CLIMATE TREND DETECTION IN A DATA-SCARCE ENVIRONMENT – A TRANSDISCIPLINARY STUDY IN THE PAMIR MOUNTAINS OF TAJIKISTAN

DISSERTATION

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"[…] there are now many voices calling for indigenous knowledge, searching for answers to the problems created by the fortress built by science, assembled by the hands of runaway materialism. Facing crises of climate change and waves of extinction, western societies are beginning to look to indigenous knowledge, as a source of new models for sustainability, as these complex problems cannot be addressed by science alone."

(Kimmerer, 2013, p. 57)

Abstract

Local climate trends remain mostly unknown in data-deficient mountain environments because of irregularly distributed station networks and the complexity of terrain. However, there is a necessity to monitor local changes in climate, as they have direct consequences on the livelihoods of traditional mountain communities, affecting the local hydrology, food systems, and ecosystems. To overcome existing data problems and foster the development of effective climate adaptation strategies, transdisciplinary research approaches are needed.

On the example of two villages in the Pamir Mountains of Tajikistan, this study aims to investigate local climate trends by synthesising information across different knowledge systems. Whereas the Pamirs are characterised by a scarce meteorological station network, local communities can possess detailed knowledge about ecological and environmental processes occurring in their immediate surroundings. Therefore, the first objective of this study is to explore communities' knowledge of weather and climate and to examine their perceptions of climate trends. Meanwhile, climate datasets are analysed for statistical trends and attempts are made to improve their spatial resolution. As the process of knowledge integration has rarely been applied in the climate sciences, conceptual and methodological guidelines remain absent. To address this research gap, the second objective of this study concentrates on the development of a transdisciplinary research framework.

In this research, a varied spatial resolution data and methodologies from various scientific fields were acquired and analysed. The spatial climate datasets Climatic Research Unit Timeseries (CRU) 4.01 and the Tropical Rainfall Measuring Mission (TRMM) 3B43 were analysed to investigate the spatiotemporal distribution of regional trends in temperature and precipitation (1950 – 2016). High-resolution temperature time series (1979 – 2018) were obtained, using a lapse rate-based statistical downscaling approach on the European Centre for Medium-Range Weather Forecast Reanalysis Fifth Generation (ERA5) dataset. In terms of snow, temporal changes in the timing and duration of the snow period were examined (2000 – 2018) using the daily snow cover product MOD10A1 from the Moderate-Resolution Imaging Spectroradiometer (MODIS). Community observations were valorised using semi-structured interviews and shared patterns of knowledge were identified by a consensus index. With regard to the second objective of this thesis, Seasonal Rounds were critically discussed as a methodology to derive information about local weather processes and to promote effective transdisciplinary research.

Results showed that instrumental climate data and community observations can provide new insights and reduce uncertainties on local climate trends, as both knowledge systems refer to different scales and variables and have their own strengths and limitations. In terms of precipitation, no local data records could be obtained for the research sites, but community members expressed high agreement on decreasing levels of rain. Regarding snow, satellite observations showed a significant decrease in the length of the snow seasons in one village, whereas community members reported a decline in the absolute amount of snow as well as a delay in the timing of snow onset. The analysis of different knowledge systems was challenged when handling contrasting observations. For instance, downscaled temperature data showed a statistically significant warming trend for summer, whereas community observations showed high consent on warming temperatures in autumn and winter. Reasons behind discordances should be identified instead of prioritising one knowledge system over another. This requires collaboration across disciplinary boundaries. To foster transdisciplinary collaboration and provide more insight into annual weather events, Seasonal Rounds seemed to be a promising method. Therefore, they present a central component in the developed transdisciplinary framework. The research framework to detect local climate trends consists of four stages, including (i) problem transformation and relationship building, (ii) generation of disciplinary knowledge, (iii) knowledge integration and validation, and (iv) assessment and impact.

Transdisciplinary research approaches are integral for addressing multidimensional research questions of the 21st century. To reduce remaining data uncertainties and to increase the impact of transdisciplinary climate studies, focus should be placed on establishing collaboration and mutual understanding across disciplinary boundaries as well as on the dissolution of existing power asymmetries. Whereas the approach taken in this thesis can be used to detect climate trends in other data-scarce environments, such as the Amazon or Arctic, additional research is needed to evaluate the proposed research framework in practice and to illuminate the limits of its applicability across different climatological and developmental contexts.

Zusammenfassung

Die Analyse lokaler Klimatrends wird in vielen Gebirgsregionen durch die komplexe Topografie und ein unregelmäßiges Netzwerk an Klimastationen erschwert. Es besteht jedoch die Notwendigkeit, lokale Klimaveränderungen zu überwachen, da sie direkte Auswirkungen auf die Lebensgrundlagen traditioneller Berggemeinschaften haben und die lokale Hydrologie, Nahrungsmittelsysteme und Ökosysteme beeinflussen. Um die Datenlücke in Gebirgsregionen zu schließen und nachhaltige Anpassungsmaßnahmen für örtliche Gemeinschaften an den Klimawandel zu entwickeln, werden transdisziplinäre Forschungsansätze benötigt.

Am Beispiel von zwei Dörfern im tadschikischen Pamir verfolgt diese Arbeit das Ziel, lokale Klimatrends durch die Synthese verschiedener Wissenssysteme zu analysieren. Während ein lückenhaftes Netzwerk an meteorologischen Stationen die lokale Klimadatenanalyse im Pamir erschwert, konnten sich oft traditionelle Gemeinschaften ortsbezogenes Wissen über ökologische und klimatologische Prozesse über Jahre hinweg aneignen. Daher ist das erste Ziel dieser Arbeit, das Wissen der örtlichen Bevölkerung über lokale Wetter- und Klimaprozesse und die gesellschaftliche Wahrnehmung von Klimatrends zu untersuchen. Zeitgleich werden räumliche Klimadatensätze auf statistische Trends hin analysiert und die räumliche Auflösung vorhandener Datensätze versucht zu erhöhen. Da die Verbindung verschiedener Wissenssysteme bisher wenig angewandt wurde, fehlen konzeptionelle und methodische Richtlinien. Um diese Forschungslücke zu schließen, konzentriert sich das zweite Ziel dieser Arbeit auf die konzeptionelle Ausarbeitung eines transdisziplinären Forschungsprozesses.

Eine Vielzahl an Daten und Methoden aus verschiedenen Fachbereichen wurden in dieser Arbeit aufbereitet. Die räumlichen Klimadatensätze Climatic Research Unit Timeseries (CRU) 4.01 und Tropical Rainfall Measuring Mission (TRMM) 3B43 wurden verwendet, um die raumzeitliche Verteilung regionaler Temperatur- und Niederschlagtrends (1950 to 2016) zu analysieren. Unter Anwendung eines statistischen *lapse rate downscalings* wurden räumlich hochaufgelöste Temperaturzeitreihen (1979 2018) von den European Centre for Medium-Range Weather Forecast Reanalysis Fifth Generation (ERA5) Daten abgeleitet. Veränderungen im Zeitpunkt und Länge der Schneedeckenperiode wurden anhand des satelliten-basierten Schneedeckenproduktes MOD10A1 von dem Moderate-Resolution Imaging Spectroradiometer (MODIS) analysiert (2000 to 2018). Die Beobachtungen der Dorfbewohner über örtliche Klimaveränderungen wurden anhand halbstrukturierte Interviews und Workshops erfasst. Beobachtete Klimatrends mit einer hohen Resonanz innerhalb der Dorfgemeinschaft wurden anhand eines Konsensus-Indexes

identifiziert. In Hinblick auf das zweite Ziel dieser Arbeit wurden *Seasonal Rounds* als Methodik zur Ableitung von Informationen über lokale Wetterprozesse und zur Förderung effektiver transdisziplinärer Forschung kritisch diskutiert.

Die Ergebnisse zeigten, dass die gemeinsame Analyse instrumenteller Klimadaten und Gemeindebeobachtungen neue Erkenntnisse liefern und Unsicherheiten über lokale Klimatrends reduzieren kann. Insbesondere, da sich beide Wissenssysteme auf unterschiedliche Skalen und Variablen beziehen und jeweils eigene Stärken und Schwächen aufweisen. Hinsichtlich der Veränderung von Niederschlag konnten für die Untersuchungsdörfer keine instrumentellen Klimadaten erlangt werden. Gemeindemitglieder äußerten jedoch eine hohe Übereinstimmung über abnehmende Niederschlagsmengen. Bezüglich veränderter Schneebedeckungen zeigten Satellitendaten eine signifikante Abnahme in der Länge der Schneesaison in einem der Dörfer, während Gemeindemitglieder von einem Rückgang der absoluten Schneemenge sowie einem verspäteten Schneebeginn berichteten. Eine Herausforderung bei der Analyse verschiedener Wissenssysteme stellte der Umgang mit unterschiedlichen Beobachtungen dar. Beispielsweise zeigten hochaufgelöste Temperaturdaten einen statistisch signifikanten Erwärmungstrend für Sommer, während die Beobachtungen der Dorfbewohner eine hohe Übereinstimmung über Erwärmungstrends im Herbst und Winter zeigten. Anstatt den Wissenssystemen unterschiedliche Wertigkeiten zuzuteilen, sollten die Gründe für existierende Unstimmigkeiten ermittelt werden, was eine Zusammenarbeit über Fachgrenzen hinweg erfordert. Um eine transdisziplinäre Zusammenarbeit zu fördern und ortspezifische Informationen über saisonale Wetterereignisse zu erhalten, scheinen *Seasonal Rounds* eine vielversprechende Methodik zu sein und bilden daher eine zentrale Komponente in dem entwickelten transdisziplinären Forschungskonzept. Das Forschungskonzept zur Identifizierung lokaler Klimatrends besteht aus vier Phasen: (i) Problemidentifikation und Beziehungsaufbau, (ii) Forcierung disziplinären Wissens, (iii) Wissensintegration und Validierung, (iv) und Bewertung und Anwendung der Ergebnisse.

Transdisziplinäre Forschungsansätze sind essenziell für die Beantwortung komplexer Fragestellungen des 21. Jahrhunderts. Um die Reichweite transdisziplinärer Klimastudien zu erweitern und verbleibende Datenunsicherheiten zu reduzieren, sollte der Fokus auf der Etablierung von Zusammenarbeit über Fachgrenzen hinweg sowie auf die Verschiebung bestehender Machtstrukturen gelegt werden. Der in dieser Arbeit gewählte Ansatz kann auch auf andere datenarme Regionen wie beispielsweise den Amazonas oder die Arktis, übertragen werden. Weitere Forschung ist jedoch erforderlich, um das erarbeitete Forschungskonzept in der Praxis zu evaluieren und die Grenzen seiner Anwendbarkeit in unterschiedlichen klimatologischen und entwicklungspolitischen Kontexten zu beleuchten.

Резюме́

Местные климатические тенденции остаются в основном неизвестными в горной среде с недостатком данных из-за неравномерно распределенной сети метеорологических станций и сложности рельефа местности. Тем не менее, существует необходимость в мониторинге местных изменений климата, поскольку они имеют прямые последствия для средств существования традиционных горных общин, тем самым влияя на местную гидрологию, продовольственные системы и экосистемы. Для преодоления существующих проблем с объемом данных и для содействия при разработке эффективных стратегий адаптации в связи с изменением климата необходимы трансдисциплинарные исследовательские подходы.

На примере двух деревень в горах Памира в Таджикистане данное исследование направлено на изучение местных климатических тенденций путем синтеза информации в различных системах знаний. В то время как Памир характеризуется ограниченной сетью метеорологических станций, местное население может располагать подробными знаниями о процессах экологии и окружающей среды, происходящих в непосредственной его близости. Поэтому первой целью настоящего исследования является изучение знаний местного населения о погоде и климате, а также изучение представлений местного населения о климатических тенденциях. Тем временем, объемы климатических данных анализируются на предмет статистических тенденций, и предпринимаются попытки улучшить их пространственное разрешение. Поскольку процесс интеграции знаний редко применялся в науках о климате, концептуальные и методологические руководства по-прежнему отсутствуют. Для устранения этого исследовательского пробела вторая цель настоящего исследования сосредоточена на разработке трансдисциплинарных рамок исследований.

В ходе этого исследования были получены и проанализированы разнообразные данные и методологии пространственного разрешения из различных научных областей. Наборы пространственных климатических данных Climatic Research Unit Timeseries (CRU) 4.01 и Tropical Rainfall Measuring Mission (TRMM) 3B43 были проанализированы для изучения пространственно-временного распределения региональных тенденций в температуре и осадках (1950-2016 годы). Были получены временные ряды температуры с высоким разрешением (1979-2018 годы) с использованием подхода к набору данных Европейского центра по среднесрочному прогнозному анализу погоды пятого поколения (European Centre for Medium-Range Weather Forecast Reanalysis Fifth Generation (ERA5)) основанного на скорости истечения срока статистического понижения. По тематике снежного покрова исследованы временные изменения времени и продолжительности снежного периода (2000-2018 годы) с помощью продукта суточного снежного покрова MOD10A1, полученного с помощью

спектрорадиометра умеренного разрешения (Moderate-Resolution Imaging Spectroradiometer (MODIS)). Наблюдения сообществ оценивались с помощью полуструктурированных интервью, а общая структура знаний определялась консенсусным индексом. Что касается второй цели этой диссертации, то Сезонные раунды были критически обсуждены в качестве методологии получения информации о местных погодных процессах и содействия эффективным трансдисциплинарным исследованиям.

Результаты показали, что инструментальные климатические данные и наблюдения на уровне общин могут дать новое понимание и уменьшить неопределенность в отношении местных климатических тенденций, поскольку обе системы знаний относятся к различным масштабам и переменным параметрам и имеют свои сильные стороны и ограничения. Что касается осадков, то не удалось получить никаких записей местных данных по исследовательским участкам, однако члены общины выразили большое согласие в связи с уменьшением уровня осадков. Что касается снега, то спутниковые наблюдения показали значительное сокращение продолжительности снежного сезона в одной деревне, в тоже время члены общины сообщили об уменьшении абсолютного количества снега, а также о задержке времени начала снегопада. Анализ различных систем знаний был затруднен при проведении контрастных наблюдений. Например, проанализированные температурные данные показывают статистически значимую тенденцию к потеплению в летний период, в то время как общинные наблюдения показали высокое согласие на потепление осенью и зимой. Прежде чем отдавать предпочтение одной системе знаний перед другой, должны быть выявлены причины их расхождений. Это требует сотрудничества, выходящего за рамки дисциплинарных границ. Для поддержки трансдисциплинарного сотрудничества и для обеспечения более глубокого понимания ежегодных погодных явлений Сезонные Раунды являются многообещающим методом. Поэтому они представляют собой центральный компонент в разработанных трансдисциплинарных рамках. Исследовательские рамки для выявления местных климатических тенденций состоят из четырех этапов, включая (i) трансформацию проблем и установление отношений, (ii) генерирование дисциплинарных знаний, (iii) интеграцию и валидацию знаний и (iv) оценку и воздействие.

Трансдисциплинарные исследовательские подходы являются неотъемлемой частью решения многоаспектных исследовательских вопросов XXI века. В целях уменьшения остающихся неопределенностей в данных и усиления воздействия трансдисциплинарных климатических исследований следует сосредоточить внимание на налаживание сотрудничества и достижение взаимопонимания, выходящего за рамки отдельных дисциплин, а также на устранение существующих асимметрий власти. В то время как подход, используемый в данной диссертации, может быть использован для выявления

климатических тенденций в других средах с дефицитом данных, таких как Амазонка или Арктика, необходимы дополнительные исследования для оценки предлагаемых рамок исследований на практике и для освещения пределов их применимости использования в различных климатологических контекстах и контекстах развития.

Preface

This dissertation was prepared within the interdisciplinary research project 'Ecological Calendars and Climate Adaptation in the Pamirs (ECCAP). The ECCAP project was founded by the Belmont Forum and the Germany Research Foundation (Grant number: SA 775/12-1). The project started in March 2016 and ended in June 2020. The aim of the ECCAP project was to document and revitalise traditional ecological calendars in communities in Central Asia and North America in order to build anticipatory capacity for climate change among selected communities. The ECCAP project constitutes a transdisciplinary research initiative, bringing together scientists from the social sciences, humanities, and natural sciences as well as practitioners from various cultural and ecological backgrounds.

Within this project, the research team of the University of Bayreuth, led by Professor Cyrus Samimi, focused on the analysis of instrumental climate data and the detection of climate trends and variability across Central Asia and at the research sites. To achieve this, weather stations were installed at three sites in the Pamir Mountains of Tajikistan and Kyrgyzstan (Savnob, Roshorv, Sary-Mogul). The presented thesis focuses on the identification of regional and local climate trends, the generation of high-resolution temperature records, and the integration of instrumental climate data with community observations. Due to logistical challenges, this thesis focused solely on the villages Savnob and Roshorv.

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From my heart, I want to thank all the **community members of Savnob, Roshorv, and Sary-Mogol** for opening their homes for us, sharing their knowledge, letting us pursue research in their villages and for being so welcoming, despite language and cultural barriers. Thanks to all of you and especially to **Mamadsho Guliev**, **Saradbeck Tohirbekov**, and **Adbish Tashbekov**. May the future hold only the best for you.

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Acronyms and Abbreviations

CCA........ *Cultural Consensus Analysis*
CRU TS........ *Climatic Research Unit Timeseries*

ECCAP........ *Ecological Calendars and Climate Adaptation in the Pamirs*

FSS........ *Full Snow Season*

GPCC .... *Global Precipitation Climatology Centre*
GTOPO30 .... *Global 30 Arc-Second Elevation*

IK .... *Indigenous Knowledge*

LK .... *Local Knowledge*

m.a.s.l........ *metres above sea level*

NDSI .... *Normalized Difference Snow Index*

SAHRT .... *State Administration for Hydrometeorology of the Republic of Tajikistan*

TEK .... *Traditional Ecological Knowledge*
TRMM .... *Tropical Rainfall Measurement Mission*

Definitions of Key Terminologies

Key terminologies used in this dissertation are briefly defined in this chapter as their understanding can vary across scientific disciplines. Terms are listed in alphabetical order.

Climate Sciences

The term climate sciences or climate research usually refers to an interdisciplinary field of study, focusing on spatial and temporal changes and variability in climate, the physical science basis of the climate system, and on interactive processes between the different components of the climate system. Therefore, areas of meteorology, geography, physics, chemistry and other natural sciences may be involved (Schönwiese, 2013). In this thesis, the terms *climate sciences* or *climate scientists* particularly refer to studies and scientists assessing statistical trends and variability in atmospheric variables using quantitative data sources (e. g. station data, reanalysis data, satellite-derived data, climate models). In contrast to climate data derived from instruments, climate information based on community observations of weather and climate will be referred to as local knowledge or local knowledge of weather and climate (see definition below). The term climate observations can refer to both measured data records and community observations.

Local Knowledge (LK)

The term LK is used in the context of this thesis to refer to communities' or individuals' knowledge of weather and climate. The concept of LK is similar to the concept of IK and TEK (see definition below). However, four important differences need to be emphasized which make LK more inclusive to different types of knowledge than TEK: LK is place-based knowledge that refers to the immediate habitat of the knowledge holder. LK does not have to be exclusively generated by a generational transfer of experiences and practices within one ethnic group and can also be influenced by external groups or knowledge sources (e. g. the media). LK can also be held by people embedded in the sociocultural context of a community but just recently joined the community (Olsson and Folke, 2001). Furthermore, LK is not restricted to certain content such as ecological processes, and may thus include any kind of knowledge (e. g. medicinal plants, sociocultural events, environmental processes, weather and climate).

Knowledge Systems

Knowledge systems are "made up of agents, practices, and institutions that organize the production, transfer and use of knowledge" (Cornell et al., 2013, p. 61). Several distinctive knowledge systems exist, for example local knowledge, indigenous knowledge, practitioners' knowledge, social science knowledge, natural science knowledge, or technical knowledge (Figure 1). Whereas individual knowledge systems develop alongside each other, new sets of information can be cogenerated by synthesising information across different knowledge systems. Cornell et al. (2013) refer to this as the "opening up of knowledge systems".

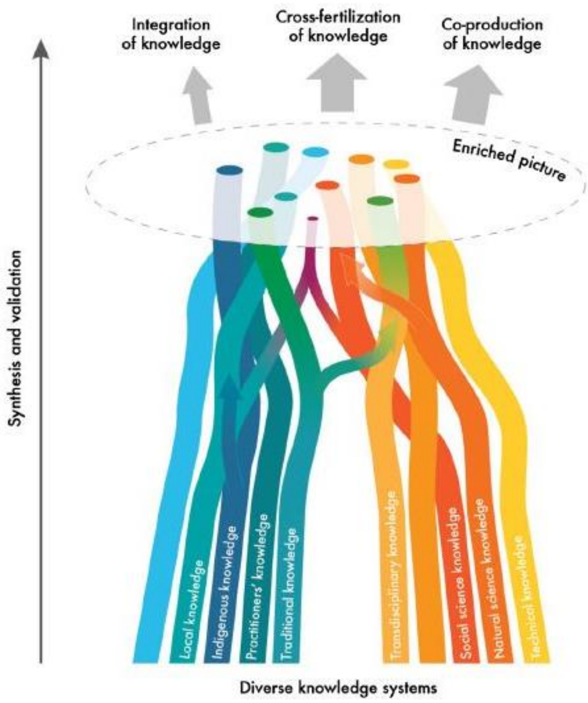

Figure 1. Different knowledge systems and the coproduction of knowledge (Tengö et al., 2014).

Scales

Two spatial scales are frequently referred to in this thesis. The regional scale, covering the region of Central Asia, and the local scale, referring to the individual research villages. Table 1 outlines the different definitions of scales used within this study. The terminologies have been chosen to differentiate between regional climate processes and weather and climate observations at the scale of villages. Therefore, they do not align with the common understanding of scales within the field of climatology and meteorology by Orlanski (1975).

Table 1. Scale definition within this study.

Scale	Resolution
Village/Local-scale	< 500 metres
Regional-scale	10 – 50 kilometres

Traditional Ecological Knowledge (TEK)

TEK is commonly defined after Berkes et al. (2000, p. 1252) as "a cumulative body of knowledge, practice, and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment". TEK differs from other terminologies such as indigenous knowledge (IK); Nyong et al., 2007) or local ecological knowledge (Olsson and Folke, 2001) in terms of its cultural and temporal components, respectively. TEK evolves over time, assuming a continuously and transgenerational relationship of the knowledge holders with their environment. Furthermore, in contrast to the concept of IK, TEK does not require the knowledge holders to be indigenous and rather refers to them as communities who are technologically less advanced or non-industrialised (Berkes et al., 2000). However, this concept often includes indigenous communities. All mentioned terminologies mutually refer to knowledge as being site-specific and acquired through communities' observations of and interactions with their natural environment. Furthermore, all knowledge systems are dynamic, have an empirical component, and are open to change (Green et al., 2010; Orlove et al., 2010).

Transdisciplinarity

Transdisciplinary research aims at overcoming the traditional boundaries between scientific disciplines by emphasizing collaboration, exchange of knowledge, and mutual learning among scientists and between scientists and practitioners. Transdisciplinary research frameworks cogenerate new knowledge by addressing and accepting different ways of knowing as equally insightful and overcome potential power asymmetries (Jahn et al., 2012). As stated in Schweizer-Ries and Perkins (2012, p. 8), the concept of transdisciplinarity further implies "the willingness to share and understand concepts of other disciplines, theories, and methods, to allow the generation of new insights and knowledge types […]". Often, transdisciplinary frameworks are used to tackle complex and heterogeneous research questions like climate change. In the process of knowledge cogeneration, a continuous collaboration and communication between the involved groups, the development of a common language, shared methodologies, and a joint analysis and validation of acquired results are each important requisites (Kassam et al., 2018; Lawrence, 2010; Mobjörk, 2010). In contrast to disciplinary, multidisciplinary, or interdisciplinary research, transdisciplinary research transgresses scientific and social boundaries (Miller et al., 2008). In this study, the concept of transdisciplinarity is only applied to the scientific research environment.

PART I

RESEARCH CONCEPT

1 Motivation and Outline

"Plants which usually blossom and ripen late, now blossom and ripen earlier and faster. Also, we can easily prepare the seeds for onions, cabbage, and tomatoes ourselves. Earlier it wasn't possible for tomatoes to ripen but now they easily do."

Zafar Kholmandov, Roshorv, 2018

Mountain communities living in the Andes, Himalaya, or Pamirs already experience immediate impacts of climate change. Whereas the consequences of global climate change can be beneficial for mountain communities (e. g. improvements in agricultural yields, new varieties in arable field fruits), consequences can also be detrimental (e. g. water stress in summer, higher risk of natural hazards). In order to offset climate risks and to take advantage of arising opportunities, tailored and use-oriented adaptation strategies need to be developed. However, the effectiveness of such strategies depends on the availability of local climate data to facilitate the analysis of local climate variability and trends. Measured climate data provided by meteorological stations, satellite observations or climate models often lack spatial accuracy when information at the village scale is needed. Particularly in mountain environments with very heterogeneous terrain and irregularly distributed meteorological stations, processed climate datasets often overlook significant atmospheric processes and weather conditions at local scales[1] due to their low spatial resolution. Despite those prevailing limitations, most climate studies still base their analyses on instrumental climate datasets. Traditional knowledge has received little attention as a potential counterbalance to measurement uncertainties and insufficient climate data. Traditional communities, living in constant interaction with their surrounding environment by engaging e. g. in subsistence-based farming and herding, have learnt to anticipate changes in their biophysical environment, which can facilitate the accumulation of detailed knowledge about local weather and

[1] See page xxii for a definition of the term scales.

climate patterns. Synthesising information across different knowledge systems[2] is a promising approach to enhance the understanding of local climate trends in data-deficient mountain environments by generating context-specific and use-oriented climate knowledge.

Exemplary for two villages in the Pamir Mountains of Tajikistan, this study integrates instrumental climate data and community observations of weather and climate to generate new insights about local trends in temperature, precipitation, and snow cover. Furthermore, this study discusses the methodological challenges arising from the integration of information across different knowledge systems. Based on the results and research experiences from this dissertation, a novel transdisciplinary research framework on the facilitation of knowledge integration was developed. The proposed research framework aims to provide guidelines for future transdisciplinary climate studies on the process of knowledge integration, which can be applied to comparable environments facing a scarcity of instrumental climate data similar to the Pamirs. This dissertation is divided into three main parts:

PART I – RESEARCH CONCEPT

In the first part of this thesis necessary background information about the research topics are provided, including a review of the most relevant publications in the fields of climate trend detection, valorisation of local knowledge[3] (LK), and integration of climate information across knowledge systems. At the end of this introduction, the research aims and questions of this dissertation are presented (chapter 2). Chapter 3 subsequently provides a description of the research areas and briefly introduces the applied data products and methodologies, relevant for the research questions of this thesis.

PART II – PUBLICATIONS

The second part constitutes the main research core of this thesis by presenting three peer-reviewed publications and one unpublished manuscript. An overview of the four manuscripts and the personal contributions of the author of this thesis is provided in chapter 4. Chapters 5, 6, 7, and 8 entail the actual manuscripts and their supplementary materials.

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[2] See page xxii for a definition of the term knowledge system.
[3] See page xxi for a definition of the term local knowledge.

PART III – SYNTHESIS

The last part of this thesis provides a summary and discussion of the acquired research results in light of the proposed research aims and questions. In addition, a novel research frame work on transdisciplinary climate trend detection is presented, based on the experience of the conducted studies (chapter 9). An outlook related to future research is presented in chapter 10.

2 Introduction

2.1 Climate Change in the Pamirs

Mountain communities in developing countries are among the most vulnerable socio-economic groups to the impacts of climate change (Kohler and Maselli, 2009; Manandhar et al., 2018). Communities' capacity to adapt to environmental and climatological change is often strained by a mix of geographic and socio-economic factors, including difficult accessibility of their living space, poorly maintained infrastructure, limited availability of resources, high risk of natural hazards, low income and development status, and little diversification of their livelihoods (Gentle and Maraseni, 2012; Kohler et al., 2010; Luthe et al., 2012). However, many mountain communities have developed measures to adapt their livelihoods to changing climatic conditions, which include transformations in agropastoral practices (Dame and Mankelow, 2010; Kreutzmann, 2012; Nüsser et al., 2012) and socio-cultural or socio-economic structures (Gentle and Maraseni, 2012; Kreutzmann, 2011; Nüsser, 2006). To support the adaptation of communities' livelihoods to the unprecedented pace of current climate change, a close understanding of local changes in climate and subsequent consequences is essential.

In the Pamirs, climate change is likely to cause a wide range of physical and biophysical impacts, with both adverse and beneficial consequences for local communities (Table 2). As the water supply of local communities relies almost completely on glacier-fed river runoffs, mass changes in regional glaciers, snow and ice packs, entail long-lasting consequences for local communities (Chevallier et al., 2014). Those consequences can include seasonal changes in the availability of water, inter-annual variability in water yields, or the risk of water scarcity in the long term, all of which are currently induced by a striking melting trend of the Central Asia glaciers (Sorg et al., 2012; Unger-Shayesteh et al., 2013). Water stress will likely intensify through increased water demand and water mismanagement by local communities (Hijioka et al., 2014; Kure et al., 2013). Climate change can further impact the conditions for local food production in the Pamirs. Seasonal temperature rise, particularly in spring and winter, may extend the growing season and facilitate new varieties of arable field fruits. Therefore, colder regions of Central Asia such as the Pamir Mountains of Tajikistan, are likely to benefit from warming temperatures regarding their yield outcomes, given that enough water can be assured (Hijioka et al., 2014). Furthermore, the distribution of animal and plant species are expected to advance towards higher elevations, which may impact land use and herding patterns (Kariyeva et al., 2012; Manandhar et al., 2018;

Mohammat et al., 2013). Herding patterns are expected to be additionally impacted by changes in local snow patterns (Dietz et al., 2014; Unger-Shayesteh et al., 2013) or by altered grassland management (Hamidov et al., 2016). However, actual climate impacts for individual villages are less clear due to the paucity of local climate records and can only be estimated from the aforementioned regional studies.

In addition to the potential impacts of climate change, the vulnerability of residing agropastoral communities in the Pamirs is compounded by their most recent history (Kreutzmann, 2012; Lioubimtseva and Henebry, 2009; Manandhar et al., 2018; Xenarios et al., 2019). Whereas communities have adapted to climate and environmental changes in the past by developing deep-rooted knowledge about their biophysical environment (Barua et al., 2014; Ingty, 2017; Nyong et al., 2007), the accumulation and intergenerational transfer of such knowledge was partly disrupted in the Pamirs during the time of the Soviet Union. Under the rule of the Soviet regime, farmers and herders experienced tremendous impacts on their traditional livelihoods due to forced collectivisation and industrialisation of agriculture, labour migration, or controlled resettlement programs (Bliss, 2006; Kassam et al., 2018). People returned to their villages and resumed their traditional livelihoods after the collapse of the Soviet Union. However, challenges for Pamiri communities continued due to the tremendous decline of Tajikistan's economy, national political and institutional upheavals, and the economic and political marginalization of Tajikistan internationally (Sievers, 2003). Because of prevailing physical, socioeconomic, and political constraints alongside disruption of traditional knowledge systems, mountain communities in the Pamirs are particularly vulnerable to climate change impacts. Therefore, further research on climate variability and long-term trends at the scale of individual villages in the Pamirs is urgently needed to understand the dimensions of local climate change and to support sustainable climate adaptation strategies for the residing communities (Fay et al., 2009).

Table 2. Expected consequences of climate change for Central Asian mountain communities.

Sector	Impact	Source
Hydrology	• Melting of glaciers, snow and ice packs	(Siegfried et al., 2012; Sorg et al., 2012)
	• Shift in maximum river-runoff from summer to spring	(Barnett et al., 2005; Hagg et al., 2013; Kure et al., 2013; Sorg et al., 2012)
	• Short-term increase in river-runoff, but decrease in the long-term	(Reyer et al., 2015)
Food Systems	• Alterations in arable field fruits and in the length of the growing season	(Kariyeva et al., 2012; Mohammat et al., 2013)

Sector	Impact	Source
	• Food systems of colder regions will benefit from rising temperatures	(Hijioka et al., 2014; Reyer et al., 2015)
Ecosystems	• Decline and limited regeneration of non-irrigated pasture lands	(Reyer et al., 2015)
	• Shifts in phenology, growth rates, and species distributions	(Hijioka et al., 2014)
Natural Hazards & Health	• Higher risk of floods and landslides	(Reyer et al., 2015)
	• Higher frequency of heat waves	(Feng et al., 2018; Reyer et al., 2015)

2.2 Climate Trends at the Local-Scale

Local trends in near-surface temperature and precipitation remain largely unknown across the Pamirs (Xenarios et al., 2019). Gridded climate datasets, which are based on interpolated station records, satellite measurements, or numerical models, can provide spatially and temporally consistent data records. However, as a consequence of their coarse grid resolution of up to 20 to 25 km, those datasets are unable to resolve the high spatial variability of near-surface climate variables in mountain environments. This situation, often described as “scale mismatch”, is a common problem in environmental and climatological research in complex terrains (Kotlarski et al., 2010; Mölg and Kaser, 2011). Gauge measurements on the other hand, which provide point-scale climate information, are often limited in number and their spatial distribution is generally skewed towards lower altitudes, i. e. valley locations in mountain regions. In the Pamirs, most meteorological stations fell into disrepair after the Soviet Union collapsed in 1990, resulting in an irregularly distributed station network and the disruption of existing long-term climate time series data (Finaev et al., 2016; Zandler et al., 2019). Considering the prevailing data restrictions, gridded data products are the only potential data source to derive local climate trends for most sites in the Pamirs.

A number of studies analysed regional temperature and precipitation changes across the geographically complex region of Central Asia using gridded climate datasets (c.f. Unger-Shayesteh et al., 2013). Whereas these datasets cannot capture climate conditions at the scale of villages, they can identify seasonal trend directions over a certain area (e. g. the Pamirs) and function as a starting point within a transdisciplinary research framework. Regional climate trend studies identified a striking warming trend for the whole region of Central Asia, which has accelerated since the 1970s (Chen et al., 2009; Feng et al., 2018; Hu et al., 2014; Zhang et al., 2019). Within the second half of the 20th century, mean annual temperatures increased over Central Asia between 0.32 °C per decade and 0.42 °C per decade (Hu et al., 2014; Zhang et al., 2019). Whereas an agreement on a general warming trend exists, study results differed regarding seasonal trend magnitudes. For example, Chen et al. (2009) showed the highest warming rates for winter, whereas Feng et al. (2018) declared the strongest warming trends occurring in spring and autumn. Unger-Shayesteh et al. (2013) clearly outlined the existing controversies in seasonal trend magnitudes. In terms of precipitation change, a heterogeneous pattern can be identified across Central Asia due to the complexity of terrain and influence of various atmospheric circulation patterns. All regions showed a net increase in annual precipitation, which is mainly induced by rising winter precipitation (Chen et al., 2011; Chen et al., 2018; Hu et al., 2017; Song and Bai, 2016; Zhang et al., 2019). However, high uncertainties in terms of precipitation trends for the Pamirs remain, as most trends were not statistically significant at the 95 % level or the model regions of the aforementioned studies did not directly coincide with the Pamir Mountains area. High uncertainties in terms of trend magnitude and missing significance are partly linked to the insufficient availability of gauge measurements in this region (Song and Bai, 2016; Wan et al., 2013). To underline the challenging data availability situation in the Pamirs, several studies evaluated the quality of gridded datasets over the data-scarce region of Central Asia and outlined the considerable data uncertainties over complex terrain for both precipitation (c.f. Guo et al., 2015; Hu et al., 2016; Hu et al., 2018; Malsy et al., 2015; Zandler et al., 2019) and temperature (Hu et al., 2014; Mannig et al., 2013). Therefore, it can be summarized that gridded climate data is suitable to detect seasonal patterns of temperature and precipitation across Central Asia in general, but still entails high uncertainties in terms of absolute data values over data-scarce regions like the Pamirs.

The spatial resolution of gridded datasets must be refined to estimate changes in temperature and precipitation at the village scale. To generate high-resolution climate information in complex terrain, dynamical downscaling of global climate models (e.g. Mannig et al., 2013), or statistical downscaling of regional climate datasets (e.g. Gerlitz, 2015; Hofer et al., 2010) are commonly applied approaches. Dynamical downscaling, which nests regional climate models into the boundary layer conditions of global climate models, comes with high computational costs and is often limited to a regional target resolution. Consequently, dynamical downscaling cannot capture topographic variations in complex terrain at the village scale when long-term simulations are required (Gutmann et al., 2012; Hofer et al., 2010; Lo et al., 2008; Xu, 1999). However, most recent studies seem to overcome the spatial restrictions of dynamical downscaling e. g. over Bavaria (Collier and Mölg, 2020). Statistical downscaling on the other hand, which is based on the relationship between large-scale climate variables (predictors) and observed local-scale variables (predictands), requires less computational costs and can be easily transferred across different geographical settings (Hewitson and Crane, 1996; Maraun et al., 2010). A number of approaches exist within the field of statistical downscaling, which can be broadly categorised into regression methods, stochastic weather generators, weather type approaches, and hybrid methodologies (Maraun et al., 2010; Wilby and Wigley, 1997). In terms of temperature downscaling, most studies apply a regression-based approach such as multiple linear regression, canonical correlation analysis, singular value decomposition, or artificial neural networks, as they are particularly suitable for simulating continuous climate variables (Coulibaly and Dibike, 2005; Fan et al., 2013; Huth, 1999; Huth, 2004; Schoof and Pryor, 2001). However, these approaches rely on the presence of high-resolution data records (e. g. gauge measurements) to fit their transfer function (Gutmann et al., 2012). As high-resolution data is mostly missing in mountain environments such as the Pamirs, downscaling approaches which work independently of ground observations are needed. For temperature, lapse-rate downscaling presents such a station-independent approach and performs well in estimating near-surface temperature records in various mountain environments such as the Alps (Gao et al., 2012), the Tibetan Plateau (Gao et al., 2017; Gerlitz et al., 2014), or the Appalachians (Lee et al., 2014).

In terms of precipitation downscaling, station-independent approaches which can be applied to estimate the local distribution of precipitation in complex terrain remain mostly absent. Most studies address this by using a dynamical downscaling approach, which brings high computational costs, but captures various factors influencing local precipitation distributions such as elevation, temperature, atmospheric circulation, or humidity (Gutmann et al., 2012; Maraun et al., 2010). In terms of statistical precipitation downscaling, one promising approach was demonstrated by Haas and Born (2011), who applied a combination of probabilistic downscaling and interpolation. Despite one limitation of this approach being the estimation of high-altitude precipitation, it provides an opportunity to downscale precipitation over mountain environments and to refine the spatial resolution of gridded datasets to a certain extent. The wider application of local precipitation downscaling studies in the Pamirs is restrained by both the minor importance of precipitation to local livelihoods due to relatively low absolute amounts and the prevailing modelling uncertainties.

2.3 Traditional Knowledge of Weather and Climate

Whereas the accuracy of instrumental climate data is often constrained at the village scale in data-scarce environments, resident communities can possess deep-rooted knowledge of local climate and weather processes. For millennia, subsistence-based communities have aimed to anticipate and predict changes in weather to enhance food security, manage livelihood activities, and use seasonal resources most efficiently (Berkes and Armitage, 2010; Green et al., 2010; Turner and Clifton, 2009). Cultural-continuity and long-term settlements enabled communities around the world to accumulate place-based knowledge of local climate and weather processes based on daily practices and observations (e.g. Boillat and Berkes, 2013; Egeru, 2012; Green et al., 2010; Ifejika Speranza et al., 2010; Ingty, 2017; King et al., 2008; Lefale, 2010; Roncoli et al., 2002). For example, communities in Uganda, who pursue rain-fed agriculture, have developed detailed knowledge of local precipitation patterns (Orlove et al., 2010). In another instance, communities living in the Arctic primarily anticipate changes in snow and ice, as those variables control their hunting and herding grounds (Cuerrier et al., 2015; Williams et al., 2018). Depending on the geography and livelihoods of communities, observations can focus on changes in temperature, wind, cloud formation, dry spells, snow, or the occurrence of extreme weather events (c.f. Egeru, 2012; Ingty, 2017; Lefale, 2010; Orlove et al., 2010; Pareek and Trivedi, 2011). LK of weather and climate, which can be considered part of communities' traditional ecological knowledge (TEK[4]), is rarely written down but rather stored in the form of local words, oral histories, ecological or environmental indicators, or applied in the use of seasonal calendars (c.f Green et al., 2010; King et al., 2008; Lefale, 2010; Orlove et al., 2010). Communities use their knowledge to evaluate current and past changes in weather and climate to predict seasonal or annual weather conditions, such as the timing of the monsoon or seasonal rainfall amounts, and to organize agricultural or sociocultural activities (Gómez-Baggethun et al., 2012; Ifejika Speranza et al., 2010; Pareek and Trivedi, 2011; Roncoli et al., 2002). Whereas those knowledge systems enabled communities to anticipate and adapt to past changes in climate, their influence on communities' decision-making and daily practices is declining (Gómez-Baggethun et al., 2012; Roncoli et al., 2002). Reasons for that can lie in the disruptions of intergenerational knowledge transfer due to altered cultural or economic livelihood conditions (e. g. through colonialization) or through the growing availability of external information, such as the internet or mobile weather forecast (Egeru, 2012; Green et al., 2010; Kassam, 2009). Such factors can diminish the constant utilisation and practice of traditional knowledge systems and prevent their adaptation to new changes in climate. Nevertheless, the potential of LK and the need for documentation and revitalisation is crucial to enhance the

[4] See page xxiii for a definition of the term traditional ecological knowledge.

adaptive capacity of traditional communities to face new climate challenges (Berkes et al., 2000; Boillat and Berkes, 2013; Kassam et al., 2018; Lefale, 2010; Naess, 2013).

