26 February 2024

Suggestions for Master Thesis Projects in the Atmospheric Dynamics Group

In the following, 10 potential projects are briefly outlined. For each project, the primary supervisor (and for some projects also the co-supervisor(s)) are listed. The co-supervisors might change depending on which projects are selected in the end. We don't intend to supervise so many projects – but we would like to give you a good choice!

If you have questions about a specific project, please contact the supervisor(s) by mail to learn more about what we have in mind.

If you decide to choose one of these projects, then please inform the supervisor(s) plus Heini Wernli (heini.wernli@env.ethz.ch) about your decision. You will then get a confirmation in case the project is still available.

For general questions about the procedure please contact Hanna Joos (hanna.joos@env.ethz.ch) and/or Heini Wernli (heini.wernli@env.ethz.ch).

Topic overview

1) How do moisture source changes shape the isotopic composition of Arctic water vapour?
2) Weather systems leading to low sea ice cover in McMurdo Sound (Antarctica) – *in collaboration with the group of Ruzica Dadic at SLF Davos*
3) Extratropical cyclones in the AI forecast system of the ECMWF
4) What determines the formation and characteristics of WCB branches?
5) The role of WCBs for the formation of tropospheric PV cutoffs
6) Tropical moisture exports in present-day and future climate simulations
7) How far do tropopause perturbations reach into the stratosphere? – *in collaboration with the group of Daniela Domeisen*
8) Stratosphere-troposphere exchange in a changing climate
9) Alpine foehn in pseudo-global warming COSMO simulations
10) Effect of Saharan dust events on hail in Europe
11) The relevance of dry intrusions for strong wind gusts over Switzerland – *offered by Christian Grams at MeteoSchweiz in collaboration with us*

How do moisture source changes shape the isotopic composition of Arctic water vapour?

Description

Arctic sea ice extent is declining strongly due to global climate change (Stroeve and Notz, 2018) leading to increased surface evaporation and surface latent heat flux (Bintanja and Selten, 2014). The Barents Sea is highly affected by sea ice loss which is expected to increase local surface evaporation and moisture availability to the adjacent continents. It has been argued that these changes in surface fluxes lead to an increase in snowfall and Eurasian cold winters (Mori et al., 2014, Bailey et al. 2021). Even though there is evidence for a link between sea-ice decline and increased Eurasian snowfall, a Lagrangian modelling approach analyzing the link between moisture sources in the Barents Sea and Eurasian water vapour has not been applied so far.

A Lagrangian measure of the atmospheric moisture cycle are stable water isotopes (SWI). SWIs are a tracer of moist adiabatic processes and give insights into the cycling of atmospheric moisture. Measurements of SWIs in Arctic regions are insightful in two ways. On one hand, such measurements can be used to identify changes in the Arctic moisture cycle. On the other hand, long-term archives, such as ice cores, often use SWIs as a temperature proxy. Improving the understanding of the Arctic moisture cycle and moisture sources will help in the interpretation of paleoarchives.

Changing Arctic moisture sources will leave distinct isotopic signatures in water vapour. The combination of SWI measurements with Lagrangian modelling tools is thus a powerful way to identify moisture source patterns. In this project, a long-term time series of SWIs in water vapour from Kiruna in Northern Sweden is evaluated for seasonal changes in moisture sources.

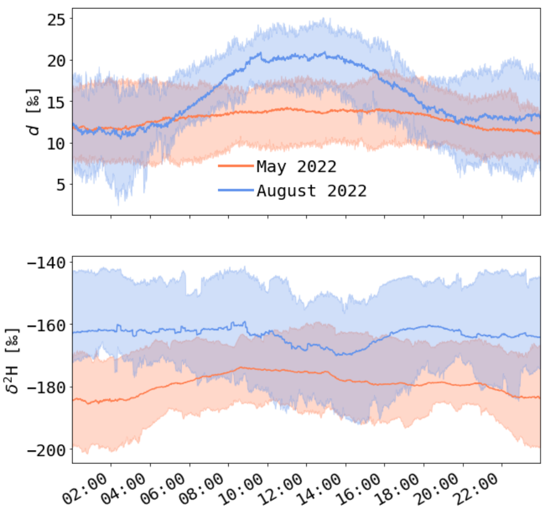

Figure 1: (left) Mean daily cycle and 25th-75th percentile range (shaded area) in isotopic composition (d-excess and δ^2H) of water vapour in May (orange) and August (blue) 2022 in Kiruna, Sweden. (right) Swedish Institute of Space Physics (IRF) in Kiruna. Photo: Torbjörn Lövgren, IRF.

Method

We are using a dataset of SWIs in water vapour measured for nearly a full year at the Swedish Institute of Space Physics (IRF) in Kiruna, Sweden, during winter to summer 2022. This dataset will be combined with LAGRANTO air parcel trajectories (Sprenger and Wernli, 2015) based on era5 reanalysis data and the moisture source diagnostic WaterSip (Sodemann et al., 2008) to characterise seasonal moisture sources patterns.

Approach

The main goal of this project is to characterise the main source regions of water vapour in Kiruna using backward trajcetories and WaterSip. This analysis includes assessing the importance of local versus remote moisture sources for the study area. In a second step, the seasonal changes in moisture source regions will be combined with the SWI measurements to identify seasonal isotope patterns and their link to moisture sources. If there is time and depending on interest, specific weather events can be analysed in detail for strong shifts in moisture source regions and combined with satellite retrievals and SWIs in precipitation; or the effect of climate change on moisture sources in the area can be assessed with model data from the Community Earth System Model (CESM; Hurrell et al., 2013) and interpreted with respect to the isotopic climate change signal in this region.

Requirements

We are looking for a motivated student who is interested in the Arctic moisture cycle, isotope meteorology and to work with observations, Lagrangian modelling tools and some programming.

Supervisors

Iris Thurnherr (iris.thurnherr@env.ethz.ch)
Katharina Hartmuth (katharina.hartmuth@env.ethz.ch)

References

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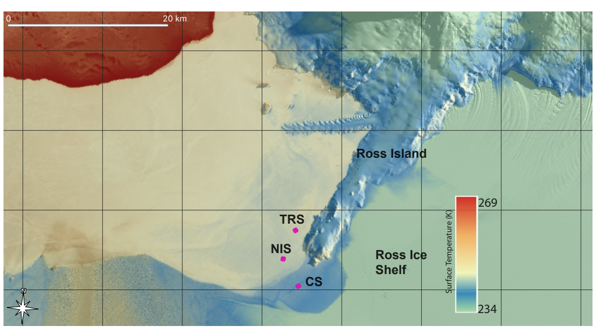
Weather systems leading to extremely low sea ice in McMurdo Sound

Description

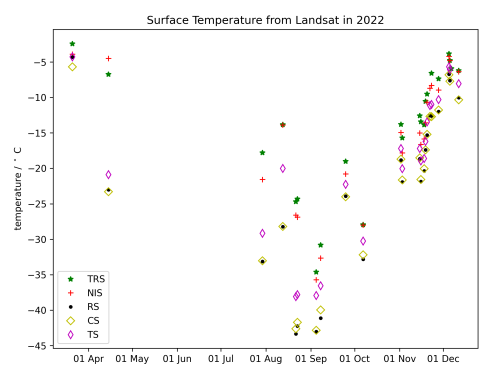
Over the last few decades, decreasing sea ice cover has been the dominant radiative feedback in the climate system (Pistone et al., 2014), and affects climate tipping points by influencing atmospheric and ocean circulation. In 2023, Arctic winter sea ice concentration continued to decline at an almost average rate, following the clear trends of the last two decades. Antarctic sea ice, by contrast, is exhibiting far below-average rates in 2023 (Eayrs et al., 2021), reaching unprecedentedly low levels for winter relative to the 45-year satellite data record (NSIDC, Monthly archives, July 2023).

