***Curriculum Vitae:* Anubha Aggarwal**

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Civil Engineering Department, Delhi Technological University.
E-mail: agrawal.anubha@gmail.com, Phone: +91-9818719508 **Nationality:** Indian

Educational Qualifications:

Degree	**Subject**	**University/Institute**	**Year**
B.Sc.	Life Sciences	Hansraj College, University of Delhi	2009
M.Sc.	Climate Science and Policy	TERI University, Delhi	2011
PhD	Glaciology, Thesis title: 'An assessment of volume of summer-accumulation type glaciers.'	TERI University, Delhi	2015
PG Diploma	Environmental Law and Policy	WWF and National Law Delhi University	2021

UGC Net qualified in Environmental Sciences

Academics/Research Experience:

Year	**Duration**	**Research field/ Department**	**Institute (In India/Abroad)**	**Designation/ Fellowship**
2014	September 2014 – December 2015	Glacier Science	Jawaharlal Nehru University	Junior Research Fellow in DST project entitled: "Development of Dynamical Mass Balance Model for Gangotri Glacier".
2016	January 2016 – May 2016	Courses taught: Environmental Science, Global Warming, Air Pollution (Lab.)	Delhi Technological University (DTU)	Guest Faculty, Environmental Engineering Department
2016	July 2016 – November 2016	Courses taught: Environmental Science	IndraPrastha College for Women, University of Delhi.	Guest Faculty
2016	August 2016 – November 2016	Courses taught: Environment Management System,	Delhi Technological University (DTU).	Guest Faculty, Environmental Engineering Department

		Environmental Microbiology		
2016	Mid-Dec 2016 – mid-March 2017	Glaciology	Chinese Academy of Meteorological Sciences, Beijing, China**.**	Post-doctoral Fellow
2017	mid-March 2017 – mid-March 2019	Glaciology, remote sensing and climate modeling	Delhi Technological University	DST SERB National Post-doctoral fellow
2019	Mid-March 2019 to April 2019	Course taught: Introduction to Environmental Science	Delhi Technological University	Guest faculty
2019	1st May 2019 - February 2020	Water Division	TERI	Research Associate
2020	June 2020	Glaciology, Civil Engineering Department	Delhi Technological University	DST Woman scientist (WoS-A)

No. of research publications:

SCI Journals	**Conference/ proceedings**	**ESCI Journals**	**Non-SCI Journals**	**Chapters in Books**	**Total**
9	2	2	1	0	14

Research Publication:

1. Agrawal, A., Upadhyay, V. K. & Sachdeva, K. 2011, Study of aerosol behaviour on the basis of morphological characteristics during festival events in India, **Atmospheric Environment**, April, vol. 45, pp. 3640 – 3644. ISSN: 1352-2310 http://www.sciencedirect.com/science/article/pii/S1352231011003621 (Impact factor 2011: 3.708) (Elsivier)
2. Agrawal, A. and Tayal, S. 2013, Assessment of volume change in East Rathong glacier, Eastern Himalaya, **International Journal of Geoinformatics**, Vol. 9, no. 1, pp. 73-82. (http://journals.sfu.ca/ijg/index.php/journal/issue/view/9) ISSN: 1686-6576 (SCI), IF: 0.25
3. P. Parth Sarthi, Anubha Agrawal & A. Rana 2014, Possible Future Changes in Cyclonic Storms (CSs) in Bay of Bengal (BoB) India under Warmer Climate, **International Journal of Climatology**, vol. 35, issue 7, pp. 1267-1277. DOI: 10.1002/joc.4053. IF: 3.609 (http://onlinelibrary.wiley.com/doi/10.1002/joc.4053/abstract) ISSN: 1097-0088 (wiley)
4. Agrawal, A., Sharma, A. R. and Tayal, S. 2014, Assessment of regional climatic changes in the Eastern Himalayan region: a study using multi-satellite remote sensing data sets, **Environmental Monitoring and Assessment**, issue 10, vol. 186, pp. 6521-6536. DOI 10.1007/s10661-014-3871-x. IF: 1.69 (http://link.springer.com/article/10.1007/s10661-014-3871-x) ISSN: 0167-6369 (springer)
5. Agrawal, A. and Tayal, S. 2015, Mass balance reconstruction since 1963 and mass balance model for East Rathong glacier, eastern Himalaya. Geografiska Annaler, Series A, Physical Geography, vol. 97, issue 4, pp. 695-707. IF: 1.67 (http://onlinelibrary.wiley.com/doi/10.1111/geoa.12109/abstract) ISSN: 0435-3676 (Wiley)
6. Agrawal, A. 2016, Estimation of Volume of An Eastern Himalayan Glacier Using A Novel Method Based On The Ice Surface Velocity Data And Basal Sliding Velocity, **International Journal of Scientific Progress and Research**, vol. 23, no. 03, 170-180. ISSN: 2349-4689. http://www.ijspr.com/citations/v23n3/IJSPR_2303_888.pdf