Climate change research rarely recognizes these communities' deep-rooted climate and weather knowledge (Alexander et al., 2011; García-Del-Amo et al., 2020). LK of weather and climate, as well as TEK in general, is often seen within the scientific community as a distinct knowledge system, separated from so called "western knowledge" or "scientific knowledge" (Aikenhead and Ogawa, 2007; Roncoli et al., 2002). While most climate studies base their analyses on instrumental climate records or numerical climate simulations, researchers across disciplines have started to valorise potential synergies between "scientific" and "traditional" knowledge and explore their areas of complementation and diversity. The integration of knowledge systems is particularly effective in fields of environmental research (e.g. Abu et al., 2019; Berkes et al., 2007; Huntington et al., 2004), ecology (e.g. Berkes et al., 2000; Moller et al., 2009; Riseth et al., 2011), plant sciences (e.g. Armatas et al., 2016; Ruelle and Kassam, 2011), biodiversity and conservation (e.g. Ambrose et al., 2014; Anadón et al., 2009; Drew, 2005), and natural resource management (Grab and Nüsser, 2001; Nüsser and Baghel, 2016). Few integrative studies are found within climate change research. Ford et al. (2016) highlighted the limited inclusion of 'indigenous knowledge systems' in the Intergovernmental Panel on Climate Change (IPCC) assessment reports AR4 and AR5. The authors clearly underlined the growing ─yet limited─ inclusion and engagement of IK in climate adaptation studies. A similar conclusion was drawn by Garcia del Amo et al. (2020) regarding climate impact studies. Besides general scepticism against the accuracy of local knowledge systems, another reason behind the limited establishment of integrative climate studies might lie in the general scale mismatch of both knowledge systems. Whereas climate studies operate at various spatial scales, community observations only provide data at local levels and for very few sites globally. This scale mismatch considerably limits the potential research field of integrative climate studies.

Integrative climate studies are particularly effective in traditional communities possessing long-standing knowledge of local climate and weather processes but are lacking measured climate data (Fernández-Llamazares et al., 2017). Studies were conducted in mountain environments like the Andes (Fernández-Llamazares et al., 2017; Kieslinger et al., 2019; López et al., 2017), Himalaya (Gentle and Maraseni, 2012; Klein et al., 2014), Karakoram (Spies, 2019), and in other data-deficient areas such as the Arctic (Cuerrier et al., 2015; Gearheard et al., 2010; Rapinski et al., 2018) and rural Africa (Ayanlade et al., 2017; Kalanda-Joshua et al., 2011; Meze-Hausken, 2004; Simelton et al., 2013). Those studies aimed at bolstering available climate information at the village scale by identifying areas of similarity and difference between instrumental climate data and community observations. Studies derived data from gridded climate products, downscaled datasets, local weather stations, interviews, focus group discussions, oral histories, and workshops. Results showed that community observations commonly coincided with measured data records, which demonstrates the high precision community observations can attain (c.f. Fernández-Llamazares et al., 2017; Hein et al., 2019; Klein et al., 2014; López et al., 2017; Rapinski et al., 2018). On the contrary, studies also reported different observations between perceived and measured data records (c.f. Abu et al., 2019; Fernández-Llamazares et al., 2017; López et al., 2017). For example, Meze-Hausken (2004) uncovered mismatching rainfall observations in Ethiopia, where farmers reported declining rainfall amounts and a shortening of the wet seasons. Those observations could not be reproduced by records from nearby meteorological stations. Reasons behind differing observations can be diverse and difficult to identify. Discordances might be caused by inaccurate climate measurements, scale mismatches between instrumental data and community observations, or by choices of informants (Fernández-Llamazares et al., 2017; Kieslinger et al., 2019; Simelton et al., 2013). As outlined by Alexander et al. (2011), individual perceptions can vary considerably even within smaller communities due to the influence of socioeconomic factors, such as profession, age, gender, or economic wealth. External factors, such as changes in housing, access to media, short-term weather fluctuations, or the occurrence of extreme weather events, can further impact peoples' perception on long-term changes in climate (López et al., 2017). Therefore, studies generally aimed to identify areas of consent within a community by using a simple consensus index (Cuerrier et al., 2015; Rapinski et al., 2018) or a more complex cultural consensus analysis (CCA; (Klein et al., 2014). Considering their respective biases and limitations, both knowledge systems provide valuable information about local changes in weather and climate. Despite areas of complementarity, it should be acknowledged that both knowledge systems are fundamentally different in their structure, worldviews, epistemologies, and values (Aikenhead and Ogawa, 2007; López et al., 2017). Therefore, each has their own uncertainties and limitations, which should be considered when integrating information across different knowledge systems (Huntington et al., 2004). Table 3 summarizes the main characteristics of scientific data and LK and their limitations in regard to climate observations.

Table 3. Characteristics of scientific data and local knowledge against the background of climate observations after Aikenhead and Ogawa, 2007; Alexander et al., 2011; Huntington et al., 2004.

	Scientific data	Local knowledge
General characteristics	• Empirical measurements or simulations • Observations and analysis through an explicit and formal process • Standard units and measurement approaches • Set of dependent and independent variables • Global verification • Reproducibility and generalisation • Hypothesis falsification	• Approximate measurements without standardised equipment • Observations and analysis through an implicit and flexible process • Complex of practice and belief developed over a sustain period • Embedded in local language and culture • Local verification
Specific limitations	• Limited in time and resolution • High uncertainties if in-situ measurements are absent	• Not uniform within communities • Varying substance and quality of reported knowledge

2.4 Transdisciplinary Climate Research

To synthesise information across knowledge systems, scientists and local knowledge holders from different scientific, professional, and cultural backgrounds must collaborate. To establish effective research environments, transdisciplinary[5] research approaches are key, as they explicitly involve extra-scientific knowledge holders and foster thinking and collaboration across disciplinary boundaries. However, the collaborative nature of transdisciplinarity simultaneously constitutes its greatest challenge. Mutual interaction and engagement of different parties contains methodological and conceptual challenges, which so far impede the wider establishment of true transdisciplinary research in many scientific disciplines (e.g. Alexander et al., 2011; Jahn et al., 2012; Miller et al., 2008; Nielsen and D'haen, 2014). Brandt et al. (2013), summarized common challenges of transdisciplinary research projects as identified by the wider research community as follows:

(1) Establishment of consistent terminologies and research frameworks within scientific studies;

5 See page xxiii for a definition of the term transdisciplinarity.

(2) Development of appropriate and reproducible methodologies;

(3) Collaborative nature of research process, including mutual identification and analysis of problems and the co-production and application of knowledge;

(4) Varying intensity in the integration of non-scientific knowledge holders[6];

(5) Impact and visibility of transdisciplinary research within the scientific community.

In addition, the absence of quality standards and the rhetorical mainstreaming of transdisciplinarity can further hinder the establishment of transdisciplinary research (Jahn et al., 2012).

In climate sciences[7], the presence of true transdisciplinary research initiatives is also limited by the aforementioned reasons (Boon et al., 2019; Jahn et al., 2012; Latulippe and Klenk, 2020; Nielsen and D'haen, 2014). However, in the field of climate research the level of practitioners' engagement is crucial and stimulates the ongoing discourse about transdisciplinarity. Whereas Mobjörk (2010) distinguished between 'consulting transdisciplinarity' and 'participatory transdisciplinarity', Brandt et al. (2013) further added the category of 'empowerment', in which the authority completely lies in non-scientific agents. Existing studies about the integration of TEK with instrumental climate data mostly fall within the category of 'consulting transdisciplinarity'. Rather than engaging community members constantly in the research process, studies compare or validate instrumental data records with peoples' perceptions of climate trends to show their complementariness and to gain additional insights (Ayanlade et al., 2017; Chaudhary and Bawa, 2011; Fernández-Llamazares et al., 2017; Gearheard et al., 2010; Kalanda-Joshua et al., 2011; Kieslinger et al., 2019; Rapinski et al., 2018; Simelton et al., 2013; Spies, 2019). Whereas consulting transdisciplinary approaches are undoubtedly promising to foster the understanding of climate and weather processes at the village level, they impose the concept of epistemological sovereignty (Miller et al., 2008). Epistemological sovereignty prescribes disciplinary values and arguments and only considers other epistemologies in a supportive role. However, this concept contradicts the understanding of transdisciplinarity within this thesis, as the process of knowledge cogeneration, engagement of communities, and establishment of respect is not granted. Only Crate and Fedorov (2013) and López et al. (2017) represent two transdisciplinary climate studies where local

[6] Non-scientific knowledge holders can refer to members of a traditional community or to stakeholders and decision makers.
[7] See page xxi for a definition of the term climate sciences.

knowledge systems are not only addressed as supportive sources of information, but where reciprocal engagement of local communities was assured throughout the research process.

Methods are needed which meet the challenges of transdisciplinary research, such as the constant engagement of local communities in the research process and the establishment of shared understanding between and among scientists and local knowledge holders. A number of methodologies exist within the fields of participatory action research (PAR) or participatory rural appraisal (PRA), which foster the inclusion of non-scientific social groups, in particular rural livelihoods, in research initiatives (Chevalier and Buckles, 2019; Kumar, 2011). The research focus becomes more use oriented and site specific when local knowledge holders are involved in multiple steps of the research process. Subsequently, it enhances the effectiveness and robustness of research outcomes (Cornwall and Jewkes, 1995). However, those methods do not facilitate space for collaborative exchange in a multidisciplinary research team. The development of Seasonal Rounds, as applied by Kassam and Ruelle (c.f. Kassam and Wainwright Traditional Council, 2001; Ruelle and Kassam, 2011), represents a research approach which addresses both the inclusion of practitioners and the establishment of inter- and transdisciplinary understanding. Seasonal Rounds convey the seasonal relationships communities have with their habitat and visualize them in the form of an annual cycle or diagram. A visualized Seasonal Round is an accumulation of knowledge used in combination with scientific findings to develop for example seasonal calendars or seasonal diagrams. The generation of seasonal calendars is a popular PRA method (Kumar, 2011) applied in several research studies (e.g. Kieslinger et al., 2019; McKemey et al., 2020; Retnowati et al., 2014; Woodward, 2010). In contrast, Seasonal Rounds explicitly valorise the multi-stage process of knowledge generation and are not just characterised by research outcomes. This process builds on the establishment of a respectful research relationship and incorporates reoccurring community workshops, where scientists and community members from different scientific and professional backgrounds participate (Kassam et al., 2018). So far, Seasonal Rounds were only applied by Kassam and Ruelle in the field of human ecology, focusing on sociocultural and ecological activities throughout the year (Kassam and Wainwright Traditional Council, 2001; Ruelle and Kassam, 2011). Transferred to the field of climate science research, Seasonal Rounds could provide new insights in local climate and weather patterns for individual communities by outlining seasonal weather phenomena, such as the timing of frost, occurrence of extreme events, or seasonal occurrence of climate impacts. Seasonal Rounds is a promising methodology for transdisciplinary climate research to secure continuous community engagement in the research process and foster collaboration and communication between research participants from different professional and academic backgrounds.

2.5 Research Aims and Research Questions

The assessment of local climate trends in data-deficient environments, such as mountain or high-altitude regions, constitutes a research challenge. The absence of regularly distributed meteorological stations impedes the availability of high-resolution in-situ measurements, which influences the accuracy of station-based datasets as well as numerical model data. However, information about local changes in climate is essential to develop effective climate adaptation strategies for traditional or subsistence-based communities residing in such data-deficient environments. On the example of the Pamir Mountains of Tajikistan, this thesis aims at providing more insights on local climate trends by integrating instrumental climate data and community observations. Using data and methodologies from different research disciplines, this study valorises different knowledge systems as equally pertinent to produce new, use-oriented insights about occurring climate trends at the community level. By taking a multi-evidence approach, the presented study contributes to the field of transdisciplinary climate research from a thematic and a methodological perspective. Therefore, the two research aims of this thesis are:

1. **Generation of new insights on temperature, precipitation, and snow cover change in two villages in the Pamir Mountains of Tajikistan by synthesising information across distinct knowledge systems.**

2. **Development of a transdisciplinary research framework to detect local climate trends in order to guide future research studies.**

To attain the proposed research aims, five research questions were developed. Figure 2 outlines the research questions with brief reviews of their context and respective manuscript numbers where these questions are addressed. Four research questions are attributed to attain research aim 1. Questions focus individually on the analysis of instrumental climate data, the valorisation of LK, and the potential synergies of both combined. Whereas the integration of independent knowledge systems may provide valuable insights, it brings methodological challenges arising from dissimilar epistemologies and requires understanding between and among scientists and local knowledge holders from different scientific and professional backgrounds. Therefore, a fifth research question evaluates the potential suitability of Seasonal Rounds to fill this methodological gap. Based on the results of this fifth research question, a transdisciplinary research framework was developed to attain research aim 2. Manuscript results, their accompanying field work experiences, and the collaborative research activities of the ECCAP project are synthesized in the proposed transdisciplinary research framework. This framework was not addressed in the manuscripts but it constitutes an integral outcome of this thesis and aims to provide a conceptual guideline for future transdisciplinary climate studies.

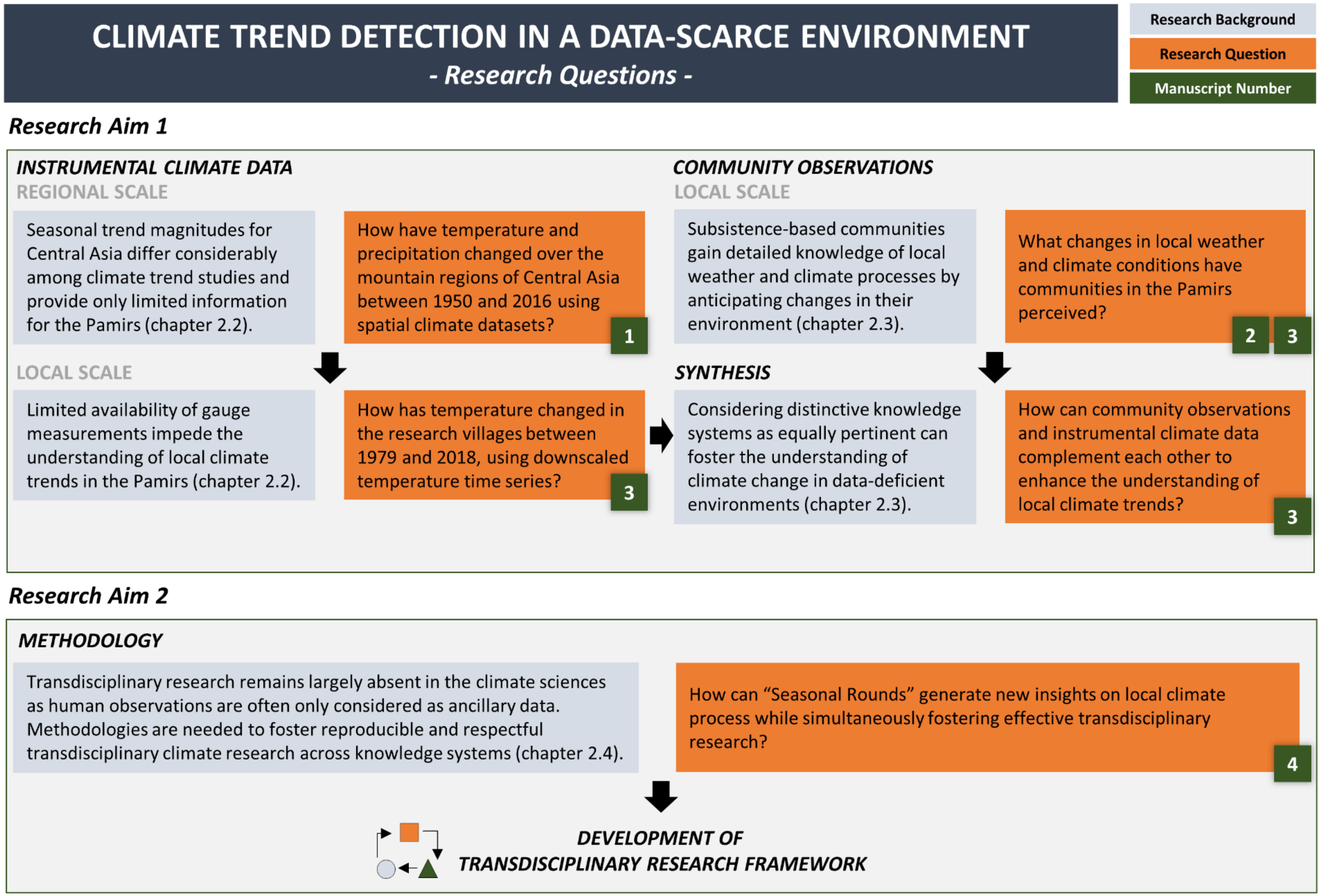

Figure 2. Conceptual overview of research questions developed to address the two research aims of this dissertation.

3 Material and Methods

This chapter describes the research sites of this thesis and briefly explains the applied datasets and methodologies. More detailed information is generally provided in the respective manuscripts (c. f. chapters 5, 6, 7, 8), which are referenced throughout this section accordingly.

3.1 Research Areas

This dissertation focuses on two study sites, addressing regional and local scales (Figure 3). The regional scale comprises the geographical region of Central Asia[8] and extends from 35°00′ to 45°00′ N and from 65°00′ to 80°00′ E. This area was used to identify spatiotemporal trends in temperature and precipitation using gridded climate datasets with particular focus on the Pamir region. Therefore, the extent was defined to include the greater Pamir region, areas of different altitudes, and different climates. With an area of approximately 1.4 million km^2, the study area covers several Central Asian mountain ranges and their adjacent forelands, such as the Tian Shan, Alai, Pamir, Hindukush, and Karakoram. This diversity in topography provides altitudinal differences between 100 metres above sea level (m.a.s.l. in the northwest and 8,000 m.a.s.l. in the southeast. The climate of the research area is controlled by its high continentality and the influence of several atmospheric forces, such as the Westerlies in the northwest and the Indian Monsoon in the southeast. This leads to arid to semi-arid conditions with different sub-climates across the north and south (Huang et al., 2014; Lioubimtseva et al., 2005; Small et al., 1999). Further information on the regional study area is provided in manuscript 1.

At the local scale, this study was conducted in the two villages Savnob (38°19′58′′ N, 72°24′32′′ E; 2675 m.a.s.l.) and Roshorv (38°19′00′′ N, 72°19′20′′ E; 3040 m.a.s.l.), which are located in the Bartang valley of the Pamir Mountains of Tajikistan. Information was gathered from these communities to understand peoples' perception of climate trends and to conduct a local-scale analysis of temperature, precipitation, and snow cover change. Communities were chosen because of the existing research relationship, which was established by the ECCAP project instructors prior

[8] The geographical region of Central Asia is not clearly defined in its extent therefore used heterogeneously across climate studies. However, it generally includes the countries Tajikistan, Kyrgyzstan, Kazakhstan, Turkmenistan, Uzbekistan, and the autonomous region of Xinjiang (c. f. Lioubimtseva et al., 2005; Hu et al., 2014).

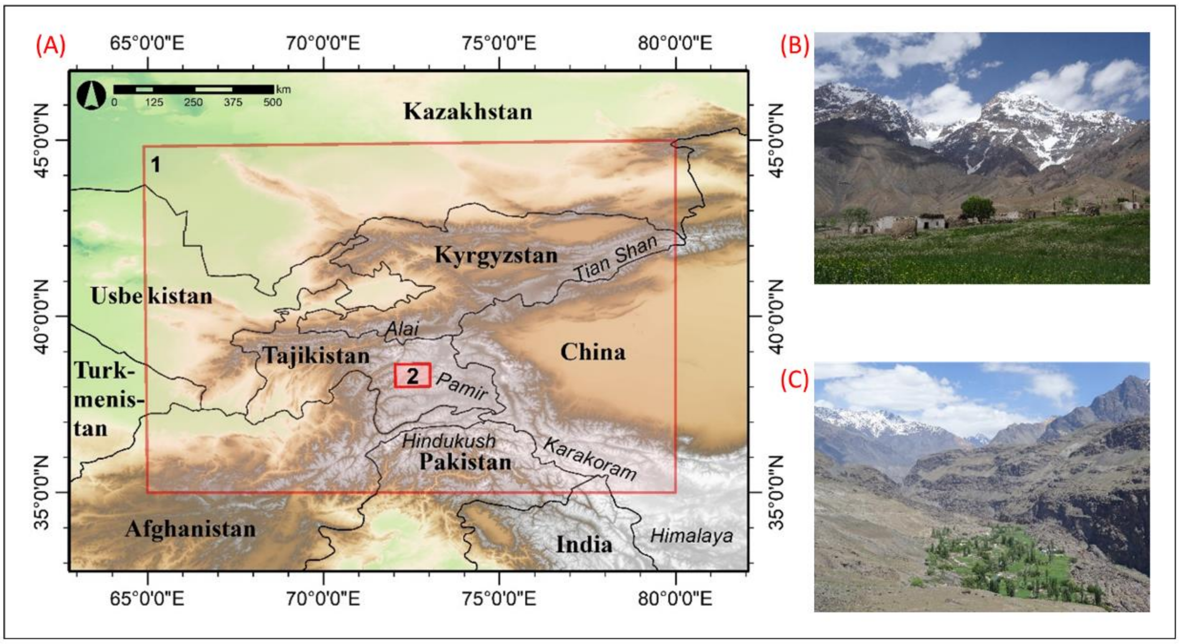

Figure 3. Map of Central Asia showing the location of the two study sites with topography in the background (A). Pictures of the research villages Roshorv (B) and Savnob (C). Map Data: OpenStreetMap WMS 30SRTM; Coordinate System: WGS 1984 World Mercator.

to the start of this dissertation. Additionally, communities have extensive habitat relations displayed in their use of ecological calendars (Kassam et al., 2011; Kassam et al., 2018). As the Pamirs are commonly divided into eastern and western parts due to climatic, topographic, and ethnographic differences (Breckle and Wucherer, 2006), assumptions drawn in this study cannot be generalized across the whole Pamir region. The research villages are located in the western Pamirs, where the landscape is characterised by rocky mountain ranges with an altitude between 5000 to 7000 m.a.s.l. and deep, narrow valleys with a general east-west orientation (Komatsu, 2016). Due to their continental location and the embedded position between high-elevation mountain ranges, the western Pamirs experience a semi-arid climate with annual precipitation between 100 and 300 mm with peaks in winter and spring[9]. Hence, glacier-fed streams and river networks are the major source of water and their availability largely shapes the livelihoods of local communities across the Pamirs (Dörre and Goibnazarov, 2018; Hagg and Mayer, 2016; Kreutzmann, 2012). Further information on the Pamirs can be found in manuscript 2 and 3.

Roshorv contains 1200 inhabitants and is located on an open plateau at the foot of a glacier with large areas of arable land. Savnob, which is seven kilometres in aerial distance from Roshorv, is situated on a small terrace and embedded between a steep mountain face and the Bartang river gorge. Savnob is the smaller of the two with only 310 inhabitants. Both communities belong to the Shia Ismaili faith and speak one of the Pamiri languages, Shugni. Villagers generally pursue a

[9] Numbers are based on the SAHRT data of this study.

subsistence-based lifestyle that largely relies on extensive farming and livestock herding (Kicherer, 2019). Both villages necessitate food independence due to the general inclement infrastructure of the region. More details about Savnob and Roshorv, including information on the establishment of a research relationship, is provided in manuscript 3 and in the supplementary material of manuscript 4.

3.2 Climate and Environmental Data

Several datasets were analysed to observe changes in temperature, precipitation, and snow cover across different spatial scales. Table 4 outlines all data products used in this study, as well as their specifications and respective areas of application.

Table 4. Overview of meteorological and environmental data products used in this study to analyse changes in temperature, precipitation, and snow cover. Order according to appearance in manuscripts.

Dataset	Selected variables	Selected timeframe	Spatial res.	Temp. res.	Methodology
CRU TS V4.01	temperature, precipitation	1950 – 2016	0.5°	monthly	regional trend analysis
TRMM 3B43 V7	precipitation	1998 – 2016	0.25°	hourly	regional trend analysis
NCDEI station data	temperature, precipitation	1950 – 2016	n.a.	monthly	validation regional climate data
GTOPO 30	elevation	-	30 arc	-	regional trend analysis
ERA5	temperature, various atmospheric parameters[10]	1979 – 2018	0.25°	hourly	statistical downscaling, local trend analysis
SAHRT station data	temperature	1995 – 2012	n.a.	monthly	validation downscaling
ECCAP station data	temperature	2016 – 2019	n.a.	hourly	statistical downscaling
MOD10A1	snow cover extent	2001 – 2018	0.005°	daily	local trend analysis

[10] Full list of parameters see manuscript 3.

3.2.1 CRU TS 4.01

The gridded Climatic Research Unit Time Series (CRU TS) dataset version 4.01 was used to detect long-term trends in temperature and precipitation over Central Asia. CRU TS was released by the Climatic Research Unit of the University of East Anglia in 2017, providing continuous climate records from 1901 until present at a spatial resolution of 0.5° for all global land areas, except Antarctica. Data estimates are based on interpolated station anomalies (base period 1960 to 1990) using a triangulated linear interpolation (Harris et al., 2014). Because of its continuous time series, CRU TS is among the most comprehensive datasets available. It is applied across different research fields, such as the examination of climate variability (e.g. Wang et al., 2013), correction of climate model and reanalysis data (e.g. Miao et al., 2016; Nabat et al., 2015; Weedon et al., 2014), or detection of climate trends (e.g. Hu et al., 2014; Jones et al., 2016; Nickl et al., 2010). However, as CRU TS only includes gauge measurements, its temporal and spatial accuracy varies as a result of regional station density and availability of gauge measurements (Harris et al., 2014).

Despite meteorological stations being the only way to measure climate variables directly, their distribution is sparse and uneven over Central Asia. Many stations fell into disrepair after the collapse of the Soviet Union in 1990, which influences the quality and availability of in-situ measurements and requires a regional evaluation of station-based datasets before use (Hu et al., 2016; Schiemann et al., 2008; Unger-Shayesteh et al., 2013). A number of studies evaluated the regional accuracy of CRU TS with focus on precipitation, as such is particularly difficult to capture due to its high small-scale variability (Hu et al., 2018; Rana et al., 2017; Zandler et al., 2019; Zhu et al., 2015). Studies showed that CRU TS, as well as other station-based datasets such as the Global Precipitation Climatology Centre (GPCC) and the Willmott and Matsuura precipitation datasets, underestimate observed precipitation in Central Asia, especially in mountain areas and in dry summer months (Hu et al., 2018; Zhu et al., 2015). Reasons for that lie in the general underestimation of precipitation by rain gauges due to wind, evaporation, splashing, or wall wetting (Hu et al., 2017). Comparing the performances of those three datasets against observations from meteorological stations, GPCC shows a higher accuracy than CRU TS and WM, which may be caused by different interpolation schemes and the selection of incorporated observation data (Hu et al., 2018; Rana et al., 2017; Zandler et al., 2019). Despite lower performance measures, CRU TS was preferred over GPCC in this study due to its better updated data record. In 2016, when manuscript 1 was in preparation, GPCC Version 7 only recorded data until 2013. GPCC's lack of most recent data was the major reason for choosing CRU TS as the latest years' data records were relevant to present to the communities. Instead, a data fusion approach based on a linear regression with the Tropical Rainfall Measurement Mission (TRMM) rainfall product 3B43 was applied to improve the data accuracy of CRU TS (see chapter 3.3.1). In April 2020, a new version of CRU TS with an improved interpolation algorithm was released (Harris et al., 2020), which makes a re-evaluation of the performance differences between CRU TS and GPCC over Central Asia relevant. Other precipitation datasets, such as reanalysis data or satellite-derived products, were not considered due to their shorter periods of data availability. Since 2020, this situation has changed considerably by the extension of the reanalysis dataset ERA5 back to 1950 (Hennermann and Berrisford, 2020).

3.2.2 TRMM 3B43

Precipitation estimates from the Tropical Rainfall Measurement Mission (TRMM) 3B43 Version 7 (Huffman et al., 2007) were acquired to linearly adjust the monthly precipitation estimates of CRU TS. TRMM 3B43 provides interpolated, 3-hour precipitation estimates from 1998 to present with a spatial resolution of 0.25° (~ 30 km). Precipitation estimates are retrieved from a variety of microwave and infrared satellites sensors, which are recalibrated by monthly rain gauge data from GPCC (Huffman et al., 2010). The full set of input sensors and further technical information about TRMM 3B43 is given in Huffman et al. (2007) and Huffman et al. (2010). TRMM 3B43 was frequently applied in local and regional climate (e.g. Karaseva et al., 2012; Mao and Wu, 2012; Shrestha et al., 2012) and hydrological studies (e.g. Bitew and Gebremichael, 2011; Shrestha et al., 2011) because of its high spatial and temporal resolution, spatial coverage, and appliance of multiple input sources. Whereas inhomogeneities in the time series and the short length of available data records impede the suitability of TRMM 3B43 for climate trend detection, the dataset is suitable for detecting local distribution of precipitation in data-deficient regions (Huffman et al., 2010). However, the accuracy of TRMM 3B43 can considerably vary at finer scales, particularly in data-deficient and semi-arid areas such as mountain environments and high-altitude regions. Those inaccuracies arise from the limited amount of in-situ measurements and difficulties by satellite sensors to measure low precipitation rates as well as frozen precipitation (Andermann et al., 2011). Over Central Asia, TRMM 3B43 showed a better performance in estimating local scale precipitation patterns than CRU TS and other reanalysis datasets (Hu et al., 2016; Song and Bai, 2016; Zandler et al., 2019). However, the absolute accuracy of TRMM 3B43 varied across the topographically complex region of Central Asia (Hu et al., 2016; Karaseva et al., 2012; Liu et al., 2015). Evaluating regional performance differences of TRMM 3B43 over Central Asia remains challenging because of the insufficient availability of long-term, independent in-situ measurements from meteorological stations. When manuscript 1 was in preparation, TRMM 3B43 was the best choice for retrieving additional high-resolution precipitation estimates.

3.2.3 NCEDI Station Data

To evaluate the performance of CRU TS over the study region, precipitation and temperature data from 14 stations was selected from Climate Data Online (CDO), hosted by the National Centers for Environmental Information (NCEDI). CDO provides a global network of historical, quality-controlled weather and climate data. However, finding suitable station records for the required time period of 1950 to 2016 over Central Asia is difficult, as most stations fell into disrepair after the collapse of the Soviet Union in 1990s (Schiemann et al., 2008). Following guidelines from the World Meteorological Organisation, only 14 stations remained suitable for validation purposes. The guidelines consider station data suitable if they provide a minimum of 80 % data coverage with less than 5 % missing values (Zahumenský, 2004). Independence of NCDEI stations cannot be guaranteed due to the low number of available stations in Central Asia and missing information about the included stations in the CRU TS and TRMM 3B43 datasets. More information about the selection procedure, location, and name of the stations can be found in manuscript 1.

3.2.4 GTOPO30

The Global 30 Arc-Second Elevation[11] model (GTOPO30), released by the U.S. Geological Survey in 1996 (Earth Resources Observation And Science (EROS) Center, 2017), was applied to detect elevation-based differences in temperature and precipitation trends across Central Asia. Data was accessed via the Spatial Data Access Tool from ORNL DAAC. GTOP30 provides global elevation information in metres above sea level, which are derived from different raster and vector-based elevation datasets. According to the respective source data, the local accuracy of the dataset can vary considerably (Harding et al., 1999). Whereas no study has assessed the vertical accuracy of GTOPO30 over Central Asia, the dataset was frequently used in this region to detect climatic variations (Böhner, 2006; Hu et al., 2014; Zhu et al., 2015) and functioned as an input source to the Central Asian precipitation dataset APHRODITE (Yatagai et al., 2012). For the analysis, GTOPO30 was aggregated to 0.5 ° to match the spatial resolution of CRU TS. Resampling of GTOPO30 was achieved using the mean of the corresponding grid cells.

[11] 30 arc-seconds correspond to a longitudinal resolution of 926 metres and a varying latitudinal resolution between 900 metres at 20°N and 550 metres at 53°N (Böhner, 2006).

3.2.5 ERA5

Two-metre temperature estimates from the reanalysis dataset ERA5 were used to downscale temperature data to the village scale. ERA5 is an atmospheric reanalysis product from the European Centre for Medium Weather Forecast (ECMWF), produced within the Copernicus Climate Change Service (C3S) program. As a reanalysis dataset, ERA5 combines and assimilates past observations with global estimates of weather models. On this basis, ERA5 provides consistent, regularly updated climate records for a suite of atmospheric, land, and oceanic variables at an hourly resolution back to 1979 (European Centre for Medium-range Weather Forecast, n.d.; Hennermann and Berrisford, 2020). With a horizontal resolution of 31 km and 137 vertical atmospheric levels, it surpasses its precursor ERA-Interim dataset and most reanalyses of earlier generations in quality, detail, and grid resolution (Dee et al., 2011; Ebita et al., 2011; Kalnay et al., 1996; Rienecker et al., 2011). However, reanalysis data includes several limitations when used for climate trend detection over Central Asia. Unger-Shayesteh et al. (2013) state that these limitations include (i) a coarse grid resolution, (ii) limited number of meteorological stations, and (iii) inhomogeneities in the time series due to (a) temporal fluctuations in the number of contributing ground stations and (b) alternations in the applied assimilation scheme.

Particularly in Central Asia, the number of meteorological stations constitutes a central problem (Schiemann et al., 2008). As most of the remaining stations are located in valley locations, reanalysis products may face difficulties in predicting temperature distribution of high elevations (Unger-Shayesteh et al., 2013). In 2019, when manuscript 3 was under preparation, ERA5 was just released and no evaluation studies over Central Asia existed. However, most lapse rate downscaling studies relied on reanalysis datasets such as ERA-Interim or NCAR-NCEP (e.g. Gerlitz et al., 2014; Gruber, 2012; Mokhov and Akperov, 2006). ERA-Interim was considered appropriate as its temperature estimates had already performed well over High Asia and outperformed other reanalysis datasets like MERRA, NCEP/NCAR, and CFSR (Bao and Zhang, 2013; Gao et al., 2017; Wang and Zeng, 2012). Furthermore, conducting a lapse rate downscaling on ERA5 over the Pamirs complements the work of Gao et al. (2017) and Gao et al. (2012), who conducted a successful lapse rate downscaling on ERA-Interim over the Tibetan Plateau. After finalising manuscript 3, recently published studies confirmed the expected adequate performance of ERA5 temperature data over complex terrain for the Himalaya (Chen and Ji, 2019) and the European Alps (Scherrer, 2020).

3.2.6 SAHRT Station Data

Temperature gauge measurements from the State Administration for Hydrometeorology of the Republic of Tajikistan (SAHRT) were applied to evaluate the performance of downscaled ERA5 data and accuracy of the downscaling approach. SAHRT data was originally acquired by the Working Group of Climatology of the University of Bayreuth in the frame of the Volkswagen-funded research project "Transformation Processes in the Eastern Pamirs of Tajikistan" (2012 – 2015) and made available for further use. SAHRT data was available for the time period of 1995 to 2012, which subsequently presents the validation time period for the downscaled ERA5 dataset. For further information on the location and altitude of these stations, please refer to the supplementary section of manuscript 3.

3.2.7 ECCAP Station Data

Weather stations were located in Savnob (2692 m.a.s.l.) and Roshorv (3139 m.a.s.l.) during the field session of the ECCAP project in 2016. The setting of the stations aims to represent the climatological condition of the villages. The stations operated between July 2016 and July 2019 and measured different atmospheric variables, including 2-metre temperature at an hourly resolution. Precipitation was not measured. ECCAP station data was used in the downscaling process to evaluate the model's performance under different pressure level combinations to calculate monthly lapse rates for the research villages.

3.2.8 MOD10A1

Temporal variations of snow cover in the research villages are detected using the snow cover product MOD10A1 from the Moderate-Resolution Imaging Spectroradiometer (MODIS) aboard the Terra satellite[12] (Hall and Riggs, 2016). With a nominal resolution of 500 metres, MOD10A1 provides daily images since the year 2000 containing a snow signal in the form of the Normalized Difference Snow Index (NDSI). The NDSI is based on the reflectance characteristics of snow. Typically, snow has very high visible (VIS) reflectance and low shortwave infrared (SWIR) reflectance. Based on this ratio of reflectance difference, snow cover can be distinguished from other land cover types and most cloud types (Hall and Riggs, 2016). MOD10A1 was chosen over other optical sensors (e. g. Landsat, NOAA AVHRR, Sentinel-2, SPOT, ERS-2, Worldview, Envisat)

[12] MOD10A1 images are also available from the Aqua satellite, but could not be acquired in this thesis due to technical reasons.

because of its high image frequency and adequate spatial resolution. Furthermore, MOD10A1 performs well in detecting snow cover changes over complex terrain (Gascoin et al., 2015; Jain et al., 2008). However, the accuracy of optical remote-sensed products to detect snow cover are influenced by the complexity of terrain, characteristics of snow, surface illumination, and cloud effects (Brubaker et al., 2005; Frei et al., 2012). Clouds constitute one of the main challenges in the analysis of satellite-borne snow cover products. Therefore, several cloud gap-filling approaches exist, including the use of additional sensors, temporal or spatial interpolation, or a combination of any of them (c.f. Hall et al., 2019). In this study, a simple gap filling approach was applied using a linear interpolation of the NDSI values. More information about the data structure, algorithms, and existing uncertainties of MOD10A1 can be found in Hall and Riggs (2016) and in manuscript 3. Information about the required pre-processing steps of the satellite images (quality assurance, removal of cloud contamination, gap filling) as applied in this study can be found in Senftl (2019).

3.3 Processing and Analysis of Climate and Environmental Data

Climate data was analysed using a linear trend analysis. Before the trend analysis, a set of pre-processing steps had to be applied, which included the linear correction of the CRU TS precipitation data, statistical downscaling of the ERA5 temperature data, and calculation of the annual snow seasons using MOD10A1 snow cover estimates.

3.3.1 Merging CRU TS Precipitation Data

A seasonal correction of the precipitation estimates was conducted because CRU TS precipitation estimates are influenced by the number of available gauge measurements and commonly underestimate precipitation in complex terrain (Hu et al., 2018). Merging different precipitation datasets is a common technique to develop a less biased dataset over a discrete regional domain. Most algorithms combine either high-resolution satellite data with gauge measurements (Li and Shao, 2010; Mitra et al., 2009; Rozante et al., 2010) or combine multiple precipitation datasets from various sources (Xie and Arkin, 1995). All techniques assume that one set of data is unbiased, which can then be used as a reference dataset. However, this assumption is unrealistic as all datasets have certain biases due to e. g. changes in measurement equipment, assimilation techniques, or the distribution of ground stations. In this study, TRMM 3B43 precipitation estimates were used to linearly adjust CRU TS because of the better performance of

TRMM 3B43 over Central Asia compared to ground measurements (c. f. chapter 3.2.2.). The statistical relationship between the two datasets was inferred from a simple linear regression approach for each month of a calendar year within the overlapping period of both datasets (1998 – 2016). The derived linear models provided the slope and intercept coefficients for each month. Afterwards, the derived 12 coefficients were used to adjust the corresponding monthly CRU TS values over the full time period (1950 – 2016). This approach assumes the historic relationship between TRMM 3B43 and CRU TS to be comparable to the identified relationship for the time period of 1998 until 2016. Due to missing in-situ measurements, no evaluation of the adjusted CRU TS precipitation time series exists. Whereas it appears justified from a statistical perspective and from the consistency of the methodologies behind the datasets during the overlapping period, no source of evaluation for the historical extrapolation exists. Furthermore, a possible autocorrelation between CRU TS and TRMM 3B43 should be considered, as both may include station records from the same meteorological stations. More information is provided in manuscript 1.