This project aims to understand the atmospheric conditions that lead to repeated breakouts of landfast sea ice in McMurdo Sound in the winter of 2022. McMurdo Sound lies within the Ross Sea and is bounded by the Ross Island in the East, the Royal Society Range in the West, the wider Ross Sea in the North, and the Ross Ice Shelf in the South. The fast ice in McMurdo Sound forms at the beginning of winter, and part of the ice breaks out around late January, usually following the arrival of the icebreaker, which supplies McMurdo Station and Scott Base. In the past, there have been exceptional years of low ice cover in the sound, where continuous ice formation in winter was hindered by repeating Southerlies (Leonard et al., 2021). In 2022, storms producing strong southerly winds regularly blew out the new-forming ice in McMurdo Sound, and the Sound remained essentially ice-free until the storms ceased in late August 2022, at which point the continuous ice cover started forming. This project would investigate the meteorological causes of the delayed formation of stable fast-ice covers in McMurdo Sound in 2022, but potentially also in earlier years with low ice cover.

This project will be performed as a collaboration of the group of Ruzica Dadic at SLF Davos – who is an expert in the role of sea ice and snow on sea ice in the climate system and who knows the McMurdo Sound region from expeditions – and the atmospheric dynamics group at ETH Zurich. The dynamics groups have access to ERA5 reanalysis data and expertise in studying weather conditions during extreme polar seasons (Thurnherr et al., 2021; Hartmuth et al., 2022).



(a) The image shows an overlay of Landsat surface temperatures over a Landsat grayscale visible image. The temperature scale is approximate only.



(b) Landsat surface temperature retrievals at different locations in the MuMurdo Sound in winter/spring 2022. The temperature differences between the stations are caused by repeated breakouts of sea ice, and reflect changes in ice thickness.

Figure 1

Possible Research Questions

- What atmospheric conditions lead to repeated strong southerly winds in the McMurdo sound?
- How unusual were the weather conditions (e.g., frequency of cyclones) in winter 2022 compared to other winters?
- Were the meteorological conditions in winter 2022 similar to other years with low sea ice cover?

Prerequisites

Interest in polar weather and climate processes, and in studying atmospheric processes and their interaction with sea ice, in particular in the dynamics of Soutern Ocean weather systems (cyclones, katabatic winds). Interest in data analysis.

Supervision

The supervision will be jointly by Ruzica Dadic (SLF Davos), Heini Wernli and another colleague from his group at ETH Zurich. The project can be based in Zurich or Davos. For more information contact
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Heini Wernli, heini.wernli@env.ethz.ch

References

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The ECMWF's Artificial Intelligence / Integrated Forecasting System (AIFS): Evaluating extratropical cyclone tracks and intensification rates

The European Centre for Medium-Range Weather Forecasts (ECMWF) has recently developed a new forecasting model based on machine-learning, the Artificial Intelligence / Integrated Forecasting System (AIFS). An alpha version of this model has been added to the operational suite of products and now produces twice-daily 10-day forecasts of physical fields on 13 pressure levels. The AIFS performs well on standard metrics used for the evaluation of forecasts such as root-mean-square error of 500 hPa geopotential height (Fig. 1) and is competitive with the high-resolution physics-based numerical forecast (IFS-HRES).

Despite of this success, many questions remain regarding the physical consistency of the forecasts and, in particular, the representation of specific weather systems. The primary goal of this master thesis is to explore how well the AIFS predicts the tracks and evolution of extratropical cyclones as a function of forecast lead-time. While cyclone forecasts with the AIFS have some obvious biases, e.g., the storms do not intensify as much as in reality, there are indications that for forecast lead-times of several days ahead, the position of the storms might be more reliably forecast by the AIFS than by the IFS-HRES (Fig. 2).

In addition, we expect a forecasting model to predict the evolution of weather systems in a physically consistent way. While a numerical weather prediction model ensures physical consistency (to a certain degree) by solving the Navier-Stokes equations, a machine-learning based model learns the physics based on the training data but contains no à-priori physical constraints. Hence, a further important aspect that can be explored in this thesis is whether the spatio-temporal evolution of cyclones occurs in a physically consistent way, and whether the principal air streams in cyclones such as the warm conveyor belt are well represented.

Possible specific research questions:

1. How well are the tracks and the intensification of extratropical cyclones predicted by the AIFS?

2. Are there systematic biases in certain quantities, e.g., the intensification rate or the minimum sea-level pressure? Do quantities exist that are better predicted by the AIFS than by the IFS-HRES?

3. Is the spatio-temporal evolution of cyclones physically consistent?

4. How well are the principal air streams in cyclones represented?

Approach:

In this master thesis you will evaluate twice-daily 10-day forecasts from the AIFS and the IFS against analyses in the period of October - March 2023 / 24. For studying cyclone tracks, you will employ an existing cyclone tracking scheme based on the sea-level pressure that you will complement by the analysis of air parcel trajectories for selected case studies.

The thesis offers a certain freedom depending on your interest. For example, you could focus more on in-depth case studies of selected storms and evaluate the physical consistency of the storms' evolution and the representation of the principal air streams, or you could decide to approach the topic mainly from a statistical perspective. Also a combination is possible of course.

Requirements: Interest in dynamical meteorology, the dynamics of weather systems, Lagrangian analyses, working with relatively large data sets (ERA5), and familiarity with programming.

Supervision: Lukas Papritz (lukas.papritz@env.ethz.ch, ECMWF / ETH), Michael Sprenger (michael.sprenger@env.ethz.ch, ETH), and Heini Wernli (heini.wernli@env.ethz.ch, ETH)

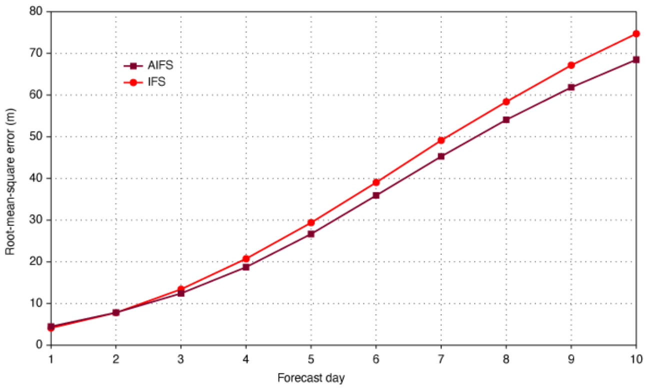

Fig. 1: *Root-mean-square error in geopotential height at 500 hPa for the IFS and the AIFS in the months of June–July–August 2023 in the northern hemisphere extratropics.*