7. Agrawal, A. and Tayal, S. 2018, Preliminary Study on Estimation of Volume of Eastern Himalayan Glaciers Using Remote Sensing Methods, **Journal of Climate Change**, vol. 4, no. 1, pp. 13-21. Doi 10.3233/JCC-180002. ISSN 2395-7611 (P), ISSN 2395-7697 (E) https://content.iospress.com/articles/journal-of-climate-change/jcc180002 (IOS press)
8. Minghu Ding, Anubha Agrawal, Heil Petra and Yang DiYi. 2019, Surface Energy Balance on the Antarctic plateau as measured with an automatic weather station during 2014. **Advances in Polar Science**. Vol. 30, issue 2, pp. 93-105. ISSN: 1674-9928, IF: 1.5
9. A. Agrawal, R. J. Thayyen and A. P. Dimri, 2018, Mass-balance modelling of Gangotri glacier., **Geological Society, London, Special Publications**, 462(1): 99. https://doi.org/10.1144/SP462.1, IF: 1.56 (Geological Society Publications), print ISSN: 0305-8719
10. Aggarwal, A. and Mandal, A. 2021, Estimation of Past and Future Mass Balance of Glaciers of Sikkim Himalaya using Energy Balance Modelling Approach and Regional Climatic Projections, **Journal of climate change**, Vol. 7, No. 3, pp. 35-43. DOI 10.3233/JCC210017 (IOS Press, ESCI, https://content.iospress.com/articles/journal-of-climate-change/jcc210017)
11. Aggarwal, A., Frey, H., McDowell, G., Drenkhan, F., Nüsser, M., Racoviteanu, A. and Hoelzle, M. 2021, Popular adaptation to climate change induced water stresses in major glacierized mountainous regions of the world (systematic review paper prepared for IPCC AR6 report WG II), **Climate and Development** (accepted, https://www.tandfonline.com/eprint/PFHN7SZ4RH6PIHNMTJWN/full?target=10.1080/17565529.2021.1971059). IF: 2.311, SCI, online ISSN: 1756-5537

Papers Under preparation

1. Anubha Aggarwal, S. Anbukumar and Anubha Mandal, Relation of downscaled temperature and precipitation, and aerosol optical depth with mass balance of an eastern Himalayan glacier.

Conference Paper

1. Tigala, S., Sachdeva, K., Sharma, A. R. Agrawal, A. 2015, Air Pollution and Health: A Review of Measurement Techniques, Journal of Advanced Research in Medicine, ADR Journals, presented in 2nd International Conference on Occupational & Environmental Health (ICOEH), 26 - 28 September 2014, vol. 2, no. 1, pp. 10-15. ISSN: 2349-7181.

2. Agrawal, A. and Mandal, A., 2017, Thickness computation for Byrd glacier, East Antarctica, paper id R059, Presented in 1st International Conference on New Frontiers in Engineering, Science and Technology, held at Delhi Technological University from 8th Jan – 12th Jan'18.

Paper presentation in Conference:

1. Anubha Aggarwal and Anubha Mandal. Assesment of past, present and future mass balance of glaciers of Sikkim Himalaya using energy balance modelling approach and regional climatic projections. Presented in 2nd International Conference on Sustainable Technologies for Environmental Management (STEM-2019) held from 25-26th March 2019 at DTU.

Poster presentation:

1. Agrawal, A. and Tayal, S. 201. Assessment of Regional Climatic and Hydrological Changes in the Eastern Himalayan Region. Paper number: C41A-0316, Accepted in session C41A: Advances in High-Altitude Glaciohydrology II, **America Geophysical Union Fall meeting 2014**. Presented on 18 December 2014. https://agu.confex.com/agu/fm14/meetingapp.cgi#Session/2836
2. Agrawal, A. 2014. Assessment of regional climatic changes in the Eastern Himalayan region: a study using multi-satellite remote sensing data sets. Presented in the Global poster presentation session, **The 2014 Gregory G. Leptoukh Online Giovanni Workshop** held from 10-14th November'14.

http://disc.sci.gsfc.nasa.gov/giovanni/additional/newsletters/2014_gregory_leptoukh_giovanni_online_workshop/

3. Agrawal, A. 18 Jan'12, An approach to assess the rate of melting of glaciers, **IITM Pune**.

4. Agrawal, A., Dimri, A. P. and Thayyen, R. 2015 Mass balance and runoff from Gangotri glacier using remote sensing methods, **International Glaciological Symposium, Kathmandu, Nepal**, March 1-6, 2015.