3.3.2 Statistical Downscaling of ERA5

Monthly means of near-surface air temperature data from ERA5 were downscaled to estimate temperature trends in the research villages. ERA5 was downscaled from its original 31 km grid resolution to point scale using an elevation correction approach. The applied elevation correction technique is based on the calculation of monthly variant vertical lapse rates from 1979 to 2018, using internal ERA5 fields of temperature and geopotential height, after the proposed method in Gao et al. (2017). Whereas lapse rates consider the empirical relationship between temperature and elevation, variant lapse rates further consider the current stratification of atmosphere by calculating both near-surface and free-air temperature lapse rates. In mountain environments, consideration of atmospheric stratification is particularly important as near-surface conditions are impacted by different processes than free-air conditions (Gao et al., 2012; Kattel et al., 2013; Minder et al., 2010). Such processes include cold air drainages, katabatic winds, insolation, the influence of inversions, as well as the synoptic situation (Blandford et al., 2008; Minder et al., 2010; Pepin and Losleben, 2002). Therefore, calculating variant lapse rates is preferred to using constant environmental lapse rates[13] in mountain terrain (Gao et al., 2012). Whereas the main strength of lapse rate downscaling using internal reanalysis fields of temperature lies in its independence of ground observations, it fails to consider other external

[13] Average environmental lapse rate accounts to 0.65 °C per 100 metres, c.f.Blandford et al. (2008).

temperature forcings except for elevation (e. g. topography, wind, vegetation, humidity). Therefore, seasonal errors caused by unresolved mesoscale and local circulation patterns likely remain in the downscaled dataset (Gerlitz et al., 2014). Other statistical downscaling approaches of temperature, such as multiple linear regression, canonical correlation analysis, singular value decomposition, or artificial neural networks, rely on the presence of ground observations and were therefore not suitable for this study. The calculation of monthly lapse rates and the downscaling procedure are explained in more detail in manuscript 3.

3.3.3 Full Snow Season

To identify temporal changes in the timing of snow onset, snow offset, and the total length of the snow period in the research villages, the full snow season (FSS) after Choi et al. (2010) was calculated. The FSS includes all weeks in which at least 50 % of the research area was covered by snow. To identify local snow cover, NDSI time series of the respective grid cells that surround the research villages were analysed. More details on the calculation of the FSS can be found in manuscript 3.

3.3.4 Linear Trend Analysis

A linear trend analysis was performed on different climate datasets and at different spatial scales. A regional and pixel-wise trend analysis was applied on CRU TS temperature data and CRU/TRMM precipitation data for the time period 1950 to 2016 (manuscript 1). At the village scale, a trend analysis was performed on the downscaled ERA5 temperature data from 1979 to 2018 and on the FSS data from 2001 to 2018, derived from MOD10A1 (manuscript 3). For each purpose, the term 'trend' refers to the calculation of linear trends. In all instances, the magnitude and statistical significance of the trends were estimated using the Theil and Sens slope estimator and the Mann-Kendall test, respectively. Mann-Kendall is a non-parametric test, which is based on the calculation of ranks to detect long-term monotonic trends and their statistical significance (Kendall, 1975). Theil and Sen's slope estimator is a non-parametric test, which estimates the trend magnitude by using the median slope (Sen, 1968; Theil, 1950). Both tests, used in combination, are often applied in scientific studies to detect trends in meteorological time series (e.g. Akpoti et al., 2016; Atta-ur-Rahman and Dawood, 2017; Jain et al., 2013). See manuscript 1 for more detailed information about both test statistics.

The main strengths of Mann-Kendall and Sens slope lie in their ability to deal with non-parametric time series and in their robustness against outliers. With these competences, they outperform the widely-applied least square regression (Croux and Dehon, 2010; Wilcox, 2001). However, results of linear trend analyses are always influenced by the time and length of the monitoring period and the quality of input data. Further, fitting a linear trend line may be adequate to identify and compare general trend tendencies, however, they cannot capture the complexity of environmental and climatological systems, which generally do not behave in a linear way (Mudelsee, 2019). To identify seasonal trends, data was accumulated according to the meteorological definitions for spring (March, April, May), summer (June, July, August), autumn (September, October, November), and winter (December, January, February).

3.4 Community Observations

Community observations of weather and climate were gathered in two consecutive field seasons (July 2018, July 2019) by conducting semi-structured interviews and community workshops (Table 5). At the same time, Seasonal Rounds were developed to revitalise traditional ecological calendars and to convey seasonal relations between communities and their habitat. Seasonal Rounds were not directly used to derive information about local climate and weather conditions for this thesis, but were essential in terms of establishing rapport and providing valuable ecological and sociocultural background information about the research communities. However, the potential applicability of Seasonal Rounds within the climate sciences is elaborated in chapter 9.2.

Table 5. Location and dates of community workshops and interviews to gain information about local knowledge of weather and climate. Research activities conducted by the author of this thesis as lead investigator are indicated with an asterisk.

Village	Semi-structured interviews 2018	Community workshop 2018	Semi-structured interviews 2019
Savnob	* 5 individual interviews (2 females, 3 males)	July 2, 2018 23 participants (4 females, 19 males)	* 20 individual interviews (7 females, 13 males)
Roshorv	* 5 individual interviews (5 males)	July 6, 2018 19 participants (16 females, 3 males)	* 20 individual interviews (2 females, 18 males)

3.4.1 Semi-structured Interviews

Semi-structured interviews were conducted to investigate individuals' perceptions of local changes in temperature, precipitation, and snow cover. These interviews, also known as informal or conversational interviews, are a commonly applied method in qualitative research fields, such as human geography, anthropology, or medicinal care (Bernard, 2006; Kallio et al., 2016; Longhurts, 2003). Semi-structured interviews are open-ended and conducted on a set of predefined questions. The interviewer has liberty to change question order and explore upcoming or interesting issues, if such arise within the conversation (Dunn, 2010; Longhurts, 2003). Whereas this flexibility further enables the interviewer to clarify inconsistencies or unexpected answers, which is particularly suitable if cultural or language barriers exist, it also creates space for the informant to elaborate on their own personal thoughts and ideas. This creation of reciprocity is one of the main advantages of semi-structured interviews (Kallio et al., 2016). Similar to other interview forms, such as structured or unstructured interviews, the interviewer is expected to be non-judgemental and to be aware of existing power relations and ethical issues related to this research method (Downling, 2010; Longhurts, 2003). Research processes can be intersected by such power relations, e. g. between researcher and informant coming from different development contexts, as they potentially influence peoples' willingness to participate. The negligence of certain social groups and the socioeconomic characteristics of the participants, such as age, gender, education, profession, or economic wealth, can further affect acquired results (Barriball and While, 1994). Those points underline that the credibility of interview data strongly depends on the quality and transparency of the interview process and the selection of participants (Kallio et al., 2016).

In this thesis, semi-structured interviews were conducted in 2018 and 2019. Because of the peripheral location of the villages and the lingual differences between the interviewer and the informants, semi-structured interviewing was most appropriate. Knowledgeable interview participants were selected during community workshops or by personal recommendations from the village leaders or other community members. Participants had to meet certain criteria related to age, living time in the village, and pursued profession. Interviews lasted 20 to 40 minutes and were conducted in participants' houses or gardens to create a comfortable environment. Interviews were audio recorded and translated from Shugni to English with help from a community researcher. Prior to each interview, free and informed oral consent was obtained from the participant. To ensure clarity, the development and formulation of the research questions constituted an iterative process and required close collaboration with the local community researcher and research colleagues from the ECCAP project. Fewer interviews were conducted in 2018 than in 2019 because of time and the development procedure. Interview questions included for example: “Is spring getting warmer or colder?”; “When does snow disappear in the village?”; “Have you experienced changes in rain?”. The exact questions can be found in the supplementary section of manuscript 3. More information about the interview process and selection procedure of participants can be found in manuscript 3. Among similar studies, semi-structured interviews were the most common interview technique applied (e.g. Boillat and Berkes, 2013; Byg and Salick, 2009; Ingty, 2017; Klein et al., 2014; López et al., 2017; Orlove et al., 2010; Simelton et al., 2013), followed by structured surveys and interviews (e.g. Hein et al., 2019; Manandhar et al., 2011; Meze-Hausken, 2004). In most studies, interviews were part of a wider research setting, that took place following extensive ethnographic fieldwork or happened in combination with additional research methods like house-hold surveys, life-long interviews, or focus group discussions.

3.4.1.1 Historical Time Markers

Historical time markers were used to help interviewees anticipate long-term changes in temperature, precipitation, and snow cover. The time markers were applied during the interviews and placed in front of the interviewees on a hand-written paper in the local language. Within this thesis, historical time markers were developed after the concept of landmark years, which is a PRA method to explore temporal dimensions of change (Kumar, 2011). Following this concept, community members are expected to remember time markers (important local events) that ideally are simultaneously relevant to the research focus. Further, time markers can appear either in the form of fixed years or time intervals (Kumar, 2011).

For this thesis, the relevance of time markers to local communities was ensured with the help of a local community researcher. However, the identified events were less related to climate change than to political events and environmental hazards. As time markers are highly site-specific and no experience was gained in previous research for those study sites, the structure of the time markers had to be developed. In 2018, time markers referred to fixed years, such as “2015 – the year of the earth quake” or “2012 – Military operation in Khorog[14]”. In 2019, the time markers were refined to time intervals, such as “before the year 2000 – civil war, visit of Imam, millennia”. This refinement facilitated more space for interviewees to anticipate historic conditions and to broaden their awareness beyond single seasons. A full description of the time markers is provided in the supplementary section of manuscript 3.

[14] Capital of the district where the research villages are located

3.4.2 Community Workshops

During the ECCAP project, community workshops were organised in Savnob and Roshorv in the years 2017 and 2018. The aim of the workshops was to identify seasonal connectivity between the communities and their biophysical habitat and to visualise those relations in the form of Seasonal Rounds (c. f. chapter 3.4.3). Community workshops, which are usually open to all community members and do not limit the number of participants, can facilitate trust and rapport, foster community engagement, and initiate a two-sided learning process (Ahmed and Asraf, 2018). In the ECCAP project, workshops were always accompanied by a shared-meal or tea. More information on the workshop settings is provided in manuscripts 3 and 4.

Community workshops were most important in terms of establishing a research relationship and providing important a-priori information about the sociocultural and ecological context of both villages. Workshops of 2018 were further used to identify knowledgeable community members for subsequent interviews by asking questions about seasonal changes in temperature, precipitation, and snow cover. In the same session, research results about regional climate trends (manuscript 1) were presented to the communities to initiate a two-way learning process. Community workshops demonstrated the diversity of knowledge within the communities and were experienced as a suitable approach to engage women in the research process. Compared to other transdisciplinary climate studies, focus group discussions are more widely applied than community workshops (c.f. Ayanlade et al., 2017; Chaudhary and Bawa, 2011; Kalanda-Joshua et al., 2011; Simelton et al., 2013). Whereas focus groups are usually limited to six to ten pre-selected participants, they can help identify areas of agreement and disagreement within a community due to high levels of interaction between participants (Hay, 2010). However, in this study, community workshops were preferred as focus was placed on the establishment of a research relationship and to provide space for many community members to engage in the research process.

3.4.3 Seasonal Rounds

Seasonal Rounds were developed during the ECCAP project in order to revitalise traditional ecological calendars in Savnob and Roshorv and to convey the seasonal relations communities have with their habitat (manuscript 4). In this dissertation, the potential of Seasonal Rounds is proposed and discussed within the transdisciplinary research framework on climate knowledge integration (chapter 9.2). As the term 'Seasonal Round' can be understood in three different ways across the scientific literature, a short outline of those understandings is given here.

First, in the field of anthropology, Seasonal Rounds are commonly understood as "patterns of seasonal movement and seasonal residence […] within and across diverse geographic and ecological areas, reflect and embrace the complex systems of knowledge and practice that integrate all of the different aspects of peoples' lifeways: harvesting food, gathering wood […], constructing shelter, […], observing animals of all kind, recounting stories […], teaching children and youth […]" (Turner, 2014, p. 4). Whereas a Seasonal Round can change over time due to altered livelihoods or technological conditions, its initial aim is to foster food security (Turner, 2014). By "moving with the seasons" (Spangler, 2009), communities use natural resources most effectively and gather food in synchrony with annual weather conditions and across different topographies and altitudes (Turner, 2014). In addition to this understanding of the term Seasonal Round, one aim of the ECCAP project was to visualise those relations for communities in the Pamirs. Therefore, Seasonal Rounds achieved a second meaning, referring to the graphical outcome of the visualisation process. Seasonal Rounds, often visualized in the form of a circle or table, can be found across different cultural contexts and thematic foci. For example, Kassam and Wainwright Traditional Council (2001) used Seasonal Rounds to demonstrate seasonal connectivity of Dene women with the Boreal forest; Kassam (2009) depicted the hunting and fishing activities of Eskimo throughout the year; and Ruelle and Kassam (2011) used Seasonal Rounds to illustrate seasonal availability of non-cultivated crops in the Standing Rock Nation in North America (c. f. Figure 4).

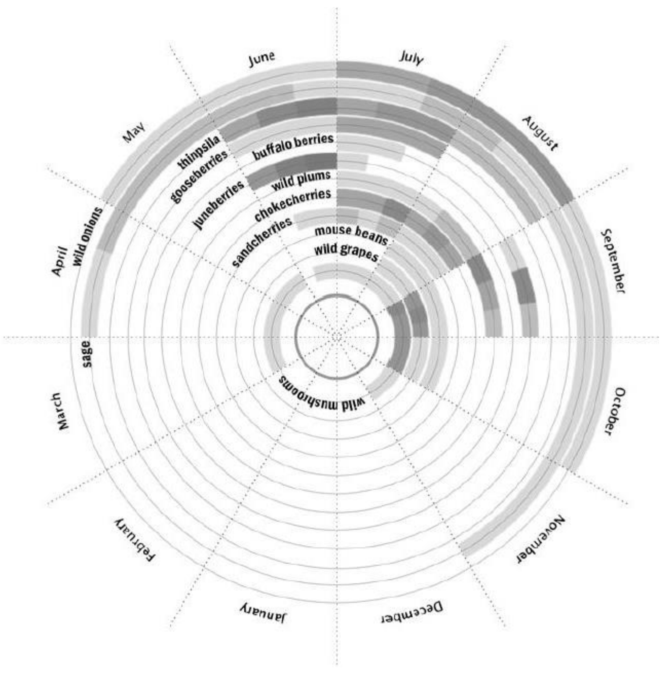

Figure 4. Example of an illustrated Seasonal Round showing the seasonal availability of non-cultivated plants in the Standing Rock Nation in North America (Ruelle and Kassam, 2011).

Those visualized Seasonal Rounds are a construct of accumulated knowledge across one research community representing an annual cycle of sociocultural and ecological activities (Ruelle, 2015). Apart from the authors Kassam and Ruelle, no literature could be found where the term Seasonal Round was applied in reference to a graphical illustration. However, references in older, printed mediums might exist.

In a third context, the development of Seasonal Rounds is described as a participatory methodology, as so is within this dissertation (manuscript 4). In the field of development studies, a participatory methodology is often referred to as a "Participatory Rural Appraisal" (PRA) and can be defined as "a family of approaches and methods to enable rural people to share, enhance, and analyse their knowledge of life and conditions, to plan and to act" (Chambers, 1994, p. 953). However, the level of participation varies in existing literature, ranging from "passive participation", with a very low level of community engagement, to "participation by consultancy" and "self-mobilisation", where community members experience full control over the research process (Kumar, 2011). Under true engagement of local communities, participation enhances efficiency and effectiveness of the research process and fosters self-reliance and sustainability of communities and the applied research activities (Kumar, 2011). Whereas a high community engagement is undoubtedly promising in theory, it encounters several challenges in reality. Limited availability of time, funding, or human resources constrains the level of community engagement as well as creates difficulties in the dissolution of existing power relations or social obstacles such as culture-bound gender gaps (Kumar, 2011). In terms of developing Seasonal Rounds, community members can be engaged in the identification of research objectives, selection of participants, visualisation process of the Seasonal Rounds, and in the validation, analysis, and discussion of the acquired data. Further information about Seasonal Rounds as a participatory methodology is provided in manuscript 4.

3.5 Analysis of Community Observations

3.5.1 Content Analysis

A content analysis was conducted to analyse the semi-structured interviews from Savnob and Roshorv and to extract information on climate indicators and the directions of climate trends (manuscript 3). A content analysis is a widely applied method in the social sciences and humanities, referring to a systematic text analysis (Mayring, 2000). Whereas no universal definition of a content analysis exists (Mayring, 2015; Schreier, 2014), two kinds of content analysis can be differentiated: qualitative and quantitative (Bohnsack et al., 2018; Krippendorff, 2019). A quantitative content analysis, also described as manifest (Hay, 2010) or conventional content analysis (Hsieh and Shannon, 2005), refers to the identification of directly visible terms, phrases, or content within the data sources, such as text, audio, or video material (Cope, 2010; Hay, 2010). The identified content simultaneously functions as code categories, which can be statistically analysed by their frequency, variation, or correlation (Cope, 2010). A manifest content analysis is suitable for effectively organizing and reducing large amounts of data and for extracting information according to a pre-defined research intent. In this dissertation, descriptive codes were developed according to seasonal climate trend observations and climate-induced impacts. For example, “winter warmer”, “summer colder”, “less snow”, or “consequence of warmer autumn”. Afterwards, codes about climate trends were analysed by their frequency using a cultural consensus index (chapter 3.5.2). Codes about climate impacts were counted and summarized in a table. This table on climate impacts in Savnob and Roshorv and further information on the content analysis can be found in manuscript 3 and in the according supplementary material.

3.5.2 Consensus Index

A consensus index was calculated to identify areas of agreement in the climate observations made by the community members. As individual perceptions do not have to represent the broader knowledge of a community (Davis and Wagner, 2003), an objective measure is needed to identify shared areas of consent within a selected group of informants. A consensus index is based on the connectivity between community agreement and truth (Crona et al., 2013). In other words, the higher the agreement regarding a certain observation within a community is, the higher the chance this trend actually occurred. The idea of cultural consent and the connectivity between agreement and truth was first proposed by Romney et al. (1986) and reinforced by Weller (2007). In terms of examining peoples’ perception on climate change and to identify consent within a group of people, different consensus indices with varying levels of complexity exist. Rapinski et al. (2018) for example, calculated a consensus index in the form of a frequency analysis counting the number of citations in ratio to the total amount of answers. More complex methods, such as CCA, are based on the same principle but further examine the variability across respondents with a factor analysis and weighting individual responses according to a “cultural competence” score (Crona et al., 2013; Klein et al., 2014). A CCA may provide more robust results than a simple consensus index, especially when the number of participants is high and their location, sociocultural background, or profession is heterogeneous. Both methods are valuable tools for the determination of shared knowledge among community members. A limitation of the derived metric is their sole focus on a central tendency across the sample, which obviously devalues individual observations which deviate from an identified shared consent.

In this dissertation, a consensus index after Rapinski et al. (2018) was calculated using interview data from 2018 and 2019 (N = 50). A simple consensus index was preferred to a CCA, as the communities were small and homogenous in regard to the sociocultural and economic situation of the community members. Further, a personal selection of the interview participants could be assured and their competence was judged by their engagement in the community workshops or identified by the village head or secular leader. After the interviews were conducted, trend observations were extracted and transferred to a binary code system (Table 6). As a result, each observation was assigned a value of -1, 0, or 1. Negative values indicate a decreasing trend and positive values an increasing trend. Based on this matrix, the consensus index was calculated after Rapinski et al. (2018), taking into account the ratio between the number of certain observations in respect to the total number of interviews. The closer the index is to 1 or -1, the higher the consent within the community in respect to the specific observation. The formula and further details about the consensus index can be found in manuscript 3.

Table 6. Numerical coding of trend observations, which were reported by the community members in semi-structured interviews, in order to calculate the consensus index.

	Direction of Change		
Observation	**-1**	**0**	**1**
Spring temperature	Colder	Same	Warmer
Summer temperature	Colder	Same	Warmer
Autumn temperature	Colder	Same	Warmer
Winter temperature	Colder	Same	Warmer
Rain	Less	Same	More
Snow	Less	Same	More
Snow Onset	Earlier	Same	Later
Snow Offset	Earlier	Same	Later

3.6 Software

R and ArcGIS have been used to process, analyse, and visualize climate and environmental data. The analysis of qualitative data was conducted using MAXQDA.

PART II

PUBLICATIONS

4 Individual Contributions to the Manuscripts

Manuscript 1 (Chapter 5)

Author: Isabell Haag, Phil D. Jones, Cyrus Samimi

Title: Central Asia’s Changing Climate: How Temperature and Precipitation Have Changed Across Time, Space, and Altitude

Journal: Climate (2019), 7 (10), 123; DOI: 10.3390/cli7100123

Status: published

Personal Contributions:

conceptualization 80 %, data analysis 100 %, methodology 70 %, writing original manuscript 100 %, review and editing 70 %, visualisation 80 %.

The concept of this study was done by IH, PJ, CS. IH analysed the data. IH, PJ, and SC interpreted and discussed the results. Figures and Tables have been designed by IH and implemented with the help of a cartographer (see acknowledgement). IH wrote the first draft of the manuscript. Review and editing of the manuscript was done by IH, PJ, and CS.

IH is the corresponding author.

Manuscript 2 (Chapter 6)

Author: Isabell Haag, Karim-Aly S. Kassam, Cyrus Samimi

Title: Ökologische Kalender im Pamir – Anpassung an den Klimawandel auf dem Dach der Welt

Journal: Geographische Rundschau (2019), 12, page 26 – 31

Status: published

Personal Contributions:

conceptualization 50 %, data acquisition 75 %, data analysis 100 %, writing original manuscript 70 %, review and editing 50 %, visualisation 50 %.

The concept of this study was done by IH and CS. Data acquisition has been done by IH, KAK, and CS. IH analysed the data. IH, KAK, and SC interpreted and discussed the results. Figures and Tables have been designed by IH and Morgan Ruelle and implemented with the help of a cartographer and the Westermann editorial team (see acknowledgement). IH and CS wrote the first draft of the manuscript. Review and editing of the manuscript was done by IH and CS.

IH is the corresponding author.

Manuscript 3 (Chapter 7)

Author:	Isabell Haag, Karim-Aly S. Kassam, Thomas Senftl, Harald Zandler, Cyrus Samimi
Title:	Measurements meet human observations: integrating distinctive ways of knowing in the Pamir Mountains of Tajikistan to assess local climate change
Journal:	Climatic Change (2021), 165 (5), DOI: 10.1007/s10584-021-02988-3
Status:	published

Personal Contributions:
conceptualization 90 %, data acquisition 80 %, data analysis 90 %, writing original draft 100 %, review and editing 80 %, visualisation 80 %.

The concept of this study was done by IH, KAK, CS. Data acquisition has been done by IH, KAK, and TS. IH and TS analysed the data. IH, KAK, HZ and SC interpreted and discussed the results. Figures and Tables have been designed by IH and implemented with the help of a cartographer (see acknowledgement). IH wrote the first draft of the manuscript. Review and editing of the manuscript was done by IH, KAK, TS, HZ, and CS.

IH is the corresponding author.

Manuscript 4 (Chapter 8)

Author:	Karim-Aly Kassam, Morgan L. Ruelle, Isabell Haag, Umed Bulbulshoev, Daler Kaziev, Leo Louis, Anna Ullmann, Iriel Edwards, Aziz Ali Khan, Cyrus Samimi, Antonio Trabucco
Title:	Engaging Transformation: Using Seasonal Rounds to Anticipate Climate Change
Journal:	Human Ecology
Status:	under review

Personal Contributions:

conceptualization 33 %, data acquisition 20 %, writing original manuscript 20 %, discussion 33 %, review and editing 33 %, visualisation 100 %.

The concept of this study was done by KAK, MR, and IH. Data acquisition has been done by KAK, MR, IH, UB, DK, IE, AAK, CS, and AT. KAK, MR, DK, LL, AU, and IE have analysed the data. KAK, MR, DK, LL, AU, and IE interpreted and discussed the results. Figures and Tables have been designed by KAK, MR, IH and implemented by IH. KAK, MR, and IH wrote the first draft of the manuscript. Review and editing of the manuscript was done by KAK, MR, IH, UB, DK, LL, AU, IE, AAK, CS, and AT.

IH is the third author of this study. KAK is the corresponding author.

5 Manuscript 1: Central Asia's Changing Climate: How Temperature and Precipitation Have Changed Across Time, Space, and Altitude

Isabell Haag, Phil D. Jones, Cyrus Samimi

Climate (2019), 7 (10), 123; DOI: 10.3390/cli7100123 climate

MDPI

Article

Central Asia's Changing Climate: How Temperature and Precipitation Have Changed across Time, Space, and Altitude

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Abstract: Changes in climate can be favorable as well as detrimental for natural and anthropogenic systems. Temperatures in Central Asia have risen significantly within the last decades whereas mean precipitation remains almost unchanged. However, climatic trends can vary greatly between different subregions, across altitudinal levels, and within seasons. Investigating in the seasonally and spatially differentiated trend characteristics amplifies the knowledge of regional climate change and fosters the understanding of potential impacts on social, ecological, and natural systems. Considering the known limitations of available climate data in this region, this study combines both high-resolution and long-term records to achieve the best possible results. Temperature and precipitation data were analyzed using Climatic Research Unit (CRU) TS 4.01 and NASA's Tropical Rainfall Measuring Mission (TRMM) 3B43. To study long-term trends and low-frequency variations, we performed a linear trend analysis and compiled anomaly time series and regional grid-based trend maps. The results show a strong increase in temperature, almost uniform across the topographically complex study site, with particular maxima in winter and spring. Precipitation depicts minor positive trends, except for spring when precipitation is decreasing. Expected differences in the development of temperature and precipitation between mountain areas and plains could not be detected.

Keywords: Central Asia; climate change; temperature trends; precipitation trends; trend analysis; seasonality

1. Introduction

Central Asia is one of the largest semi-arid areas in the world and argued to be a "hotspot" for climate change [1,2]. Temperatures are increasing more than the global mean [3,4] whereas mean precipitation only shows a minor increase [5,6]. Regional trends at the level of districts and valleys can however differ greatly from large-scale observations due to the complexity of the terrain and different atmospheric forces. Biophysical consequences of altered climate regimes are likely to include melting glaciers, changes in the seasonality of river-runoff regimes inducing seasonal water shortages, or altered vegetation patterns [7–10]. This may affect the livelihood of mountain communities who are mainly living on livestock-keeping and agriculture, and where natural resources are already limited [11]. In addition to climatic challenges, historical events have led to the fact that Central Asian countries are still confronted with political instability, poverty, or insufficient infrastructure [7,12,13]. Tackling climate change issues might, therefore, not be at the top of their priority list. Nevertheless, climate change already impacts the life of many people, particularly in rural areas, who have contributed little to anthropogenic climate change. Therefore, it is important to understand how temperature and precipitation have changed over time and space using publicly available data, to provide a basis for decision-making for impact studies and more detailed climate studies, on the level of the villages to protect the livelihood of Central Asian communities.

Previous research on Central Asians climate mostly focuses on specific subregions, like the Himalaya [14–16], Tian Shan [17–19], or Hindu-Kush/Karakoram [20–22]. Due to their functionality as over regional water towers these mountain ranges get attention in climatological and hydrological research [23]. Other studies analyze climatic changes over the topographically complex region of whole Central Asia, focusing on trends in either temperature [3,24–26] or precipitation [5,6,27,28]. These studies confirm a strong warming trend in Central Asia which has become accelerated in recent years. Temperatures do particularly increase in the Tian Shan and Himalayan region and precipitation in the westerly dominated Northwest. Although an overall trend of increasing precipitation can be seen, regional differences between lower and higher elevation areas are distinct [17,29]. In contrast to previous studies, this paper combines the two most important climate variables, temperature and precipitation, and statistically analyzes temporal and spatial trends, using well-known methods and publicly available data. Thus far, this combined approach has only been adopted by a few studies [4,12,18,19,30,31]. In addition, this paper also distinguishes between different altitudinal levels because Central Asia covers a diverse terrain.

Climate trend studies in Central Asia may obtain different results according to the dataset used. Looking at previous studies, a suite of datasets has been applied. Studies using meteorological station data [24,26,27,31] or station-based gridded products [3,5,25] benefit from the availability of station data since the beginning of the 20th century. However, the regional accuracy of these datasets is constrained by the low density of meteorological stations and their biased distribution against low-elevation areas. Further, most of the climate stations fell into disrepair after the breakdown of the Soviet Union, causing a dramatic drop in the amount of available stations after 1990 [32–34]. Station-based, gridded products like the Climatic Research Unit (CRU) [35], the Global Precipitation Climatology Centre (GPCC) [36], or the University of Delaware (UDEL) [37] are, therefore, better suited for temperature analyses than they are for precipitation, as temperature is rather uniform in space and fewer stations are required to get a robust result. Precipitation shows marked spatial heterogeneity needing a very dense homogenous station network [38]. The CRU TS has already been used in temperature analyses in Central Asia [3,25]. Satellite products, on the other hand, such as NASA's Tropical Rainfall Measuring Mission (TRMM) [39], provide spatially consistent records with high temporal resolution. While this dataset is limited to recent decades, it is suited for complex terrain [40–42]. Regional differences in the performance of precipitation datasets are more pronounced than for temperature datasets, motivating earlier studies to outline their discrepancies in Central Asian regions [21,28,32,34,43,44].

This study statistically examines seasonal temperature and precipitation trends in Central Asia from 1950 to 2016 across different terrain and altitudinal levels. By doing this it contributes to an integrative understanding of climatic change, as regional trends can differ greatly in their magnitude and temporal occurrence, inducing diverse consequences for local biophysical and social systems. To disentangle the patterns of overall changes and to differentiate their spatial intensity within the research area, linear trends have been calculated for the complete area, for the mountainous regions above 2500 m above sea level (masl) and for the lower plains under 2500 masl. To account for the problem of non-linear processes within the environmental data, we further analyzed anomaly time series to reveal low-frequency variations over time. As the applied dataset used may influence the results of trend studies, we selected publicly accessible climate datasets which provide high-spatial accuracy and long-term temporal coverage. However, the history of Central Asia and the complex terrain restrict the quality of available climate data in this region, which has to be seen as a limitation of this study.

2. Materials and Methods

2.1. Study Area

The study area extends from 35°00′ to 45°00′ N and from 65°00′ to 80°00′ E and covers the territory of Tajikistan and Kyrgyzstan and the partly bordering areas of Turkmenistan, Uzbekistan, Kazakhstan, China, Pakistan, and Afghanistan (Figure 1). The area exhibits complex terrain, with high mountain systems in the east and southeast to lower, adjacent lowlands and basins in the northwest and west. Altitudinal differences range from under 100 masl in the northwest to up to 8000 masl in the southeast. Its continental location contributes towards arid-to-semiarid conditions and high seasonal variations. The climate of Central Asia is mainly controlled by the westerlies, the Central Asian High, and the Indian Monsoon [13,45,46]. The northern part of the research area is significantly dominated by the mid-latitude westerlies and cold inflows from polar regions [6,24,34,45]. The south is influenced by the Indian Monsoon, although its moisture level is largely reduced by the mountain ranges of the Hindukush, Pamir, and Himalaya. The strength and location of the Central Asian High determines the peak of annual precipitation to be in winter and spring, when humid cyclones from the Mediterranean region enter the region from the south/southwest [46,47]. However, due to its high continentality mean annual precipitation sums are generally low. Most precipitation falls, orographically induced, along the western and southern flanks of the mountain arc. From there on, they constantly decrease towards the east, reaching their minimum in the Tarim basin. Temperature on the other hand, shows its maxima in the eastern and western lowlands, and generally decreases with an altitudinal gradient (Figure 2).

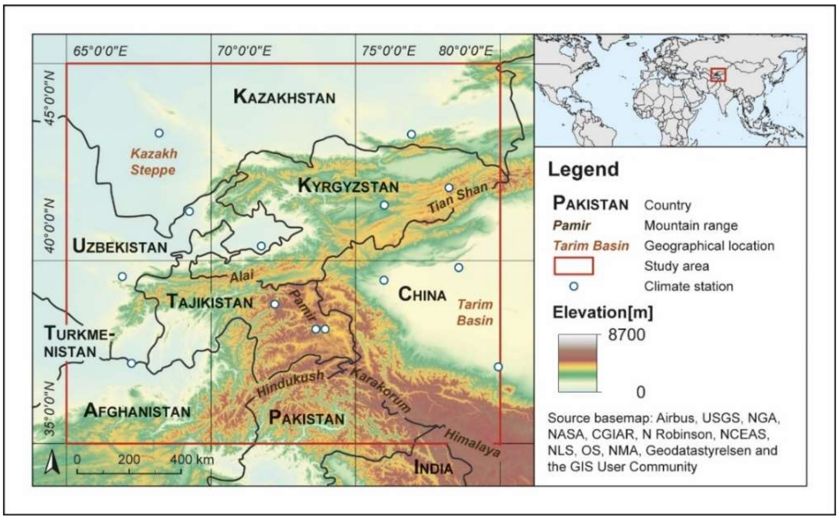

Figure 1. The research area and its geographical and topographical features, including the location of the meteorological stations used for the dataset validation.

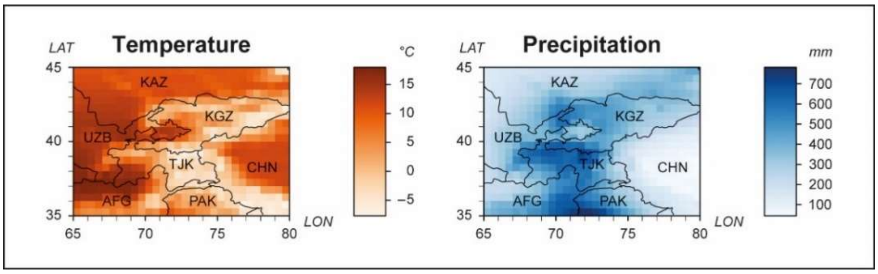

Figure 2. Mean annual temperature and precipitation sums within the study area for 1950–2016 using CRU TS 4.01.

2.2. Data

Table 1 gives an overview of the data sources used in this study. Whereas the CRU TS and the TRMM 3B43 have been used to conduct the trend analyses, the meteorological stations have been used to assess the local accuracy of the gridded products. The station requirements to be used for validation are (1) >80% of available data during 1950–2016 and (2) <5% missing values. Applying these criteria, no high altitude station is represented, which however would be important to validate the performance of the datasets over mountainous regions. Therefore, four stations above 2500 m have been additionally included, which do have at least a 50% data record coverage. The data is mostly complete for the period between 1950 and 1990. The location of the meteorological stations is shown in Figure 1.

Table 1. Overview of data sources used in this study (**A**). Information of meteorological stations used for validation (**B**).

(A)

Abbr.	Name	Variables	Spatial Resolution	Temporal Resolution	Source
OBS	Observations meteorological stations	Temperature Precipitation	Point data	Monthly	[48]
CRU TS	CRU TS v. 4.01 Climatic Research Unit	Temperature Precipitation	0.5° × 0.5°	Monthly 1901–2016	[35]
TRMM 3B43	TRMM 3B43 v. 7 Tropical Rainfall Measuring Mission	Precipitation	0.25° × 0.25°	Three-hourly since 1998	[39]

(B)

Number	WMO Code	Name	Latitude (°N)	Longitude (°E)	Elevation (masl)
1	36870	Almaty	43.23	76.93	847
2	51716	Bachu	39.80	78.57	1117
3	38618	Fergana	40.37	71.75	578
4	51828	Hotan	37.13	79.93	1375
5	no code	Irkht	38.16	72.63	3276
6	51709	Kashi	39.44	75.98	1291
7	no code	Lednik Phedchenko	38.83	72.22	4169
8	no code	Murghab	38.16	73.96	3576
9	36974	Naryn	41.43	76.00	2039
10	38696	Samarkand	39.57	66.95	726
11	38457	Tashkent	41.27	69.27	477
12	38927	Termez	37.23	67.27	309
13	36982	Tian Shan	41.88	78.23	3639
14	38198	Turkestan	43.27	68.22	206

2.2.1. CRU TS v. 4.01

To conduct the statistical analyses, the gridded dataset CRU TS v. 4.01 from the Climatic Research Unit at the University of East Anglia was used solely for temperature and in combination with TRMM 3B43 for precipitation. The CRU TS v. 4.01 was released in 2017 and is based on meteorological stations, providing interpolated data values on a 0.5° longitude/latitude grid. On average 33 and 46 stations were used between 1950–2016 for interpolating temperature and precipitation in the research area, respectively. The dataset contains ten different climatic variables, but only near-surface temperature and precipitation were used here. The dataset spans the period between 1901 and 2016. The monthly data were taken from January 1950 through December 2016. CRU TS v. 4.01 has been used in other regional climate change studies [5,34,49,50]. More information about the dataset and its influential stations can be found in [35]. To evaluate the performance of CRU we calculated the correlation coefficient after Kendall (R^2), the root mean squared error (RMSE), and the mean absolute error (MAE) for the time period 1950–2016 (Table 2). The correlation and error calculation was undertaken by comparing the available station data with the corresponding grid cell of the dataset, where the station is located. CRU shows a high correlation with observational temperature records and comparatively low RMSE und MAE values. However, a slight overfitting is possible as some of the validation stations are very likely included in the original CRU dataset. In addition, insufficient data are available for the high-altitude stations.

2.2.2. TRMM 3B43 v.7

NASA's Tropical Rainfall Measurement Mission version 3B43 V7 (TRMM 3B43) was used to provide information about recent decades' precipitation sums in the research area. The TRMM 3B43 merges high-quality microwave data with infrared data and analysis of rain gauges and is, therefore, able to account for small-scale precipitation variability [38]. The processed product is provided at hourly resolution, gridded on a 0.25° longitude/latitude grid. The dataset spans the period from 1998 to current values. The data were obtained from January 1998 through December 2016. The TRMM 3B43 precipitation data has been used in validation studies and other global and regional precipitation analyses [40,51,52]. Before conducting the trend analysis, the hourly TRMM 3B43 data was accumulated into monthly sums. In order to match the resolution of CRU TS, the monthly TRMM 3B43 were spatially aggregated to the CRU TS spatial resolution. To evaluate the performance of TRMM 3B43 in the study area, we calculated the correlation coefficient after Kendall (R^2), the root mean squared error (RMSE), and the mean absolute error (MAE) for the time period 1998–2016 (Table 2). Depending on the availability of station data, this time period could not always be fully covered. The performance measurements are undertaken by comparing the available station data with the corresponding grid cell of the dataset, where the station is located in. As many stations fell out of use after 1990, not every station remained suitable for validation. R^2 shows strong differences between the stations, whereas positive values are highly significant. High-altitude stations do not provide any data during this time period.

Table 2. Performance measurements of CRU TS 4.01 (temperature), TRMM 3B43 (precipitation), and CRU TS/TRMM 3B43 (precipitation) against 14 different meteorological stations. Model accuracy was assessed using Kendall's correlation (R^2), root mean squared error (RMSE), and mean absolute error (MAE). The validation was undertaken according to sufficient data coverage within the time period 1950–2016 for temperature, and 1998–2016 for precipitation. If the precipitation data coverage was not sufficient during that reference period, 1950–2016 was applied.

N°	Station	CRU TS 4.01 (Temperature)			CRU TS/TRMM 3B43 (Precipitation)			TRMM 3B43 (Precipitation)		
		R^2	RMSE (°C/month)	MAE (°C/month)	R^2	RMSE (mm/month)	MAE (mm/month)	R^2	RMSE (mm/month)	MAE (mm/month)
1	Almaty	0.96 *	0.62	0.46	0.64 *	10.29	8.05	0.28 *	11.77	9.67
2	Bachu	0.94 *	0.84	0.63	0.70 *	4.71	3.10	−0.04	28.40	21.70
3	Fergana	0.97 *	0.51	0.37	0.74 *	9.37	7.19	0.43 *	11.40	8.29
4	Hotan	0.97 *	0.51	0.36	0.64 *	4.58	3.57	−0.04	34.80	29.20
5	Irkht +	no data	no data	no data	0.87 *	14.38	10.32	no data	no data	no data
6	Kashi	0.95 *	0.78	0.58	0.71 *	7.48	5.06	−0.07	20.70	16.10
7	Lednik Phedchenko +	no data	no data	no data	0.88 *	23.62	17.34	no data	no data	no data
8	Murghab +	no data	no data	no data	0.39 *	24.04	18.39	no data	no data	no data
9	Naryn	0.94 *	1.16	0.84	0.59 *	10.34	7.60	0.43 *	15.26	10.72
10	Samarkand	0.97 *	0.54	0.41	0.83 *	10.60	7.93	0.53 *	13.60	10.50
11	Tashkent	0.97 *	0.56	0.42	0.84 *	8.66	6.53	0.24 *	15.64	11.56
12	Termez	0.96 *	0.68	0.50	0.82 *	9.84	6.44	0.75 *	16.10	12.10
13	Tian Shan +	no data	no data	no data	0.83 *	10.33	7.66	no data	no data	no data
14	Turkestan	0.97 *	0.71	0.50	0.94 *	6.37	4.46	no data	no data	no data

* Indicates significance at the 95% confidence level. + Indicates stations above 2500 masl.

2.3. Methods

All statistical analyses were completed using RStudio [53]. The graphics were finalized using ArcGIS (Esri Germany, Granzberg, Germany) and Adobe Illustrator (Adobe Systeme Software, Dublin, Ireland).