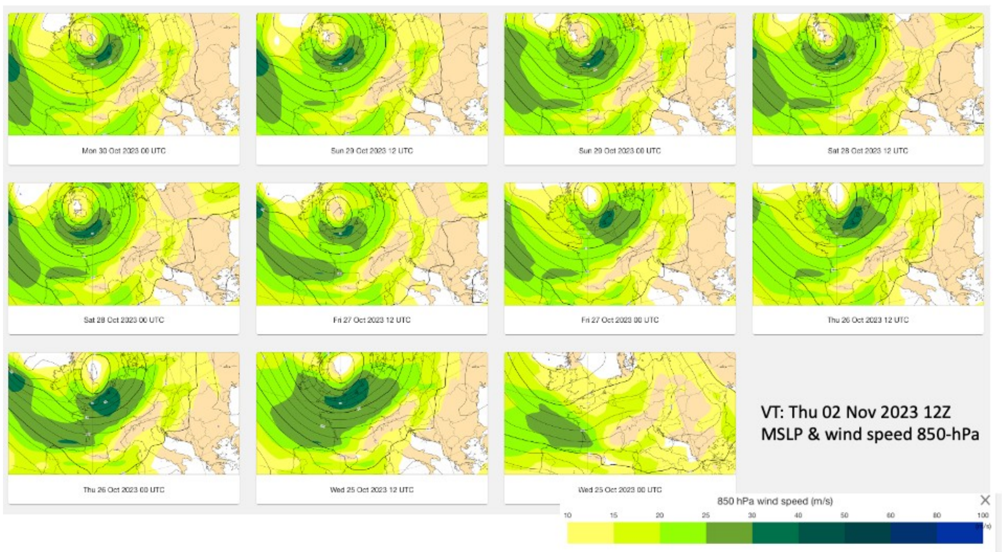

Fig. 2: *Storm Ciaran as predicted by the AIFS for different forecast lead times. The maps show mean-sea level pressure (black contours) and wind speed at 850 hPa (shading) valid at 1200 UTC 02 Nov 2023. Forecasts are initialized from 0000 UTC 25 Oct 2023 (bottom right) to 0000 UTC 30 Oct 2023 (top left) every 12 hours. This shows that the location of the storm center was surprisingly consistently predicted more than a week ahead, whereas the location of the storm center varied more in the IFS-HRES forecast (not shown).*

Literature:

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WCB branches:
What determines their formation and characteristics?

Description

The Warm Conveyor Belt (WCB) is one of three major airstreams in low-pressure systems in the mid-latitudes. The ascent of moist and warm air from the boundary layer leads to cloud and precipitation formation. Pfahl et al. (2014) showed that the WCB is in fact responsible for 70%–80% of extreme precipitation in the mid-latitudes. Additionally, the evolution of potential vorticity (PV) along the WCB ascent from the boundary layer to the upper-troposphere contributes to the formation of negative PV anomalies, which can impact the large-scale flow evolution, such as enhancing the lifespan of atmospheric blockings (Pfahl et al., 2015). Due to the wide range of implications, it is essential to enhance our understanding of WCBs.

A closer examination reveals sub-structures within the otherwise coherent WCB ascent, such as the anticyclonic (WCB1) and cyclonic (WCB2) branches illustrated for a case study in 2009 in Fig. 1 by Martínez-Alvarado et al. (2014). The authors identified differing characteristics between the two branches, with the anticyclonic branch starting at lower latitudes and ascending to higher altitudes than the cyclonic branch. Furthermore, the anticyclonic branch is associated with a distinctively more intense negative PV anomaly at the end of its ascent compared to the cyclonic branch (Heitmann et al., 2023). However, only around a quarter of all WCBs ascending in winter in the North Atlantic feature a distinct cyclonic branch, and it remains unclear what determines if a WCB ascends rather cyclonically or anticyclonically.

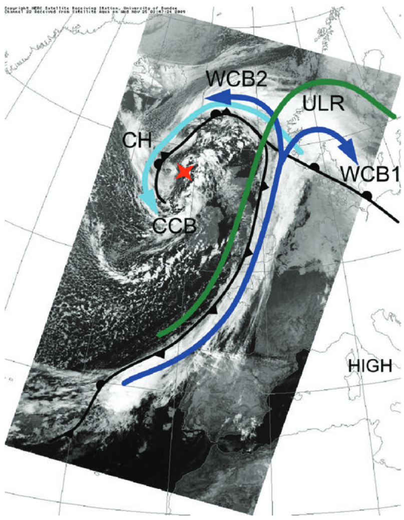

Figure 1: Location of the cyclonic (WCB2) and anticyclonic (WCB1) branches of a WCB (blue arrows) ascending at 00 UTC 25 November 2009 in the eastern North Atlantic and flowing into an upper-level ridge (ULR), resulting in the formation of a characteristic cloud band, visible in the infrared satellite image. Figure from Martínez-Alvarado et al. (2014).

Methods

First, we classify all WCBs ascending in the North Atlantic between 1980 and 2022 according to the characteristics of their branches, using the most recent reanalysis data ERA5 by the European Centre for Medium-Range Weather Forecasts. Based on this classification, we systematically characterize the cyclonic and anticyclonic WCB branches with respect to ambient variables such as PV at upper levels. Finally, by systematically studying the differences in the characteristics of the WCB branches and their ambient conditions, we aim to understand the physical reasons responsible for these differences and, more fundamentally, the driving factors for cyclonic and/or anticyclonic WCB branches.

Key questions

- Where and when are WCBs with a strong cyclonic/anticyclonic branch most frequent?
- What determines the formation of the WCB branches?
- What are the differences in the characteristics of the WCB branches, and what causes these differences?
- In which way do impacts differ between WCBs with and without distinct WCB branches?

Supervision

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References

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The Role of Warm Conveyor Belt Induced Wave Breaking in Tropospheric Cutoff Initiation

Description:

Warm conveyor belts (WCBs) with intense latent heating and cross-isentropic air transport, are identified as one of the significant synoptic systems that could modify upper-level dynamics (Madonna et al., 2014a). This substructure of extratropical cyclone constitutes rapidly ascending airstreams that reach the upper troposphere and feature divergent outflow with anomalous low potential vorticity (PV) values (in the Northern Hemisphere) at the end of its ascent. The PV anomaly associated with the WCB outflow can significantly change the distribution of upper-level PV and, thereby, the upper-level PV gradients. The upper-level PV gradient acts as a waveguide for the large-scale atmospheric waves known as the Rossby waves that propagate eastward along these waveguides of high PV gradient. The disturbances in the PV gradient waveguide can lead to the breaking of these waves (Rossby-Wave Breaking; RWB) as the amplitude of these waves grows nonlinearly, leading to distinct upper-level PV anomalies such as PV streamers and cutoffs (Wernli and Sprenger, 2007, Madonna et al., 2014b). These PV cutoffs are isolated regions of anomalously high or low PV compared to the surrounding, and it can be either stratospheric cutoff or tropospheric cutoffs and are often associated with extreme weather events (Grams et al., 2011; Wernli and Papritz, 2018).

The RWB can happen in two ways: cyclonically and anticyclonically. Cyclonic Rossby Wave Breaking is characterized by the counterclockwise rotation of PV contours in the Northern Hemisphere (or clockwise in the Southern Hemisphere), and the PV contours have a southeast-northwest (SE–NW) tilt. Whereas anticyclonic breaking involves clockwise rotation of PV contours in the Northern Hemisphere (or counterclockwise in the Southern Hemisphere) and displays southwest–northeast (SW–NE) tilt (Martius et al., 2007; Tyrlis and Hoskins, 2008). In this study, we are interested in the poleward RWB by WCB-waveguide interactions, which can lead to the formation of tropospheric cutoffs either through cyclonic or anticyclonic wave breaking.

