

Investigation of CH₄ emissions from boreal wetlands by remote sensing during the airborne CoMet 2.0 campaign

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Preface

With a passion for polar research and an enthusiasm for the Northwest Territories of Canada, I was intrigued when I came across the headline "NASA and German Scientists Gather to Study NWT Wildfires" in a Yellowknife newspaper ([Cebryk \(2022\)](#)). This caught my attention and sparked my interest in the measurements being made over Canada by the German Aerospace Center during the CoMet 2.0 campaign. Since my undergraduate studies, I have always wanted to do an internship at the German Aerospace Center in Oberpfaffenhofen. When I was accepted, I was given a choice of different topics, but I was particularly interested in the data collected during the CoMet 2.0 campaign over Canada. Then, in the summer of 2023 I had the incredible opportunity to do an internship at the Institute of Atmospheric Physics at the German Aerospace Center, working in the lidar working group led by Andreas Fix. My focus during this internship was on anthropogenic methane sources and the analysis of forest fire plumes. I very much enjoyed my internship and the opportunity to work with the CoMet 2.0 data, which provided new insights into anthropogenic methane sources. Through my time at the German Aerospace Center, I discovered that there is a significant need for improvement of methane emission inventories, especially in the context of climate change. This realisation caught my interest in natural methane emissions, particularly over the boreal wetlands of northern Canada, where these emissions may play a critical role in the overall climate balance. I was excited and grateful to have the opportunity to write my Master's thesis investigating methane emissions from these boreal wetlands using data collected during the CoMet 2.0 campaign, further deepening my understanding of this important area of research and its implications for climate science.

During my research, I gained invaluable insight into the field of remote sensing of greenhouse gases using lidar technology, as well as a comprehensive explanation of lidar construction and object-oriented programming. My time at German Aerospace Center - both during my internship and in the course of my Master's thesis - has been immensely rewarding, and I look forward to sharing my findings in the following chapters.

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Abstract

Methane (CH_4) is a potent greenhouse gas, and its atmospheric concentration has been rising due to emissions from both anthropogenic and natural sources. Recognizing its significant impact on climate change, several international treaties, such as the Global Methane Pledge, have identified CH_4 reduction as a key mitigation target. Accurately quantifying its emissions is essential for understanding their respective contributions to climate change and improving global CH_4 budgets. In particular, natural sources such as wetlands play a crucial role but remain highly uncertain, making it difficult to predict future CH_4 dynamics. Wetlands are recognised as the largest natural CH_4 source. Nevertheless, they also represent the most significant source of uncertainty in CH_4 emissions estimates. In August/September 2022, the German Aerospace Center conducted an airborne campaign over Canada. The objective of the mission was to measure the weighted column-integrated dry-air molar mixing ratios of CH_4 . These were measured below the aircraft along its flight track over boreal wetlands. The measurements were taken using an IPDA lidar, which was mounted on board the research aircraft. Several flights over the Hudson Bay Lowlands, which is one of the largest Arctic-boreal wetlands in the world with significant contribution to the global CH_4 budget were conducted as part of the campaign.

The objective of this study was to quantify regional and large scale (between 36 km and 889 km) gradients in CH_4 concentration using lidar. These gradients are used in a mass balance approach to calculate CH_4 fluxes. In this approach, a designated upwind and downwind region is established within the area of interest. Inside these regions, the difference between the inflow and outflow of methane concentration is measured to assess the increase in methane concentration. As this method requires, next to the methane concentration, also information about the transport, wind information is taken from a numerical weather prediction model.

Data from three individual flights were analysed in detail. Not all of the three flights show a general accumulation of CH_4 along the wind direction. Furthermore, the circumstances for calculating emissions vary between the three flights. The flights differ in their flight pattern, the wind speed, the homogeneity of the wind, and the CH_4 distribution. Nevertheless, it was possible to calculate fluxes that

differed for the various flights. Backward trajectories from HYSPLIT showed the history of air parcels along the wind. In order to explain the results, the backward trajectories and emission estimates from WetCHARTs are used.

Overall this study showed that a maximum gradient of up to 11 ppb (across a distance of approximately 600 km) could be observed, representing a relative increase of 0.55 %. The mass balance approach typically works best for ideal conditions: well mixed boundary layer, homogeneous wind perpendicular to upwind and downwind region, uniform methane source distribution and therefore lower upwind concentration than downwind concentrations.

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Chapter 1

Introduction

As one of the most potent greenhouse gases, methane (CH_4) plays a critical role in the ongoing climate crisis. The global atmospheric CH_4 concentration is continuously rising with a surge in recent years, as shown in Figure 1.1. The annual average concentration of CH_4 rose from around 1720 ppb in 1990 (IPCC (1992)) to 1866 ppb in 2021 (IPCC (2021)). Since the start of systematic measurement at the NOAA Global Monitoring Laboratory in 1983 the largest annual increase of 17 ppb was recorded in 2021 (National Oceanic and Atmospheric Administration (April 7, 2022)). The reason for the recent CH_4 increase is not fully understood.

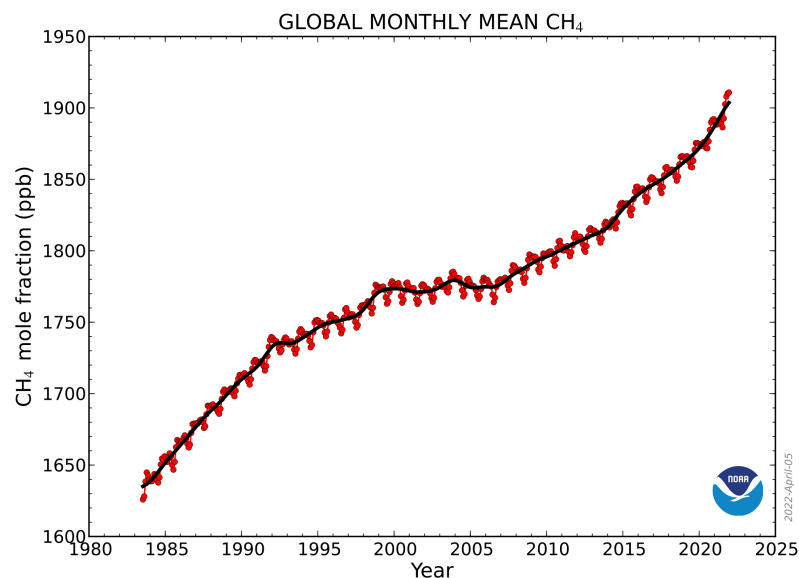


Figure 1.1: Globally averaged monthly mean atmospheric CH_4 abundance determined from marine surface sites since 1983. Values for the last year are preliminary. (NOAA National Oceanic and Atmospheric Administration (April 7, 2022))

Carbon dioxide (CO_2) and CH_4 are the two most important anthropogenic greenhouse gases. On a 20-year timescale the global warming potential of CH_4 is

84 times higher than for CO_2 (Zhang et al. (2023)). The Intergovernmental Panel on Climate Change (IPCC (2021)) report concludes, that the reduction of CH_4 emissions has significant potential for climate change mitigation.

CH_4 is emitted from anthropogenic and natural sources. Natural CH_4 forms, when plants die and decompose under water. Oxygen rises in water and is spatially separated from the organic material. The water acts as an isolator and favours many types of anaerobic microorganisms. As a result, anaerobic conditions prevail, and methanogens can break the organic materials down to produce CH_4 as a metabolic byproduct. The largest natural source of CH_4 are wetlands (Saunois et al. (2019)). Wetlands are ecosystems where soil or peat is saturated with water. Surface inundation, whether permanent or not, of either fresh, brackish or salt water influences the soil biogeochemistry and species composition.

A warmer climate leads to a positive feedback of CH_4 emissions from wetlands. This can be the consequence of rising temperatures on microbial activity (e.g. methanogenesis) and thawing permafrost. Another theory for the increase in natural CH_4 is the expansion of wetlands due to increased total precipitation based on the relationship between rising temperature and atmospheric water content (Zhang et al. (2023)). The emission rates and global distribution of CH_4 over wetlands are very uncertain. Different inventories are partly contradictory in this aspect, reflecting the complexity of the hydrogeology that shapes wetland conditions and the biogeochemistry driving CH_4 production and release to the atmosphere (Rosentreter et al. (2021)).

In a metadata analysis study Rosentreter et al. (2021) found that these highly variable aquatic ecosystems contribute half of the global CH_4 emissions. At the same time wetlands are the most important source of uncertainties in the CH_4 budget. Due to the uncertainty of the distribution of wetland emissions it is of high importance to quantify these emissions. This raises the importance of measuring the amount and the spatial distribution of sources in wetlands as well as the changes with the warming climate.

Between 1979 and 2021 the Arctic warmed nearly four times faster than the global average (Rantanen et al. (2022)), driving many of the climatological changes underway in the Arctic. Furthermore, increasing global temperatures lead to a positive CH_4 feedback. This impacts both local ecosystems and the global climate system. Consequently, boreal wetlands are of critical importance in the context of climate change.

The Hudson Bay Lowland region is the third biggest wetland in the world and second largest boreal wetland. Due to its areal extent and its nearly continuous peat coverage the Hudson Bay Lowland region is a unique region for CH_4 measurement studies over wetlands. The Hudson Bay Lowland region has a low measurement

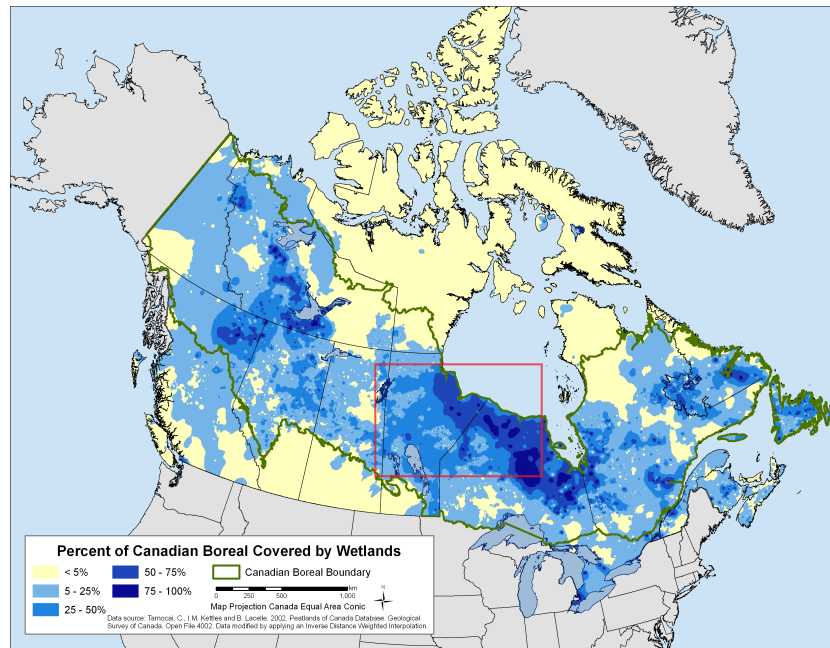


Figure 1.2: Map of the Canadian boreal wetland coverage. Most of the Canadian Boreal is covered by wetland. The region where the research flights were performed is marked by the red square. ([Canadian Geographic \(2017-02-02\)](#)),

density for greenhouse gases due to its inaccessibility.

Typical techniques for greenhouse gas emission and concentration measurements are based on: eddy covariance towers, chamber measurements, active or passive remote sensing, either ground-based, airborne or spaceborne. Measurements such as eddy covariance towers as well as chamber measurements quantify gas fluxes, whereas remote sensing observations mostly survey the column concentrations of a gas. Especially in areas with a less developed infrastructure, as in boreal wetlands very little ground-based measurements exist. The inaccessibility of those regions leads to a sparse coverage of point measurements over the boreal wetlands in Canada. The poor spatial distribution as well as the lack of ground-based point measurements can be compensated with remote sensing measurements. Remote sensing techniques can be divided into activate and passive measurements techniques.

Passive airborne or spaceborne remote sensing can only detect radiation emitted by the sun or the atmospheric components, with a wide spectral range. The spectrum ranges from visible, infrared, thermal infrared, and microwave. Therefore, passive remote sensing methods are limited by solar radiation in particular in high latitudes during the polar night. Additionally, highly reflective surfaces are needed. Thus, data recorded over less reflective surfaces like water bodies or when clouds were in the optical path has to be flagged. This makes CH_4 measurements especially challenging over wetlands with a lot of water surfaces and in higher latitudes. An example for passive remote sensing is the TROPOspheric Monitoring Instrument

(TROPOMI) on board the satellite Sentinel-5 Precursor (Sentinel-5P).

In contrast to the passive remote sensing methods, the active methods come with their own light source. Active methods are used for measuring signals transmitted by the sensor that were scattered or reflected by the Earth's atmosphere. Lidar (Light Detection and Ranging) systems operate with a laser in the optical part of the electromagnetic spectrum as its light source. Lidar systems emit pulses of light and measure the time it takes for the light to reflect back from objects or particles in the environment to the detector. The Integrated Path Differential Absorption (IPDA) lidar can be used to measure the column averaged vertical-weighted mole fraction of greenhouse gases (Ehret et al. (2008)).

As boreal wetlands are located in Arctic regions and are warming much faster than the rest of the world due to climate change, an accurate understanding of CH_4 emissions from wetlands is important. Wetlands account for about one third of the global CH_4 emissions (Saunio et al. (2019)). Thus, to improve the understanding and better quantify the CH_4 cycles and its influence on the climate the German Space Agency (DLR) together with the French Space Agency CNES (Centre national d'études spatiales) are planning on launching an Earth observing satellite called MERLIN (Methane Remote Sensing Lidar Mission). MERLIN is supposed to measure weighted column-integrated dry-air molar mixing ratios XCH_4 with an IPDA-lidar system. The Institute Physics of the Atmosphere (IPA) built a prototype of the IPDA-lidar, the so-called CHARM-F (CO_2 and CH_4 Remote Monitoring – Flugzeug), which is supposed to demonstrate MERLIN's capabilities for measuring XCH_4 . CHARM-F detects XCO_2 and XCH_4 below the aircraft along its flight track.

CHARM-F went on board two campaigns of the research aircraft HALO (High Altitude and Long Range Research Aircraft). The first campaign CoMet 1.0 (Carbon Dioxide and Methane Mission) took place in 2018 over Europe and North Africa. CoMet 1.0 concentrated on anthropogenic emission sources like coal mines, landfills or coal power plants. So far CHARM-F was only used for anthropogenic point sources or big scale gradients from Central Europe to Scandinavia during the CoMet 1.0 campaign (Fix et al. (2020); Wolff et al. (2021)).

A second campaign followed, CoMet 2.0, which took place from 2022 August till mid-September over Canada. Once again HALO took CHARM-F on board to measure the XCH_4 and XCO_2 column concentration beneath the airplane. One of the main objectives of the CoMet 2.0 campaign was to characterize emitted CH_4 emissions from boreal wetlands, besides quantifying anthropogenic emissions from oil and gas fields. Several flights over the Hudson Bay Lowland as well as the Pimachiowin Aki and the Grass, Burntwood and Upper Churchill River wetlands were conducted (Figure 1.3).

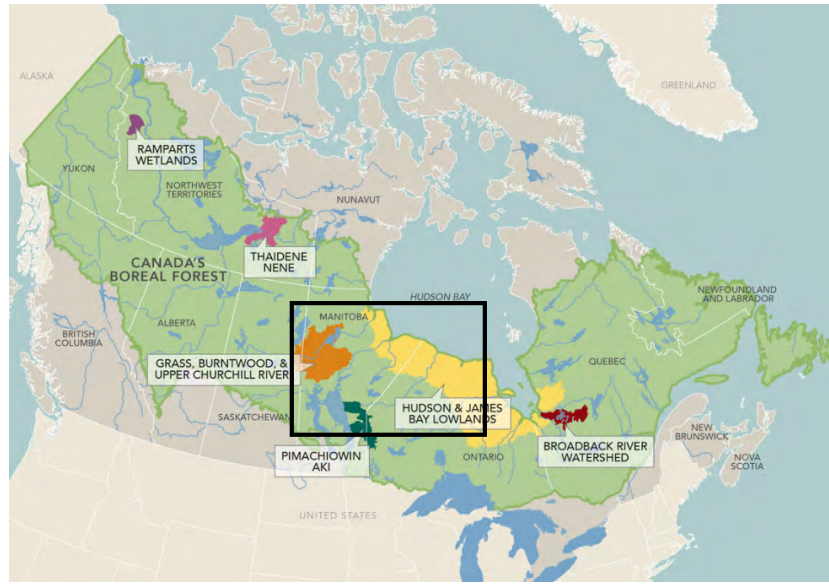


Figure 1.3: Six carbon rich boreal wetlands of conservation focus. The research flights of CoMet 2.0 took place within the region marked here with a black squared. The CH_4 measurements were conducted over the Hudson Bay Lowlands, the Grass, Burntwood and upper Churchill River and the Pimachiowin Aki wetland. ([Boreal Songbird Initiative \(2017-02\)](#))

The aim of this study is to derive CH_4 fluxes from Arctic boreal wetlands using airborne greenhouse gas lidar data through a simple mass balance approach. Therefore, this study seeks to answer the following research questions:

- How is the XCH_4 distributed over the Hudson Bay Lowland and surrounding wetland regions for all research flights respectively?
- Is it reasonable to assume a constant wind within the planetary boundary layer?
- Can the simple mass balance approach be used to calculate methane fluxes over boreal wetlands with CHARM-F data, that are comparable in magnitude to other studies?

In order to better quantify the CH_4 emission from the boreal wetlands within the Hudson Bay Lowland region this study will use the column-averaged, vertically weighted dry-air mole fraction of CH_4 measured by CHARM-F from three research flights during the CoMet 2.0 Arctic campaign. For the flux calculations the so-called mass balance approach is applied. The mass balance approach assumes that the CH_4 concentration accumulates along the wind from the upwind region to the downwind region. To estimate the CH_4 emissions, this mass enhancement of CH_4 concentration is then multiplied by the wind speed perpendicular to the upwind and downwind region. The areal flux given in $\text{kg km}^{-2} \text{h}^{-1}$. Wind speed information

are taken from the ERA-5 reanalysis data after a visual performance analysis. For the performance analysis ERA-5 vertical profiles of relative humidity, wind speed and potential temperature are compared to in situ vertical profiles of radiosondes, dropsondes released during the flight and basic meteorological measurements of the airplane system.

The instrumentation and data used is described in chapter 2. Chapter 2 begins with an explanation of the IPDA-lidar method, followed by an introduction to the CoMet 2.0 campaign, and ends with the mass balance approach. Chapter 3 provides a comprehensive description of the CH₄ total column-averaged dry-air mole fraction distribution and hence addresses the first research objective. The second research question will be discussed by an ERA-5 performance analysis with the resulting wind distribution. The obtained flux results for the three research flights, respectively will answer the last question. In chapter 4, a discussion of the flux emissions is presented. The drawn conclusion of this thesis can be found in chapter 5. A more detailed description of the ERA-5 performance analysis can be found in the Appendix A, as well as additional HYSPLIT graphics in Appendix B.

Chapter 2

Methodology

2.1 Lidar

Lidar (Light Detection and Ranging) is an active remote sensing technology that uses its own laser source and can therefore operate both day and night, and at all latitudes and seasons. Lidars are used for a wide range of applications in different fields due to their ability to measure distances and gather detailed information about the Earth's surface and atmosphere. In this study, an airborne nadir-viewing greenhouse gas lidar system is used to measure CH₄ columns in the atmosphere.

A lidar system consists of a powerful laser that emits short pulses at optical frequencies, a receiving telescope and detectors. The energy backscattered by particles or molecules in the atmosphere or at the Earth's surface is detected by the receiving telescope. The received signal can then be processed into a runtime profile. From this, the distance R at which the scattering process took place can be calculated ([Gimmestad and Roberts \(2023\)](#)):

$$R = \frac{c \cdot t}{2} \quad (2.1)$$

where c is the speed of light and t is the time between the light being emitted and received by the telescope. Due to the round trip of the signal from the transmitter to the object, where the signal scatters back to the transmitter, the division by two is performed.

The Lambert-Beer law describes how electromagnetic radiation loses intensity exponentially as it travels through a medium. This can be described by ([Seinfeld and Pandis \(2016\)](#)):

$$I(z) = I(0) \cdot e^{-\sigma(\lambda, p, T) \cdot n \cdot z} \quad (2.2)$$

where $I(z)$ is the intensity of the radiation after a penetration depth z into the medium, $I(0)$ is the initial intensity, n is the particle density, and σ is the absorption

cross section. The absorption cross-section σ depends on the wavelength of the radiation, the pressure and temperature in the atmosphere and varies for different molecules. If the frequency of the radiation is close to an absorption frequency of the molecule, the absorption cross section will be large, and the radiation will be absorbed more strongly. The exponent described in equation 2.2 is defined as the dimensionless measure of the loss of intensity that an electromagnetic wave experiences when propagating through a medium, the optical depth:

$$OD = \int_{z_{\text{sfc}}}^{z_{\text{flh}}} n(z) \cdot \sigma(p(z), T(z)) \, dz \quad (2.3)$$

z_{sfc} stands for the Earth's surface height as the lower integral limit and the upper integral limit is denoted by z_{flh} the flight height. Since pressure and temperature vary vertically in the atmosphere, and n and σ depend on them, the optical depth must be vertically integrated. While the absorption cross-section changes indirectly through its dependence on temperature and pressure, the particle density exhibits a much more significant change, decreasing exponentially with altitude. Thus, the rapid decline in $n(z)$ dominates the integral and has a greater influence on the optical depth.

2.1.1 IPDA-Lidar

For this study, the Integrated Path Differential Absorption Lidar (IPDA Lidar) CHARM-F (CO₂ and CH₄ Remote Monitoring- Flugzeug) was used to measure the column-averaged, vertically weighted dry-air mole fraction of methane XCH₄ (Amediek et al. (2017)). The German Aerospace Center's (DLR) Institute of Atmospheric Physics (IPA) devised CHARM-F as an airborne demonstrator for the MERLIN (Methane Remote Sensing Lidar Mission) space mission (Ehret et al. (2008)).

To determine XCO₂ and XCH₄ below the aircraft along its flight track, the CHARM-F laser emits two sets of double pulses for each gas, online and offline (λ_{on} and λ_{off}), as pairs in a downward direction (Figure 2.1) with a temporal separation of 500 μs . As the pulses propagate through the atmosphere, they are backscattered by reflective targets such as the Earth's surface, water bodies, and cloud layers. λ_{on} and λ_{off} have slightly different wavelengths. The wavelengths are stabilised at defined positions in the absorption spectra with known absorption cross sections. The online and offline wavelengths are carefully chosen to minimise absorption by other atmospheric gases, in particular water vapour. As only CH₄ is analysed in this study, in the following only values that are specific to CH₄ are given. Nevertheless, CO₂ is measured according to the same principle, but at different wavelengths. For CH₄, the on-line (λ_{on}) and off-line (λ_{off}) wavelengths are tuned to 1.645 55 μm and 1.645 86 μm , respectively (Amediek et al. (2017)).

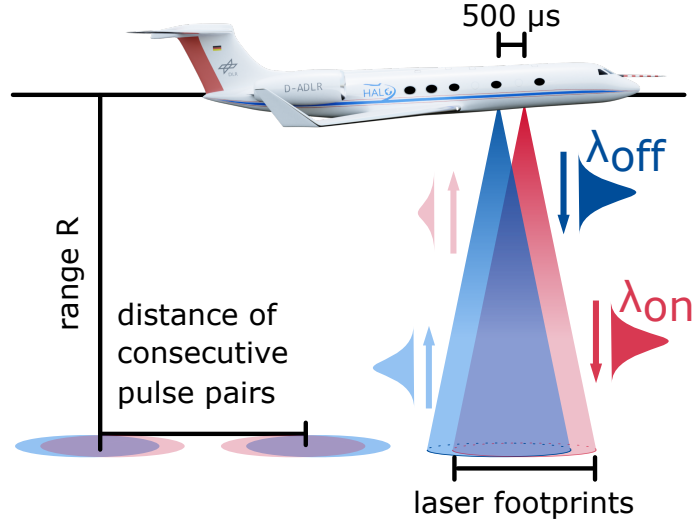


Figure 2.1: CHARM-F measurement principle onboard of HALO. The online and offline laser pulses are released in pairs with a time gap of $500\mu\text{s}$ and a frequency of 50Hz . The pulse footprint has roughly a diameter of about 10m . The distance between two footprint centres is about 3m (for a range R of 7.7km and an approximate ground speed of 150m s^{-1}). Since the footprints exceed the space between the pulse pairs, they end up overlapping. In the figure provided, they have been separated for clarity. (Adapted from [Krautwurst et al. \(2024\)](#))

As the wavelength of the online pulse corresponds to an absorption feature of the analysed greenhouse gas, the pulse is attenuated as it propagates through the atmosphere. The offline pulse is used as a reference because its wavelength is much less affected by the absorption of the analysed greenhouse gas molecules. The online and offline wavelengths are sufficiently similar in the spectral domain so that their interactions with other atmospheric components and reflective surfaces are essentially equivalent.

CHARM-F's receiving system consists of two telescopes per greenhouse gas. It has a smaller refractive telescope ($60\text{mm } \varnothing$) equipped with an Avalanche Photodiode (APD) and a larger reflective telescope ($200\text{mm } \varnothing$) with a Positive Intrinsic Negative (PIN) diode.

The ratio of the backscattered online to offline optical power entering the lidar telescope has to be measured. Therefore, the laser pulses go through an internal calibration chain to precisely quantify the ratio between outgoing online and offline optical power. To minimise the error of the power measurement, the online and offline footprint at the Earth's surface have to completely overlap. The ratio of the detected online and offline optical power can be described as ([Kiemle et al. \(2011\)](#)):

$$P_{\text{on/off}} = \rho_{\text{on/off}} \cdot \eta_{\text{on/off}} \cdot \frac{A_{\text{tel}}}{R^2} \cdot \frac{E_{\text{on/off}}}{\Delta t_{\text{eff}}} \cdot e^{-2 \cdot (OD_0 + OD_{\text{on/off}})} \quad (2.4)$$

Here, ρ represents the reflectivity of the Earth's surface at the measuring wave-

length, while η denotes the efficiency of the entire optical module, for both transmitter and receiver. Since $\rho_{\text{on/off}}$ and $\eta_{\text{on/off}}$ are ideally identical for the online and offline pulse, these quantities cancel out. If the two footprints at the Earth's surface overlap, $\rho_{\text{on/off}}$ and $\eta_{\text{on/off}}$ cancel out when calculating the optical power ratio between online and offline. The aperture of the telescope, A_{tel} , is divided by the distance to the backscattering surface R . $E_{\text{on/off}}$ is the reference energy which is measured inside the lidar instrument for each laser pulse. The energy received $P_{\text{on/off}}$ is linearly dependent on the energy emitted $E_{\text{on/off}}$ (Fix et al. (2018)). However, it is very difficult to measure the emitted energy in absolute terms. As only the ratio of $E_{\text{on/off}}$ is important, the ratio is determined using the internal calibration chain. Therefore, a small part of the laser pulse energy is deflected onto the detectors in the Lidar system using a beam splitter. Δt_{eff} refers to the effective length of the online and offline pulses. $OD_{\text{on/off}}$ is the optical depth that results from the molecular absorption of the greenhouse gas to be analysed. The optical depth resulting from the extinction by atmospheric air molecules, aerosols and clouds is referred to as OD_0 .

Rearranging equation 2.4 leads to the following equation for the optical depth:

$$OD_{\text{on/off}} = \frac{1}{2} \cdot \ln \left(\frac{P_{\text{on/off}}}{E_{\text{on/off}}} \cdot \frac{R^2 \cdot \Delta t_{\text{eff}}}{\rho \cdot \eta \cdot A_{\text{tel}}} \right) - OD_0 \quad (2.5)$$

For the IPDA lidar method, the Differential Absorption Optical Depth (DAOD) $DAOD = OD_{\text{on}} - OD_{\text{off}}$ is formed, which results in the elimination of many factors to (Amediek et al. (2017)):

$$DAOD = \frac{1}{2} \cdot \ln \left(\frac{P_{\text{off}}/E_{\text{off}}}{P_{\text{on}}/E_{\text{on}}} \right) \quad (2.6)$$

From the measured ratio of the backscattered laser signal between the online and offline pulses and the energy of the laser pulses the differential optical depth can be calculated.

Dividing the DAOD (equation (2.6)) by the integrated weighting function WF (equation (2.8)) the column-weighted average methane dry-air molar mixing ratio (in *ppm* or *ppb*) XCH_4 is given. This can be done analogously for carbon dioxide. The WF is integrated along the pressure coordinate from the aircraft position (p_{flh}) to the hard target (p_{sfc}):

$$XCH_4 = \frac{DAOD}{\int_{p_{\text{flh}}}^{p_{\text{sfc}}} WF(p, T) \cdot dp} \quad (2.7)$$

The XCH_4 can be determined solely from the lidar backscatter signals and knowledge of the weighting function. This is done with comparatively high accuracy because CHARM-F eliminates many interfering factors such as clouds or high aerosol concentrations in the atmosphere. In addition, CHARM-F can be used to measure CH_4

with high spatial resolution over large areas, regardless of weather conditions. In order to achieve high precision, the measurements have to be averaged along the flight track.

XCH_4 is a single value for the entire vertical air column and therefore indicates the mean mole fraction of CH_4 in the air column. The sensitivity of CHARM-F to CH_4 is highest close to the ground due to spectroscopic reasons (i.e. pressure broadening). However, within the lower troposphere this sensitivity changes by only a few percent (Ehret et al. (2008)) and thus is more important for higher altitudes. The weighting function depends on the differential absorption cross section $\Delta\sigma$, $m_{\text{dry-air}}$ the averaged mass of a dry-air molecule, as well as the product of the mass of a water molecule m_{H_2O} and the dry-air molar mixing ratio of water vapour r_{H_2O} (Amediek et al. (2017)):

$$WF(p, T) = \frac{\Delta\sigma(p, T(p))}{g(z(p)) \cdot (m_{\text{dry-air}} + m_{H_2O} \cdot r_{H_2O}(p))} \quad (2.8)$$

Thus, the weighting function describes the relative contribution of an atmospheric layer to the XCH_4 at a specific pressure and temperature. Since the air temperature, pressure and dry-air molar mixing ratio of water vapour are changing vertically as well as along the flight track the weighting function has to be calculated for each individual column (Amediek et al. (2017)). The differential absorption cross section $\Delta\sigma$ and the dry-air molar mixing ratio of water vapour r_{H_2O} are determined with their pressure and temperature dependence by spectroscopic laboratory measurements. $\Delta\sigma_{CH_4}$, calculated for a standard atmosphere at a planetary boundary layer (pbl) height of 1 km above ground, varies only slightly with height and is, for the purpose of this thesis, assumed to be constant in the pbl (Rothman (2021)). For the specific geolocation and time step of the measurement pressure, temperature and water vapour are taken from numerical weather models like ECMWF (European Center for Medium-Range Weather Forecasts).