2.3.1. Linear Merging of the CRU TS and TRMM 3B43 Datasets

To conduct a long-term precipitation analysis, station-based gridded products are the only data source with a suitable temporal extent. However, high spatial variability of precipitation in combination with complex terrain and low meteorological station density reduced the accuracy of gridded, station-based precipitation products. Satellite-derived data has a much higher spatial resolution and is measured consistently over space, accounting for small-scale variability. Comparing CRU TS and TRMM 3B43 precipitation data for the period 1998–2016 shows a high correlation between the datasets, but differences in their monthly relationships (Figure 3). Looking at the different months, CRU TS mostly depicts higher values than TRMM 3B43, except for the summer months, where TRMM exceeds. To take the individual monthly amounts into account, we conducted a linear regression analysis between CRU TS and TRMM 3B43 on a monthly basis during their overlapping period 1998–2016. For each month, the estimated regression parameters were used to describe the statistical relationship between CRU TS and TRMM 3B43. To statistically adjust the historical CRU TS values according to this relationship, we calculated as follows:

$$Y_i = \alpha_m + X_i \times \beta_m, \quad (1)$$

where α is the intercept for month m and β the slope for month m, with m ranging from 1–804. X_i are the monthly CRU TS values from 1950–2016, with length $i = 804$. The new dataset Y_i was used to undertake the spatiotemporal precipitation analysis. The new dataset will be referred to as CRU TS/ TRMM 3B43. Table 2 shows the evaluation of CRU TS/TRMM 3B43 against observational records. Performance measurements were undertaken using the time period 1998–2016 to make the results comparable to the original TRMM performance. If the data availability of TRMM was not given during that period, 1950–2016 was chosen. Correlation values are lower than for temperature, but still high and significant. In comparison to the original TRMM performance, R^2 strongly increased and RMSE and MAE decreased. This validation shows the improved performance of the new created CRU TS/TRMM 3B43 dataset, compared to TRMM 3B43.

2.3.2. Temporal Trend Analysis

Annual and seasonal climatic trends are computed by averaging the grid-cells in the region between 1950 and 2016. Seasons are defined as spring (MAM: March, April, May), summer (JJA: June, July, August), autumn (SON: September, October, November), and winter (DJF: December, January, February). Seasonal and annual anomaly time series were calculated in order to extract general trends and low-frequency (annual, decadal, multidecadal) variations. The anomalies were calculated by subtracting the seasonal temperature means for each year from its respective mean of the period 1950–2016. Furthermore, long-term linear trends and 10-year moving averages were separately applied to quantify the tendency of change and to smooth interannual variability, respectively. The significance of the trends is tested at the 95% confidence level. The moving average was calculated using the R-package 'forecast' [54]. In addition to the overall linear trend, a single change point detection has been applied using the R-package 'cpm' to find erratic changes in the mean of the data sequences [55].

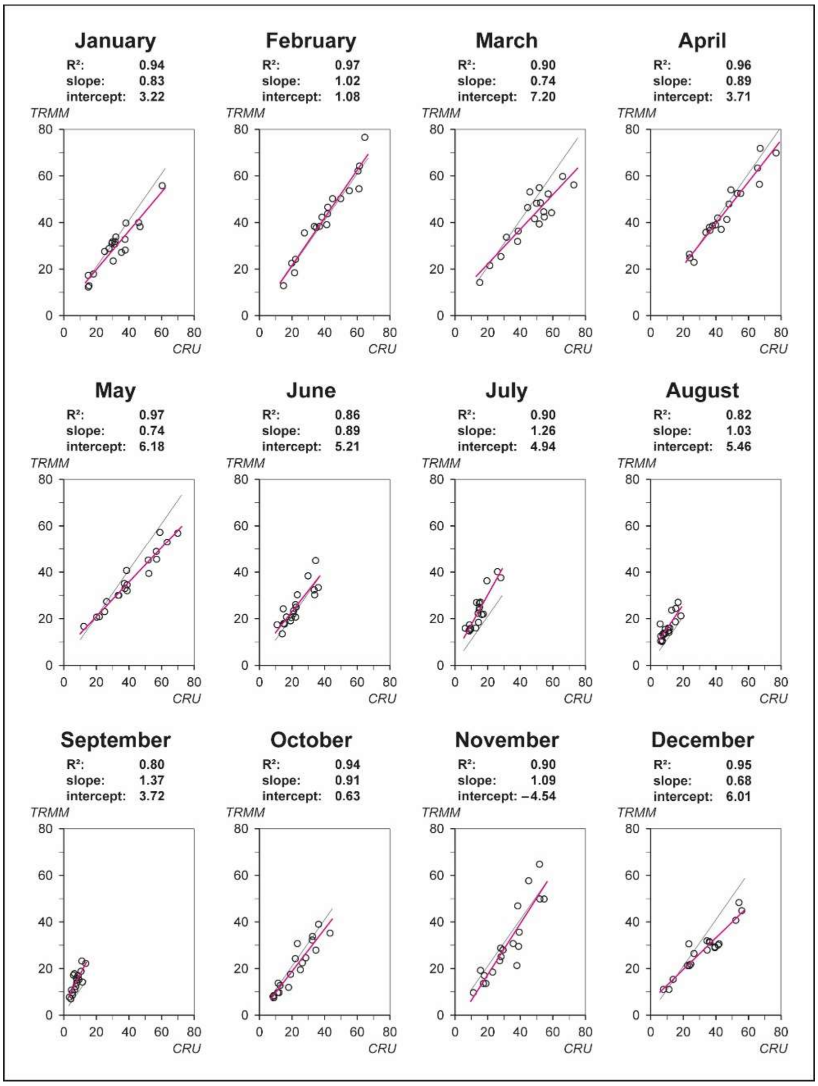

Figure 3. Monthly comparison between CRU TS4.01 and TRMM 3B43 for the period 1998–2016. The solid pink line is the linear regression and the solid black one is the 1:1 line.

2.3.3. Spatial Trend Analysis

Spatial changes in temperature and precipitation were analyzed using trend maps, showing the magnitude and significance of the derived linear trend, applied to every grid cell. Spatial differentiation between trends for higher elevation mountainous areas and lower elevation plains have been executed after the definition of the United Nations Environment Programme (UNEP). Mountain areas are defined as having (1) an elevation above 2500 m, (2) an elevation between 1500 m and 2500 m and a slope above 2°, (3) an elevation between 1000 m and 2500 m a slope above 5°, or (4) a local elevation above 300 m [56]. The significance and magnitude of the trends were derived using the function 'pwmk' from the R-package 'modifiedmk' [57]. The function 'pwmk', addresses the problem of temporal autocorrelation by prewhitening the time series prior to the trend calculation, following a similar approach to [58]. The trend magnitude is derived by Sen's slope estimator and the trend significance using the Mann–Kendall test.

Mann–Kendall Test

The Mann–Kendall test is a non-parametric, rank-based test, to test the statistical significance of a monotonic trend [59,60]. The Mann–Kendall test determines the existence of a monotonic trend in the mean of the data and its significance. The test is suitable for climatological time series as it does not have any requirements of the joint distribution of the data, and is insensitive to outliers and missing values [61,62]. The Mann–Kendall test statistic S is estimated as follows:

$$S = \sum_{i=1}^{n-1} sgn(x_{i+1} - x_i), \tag{2}$$

where n is the length of the data set; xi+1 and xi are sequential data values. The test statistic S is then standardized by:

$$sgn(\Delta x) = \begin{cases} +1, \ \Delta x > 0 \\ 0, \ \Delta x = 0 \\ -1, \ \Delta x < 0 \end{cases}, \tag{3}$$

If S is positive, an increasing trend can be assessed in the data, whereas a negative S implies a decreasing trend. After [59] and [60] the test statistic S is approximately normally distributed if $n \geq 8$. In this case, the mean (E) and the variance (Var) are calculated as follows:

$$\mathrm{E(S)} = 0, \tag{4}$$

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)}{18}, \tag{5}$$

where m is the number of tied groups and ti is size of the ith group. The standardized test statistic Z is then computed with a mean of zero and a variance of one:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}}, S > 0 \\ \frac{S+1}{\sqrt{Var(S)}}, S < 0 \end{cases}, \tag{6}$$

Theil and Sen's Slope Estimator

The Theil and Sen's slope estimator specifies the magnitude of a trend [63,64]. Sen's slope estimator was chosen over the widely used linear least square fitting method, as a normal distribution of the residuals is not always present in the climatological data. Sen's slope estimator assesses the slope of n data pairs as follows:

$$Q' = \frac{x_{t'} - x_t}{t' - t}, \tag{7}$$

where Q′ is the slope between the data points *x_t′* and *x_t*; *x_t′* is the data at time t' and *x_t* is the data at time t. The slope of the data values is the median of the N values of Q' values.

Sen's slope estimator is simply given by:

$$Q = Q'_{[\frac{N+1}{2}]} \text{ if } N \text{ is odd}, \tag{8}$$

$$Q = \frac{1}{2}(Q'_{[\frac{N+1}{2}]} + Q'_{[\frac{n+2}{2}]}) \ if \ N \ is \ even \tag{9}$$

where N is the number of calculated slopes.

3. Results

3.1. Temporal Changes in Air Temperature

Annual and seasonal mean surface temperatures increased significantly in the research area, showing a positive long-term trend, particularly in winter. Whereas annual temperatures increased at a rate of 0.28 °C per decade, the other seasonal trends lie in-between the minimum rate of 0.20 °C per decade in summer and the maximum rate of 0.32 °C per decade in winter (Table 3). However, the anomaly time series reveal the non-linear behavior of temperature change including prominent turning points in the seasonal averages (Figure 4). After the late-1990s the magnitude of the positive trend line gets accelerated in all seasons, except for winter. This warming period marks a turning point, from alternating warmer and colder years, towards a period of almost exceptionally strong positive deviations. In winter, the temperature change shows a different characteristic. Positive anomalies start to dominate in the late-1970s, inducing a longer, but less intense, time of warming.

Table 3. Linear trends of seasonal (A) and monthly (B) temperature and precipitation during 1950–2016 by Sen's slope method using a pre-whitened time series. Trend magnitudes, confidence intervals for sens slope, and z-statistics are calculated for the full area '*Full*' and for mountainous regions '*Mnt*' and lower plains '*Pln*'. * Indicates significance at the 95% confidence level.

A	**Temperature (°C/decade)**								
Season	***Full***	***z-value***	***Confidence Interval***	***Mnt***	***z-value***	***Confidence Interval***	***Pln***	***z-value***	***Confidence Interval***
Annual	0.28 *	6.47	0.22–0.35	0.13 *	3.40	0.07–0.21	0.18 *	3.84	0.11–0.29
MAM	0.30 *	4.31	0.18–0.41	0.15 *	3.36	0.00–0.20	0.17 *	3.39	0.00–0.23
JJA	0.20 *	5.31	0.14–0.27	0.07 *	4.22	0.02–0.09	0.09 *	5.28	0.05–0.12
SON	0.28 *	5.26	0.18–0.39	0.12 *	4.49	0.00–0.15	0.15 *	4.16	0.00–0.17
DJF	0.32 *	2.88	0.13–0.54	0.11 *	3.63	0.06–0.17	0.10 *	2.84	0.05–0.19
Season	**Precipitation (mm/month)**								
	Full	***z-value***	***Confidence Interval***	***Mnt***	***z-value***	***Confidence Interval***	***Pln***	***z-value***	***Confidence Interval***
Annual	3.13	0.94	−2.48–+8.21	2.22	0.73	−3.36–+8.26	2.41	1.35	−1.80–+9.33
MAM	−0.87	−0.35	−5.30–+3.35	−0.01	−0.04	−0.40–+0.30	−0.16	−0.69	−0.58–+0.29
JJA	0.68	1.05	−0.66–+2.12	0.00	0.02	−0.23–+0.20	0.15*	2.48	−0.58–+0.29
SON	1.29	0.93	−1.41–+3.78	0.14	1.12	−0.13–+0.42	0.13	1.32	−0.09–+0.33
DJF	2.48	1.98	0.01–4.87	0.28*	2.06	−0.03–+0.51	0.33	1.66	−0.13–+0.65

B	**Temperature (°C/decade)**						**Precipitation (mm/month)**					
Month	***Full***	***z-value***	***Mnt.***	***z-value***	***Pln.***	***z-value***	***Full***	***z-value***	***Mnt.***	***z-value***	***Pln.***	***z-value***
Jan.	0.40	2.95	0.37	3.25	0.37	2.35	0.12	0.19	0.21	0.43	0.56	0.54
Feb.	0.37	1.78	0.37	2.36	0.39	1.78	1.23	1.47	0.59	0.85	1.42	1.25
Mar.	0.38 *	3.20	0.28	2.60	0.37	2.45	−0.14	−0.09	−0.21	−0.15	−0.86	−0.65
Apr.	0.31 *	3.63	0.20	2.75	0.29 *	2.91	−0.64	−0.76	−0.67	−0.70	−0.95	−0.98
May	0.20	2.59	0.18	2.19	0.22	2.58	0.04	0.04	0.16	0.13	−0.49	−0.48
Jun.	0.25 *	4.29	0.20 *	3.60	0.26 *	3.73	0.19	0.48	0.02	0.07	0.46	1.18
Jul.	0.15 *	3.24	0.15 *	2.94	0.14	2.63	0.24	0.57	0.04	0.13	0.41	1.57
Aug.	0.22 *	4.05	0.12	2.74	0.18 *	3.02	0.22	0.02	0.20	0.75	0.45 *	2.18
Sep.	0.23 *	4.22	0.17 *	2.96	0.20 *	3.49	0.21	1.26	0.24	1.12	0.25	1.57
Oct.	0.26 *	3.46	0.19	2.60	0.23	2.61	0.87	1.20	0.99	1.14	0.54	0.76
Nov.	0.39 *	3.13	0.24	2.32	0.27	2.09	0.41	0.50	0.08	0.05	0.73	0.81
Dec.	0.28	2.14	0.21	1.88	0.25	1.69	1.06	1.32	1.07	1.43	0.63	0.59

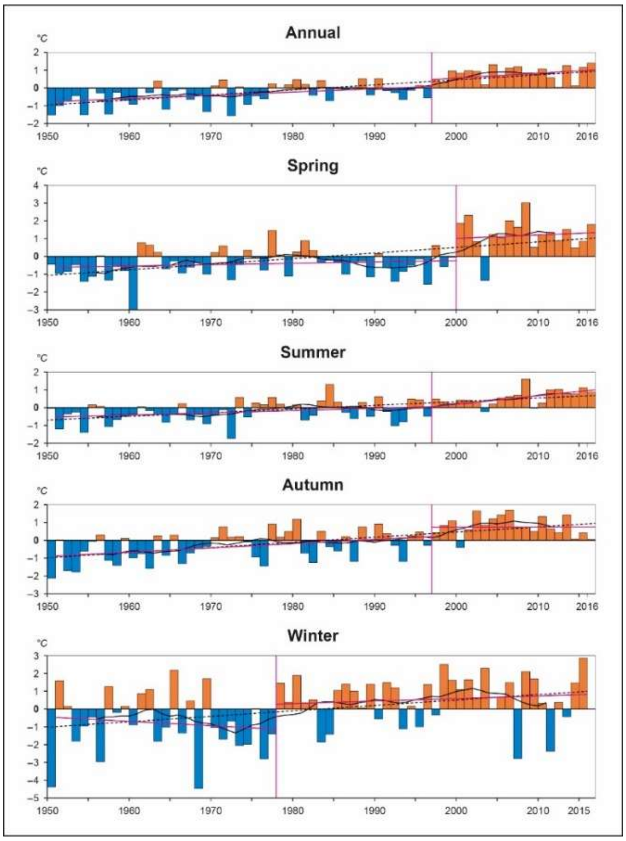

Figure 4. Seasonal and annual temperature anomaly time series from 1950–2016 for the research area. The solid black line is the 10-year moving average line and the dashed black line the linear trend. The pink lines show the year of the change point and the trend direction before and after the change point.

3.2. Spatial Changes in Air Temperature

Trend maps for 1950–2016 show the long-term magnitude and significance of linear temperature change per grid cell. The results, as shown in Figure 5, indicate a significant increase in temperature throughout the area. At the annual-mean scale, and in the spring, summer, and autumn seasons, the great majority of grid cells are significant at the 95% level, with the exception of the north of Afghanistan and Pakistan in summer and spring. In winter, a bipolar pattern of significantly higher warming rates in the east and non-significant lower warming rates in the west is visible. Regarding the intensity of the warming trend, northern regions are warming at a higher rate than southern regions (Figure 5). This north–south gradient is distinct in spring, summer, and autumn. In winter, a reducing temperature gradient from the northeast to the southwest is more pronounced. Elevation-based trend differences, according to our classification into 'mountains' and 'plains', are not distinct (Table 3). However, the lower plains show slightly higher trend rates than the mountainous region.

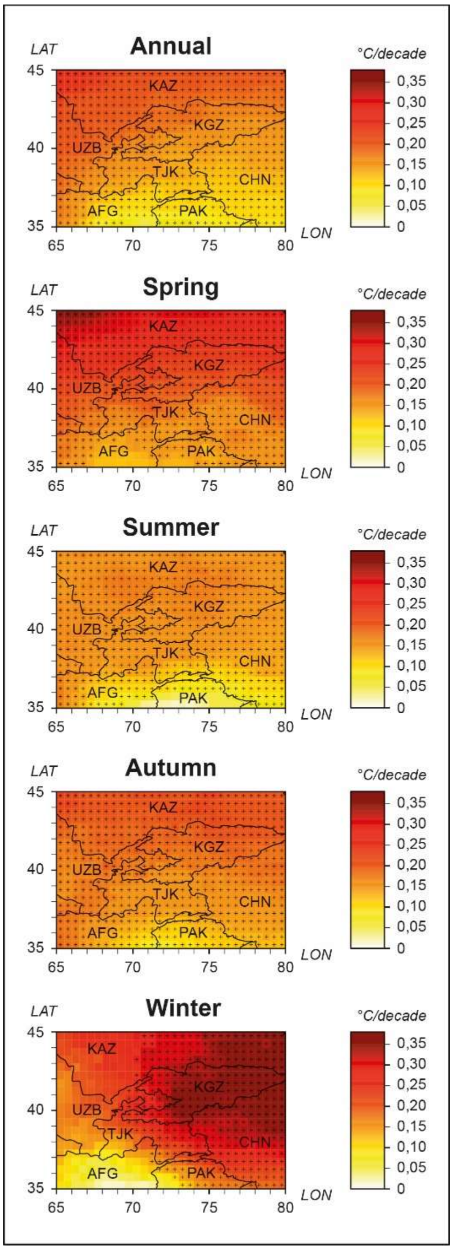

Figure 5. Seasonal and annual temperature trends across the research area for 1950–2016. Statistically significant trends are marked with a plus sign.

3.3. Temporal Changes in Precipitation

Annual and seasonal precipitation do not show any significant long-term statistical trend. Still, precipitation sums tend to increase at the annual level and in all seasons, except for spring. Annual precipitation increased by 3.13 mm per decade, mostly due to enhanced winter precipitation (Table 3). The anomaly time series reveal high year-to-year fluctuations within the seasons (Figure 6). In summer, autumn, and winter, a fluctuating pattern between consecutive years of either positive or negative anomalies is visible. In spring, anomalies alternate strongly at a yearly basis, with additional growth of the recent years' negative deviations. Considering the proportions of seasonal precipitation over time, no profound change can be detected. The highest proportion of annual precipitation occurs in spring (40%), followed by winter (29%). In these two seasons, which provide over two-thirds of the annual precipitation, the variability within the data is much higher than in the dry summer months, where precipitation is the lowest of all four seasons (13%) (Figure 7).

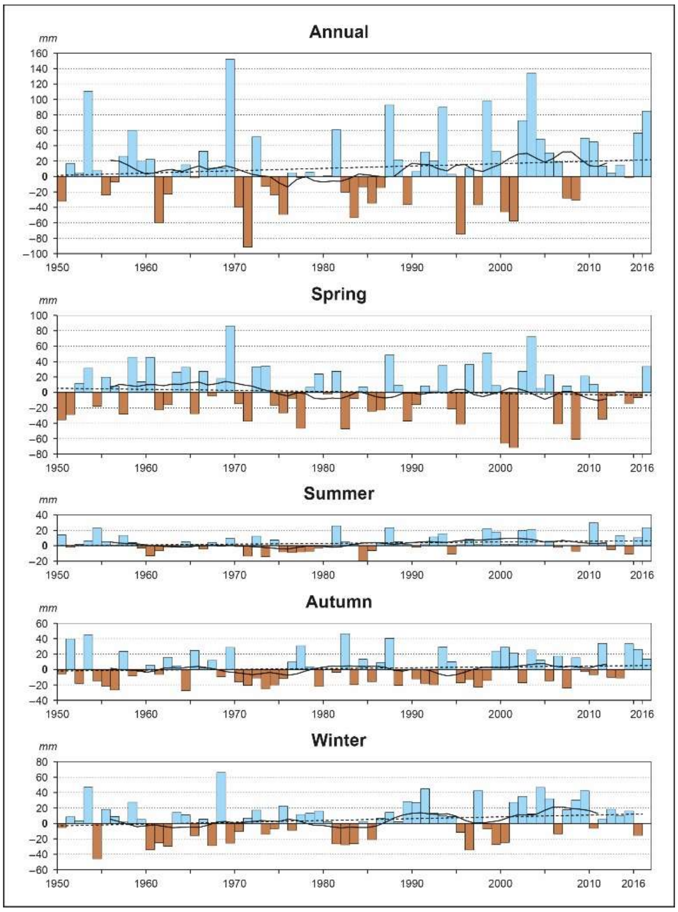

Figure 6. Seasonal and annual precipitation anomaly time series from 1950 to 2016 for the research area. The solid black line is the 10-year moving average line and the dashed black line is the linear trend.

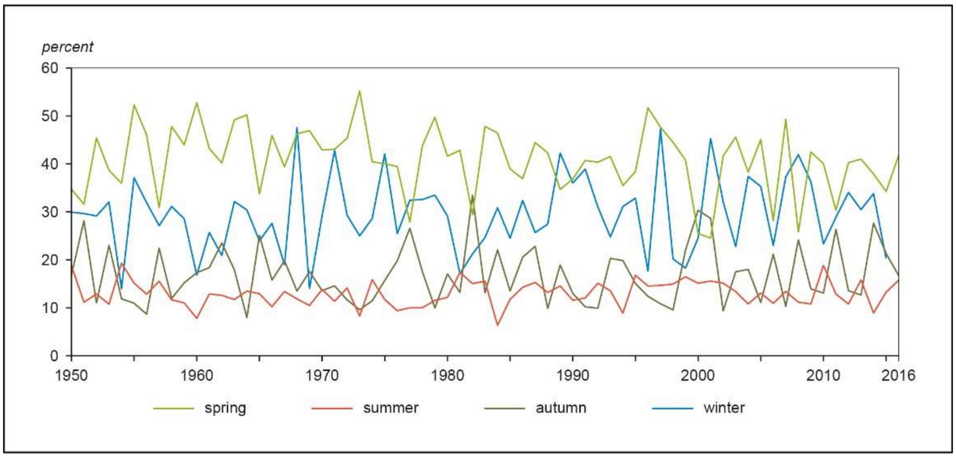

Figure 7. Seasonal proportions of annual precipitation sums in the research area from 1950 to 2016.

3.4. Spatial Changes in Precipitation

In the great majority of the research area, precipitation is not changing significantly (Figure 8). However, the summer, autumn, and winter seasons exhibit isolated patches of significant changes. In summer, the north of Afghanistan and Pakistan, and the Tajik Pamirs are significantly gaining precipitation. In winter, significantly increasing trends can be seen around West Tajikistan and in the northeastern corner of the research area. The intensity of precipitation trends is also unevenly distinct but, often, high trends coincide with the identified significance areas (Figure 8). The largest region of decreasing precipitation trends occurs in spring, covering almost the whole research area. In winter and autumn, drier regions are narrowed down towards the southeast quarter of the research area, whereas in summer, less precipitation can be observed in the region along the northern border of Kyrgyzstan. One of the most pronounced areas of precipitation are located in the north of Afghanistan and Pakistan, and in the Tajik Pamirs in summer. In autumn and winter, a diagonal zone from the southwest to the northeast displays positive trends. In both seasons, additional enhanced spots can be seen in the northeast corner of the research area and West Tajikistan, respectively. Whereas the trend maps do not reveal a clear distinction between different trend tendencies in mountainous and plain regions, Table 3 outlines a stronger increase in precipitation for the lower plains. However, this is not significant.

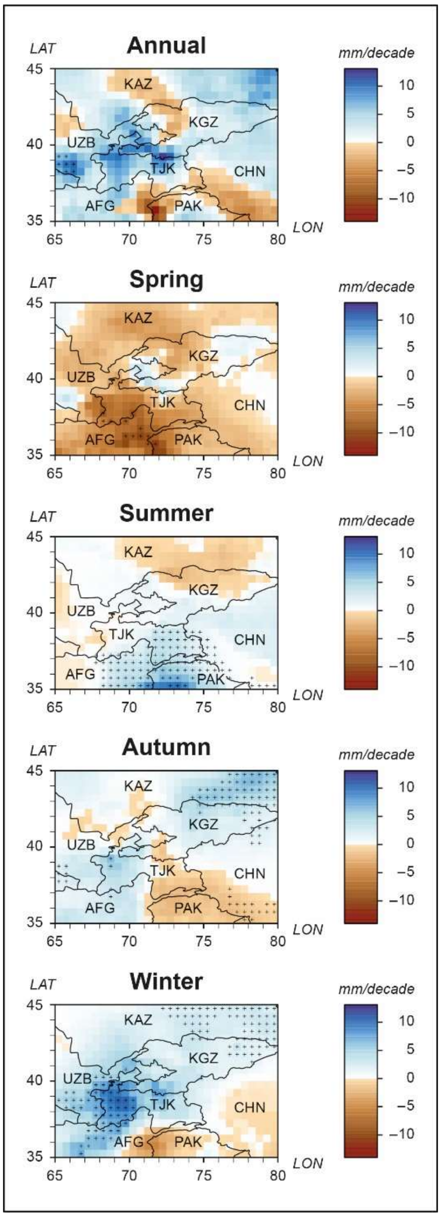

Figure 8. Seasonal and annual precipitation trends across the research area for 1950–2016. Statistically significant trends are marked with a plus sign.

4. Discussion

Our study confirms the strong warming trend of Central Asia, with an abrupt acceleration of its intensity in the mid-1990s. The significant increase in annual and seasonal temperatures has already been identified in previous studies, however with different trend magnitudes [3,24,25]. Our results indicated an annual temperature increase of 0.28 °C per decade (1950–2016), compared to the outcomes of [3] and [24], who found an annual temperature increase of 0.39 °C per decade (1979–2011) and 0.16 °C per decade (1901–2003), respectively. Discrepancies in the trend magnitudes are likely caused by different regional extents, time periods, and data sources. This methodological constraint might also affect the results of other Central Asian studies [3,5,65,66], and global studies [67], as their time series also show an abrupt change of the mean in the late 20th century. It can be summarized that, despite different time periods and different datasets, all large-scale studies agreed on a strong warming trend averaged over Central Asia, which has accelerated in recent years.

Seasonal investigations in trend characteristics showed that spring and winter are under the greatest change. Spring and winter are important seasons in Central Asian because (1) two thirds of the annual precipitation is falling during that time, and (2) water reservoirs in the form of snow and ice are built up [68]. Altered precipitation patterns during these months can induce water shortages in summer, effect agricultural yields in autumn, and modify snow-regimes [9,69,70]. However, our data does not reveal any significant changes in precipitation. In terms of temperature, both seasons show a significant increase. According to our results, winter displays the highest rate of temperature increase (0.32 °C per decade), followed by spring. These data are consistent with earlier studies that also show winter as the most rapidly warming season in this region [13,18,24]. Some studies, however, show the contrary, with spring as the greatest warming season, directly followed by winter [3]. According to [49], it can be summarized that the colder seasons of the year are warming the most in semi-arid regions.

As temporal trends are averaged over the whole research area, it is important to assess their local characteristics by using grid-based trend maps. The accuracy of the trend maps is defined by the spatial resolution of the input data. Therefore, to reveal spatial trend differences the choice of data is important. Our data has a resolution of 0.5 degree and can account for general differences between geographical regions (Figures 4 and 7). Using this data we identified a general increase in temperature across the whole research area, whereas the northern parts do warm more than the southern parts. Finding a possible explanation for this north–south gradient was beyond the scope of this study and should be further investigated in future research. In terms of precipitation no clear pattern could be identified using the visual trend maps. However, as earlier studies already assessed the importance of elevation dependent temperature and precipitation rates [71] but gained controversial results, we looked at this in more detail, calculating additional trend rates. Due to the scarce coverage of meteorological stations in high-altitude areas, it is difficult to gain significant evidence for elevation dependent gradients. Therefore, earlier study results are often contradicting. Whereas [19] does not recognize altitudinal effects on temperature change, [3] found that lower elevations warm more than higher elevations, but only in some regions in Central Asia. For precipitation it is even more difficult, as it can be spatially and temporally highly variable. However, both [17,29] detected a slight tendency towards higher trend rates in lower Central Asian plains. Our results also show higher trend magnitudes for plains, but not at a significant level (Table 3). The same situation can be seen for temperature, where plains tend to increase at a stronger rate. These results might be affected by the lack of observational data in high-elevation areas. In addition, looking at the spatial distribution of temperature and precipitation trends in Figures 5 and 8, no clear difference between trend tendencies in plains and mountains can be seen. As the mountains of Central Asia are inhabited at many different altitudinal levels and because the impacts of climate change can have different characteristics from valley to valley, it is important to build up the station network to higher altitudes. This would allow to obtain more precise information about elevation-dependent trends and impacts, especially because communities at high-altitudes are less resilient against climatic changes, as their food and water sources are limited.

The accuracy of the results is limited by the availability of accurate climate data in high altitudes and missing long-term records. The complexity of the terrain makes regional trends differ greatly from large-scale observations and the sparse meteorological stations coverage impacts the accuracy of Central Asian gridded climate datasets. Due to the low resolution of the applied gridded products, climatic processes at finer spatial and temporal scales, like extreme events or low-frequency variations are neglected [72,73]. To obtain information about fine-scale processes, which are important for assessing climate change impacts and vulnerability scenarios, various downscaling methods or stochastic models could be applied [72–74]. By applying a combined dataset of the gridded station product CRU TS and the satellite product TRMM 3B43, we attempted to account for the problem of precipitation data accuracy. Nevertheless, our trend magnitudes differed from previous studies, whereas the general tendency was in accordance. It is a challenge to analyze precipitation trends in complex and data sparse regions. However, understanding climatic change in Central Asia and investigating its regional differences is important because of the subsistence-based and natural-controlled lifestyle of the rural communities and the dependence on glacier and snow packs for the regional water supply. To provide a suitable basis for adaptation strategies, 0.5 degree resolution is insufficient in a complex mountainous terrain. Therefore, future studies should amplify their spatial resolution and focusing on the level on the villages, because that is the level where people are impacted by the consequences of climate change.

Author Contributions: Conceptualization: I.H., P.D.J., and C.S.; formal analysis: I.H.; investigation: I.H.; methodology: I.H., P.D.J., and C.S.; supervision: I.H., P.D.J., and C.S.; validation: I.H.; visualization: I.H.; writing—original draft: I.H.; writing—review and editing: I.H., P.D.J., and C.S.

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6 Manuscript 2: Ökologische Kalender im Pamir – Anpassung an den Klimawandel auf dem Dach der Welt

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Ökologische Kalender im Pamir

Anpassung an den Klimawandel auf dem Dach der Welt

Das Klima im Pamir hat sich in den letzten Jahrzehnten stark verändert. Steigende Temperaturen und veränderte Niederschlagsmuster stellen Landwirte vor große Herausforderungen. Ackerbau und Viehhaltung sind oft die einzige Lebensgrundlage in den abgeschiedenen Bergregionen. Was also tun, wenn sich Umwelt und Klima verändern und dadurch Ernteausfälle und Viehsterben die Existenz bedrohen? Die Wiederbelebung traditioneller ökologischer Kalender bietet eine vielversprechende Möglichkeit für die lokale Bevölkerung, mit den bevorstehenden Folgen der globalen Klimaveränderung umzugehen.

Der Hochgebirgsknoten des Pamir, in dem die Gebirgsketten des Karakorum, Hindukusch, Kunlun und Tian Shan zusammenlaufen, wird auch als Dach der Welt bezeichnet (vgl. Abb. 1). Die Gebirgsstruktur, die sich durch sehr große Höhe auszeichnet, und das auf 3 500–4 000 m ü. d. M. liegende Hochplateau des Ostpamir mit seinen breiten Talböden, den namensgebenden Pamiren, tragen zum Bild des Dachs der Welt bei. Überragt werden diese Pamire von bis zu 6 000 m hohen Gebirgszügen (Samimi et al. 2011). Der Westpamir zeigt eine ganz andere landschaftliche Charakteristik: tief eingeschnittene Täler und Gipfel, die Höhen von über 6 000 m ü. d. M. errei-

Foto 1: Alaital mit dem Transalai, der nördlichen Gebirgskette des Pamir. Etwas links der Straße thront der Pik Lenin mit 7134 m der vierthöchste Gipfel des Pamir, der in Tadschikistan heute Ibn Sina Peak heißt

Foto: C. Samimi

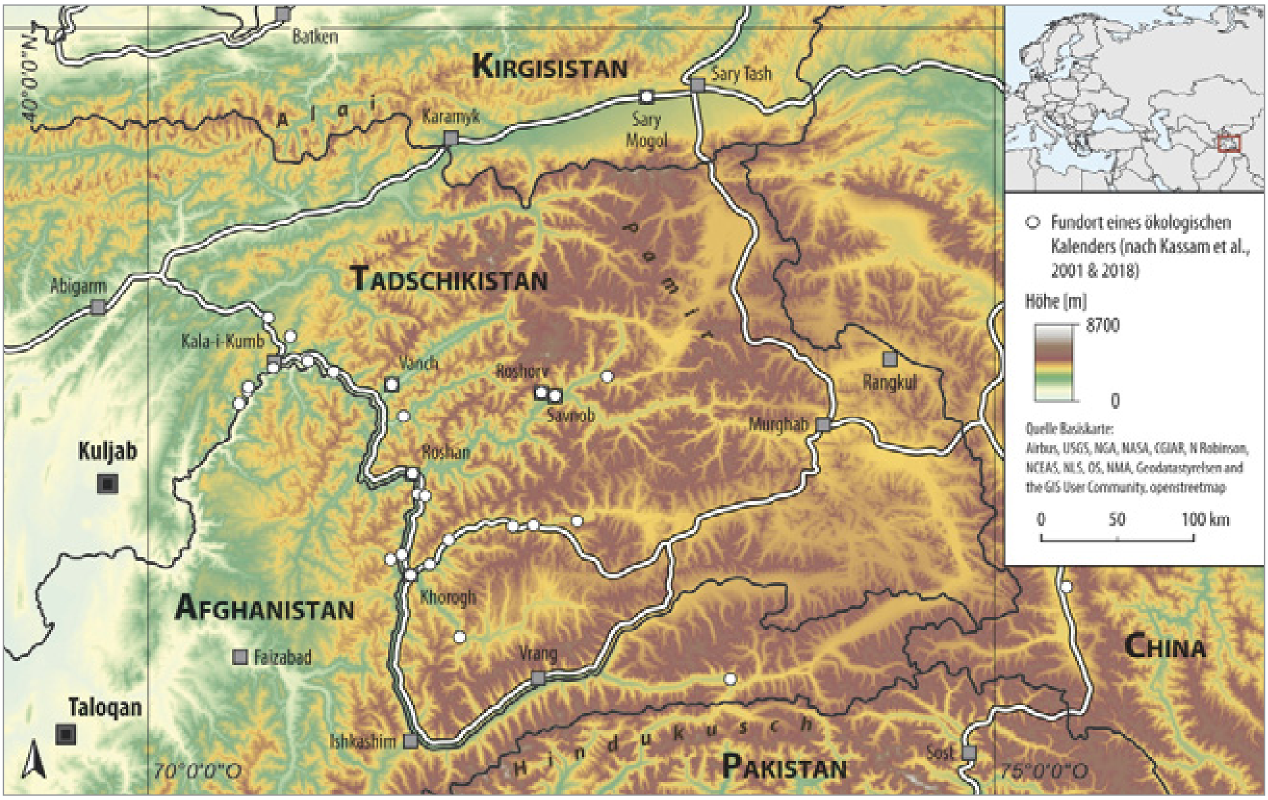

Abb. 1: Der Pamir als zentraler Gebirgsknoten in Zentralasien mit der Verortung nachgewiesener ökologischer Kalender

Quelle: Fundorte ökologischer Kalender nach Kassam et al. 2011, Kassam et al. 2018

chen; der Pik Ismail Samani verzeichnet sogar 7495 m ü. d. M. Die höchsten Gipfel befinden sich aber am östlichen Rand des Pamir in China, mit dem Muztagata (7509 m ü. d. M.) und dem Kongur (7719 m ü. d. M.). Besonders eindrucksvoll zeigt sich der Gebirgsblock von Norden betrachtet aus dem Alaital. Das Tal liegt auf einer Höhe von etwa 3000 m und wird im Süden von der deutlich über 6000 m hohen Transalai-Kette überragt (vgl. Foto 1). Die große Höhe und die ausgesprochen kontinentale Lage bestimmen das Klima des Pamir und damit die ökologischen Rahmenbedingungen für die menschliche Nutzung.

Die unterschiedliche Topographie zwischen Ost- und Westpamir bedingt deren verschiedene Vegetation und Klimata. Der Westen mit hauptsächlich Winterniederschlägen ist feuchter, wobei auch hier nur die hohen Gebirgszüge und Gebirgsränder Niederschläge von mehr als 500 mm pro Jahr erhalten. Die Tallagen verzeichnen hier einen jährlichen Niederschlag von etwa 200 mm, im Ostpamir sind es teilweise sogar weniger als 100 mm (vgl. Abb. 2). Gepaart mit den niedrigen Temperaturen führt dies zu Baumfreiheit oberhalb von etwa 3500 m ü. d. M. In tieferen Lagen stehen Bäume nur entlang von Flussläufen oder auf Überschwemmungsflächen. Ansonsten ist die Landschaft von Steppen und Halbwüstenvegetation gekennzeichnet (Vanselow 2011, Vanselow et al. 2016, Walter und Breckle 1991).

Durch die geringen Niederschlagsmengen ist die örtliche Wasserversorgung stark von Bächen und Flüssen abhängig, die aus Gletschern, Schnee und Permafrost gespeist werden. Nur mit Bewässerung lassen sich in tieferen Lagen u. a. Weizen, Kartoffeln, Bohnen und Gemüse anbauen sowie Obstbäume kultivieren. In größeren Höhen können wegen der niedrigeren Temperaturen fast nur noch Gerste, Kartoffeln und Futterpflanzen angebaut werden. Neben Ackerbau spielt auch die Viehhaltung eine wichtige Rolle. Im Sommer treiben die Hirten ihre Ziegen, Yaks, Rinder und Schafe auf entfernte Weideflächen, wo sie mit ihnen für Monate verweilen. Ehlers und Kreutzmann (2000) bezeichnen diese in Hochasien weit verbreitete Form der Landwirtschaft als kombinierte Berglandwirtschaft. Im Ostpamir kann wegen der niedrigen Temperaturen nur mobile Viehwirtschaft betrieben werden (Kraudzun et al. 2014). Im Westpamir sind im Winter ganze Regionen immer wieder durch Lawinenabgänge und im Sommer durch Hochwasser und Hangrutsche von der Außenwelt abgeschnitten, weshalb ein autarkes Nahrungssystem lebenswichtig ist.