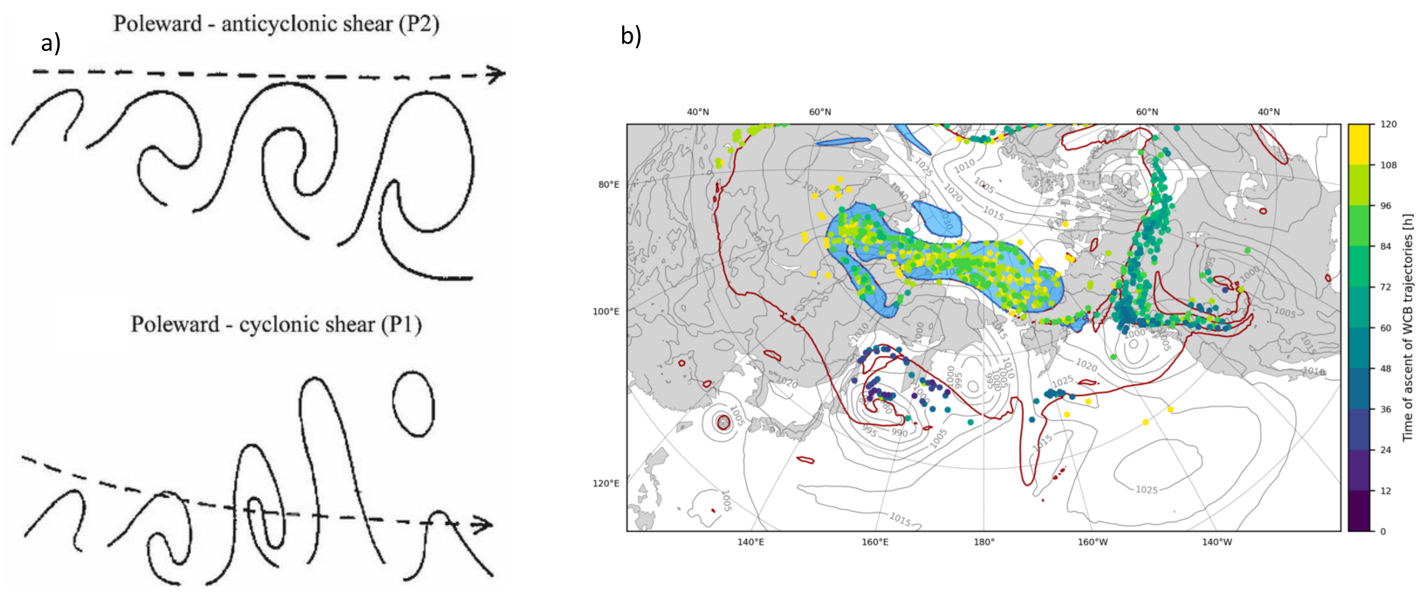

Fig: (a) Schematic from Peters and Waugh, 1996 showing the evolution of the two types of poleward wave breaking. (b) Eulerian maps showing upper-level features at 320 K over the North Pacific in October 2016, with instantaneous 2 PVU contour (red), depicting the tropospheric cutoff (blue) influenced by the WCB air parcels (dots, colored according to the age of ascent).

Methodology:

Case study of cutoff formation: The first step is to analyze a few real cases of tropospheric cutoff formation initiated by WCB-waveguide interactions. It would be interesting to observe the formation and evolution of cutoffs on isentropic levels caused by the two different types of wave-breaking and the evolution of the WCB outflow that influenced the processes. The diabatic PV rates can be used to understand the role of the diabatic process in the formation of these cutoffs.

Climatological analysis: The next step would be to do a systematic climatological analysis of the two types of wave-breaking, on isentropic levels, associated with WCB-waveguide interactions to understand whether these interactions particularly favor any one or both types of wave-breaking. For each type of WCB-induced wave breaking, the likelihood of the formation of tropospheric cutoffs will be examined. Moreover, the properties of WCB-induced cutoffs (lifetime, intensity in terms of PV anomaly) and their impact (changes in SSTs, radiation, and sea ice melting) will also be studied.

Potential research questions:

1. What are the seasonal frequency and geographical distribution of two types of wave-breaking associated with WCB-waveguide interactions?
2. What type of WCB-initiated wave breaking is typically linked to the formation of a tropospheric cutoff?
3. What are the properties of tropospheric cutoff influenced by WCB: evolution during the lifecycle, lifetime, intensity (PV anomaly), and impact?

Requirements:

Interest in large-scale midlatitude dynamics, especially potential vorticity evolution, Rossby waves and WCBs. Interest in programming (Python), learning how to analyze and visualize large datasets (ERA5 Reanalysis).

Supervisors:

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References:

Grams, C.M. et al., 2011. The key role of diabatic processes in modifying the upper-tropospheric wave guide: a North Atlantic case-study. *Q.J.R. Meteorol. Soc.* : 137(661), 2174– 2193. doi: 10.1002/qj.891

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Tropical moisture exports in present-day and future climate simulations

The transport of warm and moist air masses from the tropics into the extratropics is a crucial part of the atmospheric circulation. It plays a key role for the earth's energy and water balance and influences regional climate in many parts of the world. Furthermore, several studies have shown that tropical moisture can contribute to heavy precipitation and flooding in the midlatitudes (e.g., Knippertz and Martin 2005; Stohl et al. 2008). Knippertz and Wernli (2010) and Knippertz et al. 2013 used an objective trajectory-based identification method to compile a climatology of tropical moisture exports (TMEs) in reanalysis data. They found that TME events often occur in a longitudinally confined region and typically last for a couple of days. There are several distinct TME activity maxima with different seasonal behaviour, like, for instance, the "pineapple express" during boreal winter, which is characterised by strong moisture transport from Hawaii to the North American west coast and associated heavy precipitation along the entire path (Fig. 1). In general, TME trajectories are involved in precipitation in large parts of the extratropics, with contributions to climatological precipitation reaching up to 60% over the western North Pacific in boreal summer.

Because of the key role of TMEs for the global energy and water cycle, it is important to understand potential changes in their climatological distribution, seasonality and characteristics in a warmer climate. The aim of this project is to investigate the representation of TMEs in global climate simulations of the Community Earth System Model (CESM), based on the calculation of trajectories in 50 years of present-day climate and 50 years of future climate. Specifically, we will address the following research questions:

- Is CESM able to capture the geographical distribution and seasonal frequencies of TMEs in present-day climate simulations when compared to reanalysis data?
- How do the geographical distribution, the seasonality and the frequency of TMEs change in a warmer climate?
- How do the characteristics of TMEs like intensity, water vapor transport and contribution to precipitation in the extratropics change in a warmer climate?

Depending on the interest of the student and the progress of the project, in an additional step, the TME climatology could be compared to a recently developed CESM-based warm conveyor belt climatology (Joos et al., 2023, Binder et al. 2023) to assess the relationship between the two flow features (see also Chapter 2 in Ralph et al. 2020).

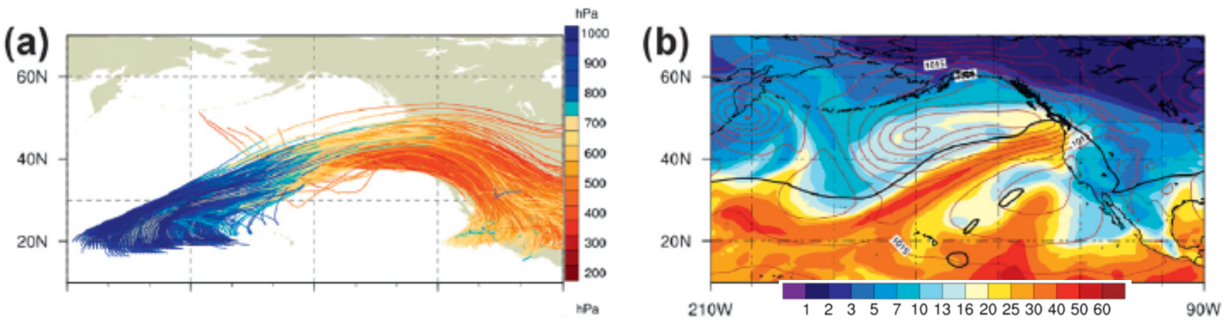

Figure 1: (a) Seven-day TME trajectories (coloured by pressure; hPa) starting at 00 UTC 24 Dec 1998, showing the transport of moisture from the central North Pacific to the US west coast. (b) Integrated water vapor (mm; shading), mean sea level pressure (red contours every 5 hPa) and the 2-PVU contour on the 330 K isentropic surface (black) at 18 UTC 27 Dec 1998, showing a narrow filament with high integrated water vapor extending from the tropics toward the US west coast, ahead of a broad upper-level trough and in between a surface cyclone to the northwest and an anticyclone to the southeast. From Knippertz et al. 2013.