2.2 Campaign

After its realisation, CHARM-F was mounted for the first time together with other instruments in 2015 (Amediek et al. (2017)) on the High Altitude and Long Range Research Aircraft (HALO) for test flights out of its home base in Oberpfaffenhofen, Germany. The first of the CoMet series of airborne campaigns, CoMet 1.0, took place between mid-May and mid-June 2018 (Wolff et al. (2021)). The objective of CoMet 1.0 was to measure anthropogenic CO_2 and CH_4 emissions from coal mines, landfills and coal-fired power plants, as well as long distance gradients over North Africa and Europe. The second CoMet campaign, CoMet 2.0 Arctic, took place over

Canada in August and September 2022. The main objectives of this campaign were to measure CH_4 and CO_2 at high Northern latitudes (Fix et al. (2024)). Some of the measurements obtained during CoMet 2.0 will be scientifically analysed in this study.

Next to CHARM-F, other remote sensing and in situ instruments were also deployed during the CoMet 2.0 Arctic campaign. The additional instruments were provided by other institutes such as Max Planck Institute for Biochemistry in Jena, Institute for Environmental Physics of the University of Bremen, Ludwig-Maximilians-University Munich and DLR - Flight Experiments. DLR Flight Experiments is responsible for the operation of the BAHAMAS (Basic HALo Measurements And Sensor system) instrument which measures basic meteorological parameters such as pressure, temperature, 3-D wind vectors and aircraft position and height Giez et al. (2023)). In addition, dropsondes were released during the research flights, which measure vertical atmospheric profiles for pressure, temperature, relative humidity, and wind direction and speed. Besides the dropsondes and BAHAMAS data as in situ data, radiosonde releases are used for the vertical atmospheric profiles.

From the CoMet 2.0 campaign base in Edmonton, Canada, a total of 18 flights were completed, over boreal wetlands anthropogenic CH_4 and CO_2 sources, and also over a forest fire. The flights have been named after local animals in order to make them easier to identify. This study analyses 3 flights over boreal wetlands: ORCA, WALLEYE and PIKE.

The XCH_4 measured by CHARM-F is analysed to determine the CH_4 fluxes over the boreal wetlands. To calculate CH_4 fluxes over the boreal wetlands it is assumed that the emitted CH_4 accumulates along the wind direction. Therefore, information about wind speed and direction is required and is derived from the ERA-5 reanalysis data consisting of 137 vertical levels (Hersbach et al. (2020)). To analyse the validity of the reanalysis data, a comparison with in situ data measured by BAHAMAS, dropsondes and radiosondes was conducted.

2.3 Mass balance approach

As a first attempt to calculate CH_4 fluxes from boreal wetlands in the vicinity of Lake Winnipeg a simple mass balance approach is used. For this, an Eulerian method is used, which is based on the mass conservation of the gas within fixed upwind and downwind regions. The resulting CH_4 fluxes represent an areal flux calculated between the upwind and downwind regions, expressed in $\text{kg km}^{-2} \text{h}^{-1}$.

For the mass balance approach it is assumed that the CH_4 concentration accumulates along the wind from the upwind region to downwind region. Hence, a higher CH_4 concentration in the downwind region is expected. The definition whether a

region is classified as upwind or downwind is done based on an analysis of the wind field. From the change in CH_4 concentration between these regions a CH_4 flux can be derived.

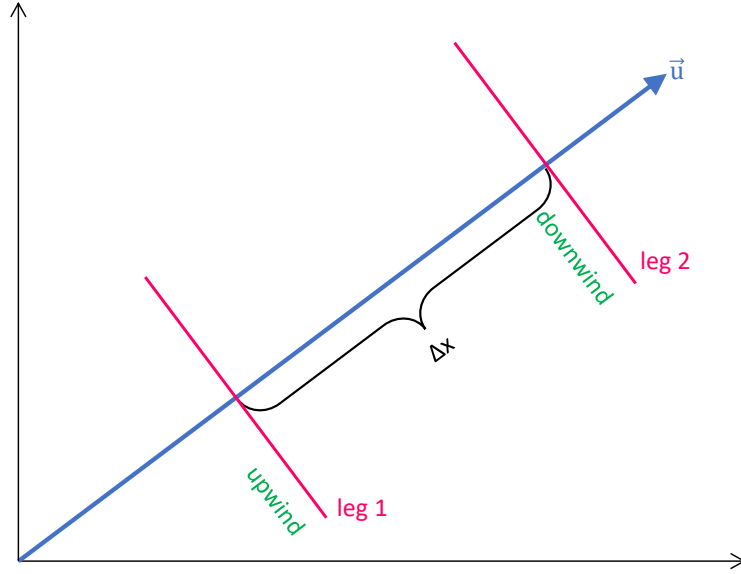


Figure 2.2: Schematic sketch of the mass balance approach with an upwind and downwind region, and an along-wind distance of Δx .

Between the upwind and downwind regions, which have an along-wind distance of Δx (Figure 2.2) and mean mass concentrations c_{uw} and c_{dw} in the upwind and downwind regions, respectively, the flux q is derived from the mass balance approach as follows (Seinfeld and Pandis (2016)):

$$q = u \cdot \frac{H_{pbl}}{\Delta x} \left(\frac{\int c_{dw} \cdot dy}{\Delta y_{dw}} - \frac{\int c_{uw} \cdot dy}{\Delta y_{uw}} \right) \quad (2.9)$$

u is the mean wind speed and H_{pbl} is the height of the box, in this case the pbl. Δy is the integrated distance between successive data points. The mean mass concentration along y is calculated by the division of Δy to account for the different lengths of the legs.

For the calculation of Δx and Δy the latitude and longitude coordinates are transformed into x and y coordinates using the Lambert conformal conic projection (Whitaker and Team (2014)).

Furthermore, several assumptions are made: The CH_4 emitted from the boreal wetland is assumed to be well mixed in the pbl. Therefore, the height of the box equals the height of the pbl. It turns out by later analysis of the vertical profiles of potential temperature, wind speed, and relative humidity that the atmosphere

was indeed well mixed and the assumption justified. Moreover, CH_4 is assumed to be inert, thus, no production or destruction by chemical reactions takes place. CH_4 is a greenhouse gas with a chemical lifetime of 9 to 10 years in the atmosphere (Prather and Zhu (2024)), which exceeds the time scales relevant for this study. Therefore, the chemical production term in the mass balance approach (equation 2.9) can be neglected as well as the loss term. The degradation reaction, in particular with hydroxide (OH) and chlorine (Cl) can thus be neglected for our short time scale of a few hours. In between upwind and downwind regions, the wind field is considered to have a constant direction. Based on the wind direction, the upwind and downwind regions are projected perpendicular to the wind field. Additionally, the mass balance approach assumes a higher CH_4 concentration in the downwind region due to advection.

To calculate CH_4 fluxes, the mass concentration from equation (2.9) is expressed in terms of DAOD which can be converted as the product of XCH_4 and the mean integrated weighting function ($\overline{IWF}$). A specific advantage of the method employed in this study is that the conversion between the DAOD measured by lidar and the mass concentration enables the calculation of areal fluxes.

$$c = \frac{M_{\text{CH}_4}}{\Delta\sigma_{\text{CH}_4}} \cdot \frac{DAOD}{H_{\text{pbl}}} = \frac{M_{\text{CH}_4}}{\Delta\sigma_{\text{CH}_4}} \cdot \frac{1}{H_{\text{pbl}}} \cdot \underbrace{\frac{DAOD}{IWF}}_{\equiv \text{XCH}_4} \cdot \overline{IWF} \quad (2.10)$$

The equation (2.10) is valid if the only difference between upwind and downwind in the mass balance approach are the changes in mass concentration c within the pbl. Under this assumption a simplification of the integral relation from equation (2.3) is made and a mean differential absorption cross-section $\Delta\sigma_{\text{CH}_4}$ is used (Wolff et al. (2021)).

By inserting equation (2.10) into the mass balance equation (2.9) the flux q can be calculated in terms of XCH_4 :

$$q = \frac{u}{\Delta x} \cdot \frac{M_{\text{CH}_4}}{\Delta\sigma_{\text{CH}_4}} \underbrace{\left(\frac{\int (\text{XCH}_4 \cdot \overline{IWF})_{\text{dw}} \cdot dy}{\Delta y_{\text{dw}}} - \frac{\int (\text{XCH}_4 \cdot \overline{IWF})_{\text{uw}} \cdot dy}{\Delta y_{\text{uw}}} \right)}_{=: \Omega} \quad (2.11)$$

Ω denotes the enhancement of the distance-weighted DAOD average along the upwind and downwind flight leg. H_{pbl} cancels out, which is not surprising since XCH_4 is a column average and, thus, mostly insensitive to the pbl height. This is an advantage of using CHARM-F compared to in situ measurements to determine CH_4 in the atmosphere. While in situ instruments would measure low CH_4 concentrations for high pbl heights, CHARM-F compensates for this effect with the weighting function. The height of the pbl is therefore irrelevant when using CHARM-F. The resulting flux q is the emitted mass of CH_4 per area and time, given in $\text{kg km}^{-2} \text{h}^{-1}$.

2.3.1 Data processing

In the preprocessing of the lidar data a number of quality criteria were applied to improve the data accuracy. One of the criteria was a cloud filter. The lidar signals cannot penetrate through optically thick clouds and get reflected. Thus, such signals are not representative for the CH_4 column down to the ground and must be omitted. This can be done by cloud filtering during the preprocessing and flagging such values with NaN (Not a Number).

Due to the aircraft speed, online and offline footprints are not perfectly overlapping at the Earth's surface. If there is a sharp transition in the non-overlapping part of the footprints (e.g. lake edges, buildings, road markings) strong differences in the backscattered signals could occur. This creates outliers, which are filtered by the so called signal-to-noise ratio (SNR) filter and the data is set to NaN. Likewise, if the albedo is too low, the noise is more pronounced and the SNR filter is also applied.

The 50 Hz repetition rate data from the two detectors, PIN and APD, are averaged with a running median over 30 seconds in order to reduce the noise. For all investigated research flights these mean DAOD values from PIN and APD ($DAOD_{\text{PIN/APD}}$) are divided by the IWF at each time step.

$$\text{XCH}_4 = \left(\frac{DAOD_{\text{PIN/APD}}}{IWF} \right) \quad \text{with} \quad IWF = \int_{p_{\text{flh}}}^{p_{\text{sfc}}} WF(p, T) \cdot dp \quad (2.12)$$

The DAOD depends on the column length underneath the aircraft and varies for example along complex terrain. A shorter geometrical length gives a smaller DAOD than for longer columns, since the time between the light being emitted and received by the telescope and the distance at which the scattering process took place and the emitter are linearly dependent (equation (2.1)). By means of equation (2.12) differences in column length due to changes in the topography, but also potential differences in flight altitude, are compensated.

An issue with the data quality was observed during postprocessing. A linear drift in the data was observed along the flight pattern of the research flights observed in this study. This linear drift is not fully understood yet. However, it seems to be a systematic instrumental error that can be corrected by fitting a linear regression on the XCH_4 values where constant values are assumed.

Warning: This drift correction should be treated with caution and is still preliminary.

For the wind speed and direction in the flux calculation, the ERA-5 137-level reanalysis product is used and interpolated onto the CHARM-F flight track. The ERA-5 reanalysis data is chosen as it provides hourly data covering the whole region of all research flights with a horizontal resolution of 31 km.

2.3.2 Wind calculations

As explained in section 2.3, the mass balance approach requires the knowledge of wind speeds within the pbl. However, the pbl height is inherently difficult to define, as different methods and variables can lead to differing results, and it cannot be measured directly from the airplane (Seibert et al. (2000)). In order to address this issue, four different pbl height definitions are used to determine the pbl height with the ERA-5 137-level reanalysis data. These four pbl height definitions are based on either

- the ERA-5 boundary layer height (referred to as ERA-5 BLH),
- the vertical profiles of relative humidity and
- the vertical profiles of specific humidity, or
- the vertical profiles of potential temperature.

To identify the pbl height based on relative humidity and specific humidity profiles the following definition is used: The pbl height is defined as the height above ground where the vertical gradient of humidity first reaches its minimum (Seidel et al. (2010)). This approach assumes a well-mixed pbl, where the transition to the drier air in the free atmosphere above is characterized by a steep drop in humidity. This results in a pronounced vertical humidity gradient.

A different definition applies when using the vertical profile of potential temperature. Under convective atmospheric conditions the simple parcel method (Holzworth (1964)) is valid to determine the pbl height. Since the flights took place at around noon local time, when solar irradiance is highest, convective conditions are assumed. If an air parcel has a potential temperature that is higher at ground level than above, it is less dense compared to the surrounding air mass and it becomes buoyant. When the less dense air parcel enters an environment where the surrounding air has the same potential temperature as the air parcel, it reaches the pbl height (Holzworth (1964)). In other words, when the potential temperature first equals the surface potential temperature during dry adiabatic ascent, the pbl height is reached (Seibert et al. (2000)).

Several trustworthy in situ measurements (dropsondes, radiosondes and the BAHAMAS system) of meteorological parameters are available for each flight pattern at different locations in the vicinity of the flight. The in situ measurements are used to generate vertical profiles of relative humidity, potential temperature, and wind speed. However, such in situ data are only available at individual locations and times collected during certain flight manoeuvres. For the analysis in hand, this data is required at the same time as the CHARM-F measurements. Therefore,

ERA-5 data is used for the pbl height calculations. But first, a visual performance analysis is conducted.

For each individual flight, the performance of ERA-5 is visually compared to radiosonde ascents ([University of Wyoming](#)), the ascent and descent of HALO with the associated data measured by BAHAMAS, and dropsonde recordings released during the research flights (analysed in section 3). For the radiosondes, data from the launch sites in The Pas, Manitoba (PIKE), Churchill, Manitoba (WALLEYE), and Pickle Lake, Ontario (ORCA) are used here. To analyse the ERA-5 data at the location and time of the in situ measurements, the reanalysis data is interpolated.

It should be noted that the BAHAMAS ascent and descent data are recorded at another time as the CHARM-F measurement used in this study.

The mean wind speed and direction along the flight for each pbl height is calculated from the ERA-5 data. In the flux equation (2.11) all four types of derivation for the wind speed u are used. Then, the resulting four CH_4 fluxes for each upwind and downwind region are averaged resulting in a single flux value. Averaging the flux results with the four different wind speeds is expected to give a better representation of the wind speeds prevailing in the atmosphere. The mass balance approach works best for surface wind speeds of more than 2 m s^{-1} ([Varon et al. \(2018\)](#)).

Backward trajectories

The wind speed and direction used in the calculations are averaged over a large spatial (500–1000 km) and temporal (2–4 hours) extent, where significant meteorological variability is likely. To assess whether the assumption of constant wind is valid for each research flight, backward trajectories along the flight pattern are calculated to check if air mass transport remained consistent within the pbl.

The Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPPLIT) for computing simple air parcel trajectories ([Stein et al. \(2015\)](#)) developed by the National Oceanic and Atmospheric Administration (NOAA) is used. HYSPLIT is a web-based model to calculate, in this case, backward trajectories. For as much as three locations per flight leg, backward trajectories are calculated with the underlying Global Forecast System (GFS) with 0.25° resolution. Three different heights for each location are chosen: (1) close to the surface at 100 m, (2) in the pbl and (3) above (at 1000 m and 2000 m). Since the pbl height varies with the different research flights analysed in this study the height within and above the pbl varies as well. The trajectories are calculated for all flights at 12 am CDT back for the past 24 hours.

2.3.3 Estimation of the flux uncertainties

The fluxes calculated in this study are at the threshold of detectability, as only minor increases in XCH_4 have been observed. Furthermore, the distances over which these fluxes are applicable are rather large, potentially exhibiting variations in wind direction and speed that may facilitate the transport of CH_4 away from the downwind area. With the estimated uncertainty associated with each flux, the reliability of the corresponding results can be assessed.

The calculation of uncertainties in the flux q is based on Gaussian error propagation. While the pbl height is not explicitly present in the flux calculation, it nevertheless indirectly affects the determination of wind speed u and wind direction. Consequently, errors in determining the pbl height propagate into the flux calculation. To account for this, the uncertainty in pbl height is calculated using realisations from its Gaussian distribution, with an ensemble size of 1000.

Since the pbl height is represented by an ensemble, the vertically average components of the wind vector below the pbl height are also represented by an ensemble. For each ensemble member (i.e., each possible pbl height), the wind components below that height are averaged vertically. This results in an ensemble of 1000 vertically averaged wind components. Using these wind components, a wind speed ensemble of 1000 members is calculated, and the standard deviation of this ensemble is taken as the error in u . For each of the four pbl height identification approaches the error in u is calculated analogously.

The airborne measurements were designed so that the upwind and downwind regions would preferably be aligned along a single line perpendicular to the wind vector, but instead they span a rectangle. However, because the wind direction was obviously not perfectly known during planning, deviations occur. Therefore, the width of this rectangle is a measure of how much the projected upwind and downwind region perpendicular to the wind direction deviates from the flight path. This deviation is used as the uncertainty in the distance Δx reflecting the accuracy of the average of the upwind and downwind measurements.

The variation in x as well as y along a flight leg due to small aircraft movements is negligibly small compared to other assumptions and errors.

The XCH_4 (see equation (2.7)) analysed in this study consists of two parts: the DAOD as the actual measurand, which is the ratio of the measured normalised on-line and off-line signals, and the weighting function, which includes variables such as $\Delta\sigma_{\text{CH}_4}$, determined from laboratory measurements. $\Delta\sigma_{\text{CH}_4}$ is calculated for a standard atmosphere and a pbl height of 1 km above ground. Since $\Delta\sigma_{\text{CH}_4}$ depends on pressure and temperature it varies slightly with height. However it can be assumed to be constant within the pbl with $1.73 \times 10^{-30} \text{ km}^2$ (Rothman (2021)). The error made here is estimated with 3 % which equals $5.19 \times 10^{-32} \text{ km}^2$.

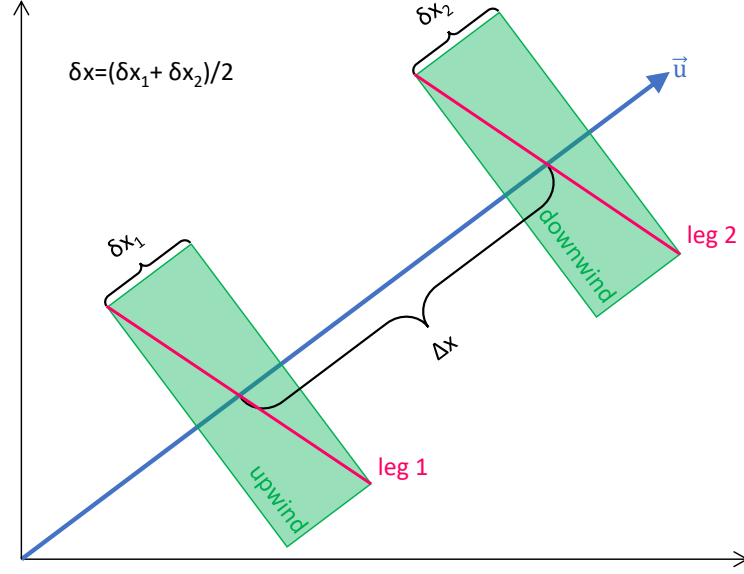


Figure 2.3: For upwind and downwind regions non perpendicular to the wind vector errors for Δx occur. The mean δx of the upwind and downwind region is used as the uncertainty in the distance Δx .

To account for uncertainties in DAOD values, an ensemble of simulated DAOD values is generated. Therefore, normal distributions of 1000 members are defined with each of the observed values as the mean and the error as the standard deviation, respectively. This ensemble of simulated DAOD values ($DAOD_{\text{ens}}$), is used to calculate the distance-weighted average along the flight leg for the upwind and downwind region, respectively. Subtracting the modelled weighted average DAOD ensemble of the upwind region from the downwind region leads to an ensemble of modelled DAOD enhancements. The standard deviation of these enhancements represents the error in Ω ($\delta\Omega$).

$$\delta\Omega = std \left(\frac{\int (DAOD_{\text{ens}})_{\text{dw}} \cdot dy}{\Delta y_{\text{dw}}} - \frac{\int (DAOD_{\text{ens}})_{\text{uw}} \cdot dy}{\Delta y_{\text{uw}}} \right) \quad (2.13)$$

The four sets of fluxes q for each pbl height approach are averaged together. Additionally, the results of the Gaussian error propagation for the averaging of q are represented in the tables 3.6 and 3.10 for the resulting flux.

Chapter 3

Results

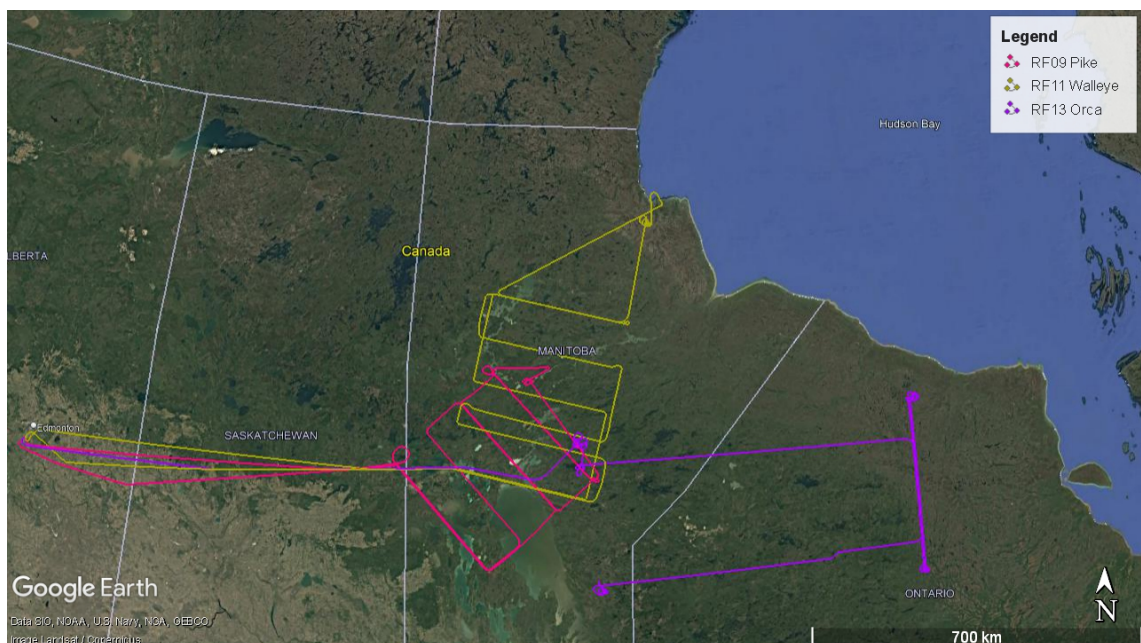


Figure 3.1: Flights over Hudson Bay Lowlands. The flight track in pink represents the research flight PIKE, the purple track represents WALLEYE and the yellow track represents ORCA.

The research flights during the CoMet 2.0 Arctic campaign are all named after animals to better distinguish between the flights. This study analyses 3 flights: PIKE, ORCA and WALLEYE, which took place over the wetlands of the Hudson Bay Lowland as well as the Pimachiowin Aki and the Grass, Burntwood and Upper Churchill River wetlands. These three wetlands are part of six carbon-rich wetland regions of conservation focus within Canada’s boreal forest and are either in need of conservation planning or are still awaiting final, permanent protection designation ([Boreal Songbird Initiative \(2017-02\)](#)). Canada’s boreal forest is almost entirely covered by wetlands (Figure 1.2). Most of the Hudson Bay Lowland is located

in Ontario, to a smaller extent in Manitoba and Quebec. The lowland lies south of Hudson Bay between 50° and 58°N , and is with about $373\,700\text{ km}^2$ larger than Germany. During the last ice age, the Hudson Bay Lowland region was covered by an ice sheet which pushed the land down towards the Earth's center. The Hudson Bay Lowland was formed by isostatic rebound. The wetland reaches from the ecoregional climate of high subarctic to low subarctic to high boreal. Wetlands mainly consist of fens, bogs and permafrost peatlands (Abraham and Keddy (2005)). The Hudson Bay Lowland and surrounding area is flat with an average slope of 0.5 m km^{-1} (Martini (1989)). This fulfils one of the fundamental requirements for the application of the mass balance approach.

The three research flights analysed in this study appear to be promising test cases for applying the mass balance approach to derive CH_4 emissions. It will be shown below that the three research flights have different meteorological characteristics that affect the applicability of the method. Furthermore the flights differ in their flight patterns. "ORCA" was planned with two sections along the wind direction and one section across the wind direction. "PIKE" and "WALLEYE" have several parallel legs, which were planned with respect to the wind direction according to the forecast in order to apply the mass balance approach.

In the subsections below the main results, which were derived according to the above given recipes are presented for all three flights respectively:

- the XCH_4 distribution,
- the planetary boundary layer height,
- the wind distribution, and
- the methane flux determination.

3.1 Research flight "ORCA"

3.1.1 XCH_4 distribution of the research flight "ORCA"

The research flight "ORCA" took place at the 7th of September 2022 between 8:28 and 14:29 CDT (local Central Daylight Time (CDT), i.e. 13:28 UTC - 19:29 UTC). The analysed CHARM-F measurements took place between 10:23 CDT and 14:29 CDT.

ORCA consists of two flight parts. In between the two flight parts HALO flew at lower levels to take in situ measurements in the pbl. The first part of ORCA was parallel to 54° north between Lake Winnipeg and Hudson Bay and ends with a southward part along 86° west. It started at 10:23 CDT and ended at 11:31 CDT.

The second part starts at 12:52 CDT, 54° north and goes southward along 86° west to 52° north. This part finishes with going along 52° north to 96° west at 14:23 CDT. During the measurements, HALO flew at a constant height of about 9200 m above ground for the first part and 8600 m for the second part due to flight regulations.

Part 1

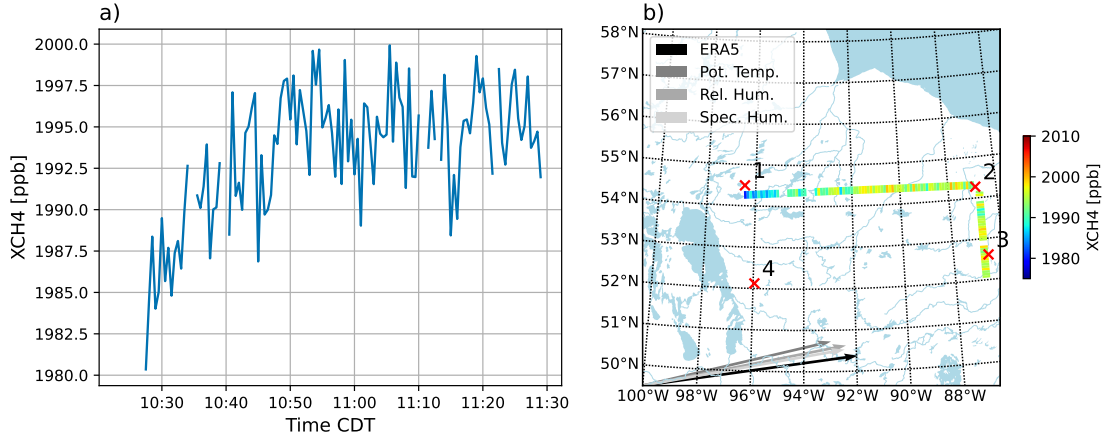


Figure 3.2: ORCA Part 1 flight pattern. a) represents the time series along the flight pattern of XCH₄. b) XCH₄ distribution along the flight. Red and blue values indicate higher and lower values of XCH₄, respectively. The locations marked with the numbers represent the dropsonde releases. The different wind directions of the four approaches are indicated with arrows in the lower left corner. For Part 1 of ORCA the minimum to the maximum wind speed within the pbl varies between 8.12 m s^{-1} for the potential temperature method and 9.12 m s^{-1} for the ERA-5 BLH method. The wind direction ranges from 76.82° for the potential temperature method to about 82.09° for the ERA-5 BLH method (further results see table 3.2). The large scale gradient over the flight time with a steep increase in the beginning and a more descent second part is especially visible in the timeseries.

The XCH₄ values during the first part range between 1980 ppb and 2000 ppb. The lowest values can be found in the west close to Lake Winnipeg. At the start of part 1 there are lower XCH₄ values, which increase with the flight path. Hence, a positive XCH₄ gradient from west to east can be identified (Figure 3.2 b)). This trend is further illustrated in Figure 3.2 a).

After the first part HALO flew in lower altitude to perform in situ measurements within the pbl. Therefore, the second part starts about one hour and 20 minutes later. During that time clouds formed. Thus, data was flagged with the cloud filter resulting in data gaps in part 2. Throughout the second part of the flight pattern XCH₄ values between 1980 ppb and 2004 ppb are observed (Figure 3.3). The XCH₄ values are lowest at the end of part 2, which are the westernmost data points in Figure 3.3 b). This aligns with the XCH₄ distribution of part 1. Low values are also

observed at the northernmost data points in Figure 3.3 b).

The XCH_4 gradient in part 1 has a steep rise at the beginning, followed by a more moderate gradient, while the XCH_4 gradient in part 2 is less steep overall, but can be seen throughout the whole section.