5. Agrawal, A., Tayal, S. and Dimri, A. P.2015 Estimation of volume of Sikkim Himalayan glaciers using remote sensing methods, GLACINIDA workshop held at School of Environmental Sciences **Jawaharlal Nehru University**, New Delhi, India, April 8-10, 2015.

6. Agrawal, A. and Tayal, S. 2015. Estimation of volume of Sikkim Himalayan glaciers using remote sensing methods, Presented in **XII-International Symposium on Antarctic Earth Sciences 2015 in Goa** (13-17, July 2015).

7. Suyash, S., Agrawal, A. and Mandal, A., 2017, Modelling of Kaya identity Climate Model, Poster id R109, Presented in 1st International Conference on New Frontiers in Engineering, Science and Technology, held at Delhi Technological University from 8th Jan – 12th Jan'18.

8. Aggarwal, A., Frey, H., McDowell, G., Drenkhan, F., Nuesser, M., Racoviteanu, A., and Hoelzle, M.: Adaptation to climate change induced water stress in major glacierized mountain regions, **EGU General Assembly 2021**, online, 19–30 Apr 2021, EGU21-5033, https://doi.org/10.5194/egusphere-egu21-5033, 2021.

9. Aggarwal, A., Frey, H., McDowell, G., Drenkhan, F., Nuesser, M., Racoviteanu, A. and Hoelzle, M., Adaptations to climate change induced water stress in major gacierized mountain regions, Abstract ID 855095, Paper no. GC22E-02, Accepted in Session: GC048 Global Environmental Change in Mountain Social-Ecological Systems I (session id 121490), **American Geophysical Union**, New Orleans, LA, USA 13-17 Dec 2021, **presented on 14th Dec 2021**
https://agu.confex.com/agu/fm21/webprogrampreliminary/Session121490.html.

10. Aggarwal, A., Mandal, A. and S. Anbukumar 2021, Relation of downscaled temperature and precipitation, and aerosol optical depth with mass balance of an eastern Himalayan glacier, Abstract ID 883133, Paper no. C34C-10, Accepted in Session: C025 Observations and Models of Glacier Change III (session id 124694), **American Geophysical Union**, New Orleans, LA, USA 13-17 Dec 2021, **presented on 15th Dec 2021**.
https://agu.confex.com/agu/fm21/webprogrampreliminary/Session124694.html

11.Anubha Aggarwal and S. Anbukumar, Relation of downscaled temperature and precipitation, and aerosol optical depth with mass balance of an eastern Himalayan glacier, abstract accepted in Session: 09_Atmospheric dynamics over cold regions in a large-scale context, id: 246, IMC 2022, Innsbruck, Austria.

12. Aggarwal, A., Frey, H., McDowell, G., Drenkhan, F., Nuesser, M., Racoviteanu, A. and Hoelzle, M., Adaptation to climate change induced water stress in major glacierized mountain regions, abstract accepted in Session: 37_Mountain climate change adaptation: data, knowledge, and governance, id 323, IMC 2022, Innsbruck, Austria.

MASTERS THESIS SUPERVISED

1. Suyash, S., Mandal, A. and Agrawal, A. 2017, Modelling of the Kaya identity Climate model, submitted in Partial fulfillment of M. Tech. degree to Department of Environmental Engineering, Delhi Technological University.

2. Gupta, P., Mandal, A. and Agrawal, A. 2018, Seasonal patterns of $PM_{2.5}$ concentration at Delhi Technological University campus, submitted in Partial fulfillment of M. Tech. degree to Department of Environmental Engineering, Delhi Technological University.
3. Yaduvanshi, A., Mandal, A. and Agrawal, A. 2018, Studying the temporal variation of the glaciers of Sikkim Himalaya using different image analyses techniques, submitted in Partial fulfillment of M. Tech. degree to Department of Environmental Engineering, Delhi Technological University.
4. Parashar, D., Mandal, A. and Agrawal, A. 2018, Assessment of indoor air quality for commercial cooking sector, submitted in Partial fulfillment of M. Tech. degree to Department of Environmental Engineering, Delhi Technological University.
5. Manish Mishra, Mandal, A. and Aggarwal, A. 2019, Study of Glacial lakes of Sikkim Himalayan region with the help of Arc GIS, submitted in Partial fulfillment of M. Tech. degree to Department of Environmental Engineering, Delhi Technological University.