Requirements: Interest in atmospheric dynamics and the Lagrangian perspective, interest in programming and readiness to work with large datasets.

Supervision: Hanin Binder (hanin.binder@env.ethz.ch) and N.N.

References:

Binder, H., Joos, H., Sprenger, M., and Wernli, H., 2023: Warm conveyor belts in present-day and future climate simulations – Part 2: Role of potential vorticity production for cyclone intensification, Weather Clim. Dynam., 4, 19–37

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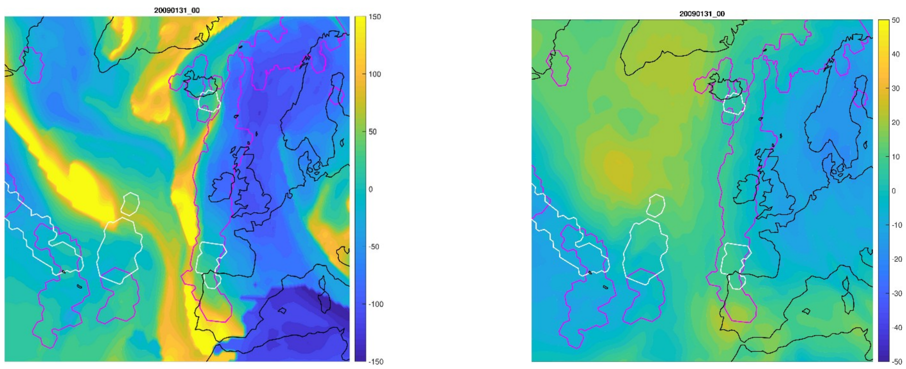
Propagation of synoptic-scale tropopause anomalies into the stratosphere

Description:

The extratropical stratosphere has since long been known to influence the weather and its predictability in the troposphere. On the other hand, signals (waves) from the troposphere can partly propagate into the stratosphere and thereby influence the stratospheric flow, but also the ozone and/or water vapour distribution. Typically, it is assumed that only the largest-scale signals are still discernible in the stratosphere, whereas small-, synoptic-scale features are filtered out as they propagate upward into the stratosphere.

The extratropical tropopause altitude (or pressure) exhibits a complex spatio-temporal bahaviour which determines, among other factors, how the stratosphere above couples to the troposphere below. The tropopause surface, identified as the 2-PVU potential vorticity (PV) surface, strongly varies in altitude due to the impact of distinct, synoptic-scale weather systems. For instance, the tropopause is lifted in warm-conveyor belt outflows or in atmospheric blocks, and it is lowered in regions with PV streamers (as proxies for Rossby-wave breaking). In stratospheric dynamics, it is often assumed that synoptic-scale signals from the troposphere are not able to propagate far into the stratosphere, i.e., they are filtered out.

In this MSc thesis, we will systematically re-visit this research subject and investigate if and to which degree extratropical tropopause perturbations are able to propagate into the stratosphere. The following figure shows that, in fact, tropopause perturbations are not completely filtered out! The left panel shows the tropopause pressure anomaly (in hPa) on 31 January 2009, exhibiting synoptic-scale excursions of ~100 hPa with respect to a 15-day running mean; on the right panel, the corresponding pressure anomaly of the 370-K isentrope within the stratosphere is shown, with synoptic-scale, but smoothed excursions of still ~40 hPa.



Specific tasks:

- ✓ Perform 1-3 case studies with strong tropopause perturbations and analyze how far the perturbation is still discernible in the stratosphere. The case studies should correspond to different weather systems perturbing the tropopause altitude, e.g., warm-conveyor belt outflows, blocks, Rossby-wave breaking events.

- ✓ Compile a five-year climatology of perturbations in tropopause altitude (or pressure) and correspondingly the altitude perturbations of isentropic surfaces (320 to 450 K) within the stratosphere. Attribute the tropopause perturbations to distinct weather systems (as in task 1).

- ✓ Identify key factors that determine how far into the stratosphere the tropopause signal is still discernible. Some factors could be: amplitude, spatial extent and lifetime of the tropopause perturbations, ambient flow conditions (wind speed and direction, stratification) within the stratosphere,…

- ✓ Reconcile the synoptic-scale, weather-system-based approach in 1) to 3) with wave-flux formalisms often used in studying stratospheric dynamics. To this aim we will calculate wave fluxes and see how the propagate and converge/diverge in the stratosphere

Key research questions:

- ✓ Which weather systems lead to substantial perturbations in tropopause altitude?
- ✓ How far in the stratosphere are the tropopause perturbations still discernible? In which fields is the stratospheric perturbation discernible (wind, ozone, water vapour)?
- ✓ Which factors determine whether the tropopause signal propagates into the stratosphere or is filtered out?
- ✓ How can a synoptic-scale perspective be reconciled with a wave-mean-interaction perspective to better understand the signal propagation into the stratosphere?

Requirements:

Interest in atmospheric dynamics, and in particular how the dynamics of the stratosphere and troposphere is coupled; willingness to work with large reanalysis datasets (ERA5); programming skills in Python, Fortran, Matlab is a benefit, but can also be acquired in the thesis.

Supervision:

- Michael Sprenger (michael.sprenger@env.ethz.ch)

- Franco Lee (franco.lee@env.ethz.ch)

- Daniela Domeisen (daniela.domeisen@env.ethz.ch)

References:

[1] Butchart, N.: The stratosphere: a review of the dynamics and variability, Weather Clim. Dynam., 3, 1237–1272, https://doi.org/10.5194/wcd-3-1237-2022, 2022.

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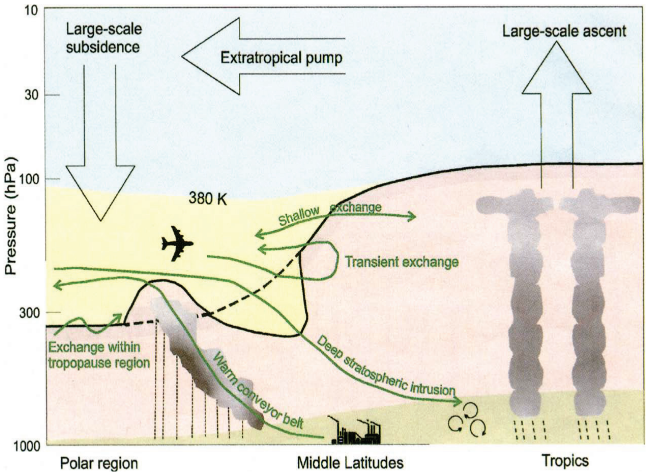
Stratosphere-Troposphere Exchange in a Changing Climate

Description:

Stratosphere-troposphere exchange (STE) refers to air masses crossing the dynamical tropopause, thereby distinguishing between transport from the stratosphere to the troposphere (STT) and vice versa (TST). STE is important because: it affects the chemical composition of the two atmospheric layers, e.g. by allow stratospheric ozone or other tracers to reach near-surface levels; it indirectly affects the climate by inducing a tracer-related radiative response; and it reflects, more generally, a basic dynamical coupling between the stratosphere and troposphere. The processes governing STE have been investigated in many case studies, but also based on multi-year reanalysis data sets (e.g., ERA-Interim, ERA5). A conceptual view on STE is summarized in the following figure (with the tropopause as the bold black line):



The aim of this thesis is to compile STE climatologies for present-day and future climate simulations, compare them to reanalysis-based STE climatologies, and to assess the processes that might be responsible for changes in STE frequencies. More specifically:

1 First, single cases of STE events will be studied in present-day CESM climate simulations (CESM-HIST). The STE events will be identified based on an established Lagrangian (trajectory-based) STE diagnostic. It will also be important to relate the spatial and temporal STE evolution to relevant Eulerian fields (e.g., the tropopause structure).