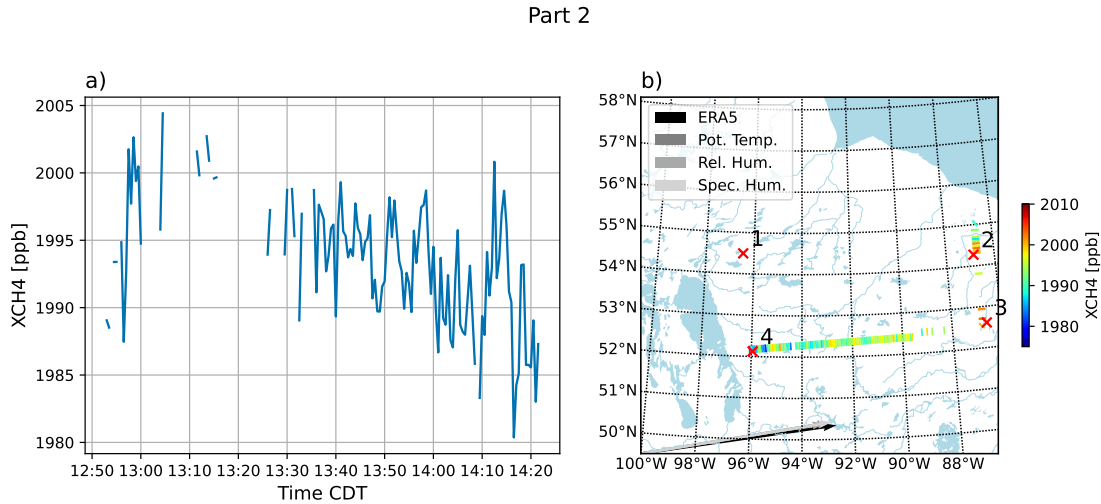


Figure 3.3: a) displays the time series corresponding to the XCH_4 measurements along the flight path of ORCA. b) shows the distribution of XCH_4 , where elevated concentrations are marked in red and lower values indicated in blue. The locations marked with the numbers represent the dropsonde releases. Additionally, the wind directions for the four approaches are represented by arrows in the bottom left corner. The range of the minimum to the maximum wind speed within the pbl for Part 2 of ORCA lies between 7.85 m s^{-1} for the relative humidity method and 8.29 m s^{-1} for the ERA-5 BLH method. The wind direction ranges from 80.23° for the potential temperature method to about 81.77° for the ERA-5 BLH method (further results are found in table 3.2). Throughout the flight, a downward trend in the time series highlights the general increase in XCH_4 concentrations towards the east. Data gaps can be explained by the cloud filter.

To calculate CH_4 fluxes using the mass balance approach, upwind and downwind regions are defined as shown in Figure 3.5. The regions have a width of 140 km. The upwind region for both parts is defined as the western most part of the flight pattern. The downwind region is found at the eastern most part of the flight pattern.

Averaging XCH_4 for the first part of the ORCA flight in the upwind region gives 1986 ppb. The downwind region of the first part has an average XCH_4 of 1995 ppb. This is a relative increase between the upwind and downwind region of about 0.45 %.

For part 2, the relative increase of XCH_4 from the upwind to the downwind region is very similar 0.55 % (11 ppb, from 1988 ppb to 1999 ppb).

Consequently, a large scale gradient is clearly observed in both segments of the ORCA flight, with values in a comparable range. Although the start and end of the flight are separated by approximately 4 hours, the concentration levels in the upwind

and downwind regions are consistent for both parts of the flight. This consistency underlines the reliability of the data collected. The fact that this gradient was measured twice during the flight further strengthens the confidence in the results and highlights the degree of accuracy of CHARM-F in detecting large-scale XCH_4 gradients. These gradients, that are expected to result from the accumulation of wetland emissions, can be used in the mass balance approach (equation (2.11)) in order to try quantifying the areal flux.

3.1.2 Planetary Boundary Layer Height analysis of the research flight "ORCA"

Next to the CH_4 concentrations which are assumed to be well mixed within the pbl, wind speeds within the pbl are necessary to quantify CH_4 fluxes (described in section 2.3). Therefore, a performance analysis of the ERA-5 data is done to gain confidence in the model data that need to be used, since no in-situ wind and pbl height data are available for the relevant times of observation. The results give an idea on how reliable the ERA-5 pbl heights are and, consequently, the assumed wind speed.

In situ data are provided by dropsondes released during the flight, radiosonde ascent from Pickle Lake, and the BAHAMAS data. Four dropsondes were released during ORCA. The first was released immediately before, the second and third during, and the fourth immediately after the CHARM-F measurements analysed in this study (Figure 3.2 b), Figure 3.3 b)).

In the following the results of the visual performance analysis of ERA-5 is shown. A more detailed analysis of the vertical profiles can be found in the appendix A.1.

Dropsonde:

- Relative humidity:

The pbl height derived from ERA-5 gives higher pbl heights than the vertical dropsonde profiles, except for the third profile. The ERA-5 BLH is above the height of the ERA-5 and dropsonde pbl in three of the four profiles.

- Potential temperature:

The vertical profiles of ERA-5 and the dropsondes are in good agreement. The parcel approach gives similar pbl heights to the humidity method for determining the pbl height. Again, the ERA-5 BLH tends to overestimate the pbl height. Therefore, it would not be surprising if the ERA-5 BLH pbl height is higher compared to the humidity or parcel approach.

- Wind speed:

Both, the ERA-5 and the dropsonde vertical profile increases with height, except the third dropsonde. For the third dropsonde the vertical wind speed profile decreases with height. A trend towards a higher or lower wind speed averaged within the pbl for ERA-5 compared to the dropsonde can not be identified. However, higher pbl heights will result for the majority of the profiles in higher averaged wind speeds within the pbl.

Radiosonde:

- Relative humidity:

For the radiosonde release at 7 CDT the vertical profiles of ERA-5 and the radiosonde agree reasonable well. However, the pbl height derived using the humidity approach of the radiosonde vertical profile would result in a higher pbl height than the ERA-5 BLH and ERA-5 pbl height. The vertical profiles of the 19 CDT release are rather contradictory. The ERA-5 BLH pbl height and the ERA-5 pbl height are at the same height, whereas the radiosonde pbl height is higher. In general, the radiosonde pbl height is higher compared to ERA-5 and ERA-5 BLH.

- Potential temperature:

The vertical profiles of ERA-5 and the radiosonde for the potential temperature are rather constant with height. However, there is a bias between the radiosonde and ERA-5 profile, with the radiosonde showing higher potential temperatures. As the maximum potential temperature is not at the surface, the parcel method can not be applied.

- Wind speed:

The wind speed profiles of the 7 CDT radiosonde release and ERA-5 agree well, whereas the profiles of the 19 CDT release are biased by about 7 m s^{-1} . No general trend of over or underestimation of the averaged wind speed within the pbl for ERA-5 can be identified. However all profiles increase with height which results in higher wind speeds for higher pbl heights.

BAHAMAS:

- Relative humidity:

The BAHAMAS vertical profiles fluctuate stronger than the ERA-5 profiles which makes it more difficult to visually determine the pbl height. However, as the BAHAMAS and ERA-5 profiles are generally in agreement, rough estimates of the pbl height can be made. Except for the first descent the ERA-5 BLH pbl height is higher than the BAHAMAS and ERA-5 pbl height.

- Potential temperature:

Due to the absence of the surface potential temperature in the BAHAMAS vertical profiles no statement about the pbl height can be made. However, the vertical profiles of ERA-5 and BAHAMAS agree reasonable well.

- Wind speed:

The vertical profiles of the wind speed in BAHAMAS and ERA-5 are in reasonably good agreement. For all profiles the wind speed increases with height. For four of the nine profiles the ERA-5 wind speed is lower than the BAHAMAS wind speed. For different pbl heights, the mean wind speed within the pbl of ERA-5 and BAHAMAS does not lead to large differences.

The performance of the ERA-5 vertical profiles to identify the pbl height can be summarised as follows: The ERA-5 pbl height is higher compared to three of the four dropsonde vertical profiles. Whereas the radiosonde pbl height is higher than the ERA-5 and ERA-5 BLH pbl height. No such trend is visible between the ERA-5 and BAHAMAS vertical profiles. The rather higher pbl height of the ERA-5 vertical profile only has small influence on the averaged wind speed within the pbl compared to the in situ averaged wind speed.

As a result, the agreement of ERA-5 compared to in situ vertical profiles can be described as reasonably good, as no significant trend towards overestimation of pbl height - and consequently wind speed - is observed. Nevertheless, the majority of the wind speed profiles from ERA-5, and in situ increases with height, which could lead to general higher wind speeds for higher pbl heights.

For the two flight parts of ORCA, the pbl height calculations with the different approaches are performed separately. The pbl heights are averaged over each

Determination Method:	ERA-5 BLH	Spec. hum.	Rel. hum.	Pot. temp.
pbl height part 1 [m]	824	748	684	628
pbl height part 2 [m]	1907	1830	2052	1781

Table 3.1: Planetary Boundary Layer Height in meter above ground of the research flight ORCA part 1 and part 2. The four different calculation methods are: Specific humidity (Spec. hum.), relative humidity (rel. hum.), potential temperature (Pot. temp.)

CHARM-F flight pattern as it can be assumed that no significant variation within the flight legs should occur. As the flight began early in the morning, the pbl height is expected to increase over time. This can be observed in the pbl heights of part 2 since that part started 1.5 hours after the first part ended. Flight pattern 1 took place between the first and the second dropsonde release. The pbl heights calculated using the ERA-5 data agree well with the first and second dropsonde vertical profile pbl heights. ORCA flight pattern no.2 started and ended shortly before the

third (13:14 CDT) and fourth (14:21 CDT) dropsonde release, respectively. From the dropsonde profiles, pbl heights between 1250 m and 2000 m are derived. The calculated pbl heights for part 2 are rather on the higher side. A possible explanation is that many data points at the beginning of part 2 (perpendicular to the wind direction) are flagged by the cloud filter. Therefore, less data points are available at which the pbl height can be calculated compared to the end of part 2, where no data gaps are present and hence more data points available. As a higher pbl height is assumed for the end of part 2 compared to the beginning of part 2, and more data points are available at the end of part 2, there are more data points with higher pbl heights from which a mean pbl height is calculated.

Noteworthy are the low values of the pbl height from the potential temperature profiles for both, part 1 and part 2. As observed in the performance analysis of ERA-5, the potential temperature profiles did not always show a convective pbl vertical profile with a high surface temperature and a pronounced inversion at the pbl top. This can lead to significant uncertainty in the calculated pbl height (Seibert et al. (2000)).

The high relative humidity pbl height of part 2 could be explained by the occurrence of clouds since a major part of the part 2 data was flagged by the cloud filter. In this case, the humidity approach detects the cloud tops instead of the pbl height (Seidel et al. (2010)). However, for most of the vertical wind speed profiles in the performance analysis, the wind speed increases with height. This could lead to higher wind speed estimates for higher pbl heights.

The four different pbl heights will result in four different wind speed estimates. As the fluxes for the four different wind speeds are later averaged together, it can be assumed that the wind speeds are more reliable and representative of the prevailing atmospheric conditions. The lower the variability of the pbl heights are for the four different calculation methods, the smaller the uncertainty is expected to be. The uncertainty contributes to the error estimate.

3.1.3 Wind distribution of the research flight "ORCA"

Determination Method:	ERA-5 BLH	Spec. hum.	Rel. hum.	Pot. temp.
wind speed part 1 [m s^{-1}]	9.1	8.6	8.7	8.1
wind speed part 2 [m s^{-1}]	8.3	8.1	7.9	8.0
wind direction part 1 [$^{\circ}$]	82.1	79.9	78.9	76.8
wind direction part 2 [$^{\circ}$]	81.8	80.7	80.7	80.2

Table 3.2: ORCA wind distribution for the four different calculation methods: Specific humidity (Spec. hum.), relative humidity (rel. hum.), potential temperature (Pot. temp.). Wind speed in m s^{-1} and direction in $^{\circ}$ from north.

According to the different methods described in chapter 2.3.2, wind speed and direction are derived. For ORCA part 1 a mean wind speed of 8.6 m s^{-1} (Range: $8.1\text{--}9.1 \text{ m s}^{-1}$) is determined (see table 3.2). The standard deviation is relatively small with 0.4 m s^{-1} . The height of the pbl varies relatively strongly between the maximum and minimum values, with more than 195 m. However, the wind speed does not appear to be strongly impacted, showing only a variation of 1 m s^{-1} between the minimum and maximum values. Very similar results are found for the second part of the ORCA flight pattern. A mean wind speed of 8.1 m s^{-1} (Range: $7.9\text{--}8.3 \text{ m s}^{-1}$) with a standard deviation of 0.2 m s^{-1} is calculated.

As analysed in the in situ vertical profiles the ERA-5 wind speed profiles tend to increase with height. Thus, it is not surprising that the lowest wind speeds can be observed for the lowest pbl height. For both parts the potential temperature parcel method results in the lowest pbl height. However, for part 2 the relative humidity approach gives the lowest wind speed. The pbl height derived from the relative humidity method for part 2 results in the highest pbl height and, hence, also in the lowest wind speed. Since for some vertical profiles the wind speed decreases above 1900 m there is a chance for lower averaged wind speeds.

The wind directions for the different approaches do not deviate strongly from each other (table 3.2). Nevertheless, this is no proof that the wind direction stayed constant for the relevant times before the flight took place. Prior to the flight, there may have been an inhomogeneous wind field that could have transported some XCH_4 away from the main flow and is therefore not detectable in the downwind region any more.

To determine if the calculated mean wind direction is a good proxy for the 4 hours of the flight, backward trajectories are calculated using HYSPLIT at 12 CDT. The plausibility of the flux results is determined by analysing these profiles.

For ORCA pattern no. 1 the wind direction within the pbl for the lateral section is about westerly for at least the past 6 to 12 hours (Figure 3.4). For ORCA pattern no. 2 westerly winds prevail not longer than 6 hours prior to the flight (Figure 3.4).

The north south section for both parts show westerly winds also at least for the past 6 hours (Figure 3.4). However, it has to be mentioned that the trajectories were calculated at a constant time at 12 CDT, which is in between part 1 and part 2.

As a conclusion, these findings provide strong evidence that the mass balance method is effective for calculating CH_4 fluxes from the upwind to the downwind region, independent of the wind. The wind does not transport CH_4 away from the main flow. This supports the argument that the mass balance approach can reliably estimate CH_4 fluxes in this case.

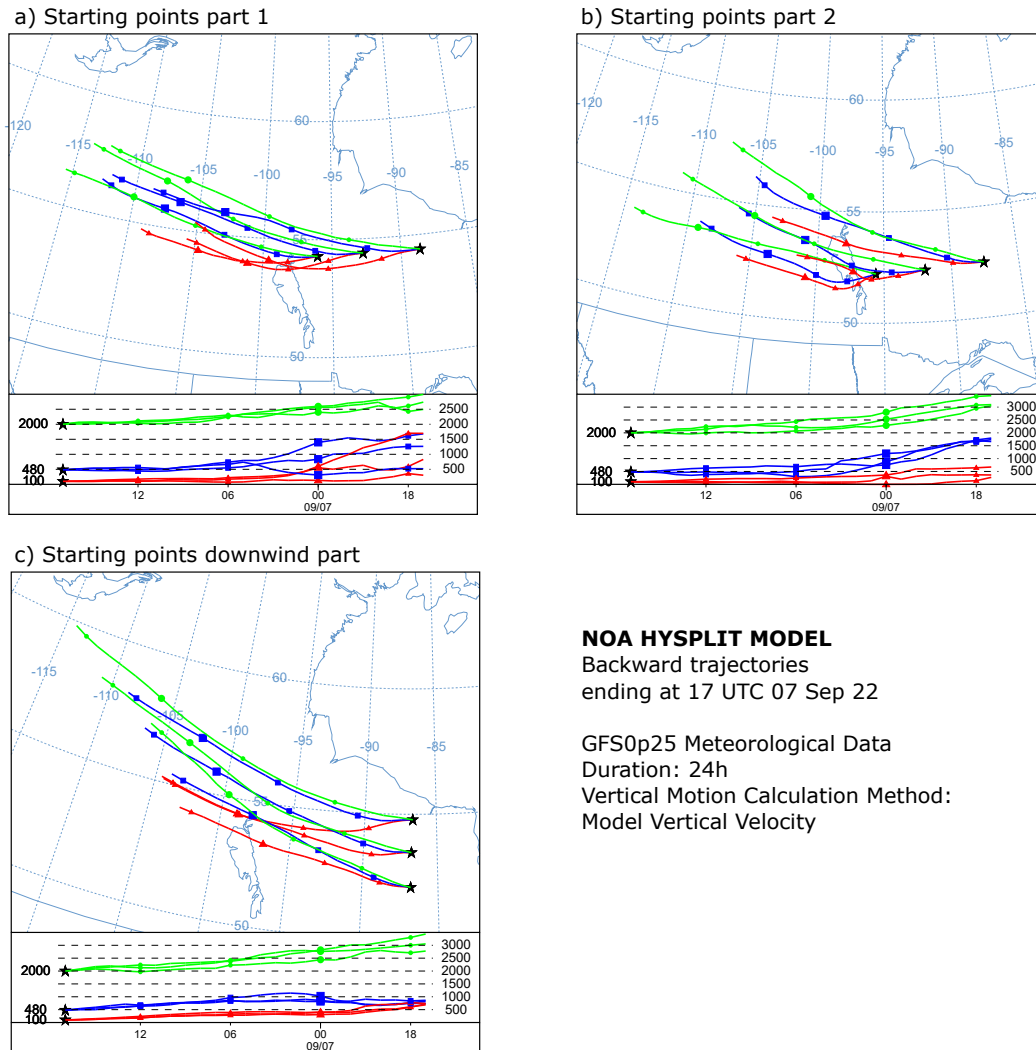


Figure 3.4: Backward Trajectories for ORCA flight at 12 CDT. Close to the ground at 100 m (red), within the pbl at 480 m (blue) and above the pbl at 2000 m (green). The wind direction in all three sections is westerly with only little wind shear with height. It is fair to assume an averaged westerly wind throughout the pbl.

3.1.4 Flux results of the research flight "ORCA"

The upwind and downwind region for the first part of the flight pattern have a mean distance in wind direction of about 603.6 km (table 3.3). According to chapter 2.3 CH_4 flux between the upwind and downwind region can be calculated using equation (2.11). The resulting CH_4 flux for the first part of the research flight pattern of ORCA equals: $1.33 \pm 0.25 \text{ kg km}^{-2} \text{ h}^{-1}$.

For the second part of the flight pattern the upwind region to the downwind region have a distance along the wind of about 608.6 km. This leads with equation

Flight pattern	Methane flux [$\text{kg km}^{-2} \text{h}^{-1}$]	Along-wind separation of the regions [km]
Part 1	1.33 ± 0.25	603.6
Part 2	0.99 ± 0.06	608.6

Table 3.3: Areal CH_4 flux results between upwind and downwind region for the research flight ORCA part 1 and part 2.

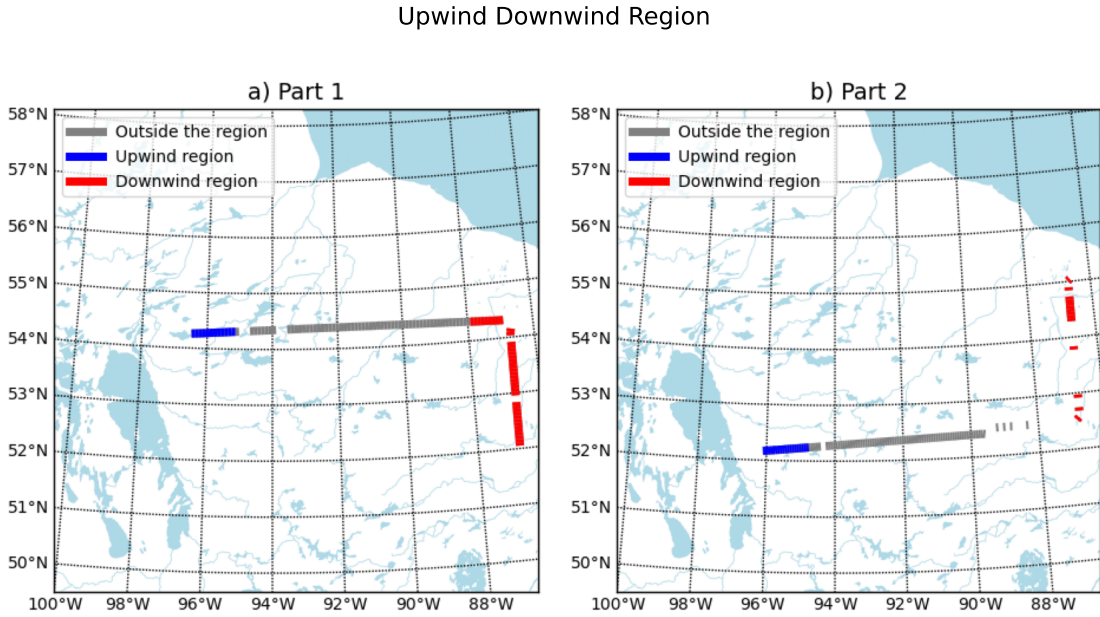


Figure 3.5: Part 1 a) and Part 2 b) flight pattern with the upwind region indicated in blue and the downwind region indicated in red. The width of the upwind and downwind region is about 140 km. The grey parts of the flight are not taken into account for the flux calculation.

(2.11) to a mean CH_4 flux of $0.99 \pm 0.06 \text{ kg km}^{-2} \text{h}^{-1}$.

The slight difference in distance between the upwind and downwind regions in part 1 and 2 is due to differences in data coverage in part 2 caused by clouds (Figure 3.5 b)). The distance is calculated by averaging the latitude and longitude coordinates of the respective regions. Consequently, this methodology results in a small difference in the calculated distances between part 1 and part 2.

The CH_4 concentrations measured during both parts of the research flight are remarkably consistent, resulting in a very similar areal CH_4 flux. This underlines that a rather constant CH_4 flux along the flight track over about 4 hours should exist. The flight part with a larger difference between the minimum and maximum wind speeds leads to a bigger flux uncertainty.

The estimated apportioning of the error contribution is somewhat different for the two flight parts: For part 1 the largest contributor to the total error, is the

difference between the along wind distance and the perpendicular distance of the upwind and downwind region, at 93 %. This is not the case for part 2, since, here, the distance uncertainty of the total error is about 1 %. This can be explained since in part 1 the distance vector between the averaged coordinates of the upwind and downwind region is orientated south-eastward whereas the wind direction vector is orientated north-eastward. The percentage of wind speed and $\delta\Omega$ of the total error for part 1 is 3 %. Whereas in part 2 the largest contribution to the total flux uncertainty comes from $\delta\Omega$ with 88 %. The wind speed of part 2 contributes with 4 % to the total error, which is similar to part 1. The error in $\Delta\sigma_{\text{CH}_4}$ attributes with 1 % for part 1 and with 7 % for part 2 to the total flux uncertainty.

The performance analysis of ERA-5 showed that there is no tendency of the ERA-5 vertical profiles to over- or underestimate the pbl height compared to the in situ vertical profiles. This gives confidence for using the ERA-5 wind information. The backward trajectories showed a relatively consistent wind direction from west within the pbl. Additionally, large scale XCH_4 gradients along the wind direction are measured for both flight patterns of ORCA. This meets all the requirements for the mass balance method to be effective in calculating CH_4 fluxes. The resulting calculated areal fluxes are presented in table 3.3.

3.2 Research flight "PIKE"

3.2.1 XCH_4 distribution of the research flight "PIKE"

Research flight "PIKE" took place on the 28th of August 2022. HALO took off at about 10 CDT in Edmonton heading eastward towards Lake Winnipeg. The CHARM-F measurements investigated in this study started at 11:13 CDT and ended at 13:41 CDT (16:13 UTC to 18:41 UTC). During the CHARM-F measurements HALO flew at a constant height of about 8520 m above ground.

The flight pattern includes four flight legs from north-west to south-east over the Grass, Burntwood and Upper Churchill River wetland as well as parts of Lake Winnipeg. The total area covered within this flight is smaller compared to ORCA and WALLEYE. Only the flight parts perpendicular to the wind direction reaching from north-west to south-east are defined as legs in the following. Due to the different quality filters (chapter 2.3.1) data gaps along the legs are visible. Since clouds were primarily present in the vicinity of leg 4 of the flight, the majority of data gaps can be attributed to the cloud filter applied. During the flight PIKE, XCH_4 values between 1958 ppb and 1997 ppb were measured.

The time series (Figure 3.6 a)) of the measured XCH_4 along the flight path shows a small overall positive gradient with flight time. This means that on average

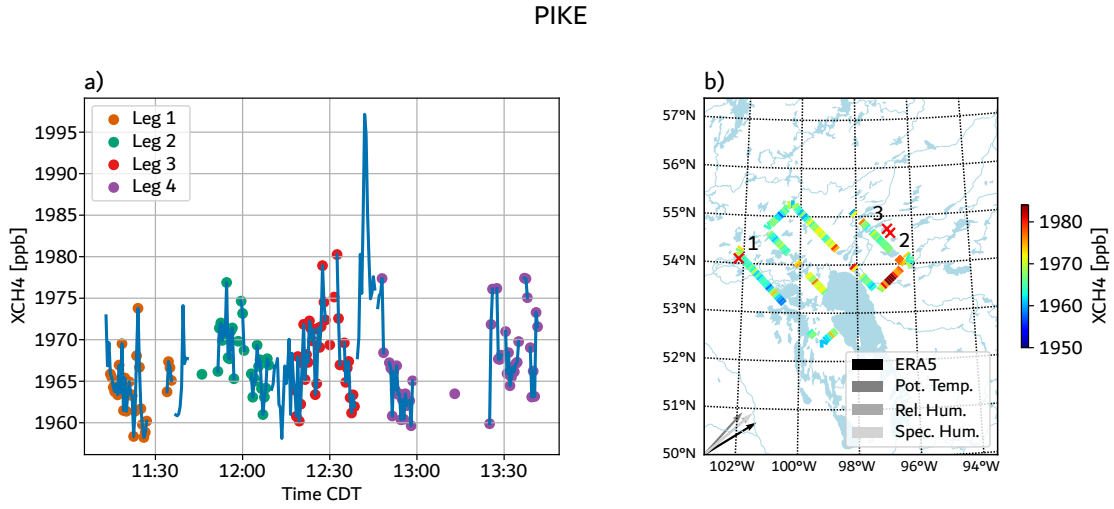


Figure 3.6: a) represents the time series along the flight PIKE of XCH_4 in blue. Different leg sections are indicated with different colours. The maximum between leg 3 and leg 4 refers to the strong XCH_4 concentration in the along wind part between leg 3 and leg 4 north east of lake Winnipeg. Leg 4 (purple color) was flown twice and has therefore a data gap around 13 CDT. Figure b) represents the XCH_4 distribution along the flight indicated with red high values and blue low values of XCH_4 . The wind direction of the four different approaches are in the lower left corner. For PIKE the minimum to the maximum wind speed within the pbl varies between 2.7 m s^{-1} for the ERA-5 BLH method and 3.3 m s^{-1} for the specific humidity method. The wind direction ranges from 43.2° for the ERA-5 BLH method to about 49.5° for the specific humidity method (see table 3.5). The locations marked with a cross and number are the dropsonde releases during the flight. Dropsonde 2 and 3 were release immediately after each other after leg 4.

the lowest XCH_4 values are found in the first (upwind) leg starting at about 54° north and 102° west going about 270 km south-east. Here, XCH_4 values between 1958 ppb and 1974 ppb with a mean of 1964 ppb can be found. The lower XCH_4 values are located in the middle of the leg, while slight increases are noticeable at both the beginning and the end, as shown in Figure 3.6 b). The first leg started at 11:14 CTD and ends at 11:35 CTD.

The second leg has a mean XCH_4 distribution of 1968 ppb (Range: 1961 - 1977 ppb). The XCH_4 values increase between leg 1 and 2. This can also be observed in Figure 3.6 between 11:46 and 12:09 CDT. The first and second leg have data gaps which are filtered by the SNR quality filter. The SNR quality filter filters the strong differences in the backscattered signal. These differences could arise because of lake edges. In Figure 3.6 b) many lakes are visible in the south of leg 1 and leg 2 which could lead to such strong differences in the backscattered signal.

The third leg records even higher concentrations of XCH_4 , ranging from 1960 ppb to 1980 ppb during the period from 12:18 to 12:38 CDT. However, the

mean XCH_4 is the same with 1968 ppb as for the second leg.

In the fourth leg a lot of values are filtered by the cloud filter. This leg was partially flown twice, resulting in a longer duration of the leg from 12:48 to 13:41 CDT. During the first part of the leg between 12:48 and 13:13 CDT lower XCH_4 values are measured with a mean XCH_4 of 1964 ppb. But the second part of leg four measured between 13:25 and 13:41 CDT represents a mean XCH_4 of 1969 ppb. Within a short period of time different XCH_4 values were measured. This could be explained since a big amount of values are filtered by the cloud filter. Processes influencing cloud formation appear to also have an impact on the XCH_4 concentration. In general the XCH_4 values in the whole fourth leg are ranging from 1960 ppb to 1977 ppb with a mean of 1967 ppb.

Overall, the CH_4 concentration is increasing between leg 1 and leg 4 as expected from Figure 3.6.

In order to calculate CH_4 fluxes over a larger region and thus to be more comparable with the ORCA XCH_4 fluxes, an upwind and downwind region is defined that includes two legs and their connecting sections (3.8). The upwind region covers leg 1 and 2 as well as their connecting part orientated south-west to north-east. Whereas the downwind region covers leg 3 and 4 with their connecting part. In the upwind area, the average concentration of XCH_4 is 1966 ppb, while in the downwind region 1970 ppb. This is a relative gradient of about 0.2 %.

The assumption of a lower concentration in the upwind region than the downwind region is fulfilled in this case. However, the gradient is not consistent along the wind within the region. This could be an indicator that the emitted CH_4 does not constantly accumulate along the wind direction. Possibly, the wind moves CH_4 out of the region and later back into the region.

3.2.2 Planetary Boundary Layer Height analysis of the research flight "PIKE"

As it is difficult to determine the pbl height, the performance analysis of ERA-5 is carried out, analogous to "ORCA". The analysis is described in more detail in the Appendix A.2.

In order to analyse the performance of the ERA-5 data along PIKE, a comparison of the in situ measurements of the dropsonde, radiosonde and BAHAMAS data with the ERA-5 data is made, analogous to the methods introduced for the research flight ORCA. In the following the vertical profiles of the in situ measurements will be analysed in the specified order. A more detailed analysis of the vertical dropsonde, radiosonde and BAHAMAS profiles compared to the ERA-5 vertical profile of relative humidity, potential temperature and wind speed can be found in the appendix

A.2.

During PIKE three dropsondes were released. The first dropsonde was released at 11:06 CDT. The second and third dropsonde were released shortly after each other at 13:47 and 13:49 CDT (Figure 3.6 b)). This corresponds to the beginning and end of the research flight PIKE.

In the following the results of the visual performance analysis is presented:

Dropsonde:

- Relative humidity:

The pbl height derived by using the humidity approach with the strongest negative gradient is higher for ERA-5 than the dropsonde in all profiles. The ERA-5 BLH is always above the strongest negative gradient of the dropsonde profiles. For two of the three profiles ERA-5 BLH agrees approximately with the ERA-5 pbl height. However in the first dropsonde profile the ERA-5 BLH is higher than the ERA-5 strongest negative gradient.