Historische ökologische Kalender

Das enge Zusammenspiel von Mensch und Natur bedingt seit Jahrhunderten die Verwendung ökologischer Kalender in Zentralasien und anderen Regionen der Erde. In Zentralasien konnte ihre Existenz im Norden Afghanistans, im tadschikischen Pamir, im kirgisischen Alaital und in der chinesischen Provinz Xinjiang nachgewiesen werden (Kassam et al. 2011, Kassam et al. 2018) (vgl. Abb. 1). Die Kalender dienen der Koordination

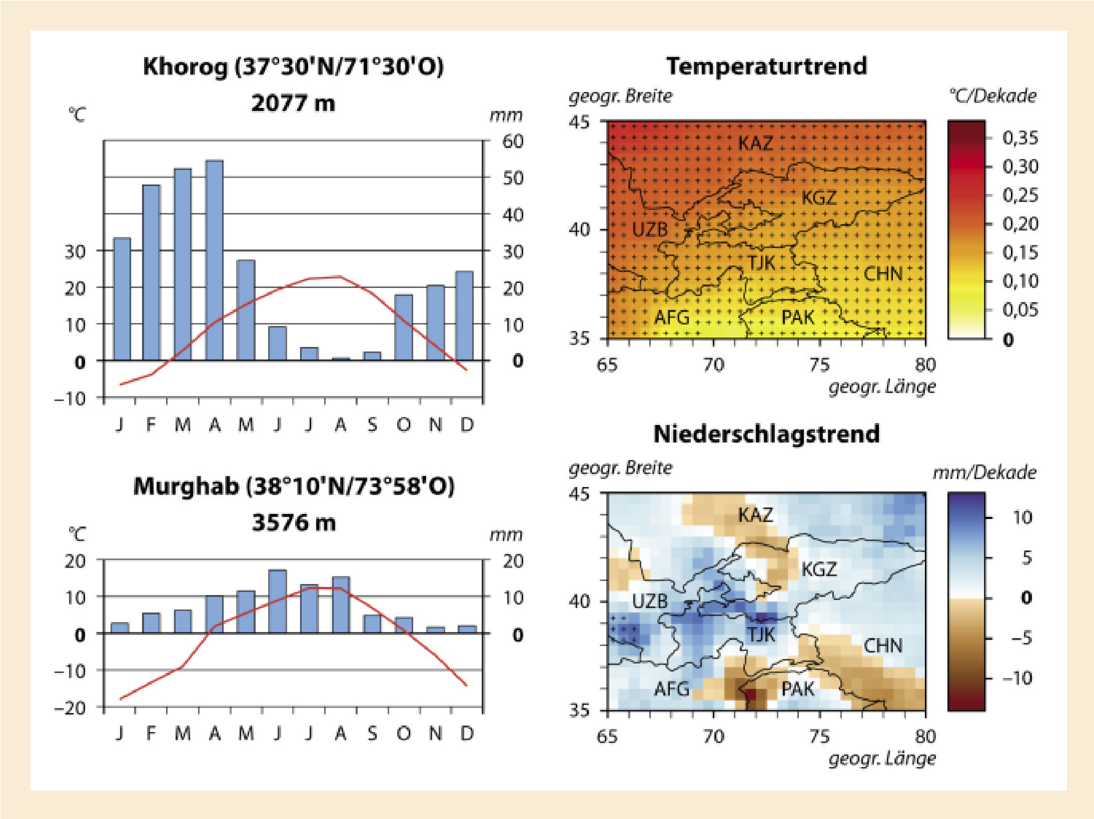

Abb. 2: Die Klimastationen in Khorog und Murghab zeigen den ausgeprägten klimatischen Unterschied zwischen West- und Ostpamir. Während der Anstieg der Temperatur seit 1950 in Zentralasien signifikant ist, zeigt der Trend des Jahresniederschlags ein heterogenes Bild

Quellen: State Administration for Hydrometeorology of the Republic of Tajikistan 2013), Datensätze CRU TS 4.01 (ttps://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.01) und TRMM 3B43 (Huffman u. Bolvin 2018)

von landwirtschaftlichen und kulturellen Aktivitäten innerhalb eines Jahres, die von bestimmten atmosphärischen, meteorologischen und ökologischen Ereignissen abhängen. Die Kalender orientieren sich am Auftreten sogenannter Indikatorereignisse und haben somit keine festgelegten Zeitabschnitte wie etwa der gregorianische und iranische Sonnenkalender oder der islamische Mondkalender. Indikatoren können der Blühbeginn einer Pflanze oder die Ankunft von Zugvögeln sein. Abbildung 3 zeigt exemplarisch die Funktionsweise eines ökologischen Kalenders. Beispielsweise kann der Zeitpunkt der Aussaat an den Blühbeginn einer Indikatorpflanze geknüpft werden. Den Wetterbedingungen entsprechend, kann dieser Zeitpunkt von Jahr zu Jahr variieren. Hierbei lässt eine Synchronisierung von landwirtschaftlichen Aktivitäten mit klimasensitiven Indikatoren einen höheren Ernteertrag erwarten, da den jährlichen Wetterbedingungen Beachtung geschenkt wird. Eine Orientierung an festen Kalendertagen kann diese Flexibilität nicht gewährleisten und birgt das Risiko einer zu frühen oder zu späten Aussaat und damit einer Gefährdung des potenziellen Ernteertrags. Insbesondere in Zeiten steigender Klimavariabilität, ist diese Flexibilität in der Landwirtschaft wichtig, wobei ökologische Kalender das Potenzial haben, diese Variabilität zu erfassen. Eine Verwendung von ökologischen Kalendern setzt jedoch ein tiefgründiges Verständnis der Ökologie und Klimatologie voraus. Um die Effizienz der Kalender zu bewahren, müssen die Menschen deshalb ihr lokales Wissen regelmäßig anwenden und es an die sich verändernden meteorologischen, ökologischen und soziokulturellen Bedingungen anpassen.

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Eine nahezu vergessene Tradition?

Während des 20. Jahrhunderts wurde die Landwirtschaft selbst in den entlegensten Dörfern des Pamir kollektiviert und modernisiert (Herbers 2006). Es wurde großflächig bewässert, technisiert und gedüngt. Kam es zu Ernteausfällen oder Futterknappheit, war eine Versorgung von außen weitgehend gesichert. Dadurch geriet die Verwendung ökologischer Kalender und das damit verbundene indigene Wissen weitgehend in Vergessenheit oder wurde teilweise sogar aktiv unterdrückt. Auch eine Verschriftlichung erfolgte kaum. Eine Ausnahme bilden nur wenig von der Außenwelt beeinflusste Dörfer in Afghanistan, in denen bis heute ökologische Kalender verwen-

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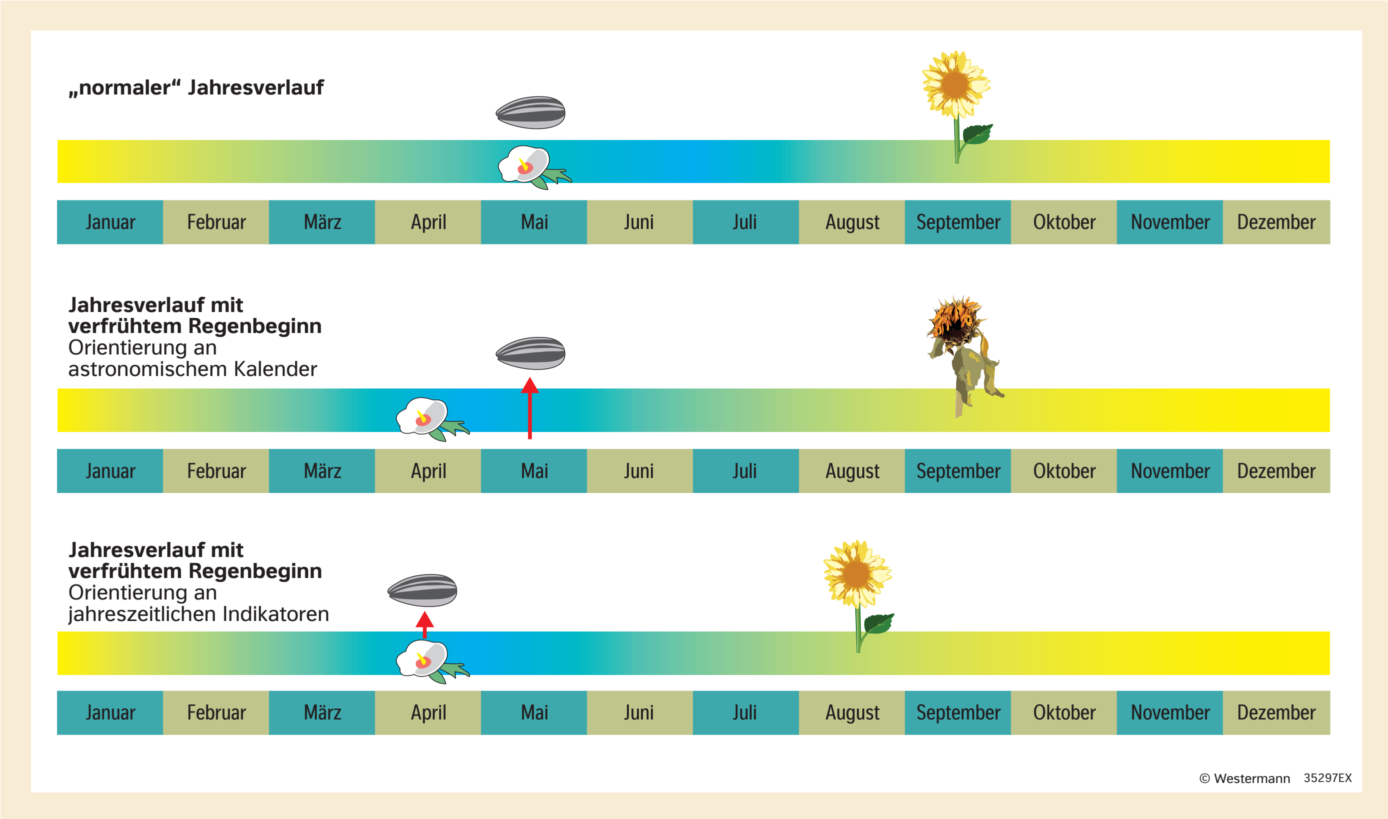

Abb. 3: Exemplarische Funktionsweise eines ökologischen Kalenders

det werden. Nach dem Ende der Sowjetunion und der damit notwendigen Refokussierung auf lokale Ressourcen, erinnern sich auch die Menschen in Tadschikistan und Kirgisistan zunehmend der ökologischen Kalender und sehen diese als Instrument für eine höhere Widerstandsfähigkeit gegenüber veränderten klimatischen Bedingungen. Selbst in China sind die Kalender noch nicht in Vergessenheit geraten (Kassam et al. 2018).

Seit Ende des 19. Jahrhunderts steigen die jährlichen Temperaturen im Pamir signifikant an (vgl. Abb. 2). Der Klimawandel führt so dazu, dass die früheren klimatischen und ökologischen Zeichen nicht mehr verlässlich sind und damit die Herausforderung entsteht, die Kalender an die heutigen Verhältnisse anzupassen. Der Temperaturanstieg beeinflusst direkt die landwirtschaftlichen Zyklen und führt zu einer deutlich längeren Vegetationsperiode, wodurch der Anbau von Feldfrüchten und Obstbäumen möglich ist, für die es in der Region früher zu kalt war. In dem auf 3000 m ü. d. M. gelegenen Ort Roshorv gedeihen z. B. nun Aprikosen und Tomaten, was bis vor kurzem nur im 300 m tiefer gelegenen Savnob möglich war (zur Lage vgl. Abb. 1). Neben der Temperaturveränderung, die maßgeblich regulierend auf die dortige Landwirtschaft wirkt, sind auch veränderte Niederschlagsmuster zu beobachten (vgl. Abb. 2). Insbesondere relevant sind hierbei die Winterniederschläge, die für die lokalen Wasserressourcen in Form von Schnee und Eis von enormer Wichtigkeit sind. Veränderte Niederschlagsmuster und Starkregenereignisse können vermehrt große Schäden an der Infrastruktur anrichten, aber auch den Ackerbau und die Viehwirtschaft beeinflussen. Hier ist besonders die höhere raumzeitliche Variabilität der Niederschläge, vor allem in Form von Schnee, von Bedeutung, da diese zu veränderten Wanderrhythmen der Hirten führen kann.

Klimaresilienz durch ökologische Kalender: eine transdisziplinäre Herausforderung

Ein transdisziplinärer Ansatz, die gemeinsame Wissensproduktion durch Wissenschaftler und Nichtwissenschaftler, soll das verloren gegangene indigene Wissen mit wissenschaftlichen klimatologischen und ökologischen Studien verbinden und damit die durch den Klimawandel notwendige Rekalibrierung der Kalender ermöglichen. Diese Herausforderung soll über eine Verschriftlichung der Indikatoren, die Dokumentation von landwirtschaftlichen und kulturellen Praktiken und die Verbindung von Indikatoren und Praktiken mit klimatischen und ökologischen Ereignissen bewältigt werden. Basis dafür sind generationen- und geschlechterübergreifende Gruppen- und Leitfadeninterviews in den Dörfern Roshorv, Savnob und Sary Mogol (vgl. Foto 2). Sie dienen dazu, das Wissen über ökologische Kalender zu reaktivieren und reflektiert zu diskutieren. Vor allem die Wahrnehmung und die Bewertung des Klimawandels spielen hier eine zentrale Rolle. Die Einschätzung durch die Bevölkerung wird dabei den gemessenen Daten zu Temperatur und Niederschlag gegenübergestellt und beides kritisch bewertet. Somit ergeben sich differenzierte Bilder zum Klimawandel und auch zu den daraus abzuleitenden Handlungsansätzen zur Kalibrierung der Kalender.

Verschiedene Beobachtungsskalen führen zu einer unterschiedlichen Wahrnehmung des Klimawandels durch Dorfbewohner und Wissenschaftler. Während Landwirte mikroklimatische Veränderungen mit direktem Einfluss auf ihren landwirtschaftlichen Ertrag beobachten, fokussieren wissenschaftliche Studien oft auf die regionale Ebene und analysieren raumzeitliche Veränderungen verschiedener klimatischer Parameter. Räumlich hochaufgelöste Klimadaten können Informationen auf Dorfebene liefern, sind jedoch im Pamir durch dessen komplexe Gebirgstopographie und die sehr geringe Dichte an langzeitlich operierenden Klimastationen nur durch hohen Rechenaufwand zu erhalten. Kleinräumige Besonderheiten im Klima können von den meisten Daten daher nicht oder nur über einen begrenzten Zeitraum erfasst werden. Um dennoch ortsspezifische Informationen über klimatische Veränderungen zu erhalten, bieten die menschliche Wahrnehmung und das Erinnerungsvermögen weitere Wissensquellen. Insbesondere bei ländlichen Gemeinschaften, deren direkte Lebensgrundlage von klimatischen Bedingungen abhängt, kann ein gutes Erinnerungsvermögen an die Wetterbedingungen der letzten Jahre erkannt werden. Um die Lücke in den Beobachtungsskalen zu schließen und ein komplexeres Verständnis über veränderte klimatische Bedingungen und deren Auswirkungen zu erlangen, werden beide Wissenssysteme gleichwertig gegenübergestellt.

Eine vergleichende Gegenüberstellung von menschlicher Wahrnehmung mit gemessenen Klimadaten der Jahre 2016 bis 2019 in den Untersuchungsorten und der ermittelten regionalen Klimaentwicklungen lieferte sowohl eine Bestätigung der Ergebnisse als auch neue Perspektiven. Eine gegenseitige Bestätigung und Ergänzung der beiden Wissenssysteme konnte bei dem Fokus auf die Temperaturveränderung festgestellt werden. Während Klimadaten Aufschluss über die raumzeitliche Intensität von Temperaturveränderung geben, liefern Interviews zusätzliche Informationen über deren lokale Auswirkungen. Alle Interviewteilnehmer sprachen von wärmeren Temperaturen, oft in Bezug zu ihrer Kindheit, und belegten dies am Beispiel früherer Erntezeitpunkte, geringerem Energieverbrauch im Winter oder dem sichtbaren Rückgang eines Gletschers. Analysen von Klimadaten belegen diesen Temperaturanstieg, der seit den 1990er-Jahren stark zugenommen hat. Deutliche Differenzen gibt es bei den Niederschlägen, die sich auf kleinstem Raum in Gebirgen sehr stark unterscheiden können, sodass regionale Klimaprodukte Schwierig-

Foto 2: Gruppeninterviews wurden meist in den örtlichen Schulen oder in öffentlichen Räumen gehalten, zu denen alle Teilnehmerinnen und Teilnehmer persönlich eingeladen wurden

Foto: I. Haag

keiten haben, diese korrekt darzustellen. Auch für die Landwirte spielen die Niederschläge im Sommer und Herbst eine eher unbedeutende Rolle, da ohnehin bewässert werden muss. Während klimatische Analysen keine erkennbare Zu- oder Abnahme der sommerlichen Regenmengen erkennen ließen, lieferten auch die Antworten der befragten Dorfbewohner kein eindeutiges Ergebnis. Im Gegensatz zu Regen spielt der winterliche Schneefall wiederum eine bedeutendere Rolle für das Leben im Pamir. Dies zeigt sich in den detaillierten und konsistenten Beschreibungen der Interviewteilnehmer über Schneemengen. Diese ersten Ergebnisse zeigen, dass eine transdisziplinäre Betrachtung klimatischer Veränderungen nur dann möglich ist, wenn die messbaren Parameter auch tatsächlich von großer Bedeutung für die örtliche Bevölkerung sind. Ist dies nicht der Fall, sinkt die Übereinstimmung zwischen den Teilnehmern und es kann keine verlässliche Information gewonnen werden.

Die vorläufigen Ergebnisse der Studie zeigen, dass transdisziplinäre Forschungen im Kontext des Klimawandels differenzierte Informationen liefern, die auch mit detaillierten Messungen und Modellierungen von Klimaelementen allein nicht zu erzielen sind. Mit transdisziplinären Ansätzen können durch Zusammenarbeit zwischen Forschenden und der lokalen Bevölkerung gemeinsam Anpassungsstrategien entwickelt werden. ■

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Summary

Ecological calendars in the Pamir mountains. Adaptation to climate change on the roof of the world

Isabell Haag, Karim-Aly Kassam, Cyrus Samimi

Ecological calendars have been used by human societies to anticipate seasonal change and the timing of livelihood, food production, and cultural activities. Using a combination of climatological, phenological and stellar signs such as the arrival of a migratory bird, changes in snow cover or movement of the stars, societies have timed their agropastoral activities to secure their livelihood and food systems. Based on ethnographic and archival research in the Pamir mountains of Central Asia, these calendars have been in use for over 600 years by diverse ethnic communities across a wide geographic region. Colonisation, industrialisation and war resulted in these calendars falling into disuse. Today they provide a potentially effective adaptation strategy to anticipate seasonal variation resulting from anthropogenic climate change, because they are grounded in the local ecology and cultures of local peoples. Using innovative transdisciplinary research methods by biophysical and social scientists as well as local indigenous knowledge holders, we are working to revitalise these calendars for use in response to climate change. In partnership with mountain communities, the objective of this research is to co-generate new knowledge to document and develop revitalised ecological calendars in order to secure local livelihood and food systems in conditions of climate change.

7 Manuscript 3: Measurements meet human observations: integrating distinctive ways of knowing in the Pamir Mountains of Tajikistan to assess local climate change

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Climatic Change (accepted)

Isabell Haag, Karim-Aly Kassam, Thomas Senftl, Harald Zandler, Cyrus Samimi

Measurements meet human observations: integrating distinctive ways of knowing in the Pamir Mountains of Tajikistan to assess local climate change

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Abstract

In mountain environments dimensions of climate change are unclear because of limited availability of meteorological stations. However, there is a necessity to assess the scope of local climate change, as the livelihood and food systems of subsistence-based communities are already getting impacted. To provide more clarity about local climate trends in the Pamir Mountains of Tajikistan, this study integrates measured climate data with community observations in the villages of Savnob and Roshorv. Taking a transdisciplinary approach, both knowledge systems were considered as equally pertinent and mutually informed the research process. Statistical trends of temperature and snow cover were retrieved using downscaled ERA5 temperature data and the snow cover product MOD10A1. Local knowledge was gathered through community workshops and structured interviews and analysed using a consensus index. Results showed, that local communities perceived increasing temperatures in autumn and winter and decreasing amounts of snow and rain. Instrumental data records indicated an increase in summer temperatures and a shortening of the snow season in Savnob. As both knowledge systems entail their own strengths and limitations, an integrative assessment can broaden the understanding of local climate trends by (i) reducing existing uncertainties, (ii) providing new information, and (iii) introducing unforeseen perspectives. The presented study represents a time-efficient and global applicable approach for assessing local dimensions of climate change in data-deficient regions.

Keywords

Climate change; Pamir Mountains; Local knowledge; Perception; Climate data; Statistical downscaling

1 Introduction

Understanding the dimensions and effects of climate change in extra-alpine mountain regions remains a research challenge because of limited availability of instrumental climate data. However, this challenge has to be overcome as subsistence-based communities, who have contributed little to the causes of anthropogenic climate change, are the ones facing its harshest impacts (Kohler et al. 2010). Changes in mean climate and enhanced climate variability affect rural livelihoods, food systems, and infrastructure (López et al. 2017; Manandhar et al. 2018). Whereas the accuracy of instrumental climate data is often lacking in mountain environments, agropastoral communities, whose lifestyle is inherently connected to their habitat, possess deep-rooted knowledge of local weather and climate. This knowledge is usually derived from close observations of their biophysical surrounding (Boillat and Berkes 2013; Byg and Salick 2009; Chaudhary and Bawa 2011). Passed down through generations this knowledge can be found incorporated into daily practices of agriculture, herding, medicine, or other sociocultural events (Kalanda-Joshua et al. 2011; Kassam et al. 2018; King et al. 2008). Whereas both knowledge systems entail their individual uncertainties and biases, integrating local knowledge with available instrumental data can broaden the scope of available climate information at the village scale, which can provide valuable information for climate adaptation or impacts studies (Ford et al. 2016; García-Del-Amo et al. 2020).

Only few studies have adopted an integrated assessment of instrumental climate data and community observations in order to investigate in local scale climate processes. Studies can be found in South America (Fernández-Llamazares et al. 2017; Kieslinger et al. 2019; López et al. 2017), the Arctic (Cuerrier et al. 2015; Gearheard et al. 2010; Rapinski et al. 2018; Williams et al. 2018), Africa (Ayanlade et al. 2017; Kalanda-Joshua et al. 2011; Meze-Hausken 2004; Simelton et al. 2013), or the Himalaya (Gentle and Maraseni 2012; Klein et al. 2014). While transdisciplinary approaches are conceptually and methodologically challenging, they appeared to be particularly promising in data-deficient environments, where local communities pursue subsistence-based livelihoods and closely anticipate changes in climate and environment over a sustain period. Studies showed, that community perceptions of climate change often coincided with measured meteorological trends (López et al. 2017; Rapinski et al. 2018). Beside concordances, studies also identified different trend observations between the two data sources (e.g. Abu et al. 2019; Fernández-Llamazares et al. 2017). To synthesise information across both knowledge systems, their individual limitations have to be acknowledged, such as uncertainties in the measurements and analysis of instrumental data records or the potential variability in the substance and quality of personal perceptions within a community (Alexander et al. 2011). Despite methodological challenges, studies concluded that the integration of instrumental data with peoples' observation can strengthen the understanding of local climate change in remote areas around the globe, and introduce new perspectives to the existing field of climate change research. Co-generated knowledge can ensure a sustainable development of local communities, strengthen their resilience towards climate change and support effective adaptation strategies and policies (Kieslinger et al., 2019; Kalanda-Joshua et al., 2011).

As previous studies have shown the potential of taking a multiple evidence approach, this study is the first one integrating community observations with instrumental climate data in the Pamir Mountains of Tajikistan. The Pamirs constitute a suitable research area for such an integrative study design as local trends and impacts of temperature and precipitation change remain mostly unknown due to a low network of meteorological stations (Xenarios et al. 2019). At the same time, local communities were shown to possess detailed knowledge of their ecological and climatological environment, which they incorporate in daily agricultural practices and store in the form of complex ecological calendars (Kassam et al. 2011; Kassam et al. 2018). In order to generate new information about local climate trends in the Pamirs, which can be crucial for climate adaptation or impacts studies, the aims of this study are threefold:

1. Generate and analyse high-resolution climate time series that match the scale of community observations.
2. Valorise community perceptions of local trends in temperature, precipitation, and snow.
3. Synthesise information about local trends in temperature, rain, and snow by integrating community perceptions and instrumental climate data.

A number of data sets and methods were used to gain information about relevant climate variables, including trends in temperature, precipitation, and snow cover. To receive high-resolution temperature estimates at the village-scale, we downscaled ERA5 temperature data using a lapse rate based approached. Lapse-rate downscaling can enhance the spatial accuracy of gridded data sets above data-scarce regions, as it works independently to meteorological ground stations (Gao et al., 2012; Gao et al., 2017). Temporal variations in snow cover were investigated using daily data from the MODIS snow product MOD10A1 (Hall and Riggs 2016). In addition to measured data products, community perceptions were gathered using semi-structured interviews and community workshops. Our research approach is built on a respectful research relationship between scientists and local communities and can be applied in other data-deficient regions around the word to foster more transdisciplinary climate research.

2 Study sites & research relationship

This study has been conducted in the Pamir Mountains of Tajikistan, in the villages of Roshorv and Savnob (**Fig. 1**). The Pamir Mountains cover the regional districts of the Tajik Gorno-Badakhshan Autonomous Oblast (GBAO), the Afghan province of Badakhshan, the Western part of the Chinese province of Xinjiang, and the southernmost part of the Kyrgyz Osh region. The research sites are located in the western part of the Tajik Pamirs, characterized by a semi-arid climate with precipitation peaks in winter and spring (Aizen et al. 2001; Finaev et al. 2016). The regions supply of water for drinking, irrigation, and energy production depends almost entirely on glacier-fed rivers, making water a valuable and limited resource (Aizen et al. 2007). The village of Roshorv is located on a spacious plateau on an altitude of 3139 meter above sea level (masl). Savnob, which is constrained by steep mountain hills and a gorge, is located on an altitude of 2692 masl. In both villages, people traditionally live as subsistence-based farmers and herders with little monetary income. Because Savnob and Roshorv are located in deep mountain valleys pervaded with a fragile network of roads and treks, inclement weather conditions or mass movements can lead to isolation, cutting them off from key supply routes. Therefore, an autonomous food supply is very important to ensure food security throughout the year. Both communities belong to the ethnicities of the “Bartangi”, speaking one of the Pamir languages “Shugni” (Kassam et al. 2011).

A research relationship with both communities was firstly established by the second author in the year 2006. Based on this relationship an action research initiative was launched in 2015, focusing on the revitalization of ecological calendars in Savnob and Roshorv to enhance the adaptive capacity of the communities to the impacts of climate change (Kassam et al. 2018). Within this research initiative, data for this study was acquired in two 2-week field sessions in summer 2018 and 2019. The integration with the overhead project on ecological calendars considerably contributed to the effectiveness of this study, because (1) a research relationship with the communities was already established since the year 2006, (2) ongoing research on ecological calendars provided important a-priori information regarding the human ecological and environmental situation of the two communities (information on ecological calendars can be found in Kassam et al. 2018), and (3) joint-research activities, such as two community workshops in 2018, were used to inform both research initiatives simultaneously and to show interlinkages. An important focus of both studies was to create an effective research relationship and to engage local knowledge holders in the research process (Woodward, 2010). Before the start of our work we informed the religious leader and the secular head of the village organization about our intentions and asked for their participation, which they always generously consented to. All interactions have been supported by a local community researcher in the native language of the communities.

Fig. 1 Map of the study region showing the Pamir Mountains of Tajikistan and the location of the research villages Savnob and Roshorv, and the meteorological stations applied in this study.

3 Material and methods

To assess climate change impacts at the level of the villages, we used a number of datasets including reanalysis data, satellite data, and community observations. A graphical outline of the applied research tasks is provided in the online resources of this manuscript. Throughout the whole research design and implementation, we valued each data type as equally insightful and each mutually guided the research process.

3.1 Downscaling and temperature trend analysis

Monthly temperature trends ranging from 1979 to 2018 have been derived by applying an elevation correction approach to the gridded temperature product ERA5 (Copernicus Climate Change Service 2017). ERA5 is provided by the European Centre for Medium Range Weather Forecast (ECMWF) and delivers various atmospheric, land-surface and sea-state parameters at different pressure levels utilizing both past observations and models. More information on the assimilation scheme and performance of ERA5 can be found in Hersbach et al. (2018). To capture the small-scale variability of near-surface temperature in complex terrain, we applied an elevation correction to the original ERA5 dataset to enhance its spatial resolution from 31 kilometres to point-scale. To apply the proposed elevation correction approach of ERA5, the following variables are needed: monthly means of the 2-meter temperature (2mT), surface pressure and orography on a single level, and temperature and geopotential at the 400, 450, 500, 550, 600, 650, 700, 750, 775, 800, 825, 850 hPa levels.

To evaluate the performance of the newly generated elevation corrected ERA5 dataset over the Pamirs we used temperature data of existing meteorological stations from different altitudes across the Pamirs. For this purpose, eleven meteorological station records have been acquired from the State Administration for Hydrometeorology of the Republic of Tajikistan (SAHRT). Station records cover the period from 1995 to 2012 at a monthly frequency (State Administration for Hydrometeorology of the Republic of Tajikistan 2013). Following the guidelines from the World Meteorological Organisation, stations with a minimum data coverage of 80 % and less than 5 % missing values were maintained (Zahumenský 2004). After the quality check, five stations remained for validation (**Fig. *1***). More information on the location and altitude of the stations can be found in Online Resource 1. Apart from SHART stations, two automated weather stations were installed in Savnob and Roshorv between 2016 and 2019 by the research team conducting this study. This station data was used to identify the most suitable combination of pressure levels to calculate monthly lapse rates for the research locations.

The elevation correction of ERA5 2mT was done after the proposed method of Gao et al. (2017), using ERA5 internal vertical temperature gradients. Those lapse rates (Γ) define the relationship between temperature and elevation and can be used to adjust the original ERA5 grid height to a target elevation. Lapse rates are determined monthly to account for atmospheric variations and are based on the temperature and geopotential height at different pre-selected pressure levels (Equation 1).

$$\Gamma = \frac{(T_{hPa\_A} - T_{hPa\_B})}{(GpH_{hPa\_A} - GpH_{hPa\_B})} \qquad (1$$

,where T_{hPa_A} and T_{hPa_B} represent the temperature at the highest and lowest pressure level, respectively. And GpH_{hPa_A} and GpH_{hPa_B} represent the geopotential height of the respective pressure levels.

To account for varying atmospheric conditions, lapse rates based on four pressure level combinations were calculated (cf. Gao et al., 2012): (1) Γ_A is based on the maximum and minimum elevation, (2) Γ_B is based on the ERA5 grid height and minimum elevation, (3) Γ_C is based on ERA5 grid height and the height of the pressure level below the target elevation, and (4) Γ_D is based on the height of the two pressure levels below and above the weather station. Whereas Γ_A captures the largest elevation difference, Γ_B accommodates higher elevation conditions, and $\Gamma_{D,C}$ accounts for local circulation patterns. Pressure levels closest to the respective reference height were applied. In case of a temporal variability of pressure levels found to be closest to one reference height, the level with the highest distance to its counterpart was chosen. To correct ERA5 2mT, equation 2 was used, with varying Γ.

$$T_{cor} = T_{ERA\_2m} + \Gamma * \Delta h \quad (2$$

,where T_{ERA_2m} is defined by the 2mT of ERA5 and h the difference between GpH_{hPa_A} and GpH_{hPa_B}.

To evaluate the elevation correction method, both original ERA5 and corrected ERA5 must be compared to the validation stations. Therefore, four accuracy measures were calculated, and model data was tested against the station inside the corresponding raster cell. As suitable accuracy measures, the coefficient of determination (R^2), the root mean squared error (RMSE), the mean absolute error (MAE), and BIAS were used. Information on the formula to calculate those accuracy measures can be found in Online Resource 1.

To test for a statistically significant performance difference between the original and corrected data sets, the paired two sample Wilcoxon Rank-Sum Test using the absolute differences between the meteorological station data and the corrected dataset was applied. As a last step, the linear trend analysis using the elevation corrected ERA5 dataset, was conducted. The trend magnitude and trend significance were derived using the Sen's slope estimator and the Mann Kendall test, respectively (Kendall 1975; Mann 1945; Sen 1968; Theil 1950).

3.2 Snow trend analysis

To detect temporal changes in local snow patterns, the snow cover product MOD10A1 based on the images of the moderate resolution imaging spectroradiometer (MODIS) on board the Terra Satellite was chosen (Hall et al., 2016). MOD10A1 provided daily images of the snow signal in form of the Normalized Difference Snow Index (NDSI) starting in spring 2000 to present, with a spatial resolution of nominal 500 meters. In this study all available MOD10A1 images from 2001 to December 2018 have been acquired via the National Snow and Ice Data Centre. More information on data structure, snow algorithm, and uncertainties can be found in Riggs et al. (2016). Whereas previous studies have confirmed the suitability of MODIS snow cover products for snow detection in mountainous terrain (e.g. Gascoin et al. 2015; Jain et al. 2008) and its high accuracy over Central Asia (Gafurov et al. 2013), uncertainties in snow cover values exists due to the influence of clouds, different snow characteristics, or illumination conditions (Brubaker et al. 2005;

Crawford 2015). Since cloud covered pixels are the main limitation of snow cover products such as MOD10A1, several gap-filling approaches exist to derive cloud-free images (c.f. Hall et al. 2019). In this study a temporal gap filling procedure was applied using a simple linear interpolation of the NDSI values. Gaps at the very beginning or end of a time series without preceding or subsequent values, were filled by using the closest available value. Whereas more complex cloud removal approaches exist (e.g. Gafurov and Bárdossy 2009), a simple temporal gap filling can already provide good results and enhance the accuracy of snow cover estimates at a given day (Hall et al. 2019).

To detect temporal changes in snow cover we used the NDSI time series for: (1) the grid cells, in which the villages are located; and (2) the grid cells intersecting a one-kilometre buffer zone around the villages. Considering the local topography, the buffer zone accounts for those areas surrounding the villages, which are visible to the communities and influence their perception of snow. To identify changes in the timing of snow onset, snow offset and changes in the length of the snow period, we defined the full snow season (FSS) after Choi et al. (2010).

$$FSS = (52weeks - FSS\ onset\ week) + FSS\ offset\ week \quad (3$$

, where $FSS\ onset\ week$ is defined as the first week after summer, where the number of days with a snow cover >50% prevail. $FSS\ offset\ week$ is defined as the first week of the year, where the number of weekdays with a snow cover <50% prevail.

For the snow trend analysis, the grid cells of the villages and the grid cells located within the buffer zone, were taken into consideration. The trend magnitude was derived using the Sen's slope estimator and the trend significance using the Mann-Kendall test. All processing steps regarding temperature and snow analysis were done using the R Software environment (R Core Team 2018).

3.3 Community observations

3.3.1 Community Workshops 2017 and 2018

A first round of community workshops were held in 2017 at the 20th of June in Savnob (20 participants) and at the 27th of June in Roshorv (18 participants) to establish a relationship between community members and scientists. Because of cultural differences and the difficult accessibility of the research villages, scientists needed to make themselves familiar with the sociocultural and biophysical situation of the communities in order to tailor the interview questions to the community livelihoods. The workshops were organised by synchronous research activities on traditional ecological calendars, where scientists of this publication were also involved. In the workshops, communities created seasonal rounds which provided insights into local livelihoods, ecological events, and environmental and climatological conditions (Kassam et al. 2018). The workshops of 2017 lasted for three hours.

In 2018, a second round of workshops was held (2nd of July in Savnob with 23 participants, 6th of July in Roshorv with 19 participants) to provide space for all community members to participate in the research and to identify knowledgeable community members to be questioned in the individual interviews. Participants were questioned about seasonal changes in temperature, precipitation, and snow. Questions were identical to the interview questions of 2018 and can be found in Online Resource 1. Workshops were further used to share scientific information about regional climate trends with the community members to initiate a two-way learning process (Haag et al., 2019). The workshops were conducted in the homes of village leaders and were always started with a shared meal. The workshops of 2019 lasted for two hours.

3.3.2 Structured interviews 2018 and 2019

Structured interviews were conducted in June 2018 and June 2019 to assess individual observations of local climate change. The aim of the interviews was to extract information about seasonal trends in temperature, precipitation, and snow cover. In 2018, only five interviews were conducted in each village with key informants, who were identified in the community workshop. Time constraints prevented a higher number of interviews. Despite the small number, interviews were important to test the structure and wording of the interview questions as cultural and linguistic differences between scientists and informants existed. In 2019, 20 more interviews were conducted in each village. New interview participants were identified with the help of the village leader and selected according to their age, gender, and ecological profession. In order to get a historical sense of weather changes, most participants were farmers and herders above the age of 50 and must have spent most of their life in the village. Interviews took place at the interviewees' home or farm. As some traditional communities can have their own seasons, informants were asked to provide a short definition of their seasonal understanding. In 2019, interviews were used to further investigate in the temporal component of climate trends and their potential indicators. Last one was investigated by asking e.g. "How do you know autumn is warming?". To help participants anticipate long-term changes in climate rather than short-term weather fluctuations, we used a set of historically time markers, whose importance for the communities was identified with the help of our local community researcher. In 2018, time markers referred to exact years, such as "2015 - the year of the earthquake" or "1990 - the collapse of the Soviet Union". In 2019, we changed the structure of the time markers from single years to periods of time to prevent interviewees to primarily refer their answers to one year or season. The full set of questions for the interviews in 2018 and 2019 and the respective time markers can be found in Online Resource 1. Before each interview, informed consent was sought to record and to use the interview for research purposes. In no instance did a community member refuse to participate.

To analyse community observations on climate trends and to identify shared patterns of knowledge, we calculated a consensus index based on Rapinski et al. (2018). Transforming qualitative data into semi-quantitative variables helps to reduce the complexity of the information and to identify general trends using the level of agreement within the community. Similar to the concept of a cultural consensus analysis, the consensus index assumes a relationship between the level of agreement within the group of respondents and the accuracy of the proclaimed observation (Romney et al. 1986). In this study, we calculated a consensus index (dFC) to quantify the magnitude and direction of change of a specific observation following the approach by Rapinski et al. (2018).

$$dFC = \sum wf/F \qquad (4$$

, where f is the number of observations and F the total number of interviews. w is the code attributed to the observation, regarding its direction. Whereas increasing trends (e.g. rising temperatures, increasing precipitation, later onset/offset of snow) received the code 1, decreasing trends received the code -1. If no trend direction was identified, the observation was coded with 0. An overview of the observations and the corresponding codes can be found in Online Resource 1.

The obtained dFC index ranks between -1 and 1, indicating the direction of change and its level of agreement within the community. If dFC equals 1 or -1, a complete agreement can be noted. If the index is close to 0, no consent could be achieved. The results of the consent analysis are based on the 50 interviews undertaken by the first author in 2018 and 2019.

4 Results

4.1 Temperature trends

To derive village scale temperature trends, we first downscaled ERA5 temperature data and validated the suitability of this approach before conducting the trend analysis. The performance of the original ERA5 data and the two best correction methods are summarized in table 1, which can be found in online resource 1 of this manuscript. Original ERA5 shows a good temporal correlation with the station data with R^2 values between 0.88 and 0.95. Whereas BIAS ranges between -12.32 °C and -16.34 °C, which indicates a general cold bias of the original ERA5 dataset, RMSE and MAE show an average error across all stations of 14.54 °C and 14.26 °C per month, respectively. Regarding the magnitude of the error measurements, a relation between the error size and the altitude difference between model and station data can be observed.

Rushan, with the greatest altitude difference of 1544 meters, shows the highest model errors. Navobob, with the smallest altitude difference of 1252 meters, depicts the lowest model errors across all stations. Savnob deviates from that trend, as its elevation difference is low, but model errors exceed all other stations. Given that four correction methods have been applied initially, only performance measures of method Γ_D and Γ_C are presented in table 1, since they delivered the best results. The presented methods show a reduction in the RMSE between 52 % to 62 % and a significant decrease in the MAE between 55 % to 65 % compared to the error measurements of the original ERA5 data. Furthermore, the initial cold bias of ERA5 was reduced by 52 % to 64 %. Although the correction methods lead to a reduction in the RMSE, MAE, and BIAS, no improvement in the temporal correlation could be achieved. Regarding the relation between error magnitude and difference in elevation, no pattern could be discerned anymore after the elevation correction was applied. Whereas the correction methods substantially improved the model performance of ERA5, unpredictable errors remained (results not shown here). Those remaining errors show a seasonal distribution, being lowest in winter.

Using the elevation corrected ERA5 dataset for the temperature trend analysis we identified a statistically significant increase in summer temperatures in both villages. Summer temperatures increased by 0.32 °C per decade and 0.38 °C per decade in Savnob and Roshorv, respectively (**Tab. 2**). The second highest trend magnitudes according to ERA5, were detected in autumn for both villages. However, those trends are not significant on a statistical basis which also applies for the two lowest trend magnitudes in spring and winter.

Tab. 2 *Annual and seasonal temperature trends per decade (°C) for the villages Savnob and Roshorv (1979-2018) using the elevation corrected ERA5 temperature data. Asterisk indicates the significance level (p<0.05).*

	Savnob	Roshorv
Annual	0.15 [-0.03 to 0.32]	0.17 [-0.03 to 0.37]
Spring	0.09 [-0.14 to 0.33]	0.07 [-0.15 to 0.3]
Summer	0.32* [0.03 to 0.61]	0.38* [0.04 to 0.76]
Autumn	0.22 [-0.17 to 0.61]	0.27 [-0.2 to 0.69]
Winter	0.11 [-0.25 to 0.49]	0.09 [-0.32 to 0.5]

4.2 Snow trends

Using the MOD10A1 snow cover product revealed temporal changes in the snow cover extent between 2001 and 2018 in the villages of Savnob and Roshorv. The results showed an increasing trend in the timing of snow onset and a decreasing trend in the timing of snow offset, combined leading to a shortening of the snow season (Fig. 2). Whereas snow tends to arrive later and melt earlier, those observations are not statistically significant. The only significant change detected in terms of snow cover extent, was the decreasing length of the snow period in Savnob (Fig. 2C). The period of snow in Savnob shortened by 5.4 weeks between 2001 and 2018.