2. In a second step, the climatological occurrence frequency and seasonality of STE will be established in the present-day climate simulation (CESM-HIST). To this aim, 50 years of STE trajectories will be analysed and compared to corresponding STE climatologies based on ERA-Interim.

3. With a CESM-HIST base climatology for the present-day climate, the Lagrangian STE diagnostic will be repeated for end-of-the-century climate simulations (based on a RCP8.5 scenario; CES-RCP85). The shift in geographical STE patterns and/or changes in the amplitude of the cross-tropopause air mass fluxes will be assessed.

4.The final part of the thesis will be dedicated to the weather systems and processes that are known to be key drivers of STE. These are in particular: jet streams, PV streamers as proxy for Rossby-wave breaking, PV cutoffs, tropopause folds. The STE fluxes in CESM-HIST and CESM-RCP85 will be related to these weather features, and potential changes in STE fluxes linked to corresponding changes in their frequencies and geographical distribution.

The essential outcome of the thesis will be a Lagrangian analysis of STE changes in a future climate, which will be compared to existing Eulerian STE diagnostics in a literature review. As a novel aspect, the STE in the climate simulations, and the potential STE changes, will be linked to corresponding changes in weather features and the structure of the tropopause.

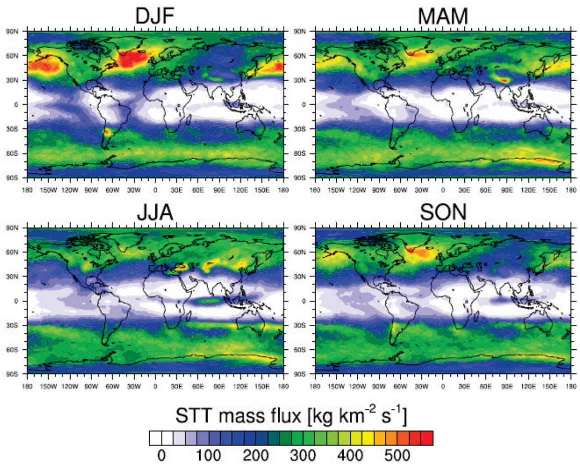
Requirements:

We are looking for a motivated student interested in atmospheric dynamics, in particular the dynamics of the upper trosposphere / lower stratosphere and the potential changes under climate change. Eulerian and Lagrangian (trajectory) analysis will be performed for a multi-year data set of climate simulations based on the CESM model, requiring some basic knowledge in programming (Python, Matlab, Fortran) or an interest in learning it.

Supervision:

Michael Sprenger (michael.sprenger@env.ethz.ch)
Franco Lee (franco.lee@env.ethz.ch)

ERA-Interim STE climatology:



Literature:

[ERA-Interim STE climatology] Škerlak, B., Sprenger, M., and Wernli, H., 2014: A global climatology of stratosphere–troposphere exchange using the ERA-Interim data set from 1979 to 2011. *Atmospheric Chemistry and Physics*, Vol. 14, 913–937.

[A recent process study on STE] Škerlak, B., Pfahl, S., Sprenger, M., and Wernli, H., 2019: A numerical process study on the rapid transport of stratospheric air down to the surface over western North America and the Tibetan Plateau. *Atmospheric Chemistry and Physics*, Vol. 19, 6535–6549.

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Alpine foehn in pseudo-global warming COSMO simulations

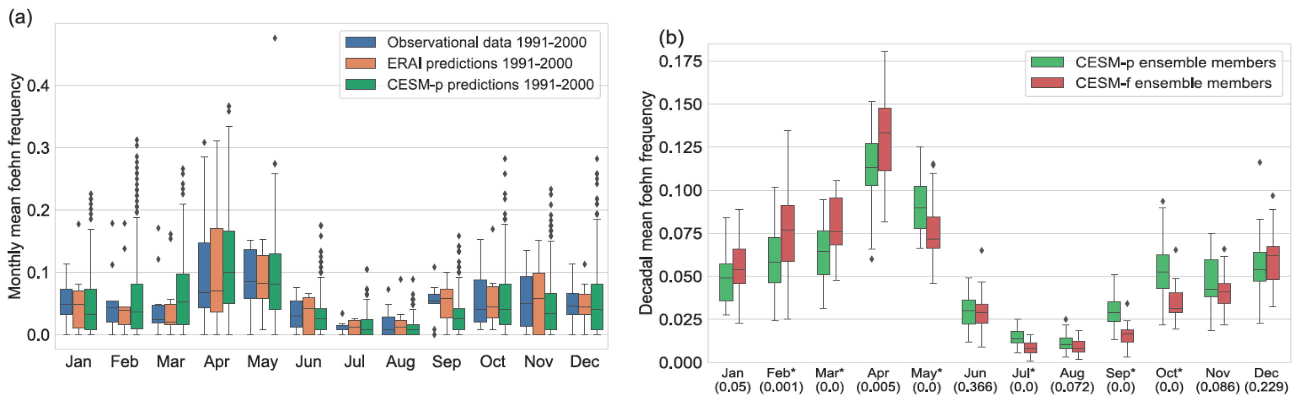
Description

The Alpine South and North foehn has a significant impact on the environment and on society. For instance, severe foehn storms can trigger or enhance the spreading of wildfires on the Alpine north and south side. Besides this adverse effect on the environment, foehn warming can have a beneficial impact on agriculture. e.g., on the ripening of wine grapes. Societal impacts are: foehn illness, ignition of fires, aviation. Alpine foehn occurs in several of the main Alpine valleys, e.g., the Rhine Valley and the Reuss Valley, and is a prominent weather feature in all seasons, with peaks frequencies in autumn to spring and a minimum in summer.

Foehn winds are reasonably represented in high-resolution (1 km) NWP models, whereas coarser climate models are not able to adequately represent the topography and thus the foehn winds in the valleys. This also makes it very challenging to predict how foehn frequencies and characteristics will change in a warming climate. First steps in this direction were undertaken in Mony et al. (2022) who applied a complex machine-learning approach to overcome resolution problems (the climate model having a 100 km mesh size). The aim of this Msc thesis is to re-visit the topic of foehn frequencies and characteristics in a warmer climate based on a unique set of climate simulation over Europe. Two climate simulations based on the COSMO-CLM model (Rockel et al., 2008; Sørland et al., 2021) are available for a 11-year period of present-day climate and a corresponding 11-year period of a warmer climate representing a 3° global warming. The present-day simulation is driven by the era5 reanalysis (Hersbach et al., 2020), and a pseudo-global warming (PGW) approach has been applied (Brogli et al., 2023) to simulate a 3° global warming over Europe. The high temporal (1-hourly) and spatial (2km) resolution of the model output promises a better a representation of foehn events than previously used, coarser global climate models.

Specific tasks are:

- ✔ 1. Identify and characterize foehn periods in the present-day COSMO simulations and validate them against observationally identified foehn events. In particular, determine how realistically the foehn frequencies are directly represented in the COSMO simulations.
- ✔ 2. Apply indirect metrics that diagnose foehn occurrence in COSMO simulations based on typical larger-scale foehn characteristics, e.g. cross-Alpine pressure differences and validate how these indirect measures are able to realistically get the foehn frequencies. In addition to more traditional approaches based on pressure differences, also machine-learning can be applied (as in Mony et al., 2022).
- ✔ 3. Determine the frequencies of distinct foehn flavors, e.g. deep foehn vs. shallow foehn, based on objective criteria and/or self-orgainsing maps (SOM)
- ✔ 4. Determine the foehn frequencies and characteristics analoguously in the warmer-climate simulations, thereby relying on the direct foehn diagnostics and/or the machine-learning/SOM approaches. In the same line, determine if foehn flavors will change in a warmer climate.