REVIEWED PAPERS FOR JOURNALS

1. Earth Science Informatics
2. Journal of Mountain Science
3. Cold Regions Science and Technology
4. ISPRS Journal of Photogrammetry and Remote Sensing
5. Expert reviewer for the **APECS Group Review of the second draft** of the **IPCC** *Special Report on Ocean and Cryosphere in a Changing Climate (SROCC)*, Chapter 2 (page 28-34).
6. International Journal of Climatology
7. Expert reviewer for the **APECS Group Review of the First Order Draft** of the **IPCC** AR 6 WG II, Chapter 2 (page 16-38)

WORKSHOPS ATTENDED (on selection basis in which travel, food and accommodation were funded by the organizers)

Sr. No.	**Title**	**Duration**	**Funding Institution**	**Organizing Institution**
1.	Training course on Snow Studies, Climate Change, and Remote Sensing	12th – 23rd December 2011	Dept. of Science and Technology, GoI	Divecha Centre for Climate Change, Indian Institute of Sciences (IISc), Bangalore, India.
2.	Indo-German workshop on “Challenges and opportunities in Air pollution and Climate Change” (CHOP-C)	16th – 18th January 2012	IITM Pune	Indian Institute of Tropical Meteorology (IITM), Pune, India
3.	Highnoon Spring School Programme	during 2nd-6th April 2012	Under EU funded project “Adaptation to Changing Water Resources Availability in Northern India with Himalayan Glacier Retreat and Changing Monsoon Pattern”	Indian Institute of Technology Delhi, India
4.	TERI-BCCR Climate Research School 2012 “Beyond	1 – 5 October, 2012.	Royal Norwegian Embassy at TERI University, Vasant Kunj,	The Energy and Resources Institute and Bjerknes Centre for

	Regional Climate Modelling – Best Practices and New insights”		New Delhi, India	Climate Research
5.	**Level-I Indo-Swiss Capacity Building Programme on Himalayan Glaciology**	April 1 -27 2013	DST Ministry of Science and Technology, GoI and Swiss Agency for Development and Cooperation SDC	School of Environmental Sciences, Jawaharlal Nehru University, New Delhi
6.	UKERC (UK Energy Research Centre) Summer School	7th – 12th July 2013	UK Energy Research Centre	University of Warwick, Coventry, UK
7.	**Indo-Swiss Capacity Building Programme on Himalayan Glaciology Level-II**	September 19th -22nd November’13	Supported by DST Ministry of Science and Technology, GoI and Swiss Agency for Development and Cooperation SDC	Chhota Shigri glacier, Himachal Pradesh (Field Training) & School of Environmental Sciences, Jawaharlal Nehru University, New Delhi (Classroom sessions)
8.	GLACINDIA workshop Training program on climate modeling and Climate Change Research, innovation and Services	April 9-10, 2015	Organized and supported by SES, JNU; Climate Service Center, Germany; NCAR, USA	School of Environmental Sciences, Jawaharlal Nehru University, New Delhi, India
9.	On Thin Ice – Arctic, Antarctica and the Himalayas	29-30th November 2016	The Royal Norwegian Embassy and Jawaharlal Nehru University, New Delhi	Jawaharlal Nehru University, New Delhi, India
10.	SERB School on Computational Meteorology	23rd October to 15th November 2017	**SERB**	KL University, Vijayawada, Andhra Pradesh
11.	Use of remote sensing and GIS techniques for Geoscience Applications: An Introductory workshop	June 3-4 2018	**UNESCO project no. 672**	Royal Thimpu College, Ngabiphu, Thimpu, Bhutan
12.	Science and Training workshop on Climate Change over High Mountain Asia	8 -12 October 2018	IITM Pune, IISc Bangalore, CCCR, ESSO	IITM Pune, India
13.	Training on Glacier Hazard Mapping using GIS and remote sensing	Nov 1-5 2018	**UNESCO project no. 672**	Dhulikhel, Nepal
14.	European Research Course on	6th January to 2nd February	**European Union**	Grenoble Alpes University, France

	Atmosphere **(ERCA)** 2019	2019		
15.	Paper writing workshop on CORDEX data	5h May 2019 – 11th May 2019	**UNESCO**	ICTP, Trieste, Italy
16.	International Mountain Conference 2019	8th Sept – 13th Sept 2019	**MRI, Switzerland**	Innsbruck, Austria
17.	Mentoring and Training program in IPCC Processes for Early Career Mountain Researchers	5th Sept – 19th Sept 2019	**MRI, Switzerland**	MRI, Switzerland
18.	10th ICTP workshop on The Theory and use of Regional Climate Model (common lessons)	8th Nov – 13th Nov 2021	**UNESCO**	ICTP, Triests, Italy (held online)
19.	Brainstorming Workshop on "WHO Air Quality Guidelines: Critical review and consideration for framing Ambient Air quality Standards in Indian Context", 5th May 2022, CSIR-NERI, New Delhi.	5th May 2022	**CSIR-NEERI**	CSIR-NEERI, New Delhi campus.

TAUGHT IN WORKSHOP

2018 Training on climate data analysis for the Glacier Hazard Mapping using GIS and remote sensing workshop, held from Nov 1-5 2018 in Dhulikhel, Nepal.