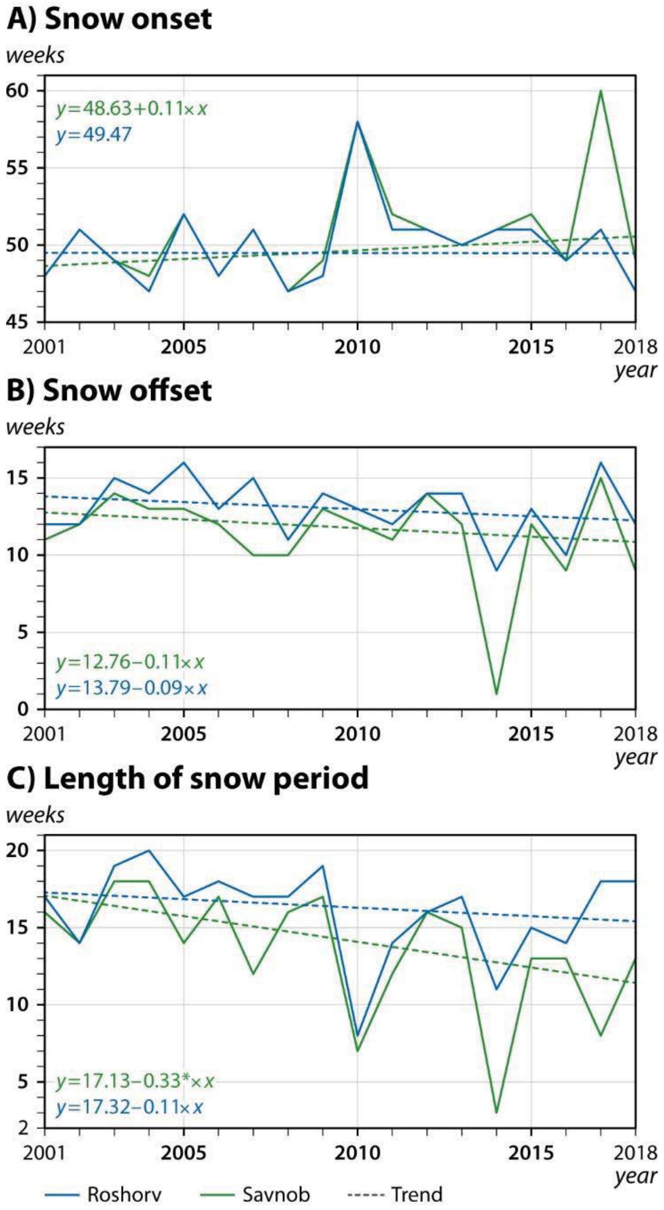

Fig. 2 Changes in the timing of snow onset, snow offset and in the duration of the snow period in weeks for the villages Savnob and Roshorv. Data was derived from the satellite-based snow cover product MOD10A1. Asterisk indicates the significance level ($p<0.05$).

4.3 Community observations and indicators

As community observations can be multidimensional and complex, a consensus index enabled to identify shared patterns of observations (Fig. 3). In this study, we consider a dFC index between 0.3 and 0.65 as moderate consent, between 0.65 and 0.8 as strong consent, and above 0.8 as very strong consent. This stratification follows the scheme outlined in Rapinski et al. (2018), with an additional class to differentiate high levels of consent. Observations reaching a consent under 0.3 are not further considered in this study. In Roshorv, the community members reached very strong consent regarding decreasing levels of snow (dFC of -0.82). Moderate agreement was reached in terms of increasing autumn and winter temperatures, decreasing levels of rain, and a delay in the timing of snow onset. In Savnob, moderate consent was reached for decreasing levels of snow and rain (dFC of -0.5) and increasing temperatures in winter (dFC of 0.5).

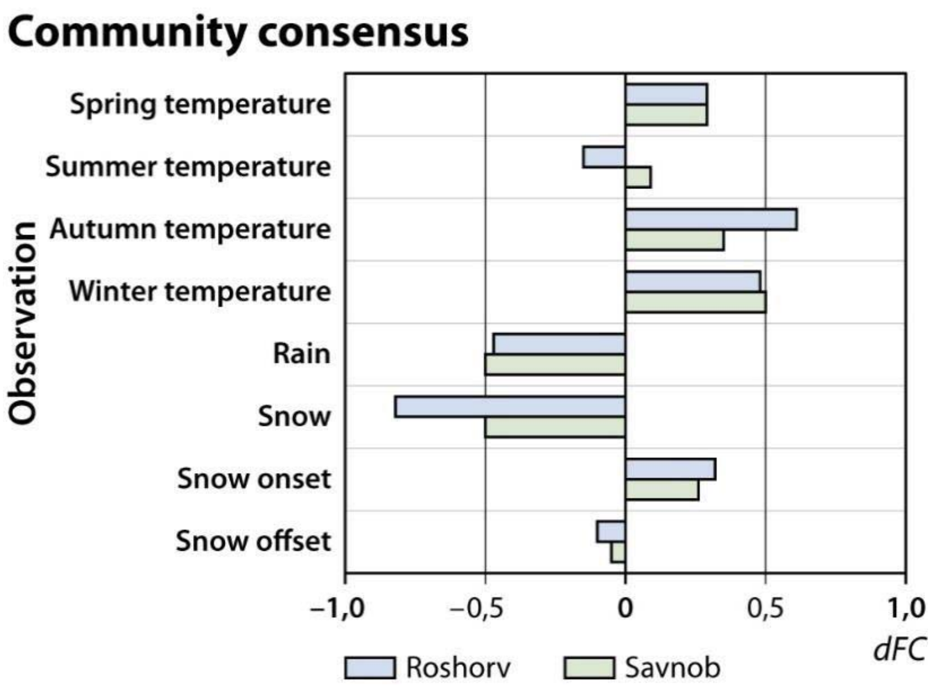

Fig. 3 Observations of meteorological changes, reported by the villagers of Savnob and Roshorv. The dFC index shows the direction of change and its consent among the community members. The closer the index to -1/1, the higher the agreement. Positive index values indicate an increase/delay, and negative values a decrease/earlier start. The consensus index is based on 50 interviews, which were conducted in Savnob and Roshorv in 2018 and 2019.

Whereas changes in weather and climate are often not directly visible, community members explain their perceptions by ecological or sociocultural indicators and impacts. In Savnob and Roshorv, indicators were identified in regard to agriculture, infrastructure, natural environment and daily routines. Indicators mentioned three or more times in the interviews are listed in Fig. 4. Indicators reported in both villages include an earlier time of harvest, earlier start of fieldwork, decreasing demand for heating resources, earlier melting of snow, and a more comfortable feeling because of warmer temperatures.

"In the past, we harvested later. Sometimes it took us until October. Now, we finish our harvest in September. Wheat, barley, and beans have ripened at that time." **(R13, 2019)**

In Roshorv, conflicting observations were made about the availability of water, which is provided to the village by a glacier-fed stream. According to eight respondents, there is less water in the stream resulting in insufficient water availability for irrigation. However, four other respondents stated a sufficient water supply for irrigation. Regardless its effects on agriculture and irrigation, community members independently reported less water in the stream and a decrease in the size of the glacier above the village. Concerning the communities' infrastructure, people in Roshorv explained that their roads and paths are less blocked by snow in winter, due to shrinking levels of snow.

"Since the 1980s snow is becoming less and less. Before the 1990s we had to clean the roads to Gudara and Savnob every winter. Now, cars can drive there without having to clean the road first." **(R17, 2019)**

Decreasing amounts of snow have also been reported in the villages of Savnob. People remember that in earlier times they spread sand on the snow to hasten the melting process.

Although, nature-based communities have learnt over generations to anticipate changes in weather and climate, community members frequently mentioned enhanced variability in the weather. Annual fluctuations in the timing of plant blossoming and field fruit maturity have been mentioned as indicators for increased weather variability. Additionally, three people directly reported that the weather is getting more variable and the seasons more unpredictable. For subsistence-based farmers, higher variability in the weather can have severe impacts on their harvest and unpredictability of seasons results in anxiety (Kassam et al., 2011). At no time, people associated anthropogenic climate change as a potential cause behind their experienced impacts. Instead, people argued that their perception of changes in weather and climate might rather be influenced by their age, health, ecological profession, beliefs, changes in machinery, or availability of heating resources.

"We feel that it is getting warmer. An explanation is that in the past we had community farms (Kolkhoz) and state farms (Sovkhoz) and not everyone had to work on the fields. Maybe after this period we started feeling the heat because more people became farmers and had to work on the fields again. However, people started to become farmers in 1991 [after collapse of the Soviet

Union and during the civil war] and we started to feel that it is getting warmer around 1995/1998." **(R5, 2019)**

Community	Category	Experienced impacts & consequences by communities	Spring	Summer	Autumn	Winter	No season specified	Snow level
Roshorv	Agricultural work	- Earlier harvest (22)	+	+	+			
		- Irrigation problems due to water scarcity (8)	−	−	−		−	
		- Earlier start of fieldwork (6)	+					
		- Earlier finish of firewood collection, preparation of hay, preparation of seeds and longer usage of the water-driven mill (4)		+	+	+		
		- Enough water for irrigation (4)		+				
		- Decreasing depth of frozen soil. Therefore, potatoes can be stored less deep. (3)				+		
	Daily life	- Wearing of lighter clothing and feeling comfortable due to warmer temperatures (8)	+		+	+		
		- Decreasing demand for heating resources (6)				+		
		- Kids do not swim in the pool anymore in summer (5)		−				
	Natural environment	- Less water in the stream (10)	+					
		- Retreat of glacier (6)	+				+	
		- Earlier melting of snow (4)	+					
		- Enough water in the stream (4)		+	+			
		- Less roads are blocked due to snow (5)			+	+		−
Savnob	Agricultural work	- Earlier harvest (5)		+	+			
		- Shift in the varieties of potential field fruits and crops (5)	−	−	−			
		- Temporal changes in the seasonal plant circle:						
		· Earlier ripening (5)		+	+			
		· Later ripening (3)	−					
		· No direction given (3)		−				
		- Earlier start of fieldwork (3)	+					
	Daily life	- Feeling more comfortable due to warmer temperatures (8)	+	+	+	+		
		- Decreasing demand for heating resources (7)				+		
		- No need to spread sand on the snow anymore to fasten the melting process of snow (4)	+					−
	Natural environment	- Earlier melting of snow (3)	+					−

Temperature in: Spring, Summer, Autumn, Winter, no season specified; Snow level; + Increase; − Decrease; (x) Number of times mentioned

Fig. 4 Impacts and indicators of climate change reported by the community members of Savnob and Roshorv in the interviews of 2019 Numbers in parenthesis indicate how many times an indicator was mentioned within a community. Climate-induced drivers (i.e. seasonal changes in temperature and snow) have been identified by the community members in relation to their reported indicator. For example, 22 respondents in Roshorv reported that harvest is occurring at an earlier time of the year. Possible drivers for that change have been identified as increasing temperatures in spring, summer, and autumn.

4.4 Cogeneration of knowledge using community observations and instrumental data

In order to derive more detailed information about local climate trends in Savnob and Roshorv, instrumental data records and community observations were integrated and areas of similarity and difference identified. No concordances could be identified in terms of temperature trends. Whereas a significant increase in summer temperatures was shown by the downscaled ERA5 records, community members of Roshorv reached strong consent on warming temperatures in autumn and winter. In Savnob, strong consent was only reached on warming temperatures in winter. ERA5 also showed a warming trend for autumn and winter but not on a statistically significant level. In terms of snow, community observations and instrumental data related partly to different characteristics of snow. Whereas community members anticipated the amount of snow, the applied remote sensing data provided long-term measurements of snow cover extent. Community members of both villages indicated decreasing levels of snow and the analysis of satellite images revealed a shortening of the snow season in Savnob. Evidence for a shorter time period was also derived from the community observations of Roshorv. Community members identified a delay in the timing of snow onset. In terms of rain, only community observations provided information about possible trends directions. With a moderate level of agreement, communities indicated a decrease in rain. No information could be achieved by using instrumental climate data.

5 Discussion

5.1 Instrumental climate data

In extra-alpine mountain environments, gridded data products can show high uncertainties in predicting local-scale climate conditions because of their low grid resolution and the limited availability of in-situ measurements (Hu et al. 2016). In the Pamirs, those data restrictions lead to prevailing uncertainties about local-scale climate trends (Unger-Shayesteh et al. 2013). One objective of this study is to generate high-resolution climate data for the villages Savnob and Roshorv to investigate in local trends of temperature and snow. In terms of temperature, local time series were generated by downscaling ERA5 data, using a lapse rate based approach (c.f. Gao et al. 2017). Our downscaling resulted in a maximum reduction of the RMSE and MAE of 62 % and 65 % compared to the uncorrected dataset over the Pamir, respectively. The magnitude of this error reduction is in accordance with previous studies carried out by Gao et al. (2012) and Gao et al. (2017) using the precursor dataset of ERA5, ERA-Interim, over the Tibetan plateau. Although, the proposed method shows a good model performance over the Pamirs, the evaluation is limited to the regional scale due to the low number of available validation stations. However, this situation is characteristic for large areas worldwide (Zandler et al. 2019). In addition, unpredictable residuals with a seasonal pattern remained in the corrected ERA5 data. Drawing on the conclusion made in Gerlitz et al.

(2014), those seasonal patterns could be related to unresolved incoming solar radiation or meso- to local-scale circulation patterns. Further possible factors controlling near-surface temperature, which remain unresolved in the proposed elevation correction approach include latent heat transfer, topographic effects, observational errors, large-scale biases, or internal model background errors (Gao et al. 2017; Gerlitz et al. 2014). A trend analysis of the downscaled ERA5 data finally revealed an increase in temperature between 1979 to 2018 throughout all seasons in Savnob and Roshorv. However, only summer warming was statistically significant with 0.32 °C per decade and 0.38 °C per decade, respectively (**Tab. 2**). Regional studies on temperature change in Central Asia also agreed on a general warming trend but with varying trend magnitudes among the seasons (Chen et al. 2009; Finaev et al. 2016; Haag et al. 2019; Hu et al. 2014). Our results show, that uncertainties of local climate change, arising from counterintuitive findings of regional temperature studies, can be substantially reduced by generating village scale temperature trends using the elevation-correction approach based on ERA5 internal vertical lapse rates after Gao et al. (2017). Despite remaining uncertainties, lapse rate downscaling can provide more accurate temperature estimates for Savnob and Roshorv than received from the original ERA5 data.

Trends in local snow patterns were directly derived from the snow cover product MOD10A1 with a pixel resolution of 500 meters. Results showed a statistically significant shortening of the snow period in Savnob. Results on snow variations in Roshorv and temporal variations in the timing of snow onset and snow offset in both villages were not statistically significant. Other regional studies over the Pamirs also indicated a decrease in snow cover as well as a shift towards earlier snow melt in spring (Dietz et al., 2014; Li et al., 2018). Different study results or missing statistical significance can be caused by the fact that patchy snow cover in the subpixel scale might not be detected by MOD10A1 (Hall and Riggs 2007). Furthermore, the general availability and accuracy of optical remote sensing images can be constrained by cloud cover, solar illumination, and sensor viewing geometry and thus influence the estimation of snow cover in mountainous terrain (Crawford 2015). Whereas MOD10A1 can provide reasonable information about local variations in snow cover, community members of Savnob and Roshorv showed a higher anticipation of snow amounts rather than snow extent. It was not possible to assess the depth of snow using instrumental data, as operational observations of snow depth still face technical limitations in their spatial, temporal, and vertical resolution in mountain environments (Lievens et al. 2019).

5.2 Community observations

Traditional communities around the world were shown to possess detailed knowledge of weather and climate, which is based on daily practices and observations (e.g. Green et al. 2010; Ifejika Speranza et al. 2010; Ingty 2017). In the Pamirs, Kassam et al. (2018) already reported a close anticipation of ecological and environmental processes by the community members of Savnob and Roshorv. Building on those results, this study aims to investigate in community perceptions of local climate trends. Results show, that both communities shared a high consent in regard to decreasing trends in rain and snow, and increasing temperatures in winter. Community members of Roshorv further identified a warming trend in autumn and a delay in snow onset (Fig. 3). According to previous studies, community observations are (i) biased towards changes which are directly visible or affect local livelihoods (c.f. Rapinski et al. 2018; Riseth et al. 2011), and (ii) vary in their quality and substance between community members (Fernández-Llamazares et al., 2017). First one applies to the high community consent in Savnob and Roshorv in regard to decreasing levels of snow. Whereas snow is directly visible to the people, it also dictates the timing of herding activities and controls the hydrological cycle in the villages. Furthermore, communities face isolation when there is too much snow, impeding any contact with neighbouring villages and disabling any kind of external provisioning. Therefore, people pay close attention to changes in snow, which enhances the reliability of such observations. Similar to the communities of Savnob and Roshorv, resource-based communities were shown to anticipate changes in temperature by using a set of ecological or sociocultural indicators, such as changes in the timing of agricultural activities, agricultural yields, livestock, infrastructure, or health (c.f. Ayanlade et al. 2017; Kieslinger et al. 2019; Klein et al. 2014). Considering the frequency of reported impacts for each season in Savnob and Roshorv supports this argumentation (Fig. 4). Most impacts are reported in association with increasing autumn and winter temperatures. Whereas biophysical impacts and signs can be strong evidence for local changes in climate, their causes can be diverse. Therefore, scientists should aim to understand the sociocultural context where the information originated from. In Savnob and Roshorv, consent about warming temperatures in autumn and winter may be reinforced by a higher attention of the community members towards changes in their biophysical environment at this time of the year, as those seasons are important for local livelihoods and food systems. On the other side, less attention may be paid to indicators occurring in other seasons, which could explain the low consent about changes in summer temperature. Given the preceding argumentation, it came unexpected that decreasing levels of rain reached high consent in both communities. Neither is rain occurring frequently in the villages, due to semi-arid climate conditions, nor have many impacts been reported by the community members regarding rainfall events.

Whereas the reliability of community perceptions can differ between climate variables, the quality and substance of observations can also vary between community members (Fernández-Llamazares et al. 2017). As individual viewpoints can be influenced by socioeconomic factors such as age, gender, or profession, we selected a homogenous group of participants in terms of age and profession to ensure a sound understanding of local climate and weather processes. Although, mean and women may perceive changes differently (Kalanda-Joshua et al. 2011), we did not enforce an equal gender distribution to respect local norms. Our results showed, that individual perceptions can be further influenced by existing daily routines of the respective communities. For example, community members of Roshorv experienced the availability of irrigation water differently (Fig. 4). As irrigation in Roshorv is strictly scheduled by an irrigation plan, it is likely, that individual perceptions of water availability may be influenced by the respondents' position in the order of irrigation. To enhance the quality of the research results, understanding the context where information originate from is essential for scientists. A further challenge in the analysis of peoples' perception of long-term climate trends, constitutes the influence of short-term weather fluctuations and extreme weather events (Reyes-García et al. 2016). In this study, we used historical time markers to help people anticipate long-term changes in climate. This method showed promising results as interviewees memorized the identified time period in the past and did not refer their answers to the last seasons or extreme events. However, to ensure the effectiveness of this method time markers have to be remembered by all community members and should appear in the form of time periods, rather than single years, to prevent seasonal biases. Whereas certain measures can be taken to enhance the reliability of community observations, a validation of the result, probably at a different time of the year than the initial stage of inquiry or with an independent sample, remain often missing in social science research. Due to time limitations a validation stage could not be included in this study but is strongly encouraged for future research.

5.3 Cogeneration of knowledge across knowledge systems

Cogenerating knowledge across different epistemologies is conceptually and methodologically challenging. Knowledge systems differ in their structure, values, and worldviews, and therefore entail their own strengths, limitations, and uncertainties (Aikenhead and Ogawa 2007; López et al. 2017). Against this background, we aimed to generate new information about local climate trends in the Pamirs by integrating instrumental climate data and community observations. Whereas our results showed different trend observations between both knowledge systems, we argue that both data types are highly complementary in detecting local climate trends in a peripheral mountain environment, as they (i) reduce existing uncertainties, (ii) provide new information, and (iii) introduce new perspectives. In terms of temperature, both knowledge systems provided information about seasonal temperature trends, however with different outcomes. ERA5 only showed a significant warming trend for summer, whereas community members identified autumn and winter as warming. Integrative studies in other regions also reported on different trend observations, which they argued with an existing scale mismatch between both knowledge systems (Fernández-Llamazares et al. 2017; Kieslinger et al. 2019). Whereas in our study a scale mismatch was prevented by downscaling ERA5 data to village-scale, the limited accuracy of the original ERA5 datasets due to missing in-situ measurements still influences the spatial accuracy of downscaled temperature estimates and their significance measures. Community observations can reduce prevailing uncertainties by providing further evidences for local changes in temperature in the form of biophysical signs and indicators.

Whereas those observations are limited in terms of objectivity and do not exist in the form of empirical, formal measurements, they are rooted and verified by daily observations and practices. Therefore, community observations can broaden the amount of available climate information at the site of specific villages and counteract prevailing uncertainties of instrumental data products.

In terms of snow, community observations and satellite data are highly complementary as they provide exclusive information about different snow variables. In peripheral areas, remote sensed products are often the only way to gain quantitative information about local snow patterns. However, those products perform better in estimating local snow cover extent than snow depth, if no in-situ measurements exist (Hoelzle et al. 2019). Resident communities on the other side, pay attention to other characteristics of snow. In the Pamirs, communities relate their observations to the amount of snow. In Norway, communities were shown to entail extensive knowledge about different types of snow (Riseth et al. 2011). Whereas both observations entail their limitations, such as uncertainties in satellite estimates due to cloud cover or missing standardized measurements by people, they can provide detailed information which cannot be gained using one knowledge system exclusively. Further, satellite images are generally restricted in the length of their observation period, providing data for the last two decades. Community observations can include generational or even trans-generational information about local snow characteristics. A combination of both knowledge systems can provide new and site-specific information about local snow characteristics. In the Pamirs, such information can have substantial benefits for predicting seasonal run-off regimes and subsequently the availability of drinking and irrigation water for local communities (Unger-Shayesteh et al. 2013).

6 Conclusion

The assessment of local climate trends in mountain environments constitutes a global research challenge. Uncertainty in climate data, which may result from a limited availability and temporal persistence of meteorological stations as well as coarse resolution gridded products, constrains the reliability of the conclusions drawn from such data sources. Therefore, it is of utmost importance for any locally adapted conclusions on climate change to reduce the uncertainty of the underlying data set. This study addresses this issue by integrating instrumental climate data and community observations on local climate trends in order to investigate complementarity. We applied a multi-method approach using downscaled ERA5 temperature data, the snow cover product MOD10A1 from MODIS, qualitative interviews, and community workshops. Seasonal trends in data from ERA5 and MOD10A1 were investigated using a statistical trend analysis. Shared pattern of knowledge in community observations on climate trends were identified using a consensus index. Our result showed that agropastoral communities in the Pamirs have deep-rooted knowledge of weather and climate which they derived from daily practices and long-term observations of their biophysical surroundings. Comparing communities' consent about local climate trends with instrumental climate records did not provide coinciding results. For temperature, instrumental climate data indicated an increasing trend in summer temperatures, whereas community observations identified a warming trend for autumn and winter. Discordant trend observations may essentially arise from multiple reasons, such as the statistical uncertainty in the downscaled temperature data or a seasonal bias in the communities' perception of climate trends. In terms of snow, both knowledge systems provided information about different snow parameter, which could not be derived by using one knowledge system exclusively. Community members reported on decreasing levels of snow, whereas satellite data demonstrated a shortening of the snow period in one of the villages. Indications for decreasing rainfall amounts could only be derived from community observations as local instrumental rainfall estimates are not available for the Pamirs.

Integrating data from independent knowledge systems is challenging, as knowledge systems differ in their structure and values, entailing their individual strengths and limitations. Given the high uncertainties of instrumental climate data in the Pamirs, we argue that community observations can reduce such uncertainties by providing new information about local climate trends. However, scientists have to carefully assess the context were human observations originate from to strengthen the reliability of such data. Establishing rapport and a respectful research relationship between scientists and local knowledge holders should be obligatory and acknowledged in the funding period of transdisciplinary research projects. Whereas this study was conducted in the Pamirs, the proposed approach can be transferred to other data-scarce, peripheral regions, such as the Himalaya, Andes, or rural parts of Africa, where traditional communities share a strong connectivity with their biophysical habitat. Further, integrated results from different knowledge systems at the scale of individual villages can provide valuable information for local climate adaptation or impact studies.

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7.1 Supplementary Material Manuscript 3

Measurements meet human observations: integrating distinctive ways of knowing in the Pamir Mountains of Tajikistan to assess local climate change

Climatic Change

Isabell Haag*, Karim-Aly Kassam, Thomas Senftl, Harald Zandler, Cyrus Samimi

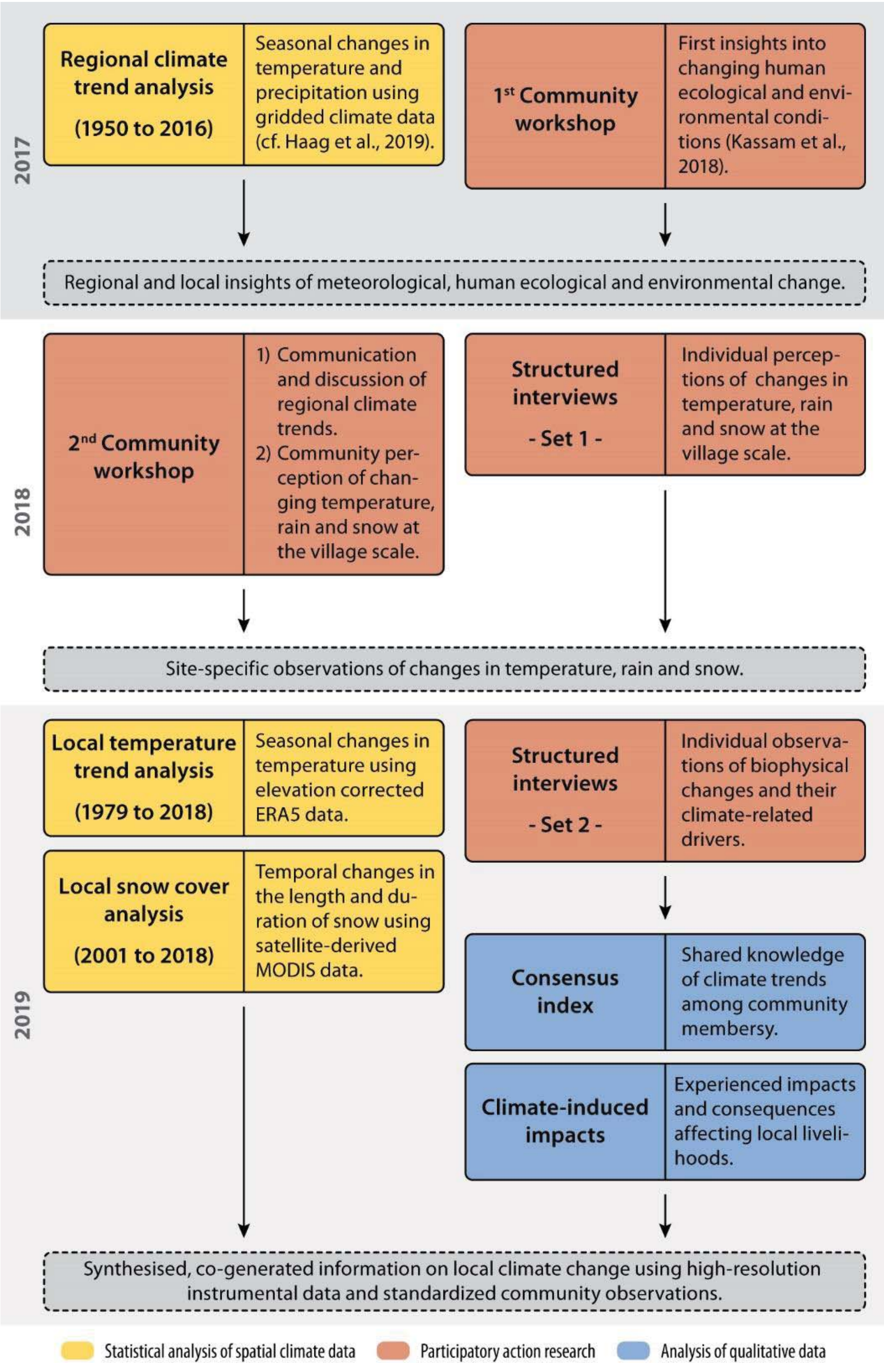
– Supplementary Material –

1 Meteorological stations

Overview of meteorological stations used in this study and corresponding ERA5 grid height of the raster cell the SAHRT acquired stations are located in.

Station	**Latitude (°N)**	**Longitude (°E)**	**Altitude Station (masl)**	**Grid Altitude ERA5 (masl)**
SAHRT station				
Ishkashim	36.72	71.60	2530	3833
Rushan	37.95	71.55	1981	3525
Khorog	37.50	71.50	2077	3586
Savnob	38.32	72.40	2880	4358
Navobob	37.67	71.83	2570	3822
Village station				
Savnob	38.31	72.41	2692	-
Roshorv	38.32	72.33	3139	-

2 Workflow



Overview of the applied research steps conducted between 2017 and 2019. Methods from the social sciences as well as the natural sciences were used to analyse meteorological data, satellite-derived data, and community observations

3 Formula Accuracy Measures

$$R^2 = \left(\frac{\sum_{i=1}^{N}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{N}(x_i - \bar{x})^2 \sum_{i=1}^{N}(y_i - \bar{y})^2}\right)^2$$ (3

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - y_i)^2}$$ (4

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|x_i - y_j|$$ (5

$$BIAS = \frac{1}{N}\sum_{i=1}^{N}(x_i - y_i)$$ (6

, with N= number of observation, $\bar{x}$= mean of model data values, $\bar{y}$= mean of the station values, x_i= model data at time i, and y_i= station data at time i.

4 Downscaling ERA5 Temperature data

Table 1. (A) Performance measures of original ERA5 and corrected ERA5 compared to meteorological stations. Absolute RMSE, MAE and BIAS are in °C/month. (B) Relative differences in performance measures between original ERA5 and corrected ERA5. The largest performance improvements are indicated in bold text. Asterisk behind MAE value indicates the significance level of absolute differences ($p<0.05$)

A												
	Original ERA5				**Corrected ERA5 – Method Γ_D**				**Corrected ERA5 – Method Γ_C**			
	R^2	**RMSE**	**MAE**	**BIAS**	**R^2**	**RMSE**	**MAE**	**BIAS**	**R^2**	**RMSE**	**MAE**	**BIAS**
Station												
Ishkashim	0.94	13.10	12.89	-12.89	0.95	5.72	5.33	-5.23	0.94	5.54	5.11	-5.02
Rushan	0.95	15.90	15.69	-15.69	0.95	7.02	6.65	-6.65	0.94	7.19	6.73	-6.73
Khorog	0.95	14.27	14.07	-14.07	0.95	5.59	5.10	-5.06	0.95	5.37	4.87	-4.79
Savnob	0.91	16.63	16.34	-16.34	0.92	7.89	7.34	-7.28	0.91	8.42	7.89	-7.81
Navobob	0.88	12.82	12.32	-12.32	0.89	5.90	5.15	-4.82	0.88	6.28	5.44	-5.12
Village												
Savnob	0.93	17.67	17.45	-17.45	0.94	9.06	8.69	-8.69	0.93	9.65	9.28	-9.28
Roshorv	0.94	15.60	15.40	-15.4	0.94	8.78	8.43	-8.43	0.93	8.76	8.36	-8.36
B												
Station												
Ishkashim	-	-	-	-	**1.06%**	-56.34%	-58.65%*	59.43%	0.00%	**-57.71%**	**-60.36%***	**61.06%**
Rushan	-	-	-	-	**0.00%**	**-55.85%**	**-57.62%***	**57.62%**	-1.05%	-54.78%	-57.11%*	57.11%
Khorog	-	-	-	-	**0.00%**	-60.83%	-63.75%*	64.04%	**0.00%**	**-62.37%**	**-65.39%***	**65.96%**
Savnob	-	-	-	-	**1.10%**	**-52.56%**	**-55.08%***	**55.45%**	0.00%	-49.37%	-51.71%*	52.20%
Navobob	-	-	-	-	**1.14%**	**-53.98%**	**-58.20%***	**60.88%**	0.00%	-51.01%	-55.84%*	58.44%
Village												
Savnob	-	-	-	-	**1.08%**	**-48.73%**	**-50.20%***	**50.20%**	0.00%	-45.39%	-46.82%*	46.82%
Roshorv	-	-	-	-	**0.00%**	-43.72%	-45.26%*	45.26%	-1.06%	**-43.85%**	**-45.71%***	**45.71%**

5 Interview questions used in 2018

1. Site-specific questions for each village

Roshorv:

a) When does the stream gets flooded?
b) Is there a difference in climate between the East-West and North-South of Roshorv?

Savnob:

a) Have you seen changes in the timing of *taaf*[1]?

2. Climate

2.1. Is it getting colder or warmer in *spring/summer/autumn/winter*?
2.2. Is there more or less rain in *spring/summer/autumn?*
2.3. Do you have more rain or more snow in *spring/summer/autumn*?
2.4. Is there more or less snow in winter?

3. Seasons

3.1. Can you write down the months you associate with each season?

[1] *Taaf is a local word, meaning when steam is coming out of the soil in spring*

6 Interview questions used in 2019

1. **Seasons**
    1.1. When is spring?
    1.2. When is summer?
    1.3. When is autumn?
    1.4. When is winter?

2. **Temperature**
    2.1. Is *spring/summer/autumn/winter* getting warmer or colder?
    2.2. Since when is *spring/summer/autumn/winter* getting warmer or colder?
    2.3. How do you know *spring/summer/autumn/winter* is getting warmer or colder?

3. **Snow**
    3.1. When is *Savnob/Roshorv* covered by snow?
        3.1.1. Has *Savnob/Roshorv* always been covered by snow around [*Answer given in 3.1*]?
        3.1.2. **If the answer of 3.1.1 is No**: Since when is snow coming *earlier/later*?

    3.2. When does snow disappear in *Savnob/Roshorv*?
        3.2.1. Has snow always disappeared around [*Answer given in 3.2*]?
        3.2.2. **If the answer of 3.2.1 is No**: Since when is snow disappearing *earlier/later*?

    3.3. Has the amount of snow changed?
        3.3.1. **If the answer of 3.3 is Yes:** Since when you do have *more/less* snow?

4. **Rain**
    4.1. Have you experienced changes in rain?

5. **Open End**
    5.1. Is there anything you would like to say or add?

7 Historical time markers used in Savnob and Roshorv

Time Marker 2018	Time Marker 2019
2000 – Millennia **2012** – Military operation in Khorog **2015** – Occurrence of earthquake **2017** – Last year **2018** – This year	**Before the year 2000** – Civil war/ visit of Imam/ Millennia **2000 to 2012** – Military operation in Khorog **After the year 2012** – Rehabilitation of channel/ Earthquake

8 Coding Consensus Index

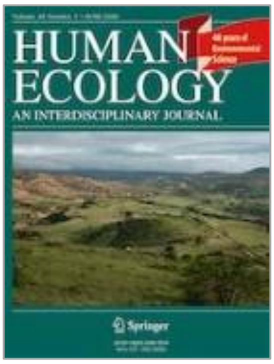
Numerical coding of the community observations identified in the interviews for calculating the consensus index.

	Direction of Change		
Observation	**-1**	**0**	**1**
Spring temperature	Colder	Same	Warmer
Summer temperature	Colder	Same	Warmer
Autumn temperature	Colder	Same	Warmer
Winter temperature	Colder	Same	Warmer
Rain	Less	Same	More
Snow	Less	Same	More
Snow Onset	Earlier	Same	Later
Snow Offset	Earlier	Same	Later

8 Manuscript 4: Engaging Transformation: Using Seasonal Rounds to Anticipate Climate Change

Karim-Aly Kassam, Morgan L. Ruelle, Isabell Haag, Umed Bulbulshoev, Daler Kaziev, Leo Louis, Anna Ullmann, Iriel Edwards, Aziz Ali Khan, Cyrus Samimi, Antonio Trabucco

Human Ecology (manuscript)



Engaging Transformation: Using Seasonal Rounds to Anticipate Climate Change

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Abstract

Seasonal rounds are a deliberative articulation of a human community's sociocultural relations with their ecological system. Conveying complex connectivity between humans and their habitats, the process of visualizing seasonal rounds can be the basis of transdisciplinary research. This paper presents a methodological approach for *communities of enquiry* such as biophysical and social sciences as well as the humanities to engage *communities of practice*, including farmers, fishers, herders, hunters and so on, in examining context-specific sociocultural and ecological relations driven by seasonal change. A historical précis of the concept of seasonal rounds is first presented by outlining spatial and temporal dimensions of a community's occupancy of landscapes as well as their movement within them. Subsequently, drawing on current international research among Indigenous and rural communities, the role of seasonal rounds to partnership formation, creation of a common vocabulary and mutual respect for multiple ways of knowing, validation of co-generated knowledge, vista into disciplinary pathways of research, and insights into seasonal change are described. By investigating the relationship between specific biophysical indicators and livelihoods of local communities, the paper demonstrates that seasonal rounds are foundational to developing anticipatory capacity for anthropogenic climate change.

Keywords: Adaptive capacity, Badakhshan, Central Asia, Dakota/Lakota, Ecological Calendars, Indigenous Knowledge, Kyrgyz, Local Knowledge, Oneida Lake, Pamir Mountains.

Introduction

Living organisms, including humans, evolve through relations with their habitat across space and time, according to the rhythms of seasonal change within landscapes (Dunlap et al. 2004). From an evolutionary standpoint, populations of organisms continuously adapt – at different rates – to climate variability (Petit and Hampe 2006). Similarly, human knowledge derives from engagement and performance in the spatial and temporal dimensions of climatic and ecological cycles.

To recognize and respond to climate change, we must appreciate the complex connectivity between the sociocultural and ecological. Relational thinking is fundamental to grasping the implications of climate change at the scale of local communities (Gaston et al. 2018). Developing a relational understanding of climate change confounds disciplinary approaches because it forces us to think across epistemological and ontological boundaries. A being "is" in relation to a continuum of beings within its habitat (Ingold 2000). Furthermore, there is a "necessary unity" between humanity's relations to its physical and informational environment (Bateson 2002). Therefore, insights into seasonal changes and climatic variation emerge from the sociocultural and ecological relations of communities with their habitats (Kassam 2009).

Engaging the complex connectivity between humans and their habitats is empirically demanding and textured with nuance. Adaptation to climatic changes requires synthesis of ecological, sociocultural, and economic frameworks in order to be effective (Klein et al. 2015). Investigation of the impacts of climate change at the scale of villages and towns requires not only *interdisciplinary* collaboration among the sciences and humanities, but *transdisciplinary* partnerships with indigenous and other local knowledge holders. People engaged in farming, fishing, gathering, herding, hunting, tending orchards, and other ecological professions are the *communities of practice* who contribute to the cogeneration of knowledge with *communities of enquiry* from the social and biophysical sciences as well as the humanities (Argyris et al. 1985; Kassam 2009). Based on these conceptualizations of transdisciplinarity and relational thinking, this paper provides a participatory methodology for collaborative and applied research to develop anticipatory capacity for climatic change in rural and indigenous communities (Kassam et al. 2018).

Seasonal variation is fundamental to life on earth. Across the globe, ecosystems rely on biophysical rhythms, i.e. cycles of temperature, precipitation, and the development and behavior of organisms. Human food systems also depend on seasonal change (Kassam 2021). These cycles are never entirely predictable, and communities across the globe have developed mechanisms to deal with varying degrees of uncertainty. However, rapidly increasing concentrations of greenhouse gases in the atmosphere are driving unprecedented changes across the climate system, including increasing weather variability, that pose existential challenges to humanity (Field et al. 2014). For instance, people who contributed least to anthropogenic climate change are facing its harshest impacts to their food systems (Kassam et al. 2011, 2018). *Communities of enquiry* located in industrialized nations most responsible for climate change are obligated to generate knowledge that has immediate application for adaptation and to build anticipatory capacity for increasing climate variability (Tschakert and Dietrich 2010). However, such efforts require close collaboration with affected communities throughout the research process, to include their nuanced knowledge of their habitat, cogenerate new knowledge to address their priorities, and disrupt the power structures that prevent climate justice (Haverkamp 2017; Kassam 2013).

Anthropologists and geographers use the term ‘seasonal round’ in reference to patterns of human activities associated with cyclical changes in their ecosystem. The seasonal round of a community is based on – and therefore reflects - the knowledge of complex relationships among abiotic and biotic processes as well as sociocultural phenomena (Turner 2014). Seasonal rounds are often recounted as place-based narratives that give insight into the living world and the sequence of festivals and other events that link a people to their habitat. Seasonal rounds lend themselves to a wide aesthetic; and therefore, may be described through texts, tables, graphs and circular figures illustrating a calendar of events expressing human ecological relations. As one element of participatory research, the discussion and visualization of seasonal rounds enable *communities of practice* and *enquiry* to cogenerate knowledge that is multidimensional, layered, and nuanced with respect to human-ecological relationality through space and time. The development of seasonal rounds is an ethnographic approach to establish a common vocabulary for dialogue about change and gain insight from local and indigenous knowledge holders. As a participatory methodology, seasonal rounds not only facilitate understanding of the entangled implications of anthropogenic climate change but generate insight as to how communities might develop context-specific adaptation strategies that anticipate and respond to emergent climate challenges.