- Potential temperature:

The pbl heights derived using the parcel method give very similar pbl heights to the humidity approach, with the ERA-5 being always higher than the dropsonde pbl height. Although it is difficult to determine the pbl height visually using the parcel method.

- Wind speed:

The first dropsonde vertical wind speed profile is in good agreement with the ERA-5 vertical profile. Both profiles are rather constant with height. The second and third profile of the dropsonde and ERA-5 deviate between 600 m and about 1250 m. Therefore no general conclusion can be drawn about higher or lower mean wind speeds within the pbl for different pbl heights.

Radiosonde:

- Relative humidity:

For the first radiosonde the pbl heights for ERA-5, radiosonde and ERA-5 BLH are all at the same height. For the second radiosonde release the pbl heights deviate strongly. Hence no general conclusion can be drawn about higher or lower pbl heights for ERA-5.

- Potential temperature:

The maximum potential temperature in the vertical potential temperature profiles is not at the surface. Therefore the parcel method cannot be applied.

However, there is a bias between the ERA-5 and radiosonde profile with higher temperatures for the ERA-5 profile.

- Wind speed:

The vertical profiles for the first radiosonde and the ERA-5 are in good agreement. No major differences in mean wind speed within the pbl are expected for different pbl heights. For the 19 CDT radiosonde release the vertical profiles indicate that the mean wind speed within the pbl will be higher for ERA-5 compared to the radiosonde. However, there is no general tendency for higher or lower wind speeds within the pbl for different pbl heights.

BAHAMAS:

- Relative humidity:

The ERA-5 pbl height derived with the humidity approach is in most cases higher than the pbl height of the BAHAMAS. There is no trend for the ERA-5 BLH to be higher or lower than the ERA-5 and BAHAMAS profiles.

- Potential temperature:

Due to the absence of the surface temperature the parcel method can not be applied. However, most of the ERA-5 profiles are in very good agreement with the BAHAMAS vertical profiles. Only in two profiles ERA-5 is higher than the BAHAMAS profile. Therefore no over or underestimation of ERA-5 is observed.

- Wind speed:

The wind speed profiles of ERA-5 and BAHAMAS show a good agreement. Therefore, no major differences in mean wind speed within the pbl are expected for ERA-5 compared to BAHAMAS. If the pbl height is below the wind speed maximum, the mean wind speed within the pbl will be lower than above the wind speed maximum observed in all profiles.

It can be concluded that the ERA-5 data overestimate the pbl height in certain cases compared to the in situ vertical profiles. The wind speed analysis showed that no major differences can be expected, especially between ERA-5 and BAHAMAS. However, no general trend of increasing wind speed with height was observed in the analysed profiles. This leads to the assumption that the discrepancy between the averaged wind speeds within different pbl heights will be small.

It is not surprising that the specific and relative humidity pbl height are very close together, hence the in situ profiles represent a well mixed boundary layer. Additionally, the majority of the flight pattern was cloud free, with the exception of parts of leg 4.

Determination Method:	ERA-5 BLH	Spec. hum.	Rel. hum.	Pot. temp.
pbl height [m]	455	745	741	583

Table 3.4: Planetary Boundary Layer Height in meters for PIKE for the four different determination methods. The humidity approach is used for the vertical profiles of the specific humidity (Spec. hum.) and relative humidity (Rel. hum.). The parcel method is applied for the vertical profiles of the potential temperature (Pot. temp.).

The vertical profiles of the dropsondes and BAHAMAS indicate pbl heights very similar to the presented pbl heights in table 3.4. This confirms the plausibility of the calculated pbl heights. The calculated pbl heights vary from the minimum to the maximum value by more than 289 m. However, as will be demonstrated in the subsequent section, such variation of the pbl height does not significantly influence the modelled mean wind speed.

3.2.3 Wind distribution of the research flight "PIKE"

The standard deviation of the wind speed calculated from the four different pbl height identification approaches indicate small variations with 0.2 m s^{-1} for a mean wind speed of 3 m s^{-1} (Range: $2.7 - 3.3 \text{ m s}^{-1}$). This underlines the theory that, even though the pbl height varies for all four different methods, the wind speed variability is small. The wind speed of 2.7 m s^{-1} are just above those at which the mass balance approach can be applied (Varon et al. (2018)). The wind speeds for the research flight PIKE are significantly lower than for ORCA (Range: $7.9 - 8.3 \text{ m s}^{-1}$).

For PIKE, the lowest pbl height indicates the lowest wind speed and the wind direction being more towards north-east. Conversely, a higher pbl height corresponds to higher wind speeds and a wind direction towards south-east. This can be explained since the majority of the wind speed vertical profiles increase with time.

Determination Method:	ERA-5 BLH	Spec. hum.	Rel. hum.	Pot. temp.
wind speed [m s^{-1}]	2.7	3.3	3.2	2.9
wind direction [$^{\circ}$]	43.2	49.5	49.4	47.2

Table 3.5: Model wind speed and direction for the research flight PIKE with the four different methods to identify the pbl height.

The CHARM-F data recorded during the flight covers about two hours. In order to check whether the modelled wind direction given in the table 3.5 is reasonable, and also to check whether it is fair to assume a constant average wind direction through the atmosphere, backward trajectories are calculated using HYSPLIT.

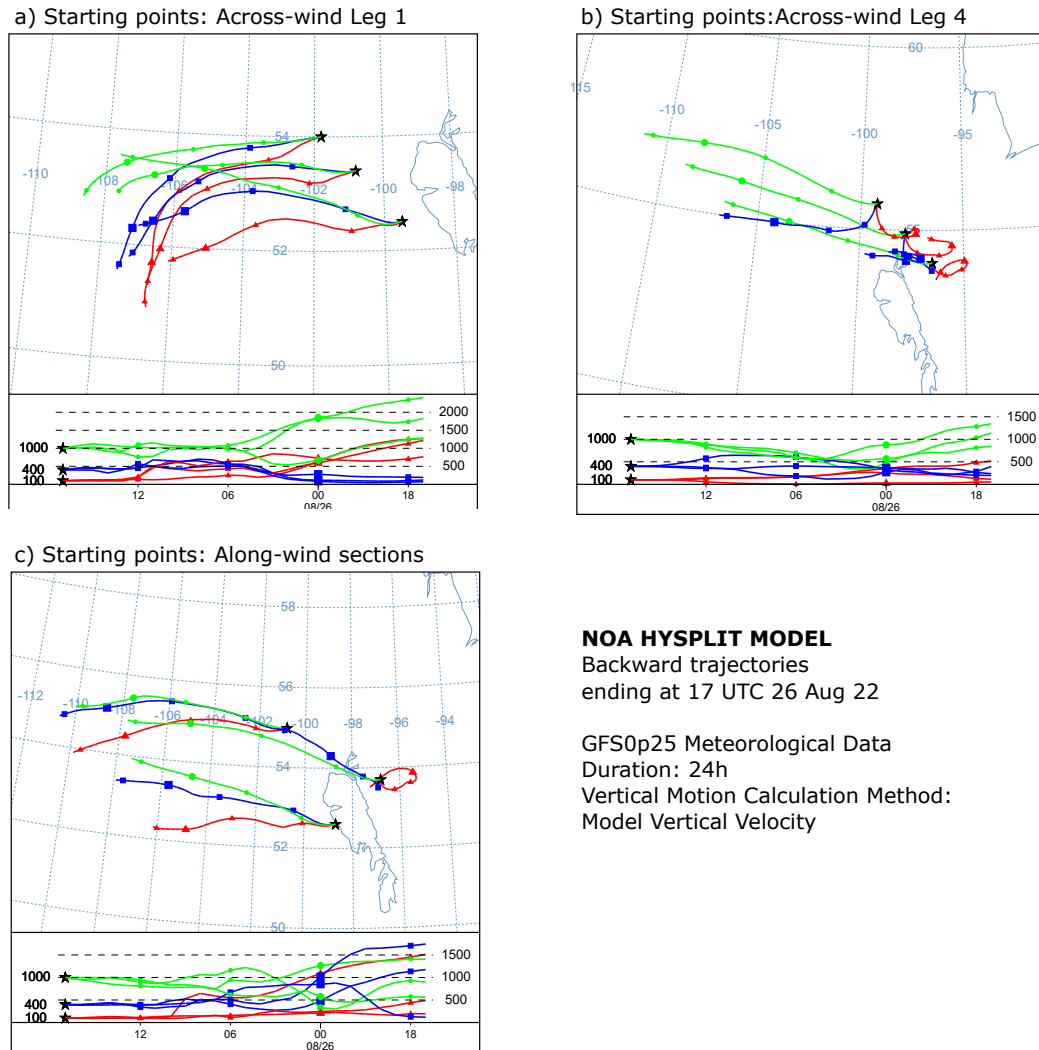


Figure 3.7: Calculated back-trajectories for PIKE launched at 12 CDT. These trajectories were calculated at various altitudes: near the ground at 100 m, within the pbl at 400 m, and above the pbl at 1000 m. Leg 1 (a) as well as Leg 2 and Leg 3 (B.1) align with a westerly wind direction throughout the pbl. Remarkable is the prevailing of the wind within the same area especially for the surface and 400 m winds in Leg 4 (b) and the eastern along wind part (c).

For the first leg, all three locations show similar wind directions. There is a small wind shear between the surface wind direction and the wind direction within (at 400 m) and above (at 1000 m) the pbl height (Figure 3.7 a)). But it can clearly be observed that west-wind prevailed, at least for the past 6 hours. Furthermore, a vertical wind shear to northerly winds is noticeable. The trajectories for the second leg shows similar results with wind directions from west for the past 6 hours and a vertical wind shear (Figure B.1 a)). Hence leg 1 and leg 2 represent the same

results, only leg 1 is shown in Figure 3.7 a). The trajectories over the north-east part of lake Winnipeg show non laminar features like in leg 3 (Figure B.1 b)) at a height of 100 m above ground. For as much as 24 hours the air mass remains in the same area and lingers, this is best seen in Figure 3.7 b).

Additionally, trajectories for the along-wind parts connecting the legs are modelled (Figure 3.7 c)). The leg connecting parts trajectories show different wind direction patterns. For the south-east trajectories of the connecting part of leg 1 to leg 2 and for the trajectories of the north-west connecting part of leg 2 to leg 3 the wind direction is from west for the past 6 hours. The trajectories connecting leg 3 with leg 4 shows similar pattern in the 100 m winds as for all trajectories of leg 4. The past 24 hours the wind circles around the releasing location of the trajectories. The XCH_4 measured at the north eastern part is an accumulation of CH_4 over the past 24 hours.

The following conclusion can be drawn from the trajectory analysis: For a big part of the flight region the wind direction remained consistent within the pbl over time. However, in the north eastern part of the flight region wind shear within the pbl height and a circular pattern of the wind at one location is observed. The circular wind pattern indicates that the CH_4 concentration could be higher there, since the air mass remained at this location for a longer time period and experienced accumulation.

With these results the conditions for calculating CH_4 fluxes using the mass balance approach are not ideal. Nevertheless, flux calculations are done. To determine if the fluxes are in a realistic range, the results will be compared to other studies (see chapter 4).

3.2.4 Flux results of the research flight "PIKE"

In table 3.6 the calculated CH_4 fluxes (according to equation (2.11)) between the different across wind flight legs are presented.

For the PIKE flux comparison the assumption of lower XCH_4 values in the upwind region and higher values in the downwind region only applies with restrictions. The mean XCH_4 increases clearly between leg 1 and 2. This suggests that the largest sources of emissions are located between leg 1 and 2. Between leg 2 and leg 3 the mean XCH_4 increase is small. However, the distance-weighted average DAOD along the flight legs does not show an increase from leg 2 to leg 3. The distance-weighted averaged DAOD along the flight leg is rather decreasing from leg 2 to leg 3 resulting in a negative Ω and therefore negative calculated flux. The mean XCH_4 values between leg 3 and 4 and between leg 2 and 4 decrease, which results in calculated negative fluxes. The highest flux can be observed between leg 1 and leg 2. This is

Leg gap	Methane flux [$\text{kg km}^{-2} \text{h}^{-1}$]	Along-wind separation of the flight legs [km]
Leg gap 1-2	2.04 ± 0.22	84
Leg gap 2-3	-0.11 ± 0.13	83
Leg gap 3-4	-0.89 ± 0.24	57
Leg gap 1-4	0.48 ± 0.06	230
Leg gap 1-3	0.97 ± 0.10	167
Leg gap 2-4	-0.42 ± 0.08	143

Table 3.6: Areal CH_4 flux results between different legs. The first leg always serves as the upwind leg where the second leg represents the downwind leg. Given that the along wind distance between the upwind and downwind region with its reciprocal significantly influences the flux results, the distance is documented in the third column.

also were the strongest XCH_4 increase is observed. The bigger the distance between the upwind and downwind leg the smaller the calculated areal flux between these regions due to the division by the along wind distance of the legs. Bigger upwind

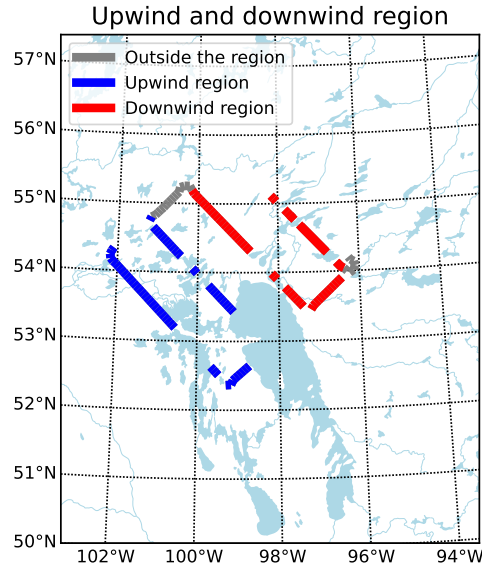


Figure 3.8: Upwind region marked in red and downwind region marked in blue. The grey values represent the data not taken into account for the flux calculation between these two regions.

and downwind regions covering multiple legs are defined. These regions average more data points together, which smoothens the data and gives more confidence in the data. However, this way, the flux for a comparable small region between the upwind and downwind region is calculated. Consequently smaller errors are made in Ω and bigger errors will occur for the along wind distance.

The increased XCH_4 values in the downwind region compared to the upwind

Methane flux [$\text{kg km}^{-2} \text{h}^{-1}$]	Along-wind separation of the regions [km]
0.58 ± 0.13	276

Table 3.7: Methane fluxes for the upwind and downwind region covering multiple legs and their along wind connecting parts. These regions are defined in order to average over a larger region to make the results more comparable with the research flight ORCA.

region result in a positive CH_4 flux (see table 3.7). The flux from the upwind to the downwind region is calculated as $0.58 \pm 0.13 \text{ kg km}^{-2} \text{h}^{-1}$. 83 % of the total uncertainty is attributed by the difference between the perpendicular distance between the upwind and downwind region and the along wind distance. The wind speed uncertainty contributes with 13 % to the total error, $\delta\Omega$, the integrated DAOD enhancement contributes with 4 % and the error for $\Delta\sigma_{\text{CH}_4}$ contributes with less than 1 % to the total flux uncertainty.

In the following, the mean relative error contribution over all leg gaps are given. The largest contribution to the reported errors is caused by the DAOD measurement itself. The relative error in Ω averaged over all calculations contributes with 63% to the total uncertainty. The relative wind speed error accounts for 27% of the total error. The difference between the perpendicular distance between the legs and the along wind distance contributes with 9% to the total flux uncertainty. The wind speed and distance error terms are influenced by the performance of ERA-5. The error term contribution of $\Delta\sigma_{\text{CH}_4}$ is negligible small with less than 1% to the total flux uncertainty. This shows that pbl height variations and the resulting wind speed variations contribute to the error term, but are not the main contributors.

The error contribution between the different leg gaps varies. Especially small CH_4 fluxes with big error terms (100 % of the flux or more) have relative errors of 99 % for the integrated DAOD enhancement, Ω . For small measured DAOD gradients, the sensitivity to the error is high.

Although the wind direction within the pbl shows spatial variation and the XCH_4 distribution does not increase linearly with the wind direction, the conditions for calculating CH_4 fluxes using the mass balance approach are not ideal. Nevertheless, positive fluxes are calculated but should be treated with caution.

3.3 Research flight "WALLEYE"

3.3.1 XCH_4 distribution of the research flight "WALLEYE"

The research flight "WALLEYE" on the 3rd of September 2022 started at 10 CDT in Edmonton with the CHARM-F measurements over the target area starting at 11:02 CDT until 13:48 CDT. The remote sensing flight pattern for WALLEYE analysed

in this study took place at an altitude of between 8720 m and 9545 m above ground and are not disturbed by lower altitudes.

The XCH_4 distribution of the flight WALLEYE north of Lake Winnipeg varies between about 1934 ppb and 1981 ppb. The time series Figure 3.9 a) represents the CH_4 distribution. No along wind positive CH_4 gradient is observed. This is underlined by Figure 3.9 b) with no XCH_4 increase along the wind direction. A gradient perpendicular to the wind direction is visible in the graphic. The legs are

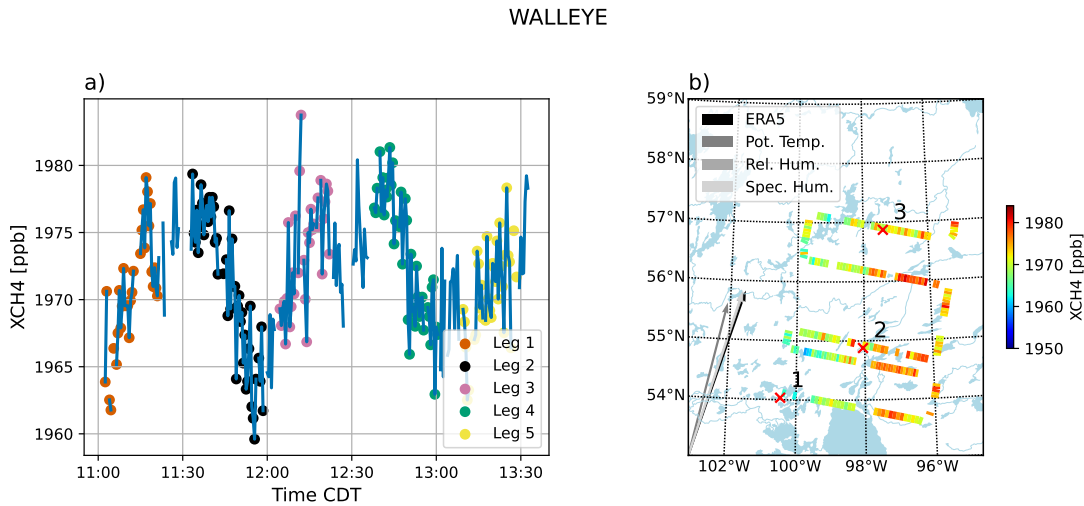


Figure 3.9: WALLEYE flight pattern. a) time series along the flight pattern of XCH_4 . b) XCH_4 distribution along the flight indicated with red high values and blue low values of XCH_4 . The arrows represent the different wind directions calculated with the four approaches. The red crosses indicated with numbers are the location of the dropsonde releases. In the time series it can be seen that the minimum values during the flight were recorded in leg 2. However the maximum XCH_4 values for WALLEYE can be found in leg 3. b) doesn't indicate an along wind gradient nevertheless an east-west gradient can be observed. For WALLEYE the minimum to the maximum wind speed within the pbl varies between 7.69 m s^{-1} for the ERA-5 BLH method and 8.76 m s^{-1} for the specific humidity method. The wind direction ranges from 13.12° for the ERA-5 BLH method to about 19.51° for the relative humidity method (further results see table 3.9).

orientated from south east to north west. The legs were planned during the flight planning to be perpendicular to the wind direction. The four legs are parallel to each other and connected with a north eastern part. The distances between the parallel flight legs are not as evenly spaced (Figure 3.9 b)) as the flight legs of PIKE. The most southern leg, leg 1 started at 11:02 CDT from about 54.1° north and 100.5° west continuing to 53.6° north and 96.4° west and ended at 16:21 CDT. Leg 1 has a mean XCH_4 value of 1971 ppb with a minimum of 1962 ppb and maximum of 1979 ppb.

The second leg starts at 11:33 CDT 54.4° north and 96.6° west continuing to end

at 11:58 CDT at 54.9° north and 100.2° west. During the second leg of WALLEYE, the minimum XCH_4 concentration of the whole research flight was measured with 1960 ppb. The maximum XCH_4 of leg 2 is 1979 ppb. This XCH_4 range results in an average XCH_4 of 1971 ppb, like in leg 1.

After a short connecting part along the wind, the third leg starts at 12:04 CDT. Leg 3 goes from 55.2° north and 99.9° west to 54.7° north and 96.2° west. Leg 3 ended at 12:21 CDT. The highest concentrations of XCH_4 were recorded during leg 3, with a maximum value of 1984 ppb. The corresponding minimum concentration of XCH_4 during this leg was 1967 ppb, resulting in an average concentration of 1974 ppb. After the third leg a longer distance along the wind direction was flown to connect to the next leg.

Leg 4 started at 12:37 CDT at 55.9° north and 95.7° west and ends at 56.4° north and 99.7° west at 13:00 CDT. The fourth leg XCH_4 concentration ranges between 1963 ppb and 1981 ppb yielding in a mean XCH_4 of 1973 ppb.

The last leg, leg 5 goes from 57.1° north and 99.5° west to 56.7° north and 95.6° west. This leg started at 13:09 CDT and ended at 13:28 CDT. During that time an average XCH_4 concentration of 1971 ppb was measured. The lowest recorded value for XCH_4 was 1963 ppb, while the highest reached 1978 ppb. After the fifth leg HALO continued to fly towards the Hudson Bay into north east direction to perform in situ measurements.

An upwind and downwind region covering multiple legs and their connecting parts is defined to calculate XCH_4 mean concentrations for these regions (Figure 3.11). This allows the flux results to be compared with the ORCA results. The southern region is defined as the upwind region within a mean XCH_4 concentration of 1971 ppb. The downwind region average XCH_4 concentration of 1972 ppb indicates a small CH_4 gradient along the wind (1 ppb). This results in a relative gradient of 0.05 %. The small relative gradient is not surprising as Figure 3.9 b) shows an east west gradient and no clear south north gradient.

3.3.2 Planetary Boundary Layer Height analysis of the research flight "WALLEYE"

Likewise to PIKE three dropsondes were released during the research flight WALLEYE. The vertical profiles of the dropsonde, radiosonde and BAHAMAS relative humidity, wind speed and potential temperature are used for the ERA-5 performance analysis.

All three dropsondes launched during the research flight WALLEYE were released within the time frame of the CHARM-F measurements analysed in this study. The results of the vertical profile analysis of the dropsonde, radiosonde and ERA-5

are summarised below. A more detailed analysis can be found in the appendix [A.3](#).

Dropsonde:

- Relative humidity:
The vertical profiles of the dropsonde and ERA-5 agree well. The pbl height derived from the strongest negative gradient for the dropsonde and ERA-5 are within a few meters, only.
- Potential temperature:
The vertical profiles of all dropsondes and ERA-5 are in good agreement. The pbl heights derived by the parcel method of ERA-5 and the dropsondes are very close together. The ERA-5 BLH is rather higher than the pbl height identified by the parcel method.
- Wind speed:
All ERA-5 and dropsonde vertical profiles agree well. The mean wind speed within the pbl will be different for different pbl heights, since the profiles have a wind speed maximum at 750 m. However, there will be no big differences in the mean wind speed within the pbl of the ERA-5 and the dropsonde.

Radiosonde:

- Relative humidity:
The radiosonde relative humidity profiles of the 7 CDT release agrees well with the ERA-5 vertical profile. In the 19 CDT profiles the ERA-5 BLH is higher than the ERA-5 and lower than the radiosonde pbl height. It is therefore not possible to draw any general conclusion.
- Potential temperature:
As in the other radiosonde profiles the potential temperature profiles of ERA-5 and the radiosonde are biased. As the maximum potential temperature is not at the surface, the parcel method cannot be used.
- Wind speed:
The wind speed vertical profiles for the radiosonde and ERA-5 agree well. Therefore, the wind speed averaged within the pbl will not differ significantly between ERA-5 and the radiosonde. However, no general conclusions can be drawn as to how the mean wind speed varies for different pbl heights.

BAHAMAS:

- Relative humidity:

ERA-5 and BAHAMAS vertical profiles show the strongest negative gradients at different heights. In addition the ERA-5 BLH is at different heights to the ERA-5 and dropsonde pbl height.

- Potential temperature:

There is good agreement between the vertical potential temperature profiles of ERA-5 and BAHAMAS. However, due to the absence of the surface potential temperature the pbl height derived by the parcel method cannot be identified.

- Wind speed:

The trends of the vertical wind speed profiles in BAHAMAS and ERA-5 are slightly different. However, the average wind speed within the pbl for ERA-5 or BAHAMAS will not show a large difference. There is no general tendency in how the averaged wind speed behaves for different pbl heights.

Summarising the performance analysis of ERA-5: In general, the ERA-5 vertical profiles do not over- or underestimate the pbl height compared to the highly accurate in situ vertical profiles. The vertical wind speed profile of ERA-5 does not deviate much from the in situ wind speed profiles. Although the pbl height estimates may vary, the effect on the average wind speed within the pbl is minimal. Nevertheless, in many profiles the wind speed increases with height up to 1000 m.

Determination Method:	ERA-5 BLH	Spec. hum.	Rel. hum.	Pot. temp.
pbl height [m]	592	783	767	658

Table 3.8: Planetary Boundary Layer Height in meters for the research flight "WALLEYE". The pbl height for specific humidity (Spec. hum.) and relative humidity (Rel. hum.) is derived using the humidity approach, while the pbl height for potential temperature (Pot. temp.) is derived using the parcel approach.

The pbl heights presented in table 3.8 fit to the pbl heights identified in the dropsonde vertical profiles. Depending on the different calculation methods for the pbl height, the measured heights range from a minimum to a maximum difference of more than 191 m. The minimum pbl height is derived using the ERA-5 BLH. The high pbl height values for the humidity approach are not unusual, as this approach tends to estimate the height of the pbl top (Seidel et al. (2010)). Based on the performance analysis these pbl height variations will, however, have a minor influence on the mean wind speed and direction within the pbl.

3.3.3 Wind distribution of the research flight "WALLEYE"

The wind speed and direction for the different pbl height calculations of the ERA-5 data is distributed as follows:

Determination Method:	ERA-5 BLH	Spec. hum.	Rel. hum.	Pot. temp.
wind speed [m s^{-1}]	7.7	8.8	8.7	8.0
wind direction [$^{\circ}$]	13.1	18.4	18.5	14.7

Table 3.9: Wind speed and direction within the pbl for the research flight WALLEYE, calculated based on the different pbl heights.

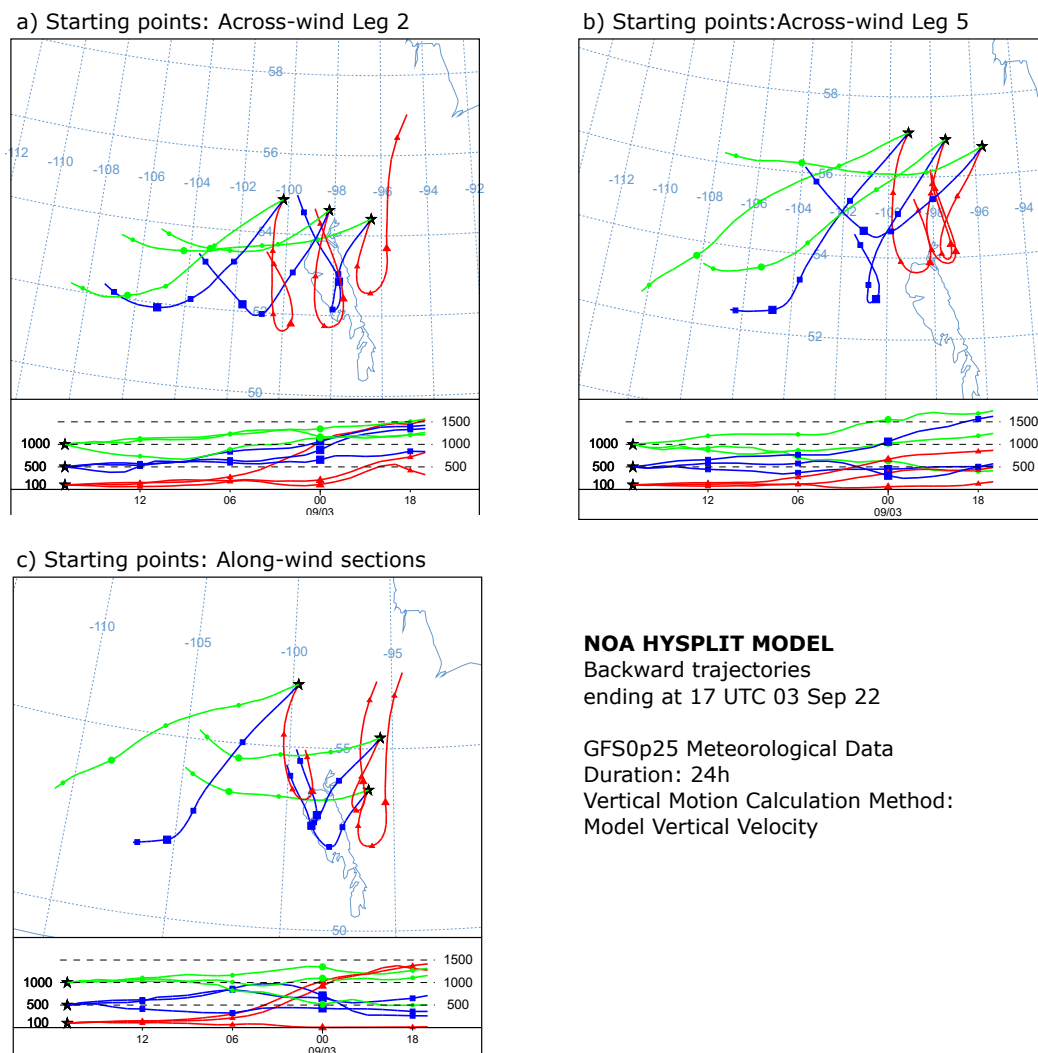


Figure 3.10: A wind shear within the different pbl heights at 100 m, 500 m and 1000 m is observed for the backward trajectories calculated for WALLEYE at 12 CDT. Similar results as presented in leg 2 and leg 5 are found for leg 1, leg 3 and leg 4.

