern hemisphere the Southern Annular Mode (SAM) index is an important regulating factor for the wind. The SAM index has oscillated throughout history and is according to Abram et. al. [16] at this moment at its highest value ever. A high value of the SAM index is associated with a strengthening and poleward contraction of the southern hemisphere westerly jet stream. This strongly affects the polar air outbreaks on the southern hemisphere. At this moment the mass flux on the mid latitudes on the southern hemisphere is polewards nearly everywhere as seen in fig. 20 and fig. 21. This poleward mass flux keeps the potentially cold air in the Antarctic and decreases the chance of an polar air outbreak to happen. This stands in great contrast with the mass flux on the mid latitudes on the northern hemisphere there is a strong equatorward mass flux on the west side of the oceans.

A high SAM index is connected to this poleward mass flux on the mid latitudes on the southern hemisphere, so the SAM index is an important factor in regulating the size of the Lower Underworld on the southern hemisphere. However further investigation is needed to find the exact relation between the SAM index and the poleward mass flux on the southern hemisphere. As said earlier the SAM index has been high for the past decades and is at this moment at its highest value ever. [16] This could be a cause for the relatively stable size and slight growth of the Lower Underworld in Antarctica in the past decades. This is because the SAM index does not only affect the mass flux in the Lower Underworld but also the sea ice drift, as described by Nghiem et. al.. [1] It could be the reason why the effects of global warming are not as apparent in Antarctica as they are in the rest of the world.

Another interesting feature is found in fig. 18, fig. 19, fig. 20 and fig. 21. When we look at the mass flux in the Lower Underworlds we can see that with the increase or decrease of the Lower Underworld, the mass flux increases or decreases respectively. This increase (decrease) in mass flux is visible in fig. 21 (fig. 20). As mentioned in section 1.5, the mass flux in the Lower Underworld is part of the Brewer-Dobson circulation. This is an interesting subject for further research. The decrease or increase in size of the Lower Underworld could influence the speed of the Brewer-Dobson circulation. It could also be the other way around. The speed of the Brewer-Dobson circulation could be changing due to global climate change, which affects the mass flux in the Lower Underworld.

That this is an important factor in regulating the size of the Lower Underworld is evident from the work of Kanno et. al. [3]. They investigated the residence time of the air mass in the Underworld. One of their conclusions is that the residence time in the Underworld is much higher on the northern hemisphere than it is on the southern hemisphere. This could attribute to the difference in size between the two Lower Underworlds. So a change in the speed of the Brewer-Dobson circulation could greatly affect the size of the Lower Underworld. Also when we compare fig. 18 and fig. 19 with fig. 12 and fig. 13, it seems the meridional mass flux at the west side of the oceans affects the shape of the Lower Underworld. Fig. 12 and fig. 13 both show that the Lower Underworld on the northern hemisphere extents the furthest on the west side of the oceans. It makes sense that the Lower Underworld extents furthest where the equatorward mass flux is the greatest. Interestingly though, this happens without significant flattening of the Lower Underworld in the latitudes above the west side of the oceans.

5 Conclusions

A clear conclusion can be drawn from fig. 10: since 1979 the Lower Underworld on the northern hemisphere has decreased in size and the Lower Underworld on the southern hemisphere has increased in size.

It is very hard to find the reason for this difference in trend in the size of the Lower Underworlds and this study does not point out a clear cause for this difference. However two aspects stand out that probably play a big role in this difference in trend in the size of the Lower Underworlds.

The first is the snow cover on the northern hemisphere. The last 37 years the snow cover on the northern hemisphere has decreased, see fig. 26.

The second is the sea ice cover on both the hemispheres. Where the sea ice cover on the southern hemisphere has remained more or less constant, the sea ice cover on the northern hemisphere has decreased since 1979 as seen in fig. 25. The difference between the trends in sea ice cover between the northern and southern hemisphere is explained by Nghiem et al.. [1]

Next to these probable causes we also found several clear differences between the two Lower Underworlds. Whether or not these differences are a cause for the difference in trend in the size of the Lower Underworlds is not clear.

The first one is evident from fig. 10. The Lower Underworld on the northern hemisphere is a lot bigger than the Lower Underworld on the southern hemisphere.

The second one is the meridional profile of the Lower Underworld, see fig. 8 and fig. 9. The Lower Underworld in the Arctic has more of a 'mountain' profile, it keeps increasing in thickness with increasing latitude. The profile of the Lower Underworld in the Antarctic is more of a 'sheet' profile, it stays approximately the same thickness with decreasing latitude.

Thirdly is the seasonal cycle of both the Lower Underworlds. Fig. 11 shows that the seasonal cycle for the Lower Underworld in the Arctic is much stronger than for the one in the Antarctic. In the summer on the northern hemisphere, the Lower Underworld there decreases to less than one sixth of its winter size. Whereas in the summer on the southern hemisphere the Lower Underworld there only decreases to one third of its winter size. Lastly the poleward mass flux of both the Lower Underworlds differs greatly. When we look at the equatorward mass flux in the lower (higher) latitudes for the northern (southern) hemisphere we see a big difference between the northern and southern hemisphere. Where the mass flux on the southern hemisphere is poleward almost everywhere on the mid latitudes of the southern hemisphere, this is not the case for the northern hemisphere. On the northern hemisphere there is an equatorward mass flux on the mid and lower latitudes. This equatorward mass flux happens mainly at the west side of the oceans.

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