Specifically, in this research, seasonal rounds are used to help develop and revitalize *ecological calendars* that anticipate climate change at the community level. In previous work, we have described *ecological calendars* as: ‘knowledge systems to measure and give meaning to time based on close observation of one’s habitat. They are comprised of seasonal indicators that include abiotic phenomena, such as the first snowfall or last frost, as well as biotic events, such as the flowering of a certain tree or the arrival of a migratory bird species. These calendars differ from celestial calendars, such as the familiar Gregorian calendar, in that they do not rely solely on fixed cycles of the sun, moon, or stars. Unlike those cycles, the indicators within an *ecological calendar* respond to climate and other seasonal processes that directly impact livelihood activities. By referring to seasonal cues, the measurement of time becomes flexible with respect to celestial cycles, and communities can identify the optimal timing for their activities. Therefore, *ecological calendars* may enhance anticipatory capacity for climate change by enabling communities to synchronize their activities with their ecosystem to accommodate climate trends and increasing variability.' (Kassam et al. 2018, p. 250). In order to develop an *ecological calendar*, construction of a community's contemporary seasonal round is essential.

A seasonal round has two spatial and temporal dimensions, respectively. The spatial components include: 1) *occupancy* of diverse landscapes by human communities, and 2) seasonally determined patterns of *movement* or *migration* within those landscapes. For example, the attributes of the spatial dimension are illustrated by agropastoral communities moving livestock across winter, spring, summer, and autumn pastures or the migration of hunting societies through different ecological zones to secure their food supply. The temporal dimension includes: 1) knowledge of *seasonal indicators* that inform the timing of livelihood activities; and 2) *intergenerational transfer* of this cumulative knowledge to secure future livelihoods. For example, farmers may decide to start ploughing their fields based on the snow-cover on a mountainside or the calls of spring peepers (*Pseudacris crucifer*) filling the soundscape. In turn, this knowledge is passed down to their children to guide their activities.

The goal of this paper is to demonstrate the process of developing seasonal rounds as a participatory research methodology to anchor transdisciplinary climate change research at a community scale. Section 2 explores the history of scholarship on seasonal rounds across a wide range of sociocultural and ecological contexts. Section 3 presents ongoing transdisciplinary climate change research in North America and Central Asia in which seasonal rounds serve as a starting point for revitalization and development of *ecological calendars*. We reflect on how the process of developing seasonal rounds with communities can facilitate cogeneration of actionable insights. Section 4 concludes with a synthesis of lessons learned.

1 Ethnographic Précis of the Seasonal Round

Given that climate change has anthropogenic antecedents situated within specific human cultures, it is important to review the work of ethnographers in the disciplines of anthropology, geography, and human ecology who have long been interested in seasonal patterns of life, and how those patterns relate to the local environmental conditions.

Franz Boas's *The Central Eskimo*, his first major ethnographic contribution to cultural anthropology, detailed the seasonally guided relationships the Inuit communities of Baffin Island had with their habitat in 1883 and 1884 (Boas 1964). Based on changing seasonal rhythms, Inuit settlement and migration on Baffin Island was directly driven by their perception of biophysical indicators to secure their food systems through hunting, fishing, gathering, and trade. Boas marveled at the geographic knowledge the Inuit communities had of their habitat which fundamentally informed his own map-making agenda (Kassam 2009).

Similarly, Alfred Louis Kroeber, a student of Boas, acknowledged the role of ecological context and how the relationships human societies have with their habitat contribute to the diversity and geographic distribution of cultures. While being sensitive to the dangers of environmental determinism common during this time, Kroeber recognized that cultures as a "whole" were dynamic processes emerging from their relations with the biophysical aspects of their ecology. His rather ambitious work, entitled *Cultural and Natural Areas of Native North America* (1939), was limited by a colonial outlook towards indigenous cultures. Nonetheless, he examined the relations of indigenous cultures to seasonal change, including temperature and precipitation patterns as well as engagement with plants and animals. Despite its limitations, his work outlined the connectivity of human cultures to the biophysical rhythms of their habitat, which in turn influenced their ecological professions, livelihoods, and food systems. While not directly speaking of seasonal rounds, he argued that diverse cultural manifestations emerge from a complex connectivity of relations within and across ecological zones.

Kroeber's student Julian Steward, a founder of cultural ecology and ecological anthropology, studied the movement of Western Shoshone bands as a model of adaptation to the seasonal availability of plants and animals across the Great Basin (Steward 1938). In mapping their movement over the course of the year, Steward sought to understand the particularities and similarities of cultural development under comparable environmental conditions. Steward combined Boas and Kroeber's ideas about the context-specificity of culture with an analysis of universally shared patterns of human relations across diverse environments (Orlove 1980; Thomas 1973).

Evans-Pritchard (1939, 1940) was among the first anthropologists to visualize time as a cycle of interaction between social and ecological phenomena. While Boas, Kroeber, and Steward had literally mapped human sociocultural and ecological relations with their habitat, Evans-Pritchard provided additional insight by illustrating the seasonal cycle as distinct but not exclusive of geography or place. His work with the Nuer in what is now South Sudan demonstrated their reckoning of time as flexible, understood in relation to lunar cycles as well as climatic and ecological processes. He drew circular diagrams of the Nuer seasonal round that elucidated connections between weather and human sociocultural and ecological relations (Evans-Pritchard 1939, pp. 197–198, 1940, pp. 98–99).

Whereas early twentieth century ethnographers tended to divide the study of space from time, later scholars of ecological time have been interested in their interaction. Basso's (1996) *Wisdom Sits in Places* articulates how Western Apache communities integrate spatial and temporal relationality with their landscapes. Turner (2014, vols. 2, 4) describes seasonal rounds as "patterns of seasonal movement and residence … within and across diverse geographic and ecological areas, [which] reflect and embrace the complex systems of knowledge and practice that integrate all the different aspects of peoples' lifeways." Historically, movement of people across territories has been deliberate, following a predictable pattern to engage landscapes based on knowledge of seasonal change across space. The relationships between weather, its ecological consequences, and human action is fundamental to survival (Bearchum 2007; Ridington 2013; Turner 2014). While continuity of the seasonal round requires sharing of knowledge across generations, patterns of activity necessarily change over time in response to environmental as well as sociocultural change. For example, colonization and forced sedentarization have had dramatic impacts on the seasonal rounds of many indigenous peoples. In contrast to European colonization of the Americas, Australia, New Zealand and other regions of the world, the movement of indigenous societies followed a seasonal pattern informed by ecological indicators and was functional with respect to livelihoods.

Scholars of indigenous ecological knowledge have studied seasonal rounds to explore the mutually reinforcing relationship between culture and habitat. As part of their stewardship practices, diverse cultures have developed rules regarding utilization of plants and animals in time and space (Burch 1998, 2005; Kassam 2010, 2015; Lantz and Turner 2003; Woodward and McTaggart 2019). Mindful relations with plants and animals include carrying out activities such as gathering or herding at specific times of year to the benefit of those organisms (Turner 2014). Furthermore, arrangements between cultural groups practicing different ecological professions (e.g. farmers and herders) to occupy the same spaces at different times of year is fundamental to those groups' relations with their habitat and each other (Kassam 2010).

Earlier work has demonstrated the value of indigenous ecological knowledge to address context-specific challenges. Now, in the 21st Century, biophysical scientists are increasingly interested in how such knowledge can inform responses to global problems, including climate change (Alexander et al. 2011; Fernández-Llamazares et al. 2017; Reyes-García et al. 2016; Ruckelshaus et al. 2020; Woodward et al. 2012). As the potential of indigenous ecological knowledge becomes more visible to a larger group of scientists, collaborations between *communities of enquiry and practice* require close attention to power dynamics (Kassam 2013; Nadasdy 1999). In many cases, the impetus to illustrate seasonal rounds comes from knowledgeable community members who are concerned about loss of knowledge for future generations. In her work with aboriginal communities in Australia, Emma Woodward has demonstrated the use of seasonal rounds as a way to sustain communities' relations with their habitat based on respectful and reciprocal partnerships between scientists and indigenous communities (Woodward 2010; Woodward et al. 2012; Woodward and McTaggart 2019). The process of generating and visualizing seasonal rounds can be an integral part of building strong and respectful working relationships within and among these communities.

2 Application of Seasonal Rounds to Climate Change Adaptation

Based on the historical development of seasonal rounds and their own recent research applications (Supplementary Materials 1), the authors launched a new participatory action research initiative (2015-2021). As noted above, the development of seasonal rounds served as the basis for revitalization and development of *ecological calendars* to anticipate climate change (Kassam et al. 2018). The project brought together social and biophysical scientists and their students with indigenous and rural communities in North America and Central Asia (Figure 1, Table 1). Short descriptions of the study sites can be found in Supplementary Materials 2. Collaboration in the creation of seasonal rounds has served as the primary methodology to facilitate communication among participants and generate new insights about the impacts of climate change and the possibilities to anticipate increasing climate variability. Figure 2 illustrates the iterative process which guided the transdisciplinary research and the subsequent sections provide a distillation of best practices learned through this approach.

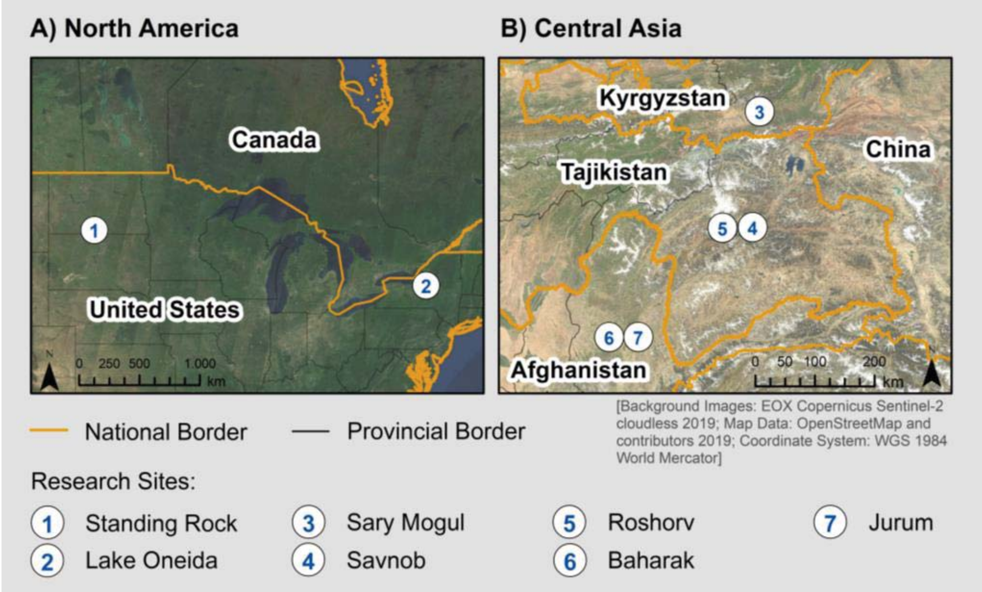

Figure 1. Locations of research sites in North America and Central Asia.

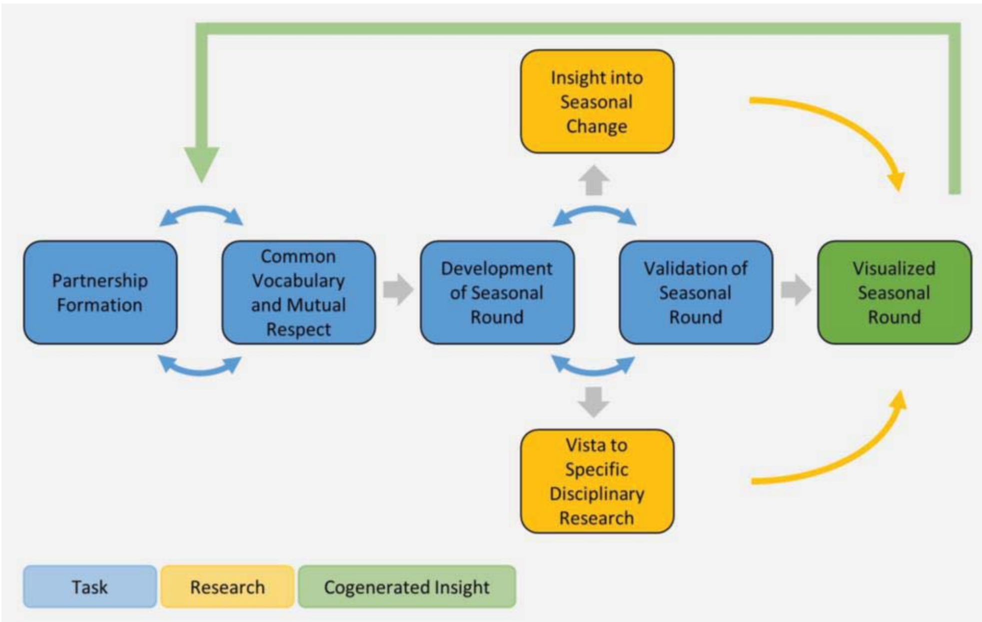

Figure 2. Dynamic process of creating seasonal rounds.

Table 1. Research contexts, including geographical locations and basic demographics.

Location	Latitude	Longitude	Elevation (meters asl)	Population	Majority cultures
Standing Rock Nation (USA)	46°05’13” N	100°37’48” W	500	8,581	Lakota, Dakota
Oneida Lake (USA)	43°10’22” N	75°56’12” W	120	266,000	Euro-American
Sary Mogul (Kyrgyzstan)	39°40’33” N	72°53’03” E	2985	5,156	Kyrgyz
Savnob (Tajikistan)	38°19’58” N	72°24’32” E	2675	310	Bartangi
Roshorv (Tajikistan)	38°19’00” N	72°19’20” E	3040	1,200	Bartangi
Baharak (Afghanistan)	37°00’00” N	70°53’00” E	1470	46,093	Tajik, Uzbek
Jurum (Afghanistan)	36°51’50” N	70°49’50” E	1560	50,190	Tajik Uzbek

2.1 Partnership Formation

Long-term research relationships facilitate communication and contribute to a growing trust relationship. In each of the research sites except for one (Oneida Lake, USA), members of the research team had established long working relationships, at least 10 years, with the respective community partners. Awareness of and sensitivity to the diverse cultural contexts further made formation of research partnerships possible. The research team usually initiated the partnership with the secular leadership such as the Tribal Chairman or Village Organization President followed by a similar conversation with local spiritual leaders such as *Khalifas*, *Imams*, or Traditional Elders. The conversation with community leaders centered on *ecological calendars* as a practice with which they could identify both historically and culturally. The project objectives, its collaborative nature, and expected outcomes were also discussed. As a result, they could foresee the potential benefits of this approach for anticipating climatic variation.

Once there was unanimous agreement to proceed with research, a date was set for a formal inception workshop accompanied by a meal (Figure 3). Participants representing various ecological professions who could contribute to the process of knowledge cogeneration were identified. Cultural context determined the way in which invitations were conveyed. Whereas in North America, participants were contacted by phone, email and letters; in the Pamir Mountains of Central Asia, personal visits were necessary. A community leader or key member of the research team visited community members in their homes or fields. Similarly, in the Standing Rock Nation, it was appropriate to visit Elders to invite them to the workshop.

Figure 3. Meal with Community Members in Savnob during the inception Workshop, 2017. Photo Credit: Isabell Haag.

At Oneida Lake, the only research site consisting of non-indigenous Euro-American settlers, the *community of enquiry* did not have established relationships. Therefore, the process of finding knowledgeable participants followed a slightly different approach. For over 60 years, Cornell University has maintained a Biological Field Station at Shackleton Point, located on the south shore of the lake. Staff of the Biological Field Station who live within the watershed assisted in identifying potential knowledge holders. In addition, Cornell Cooperative Extension staff from the four counties within the watershed also suggested names of individuals.

On the day of the inception workshop, everyone gathered for a meal, usually lunch, and a formal audio-visual presentation was given about the project. The *community of enquirers,* including the students, were introduced to the *community of practice*. The funding agencies and contributing institutions were identified. The objectives of the project were explained and the need for anticipatory capacity for climate change was discussed, linking it specifically to the community's food and livelihood systems. Furthermore, the geographic diversity and locations of all research sites were shown to demonstrate the breadth of the project (Supplementary Materials 2). The notion of *ecological calendars* was introduced, and connections were made to the respective community's ecological context. Finally, the expected outcomes and products resulting from the project were explicitly stated. Informed consent for participation was obtained. The meal was prepared by a community member but hosted and financed by *the community of enquirers*.

The principal investigators and students served the participants. The meal began with an invocation of thanks usually led by a locally recognized spiritual leader.

In addition to providing the basis for building trust relationships between the *community of practice* and *enquirers*, the meal itself was an impetus for a conversation on achievements of local food sovereignty as a key outcome of the project. While the meal was hosted by the *community of enquirers*, the *community of practice* also tended to the needs of the hosting-visitors. This event provided an opportunity to learn about their diverse backgrounds, discuss the project and its potential relevance, and tend to one another. The meal was the first concrete event where mutual care and respect were established.

While women were present, their numbers varied with respect to the cultural context, especially in Central Asia (Table 2). For example, in the religiously conservative community of Sary Mogul, trust needed to be established and consent provided by the *Aksakals* (a Kyrgyz term for male Elders) before researchers could speak with both women and men. A number of other sociocultural factors led to women participating more in individual interviews than in public events like the inception and validation workshops. First, the transdisciplinary research group tended to arrive in large teams of scientists and their students, and women tended to be reticent to engage such a large group of outsiders. Second, a few of the women in the villages of Savnob and Roshorv did not consider themselves experts about the landscape because they were from other villages and had married into the community. Nonetheless, men openly acknowledged the skills of those women, identifying one as a skilled hunter and another as the most knowledgeable orchardist. Third, during the summer field season, the burden of labor on women is high. Women have less time to participate in research due to agricultural as well as domestic responsibilities. The best time to talk to women would be in the late autumn, winter, and early spring, but then villages are not accessible as a result of inclement weather and road conditions, and the academic calendar makes travel during this time difficult. Given these constraints, the *community of enquiry* explicitly acknowledges low participation of women as a weakness. Potentially, graduate students have an opportunity to spend the whole calendar year in communities to access women's insights and experiences. As the research project is iterative, women's embodied knowledge needs to inform future research. To ignore women's knowledge would be perilous for effective transdisciplinary research.

Table 2. Locations and dates of workshops and other research activities to develop seasonal rounds for climate adaptation.

Location	Inception Workshop	Further research activities	Validation Workshops
Standing Rock Nation (USA)	December 8-10, 2015: 34 participants (20 females, 14 males)	8 community meetings, 43 participants (26 females, 17 males); 8 individual interviews, 10 participants (6 females, 4 males)*	October 8-11, 2018: 32 participants (30 females, 12 males)
Oneida Lake (USA)	June 3-4, 2016: 20 participants (6 females, 14 males)	45 individual interviews, 55 participants (15 females, 40 males)*	February 22-23, 2019: 18 participants (6 females, 12 males)
Sary Mogul (Kyrgyzstan)	July 13, 2016: 24 participants (all male)	39 individual interviews, 39 participants (20 females, 19 males)	July 12, 2018: 25 participants (3 females, 22 males)
Savnob (Tajikistan)	June 20, 2017: 20 participants (5 females, 15 males)	20 individual interviews, 20 participants (6 females, 14 males	July 2, 2018: 23 participants (4 females, 19 males)
Roshorv (Tajikistan)	June 27, 2017: 18 participants (3 females, 15 males)	17 individual interviews, 17 participants (3 females, 14 males)	July 6, 2018: 19 participants (16 females, 3 males)
Baharak (Afghanistan)	June 27, 2018: 14 participants (all male)	NA	NA
Jurum (Afghanistan)	June 28, 2018: 14 participants (all male)	NA	NA

* Including participating spouses, parents and friends.

2.2 *Creating a Common Vocabulary and Mutual Respect for Different Ways of Knowing*

Developing seasonal rounds simultaneously requires and establishes a common vocabulary. It also stimulates reciprocal respect for different ways of knowing between and among scientists and local knowledge holders. As the research was undertaken by a multidisciplinary team working across different conceptual paradigms, mutual understanding and respect need to grow from the beginning of the research process. Therefore, to create an enabling environment for cogeneration of knowledge, the valorization of different ways of knowing first had to occur among the members of the *community of enquiry* for each other; and second, appreciation of the depth, breadth, and diversity of indigenous or place-based knowledge among the heterogeneous members of the *community of practice* followed.

Documentation of seasonal rounds is a means of focusing the *community of enquiry* by providing a common basis to begin their research. During this process, relevant terminologies have to be clarified to ensure mutual understanding between the research team and the local knowledge holders. For example, identifying culturally specific starting points of seasons or how communities understand the notion of "rain", required conversation. While conducting interviews on a rainy day in Savnob, a rare occurrence in the summer in the Western Pamirs, the research team discovered different understandings of the word "rain". Although it was raining outside, one of the villagers said that they don't experience rain in the summer. Through discussion the scientists realized that they were using a meteorological definition of rain, which would include any kind of liquid precipitation, while the community members differentiated *tsirak pirak*, an onomatopoeia for soft rain that does not wet the earth or destroy crops, from *sharrast thyad*, another onomatopoeia for harder rain that soaks the ground and can damage crops. As it is *sharrast thyad* that matters to local livelihoods, villagers were only considering the heavier rain when answering questions.

Creating a shared understanding and mutual respect cannot be achieved within one field season. The reoccurrence of research steps required by the effective development of seasonal rounds, including iterative stages of data gathering and validation, provides continuity for the research process. It also sustains long-term relations between the *community of enquiry* and *community of practice*. It is through this process that members of the *community of practice* also began to recognize the heterogeneity of knowledge and experiences among themselves. This creates further opportunities for collaboration and common understanding, so that the research project gains meaning and relevance for all involved.

2.3 Development of Seasonal Rounds

As a fundamental component of partnership formation and building trust, the aim of the inception workshops was to establish at the outset the collaborative process of knowledge generation which is a key tenet of this transdisciplinary research initiative. Therefore, the idea of seasonal rounds was also introduced and collectively visualized. Creation of seasonal rounds at workshops enabled conversation of the phenomenological reality faced by the *community of practice* with respect to seasonal change, climatic variation, and their respective impacts on the local livelihood and food systems.

The process of discussing and illustrating a seasonal round begins with a facilitator from the *community of enquiry* explaining the purpose of the activity and explaining how the activity will proceed. The research team places a large sheet of paper printed with a series of concentric circles on the wall. The first questions pertain to the seasons, for example: How do you know the winter has ended? How do you know the next season has begun? How many seasons follow? What are the names of those seasons? The answers to these questions are used to identify important reference points on the seasonal round to which participants can relate other knowledge that emerges through discussion.

Discussion of the seasonal round starts at a specific time of year and proceeds through the seasons. In Standing Rock, the annual cycle begins with the first singing of the Western meadowlark (*tȟašíyagmuŋka*, *Sturnella neglecta*), so discussion began with spring and proceeded through subsequent seasons. At Oneida Lake, the conversation started with seasonal changes occurring at the time of the workshop and then moved through the rest of the year. The discussion of processes and events often reminds participants of related phenomena and human activities in seasons that have already been considered, and it is important to document such knowledge whenever it arises. Thus, from the very beginning, developing seasonal rounds is an iterative process, rather than a strictly linear one (Figure 2).

As the discussion moves from season to season, the facilitator gears questions toward the specific ecological professions within the community. For example, the facilitator might ask herders questions about the time for moving animals, whereas farmers will know more about the best time to plant and harvest each crop, and other relevant agronomic activities. Other knowledge, such as the timing of sociocultural events like festivals and celebrations, are typically shared across the community. Furthermore, one of the roles of the facilitators is to encourage participants to share what may seem to be contradictory knowledge based on different experiences. Engaging this diversity of knowledge is often challenging, especially when some participants are regarded as authorities. Facilitators emphasize that the goal is not to achieve consensus, but to enrich the seasonal round with knowledge derived from a diversity of experience.

Concerns about climate change impacts often arise on their own, but it is important to ask questions about these impacts once most of the seasonal round has been documented. The facilitator asks if participants have noticed any changes in the weather in the past 10 years. Participants often describe the uncertainty and anxiety associated with climate change, particularly the increasing frequency of unusual weather events. These discussions inform the *community of enquiry* as to the need for further research that will enhance the anticipatory capacity of the *community of practice*. In addition to climate change, participants often raise immediate priorities such as access to education, malnutrition, and poverty. The fact that such concerns arise indicates that climate change is already exacerbating existing inequities.

During the process of generating seasonal rounds, members of the research team are assigned various tasks. A community researcher assists with both translation and explanation. In many cases, Elders also help with translation and elaboration across various languages. Another team member records information on the circular diagram so that participants can review what is documented. Different colored markers are used to categorize information; e.g. green is associated with plants, brown with animals, and red with hazards. Meanwhile, other members of the *community of enquiry* listen attentively and take detailed notes to ensure that the nuances of the conversation are captured from different disciplinary perspectives. If culturally appropriate and accepted by the community, the process is photographed, leaving not only a written but also a complementary visual record. After the community meeting, documentation of the seasonal round continues with individual interviews.

2.4 Validation

As information through individual and group interviews is gathered, compiled, and analyzed, an empirically rich and more detailed seasonal round emerges. The *community of enquirers* returns to the respective research site to share their findings through a validation workshop. Again, discussions are first held with the secular and religious leaders. Then a community wide meeting is called, inviting all the original participating members, individual interviewees, and others who are interested to the validation workshop. As in the inception workshop, a locally prepared meal hosted by the research team provides the social context for discussion and insight. A new seasonal round based on information from interviews that has been gathered and analyzed is presented. The key questions are: Is the seasonal round accurate? Did the *community of enquirers* understand the *community of practice*? What was misunderstood? What is missing? Validation workshops were conducted at all research sites between 2018 and 2019 (Table 2).

The process allows for corrections, greater nuance, more information, and new insights. At the validation workshop in the village of Savnob, participants arrived 45 minutes early at the local schoolhouse, keen to get started and ask questions. An important new insight from the workshop was that ploughing depends on the availability of oxen. There are six oxen available in Savnob, and a pair is required for ploughing. Villagers must borrow extra oxen from the village of Roshorv at the start of Spring. Therefore, even if biophysical cues indicate time for ploughing, there is a delay based on availability of oxen. This shows that when designing an *ecological* *calendar*, other factors such as availability of labour influence livelihood activities that are informed by seasonal indicators.

At the validation workshop in Roshorv, an important correction to the collected information was that villagers also had agricultural lands in the nearby village of Yapshorv, which is located at a different altitude. There is at least a 25-30-day time lag in key agricultural activities between Yapshorv and Roshorv. Lands from both these villages contributed to the food security of the people of Roshorv, so it was necessary to disaggregate the seasonal indicators that had been collected for these two villages. Furthermore, it became clear during validation that physical hazards may serve as cues for livelihood activities. Increasingly, landslides are a major threat to mountain communities; for instance, villagers explained that a major landslide and subsequent destruction of houses in Yapshorv led to the settlement of Roshorv. Arguably, landslides are also part of the seasonal cycle of mountain communities. In fact, in Yapshorv, the first landslide is associated with the ripening of apricots.

In transdisciplinary research, it takes time for a common understanding and insights to emerge. For instance, until the validation workshop in Sary Mogul, it was not apparent that Kyrgyz communities had historically used *ecological calendars*. However, during the validation workshop it became clear the cosmological relationships were embedded and informed by their habitat. This aspect of a universally shared practice was simultaneously accompanied by biophysical indicators that are unique to the cosmology of this particular agropastoral culture conveying their ecological and cultural distinctiveness (Fielstrup 2002, pp. 210–217; Schuyler 1877, p. 329). The validation workshop firmly corroborated the shared legacy of *ecological calendars* across diverse ethnicities, ecological professions, and geographical locations.

Validation at Standing Rock Sioux Nation was conducted in six communities in October 2018 after similar workshops had been organized in the Pamirs. As a result, the research team had identified best practices that could be modified for these Native American communities. For example, data collected during the first phase were presented in two forms: first, a seasonal round in table format as in the Pamirs; and second, a circular diagram in which the same information had been digitized (Figure 4). As at the other sites, these validation activities were extremely important in that they revealed shortcomings of previous data and elicited more knowledge, in part due to participation of different individuals, and because participants could more easily envision the ultimate value of the research. As in Pamir communities, celestial indicators, such as the sun and moon are utilized by communities not as fixed occurrences in time but in direct relation to biophysical events such as “the moon when the cherries are black” or “the moon of snow blindness”.

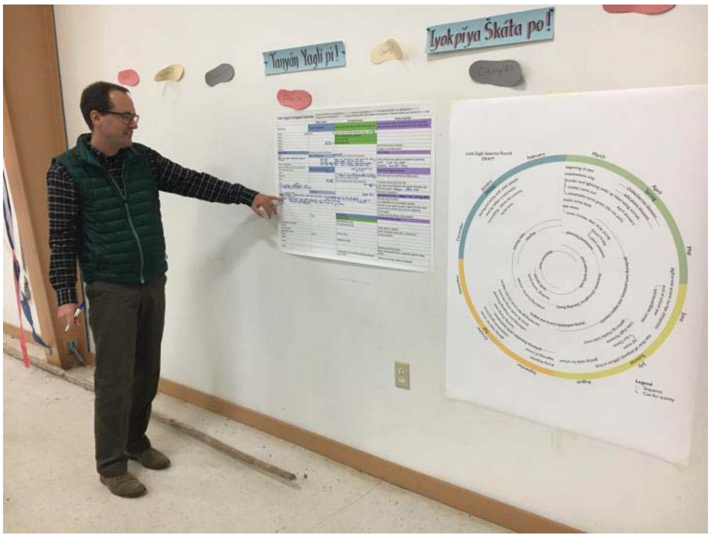

Figure 4. Dr. Morgan Ruelle undertaking validation of seasonal rounds at Standing Rock Sioux Nation, 2018. Photo Credit: Karim-Aly Kassam.

At the validation workshop in the Oneida Lake watershed, information was presented as both a table and a circular diagram to facilitate discussion, correction, and new insights. The validation workshop was different in character and content than the project inception workshop. At Oneida Lake, the majority of the Euro-American settler community did not accept the existence of anthropogenic climate change on ideological grounds. However, in the validation workshop, discussion of climate change was much more nuanced, and the ideological divide was not a significant factor; collaboration was seen as the priority. Furthermore, the conversation conveyed a greater sense of urgency. Keeping in mind that the project was initiated in 2016 during an unusually dry season where farmers had to cull their herds due to a lack of fodder; two and half years later, there was a palpable anxiety associated with livelihood activities being affected by unusual weather events. Moreover, valuable insights regarding the relationship between the fixed photoperiod and changing temperatures and precipitation were discussed in terms of impact on fish, plants, and poultry. Participants not only represented their own ecological professions but also represented various community associations, taking a long-term view and showing a concern for future generations. As in Standing Rock, there was a deep concern about loss of local ecological knowledge among the youth related to beekeeping, farming, fishing, herding, hunting, and orcharding. The dignity, mutual respect, mindfulness and care demonstrated by the participants at the validation workshops in the Oneida Lake watershed reflected similar qualities found among Elders in indigenous communities in Central Asia and Standing Rock.

As an iterative process, the seasonal round facilitates validation at vital stages in the transdisciplinary process. It also provides an opportunity to identify areas of difference and synthesis which are essential to any knowledge cogeneration process. First, the validation process is about testing the credibility of the cogenerated knowledge; specifically identifying seasonal indicators for developing anticipatory to anthropogenic climate change. Second, it is also an exercise in communication by illustrating the value of each of the various knowledge systems and combining the diversity of expertise found within the *community of enquirers* as well as *community of practice*. Unlike the blind peer review process, in this form of validation, difference is valorized as community members and researchers engage in discussion to establish mutual understanding. Participants can see and respond to each other, using verbal as well as non-verbal communication. The process is transparent and shared, hence engendering dialog and reflection.

Because the research team is visiting the *community of practice*, there is opportunity for further collaborative reflection and new insights may emerge even after the formal validation meeting has concluded. In fact, after the validation there were opportunities for additional interviews and data collection related to specific biophysical indicators. Whereas in each of our study sites, one validation workshop has been conducted, it can be possible that several validation stages are needed or that further development of certain details have to be pursued.

Final validation workshops presenting a draft *ecological calendar* for each of the research sites are scheduled for 2020 but were delayed due to the COVID-19 pandemic. These validation workshops will present drafts of *ecological calendars* for use and implementation by each community. The *ecological calendar* will be framed by the transdisciplinary understanding gained by the cogenerative process described above. Each *ecological calendar* will be simultaneously particular and universal. It will be unique as framed within the cosmology and ecological context of each research site and common in that it will be conveyed in a vocabulary and methodology familiar to all the communities.

2.5 Vista to Specific Disciplinary Research

The relationality revealed by articulating the seasonal round of each research site enables the members of the *community of enquiry* to (1) find elements within the rich information provided that was directly relevant to their respective discipline, and (2) to recognize the research pathway, value, and role of each contributing element from the varied ways of knowing assembled to the overall research aim. The process of generating the seasonal round simultaneously spurs humility by illustrating what is not known as well as generates mutual respect by showing the contributions other ways of knowing can make to one's own discipline and understanding. This sets the stage for further transdisciplinary research feeding into the process of developing *ecological calendars*:

- Ethnographic interviews were undertaken to gather biophysical indicators, cues, and sequences of seasonal livelihood activities;
- Weather stations and soil loggers were installed in the mountain communities to measure key meteorological variables, as no long-term data records exist;
- Vegetation cameras were installed to monitor intra-annual changes in phenology and snow cover;
- Information on the vegetative and reproductive development of key agricultural species, as well as planting and harvesting times, was recorded with the assistance of farmers to use for phenological forecast modelling based on climate conditions;
- Farmers and herders were asked to keep diaries and take regular photographs to document phenology and weather conditions.
- Long-term regional climate data were downscaled and complemented with community observations (Haag et al. 2021).

Having established the collaborative process, while walking through the village, people came out to tell stories, and wanted to show their gardens, greenhouses and other agricultural operations. This strong engagement of community members can provide further insights and inform new research ideas.

2.6 Insight into Seasonal Change

Any strategy to anticipate climate change needs to be grounded in the local sociocultural and ecological context. Climate models can tell us something about how regional weather systems might change but lack predictive capacity at the scale of a village or valley (Hall 2014; Kassam et al. 2018). In the three Pamir communities, during the validation process climate scientists were invited to present the results of their regional climate analyses to the communities (Haag et al. 2019). By sharing those results communities can complement instrumental data records and provide new insights on how local climate and weather conditions differ from the regional level. Those insights are particularly valuable, as local-scale climate records are scarce across the Pamirs and regional data sets cannot accurately capture small-scale variations of temperature and precipitation in complex terrain. For example, residents of Roshorv confirmed that they perceive a warming trend in spring, autumn and winter, but they disagreed that summer is warming. In Savnob, further insights about changes in the timing of snow were shared, and in Sary Mogul community members disagreed that seasons are warming at all, except for winter. Building anticipatory capacity requires an understanding of local weather patterns and microclimatic conditions over the long-term. Microclimates are often oversimplified in large scale studies and gaining insight into their impact can be difficult and time consuming (Potter et al. 2013). From the standpoint of *communities of enquiry*, a genuinely transdisciplinary methodology is necessary to engage the communities of practice who hold such knowledge and cogenerate new systems that enhance their abilities to anticipate change.

Seasonal rounds are context-specific and, therefore, serve as an entry point for understanding a community's sociocultural and ecological relationality. When collected from heterogeneous community members such as farmers, fishers, herders, hunters, orchardists and so on, the insights are revealing to the *community of enquiry* as well as to the *community of practice*. For the enquirers, the process yields theoretical insights about the relationship between climate data and local ecosystems, such as phenological indicators that maintain synchronies with seasonal change. For community members, a focused discussion of the seasonal round provides an opportunity to synthesize diverse knowledge about the seasonal rhythms of their habitat emerging from different livelihood activities.

Although much of this work has been conducted with indigenous communities, the Oneida Lake watershed provided an opportunity to engage a predominately Euro-American settler community. Some of the workshop participants and interviewees in Oneida Lake were skeptical about anthropogenic climate change; however, they were excited to engage in a discussion of their seasonal activities, and willing to talk about how changes in the weather have affected their own livelihood activities. The discussion of seasonal rounds created a space for engagement around common interests and concerns, avoiding assumptions based on political or ideological positions or affiliations. In a telling moment, the lead principal investigator asked a participant, who is a hunter and tour operator: "What are your priorities and concerns?" After some hesitation, he answered: "I don't know. I need time to think. We have never been asked about our needs. We are [usually] asked to take surveys". After a long pause he began listing concerns that directly linked his seasonal livelihood activities to the ability to anticipate climatic variation. The process of documenting seasonal rounds facilitated genuine engagement. At this early stage in research, the primary role of the *community of enquiry* is to listen. A foundational element of using seasonal rounds is the understanding that knowledge does not emanate from the heads of experts but through a *community of practice*'s engagement with their habitat. Thus, creating a responsive space, to cogenerate original, empirical insights about seasonal change.

3 Conclusion

Seasonal rounds are an articulation of a community's engagement of the sociocultural with the ecological in their habitat. The historical précis of the evolution of seasonal rounds reveals that while these rounds were originally thick ethnographic descriptions of spatial and temporal expressions of an indigenous people's seasonal relationship with their ecological habitats, these relationships can be visualized in support of transdisciplinary research aimed at understanding climate change at the local level. The process of visualization facilitates communication across cultural and disciplinary boundaries. A temporal visualization of the research process reveals that as a result of a respectful partnership between the *community of practice* and the *community of enquiry*, a common vocabulary is foundational to an emergent understanding of seasonal change and specific disciplinary insights. The development of the seasonal round and the iterative process of validation then contribute to cogenerated knowledge that is transdisciplinary in character (Figure 5). This cogenerated knowledge is a key building block to developing anticipatory capacity for climate change using *ecological calendars*.

Seasonal rounds are simultaneously particular or context-specific to individual indigenous and rural societies across the planet as well as universal in terms of a shared human heritage and practice of application of this spatial and temporal knowledge transmitted across generations over several millennia. Over these millennia, climatic variation has transformed habitats and altered use of resources within them, thereby affecting peoples' food and livelihood systems.

In order to make explicit the value of this ethnographic approach to understanding and building adaptive capacity to anthropogenic climate change, we recognize two aspects of the spatial and temporal dimensions of seasonal rounds. The spatial feature addresses seasonally determined *movement* and *occupancy* across landscapes. The temporal factor provides insights into *seasonal indicators* and *cues* and while building a cumulative body of knowledge within a community to *transfer to future generations*. These components generate empirically rich indigenous or local knowledge which has the potential to inform gaps in the biological, physical and social sciences. However, the rapidity anthropogenic climate change is breaking the linkages that are foundational to this spatial and temporal understanding. In a time of ecological uncertainty and sociocultural stress, this approach provides an enabling environment for cogeneration of knowledge that may help anticipate climatic variation for local communities.

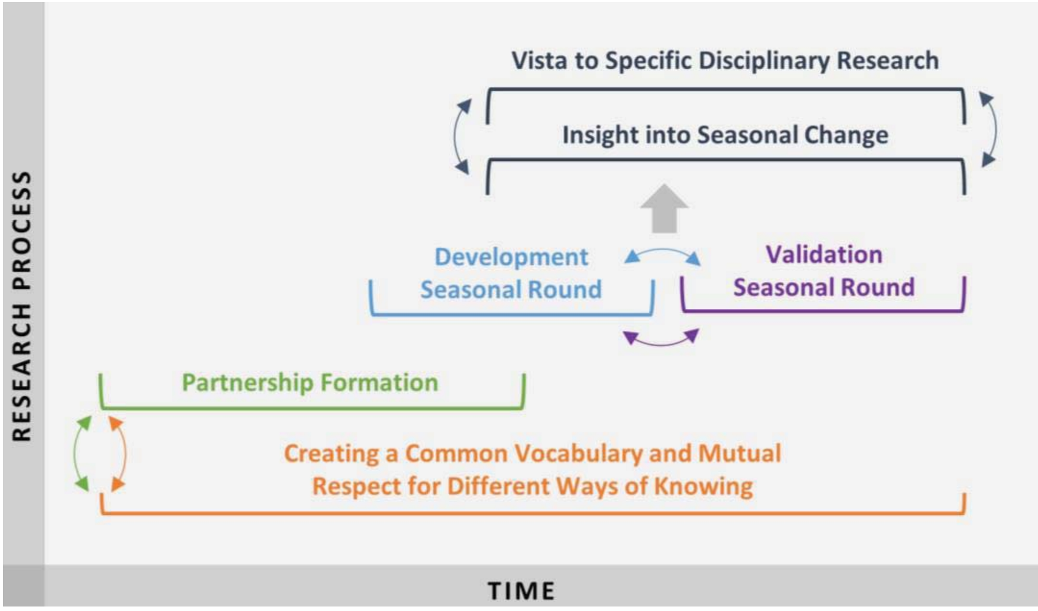

Figure 5. Temporal visualization of the transdisciplinary research process.

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8.1 Supplementary Material Manuscript 4

- Supplementary Material 1
- Supplementary Material 2

Engaging Transformation: Using Seasonal Rounds to Anticipate Climate Change

Supplementary Material 1

Past Use of Seasonal Rounds in Participatory Research

Since the 1990s, seasonal rounds have been used to gain insight into the depth and breadth of a people's relations with their habitat. Brief summaries of these projects demonstrate the diverse cultural contexts in which seasonal rounds have been applied to a wide range of community-driven projects:

- Robinson and Kassam (1998) documented the seasonal rounds of the Sami on the Kola Peninsula in Lovozero (Russia) to facilitate recognition of indigenous land-use rights after the collapse of the Soviet Union. The spatial movement of Sami reindeer herds through the seasons provided context-specific understanding of relations with other ungulates such as elk and wild reindeer (caribou), fur bearing animals, fish, waterfowl, raptors, trees, medicinal plants and berries across taiga and the tundra.