Comparing the wind speed and direction for the different approaches to the pbl height calculations from table 3.8 the minimum pbl height leads to the lowest wind speed and the maximum pbl height leads to the highest wind speed. This was expectable based on the performance analysis of ERA-5. For pbl heights below 750 m, most in situ and ERA-5 vertical wind speed profiles showed increasing wind speed profiles. The standard deviation of the wind speed indicates very little variation throughout the approaches with 0.5 m s^{-1} . The mean wind speed is 8.3 m s^{-1} (Range: $7.7 - 8.7 \text{ m s}^{-1}$). These wind speeds are similar to ORCA and thus significantly higher than for the research flight PIKE. The wind direction varies throughout the different approaches by more than 5° . This variation is very comparable to the other flights.

To determine if the wind direction remained constant for the time of the flight, backward trajectories are calculated at 3 locations of the legs and at the along-wind parts at 12 CDT (Figure 3.10). For all five legs as well as their connecting parts wind shear within the pbl occurs. For all legs similar results with surface winds at 100 m coming from south for the past 12 hours and rather northerly for the past 24 hours are found. The wind direction within the pbl at 500 m changes slightly within the leg. For the past 12 hours the trajectory indicates a south-westerly wind direction at 500 m. The wind direction was westerly for the winds above the pbl at 1000 m. Likewise for the research flight PIKE the air mass remains in the same area and lingers around in the most eastern locations of the along-wind track between leg 1 to 2 and leg 3 to 4 (Figure 3.10 c)).

The wind shear within the pbl could result in irregularities in the XCH_4 concentration, as well as a positive gradient from east to west instead of the expected south to north along the wind. Due to the inhomogeneity of the wind field, the conditions are not ideal for applying the mass balance approach. In addition, there is no general increase of XCH_4 over all legs. Despite the poor conditions for the mass balance approach, an attempt was made to calculate CH_4 fluxes, which should be treated with caution.

3.3.4 Flux results of the research flight "WALLEYE"

The mass balance approach, assumes that CH_4 concentrations in the upwind region are lower than those in the downwind region in order to calculate a positive CH_4 flux. An analysis of Figure 3.9 b) shows no clear positive XCH_4 gradient along the wind. This lack of positive gradient and the inhomogeneity of the wind field explains the fact that not all CH_4 flux results in table 3.10 are positive. For a CH_4 flux to be considered positive, the mean XCH_4 concentration in the upwind area has to be greater than that in the downwind area. However, this is not observed for the leg

concentrations in WALLEYE, leading to some negative fluxes. The XCH_4 values increase from leg 1 to leg 2 to leg 3, but then decrease from leg 3 to leg 4 to leg 5, which is visible in the flux results.

Leg gap	Methane flux [$\text{kg km}^{-2} \text{h}^{-1}$]	Along-wind separation of the flight legs [km]
Leg gap 1-2	0.08 ± 0.29	85
Leg gap 2-3	5.55 ± 1.81	36
Leg gap 3-4	0.53 ± 0.21	135
Leg gap 4-5	-3.65 ± 0.64	86
Leg gap 1-4	1.07 ± 0.12	256
Leg gap 1-3	1.69 ± 0.28	121
Leg gap 2-4	1.57 ± 0.19	171
Leg gap 1-5	-0.11 ± 0.09	341
Leg gap 2-5	-0.17 ± 0.11	256
Leg gap 3-5	-1.1 ± 0.16	220

Table 3.10: Areal flux results between the upwind and downwind legs for the research flight WALLEYE. The along-wind distance between the legs are given in km.

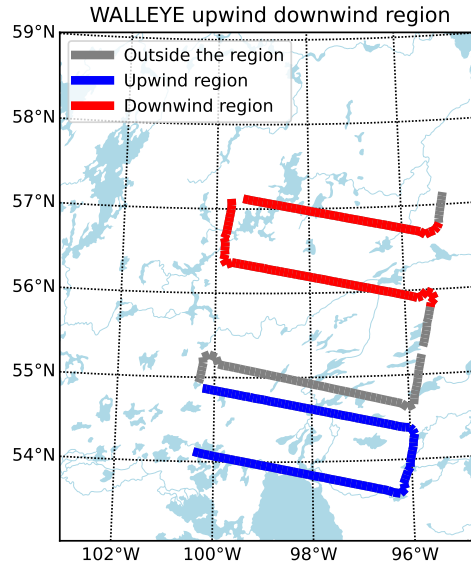


Figure 3.11: WALLEYE upwind and downwind region covering multiple legs. The upwind region indicated in blue and the downwind region indicated in red. The grey data is not taken into account for the flux calculations.

To calculate the CH_4 fluxes between the more extensive upwind and downwind regions, those regions are defined to cover multiple legs (Figure 3.11). The upwind region includes the first two flight legs and their connecting parts coloured in blue in Figure 3.11. The downwind region, coloured in red in Figure 3.11 is placed north of

the upwind region and covers leg 4 and leg 5 with their connecting part. The upwind and downwind region have a distance of 889 km as presented in table 3.11. The areal CH_4 flux between the upwind and downwind region is $0.06 \pm 0.02 \text{ kg km}^{-2} \text{ h}^{-1}$.

Methane flux [$\text{kg km}^{-2} \text{ h}^{-1}$]	Along-wind separation of the regions [km]
0.06 ± 0.02	889

Table 3.11: The upwind and downwind region covering multiple regions are defined in order to average over a larger region to make the results more comparable with the research flight ORCA. Presented here are the areal fluxes between these regions.

The averaged relative contributions of the different error terms to the total flux uncertainty for all leg gaps are as follows: the largest portion of the total error comes from the DAOD error with 73 %, followed by the difference between the perpendicular distance between the legs and the along wind distance contributing with 24 %, the wind speed error with 3 %, and the error for $\Delta\sigma_{\text{CH}_4}$ with about 1 % to the total uncertainty. This highlights that the pbl height and the resulting wind speed and direction is influencing the flux calculation but not significantly.

The relative error contribution of the total flux uncertainty is similar to the research flight PIKE. Small fluxes are more sensitive to the DAOD measurement itself. For example is the relative error contribution of the difference between the perpendicular distance between the legs and the along wind distance for the leg gap 2 to 3 about 81 % of the total uncertainty. And only about 18 % for Ω .

The results of the studied CH_4 fluxes for WALLEYE show that it might be more complicated to determine CH_4 fluxes in this region than the simple mass balance approach assumes. As shown in the analysis of the backward trajectories the wind field was not constant with height. This could result in CH_4 transport out of the region. Since it is not known where the highest CH_4 sources are in this region, it could be that the majority of the CH_4 was emitted in the south east and therefore no uniform CH_4 source distribution can be assumed. These reasons may have led to the negative calculated CH_4 fluxes.

3.4 Result comparison of all three research flights

In summary it was found that all three flights show very different conditions for calculating the areal CH_4 flux. During the research flight ORCA, clear along wind XCH_4 gradients were measured, whereas no explicit gradient was measured for the flights PIKE and WALLEYE. A XCH_4 gradient that is rather perpendicular to the wind direction is observed in flight WALLEYE. The wind field during the research flight ORCA was homogeneous, unlike the wind field during PIKE and WALLEYE.

During PIKE, strong wind shear is observed only in the easternmost parts of the flight pattern, with air masses lingering in one place. Strong vertical wind shear is present at all locations of the backward trajectories of WALLEYE. The mean wind speed for ORCA is ranging between 7.9 and 9.1 m s^{-1} , while the mean wind speed for PIKE is significantly lower with a range between 2.9 and 3.3 m s^{-1} . The mean wind speeds for WALLEYE are similar to ORCA with a range between 7.7 and 8.8 m s^{-1} . For the same CH_4 flux, the gradients become smaller at higher wind speeds.

The areal CH_4 fluxes covering multiple legs of WALLEYE and PIKE are lower than the fluxes for ORCA. The fluxes for the flight with the poorest conditions for the mass balance approach, based on the strongest wind shear of the wind field, result in the lowest estimated fluxes. Thus, WALLEYE has the lowest areal flux results compared to the other research flights. If the conditions are ideal for applying the mass balance approach, with strong large scale XCH_4 gradients, a homogeneous wind field and a high density of upwind and downwind measurement points, the calculated fluxes may be higher. The flux results for ORCA, PIKE and WALLEYE in comparison with other studies are discussed in the following [chapter 4](#).

Chapter 4

Discussion and Summary

The aim of this study was to quantify methane emissions from Arctic boreal wetlands. A simple mass balance approach was used, with data measured by an airborne lidar to detect greenhouse gases. In order to do this, three research flights, “ORCA”, “PIKE” and “WALLEYE” of the CoMet 2.0 Arctic campaign were analysed over the Hudson Bay Lowland as well as the Pimachiowin Aki and the Grass, Burntwood and Upper Churchill River wetlands. For this, XCH₄ measurements of the IPDA lidar CHARM-F were used. All three flights have different flight patterns. For ORCA, most of the flight pattern is along the wind direction, whereas PIKE and WALLEYE were planned to have multiple flight legs perpendicular to the wind direction. One of the key objectives of this study was to analyse how the XCH₄ is distributed across the wetland region. For all three research flights large scale XCH₄ gradients were observed. Therefore, the first research question of how the XCH₄ is distributed across the Hudson Bay Lowland and surrounding wetlands can be answered as follows:

XCH₄ gradients along the wind direction were measured during the research flight ORCA. The analysis performed as part of this thesis shows that the conditions for measuring CH₄ fluxes for the research flight ORCA were ideal, with a homogeneous and consistent wind field. The flight pattern consists of two along-wind legs (part 1 and part 2) and two perpendicular across-wind legs. Unlike the other flights, ORCA did not include a dedicated upwind leg perpendicular to the wind direction. Instead, the upwind region was defined to cover data points from sections of the along-wind legs, allowing for flux calculations despite the lower data density in that region. The different setup of the flight pattern did not influence the flux calculations. An average areal CH₄ flux of $1.16 \pm 0.16 \text{ kg km}^{-2} \text{ h}^{-1}$ was calculated for ORCA. The homogeneity and consistency of the wind direction leads to high confidence in the areal CH₄ distribution.

Different to ORCA, the XCH₄ gradients for WALLEYE and PIKE are not consistently orientated along the wind, at least not for the entire region. For WALL-

EYE, the gradient is more perpendicular to the wind direction, which has increasing concentrations from north-west to south-east. The backward trajectories of WALL-EYE show strong vertical wind shear. Near-surface air masses did not follow a steady, straight flow, but moved in a circular pattern. This motion kept the air longer over areas emitting CH_4 , allowing CH_4 to accumulate rather than disperse. As a result, the distribution of CH_4 deviated from the expected transport along the wind.

Prior to the flight PIKE, air masses remain in the same area and linger around for the easternmost trajectories. PIKE exhibits a reasonable homogeneous wind field, whereas the wind field for the research flight WALLEYE for calculating CH_4 fluxes were found to be rather inhomogeneous. The wind shear may have caused CH_4 to be transported into the main flow over the duration of the research flight, as some air masses circulate over regions of stronger CH_4 emissions. This is a possible explanation of the missing along wind XCH_4 gradient. Additionally an inhomogeneous source distribution of CH_4 might also influenced the lack of the along wind gradient.

Wetland emission have a spatial and temporal variability due to atmospheric conditions like temperature, precipitation and radiation. In the Hudson Bay Lowlands, very few CH_4 emission measurements exist, and those that do are often localized rather than representative of the entire region. As a result, there is a lack of information on the broader spatial variability of CH_4 fluxes. The map of estimated CH_4 emissions from the WetCHARTs v1.3.1 model from August 2022 (see figure 4.1) shows an increased CH_4 flux distribution with hotspots over the wetlands investigated here.

The wind field is inhomogeneous and inconsistent for PIKE and WALLEYE, nevertheless CH_4 fluxes are calculated. The calculated fluxes over the upwind and downwind region covering multiple legs of $0.58 \pm 0.13 \text{ kg km}^{-2} \text{ h}^{-1}$ and $0.06 \pm 0.02 \text{ kg km}^{-2} \text{ h}^{-1}$ for PIKE and WALLEYE respectively are therefore not generally representative of the region covered by these flights. The simple mass balance approach is limited for inhomogeneous CH_4 source distribution and a inhomogeneous wind field such as during PIKE and WALLEYE. For homogeneous wind conditions and a uniform distribution of CH_4 sources, representative fluxes can be calculated, e.g. for ORCA. With WetCHARTs, a mean CH_4 emission can be estimated for each region covered by the flight pattern:

Region	ORCA	PIKE	WALLEYE
WetCHARTs mean methane flux	1.32	1.23	1.14

Table 4.1: The mean WetCHARTs methane fluxes for the regions covered by the flights are given in $\text{kg km}^{-2} \text{ h}^{-1}$ respectively for each research flight.

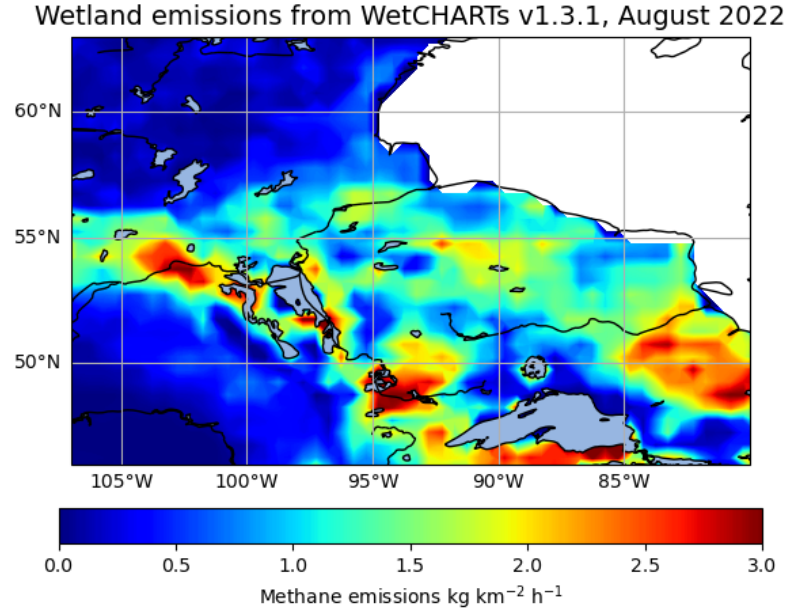


Figure 4.1: Methane emission distribution over North America from the WetCHARTs v1.3.1 model from August 2022 (Bloom et al. (2017)). Inhomogeneous CH_4 emission distributions over the wetlands are visible.

To answer the second research question, whether it is reasonable to assume a constant wind within the pbl, a performance analysis of ERA-5 was conducted. For this, ERA-5 vertical profiles of wind speed, potential temperature and relative humidity are compared with in situ vertical profiles from dropsondes, radiosondes and the BAHAMAS in situ data. In general, the ERA-5 and in situ vertical profiles are in reasonably good agreement, with a small tendency to overestimate the pbl height in the ERA-5 vertical profiles compared to the in situ vertical profiles. However, this is not an unusual phenomena in comparisons between ERA-5 and in situ data (Sinclair et al. (2022)). Nevertheless, no general major overestimation can be observed in the vertical profiles. The used ERA-5 wind information, thus, can be assumed to represent the prevailing atmospheric state fairly well.

The parcel approach as well as the humidity approach to derive the pbl height have limitations for a non-well mixed convective pbl. The pbl height increases as the sun rises and solar radiation intensifies. This makes it difficult to calculate a representative pbl height. Since the parcel method estimates the pbl height rather at the low end and the humidity approach at the high end especially when clouds are present, averaging over the four pbl heights is assumed to provide a more reliable pbl height. This also should hold true for the averaged wind speed within the pbl. The largest deviation between the minimum and maximum pbl heights determined

with the four approaches is less than 290 m for all three flights. As shown in the in situ vertical profiles, the wind speed profiles do not have strong gradients within 290 m, resulting in no strong deviation of wind speed for different pbl heights. This leads to the assumption that the averaged wind speeds within the pbl represent quite realistic values.

One simplification for the mass balance approach has to be done in this study: Constant wind speed and direction within the pbl is assumed for the duration of the flight time. The research flight, for which the most homogeneous wind field was found, results in the largest along-wind XCH_4 gradient. This emphasises that, if all the basic assumptions (as described in chapter 2.3) are met, large scale XCH_4 gradients can be measured with CHARM-F from which CH_4 emissions can be calculated. The applicability of the mass balance approach used in this study is limited by an inhomogeneous wind field. However, fluxes are calculated by assuming a constant wind direction within the pbl. The uncertainties associated with varying winds are estimated as described in section 2.3.3.

For small XCH_4 gradients measured over large areas, the measurement is sensitive to the single shot measurement of DAOD, since the single shot uncertainty for DAOD is about 5 %. This is represented in the error term distribution. One example is the error distribution for the upwind and downwind region covering several legs and their connecting parts of the research flight WALLEYE. A relative XCH_4 gradient of 0.05 % was measured resulting in a flux of $0.06 \pm 0.02 \text{ kg km}^{-2} \text{ h}^{-1}$. The highest relative error contribution comes from the integrated DAOD enhancement, $\delta\Omega$ which contributes 87 % to the total flux uncertainty. Because the gradient is so close to the detection limit, a small error in the measured gradients has a large effect on the calculated flux. This means that for small concentration differences, individual measurement outliers are given more weight. It is therefore advisable to average over many measurement points in order to eliminate these outliers by smoothing.

For CH_4 fluxes above approximately $0.95 \text{ kg km}^{-2} \text{ h}^{-1}$ the relative error of either the wind speed or the difference between the perpendicular distance between the upwind and downwind region and the along wind distance contributes the most to the flux error. Likewise, the flux between leg 2 and leg 3 for WALLEYE with $5.55 \pm 1.81 \text{ kg km}^{-2} \text{ h}^{-1}$, where the difference between Δx and the along wind distance is the largest relative error contributor with 81 %. The error for the enhancement of the distance-weighted DAOD average along the upwind and downwind leg, $\delta\Omega$ contributes with only 18 % to the total flux uncertainty. The wind speed variation contributes with 1 % and the error in $\Delta\sigma_{\text{CH}_4}$ with less than 1 %.

The error distribution of the flux between leg 1 and leg 3 for PIKE of $0.97 \pm 0.1 \text{ kg km}^{-2} \text{ h}^{-1}$ is similar to the error distribution of WALLEYE leg 2 to leg 3. The

uncertainty in the wind speed attributes with about 53 %, the $\delta\Omega$ with 41 %, the error in the differential absorption cross section with 2 % and the uncertainty in the relative wind direction with about 3 %. These two examples of error contributions are rather similar to the values expected from other studies like [Wolff et al. \(2021\)](#). [Wolff et al. \(2021\)](#) studied the data of the anthropogenic point sources of CO_2 measured by CHARM-F during the CoMet 1.0 campaign. A mass balance approach was used to determine CO_2 fluxes. Here the uncertainty in the determination of the integrated enhancement of the DAOD signal accounts for 2/10 of the flux error. The mean horizontal wind speed contributes with 7/10 and 1/10 is attributed by the mean differential absorption cross section and the relative wind direction taken together. This underlines that the uncertainty contribution for this study is realistic and comparable to other studies.

The flux uncertainties depend strongly on the reliability of the DAOD single shot measurement. If many data points are averaged and strong gradients are observed, the integrated DAOD enhancement uncertainty is small compared to the wind speed and the directional deviation. Hence, the reliability of the data depends on the repetition rate of the single shot measurements and the CH_4 emission accumulation along the wind direction. Additionally, the error increases when the upwind and downwind region are not orientated perpendicular to the wind direction. This is observed for all three research flights. In order to apply the mass balance approach used in this study, it is advisable to orientate the upwind and downwind legs of the research flights perpendicular to the wind direction.

However, for larger fluxes exceeding $0.95 \text{ kg km}^{-2} \text{ h}^{-1}$ the flux results are generally less prone to error. Considering all CH_4 fluxes of the three flights, for the majority of the fluxes the error amount of the total flux result are below 30 %. For fluxes of more than $0.95 \text{ kg km}^{-2} \text{ h}^{-1}$ the mean uncertainty amount of the total flux is about 15 %. For smaller fluxes error ratios of up to 360 % have been estimated.

A positive flux between the upwind and downwind region is calculated for ORCA and all leg gaps of WALLEYE, except the fluxes including leg 5. The calculated CH_4 fluxes for PIKE are only positive between leg 1 to leg 2, leg 1 to leg 3 and for the upwind and downwind region covering several legs. The values for the positive fluxes are between $0.06 \pm 0.02 \text{ kg km}^{-2} \text{ h}^{-1}$ for the flux between the upwind and downwind region including multiple legs of WALLEYE and $5.55 \pm 1.81 \text{ kg km}^{-2} \text{ h}^{-1}$ for the leg gap 2 to 3 in WALLEYE. The majority of the positive fluxes are between about 1 and $2 \text{ kg km}^{-2} \text{ h}^{-1}$. [Pickett-Heaps et al. \(2011\)](#) quantified CH_4 emissions over the Hudson Bay Lowland by using the GEOS-Chem chemical transport model to simulate aircraft measurements together with continuous 2004–2008 surface observations at Fraserdale (southern edge of Hudson Bay Lowland) and Alert (Arctic background). In this study a yearly CH_4 emission within the Hudson Bay Low-

land of 2.3 Tg yr^{-1} was modelled. This is equivalent to $0.82 \text{ kg km}^{-2} \text{ h}^{-1}$ assuming a year with 8766 hours and the areal extent of the Hudson Bay Lowlands of about $320\,000 \text{ km}^2$. As [Pickett-Heaps et al. \(2011\)](#) states the results are significantly higher than previous estimates for the region. The higher flux results in [Pickett-Heaps et al. \(2011\)](#) study also account for constant fluxes over the course of the year, which have not been taken into account in this study. 1990 the airborne and ground campaign ABLE-3B/NOWES estimated CH_4 emissions of $0.18 \pm 0.11 \text{ kg km}^{-2} \text{ h}^{-1}$ ([Roulet et al. \(1994\)](#)). With inverse methods to interpret observations from the Alert and Fraserdale Canadian sites [Worthy et al. \(2000\)](#) obtained CH_4 emissions of 0.07 to $0.18 \text{ kg km}^{-2} \text{ h}^{-1}$. The smaller fluxes from [Roulet et al. \(1994\)](#) and [Worthy et al. \(2000\)](#) compared to [Pickett-Heaps et al. \(2011\)](#) can be explained by gradients of CH_4 emission within the Hudson Bay Lowlands that were not accounted for in the previous studies.

Another study analysing modelled thermokarst-lake ($> 60^\circ$ North) fluxes from flux observations, estimated a mean annual CH_4 flux of between 12 and $43 \text{ g}^2 \text{ m}^{-1} \text{ yr}^{-1}$ ([Matthews et al. \(2020\)](#)). This equals to about 1.37 to $4.91 \text{ kg km}^{-2} \text{ h}^{-1}$. The substantially lower values in the early studies compared to the recent studies, can be explained by considering the climate change and the increased ice-free season in the Arctic the wetland CH_4 emissions rose between 1994 and 2011 ([Wik et al. \(2016\)](#)). Previous studies have omitted certain fluxes within the wetlands and have extrapolated the results differently to the scale of the Hudson Bay Lowlands. All the studies presented above confirm that the fluxes measured and calculated in this study with fluxes between 0.06 and $5.55 \text{ kg km}^{-2} \text{ h}^{-1}$ are realistic and comparable to other studies.

The above mentioned studies either modelled or integrated and weighted the in situ fluxes over the respective region. To verify the magnitude of the measured CH_4 fluxes, they are compared with anthropogenic sources. Although, the flux results derived from wetlands are significantly lower compared to the anthropogenic point sources.

[Fiehn et al. \(2020\)](#) used in situ data from the first CoMet campaign to estimate CH_4 emissions from coal mining and industrial activities in the Upper Silesian Coal Basin with a airborne based mass balance approach. Anthropogenic flux calculations always strongly depend on the emission output of the source. Comparing wetland fluxes to anthropogenic CH_4 emissions the results of anthropogenic sources can deviate strongly not only by the emission rate of the source, also by the wind direction in which the trace gas is transported. Comparing anthropogenic emissions with wetland emissions is only useful for estimating the magnitude of methane emissions from wetlands. For the entire Upper Silesian Coal Basin, fluxes between an upwind and downwind region of about $13.8 \pm 4.3 \text{ kg s}^{-1}$ (equals $49\,680 \pm 15\,480$

kg h^{-1}) for the first flight and $15.1 \pm 4.0 \text{ kg s}^{-1}$ (equals $54\,360 \pm 14\,400 \text{ kg h}^{-1}$) for the second flight were found.

The in this study calculated minimum flux of $0.06 \text{ kg km}^{-2} \text{ h}^{-1}$ can be converted to a flux of $10\,401.3 \text{ kg h}^{-1}$ for an area of about $173\,355 \text{ km}^2$ (equivalent to the averaged leg length of 195 km^2 multiplied by the leg distance 889 km^2). Converting the maximal flux measured in this study of $5.55 \text{ kg km}^{-2} \text{ h}^{-1}$ between the upwind and downwind region area of 7020 km^2 (equivalent to the averaged leg length 195 km^2 multiplied by the leg distance 36 km^2) gives $38\,961 \text{ kg h}^{-1}$. The fluxes measured for an agglomeration of anthropogenic point sources can be significantly higher than the flux determined for the wetlands. However, they are of the same order of magnitude. Thus, the third research question, whether the calculated CH_4 fluxes are comparable to other studies, can be answered with yes, they are.

In summary, this study presents the measured CH_4 gradients over the boreal wetlands of the Hudson Bay Lowland and surrounding areas using CHARM-F. From the gradients measured XCH_4 gradients, fluxes were calculated using a simple mass balance approach. Not all calculated areal fluxes appeared to be positive due to the absence of an along-wind XCH_4 gradient. The observed positive fluxes, range from 0.06 to $5.55 \text{ kg km}^{-2} \text{ h}^{-1}$. These findings are consistent with recent studies. The lower flux results in earlier studies compared to today's studies reflect improvements in measurement techniques as well as the increase in wetland emissions in the context of climate change due to warmer water temperatures ([Wik et al. \(2016\)](#)).

Chapter 5

Conclusions and Outlook

The study revealed challenges of using the mass balance approach. However, the uncertainties are rather small for measurements for appropriate meteorological conditions and fulfilled assumptions of a homogeneous wind field, uniform distribution of CH₄ sources and all basic assumptions described in section 2.3. This gives great hope that the measurement technique can be used to quantify CH₄ emissions on a large scale in order to verify CH₄ emission inventories. Big advantages of the IPDA-lidar measurement technique employed in this study compared to in situ measurements are: 1) the large spatial resolution over large areas as it is a remote sensing technique, 2) CHARM-F measures regardless of ground accessibility of in situ measurements, 3) high accuracy of the single shot DAOD value of about 5% 4) the method is applicable to satellite measurements, allowing global measurements to be taken at any time of day or night. The measurement technique described in this study for quantifying CH₄ emissions over boreal wetlands can be used to improve process-based wetland models. Nevertheless, ongoing research will be essential as global temperatures rise and wetland ecosystems are subject to change.

The relative error distribution of the calculated CH₄ fluxes show the sensitivity in Ω for outliers of the measured DAOD. To obtain more reliable data, averaging over more data points can help to minimize the effects of random fluctuations and outliers. Therefore the repetition rate of the measurement should be increased or more flight legs should be flown within the region. Averaging over more data points results in data sets with no or fewer outliers. And therefore leads to a clearer and more accurate representation of the underlying patterns or trends like gradients.

For CH₄, which accumulates along the wind direction, the calculated fluxes are positive. The range of the positive fluxes are between $0.06 \pm 0.02 \text{ kg km}^{-2} \text{ h}^{-1}$ and $5.55 \pm 1.81 \text{ kg km}^{-2} \text{ h}^{-1}$. However, also negative fluxes were calculated. Overall, the results are comparable to other studies calculating CH₄ fluxes from in situ measurements and modelling.

To calculate CH₄ fluxes using the mass balance approach, wind information

within the pbl is necessary. In this study, ERA-5 data were used to estimate the wind field. In order to determine the reliability of these ERA-5 data, a performance analysis is conducted. This analysis shows that the vertical profiles of the ERA-5 data and the in situ vertical profiles measured by either radiosondes, dropsondes or sensors onboard the HALO aircraft agree well. Therefore, the ERA-5 reanalysis data are considered appropriate for the calculation of averaged wind direction and speed within the pbl.

However, wind shear is observed in the backward trajectories produced with the HYSPLIT model. Wind shear has been considered as a possible explanation for the lack of strong along-wind XCH_4 gradients during the PIKE and WALLEYE research flights. Due to wind shear, different layers of the atmospheric column originated from different transport pathways, leading to a mixing of air masses with varying CH_4 concentrations. Additionally, near-surface air masses followed non-linear trajectories, with some recirculating or lingering over areas of strong CH_4 emissions. This resulted in localized accumulation and disrupted the expectation of a clear along-wind gradient in the total column measurements.

Potential hotspots in the Hudson Bay Lowlands and the surrounding wetlands, affects the CH_4 distribution. A combination of wind shear and the inhomogeneous distribution of CH_4 emission sources are potential reasons for the XCH_4 gradient perpendicular to the wind. To prove this and to detect potential hotspots more flights within the region of interest and additional more vertical wind measurements should be conducted. Moreover, a nadir viewing wind lidar could be additionally mounted to the aircraft to remotely sense the 3D wind field along the flight track.

The simple mass balance approach applied in this study is limited by the inhomogeneous wind field. To better understand the CH_4 source distribution and to calculate fluxes also for times when wind conditions are not homogeneous and consistent, simulations of the CH_4 emission would be beneficial. As seen in the HYSPLIT analysis, the inhomogeneous wind field can be simulated and therefore used in inverse modelling to quantify the observed CH_4 fluxes. This is a great advantage, as the simple mass balance approach is limited by the inhomogeneous wind fields and the inhomogeneous CH_4 emission source distribution.

In order to minimise the error in the perpendicular distance to the upwind and downwind regions and the distance between the regions along the wind, the upwind and downwind regions must be selected to be aligned along the wind. Multiple parallel flight legs that are close to each other along the wind direction should be conducted. Therefore, the orientation of the upwind and downwind region can be set after analysing the actual wind direction. This would help to minimise the error, as it is difficult to forecast the actual mean wind direction over the area.