First results showing that the seasonal cycle of Alpine foehn can reasonably be captured in present-day climate (CESM-p) simulations in comparison to observations and reanalysis data (left), and that in a warmer (RCP8.5 scenario) climate exhibits distinct seasonal shift from present-day (CESM-p) to a warmer-climate (CESM-f) simulations. [Figure taken from Mony et al., 2021].

Requirements

Interest in mountain meteorolgy, in particular foehn flows; willingness to analyse large climate data sets; programming skills in Python and Linux are a benefit, but can be acquired in the thesis

Supervision

- Michael Sprenger (michael.sprenger@env.ethz.ch)
- Iris Thurnherr (iris.thurnherr@env.ethz.ch)

Literature

A) Foehn frequency and diagnostics

[1] Mony, C., L. Jansing, and M. Sprenger, 2021: Evaluating Foehn Occurrence in a Changing Climate Based on Reanalysis and Climate Model Data Using Machine Learning. Wea. Forecasting, 36, 2039–2055, https://doi.org/10.1175/WAF-D-21-0036.1.

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Effect of Saharan dust events on hail in Europe

1 Description

This research project aims to investigate the influence of Saharan dust events on hail formation in Europe. Saharan dust events, characterized by the transport of fine mineral dust particles from the vast Sahara Desert across the Mediterranean into European regions, are notable atmospheric phenomena with wide-ranging impacts. While previous studies have investigated the effect of Saharan dust on weather systems, the specific relationship between these dust events and hail formation remains less well understood (Ilotoviz et al., 2018).

Hail is among the costliest atmospheric phenomena in mid-latitudes as it causes extensive damage to agriculture, buildings, and cars. Understanding how Saharan dust events interact with hail formation processes is crucial for enhancing our ability to predict and mitigate the impacts of severe weather events in Europe.

This study will delve into the complex dynamics of Saharan dust events and their potential influence on hail occurrence. By examining historical data from sources such as the ECMWF CAMS model (Inness et al., 2019), radar observations, localized measurements from hail sensors, and crowd-sourced reports, this research aims to identify patterns and correlations between dust events and hail formation events across Europe.

Furthermore, this project will assess the performance of regional, convection-resolving weather models, such as ICON and COSMO (Steppeler et al., 2003), to predict the occurrence of hail using a one-dimensional hail growth parameterization (HAILCAST, Adams-Selin and Ziegler, 2016) during Saharan dust episodes compared to control periods. By comparing forecast skills and accuracy between dust-impacted and dust-free scenarios, insights into the challenges and opportunities for improving model predictions in the presence of dust aerosols will be gained. A modeling case study investigating the interplay of summertime precipitation over the Alps and Saharan dust has been previously performed (Eirund et al., 2022), and this study aims to further our understanding of the processes at play.

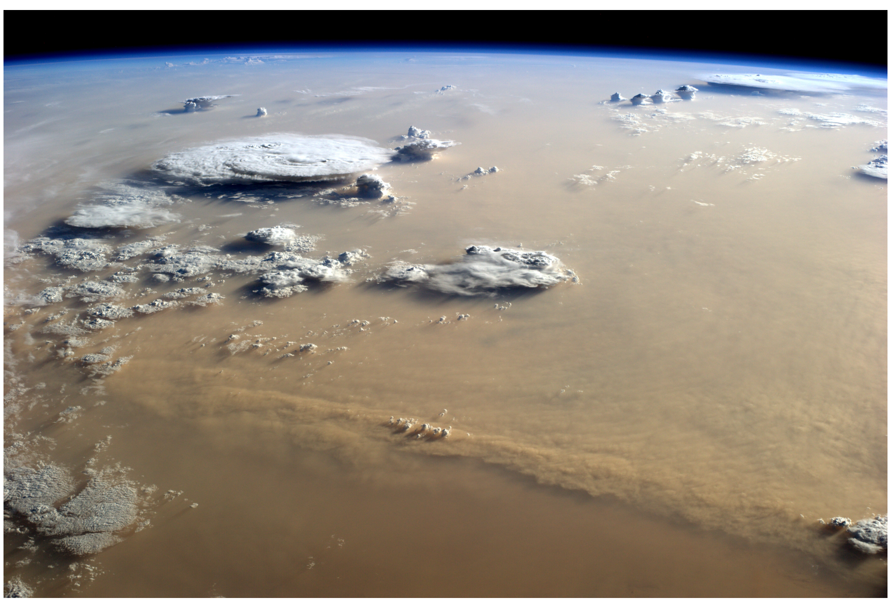

Figure 1: Photograph of billowing cumulonimbus cloud above a Saharan dust storm, taken on September 8, 2014, from the International Space Station over Libya. Image source: NASA.

2 Research questions

- How often Saharan dust reach Central Europe during the hail season?
- How do Saharan dust events affect the occurrence of hail in Europe?
- How do regional weather models perform during dust events compared to control periods?

3 Prerequisites

This project requires a basic understanding of atmospheric dynamics and motivation to do programming in Python. Interest in working with reanalysis and radar data is highly beneficial for this project.

4 Supervisors

Killian Brennan (killian.brennan@env.ethz.ch)
Ellina Agayar (ellina.agayar@env.ethz.ch)

References

Steppeler, J., G. Doms, U. Schättler, H. W. Bitzer, A. Gassmann, U. Damrath, and G. Gregoric (2003). Meso-gamma scale forecasts using the nonhydrostatic model LM. *Meteorology and Atmospheric Physics* 82.1, 75–96. DOI: 10.1007/s00703-001-0592-9.

Adams-Selin, R. D. and C. L. Ziegler (2016). Forecasting hail using a one-dimensional hail growth model within WRF. *Monthly Weather Review* 144.12, 4919–4939. DOI: 10.1175/MWR-D-16-0027.1.

Ilotoviz, E., A. Khain, A. V. Ryzhkov, and J. C. Snyder (2018). Relationship between Aerosols, Hail Microphysics, and ZDR Columns. *Journal of the Atmospheric Sciences* 75.6. Publisher: American Meteorological Society Section: Journal of the Atmospheric Sciences, 1755–1781. DOI: 10.1175/JAS-D-17-0127.1.

Inness, A., M. Ades, A. Agustí-Panareda, J. Barré, A. Benedictow, A.-M. Blechschmidt, J. J. Dominguez, R. Engelen, H. Eskes, J. Flemming, V. Huijnen, L. Jones, Z. Kipling, S. Massart, M. Parrington, V.-H. Peuch, M. Razinger, S. Remy, M. Schulz, and M. Suttie (2019). The CAMS reanalysis of atmospheric composition. *Atmospheric Chemistry and Physics* 19.6. Publisher: Copernicus GmbH, 3515–3556. DOI: 10.5194/acp-19-3515-2019.

Eirund, G. K., S. Drossaart van Dusseldorp, B. T. Brem, Z. Dedekind, Y. Karrer, M. Stoll, and U. Lohmann (2022). Aerosol–cloud–precipitation interactions during a Saharan dust event – A summertime case-study from the Alps. *Quarterly Journal of the Royal Meteorological Society* 148.743. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/qj.4240, 943–961. DOI: 10.1002/qj.4240.