- Kassam and Soaring Eagle Friendship Center (2001) led a participatory research project with Dene women of Hay River, Northwest Territories, Canada. The articulation of seasonal rounds yielded information on their historic and current connectivity to the boreal forest. Specifically, the women's and their kinfolk's relationship with their habitat including hunting, fishing, trapping of specific animals; gathering of medicinal plants and berries; and spiritual engagement with features of the northern landscape illustrated their past and continued land use despite a tragic history of colonization and subsequent devastation caused by disease and sedentarization.

- Kassam (2009; with the Wainwright Traditional Council 2001) conducted a transdisciplinary applied research project on the impact of chemical pollutants on the food systems of Arctic coastal communities, including documentation of seasonal rounds of the Iñupiat community of Wainwright, Alaska, USA and the Inuvialuit community of Ulukhaktok (Holman), Northwest Territories. Seasonal rounds provided information on species of marine and terrestrial mammals, fish, birds, and plants that were part of their food system. Documenting these communities' human ecological relations in time and space has meant that oil and gas development initiatives have to be cognizant of the complex connectivity of Indigenous peoples. Illustrating seasonal rounds highlighted the significance and vulnerability of biodiversity within the local food system.

- Ruelle and Kassam (2011, 2013) conducted research with Elders in the Standing Rock Nation of North and South Dakota (USA) to understand how revitalization of relations with plants used in traditional foodways might address diet-related disease. Given the diverse experiences of Elders across heterogeneous environments, use of plants for different purposes, and strategies for gathering multiple species, each Elder illustrated her or his own seasonal round, which were overlaid with high transparency to reveal patterns of convergence and differentiation. The compiled round was used to plan activities for youth and elders to gather plants together and strengthen their knowledge of plants.

- Ruelle (2015; et al. 2019) documented how subsistence farmers in the Semien Mountains of Ethiopia use hundreds of domesticated and non-domesticated plants species in their food system. Increasing unpredictability in patterns of precipitation require strategic timing of planting and harvesting field crops. Discussion and analysis of the seasonal round revealed important synchronies between domesticated and non-domesticated species that could serve as effective seasonal cues for agriculture.

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Engaging Transformation: Using Seasonal Rounds to Anticipate Climate Change

Supplementary Material 2

Brief Descriptions of Collaborative Research Sites

Below is a description of each of the locations for participatory research involving seasonal rounds.

<u>Standing Rock Sioux Nation, USA</u>

The Standing Rock Nation is located in the Northern Great Plains of the United States, encompassing 9300 km^2 west of the Missouri River in North and South Dakota. The population of Standing Rock (8,581 as of 2018) is predominately Native American (78.2%), mainly Lakota and Dakota. Most of the reservation's forests were lost following the construction of the Oahe Dam by the U.S. Army Corps of Engineers in the 1950s (Ruelle, 2017). Beginning in 2016, Standing Rock was the site of international protests against the construction of the Dakota Access Pipeline across the Missouri at the northern edge of the reservation. The seat of tribal government is located at Fort Yates. Seasonal rounds were developed with eight communities, including Fort Yates, Cannonball, Solen, Porcupine, Kenel, Little Eagle, Bullhead, and Wakpala.

<u>Oneida Lake, New York, USA</u>

Oneida Lake, a remnant glacier lake, is located in central New York State, to the east of the city of Syracuse and south of Lake Ontario. It is a shallow lake with an average depth of 6.8 m covering around 207 km^2 (Rudstam et al., 2016). The Oneida Lake Watershed includes 3,877 km^2, which is home to 1,151 farms. The average farm size is approximately 78 hectares (USDA, 2017).

The research included communities living throughout the Oneida Lake Watershed. As a Euro-American settler community, a significant portion are working as farmers and in other ecological professions (e.g., hunting, trapping, fishing, and more); half of interviewees have engaged these professions for more than 20 years, and many had parents or grandparents following the same professions in the region.

Sary Mogul, Alai Valley, Kyrgyzstan

Sary-Mogol is part of the Alai Region of Osh Oblast (province) of Kyrgyzstan. Ranging from 2900 - 3100 meters a.s.l., the village is situated in the Alai Valley of southern Kyrgyzstan along the northern margin of the Pamir Mountains. The majority of inhabitants are of Kyrgyz descent, practicing Sunni Islam. The Kyrgyz language belongs to the Altaic family and has different origins than their Pamiri neighbors. The total population of the village is 5165 people (Ayil Ökmötü Sary-Mogol, 2010). There is a long history of agropastoral activities in the valley (Bernshtam, 1950 p. 187-188), which remains the basis of the economy (Shirasaka et al., 2016). Although, many families are still involved in seasonal livestock keeping and small-scale cropping, people also work in local institutions like shops, in the bank, or at the coal mine.

Savnob, Bartang Valley, Tajikistan

The village of Savnob is located in the Bartang Valley in the autonomous district of Gorno-Badakhshan (GBAO) in the Pamir Mountains of Tajikistan. The Bartang Valley is a nexus of diversity because the Silk Road provided contact to a variety of other cultures. Savnob is situated on a narrow terrace bounded on one side by the Bartang Gorge and on the other by a steep rocky slope. The 310 inhabitants occupy only 10 ha arable land. Belonging to the Shia Ismaili faith, they speak an Indo-European language of the Pamiri family. Although most interviews were conducted with individuals who professionally identified as farmers and teachers, rather than herders, it is common for many people to have additional professions. Often male community members migrate to Russia to send remittances for support. This migratory movement while positive in terms of potential income, has significant implications for families, the gender burden of labor upon women, and transmission of agricultural knowledge. Communities in the Bartang Valley are particularly vulnerable to climatic variation because they are located at high elevations. Furthermore, they have withstood the collapse of the Soviet command economy followed by nearly a decade-long civil war. In 2006, while undertaking field work in Savnob, we were first introduced to calendar of the human body, a context-specific ecological calendar (Kassam et al., 2011). Therefore, this village provided the impetus for our current research.

Roshorv, Bartang Valley, Tajikistan

Roshorv is also located in the Bartang Valley of the GBAO in the Pamir Mountains of Tajikistan and has withstood similar pressures and challenges as Savnob. The village is situated on a gently sloping plateau and a glacier-fed stream supports its agriculture. This geographical setting provides for a larger area of arable land (150 ha) than in Savnob, supporting a greater population of 1,200 inhabitants, most of whom are subsistence farmers and livestock herders.

Baharak and Jurum, Badakhshan, Afghanistan

The original site for our collaborative research was at Lake Shiva in the Shugnan valley of Badakhshan, Afghanistan. However, this region was overrun by invading extremists. Therefore, in 2018, the districts of Baharak and Jurum were chosen. Baharak, situated on a spacious alluvial fan in the Kokcha valley, is surrounded by intensively used arable land. Jurum is located along a tributary of the Kokcha river. Baharak and Jurum, while sharing a close cultural, linguistic and religious connections with the Pamiri communities of Tajikistan, are mostly Sunni Muslims. Research in this area is precarious because of Taliban presence.

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PART III

SYNTHESIS

9 Results and Synthesis

This thesis aimed at providing insights on local climate trends in two Pamiri villages, Savnob and Roshorv, by integrating instrumental climate data and community observations. In addition, this thesis provided a methodological discussion of the concept of Seasonal Rounds in light of transdisciplinary climate research, which fed into the development of a transdisciplinary research framework to guide future studies on climate knowledge integration. A variety of qualitative and quantitative datasets and research methods was applied to meet the research aims of this thesis, which were proposed as follows:

> RESEARCH AIM 1:
> **Generation of new insights on temperature, precipitation, and snow cover change in two villages in the Pamir Mountains of Tajikistan by synthesising information across distinct knowledge systems.**
>
> RESEARCH AIM 2:
> **Development of a transdisciplinary research framework to detect local climate trends in order to guide future studies.**

To investigate the two research aims, five research questions were developed and addressed individually in four publications (Figure 5). This chapter provides a summary of the results from the publications and an integrative discussion of them in relation to the research aims.

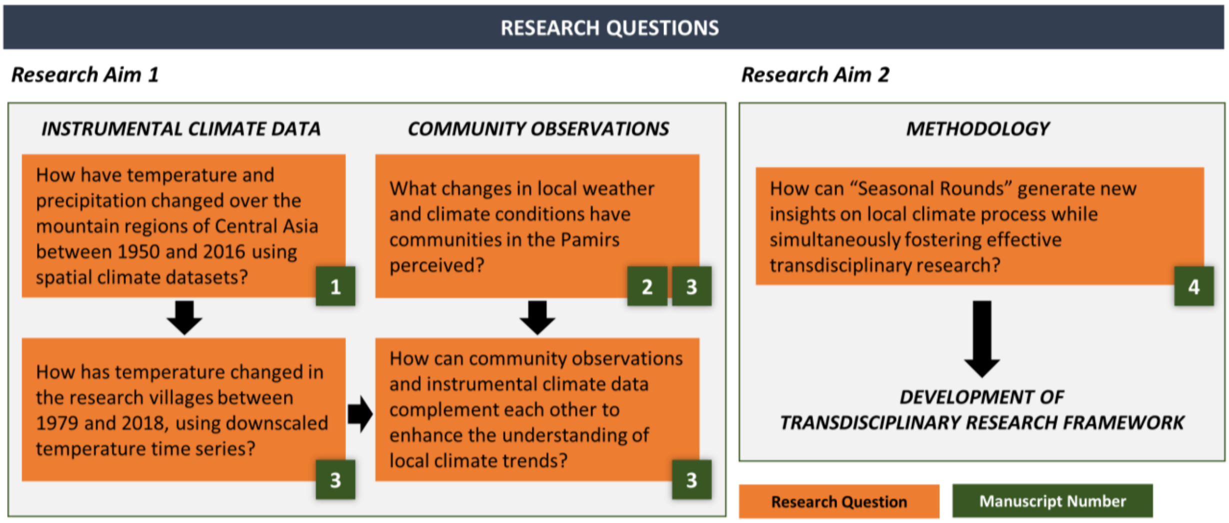

Figure 5. Summary of proposed research questions regarding the research aims of this thesis. See figure 2 for original graphic.

9.1 Integrative Assessment of Climate Trends in Savnob and Roshorv

Instrumental climate data and community observations provided independent information on local climate trends in the Pamirs, covering different scales and variables. Spatial climate datasets were only available with a coarse grid resolution, enabling the analysis of regional climate trends across Central Asia but impeding the detection of local climate trends. The regional climate trend analysis using CRU TS and TRMM 3B43 revealed a warming trend for all seasons between 1950 to 2016, with spring and winter showing the highest warming rates, followed by autumn and summer (manuscript 1). To identify temperature trends at the village scale, ERA5 reanalysis data was downscaled using a station-independent lapse rate-based elevation correction approach (manuscript 3). As expected, the magnitude of local temperature trends differed from regional averages. From 1979 to 2018, summer was the only season depicting a statistically significant increase in temperature. Autumn, winter, and spring also showed warming trends, but not at a statistically significant level. Whereas downscaled temperature records can produce more robust trend estimates than coarse-resolution gridded datasets, errors and statistical uncertainties remain due to the absence of ground measurements. To gain further information about local temperature trends, community perception of seasonal temperature change was examined using a consensus index (manuscript 3). The communities of Savnob and Roshorv were expected to show a high anticipation of changes in weather and climate due to their subsistence-based livelihoods and their former use of traditional ecological calendars (manuscript 2). Local ecological calendars showed that both communities closely observe changes in their biophysical environment to guide agricultural and sociocultural activities. In contrast to downscaled temperature trends, communities mutually expressed high agreement on warming temperatures in autumn and winter and low agreement on spring warming. In terms of local precipitation trends, data could only be derived from community observations as the absence of meteorological stations and limited computational capacity impeded a downscaling of precipitation data to the local scale. A regional analysis of CRU/TRMM precipitation data showed a significant increase in summer precipitation over the Pamirs, however, the grid resolution is too coarse to derive information about village-scale precipitation trends (manuscript 1). Both communities were in high agreement on decreasing levels of rain. In terms of snow, data from the satellite-based MOD10A1 snow cover product and from community observations complemented each other, as both monitored different characteristics of snow at the same spatial scale. Satellite observations showed a significant decrease in the length of snow seasons in Savnob, whereas community members of both villages reported a decrease in absolute snow amount as well as delayed snow onset (manuscript 3).

Against the background of producing use-oriented and site-specific information on local climate trends in a data-deficient environment, results show that the analysis of different knowledge systems entails several benefits in contrast to taking a single-evidence approach. One central advantage lies in the increased amount of available information, which can (i) reduce uncertainties, (ii) guide research initiatives, or (iii) provide new insights and perspectives for scientist and communities. The latter was shown in the precipitation and snow data example. Whereas instrumental climate data was unsuitable to provide local estimates of precipitation, community members directly perceived the occurrence of rainfall events and anticipated potential changes. Perceptions of rainfall may be even stronger in communities living in humid, tropical, or monsoonal climates. Regarding snow, information from different knowledge systems provided complementary data by referring to different snow parameters, including snow cover extent and snow depth at different temporal scales. New information was also obtained from different observation periods. Whereas measured climate data, in particular satellite-born data products, are temporally limited to recent decades, community knowledge and observation is intergenerationally accumulated, given the community has resided there long term. If both knowledge systems report identical trend observations and refer to the same spatial scale and variable, individual data and measurement uncertainties can be potentially reduced (c.f.Rapinski et al., 2018). Importantly, the advantages of using multi-evidence approaches are not found in the absolute quantification of climate trends, estimation of more precise data values, or in re-evaluation of statistical significance measures. Rather, their utility produces timely site-specific and use-oriented climate adaptation information relevant for scientists, stakeholders, and local communities themselves.

Working with different knowledge systems also involved several challenges, especially in dealing with different or contradicting observations. Such a situation was identified with temperature observations during this research. Downscaled temperature data depicted a significant increase in summer temperatures, but communities only identified warming trends in autumn, winter, and spring. To evaluate the reliability of respective results and to identify potential causes for different trend observations, it is indispensable to consider the limitations and uncertainties of the underlying data sources. Regarding measured climate data, uncertainties are clearly identified through statistical accuracy measures and technical documentation. In the Pamirs, uncertainties and limitations of available climate datasets mainly result from the absence of a homogenous network of long-term operating meteorological stations in combination with the topographical complexity of terrain. This decreases data accuracy, particularly affecting high-resolution data estimates in both space and time. Although station-independent downscaling approaches can increase the absolute accuracy of climate data at the local scale, these approaches are still insufficient for climate variables with high spatial variability (e. g. precipitation) or if high temporal resolution is required (e. g. below monthly averages). Furthermore, the lack of meteorological stations prevents an independent validation of both spatial datasets and downscaled time series. In contrast to measured climate data, a uniform system of error determination is missing in the collection and analysis of qualitative data. Community observations are influenced by several factors leading to a high level of subjectivity. In addition, applied methodologies to derive qualitative data are often incomprehensively communicated in social science publications (Davis and Wagner, 2003; Kallio et al., 2016; Nielsen and D'haen, 2014), which fosters scepticism in climate science regarding the reliability of qualitatively-derived data (Alexander et al., 2011). However, scepticism of methodological limitations should not devalue community observations, which are also empirically derived and locally verified through daily practice and observation. Focus should rather be placed on strengthening methodological approaches and communicating them coherently. In this thesis, qualitative research methods were clearly explained, including the choice of participants, development of interview questions, and organisation of community workshops and interviews. Besides a clear explanation of methodologies, reliability of community observations was further enhanced by focusing on community consent rather than individual viewpoints. However, further steps could increase the reliability of community observations. These steps may include sampling data longer term, transferring research tasks to local residents, validating acquired interview results using an independent group of informants, or conducting field work during different seasons. The proposed methods could considerably reduce uncertainties of community observations but accrue higher costs in terms of time and money, particularly when working in remote communities.

Another challenge in dealing with different trend observations is the acceptance of several truths and the establishment of mutual understanding. Whereas a collaboration of researchers and local knowledge holders from different disciplinary, cultural, and professional backgrounds can increase the breadth and depth of research projects, it requires equal acceptance of different epistemologies, values, and world views. In the context of this thesis, the question may arise regarding how community observations can be knowledge (c. f.Yeh, 2016). Or vice versa, local knowledge holders may be sceptical towards western knowledge systems, especially when they differ from their own cultural norms. Differences in understanding can also occur among scientists from different research disciplines. As outlined by the development researcher Robert Chambers in 1983, the establishment of mutual understanding can be particularly difficult if a high level of specialisation among researchers exists.

> *"Sometimes the more the disciplines, the more cautious people become not to trespass on the territory of others, and the more they focus the beams of their searchlights to shine brighter on smaller patches which they can safely claim their own. The more the disciplines and the larger the team, so too [sic!] the more difficult it becomes to communicate and to integrate work."*
>
> *(Chambers, 1984, p. 180)*

Transdisciplinary collaboration and problem-oriented research objectives require constant reflexivity of all agents involved and space for exchange and communication throughout the research process. Exchange and communication are important not only to identify similarities and differences between knowledge systems, but also to determine factors that influence knowledge systems over time. In the Pamirs, for example, knowledge systems might be influenced by the time of the Soviet Union, which was accompanied by a change in working and living conditions. In more recent times, LK can also get influenced by other knowledge systems, such as scientific knowledge, due to the rising availability of external media reports. However, last point can be considered as relatively low in the Pamirs, due to their remote living location. Within this process of exchange and investigation, all parties must accept that there might be several truths and that one knowledge system should not be considered inferior only because it differs from another. Instead, as clearly underlined in Yeh (2016), focus should be on identifying reasons behind existing discrepancies, which can be a time consuming process.

To conclude, the integration of knowledge systems provides new insights on local climate trends in data-scarce environments, like the Pamirs. As distinct knowledge systems are based on different epistemologies and have their own strengths and limitations, they can complement each other and potentially reduce their individual uncertainties. Especially in data-deficient environments, where the level of climate data accuracy strongly depends on long-term computational progress, the absence of in-situ measurements will continue to restrain data accuracy at the local scale, especially in the near future. Utilizing both LK and TEK approaches bring timely new insights and supports the development of effective climate adaptation strategies. However, the greatest challenge to achieving this is the acceptance of several ways of knowing and the willingness of all participants to collaborate and communicate across disciplinary, professional, and cultural boundaries. Finally, the integration of knowledge systems may not only be beneficial for the detection of climate trends, but also for the analysis of local changes in hydrology, phenology or climate impacts. In all cases, scientists should never forget to consider local communities both as agents and consumers of knowledge (Orlove et al., 2010).

9.2 Seasonal Rounds and Transdisciplinary Climate Research

With the goal of developing a transdisciplinary research framework in mind, the role of Seasonal Rounds as a participatory methodology will first be summarized regarding their application in the ECCAP project and then transferred to the field of climate science research.

Seasonal Rounds were developed over the course of two years within the ECCAP project to determine communities' seasonal relationships with their habitat and to mutually engage scientists and local knowledge holders in the research process (manuscript 4). Besides generating insights into seasonal change, the process of developing Seasonal Rounds contributed to an effective transdisciplinary research process in various ways. These included (i) the establishment of a research relationship, (ii) the development of shared understanding and respect for several ways of knowing, (iii) the opportunity to validate findings, and (iv) the provision of insights and incentives for further disciplinary research initiatives. Further, a finalised Seasonal Round can preserve LK for younger generations. By establishing common ground and providing space for different social and professional groups to communicate and collaborate, the development of Seasonal Rounds contrasts most other methods, such as interviews, focus groups, and oral histories. However, the effectiveness of Seasonal Rounds is influenced by the level of involvement and diversity of participating scientists and practitioners. Diversity is important to capture the multiple nuances of TEK and LK and to transfer them into respective follow-up research activities. In this study, scholars from the humanities, social and biophysical sciences as well as local community researchers and practitioners pursuing different professions participated in the inception and validation workshops. The number of participating community members was consistently high in both workshops, which could have resulted from the existing research relationship. Since 2006, reoccurring visits by the lead investigator of the ECCAP project and conversations with the village head and secular leader established a respectful research relationship and provided a fruitful basis for this study and the ECCAP project. Despite a strong research relationship, existing power relations between scientists and local communities or even within the community members themselves can still influence the number and willingness of individuals or social groups to participate in the research. Considering the level of community engagement in this study, the development of Seasonal Rounds can be classified as consulting transdisciplinary (c. f. Kumar, 2011; Mobjörk, 2010), as community members were involved in the generation and validation of data but control over the research process remained with the scientists. Community members had no direct say in the collective identification of research objectives, selection of applied methodologies, or knowledge integration, and were not involved in the process of data analysis. Given sufficient time and monetary resources, greater participation from local community members in future research could be considered to further strengthen the applicability and reliability of the results.

So far, Seasonal Rounds were only applied to gain insights into communities' sociocultural and ecological relations with their habitat. However, Seasonal Rounds could also be transferred to the climate sciences to derive more robust information on site-specific weather and climate processes, while simultaneously strengthening effective transdisciplinary research. In the climate sciences, most methodological approaches to derive information about local weather and climate processes are based on interviews, focus groups, and oral histories. Those methods utilise predefined research questions and objectives and usually involve a few people who were previously selected by scientists. This makes those methods particularly effective in addressing specific questions. However, when integrating community observations with scientific measurements, additional focus must be placed on the context where observations originate from, the establishment of a common language, and the integration of different epistemologies. Further, methodological measures for data validation are needed to improve the reliability of qualitatively-derived information. Seasonal Rounds could fill this methodological gap. At the start of the research process, community workshops on the development of Seasonal Rounds provide understanding of the sociocultural, climatological, and environmental settings of the respective communities and provide space to identify shared research objectives. Consequently, relevant climate variables pertaining to the respective communities may be identified by the scientists. In a second step, Seasonal Rounds can be used to visualize information gained from disciplinary research, such as the analysis of climate data or interview results, over the course of a year. Such information may include the occurrence of frost events, duration of both snow and rain periods, annual variations in water levels, occurrence of dry spells, or the timing of climate indicators. The visualisation process may reveal connections and dependencies of different events and processes, improving scientists' understanding of where community observations have derived from. This information improves effectiveness of subsequent interviews or focus group sessions, particularly for research in remote communities. However, the type of information collected in a Seasonal Round is limited to seasonal-dependent events. Single events, such as hazards or extreme weather events, can only be captured of they occur regularly. In this study for example, Seasonal Rounds would have helped in examining the community expectations of the research process and more specifically, to understand the importance of rain to local communities and to tailor interview questions accordingly. In a last step, finalized Seasonal Rounds can be validated by local community members to ensure accuracy of the derived information. Whereas Seasonal Rounds have not yet been applied exclusively towards weather and climate, they may represent a suitable tool to (i) contribute to the establishment of a research relationship and common terminology between all participants, (ii) extract more robust weather and climate information, especially regarding potential dependencies and relations, (iii) strengthen the impact and use-orientation of research outcomes by providing space for collective identification of research aims, and (iv) to support the development of more target-oriented disciplinary research methods, such as interviews. Climate scientists working in remote communities should reconsider conventional ways of knowledge production and start developing research approaches across disciplinary boundaries to meet complex research challenges of the 21st century.

9.3 Research Framework

Transdisciplinary research approaches can foster the development of use-oriented and site-specific knowledge through engagement of extra-scientific knowledge holders and the co-production of knowledge. Whereas practical guidelines for transdisciplinary research are mostly missing (Brandt et al., 2013), theoretical concepts of the research process exist. According to Lang et al. (2012) and Jahn et al. (2012), the research process usually consists of three phases, which include (1) problem framing and team building, (2) co-production of knowledge and collaboration between disciplines, and (3) assessment of results and their impact on scientific and social contexts. In detail, these three phases harbour further challenges accompanying transdisciplinary research and should be considered in the development of a research framework. In phase 1, the focus lies on initiating cooperation between different groups, usually including scientists, practitioners, and funders (Polk, 2015). This diversity creates one "major cognitive challenge of transdisciplinarity" (Jahn et al., 2012, p. 3), which is the integration of different epistemologies, perspectives, objectives, and problem framings. To ensure effective integration of different knowledge systems, it is important to establish common ground, mutual respect, and to acknowledge individual strengths and weaknesses of the involved knowledge systems (Brandt et al., 2013; Polk, 2015; Roux et al., 2010). In phase 2, a practical research framework should further consider potential power asymmetries and the varying responsibility and commitments between scientists and practitioners (Campbell et al., 2015; Polk, 2015). Engagement is crucial and facilitates the process of mutual learning and collaboration. The assessment of results in phase 3 brings two additional components of transdisciplinarity into play: reflexivity and adaptation (Jahn et al., 2012; Polk, 2015; Roux et al., 2010). Individual phases or sequences may have to be adapted and iteratively applied to achieve the research goals. In this instance, a continuity of personnel is favourable for the research process (Campbell et al., 2015). Lastly, the outcomes of transdisciplinary research should positively impact all participating groups. Practical examples of transdisciplinary research frameworks are seen in the development of a sustainable mobility system (Gebhardt et al., 2019), implementing phase 1 of a transdisciplinary research process in the riparian forests of Central Asia (Woltersdorf et al., 2019), and adapting to climate change (Serrao-Neumann et al., 2015). Commonly featured throughout these examples is the orientation towards the three phases of transdisciplinary research, inclusion of different participating social groups, and indication of applied methods and experienced challenges. However, these examples also show the diversity of research frameworks depending on the particular research question. The literature review yielded no practical transdisciplinary research framework that focuses on the coproduction of climate knowledge.

Against the background of this study, a practical transdisciplinary research framework on the process of climate trend detection was developed (Figure 6). The research framework is derived from experiences and lessons learnt from this research and aims to provide conceptual guidance for future studies on climate trend detection in data-deficient areas globally. The research framework has four central stages, which include the identification of a shared research aim, the co-generation of knowledge, the integration and validation of knowledge, and the application of final outcomes. STAGE ONE orients and frames the research process. Firstly, available spatial climate datasets or data from nearby meteorological stations is reviewed. A preliminary trend analysis of available climate data provides important *a priori* information about potential climate processes occurring at the respective scale. Simultaneously, researchers start to explore communities' TEK, in particular in terms of weather and climate. This can be done by developing a first set of Seasonal Rounds while simultaneously creating space for scientists and practitioners to meet and establish reciprocal trust and respect. After the initial data review, a community workshop is organised where preliminary results from the climate data analysis and the exploration of TEK are shared. The workshop is integral to identifying shared research objectives and incentives for further research. For climate trend detection, research objectives may include analysing specific climate variables for certain time periods (e. g. since 1950) or frequency intervals (e. g. weekly, monthly, seasonally). Workshops further allow for identifying potential participants for follow-up interviews. STAGE TWO presents in-depth, targeted research activities. Climate scientists analyse local trends of climate variables while considering different downscaling approaches. Social scientists conduct interviews on individual perceptions of climate trends and organise a second session of Seasonal Rounds to obtain additional information on yearly weather processes. Seasonal Rounds workshops are hosted primarily by social scientists but the attendance of climate scientists can be favourable in terms of developing mutual understanding. STAGE THREE integrates and validates the acquired results from each discipline. Integrating different knowledge types should be done by scientists, trained in transdisciplinary research and who have already

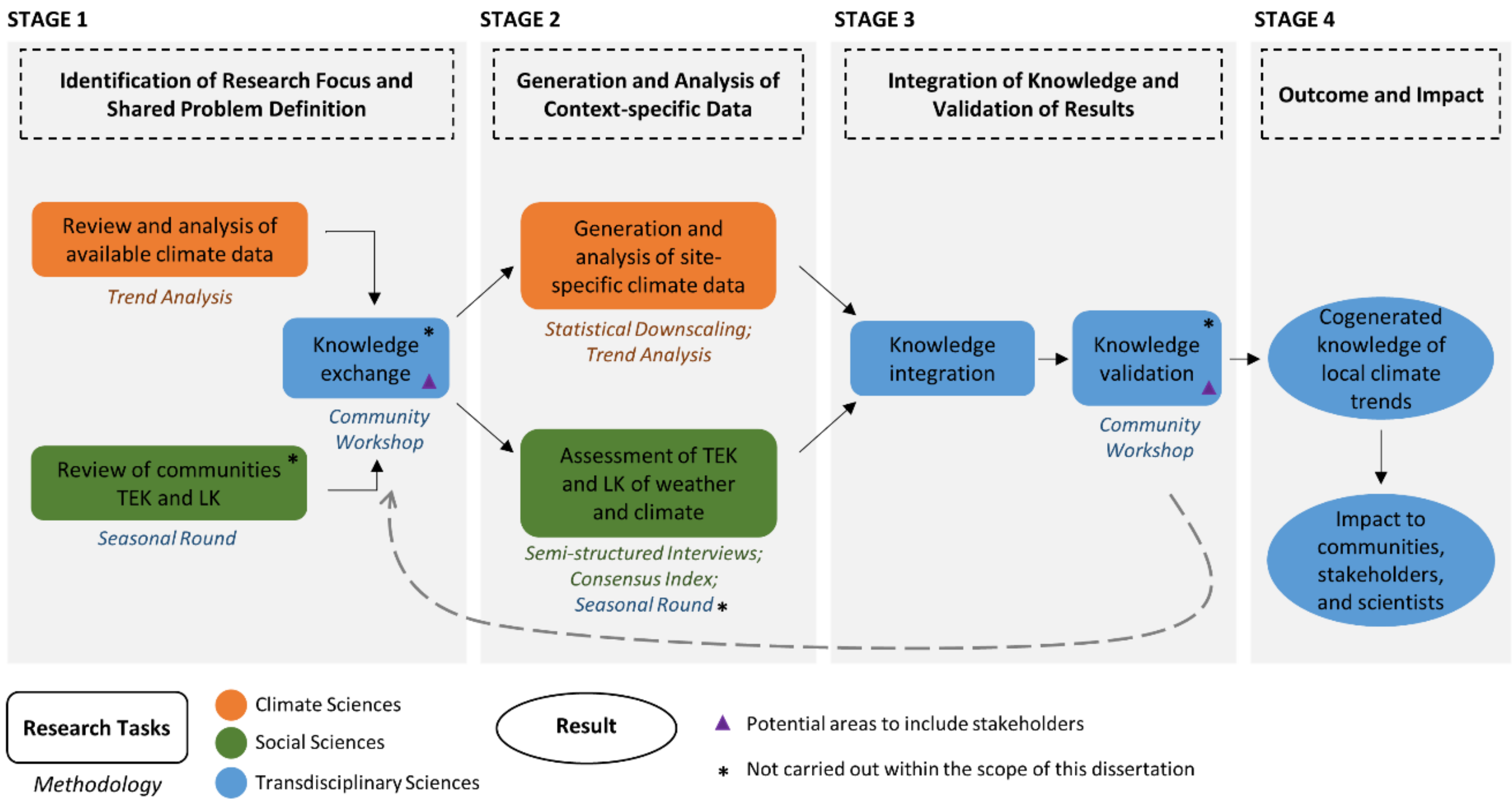

Figure 6. Transdisciplinary research framework on the process of knowledge integration using measured climate data and community observations to produce new insights on climate trends at the local scale in data-deficient environments.

participated in the current research process. The knowledge integration process reveals similarities, differences, or discrepancies between results. These results are presented in a community workshops to all participating groups and individuals in order to mutually evaluate and discuss findings and to identify further areas of research. Individual tasks or sequences should then be adjusted or repeated to meet the research aims. In STAGE FOUR the co-produced outcomes must be transferred and applied to different social and scientific contexts. Local climate trend information may foster the development of local climate adaptation strategies, serve as input data for hydrological or agricultural modelling studies, or inform communities about past changes in climate.

The presented framework is based on few assumptions, which should be considered in addition to the workflow. It is expected that a respectful research relationship has been established between researchers and local communities prior to STAGE ONE of the research process. This may take several years and requires multiple revisits. An existing research relationship with communities not only promotes trust and willingness of community members to participate in the research, but also initially assesses if transdisciplinary research can be carried out at this location. After completing STAGE ONE, it should be evident that communities actively perceive changes in their biophysical environments, have proven long term settlement of the area, and that accumulated knowledge finds regular application in daily practice. At the same time, communities should also have a vested interest in the research being conducted. For example, one motivation could be the rising awareness of impeding climate change risks. One central limitation of the developed research framework is that it has not yet been practiced in this form. Research tasks which were not applied in practice are marked with an asterisk in figure 6. Therefore, unanticipated limitations and challenges may arise. According to Lang et al. (2012), challenges of transdisciplinary research can include insufficient problem framing, existing power asymmetries, conflicting quality standards, lack of knowledge integration, discontinuous participation, or ambiguous results. In contrast to other transdisciplinary frameworks, stakeholder participation was not considered while conducting this study. However, stakeholder presence at certain stages of the research process may be highly relevant when implementing local climate adaptation strategies. Therefore, potential areas of stakeholder inclusion have been outlined in figure 6 with a purple triangle.

Based on the theoretical guidelines of transdisciplinary research in combination with practical and methodological experience from this study, a transdisciplinary research framework on the detection of climate trends was developed. Whereas the research framework could not yet be applied in its entirety in practice, it may support the detection of climate trends in other traditional communities living in data-deficient environments such as the Andes, Himalaya, or Arctic. As it is the first of its kind, it likely requires methodological or conceptual adjustments depending on the location or context it is transferred to. Nevertheless, it is an important starting point to provide practical advice on transdisciplinary climate research.

10 Outlook

Pursuing research objectives in the growing but limited field of transdisciplinary climate research leads inevitably to the identification of shortcomings and further research directions. Above all, the outcomes of this thesis should be considered as new experiences which strengthen the growing field of transdisciplinary climate research. Whereas the proposed research framework on the detection of local climate trends provides methodological guidance for future studies, it has not yet been wholly practiced. Therefore, proceeding steps should practically apply the proposed research framework to evaluate its suitability, strengths, and limitations.

The conducted study remained very local, focusing on two communities in the Pamirs which have similar livelihoods, sociocultural conditions, and climatological and environmental settings. Additional research is needed to assess the applicability of the presented research towards other regions. More research on climate trend detection could be conducted with subsistence-based communities in regions that have different climatological conditions than the Pamirs, such as the Arctic, the Amazon, or northern India. Representing a completely new approach, future research could concentrate on further developed societies, for example in Germany or Scandinavia. Even in industrialised countries, where an increased separation between nature and society is taking place and decision-making processes are no longer based on observations of ecological indicators, people such as winemakers, orchardists, and farmers may still exhibit heightened awareness of local weather events, long-term trends, or climate-related indicators, as their yields depend directly on seasonal weather conditions. In this context, two questions may be interesting to pursue:

- Which social groups, other than traditional or indigenous communities, may possess knowledge about changing climate and weather processes?
- Can the shared analysis of human observations and measured climate data provide additional insights on local climate and weather processes in regions with high-quality networks of long-term operating meteorological stations?

The integration of community observations with measured climate data provides new insights as both knowledge systems are complementary. Depending on the climatological setting of the communities, this approach can also be applied to examine trends in other climate variables, such as wind, ice, or phenology. Future research could also detect temporal changes in the occurrence or intensity of meteorological events, such as extreme weather events, frost days, or dry spells. The selection of variables is only limited by the availability of quantitative measurements and the perception of climate variables by the local communities. In this context, the temporal resolution of the data must also be considered. Whereas this study only examined monthly climate data and long-term trend observations, the reliability of perceptions for singular events as well as the measurement uncertainties for daily or weekly data in data-scarce environments should still be explored. Apart from the climate sciences, a combined analysis of community observations and quantitative measurements also constitute a promising approach to other research disciplines facing insufficient data accuracy at the local level. This may include hydrological studies, natural risk assessments, or climate impact studies.

The selection of the methods applied in this study was considerably influenced by the available time, access to in-situ measurements, and computational capacities. If long-term station measurements are available, future studies should consider station-dependent downscaling approaches to obtain local temperature time series, such as machine learning methods (e. g.Ebrahimy and Azadbakht, 2019) or interpolation techniques (e. g.Frei, 2014). Especially when a higher temporal resolution of the data is required, more complex statistical downscaling approaches should be considered. In terms of local precipitation estimates, which could not be obtained in this study, either experts on dynamical downscaling with access to high computational capacities should be involved or methods such as a probabilistic downscaling with interpolation should be considered (c. f.Haas and Born, 2011). With respect to the analysis of qualitative data in this study, the use of a simple consensus index to identify shared patterns of knowledge among community members was justified by the small size of the communities and homogeneity in terms of livelihoods. If communities show more diverse internal structures or if results between different communities should be compared, future studies should apply a more complex CCAs (c. f. Klein et al., 2014). Lastly, the efficiency of transdisciplinary research projects is mutually determined by the methodological and practical expertise of individual team members as well as their willingness to engage in transdisciplinary collaboration.

Transdisciplinary research approaches are needed to address the complex challenges of the 21st century and to develop effective climate adaptation strategies for traditional and indigenous communities. However, to increase the visibility and impact of transdisciplinary research projects, community engagement in the research process should be strengthened. There may even be a reversal of power distributions in the future. This is indicated through one talk of an Inupiaq Whaling Captain, who clearly outlined the consequences Arctic communities are facing due to climate change and appealed to scientists for collaboration to foster sustainable and timely climate adaptation strategies (Brower, 2020). Letting local communities engage in transdisciplinarity by framing research problems alongside young scientists in-training may not only lead to a higher efficiency of research projects but also provide opportunities to store and conserve traditional knowledge systems.

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PART IV

APPENDIX

A.1 List of the Author's Further Contributions

Only outputs related to this dissertation are listed here.

Organised Events

Mountains of Tajikistan – Nature and People at the Forefront of Climate Change. Research Symposium, Bayreuth, Germany, 10.01.2020.

Publications

Zandler, H.; Haag, I.; Samimi, C. (2019): Evaluation needs and temporal performance differences of gridded precipitation products in peripheral mountain regions. Scientific Reports, 9, 15118, DOI: 10.1038/s41598-019-51666-z.

Samimi, C. and Haag, I. (2018): Ökologische Kalender. Spektrum – das Wissenschaftsmagazin der Universität Bayreuth (1), 52 – 55.

Presentations

Haag, I.: Der Pamir im ökologischen und klimatischen Wandel. Eine transdisziplinäre und multimethodologische Herausforderung. Deutscher Kongress für Geographie, Kiel/Deutschland, 25.-30.09.2019.

Haag, I.: Large-scale climate data meets local Pamiri reality: Investigating climate change in Central Asia through diverse spatial and methodological lenses. International Symposium on Water and Land Resources in Central Asia. Almaty/ Kazakhstan, 09.-11.10.2018.

Haag, I. and Samimi, C.: Raumzeitliche Veränderung von Temperatur und Niederschlag in Zentralasien. Arbeitskreis Hochgebirge, Innsbruck/Austria, 02.-03.02.2018.

Conference Posters

Haag, I.; Kassam, K.-A.; Ruelle, M.; Samimi, C.: Large-Scale Climate Data Meets Local Pamiri Reality. AGU Fall Meeting, Washington/USA, 10.-14.12.2018.

Haag, I.; Jones, P. D.; Samimi, C.: Spatiotemporal Climate Trend Analysis in Mountainous Western Central Asia. 36. Jahrestreffen Arbeitskreis Klima, Rauischholzhausen/Germany, 27.-29.10.2017.

Haag, I.; Jones, P. D.; Samimi, C.: Spatiotemporal Climate Trend Analysis in Mountainous Western Central Asia. 16th Swiss Climate Summer School, Ascona/Switzerland, 03.-08.09.2017.

Haag, I.; Jones, P. D.; Harpham, C.; Samimi, C.: Climate trend analysis in western Central Asia. 35. Jahrestreffen Arbeitskreis Klima, Bad Dürkheim an der Weinstraße/Germany, 04.-06.11.2016.

A.2 Eidesstattliche Versicherungen und Erklärungen

(§ 9 Satz 2 Nr. 3 PromO BayNAT)
Hiermit versichere ich eidesstattlich, dass ich die Arbeit selbstständig verfasst und keine anderen als die von mir angegebenen Quellen und Hilfsmittel benutzt habe (vgl. Art. 64 Abs. 1 Satz 6 BayHSchG).

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Hiermit erkläre ich, dass ich die Dissertation nicht bereits zur Erlangung eines akademischen Grades eingereicht habe und dass ich nicht bereits diese oder eine gleichartige Doktorprüfung endgültig nicht bestanden habe.

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Hiermit erkläre ich, dass ich Hilfe von gewerblichen Promotionsberatern bzw. -vermittlern oder ähnlichen Dienstleistern weder bisher in Anspruch genommen habe noch künftig in Anspruch nehmen werde.

(§ 9 Satz 2 Nr. 7 PromO BayNAT)
Hiermit erkläre ich mein Einverständnis, dass die elektronische Fassung meiner Dissertation unter Wahrung meiner Urheberrechte und des Datenschutzes einer gesonderten Überprüfung unterzogen werden kann.

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Hiermit erkläre ich mein Einverständnis, dass bei Verdacht wissenschaftlichen Fehlverhaltens Ermittlungen durch universitätsinterne Organe der wissenschaftlichen Selbstkontrolle stattfinden können.

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Ort, Datum, Unterschrift