With these improvements the uncertainties of the calculated fluxes would de-

crease and the data accuracy increase. In order to analyse and prove the reliability of the boreal wetland emissions of the Hudson Bay Lowlands more remote sensing campaigns flying in perpendicular patterns to the wind direction are needed. In any case, a better understanding and quantification of global wetland emissions is required to understand the CH_4 cycle and its influence on climate.

Currently, DLR plans another campaign focussing on wetland XCH_4 : In 2026 a similar field experiment (CoMet 3.0 Tropics) shall take place in South America using the same instrumental payload. Similar to the Hudson Bay Lowlands, the wetlands in South America are also difficult to access, resulting in a lack of reliable greenhouse gas flux estimates. Additionally, the convective cloud cover makes it difficult for passive satellite instruments to measure greenhouse gases. CoMet 3.0 Tropics in 2026 will focus on tropical conditions in order to further learn and improve CHARM-F measurements. The CoMet series of campaigns thus also serves as preparatory activities for the first CH_4 lidar satellite mission MERLIN foreseen for launch in about 2029. The methods derived within this thesis do not only show potential for airborne but also for spaceborne IPDA measurement from this satellite mission. This study used the measured large scale CH_4 emissions by CHARM-F and calculated the resulting CH_4 flux. The MERLIN mission will benefit from these findings, as understanding the method's limitations will serve as valuable preparation for identifying CH_4 emission sources and hotspots.

Campaigns such as the CoMet 2.0 Arctic campaign provide a valuable contribution to the verification of CH_4 emission inventories and satellite measurements. Nowadays it is crucial to understand the CH_4 sources for the global budget in order to minimise uncertainties in the methane budget. Knowledge of CH_4 emissions prepare for further climatological changes and provides a rationale for action against climate change, as CH_4 is one of the most potent greenhouse gases.

Appendix A

Detailed ERA-5 performance analysis

A.1 ERA-5 performance analysis research flight "ORCA"

In this section the performance of ERA-5 compared to the in situ vertical profiles of the dropsonde, radiosonde and BAHAMAS is assessed. The section starts with going through the dropsonde profiles of relative humidity, potential temperature and wind speed. The analysis of the radiosonde profiles will follow. At the end of this section is the analysis of the ascent and descent profiles of BAHAMAS.

The first dropsonde was released at about 9:44 CDT which was less than 45 minutes before the time period of the CHARM-F data analysed in this study. The second dropsonde was released at 11:09 CDT, the third at 13:14 CDT and the fourth was released at 14:21 CDT, thus, immediately after the CHARM-F measurements studied for ORCA.

In the following, the vertical profiles of the dropsondes are analysed by examining the different parameters, starting with the relative humidity profiles, followed by the potential temperature and wind speed profiles.

In the vertical relative humidity profiles of the first two dropsondes (figure [A.1 1](#)), [2](#))), the strongest negative gradient in humidity is about 125 m lower than the ERA-5 vertical profile. In the third dropsonde profile no negative gradient below 2000 m can be identified for the dropsonde data (figure [A.1 3](#))). The fourth dropsonde and ERA-5 vertical relative humidity profile align well and the pbl height can be estimated at the same height within only a few meters deviation. The ERA-5 BLH pbl height is at different heights for all four profiles. For the first dropsonde profile, the mean ERA-5 BLH pbl height is slightly above the pbl height of the ERA-5 and the dropsonde identified with the humidity approach (figure [A.1 1](#))). For the

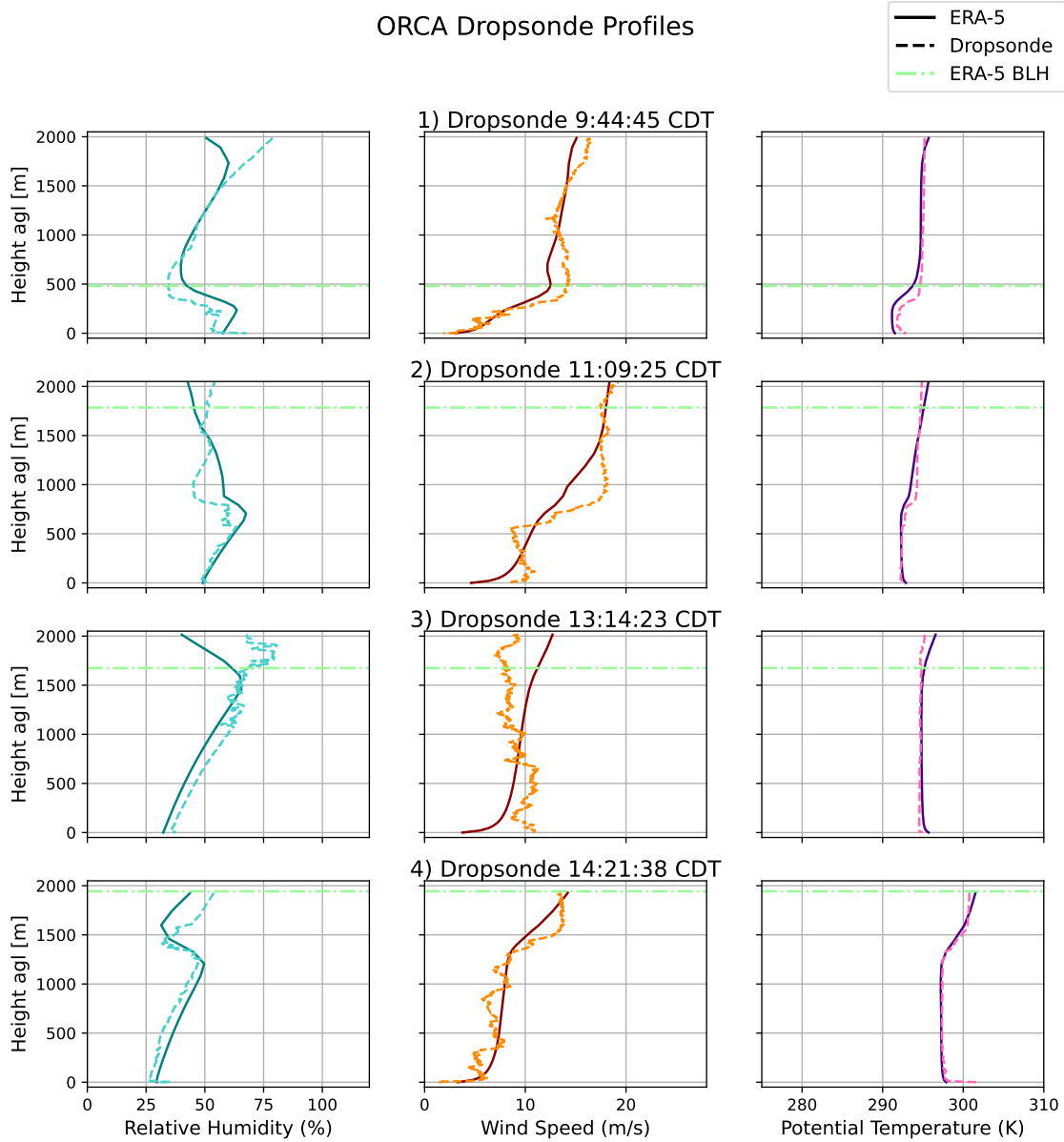


Figure A.1: The four dropsondes released at 9:44 CDT, 11:09 CDT, 13:14 CDT and 14:21 CDT. Vertical profiles with height above ground of the in situ measurements compared to the ERA-5 interpolated data. The solid line represents the ERA-5 data interpolated in location and time. The dashed line represents the vertical profiles of the dropsonde. The green dashed line denotes the ERA-5 BLH pbl height. In general the ERA-5 vertical profile trend tend to follow the in situ measurements.

second and fourth dropsondes, the ERA-5 BLH pbl height is above the pbl height estimated with the humidity approach for the ERA-5 and dropsonde profile. For the third dropsonde, the ERA-5 BLH pbl height is about 150m below the pbl height identified in the ERA-5 vertical profile (figure A.1 3)). In summary, it can be said that the ERA-5 vertical profiles result in a higher pbl height than the dropsonde

profiles, except for the third profile. The ERA-5 BLH pbl height does not show any trend of over- or underestimation of the pbl height identified by the ERA-5 or dropsonde vertical profile.

For the identification of the pbl height with the potential temperature profiles the parcel method is used. The PBL height can be determined once the surface potential temperature is reached during the ascent. It is not easy to visually determine the pbl height with the parcel method. For the position of the first dropsonde, the ERA-5 vertical profile results in a pbl height of about 450 m (figure A.1 1)). The dropsonde data indicates the pbl height at about 350 m. The ERA-5 BLH pbl height (green horizontal line in figure A.1 1)) is at about 500 m, which is higher than the pbl height of ERA-5 or the dropsonde vertical profile. The second and fourth profile show similar results with the ERA-5 pbl height being at about the same height as the dropsonde pbl height. For the second dropsonde the ERA-BLH pbl height is about 900 m higher than the pbl height derived using the parcel approach with the ERA-5 or dropsonde vertical profile. The ERA-5 BLH pbl height is also higher than the pbl height determined with ERA-5 and the dropsonde in the fourth dropsonde potential temperature profile (A.1 4)). Only in the third dropsonde profile the ERA-5 BLH pbl height is lower (about 100 m) than the pbl height identified from the ERA-5 and dropsonde vertical profile. In general, the ERA-5 vertical profiles agree well with the dropsonde profiles. Using the parcel approach for the ERA-5 and dropsonde data to identify the pbl height results in rather lower pbl heights compared to the ERA-5 BLH pbl height. However, the humidity approach and the parcel approach result in similar altitude levels for the pbl height.

The wind speed profiles are only used for the performance analysis of ERA-5 not the pbl height identification approaches. In the second and third dropsonde vertical profile for wind speed the surface wind of ERA-5 is lower than for the in situ measured wind speed (figure A.1 2), 3)). For all ERA-5 vertical profiles the wind speed increases with height. Likewise for the dropsonde vertical profiles, except the third. For the third dropsonde profile the wind speed decreases with height (figure A.1 3)). For the first and fourth dropsonde the vertical profiles of the ERA-5 and the dropsondes agree reasonable well. In the second vertical dropsonde profile a wind speed minimum at about 550 m and a maximum at about 900 m is present, where the ERA-5 vertical profile increases linearly (figure A.1 2)). Since the wind speed will be averaged within the pbl, the lower surface wind speeds of ERA-5 compared to the dropsonde might cancel out within the pbl. In general it can be said that the higher the pbl height the higher the wind speed due to the increase of the wind speed with height. A trend towards higher or lower averaged wind speeds within the pbl between the ERA-5 and the dropsonde data can, however, not be identified.

The radiosonde releases from Pickle Lake are used here for an additional perfor-

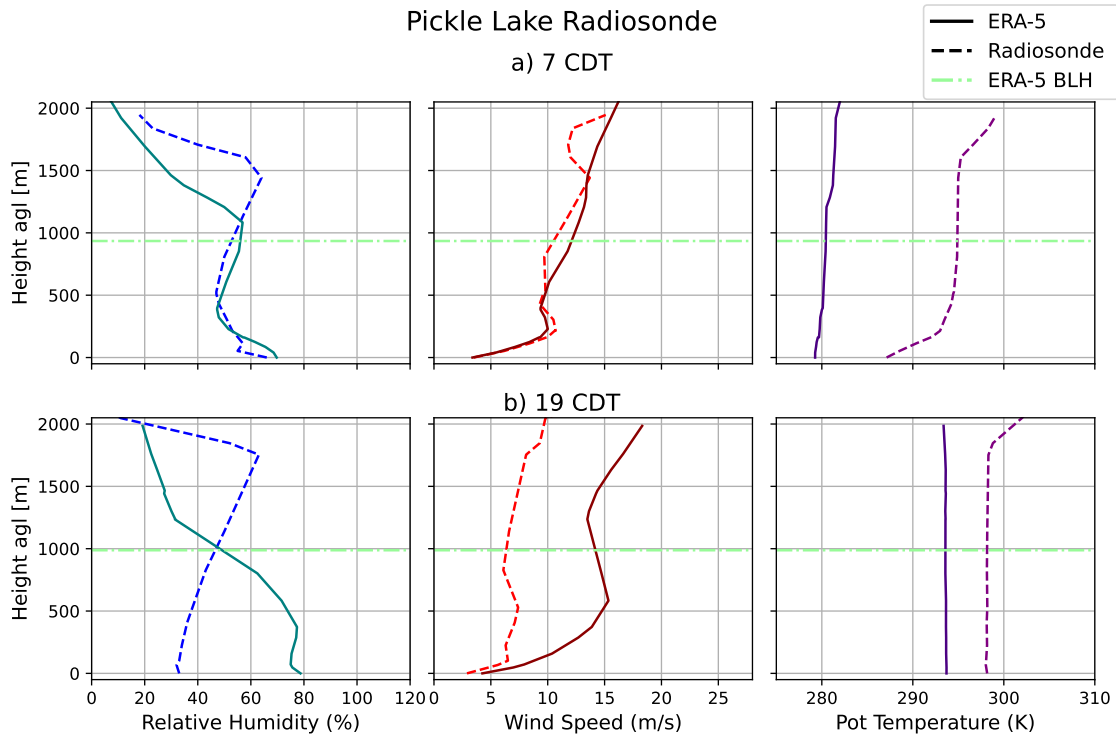


Figure A.2: Radiosonde releases at Pickle Lake at 07:00 CDT and 19:00 CDT, illustrating vertical profiles for relative humidity, wind speed, and potential temperature. The dashed line represents the radiosonde vertical profile, while the solid line indicates the ERA-5 vertical profile. The green dashed dotted line refers to the ERA-5 BLH pbl height. Both radiosonde profiles and ERA-5 show an increase in wind speed with height, suggesting that higher pbl heights correlate with higher wind speeds.

mance analysis. One radiosonde was released before the CHARM-F measurements analysed in this study at 7 CDT and a second one at 19 CDT after the CHARM-F measurements analysed in this study. The potential temperature vertical profiles of both radiosondes and ERA-5 are rather constant with height. For the radiosonde at 7 CDT the vertical profile of ERA-5 increases little with height by about 3 K, with the lowest potential temperature at the surface (figure A.2 a)). Therefore, the parcel method for identifying the pbl height can not be applied. The radiosonde profile also starts with a minimum at the ground increasing with height. However, ERA-5 and the radiosonde vertical profile have a bias at the surface potential temperature of about 9 K. Similarly for the 19 CDT radiosonde profile (figure A.2 b)). Here, the potential temperature vertical profile of ERA-5 is very constant with height. The radiosonde profile is up to 1800 m also very constant with height. However, the ERA-5 and the radiosonde vertical profile have a bias of about 5 K.

The relative humidity vertical profile of the 7 CDT radiosonde has its strongest negative gradient at about 1750 m. From the ERA-5 vertical profile the pbl height

can be identified at about 1250 m. However, the ERA-5 BLH indicates the pbl height just below 1000 m. Different trends can be observed for the the radiosonde released at 19 CDT. Here, the ERA-5 and radiosonde vertical profile show contradictory trends. The radiosonde starts with a low relative humidity at the surface and increases with height, whereas ERA-5 starts with a maximum relative humidity at the surface and decreases with height. The strongest negative gradient for ERA-5 can be identified at the same height as the ERA-5 BLH pbl height at 1000 m. The strongest negative gradient of the radiosonde is about 1000 m above the pbl height.

The wind speed profiles of ERA-5 and the radiosonde both start with roughly the same surface speed. At the 7 CDT radiosonde the ERA-5 and the radiosonde vertical profiles align up to 500 m (figure A.2 a)). The vertical profiles both increase with height and follow the same trend. The averaged wind speed within the pbl of the radiosonde and the ERA-5 will roughly be the same. Differently for the 19 CDT radiosonde release (figure A.2 b)), where the radiosonde and ERA-5 wind speed does not agree that well with height. Even though the ERA-5 and radiosonde start with approximately the same surface wind speed, the ERA-5 wind decreases more with altitude than the radiosonde. Therefore, the averaged wind speed within the pbl for the radiosonde will always be lower (approximately about $3 - 5 \text{ m s}^{-1}$) than ERA-5.

Overall it is found that the ERA-5 pbl height is rather higher than the radiosonde pbl height. However, no general over or underestimation of the ERA-5 wind speed within the pbl height can be identified. Nevertheless, the wind speed in both radiosonde profiles and the ERA-5 increases with height. Higher pbl heights would result in higher mean pbl wind speeds.

Between part 1 and part 2 of ORCA several ascents and descents of HALO were performed. The resulting 9 vertical profiles go down to about 500 m. No clear statement can be made about the pbl heights identified using the parcel approach, as no surface potential temperatures are given from the BAHAMAS vertical profiles. However, it can generally be said that all vertical profiles of BAHAMAS potential temperature agree reasonably well with the ERA-5 data. Looking at the relative humidity profiles the BAHAMAS data fluctuates significantly stronger than the ERA-5 data. However, the trends of the profiles are similar. An explicit pbl height can not be determined using the BAHAMAS vertical profile due to the fluctuations of the profile. Nevertheless, a strong negative gradient in the ERA-5 vertical profile indicates the pbl height, which is always below the ERA-5 BLH pbl height, except for the first descent. This implies an overestimation of the ERA-5 BLH pbl height.

The wind speed of ERA-5 and BAHAMAS do not deviate strongly from each other. For four vertical profiles (figure A.4 c), A.5 a), A.5 b), A.5 c)) the ERA-5 wind speed is lower than the BAHAMAS wind speed. For all of the vertical wind speed profiles the wind speed increases with height. A change in pbl height would

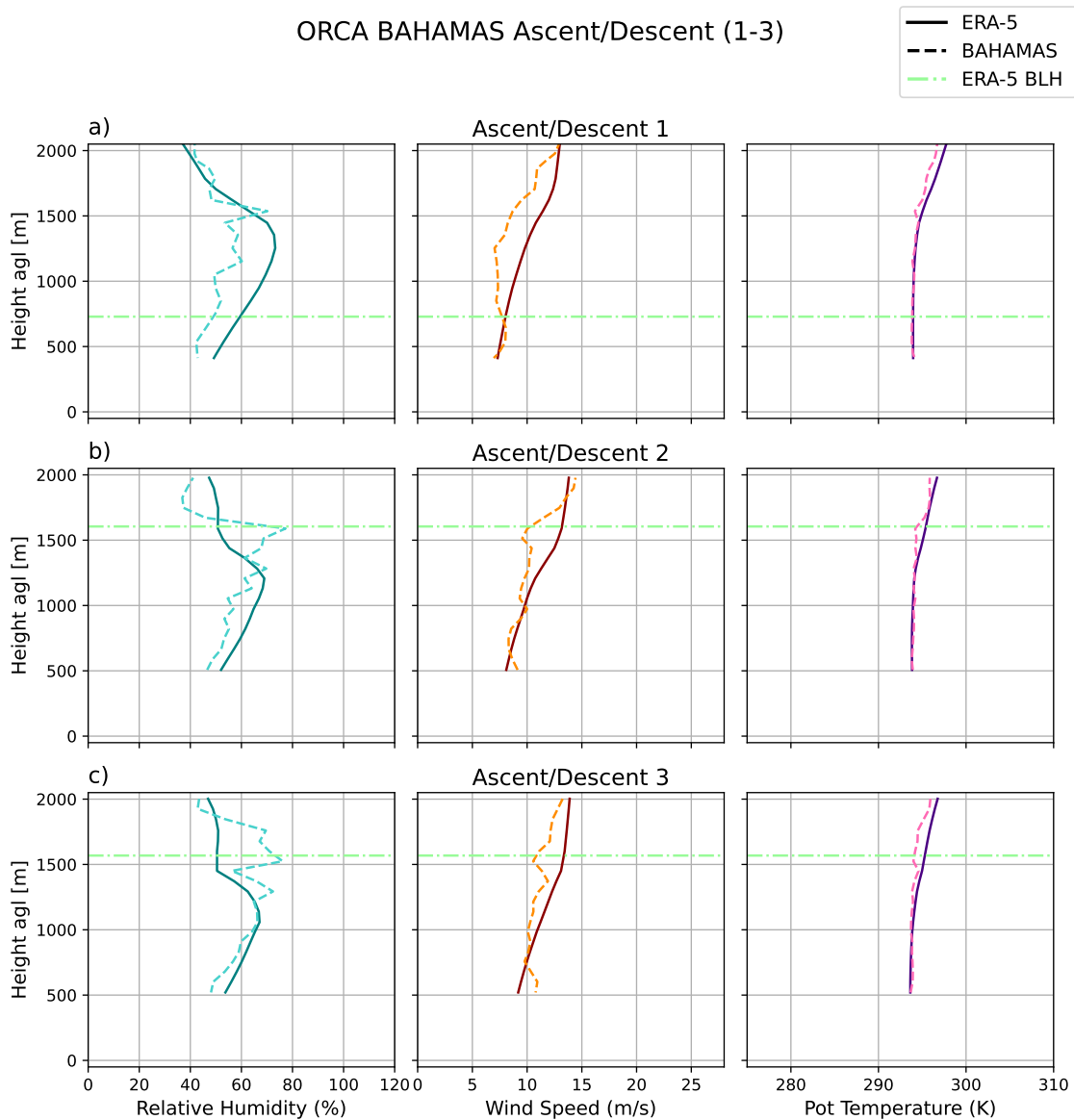


Figure A.3: Vertical profiles of the BAHAMAS ascent and descents (dashed line) with ERA-5 vertical profiles (solid line). The ERA-5 BLH product indicates the pbl height with a green dashed dotted horizontal line. The trends of the vertical potential temperature profiles of the BAHAMAS and ERA-5 data agree well. The relative humidity vertical profiles deviate more with no clear tendency of the ERA-5 vertical profile being above or below the BAHAMAS profile. The pbl height estimated by the humidity approach does not agree well with the ERA-5 BLH pbl height. The wind speed increases with height for both BAHAMAS and ERA-5.

not result in large differences between ERA-5 and BAHAMAS for the average wind speed within the pbl. The higher the pbl the higher the average wind speed due to the increasing profiles.

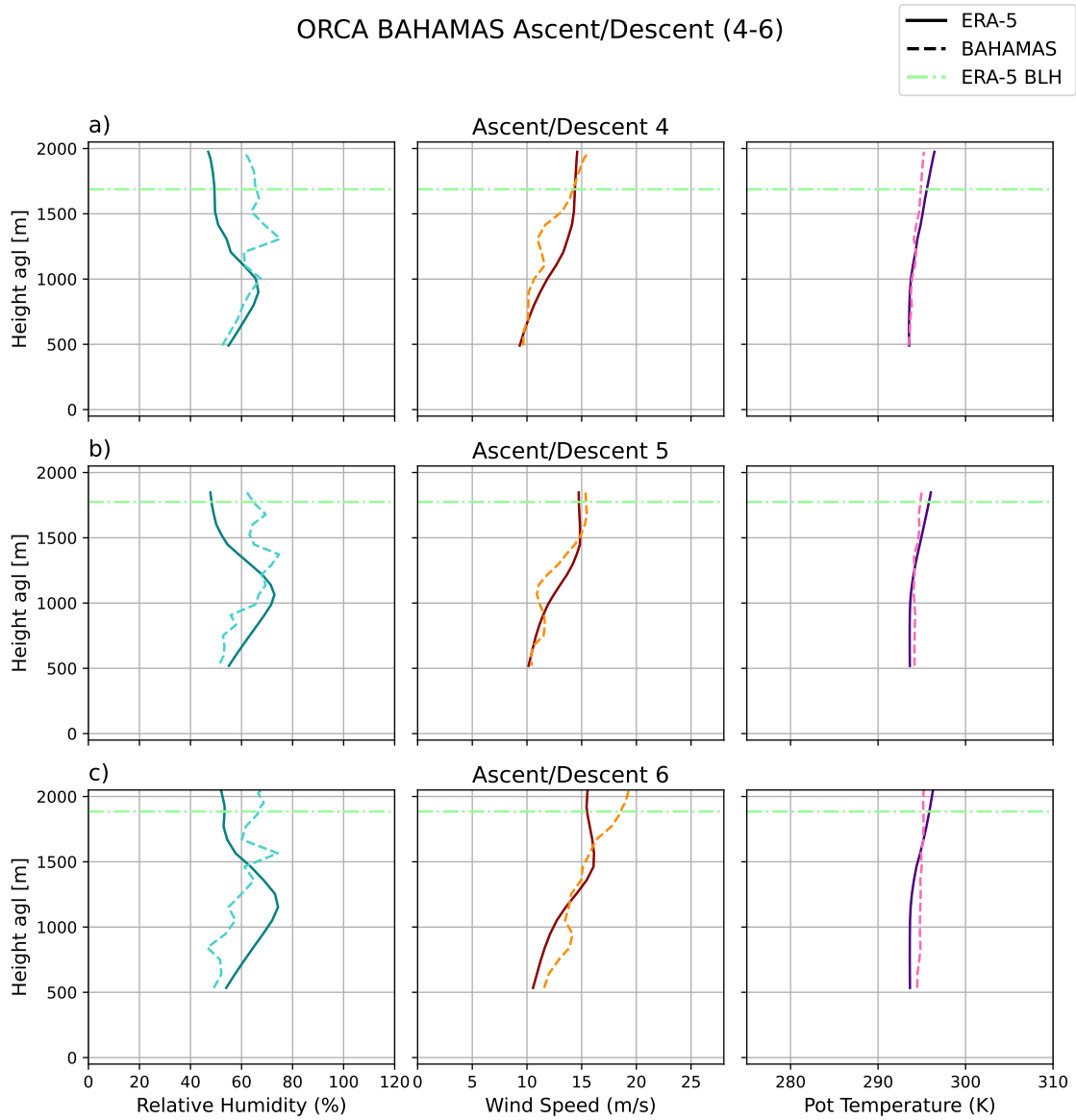


Figure A.4: Vertical profile of the BAHAMAS (dashed line) and ERA-5 (solid line) relative humidity, wind speed and potential temperature. The horizontal dash dotted green line represents the ERA-5 BLH pbl height. The potential temperature vertical profile of BAHAMAS and ERA-5 align very well. However, no statement about the pbl height using the parcel method can be done due to the absence of the surface temperature. The wind speed vertical profiles of ERA-5 and BAHAMAS align closely with an increase in the wind speed with height. For all three profiles the ERA-5 BLH pbl height is above the ERA-5 and BAHAMAS pbl height using the humidity approach.

In general, for the BAHAMAS vertical profiles it cannot be determined whether ERA-5 over- or underestimates the pbl height compared to BAHAMAS. On average the wind speed within the pbl for BAHAMAS and ERA-5 will not deviate strongly.

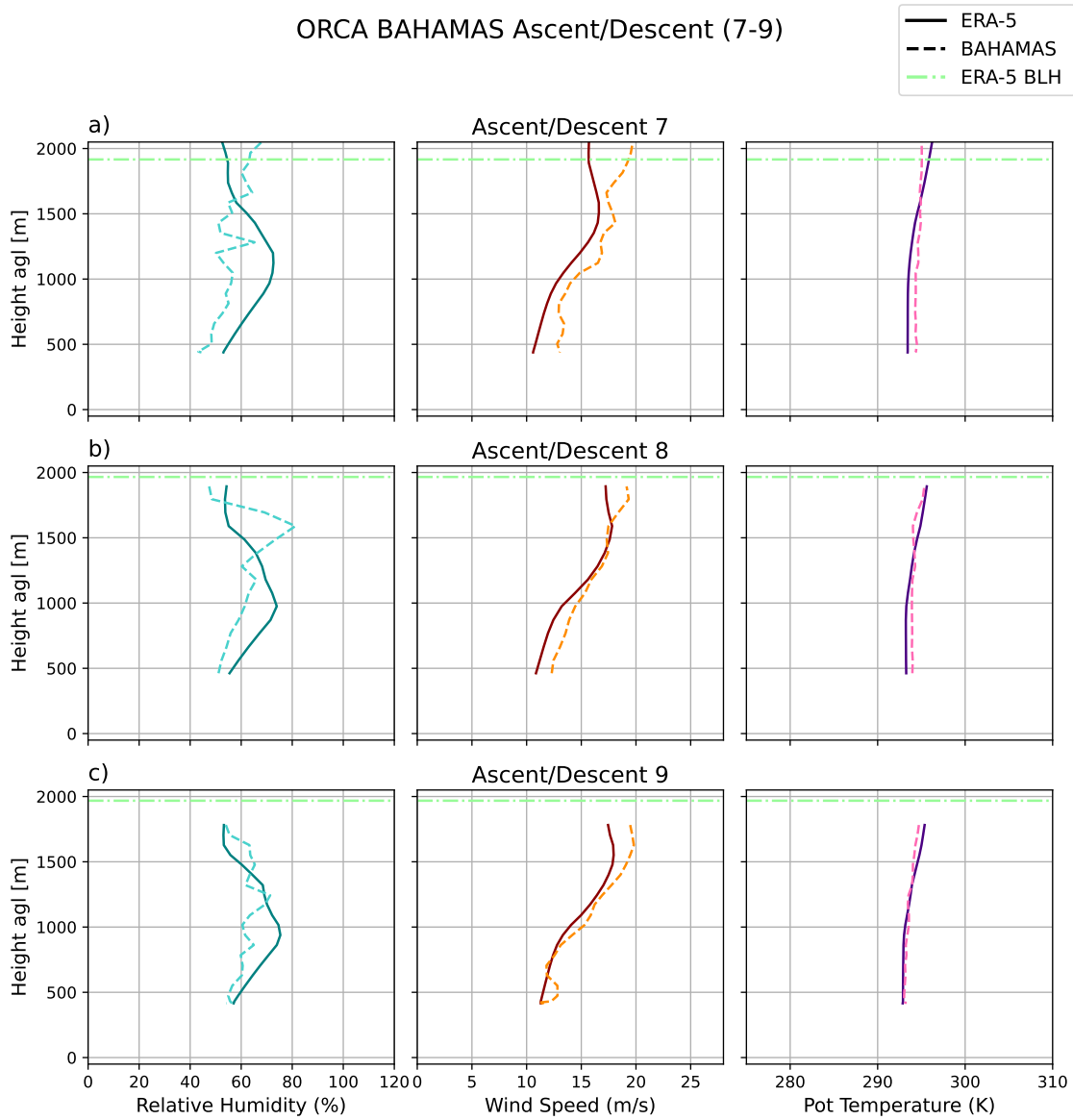


Figure A.5: Vertical profiles of the BAHAMAS ascent and descent data (dashed line) and the ERA-5 vertical profiles (solid line). The horizontal green dashed dotted line represents the ERA-5 BLH pbl height. As in the 6 profiles before the potential temperature vertical profiles align very well with each other. Due to the absence of the surface potential temperature the parcel approach can not be applied. The wind speed profiles increase with height very similarly to the profiles 1 to 6. The ERA-5 BLH pbl height is for all three profiles shown here significantly higher than the strongest negative gradient of the relative humidity vertical profiles.