2022 Anubha Aggarwal, Kamna Sachdeva, S. Anbukumar, Anubha Mandal, Amit Aggarwal, expressed views in Brainstorming Workshop on "WHO Air Quality Guidelines: Critical review and consideration for framing Ambient Air quality Standards in Indian Context", 5th May 2022, CSIR-NERI, New Delhi.

Invited Lectures

01st Oct 2021 Delivered lecture on 'Global climate change: Glacier change in high mountain regions' to 3rd Semester MSc students of TERI School of Advanced Studies for Seminar Course on Global Environmental Change.

Workshop/ Conferences attended (others)

Sr. No.	Title	Duration	Funding Institution	Organizing Institution

1.	Utkarsh 2018 International conference Empowering Women in Science	30th – 31st October 2018	CSIR National Environmental Engineering Research Institute (NEERRI)	NASC Complex, Pusa road, New Delhi.
2.	2nd International Conference on Sustainable Technologies for Environmental Management (STEM-2019)	25-26 March 2019	TEQIP	Delhi Technological University
3.	National Workshop on Emerging Pollution challenges on Earth Ecosystem – SAFAR, India's Novel Initiative	26th March 2019	Ministry of Earth Sciences	Environment Pollution Laboratory Department of Environmental Studies University of Delhi

RECEIVED FINANCIAL SUPPORT

1. 2015 Financial support (registration fee waiver and accommodation) for attending XII-International Symposium on Antarctic Earth Sciences 2015 in Goa (13-17, July 2015).
2. 2015 Student travel support given to attend IGS Symposium on Glaciology in High Mountain Asia to be held in Nepal from 1-6 March'15. Travel support is being given from the pool of the funds from ICIMOD, Université Joseph Fourier, LTHE, and DFID
3. 2015 Financial support, for registration, accommodation and per diem during the IGS Symposium on Glaciology in High Mountain Asia to be held in Nepal from 1-6 March'15, given by DST/ SERB.
4. **International travel grant from SERB** under ITS scheme to travel to France for ERCA 2019 school

SCHOLARSHIPS, ACHIEVEMENTS AND AWARDS

1. 2019 Participant in 'Mentoring and Training program in IPCC Processes for Early Career Mountain Researchers', a program implemented by Swiss Agency for Development and cooperation with the Mountain Research Initiative, University of Zurich and ICIMOD.
2. 2011 Stood second in M.Sc. Climate Science and Policy
3. 2010 Coordinator TUMAC (TERI University Music Appreciation Club)
4. 2009 Best Team Member B. M. Johri Rolling Shield Award, Junior Category, Botany Department, University of Delhi
5. 2008-2009 President, Biological Society, Hansraj College, University of Delhi
6. 2008 Best Speaker Vice Chancellor's Trophy Award (paper presentation competition), University of Delhi.
7. 2008 Started college society magazine 'SRISHTI'

SOFTWARE SKILLS

1. Remote sensing & GIS softwares: ERDAS Imagine 9.1, LPS, ENVI, Arc GIS 9.1,
Arc view 3.2, Quantum GIS, COSI-corr
2. Statistical software: Minitab, R-tool (basic level), ITSM, Minitab
3. Climate data display software: GrADS, Panoply

4. Climate data analysis software: CDO, NCO
5. Climate Modelling: Regional Climate Model (RegCM), Weather and Research Forecasting Model (beginner's level)
6. Fortran

Field Experience:
Visit to East Rathong glacier, Sikkim Himalaya from 16th May'11 to 3rd June'11, as part of TERI's team.
Visit to Chhota Shigri glacier, Himachal Pradesh, Central Himalaya from September 19th -22nd November'13, as a participant of Indo-Swiss Capacity Building Programme on Himalayan Glaciology Level-II.

DECLARATION
I hereby declare that all the above information is true to the best of my knowledge and belief.

Anubha Aggarwal

CLIMATE AND DEVELOPMENT
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REVIEW ARTICLE

Check for updates

Adaptation to climate change induced water stress in major glacierized mountain regions

Anubha Aggarwal [a], Holger Frey [b], Graham McDowell [b,c], Fabian Drenkhan [b,d,e], Marcus Nüsser [f], Adina Racoviteanu [g] and Martin Hoelzle [h]

[a]Department of Civil Engineering, Delhi Technological University, Delhi, India; [b]Department of Geography, University of Zurich, Zurich, Switzerland; [c]Canadian Mountain Assessment, University of Calgary, Calgary, Canada; [d]Department of Civil and Environmental Engineering, Imperial College London, London, UK; [e]Departamento de Humanidades, Pontificia Universidad Católica del Perú, Lima, Peru; [f]South Asia Institute, Department of Geography, Heidelberg University, Heidelberg, Germany; [g]Department of Geography and Earth Sciences, Aberystwyth University, Aberystwyth, UK; [h]Department of Geosciences, University of Fribourg, Fribourg, Switzerland