MSc project in collaboration with MeteoSchweiz

The relevance of dry intrusions associated with cold front passages for strong wind gusts over Switzerland

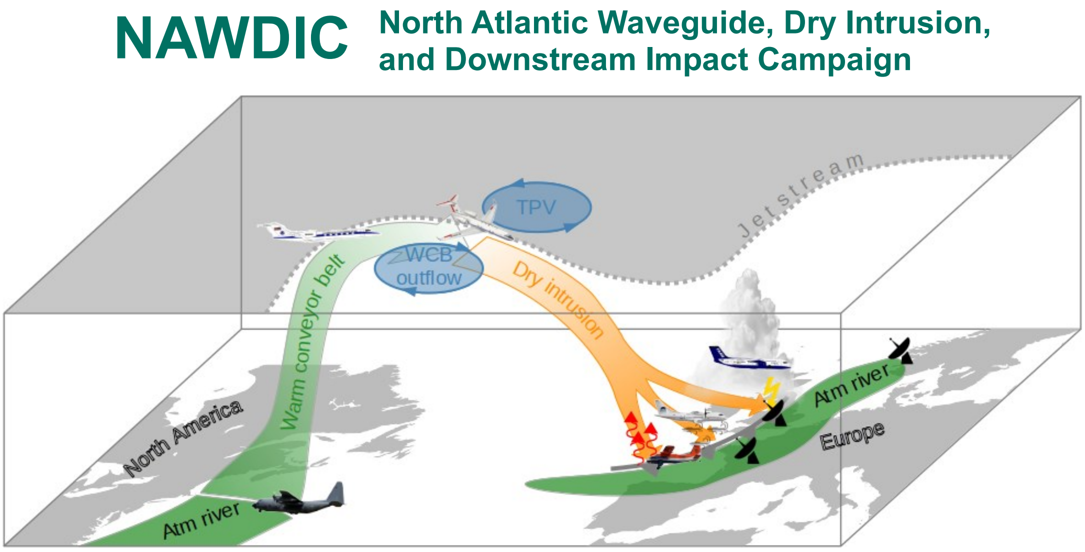

Figure 1: Schematic sketch of anticipated research flight operations for the planned NAWDIC research measurement campaign during an idealised dry intrusion situation over Europe. Different operating aircraft, ground-based measurements and weather systems

Description:

Dry intrusions (DIs) are slantwise descending airstreams in extratropical cyclones. They typically occur behind cold fronts. Within DIs, air masses descend from near the tropopause towards the cold front of the cyclone downstream, where they are climatologically associated with enhanced vertical mixing in the planetary boundary layer, heavy frontal precipitation, and severe wind gusts (Raveh-Rubin, 2017). To advance our understanding of the synoptic- to meso-scale dynamical processes leading to such potential high impact events, colleagues at KIT, Germany, initiated a major international field campaign called “North Atlantic Waveguide, Dry Intrusion, and Downstream Impact Campaign” which is scheduled for January / February 2026 (Fig. 1, NAWDIC). One of the research foci of NAWDIC is the interaction of DIs with the planetary boundary layer and its impact on surface gustiness. Preparatory work investigated the evolution of the planetary boundary layer prior, during and after DI passages over the Azores, representative of a maritime environment (Ilotoviz et al. 2021) and coastal environment (MSc Thesis KIT, C. Sperka 2024). They found a characteristic deepening of the planetary boundary layer with the DI and an increase in wind speed prior to and during the DI passage due to enhanced turbulence and hypothesised downward mixing of momentum (cf. Fig. 2). The proposed master thesis project aims to assess the climatological relevance of DIs for surface wind gusts in the densely populated Swiss Plateau region. Wind gusts here are of particular interest, e.g. in aviation, as they occur intermittently, are difficult to predict, potentially cause damage to forests and infrastructure, and critically affect airport operations. To this end we are interested in exploring the evolution of the structure of the boundary layer during the passage of DIs and its link to surface gustiness over Switzerland, based on selected case studies and a climatological analysis using observational data from MeteoSwiss and ERA5 atmospheric reanalysis.

MeteoSwiss routinely measures vertical profiles of different meteorological variables in Payerne twice daily. In addition, wind profilers give information at higher temporal resolution about the vertical evolution of wind speed over the major airports of Zurich and Geneva. Combined with surface observations, these measurements allow to assess the typical wind profile, boundary layer height, and evolution of temperature and humidity during DI and front situations over Switzerland (cf. Fig. 2). Such an analysis will complement the earlier work by Ilotoviz et al. (2021) for the continental atmospheric environment over Switzerland and inform the planning of the NAWDIC campaign. The different meteorological situations will be determined from a readily available climatological data set

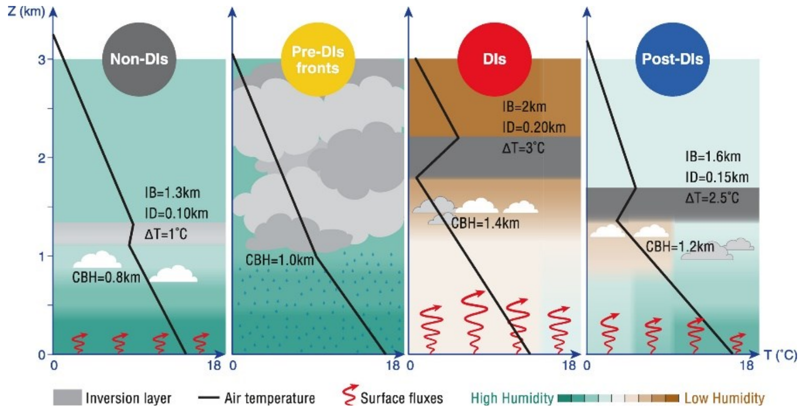

Figure 2: Schematic of evolution of the planetary boundary layer during the passage of a dry intrusion. Fig. 14 from Ilotoviz et al. (2021).

of DI, computed with the LAGRANTO trajectory tool (Sprenger and Wernli, 2015), and of cold front occurrence provided by Shira Raveh-Rubin at the Weizmann Institute. Special attention will be paid on surface gustiness in these situations and an assessment if gusts are comparably extreme and are therefore of relevance e.g. in aviation. Depending on the progress of the work, the analysis may be extended to the evaluation of the representation of DI environments and the prediction of associated wind gusts in current numerical weather prediction models.

Research questions

- What is the typical evolution of the planetary boundary layer during the passage of a dry intrusion in the continental environment of Switzerland?
- Do dry intrusions affect gustiness over Switzerland during the passage of cold fronts in winter?
- How extreme are surface wind gusts during the dry intrusion passage, compared to other situations?
- How relevant are wind gusts during dry intrusions for aviation at Zurich and Geneva airport?
- How well are wind gusts predicted for dry intrusion situations?
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Approach

- Explore co-occurrence of strong wind gusts and dry intrusions over Switzerland climatologically and in case studies via a combination of observational and reanalysis data.
- Investigate evolution of vertical (wind) profile for selected MeteoSwiss measurement sites.
- Assess relevance of wind gusts for airport operations at Zurich and Geneva airport.
- Inform potential flight strategies for NAWDIC measurement campaign.
- Optional: validate model forecasts for wind gusts.

Prerequisites

We are looking for a highly motivated student with general interest in synoptic meteorology and boundary layer meteorology and specific interest in the dynamics of extratropical cyclones and associated weather phenomena. Ideally, the student should be familiar with Linux environments, programming (e.g., in Python, R, NCL, or Fortran), and the investigation of meteorological data, but basic programming knowledge and willingness and motivation to learn are sufficient. Although the student will be primarily integrated in the Atmospheric Dynamics group at IAC ETH Zurich, the student will also have the opportunity regularly visit the co-advisor at MeteoSwiss and to collaborate remotely with partners at KIT, Germany and the Weizmann Institute in Israel.

Supervision

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Further reading:

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