A.2 ERA-5 performance analysis research flight "PIKE"

In the following the performance analysis will be done by going through the vertical profiles of the dropsonde measured meteorological parameters, starting with relative humidity, followed by potential temperature and wind speed.

The vertical profiles of the second and third dropsondes (figure A.6 2), A.6 3)) show only minor differences in their vertical profiles as they were released immediately after each other. Therefore, the following results are valid for both the second and third dropsonde release.

For the first dropsonde (figure A.6 1)) the pbl is still shallow at about 250 m when identifying the pbl height with the relative humidity approach of the dropsonde data. Whereas when using the ERA-5 data the pbl height is indicated with the strongest negative relative humidity gradient at about 350 m. The ERA-5 BLH pbl height is for the first dropsonde at about 500 m. As in the first dropsonde profile the relative humidity approach identifies the pbl height for the second and third dropsonde below the ERA-5 vertical profile. The dropsonde pbl height is at about 700 m, whereas the ERA-5 pbl height is at about 950 m and the ERA-5 BLH pbl height is at about 900 m. In all three relative humidity profiles is the ERA-5 vertical profile above the dropsonde profile and therefore results in higher pbl heights.

Using the parcel method for the potential temperature profile gives similar results to the humidity approach. The ERA-5 vertical profile shows higher pbl heights compared to the dropsonde data. The pbl height identified with the parcel method are very similar to the pbl height identified with the humidity approach.

The vertical wind speed profiles of the first dropsonde and ERA-5 are in good agreement, differing by only a few metres per second (figure A.6 1)). The difference between the two profiles is estimated to be less than 5 m s^{-1} . Up to the ERA-5 BLH pbl height the wind speed for both profiles increases. Above the ERA-5 BLH pbl height the wind speed profiles remain rather constant. Therefore, if the pbl height is at or above the ERA-5 BLH pbl height the averaged wind speed within the pbl height will be approximately the same. However, if the pbl height varies below the ERA-5 BLH pbl height the averaged wind speed decreases with decreasing pbl height.

For the second and third dropsonde the wind speed vertical profile of ERA-5 and the dropsonde do not align as closely as for the first dropsonde (figure A.6 2), 3)). Up to a height of about 500 m both profiles remain fairly constant with a slight increase of less than 3 m s^{-1} . Above 500 m, the dropsonde wind speed increases to its maximum, 12 m s^{-1} , at about 850 m. The ERA-5 wind speed starts to increase at about 750 m and reaches its maximum (12 m s^{-1}) at about 1250 m. For pbl heights

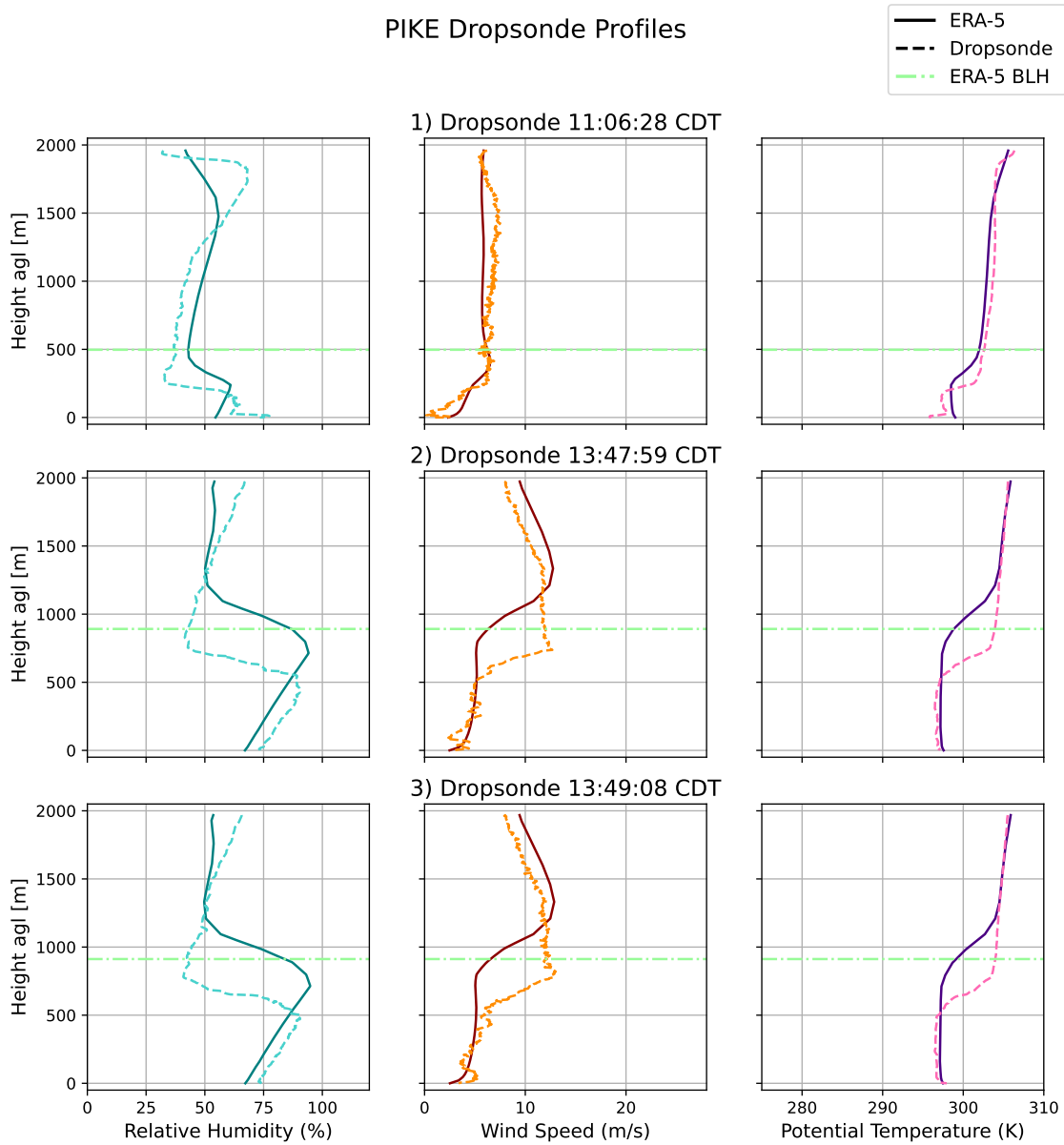


Figure A.6: Vertical profile of the three dropsondes released during the research flight PIKE. Relative humidity, wind speed and potential temperature are vertically expressed along height above ground. The solid line represents the ERA-5 data and the dashed line represents the dropsonde vertical profile. The green dashed dotted line shows the pbl height estimated by the ERA-5 BLH product. In general are the ERA-5 vertical profiles above the dropsonde profiles which leads to higher pbl heights. However no clear trend of a higher or lower wind speed for different pbl heights can be observed.

below 500 m the averaged wind speed within the pbl might be the same for ERA-5 and the dropsonde. Is the pbl height between 500 m and 1250 m the average wind speed within the pbl for the dropsonde will be slower than for ERA-5. Above 1250 m the average wind speed within the pbl might be the same for both, the ERA-5 and

the dropsonde.

For all dropsonde profiles, it can be generally concluded that the ERA-5 vertical profiles overestimate the pbl height compared to the dropsonde vertical profiles. However, the ERA-5 BLH pbl height is even above the identified pbl height of the vertical ERA-5 profiles. No general conclusion can be drawn regarding the average wind speed change within the pbl for varying pbl heights.

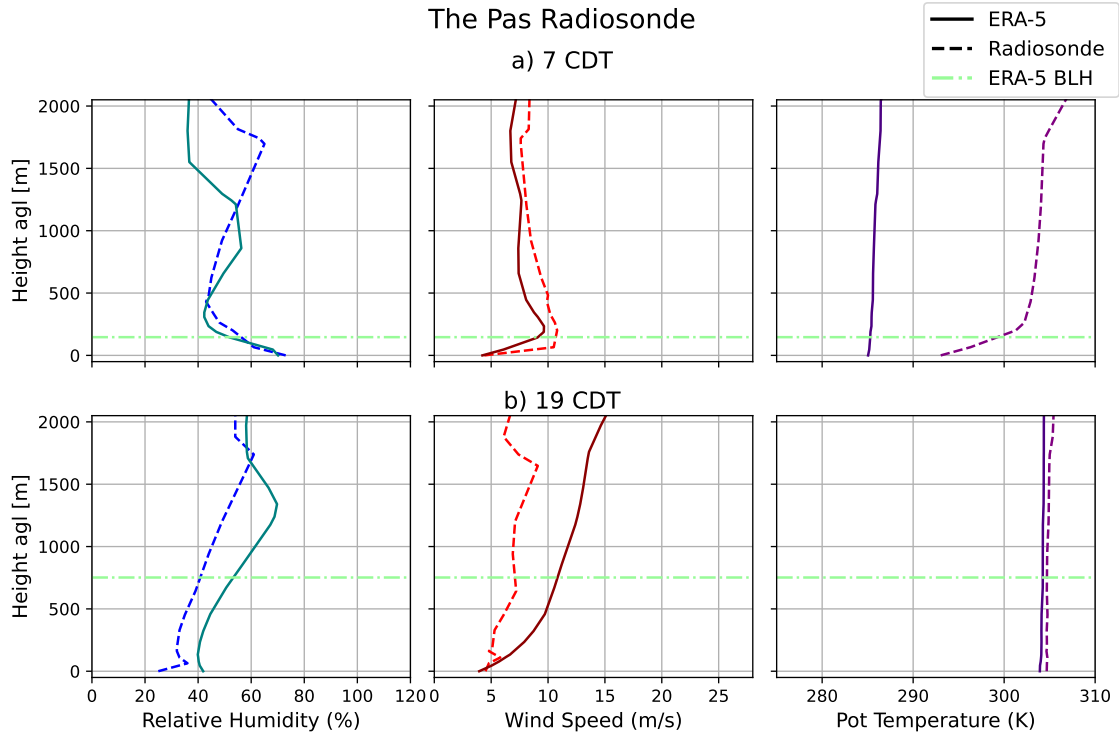


Figure A.7: Radiosonde vertical profile at the observatory The Pas. Solid line marks the ERA-5 vertical profile, dashed line the radiosonde profile. The green dashed dotted line represents the ERA-5 BLH pbl height. Upper graphs a) represent the radiosonde release at 7 CDT and the lower graphs b) are the vertical profiles for the radiosonde release at 19 CDT. The potential temperature vertical profiles have a bias between the radiosonde and the ERA-5 vertical profile. No pbl height with the parcel approach can be identified. For a) the strongest negative relative humidity gradient for the ERA-5 and the radiosonde data are at the same height as well as the ERA-5 BLH pbl height. Different in b), where there is no correspondence between the strongest negative gradient and ERA-5 BLH. With the vertical wind speed profiles no general conclusion can be drawn about the wind speeds within the pbl for different pbl heights.

Another in situ data resource for the ERA-5 performance analysis are the radiosonde releases at the observatory The Pas at 7 CDT and 19 CDT (figure A.7).

In order to define the pbl height using the parcel method the maximum potential temperature has to be at the surface. This is not the case for the radiosonde and ERA-5 potential temperature profiles. Using the parcel method, no reliable state-

ment can be made about the pbl height. There is a bias in the surface potential temperature between the radiosonde and ERA-5 for the 7 CDT radiosonde release of about 8 K. ERA-5 is about 8 K colder at the surface than the radiosonde. In the 19 CDT vertical profile of the potential temperature the bias in the surface potential temperature is only about 2 K. The vertical profile is constant with height at about 304 K. The agreement of the vertical potential temperature profiles differ for the different radiosonde releases.

For the 7 CDT radiosonde release (figure A.7, a)) the humidity approach indicates the pbl height for ERA-5, the radiosonde and the ERA-5 BLH at the same height. In the second profile at 19 CDT (figure A.7 b)), the ERA-5 pbl height is at about 1500 m and the radiosonde profile gives a pbl height of about 200 m. The ERA-5 BLH pbl height for the 19 CDT release is at 750 m. The large deviation of the height of the strongest negative gradient highlights the difficulty of identifying the height of the pbl with the humidity approach. The vertical profiles of potential temperature and relative humidity don't show any tendency of overestimation or underestimation between the ERA-5 and the radiosonde.

The vertical wind speed profile of the radiosonde released at 7 CDT increases from the surface to the height of the ERA-5 BLH pbl height. The radiosonde profile reaches its maximum with 12 m s^{-1} at about 100 m, before the ERA-5. ERA-5 reaches its maximum with 10 m s^{-1} at about 250 m. After reaching the maximum, both profiles are rather constant with a tendency to decrease. The wind speed at the 19 CDT starts for ERA-5 and the radiosonde with the same surface speed. However, ERA-5 increases stronger with height. At the ERA-5 BLH pbl height of 750 m the wind speed of ERA-5 is more than 5 m s^{-1} higher than the radiosonde. The wind speed profiles at 7 CDT and 19 CDT show very different trends. In the 7 CDT profile the radiosonde shows higher general wind speeds whereas at the 19 CDT ERA-5 shows higher wind speeds. The 7 CDT profile decreases with height, while the 19 CDT profile increases with height. Therefore, no overall conclusion can be drawn about how the average wind speed within the pbl varies at different pbl heights.

Additional in situ measurements of relative humidity, potential temperature and wind speed were taken during ascent and descent of HALO with the BAHAMAS system. HALO did not reach the ground, so the pbl height cannot be determined using the parcel method as the surface potential temperature is not known. However, the vertical profiles of potential temperature show similar trends for ERA-5 and BAHAMAS data (figure A.8, figure A.9, figure A.10). In both the ERA-5 and BAHAMAS profiles, a positive gradient is observed during the first and second ascents and descents (A.8 a), b)). This positive gradient could indicate the pbl height since often the pbl height is identified at a positive gradient. Commonly at

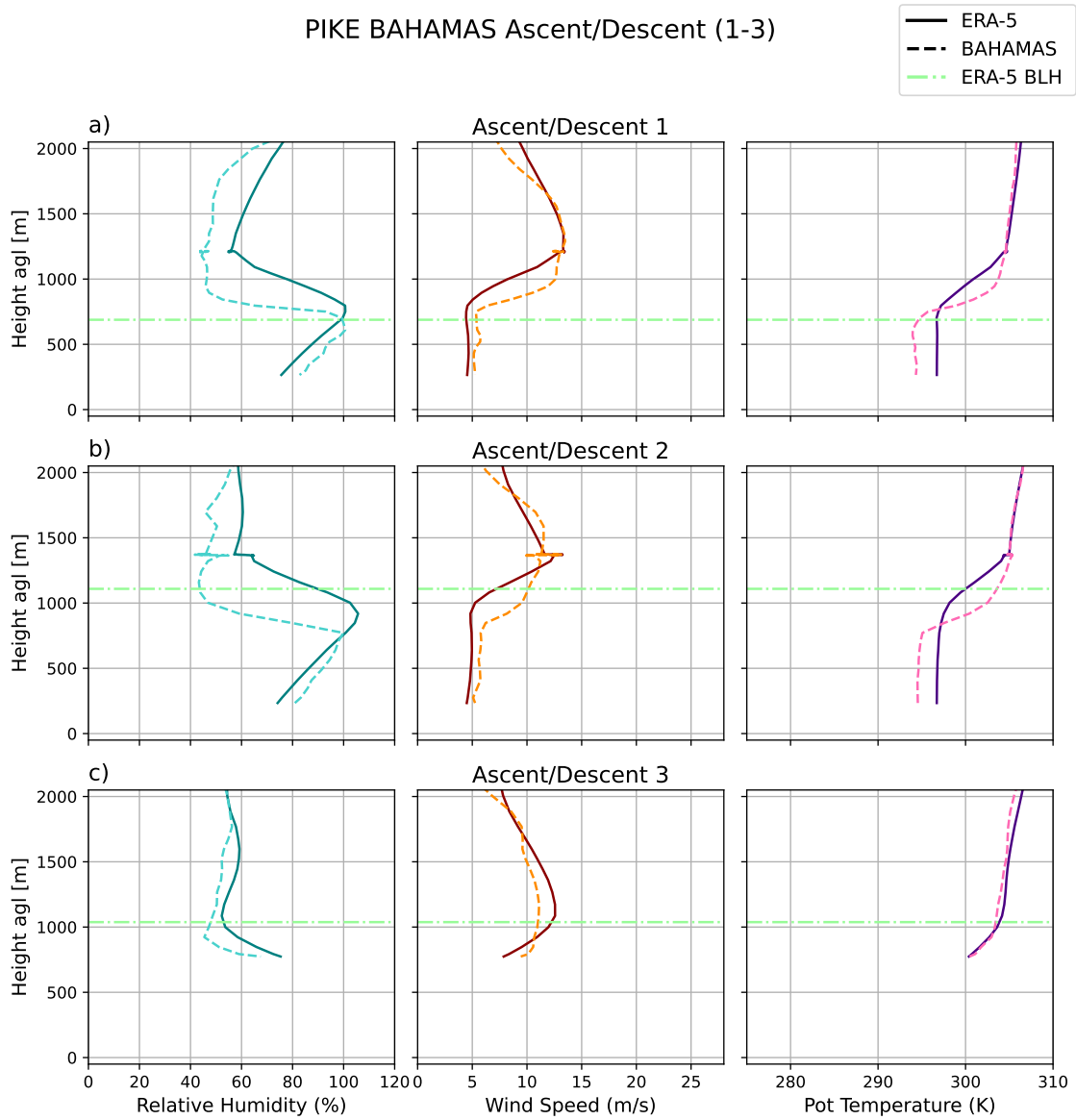


Figure A.8: Shown here are the vertical profiles of relative humidity, wind speed and potential temperature measured by BAHAMAS during the PIKE flight for both the ascent and descent phases. Vertical profiles of potential temperature from both ERA-5 (solid line) and BAHAMAS data (dashed line) showed consistent trends, with a positive gradient occurring at lower altitudes in BAHAMAS vertical profile. This suggests that ERA-5 may overestimate the pbl height. In the relative humidity profiles BAHAMAS reached the strongest negative gradient earlier than ERA-5. The ERA-5 BLH (green dashed dotted line) pbl height is within 500 m of the relative humidity negative gradient. Lower wind speeds in ERA-5 below 1000 m suggest potential underestimation of the ERA-5 averaged wind speeds compared to BAHAMAS.

this positive gradient the pbl height is reached. This gradient is reached first for BAHAMAS than for ERA-5. This could give a hint that the ERA-5 profile might

tend to represent the pbl heights at higher altitudes. However, this is not the case for the remaining seven potential temperature profiles.

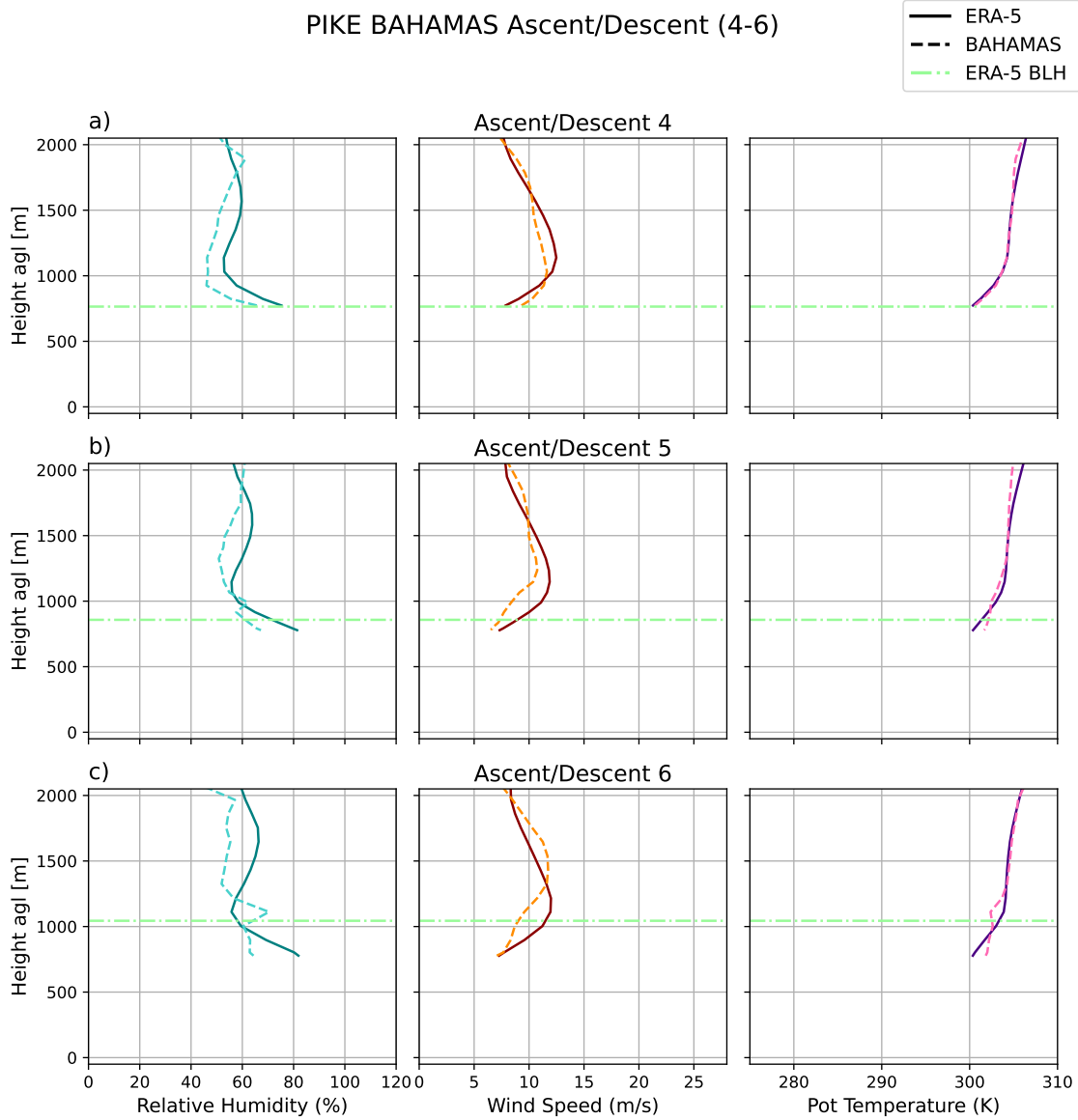


Figure A.9: This figure displays the vertical profiles of relative humidity, wind speed, and potential temperature captured by BAHAMAS during the ascent and descent phases of the PIKE flight. Both BAHAMAS (dashed line) and ERA-5 (solid line) showed comparable trends in potential temperature, but BAHAMAS indicated the positive gradient at lower altitudes, hinting at a possible overestimation of the pbl height by ERA-5. Additionally, BAHAMAS detected the strongest negative gradient in relative humidity earlier than ERA-5. While ERA-5 BLH estimates generally match or were lower than those of BAHAMAS, the lower wind speeds noted in ERA-5 below 1400 m imply a likely underestimation of wind speeds within the pbl.

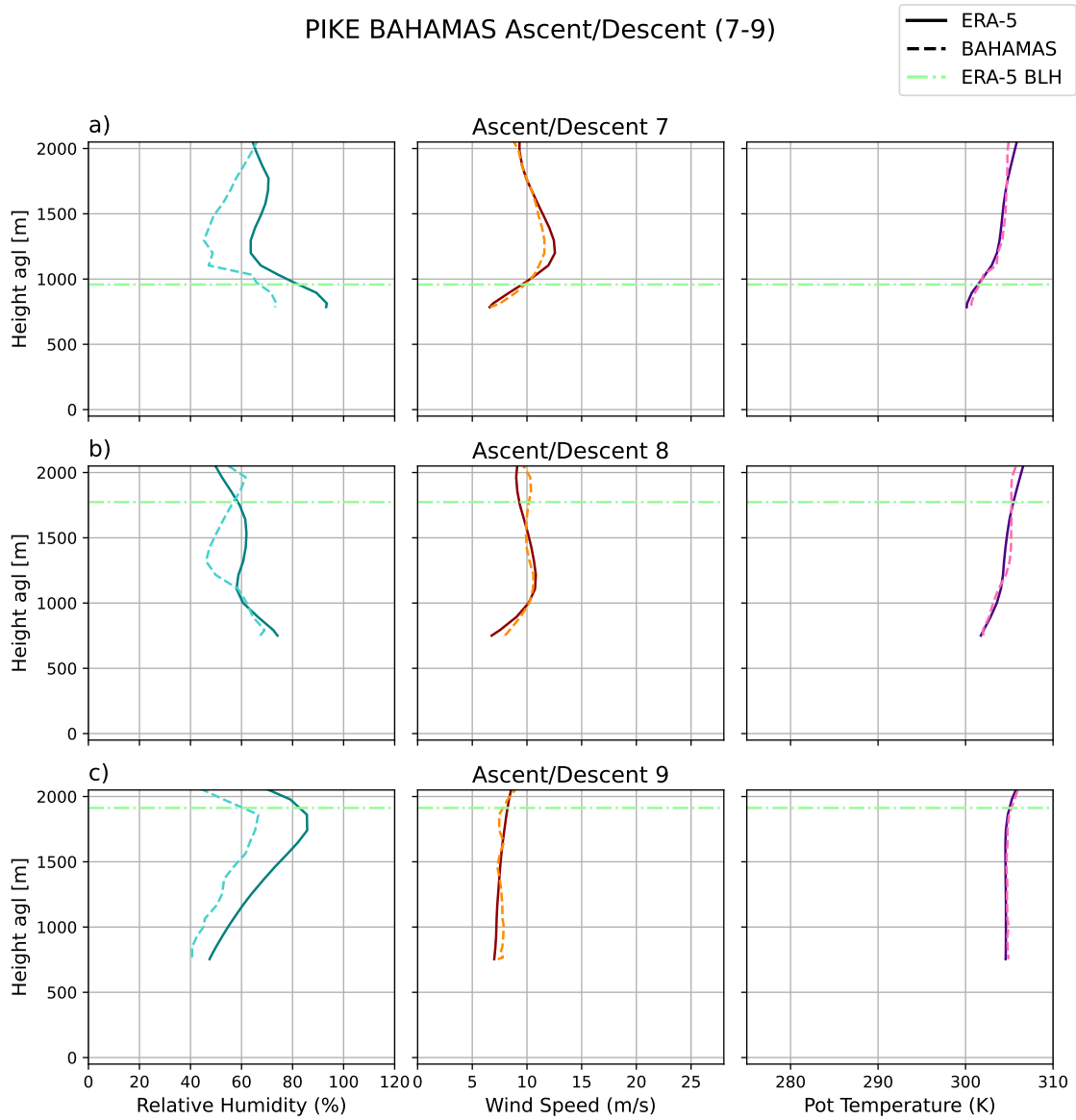


Figure A.10: The vertical profiles of relative humidity, wind speed, and potential temperature recorded by BAHAMAS during the PIKE flight are presented here for both ascent and descent phases. The potential temperature profiles from ERA-5 (solid line) and BAHAMAS (dashed line) exhibited similar trends. The relative humidity profiles revealed that BAHAMAS identified the strongest negative gradient earlier than ERA-5. The ERA-5 BLH (dashed dotted green horizontal line) pbl height is at very different heights compared to the pbl height identified with the relative humidity approach. The vertical wind speed profiles of ERA-5 aligns well with BAHAMAS. However no trend towards a general increase or decrease with height can be observed.

The relative humidity profiles show also a trend towards an overestimation of the ERA-5 pbl height compared to BAHAMAS. With the humidity approach the strongest negative gradient for the BAHAMAS vertical profile is reached before

ERA-5. No clear trend of the ERA-5 BLH pbl height being above or below the pbl heights identified by BAHAMAS or ERA-5 can be observed.

The wind speed profiles of ERA-5 and BAHAMAS show very similar trends. Most profiles increase up to a maximum and decrease again. This has impact on the wind speed averaged within the pbl. Estimated pbl heights beyond the wind speed maximum will result in higher wind speeds. Estimated pbl heights below the maximum, in contrast, will result in lower mean wind speeds.

A.3 ERA-5 performance analysis research flight "WALLEYE"

The vertical profiles of the three dropsonde releases will be analysed by going through the different parameters starting with potential temperature profile.

The ERA-5 BLH pbl height is at about 600 m for the first dropsonde. Using the parcel method to estimate the pbl height the ERA-5 vertical profile results in a pbl height of approximately 300 m. The dropsonde vertical profile indicates a pbl height of about 250 m. Thus, the ERA-5 BLH pbl height is approximately 500 m above the ERA-5 and dropsonde pbl height. For the second dropsonde the ERA-5 BLH pbl height is at about 750 m. The dropsonde profile indicates a pbl height of about 600 m like the ERA-5 vertical profile. The pbl height decreased in the vertical profiles of the third dropsonde compared to the second dropsonde. Using the parcel method the ERA-5 BLH pbl height lies about 20 m above the ERA-5 pbl height. The dropsonde pbl height is about 10 m below. In general are the dropsonde and ERA-5 vertical profiles very close together and the pbl differs less than 50 m.

Similar results to the potential temperature profiles can be observed for the relative humidity profile by using the strongest negative gradient. Again, the dropsonde and ERA-5 vertical profiles differ only slightly, whereas the ERA-5 BLH pbl height is in two of the three profiles above the dropsonde and ERA-5 vertical profile pbl height.

The surface wind speed of ERA-5 are in all three profiles below the surface wind speed of the dropsondes. In all three dropsonde profiles both the ERA-5 and dropsonde wind speed increases to its maximum at around 750 m. Above this maximum the wind speed decreases again. This results in different average wind speeds within the pbl. Is the pbl height below 500 m the averaged wind speed within the pbl will be lower than for a pbl height above 100 m.