ABSTRACT

Mountains are a critical source of water. Cryospheric and hydrological changes in combination with socio-economic development are threatening downstream water security triggering the need for effective adaptation responses. Here, we present a global systematic review (83 peer-reviewed articles) that assesses different water-related stressors and the adaptation responses to manage water stress in major glaciated mountain regions. Globally, agriculture (42%), tourism (12%), hydropower (8%) and health and safety (4%) are among the main sectors affected by hydrological and cryospheric changes . A broad set of adaptation measures has already been implemented in the world's mountain regions. We find that globally the most commonly used adaptation practices correspond to the improvement of water storage infrastructure (13%), green infrastructure (9.5%), agricultural practices (17%), water governance and policies (21%), disaster risk reduction (9.5%) and economic diversification (10%). Successful implementation of adaptation measures is limited by reduced stakeholder capacities, collaboration and financial resources, and policies and development. To overcome these limitations, funding for climate change adaptation and development programmes in mountains and trust-building measures such as shared stakeholder activities need to be strengthened. Local awareness raising of both, the adverse effects of climate change and potentially positive implications of specific adaptation measures can help to support successful adaptation.

ARTICLE HISTORY
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Accepted 12 August 2021

KEYWORDS
Mountains; Water stress; Cryosphere; Adaptation; Limitation

Introduction

Mountains are the source for water provision of major river systems, rich in biodiversity and represent clear indicators of climate change impacts. (Hock et al., 2019). Mountain regions are also known as 'water towers' as they supply disproportional runoff as compared to the adjacent lowland area to sustain environmental and human water demand downstream (Immerzeel et al., 2019; Viviroli et al., 2020).

About 1.1 billion or 15% of the world population live in mountain regions (Romeo et al., 2020). Water stress can affect 1.9 billion people living in or directly downstream of mountain regions (Immerzeel et al., 2019). The lowland population depending on essential mountain runoff contributions has grown from ~0.6 billion (23% of the total lowland population) in the 1960s to ~1.8 billion (39%) in the 2000s (Viviroli et al., 2020).

About 90% of the global mountain population lives in the countries of the Global South from which only 8% live above 2500 m asl. However, most of the high-mountain societies live in poverty and are considered highly vulnerable to climate change and food insecurity (Körner & Ohsawa, 2005). The rough terrain, complex climatic patterns and data scarcity are limiting the process understanding of mountain areas. Along with this, socio-economic constraints often reduce local adaptive capacity, leading to difficulties in designing and implementing adaptation strategies. Adaptation to climate change is defined as an adjustment in ecological, social or economic systems in response to observed or expected changes in climatic stimuli and their effects and impacts in order to alleviate adverse impacts of change or take advantage of new opportunities (IPCC, 2001).

There are more than 0.2 million mountain glaciers outside Antarctica and Greenland Ice Sheets, with 0.7 million km^2 area and $158 \pm 41 \times 10^3$ km^3 volume, all around the world (Farinotti et al., 2019). Glacier mass loss affects regional runoff and global sea level. From 2006 to 2016 glaciers of Western Canada and the USA, Central Europe, Central Asia, Southern Andes, Africa and New Zealand have shown a mass change of -0.83 ± 0.40, -0.87 ± 0.07, -0.15 ± 0.12, -1.18 ± 0.38, -1.03 ± 0.83 and -0.68 ± 1.15 m w.e. yr^{-1} respectively (Zemp et al., 2019). The rapid shrinking of mountain glaciers (Hock et al., 2019; Zemp et al., 2015) leads to rapidly growing lakes in recently exposed areas (Drenkhan et al., 2019; Shugar et al.,

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Supplemental data for this article can be accessed at https://doi.org/10.1080/17565529.2021.1971059

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Estimation of Past and Future Mass Balance of Glaciers of Sikkim Himalaya using Energy Balance Modelling Approach and Regional Climatic Projections

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Abstract: In this study, the mass balance of Sikkim Himalayan glaciers is computed by the energy balance modeling approach using REMO and APHRODITE data. According to the present work, the glaciers show a mass balance of ~0, +0.31 and –0.32 m w. e. yr^{-1} for time periods 1981-1990, 1991-2000 and 2001-2005.

To investigate the possible changes in the near future (2006-2049) and far future (2070-2099), REMO data under different representation concentration pathway scenarios 2.6, 4.5 and 8.5 are also analysed. For the time period 2006–2100, RCP2.6, RCP4.5 and RCP8.5 give an average mass balance of -0.75 m w. e. yr^{-1}, -1.04 m w. e. yr^{-1} and -1.4 m w. e. yr^{-1}, respectively. The results are comparable to other studies. This study is one of the few studies carried out to estimate the mass balance of glaciers using only climate model data.

Keywords: Mass balance; Energy balance; Representative Concentration pathway; REMO.

Introduction

Fresh water is an important resource and mountain regions provide a substantial proportion of freshwater to the world (Viviroli et al., 2020). Regional water availability is affected by glacier retreat and thinning (Zemp et al., 2019). Himalayan glaciers are an important freshwater resource in Asia and hence have become a widely studied area. But because of the difficult terrain and extreme weather conditions of these regions, collecting continuous field data is very difficult (Azam et al., 2018). For this reason, less observational data is available from these areas and also it is hard procuring the available data. Hence, remote sensing became a suitable method to study glaciers a long time back (Paul et al., 2004; Agrawal and Tayal, 2013; Agrawal et al., 2014). Gradually climate model data has also become popular to study glacier-atmosphere interactions in these regions (Rounce et al., 2020; Kumar et al., 2019).

*Corresponding Author

Glacier mass balance is being widely studied (Azam et al., 2018) as changes in mass balance and area of the glacier are correlated with climate change (Zemp et al., 2019). It is reported that glacier mass changes are negative in all regions over the latest observational decade, from 2006 to 2016. Mass balance of glaciers in South America is −1.0 m water equivalent (w.e.) per year; in the Caucasus, Central Europe, Alaska, and Western Canada and the USA is −0.8 m w.e. yr^{-1}, that is in the Southern Andes, it is –1.18 m w.e. yr^{-1}, while in Central Asia it is –0.15 m w.e. yr^{-1}, etc (Zemp et al., 2019). In the Himalayan region, mass balance is studied using a glaciological or on-field method only on 24 glaciers where the longest continuous series is only 12 years for Chhota Shigri Glacier (–0.56 ± 0.40 m w.e. a^{-1} over 2002–14) (Azam et al., 2018). Bolch et al. (2012) and Singh et al. (2018) have compiled mass balance data from a large number of studies based on glaciological/geodetic/hydrological/AAR

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· Article ·

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Surface energy balance on the Antarctic plateau as measured with an automatic weather station during 2014

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Abstract AWS data during 2014 collected at PANDA-N station, on the East Antarctica Plateau, are analysed. Net Short Wave Radiation (Q_{SWR}), net Long Wave Radiation (Q_{LWR}), sensible (Q_H), latent (Q_L) and subsurface or ground (Q_G) heat fluxes are computed. Annual averages for Q_{SWR}, Q_{LWR}, Q_H, Q_L and Q_G of 19.65, −49.16, 26.40, −0.77 and 3.86 W·m^{-2} were derived based on an albedo value of 0.8. Q_{SWR} and Q_H are the major sources of heat gain to the surface and Q_{LWR} is the major component of heat loss from the surface. An iterative method is used to estimate surface temperature in this paper; surface temperature of snow/ice is gradually increased or decreased, thereby changing longwave radiation, sensible, latent and subsurface heat fluxes, so that the net energy balance becomes zero. Mass loss due to sublimation at PANDA-N station for 2014 is estimated to be 12.18 mm w.e.·a^{-1}; and mass gain due to water vapour deposition is estimated to be 3.58 mm w.e.·a^{-1}. Thus the net mass loss due to sublimation/deposition is 8.6 mm w.e.·a^{-1}. This study computes surface energy fluxes using a model, instead of direct measurements. Also there are missing data especially for wind speed, though 2 m air temperature data is almost continuously available throughout the year. The uncertainties of albedo, wind speed and turbulent fluxes cause the most probable error in monthly values of Q_{LWR}, Q_H, Q_L, Q_G and surface temperature of about ±4%, ±20%, ±50%, ±11% and ±0.74 K respectively.

Keywords energy balance, Antarctica, surface mass loss, CHINARE

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1 Introduction

Antarctica is the coldest, windiest and driest place on Earth. It has three parts, East Antarctica, West Antarctica and the Antarctic Peninsula. In comparison to mountains of mid-latitude regions, it has very flat topographic relief except in some coastal areas. Due to the threats like sea level rise, changing wind patterns and loss of biodiversity, polar research is given importance in context of global climate research. The Antarctic Ice Sheet's (AIS) role as the major heat sink for Earth's atmospheric circulation makes it a very important region on the globe. However, learning about AIS is still a challenge because of its remote location, inaccessibility, harsh weather conditions and expensive expedition logistics.

The surface energy balance (SEB) of AIS is studied to learn about its climate processes and to monitor the impact of global climate change on the AIS (Van den Broeke et al., 2006; Hoffman et al., 2008; Ma et al., 2011a, 2011b). In particular, information about surface energy fluxes may be used for validation of climate models for Antarctica (King and Connolley, 1997). The Antarctic atmosphere is highly transmissive for solar radiation, especially on the high interior plateau where the atmosphere is thin and concentrations of clouds, water vapour and aerosols are low.