For all three dropsonde releases the ERA-5 and dropsonde pbl height are very close together. However, the ERA-5 BLH pbl height is biased by about 500 m, especially in the first dropsonde release. The mean wind speed within the pbl will

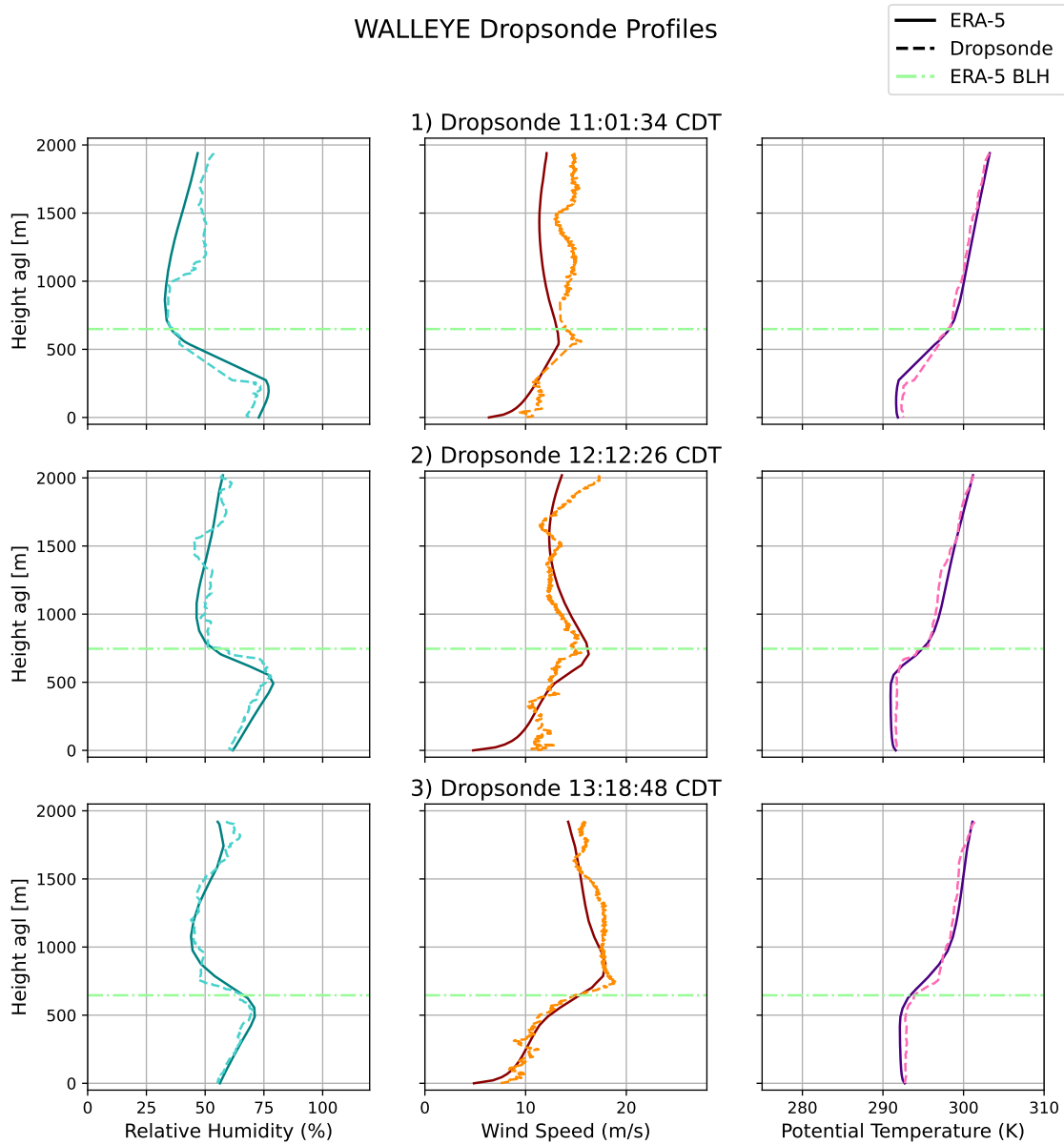


Figure A.11: Dropsonde vertical profiles (dashed line) compared to ERA-5 profiles (solid line), with ERA-5 BLH pbl height marked by the green dashed-dotted line. The ERA-5 and dropsonde vertical profiles align well. The ERA-5 pbl height might be a few meters below the dropsonde pbl height. For 3) the ERA-5 BLH pbl height corresponds to the dropsonde and ERA-5 pbl height. The wind speed increases up to 750m. The average wind speed in the pbl is expected to not show big variation between the ERA-5 and the dropsonde data, since both vertical profiles exhibit comparable trends.

not differ significantly between the ERA-5 and the dropsonde, as the both vertical profiles show similar trends.

Additionally the radiosonde data from Churchill at 7 CDT and 19 CDT is used for the graphical comparison (figure A.12). The radiosonde released in Churchill has

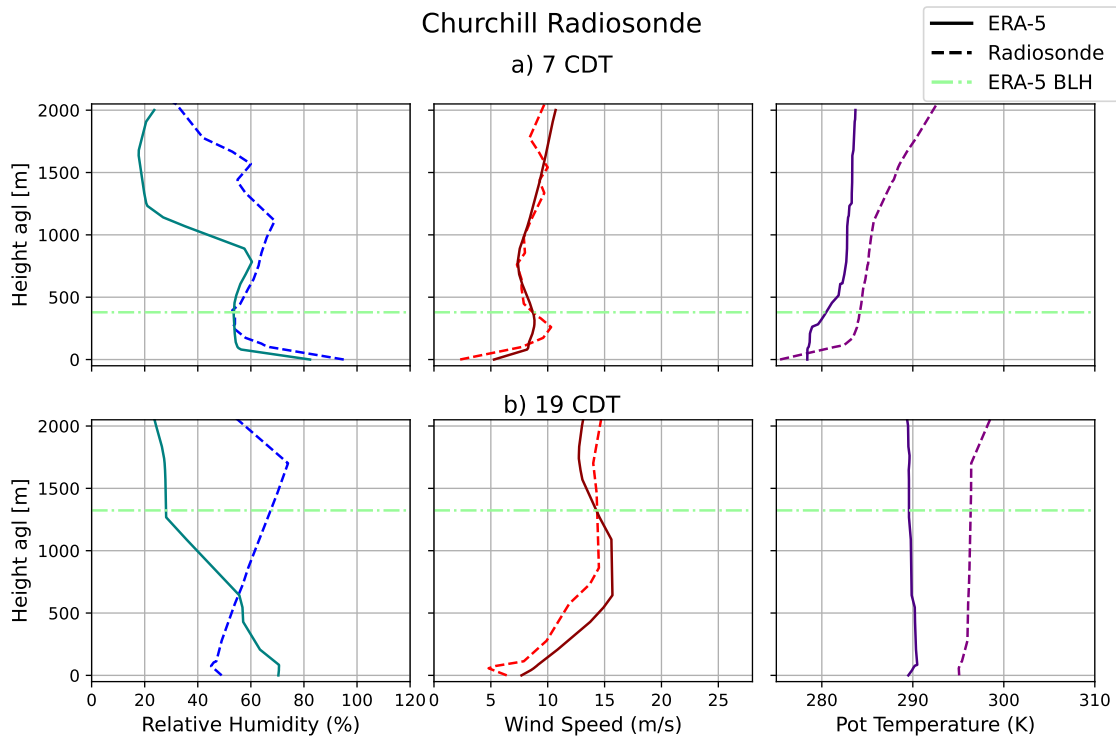


Figure A.12: Vertical profiles from radiosonde releases at Churchill at 07:00 CDT and 19:00 CDT compared to ERA-5 data. The solid lines represent the ERA-5 data and the dashed lines representing the radiosonde profiles. The green dashed dotted horizontal line corresponds to the ERA-5 BLH pbl height. Since the potential temperature vertical profiles do not have their maximum at the surface the parcel method can not be applied. However, the profiles of the radiosonde and ERA-5 show a bias for both radiosonde releases. The relative humidity show different results in the 7 CDT and 19 CDT release. For the 7 CDT ERA-5 and the radiosonde profile show similar trends whereas in the 19 CDT release the ERA-5 decreases and radiosonde increases with height. The wind speed vertical profiles show an increase for both profiles with height half way up to the ERA-5 BLH pbl height. The average wind speed within the pbl for the radiosonde is expected to be the same than for ERA-5.

similar vertical profiles as the radiosonde of ORCA and PIKE. The potential temperature profile of the 7 CDT radiosonde release starts at 275 K for the radiosonde and increases within 250 m to 285 K. The ERA-5 vertical profile has a surface potential temperature of about 278 K increasing to its maximum at 1250 m with 283 K. The 19 CDT radiosonde release does not increase with height. The rather constant profile of ERA-5 and the radiosonde have a bias of about 7 K. Consequently, for both radiosonde releases no pbl height applying the parcel method can be identified.

Since the relative humidity profiles of the 7 CDT release starts with a maximum it decreases immediately from the surface. This leads to the strongest negative gradient for both, ERA-5 and the radiosonde profile close to the ground. The ERA-

5 BLH pbl height is therefore about 300 m above at about 600 m. Different for the 19 CDT profiles. The ERA-5 vertical profile surface relative humidity is lower at the surface increasing with height to then decrease at about 100 m above ground. This means that the pbl height would be identified at this height. However the radiosonde vertical profile strongest negative gradient is observed at about 1750 m. The ERA-5 BLH pbl height is at 1400 m. Neither the parcel method nor the humidity approach provides any results for determining a reliable pbl height.

The radiosonde surface wind speed is slightly lower than the ERA-5 wind speed. For the radiosonde release at 7 CDT the wind speed increases with height to a maximum wind speed of about 11 m s^{-1} at about 250 m. However, the ERA-5 surface wind speed is higher but the maximum is lower with 7 m s^{-1} . After the maximum both profiles decrease again to then increase again at 750 m. At the 19 CDT radiosonde release the radiosonde vertical profile shows lower wind speeds up to a height of 1400 m. Both, the ERA-5 and the radiosonde wind speed increase up to a height of 1000 m. In conclusion, the wind speed averaged within the pbl of ERA-5 and the radiosonde will not differ much. Similarly to different pbl heights have no major impact on the averaged wind speed within the pbl.

The BAHAMAS ascent and descent vertical profiles of WALLEYE (figure A.13, A.14, A.15) represent very similar results to ORCA and PIKE. A statement regarding the pbl height based on the potential temperature profile using the parcel method cannot be made due to the absence of the surface temperature data. However, the ERA-5 and the BAHAMAS profiles have similar shapes. The ERA-5 vertical profile tends to have lower potential temperatures in all profiles except the first two (figure A.13 a), b)). The relative humidity vertical profiles of ERA-5 have a strong negative gradient at the same height than the ERA-5 BLH for the first two and last two vertical profiles of ascend and descends (figure A.13 a), b), A.15 b), c)). For all the remaining profiles the ERA-5 BLH estimates the pbl height lower than the relative humidity approach. Consequently, it is impossible to determine whether the ERA-5 vertical profile overestimates or underestimates the pbl height in comparison to the BAHAMAS vertical profiles. However, the height variation will have a small impact to the averaged wind speed within the pbl. The vertical profiles of the wind speed increase up to about 1000 m to then decrease again for the majority of the profiles. Due to the averaging over the pbl height only small variations in the mean wind speed for different pbl heights are expected.

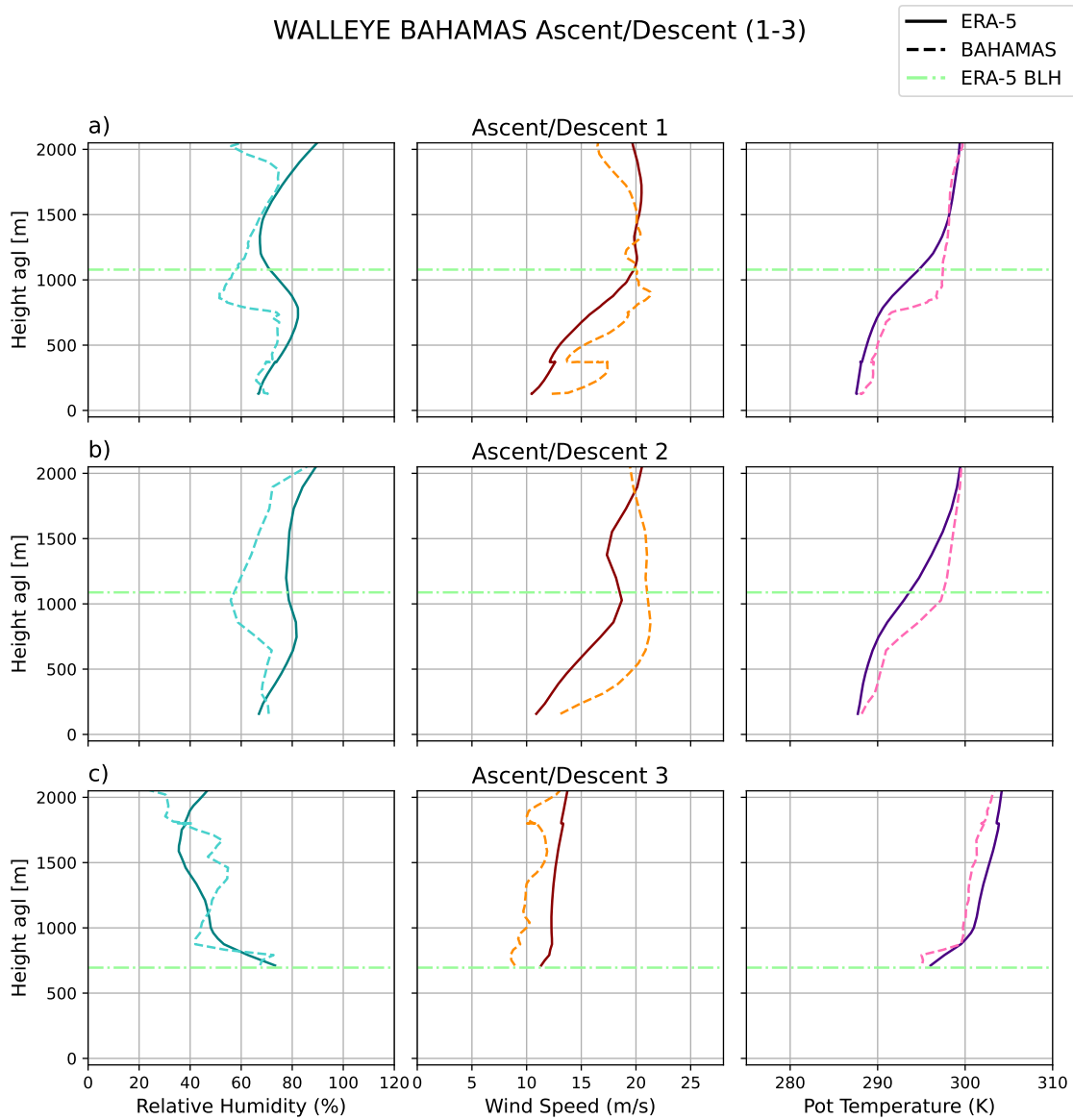


Figure A.13: BAHAMAS ascent and descent (dashed line) and ERA-5 (solid line). The green horizontal line represents the ERA-5 BLH pbl height. Using the relative humidity vertical profiles to identify the pbl height BAHAMAS reaches the pbl height before the ERA-5 vertical profile. ERA-5 BLH is for a) and b) approximately at the same height than the pbl height of for ERA-5. In c) ERA-5 BLH is below the pbl height of ERA-5 and BAHAMAS. The pbl height of BAHAMAS is in all three profiles below the ERA-5. The wind speed increases with height. For the potential temperature vertical profiles the parcel approach can not be applied due to the absence of the surface temperature.

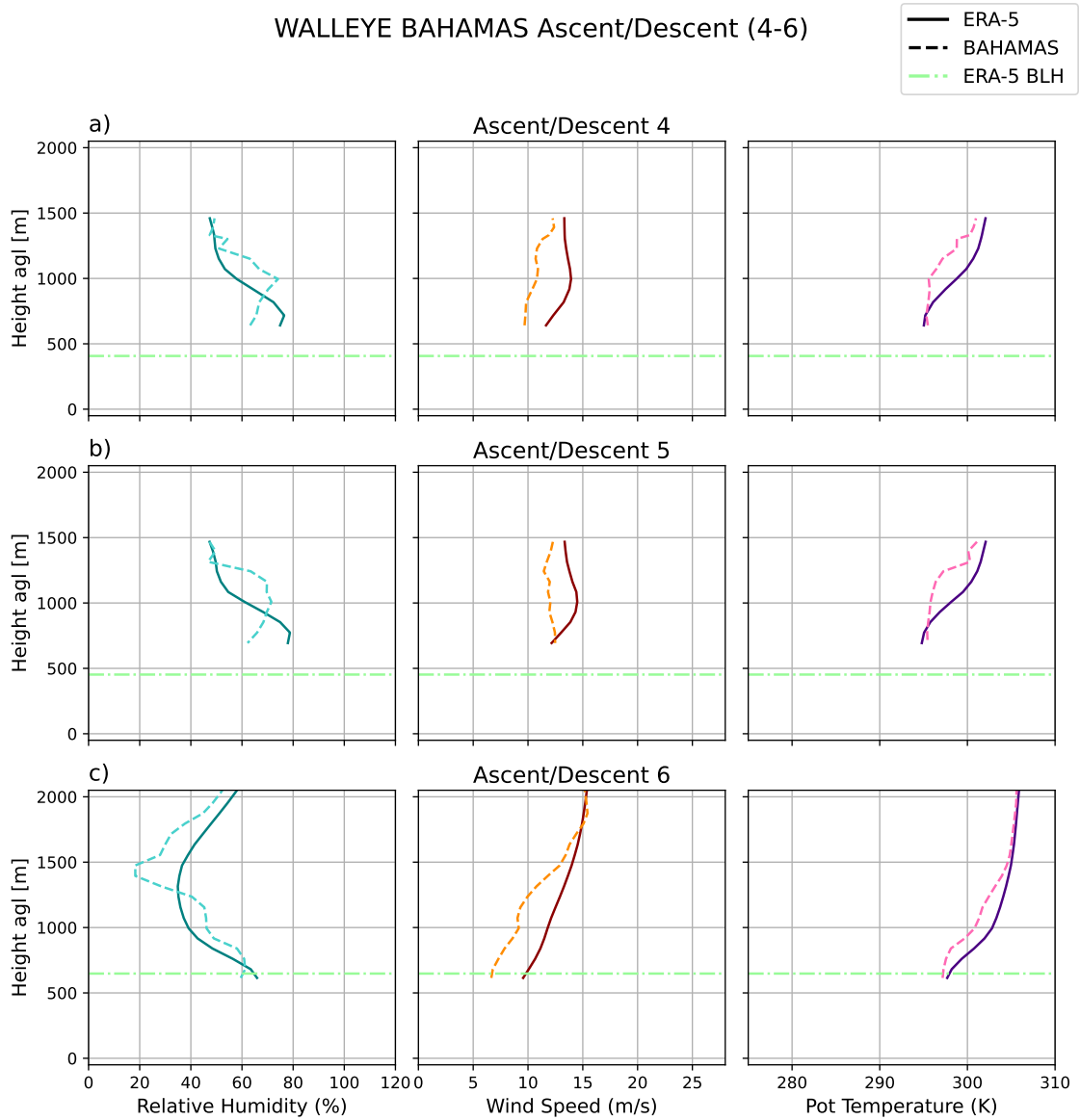


Figure A.14: Vertical profile of BAHAMAS (dashed line) and ERA-5 (solid line) relative humidity, wind speed and potential temperature. Horizontal dashed dotted green line represents the ERA-5 BLH pbl height. The potential temperature vertical profile of BAHAMAS and ERA-5 align with a small bias but no pbl height can be determined due to the absence of the surface temperature. The wind speed vertical profile increases with height. The ERA-5 wind speed tends to be higher than BAHAMAS. The relative humidity profiles do not have the same trend. a) and b) are very short profiles. No clear statement about the pbl height can be made here.

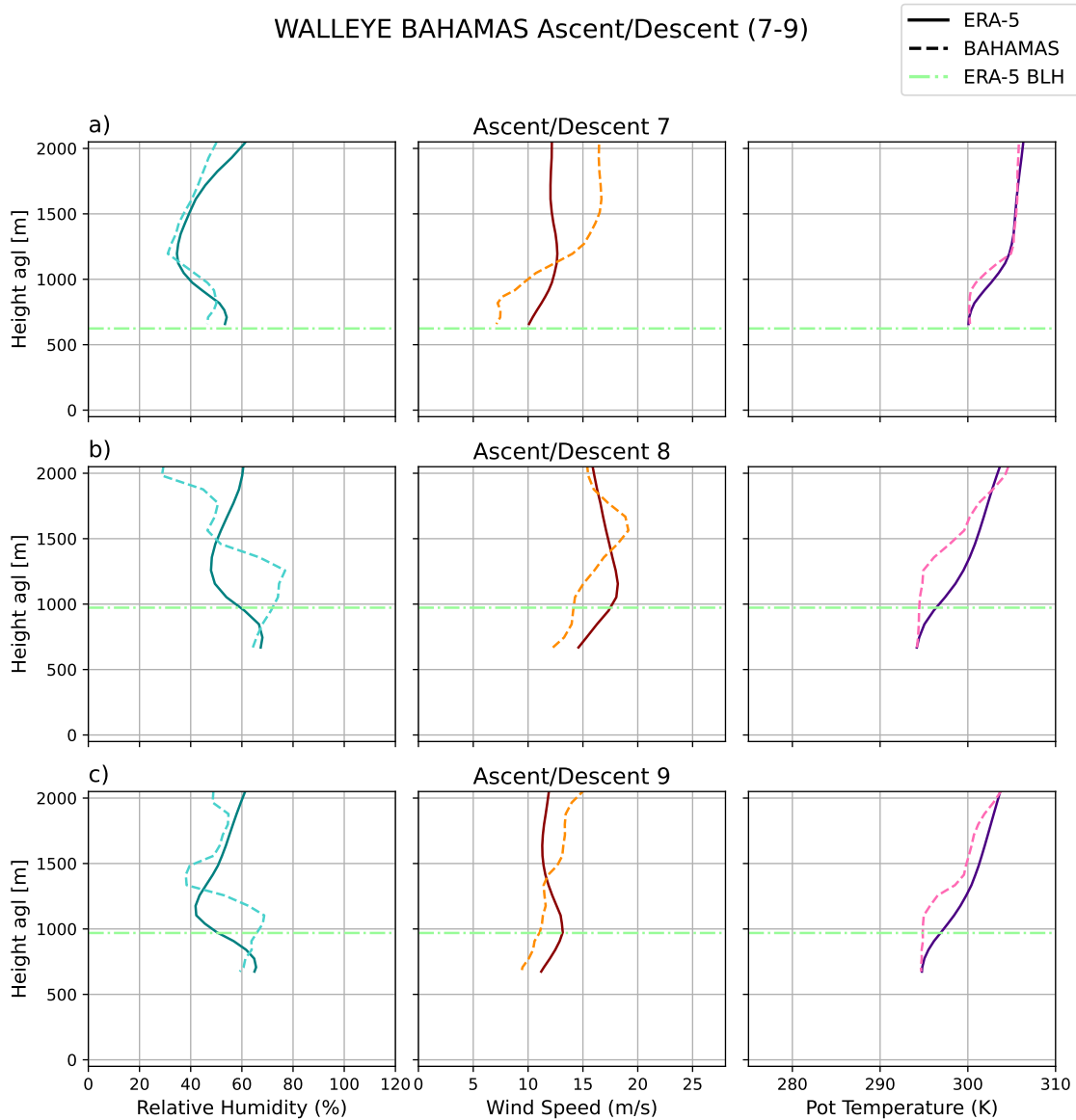
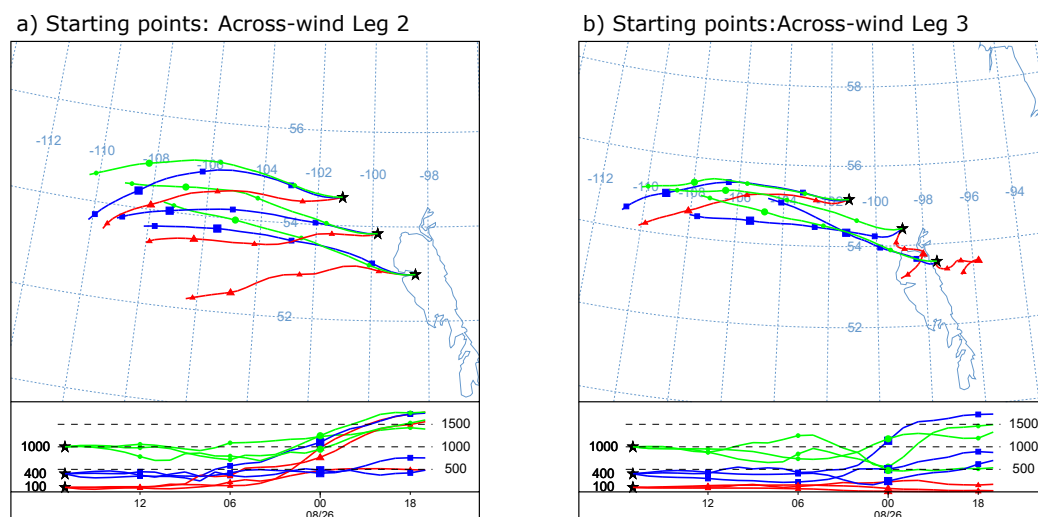


Figure A.15: BAHAMAS (dashed line) and ERA-5 (solid line) vertical profile of relative humidity, wind speed and potential temperature. The potential temperature profile of BAHAMAS and ERA-5 aligns well with small biases in b) and c). Due to the absence of the surface temperature the parcel approach can not be applied. The wind speed profiles of ERA-5 and BAHAMAS show roughly similar trends with a bias up to 5 m s^{-1} . In general the BAHAMAS wind speed increases with height. The pbl height indicated with the relative humidity approach shows the same height for BAHAMAS and ERA-5 in a) with the ERA-5 BLH pbl height being about 250 m below. For b) and c) the ERA-5 pbl height and the ERA-5 BLH pbl height align well whereas the BAHAMAS pbl height is approximately 500 m above.

Appendix B

Additional HYSPLIT graphics

B.1 Research flight "PIKE":



NOA HYSPLIT MODEL

Backward trajectories
ending at 17 UTC 26 Aug 22

GFS0p25 Meteorological Data
Duration: 24h
Vertical Motion Calculation Method:
Model Vertical Velocity

Figure B.1: Calculated back-trajectories for PIKE launched at 12 CDT. These trajectories were calculated at various altitudes: near the ground at 100 m, within the pbl at 400 m, and above the pbl at 1000 m. Leg 1 as well as Leg 2 (b) and Leg 3 (c) align with a westerly wind direction throughout the pbl. Remarkable is the prevailing of the wind within the same area especially for the surface and 400 m winds in Leg 4 and Leg 3 (b) and the eastern along wind part (c).

B.2 Research flight "WALLEYE":

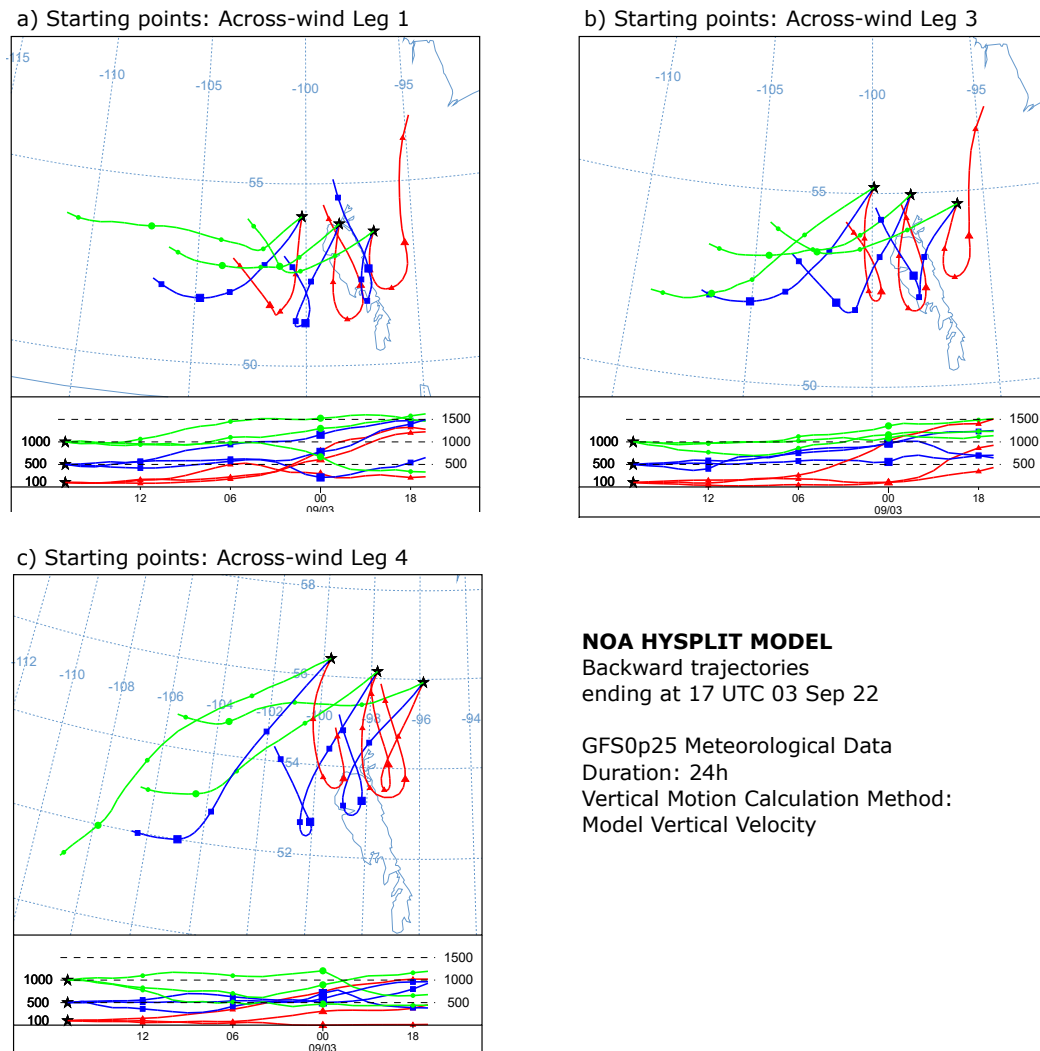


Figure B.2: A wind shear within the different pbl heights at 100 m, 500 m and 1000 m is observed for the backward trajectories calculated for WALLEYE at 12 CDT. Similar results as presented in leg 1, leg 3 and leg 4 are found for leg 2 and leg 5.

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Use of Generative AI

In this thesis, artificial intelligence (AI) has been used to correct grammar, optimise formulations and debug my programming code. I have always reviewed and edited the content as necessary. I hereby declare that this was the only use of AI. Besides that, all the work was done independently and I take full responsibility for the content of this Master's thesis.