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Mass-balance modelling of Gangotri glacier

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Abstract: The sensitivity of glacier mass balance (MB) in response to climatic perturbations has made it an important parameter of study from hydrological, climatological and glaciological point of view. To monitor the health of any glacier system, long-term MB observations are required. These observations among Himalayan glaciers are not available consistently and large glaciers are not often monitored for mass balance due to logistical challenges. One such glacier is the Gangotri, situated in the western Himalaya. In the present study an attempt is made to model the MB over the Gangotri glacier, the biggest glacier in the Ganga basin and also the point of origin of the River Ganges. The mass balance of the Gangotri glacier is estimated during the time period 1985–2014 using two different methods: ice-flow velocity; and energy balance modelling using regional model (REMO) outputs and *in situ* automatic weather station (AWS) data. The geodetic method is used for the nearby Dokriani glacier, where field-based MB measurements are available. MB of Gangotri glacier estimated for 2001–14 using the ice-flow velocity method is -0.92 ± 0.36 m w.e. a^{-1}; for 2006–07, MB using AWS and Tropical Rainfall Monitoring Mission (TRMM) data with the energy balance modelling approach is -0.82 m w.e. a^{-1}; and for 1985–2005, MB using REMO data with the energy balance modelling approach is -0.98 ± 0.23 m w.e. a^{-1}. Using the surface velocity method, it is estimated that the glacier lost 9% of its volume during the period 2001–14. The glacier vacated an area of 0.152 km^2 from the snout region, and retreated by 200 m in the last 14 years. MB values estimated for the Gangotri glacier from different methodologies are remarkably close, suggesting them to be suitable methods of MB estimation. TRMM, High Asia Refined (HAR-10) and Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation of water resources (APHRODITE) data are used to estimate the precipitation over the glacier. The study suggests that the glacier-wide estimation of weather parameters needs to be improved for more accurate estimation of glacier mass balance.

Supplementary material: The snow-covered area, for months Jan-Dec, obtained for Gangotri glacier using Landsat data and NDSI (normalized differencing snow index) for year 2014 is available at https://doi.org/10.6084/m9.figshare.c.3888091

The study of glaciers is of immense significance for understanding and predicting global environmental change. They play a very important role in the regulation of Earth's energy budget. Whenever there is a climatic perturbation glaciers respond by gaining or losing mass, eventually leading to a change in their length, area and elevation. Change in glaciers causes change in the regional hydrology and therefore downstream flow regimes (Thayyen & Gergan 2010). So far, mass-balance (MB) studies in the Himalaya have been concentrated among a few medium- and small-sized glaciers (Dobhal *et al.* 2008; Bolch *et al.* 2011). However, in the Himalayan catchments where downstream flows are dominated by the monsoon during the peak glacier melt period of July and August (Thayyen & Gergan 2010), contributions from these small glaciers have a limited influence. Larger glaciers such as Gangotri glacier have a decisive impact on the downstream flow regimes of the headwater reach of the River Ganga. The mean annual summer runoff from the Gangotri glacier catchment, including 258.56 km^2 of Gangotri glacier system, is about 522 million cubic metres (MCM; Kumar *et al.* 2002). In comparison to this, average summer runoff generated from the nearby Dokriani glacier catchment (15.7 km^2) with 7 km^2 glacier cover is merely 54 MCM (Thayyen & Gergan 2010). Being the largest glacier in the Ganga headwater region as well as the source of the River Ganga, the MB perturbations of Gangroti are of immense scientific interest. There are a number of varying views regarding the response of the Gangotri glacier to the changing climate of the region. Some suggest that the Gangotri glacier has retreated fast during the past three decades (IPCC 2007), while others suggest that the retreat of the glacier has slowed down during the recent past (Kumar *et al.* 2008; Raina 2009). There are also viewpoints which caution against linking the present climate response of glaciers with that of glacier recession of the large 30 km long glaciers such as Gangotri (Thayyen 2008). The uncertainty over the response

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Thickness Computation for Byrd Glacier, East Antarctica

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Abstract: *Byrd Glacier is an outlet glacier draining ice from the East Antarctica Ice sheet to the Ross Ice Shelf. Using surface based velocity measurements made in 1978-79; thickness is estimated for Byrd glacier using an algorithm based on surface velocity. Earlier, ice thickness has been reported using surface elevation from ground surveys and bed topography from air borne radar sounding.*

Keywords: *Antarctica; Thickness; velocity*

1. INTRODUCTION

Byrd glacier (Fig. 1) is one of the largest outlet glaciers of Antarctica with its catchment basin having an area of 1070400 km^2 and the ice being funneled into a ~20 km wide and ~100 km long fjord through the Transantarctic Mountains and after that diverging into the Ross ice Shelf [1]. There have been many quantitative glaciological investigations for Byrd glacier [2, 3, 4]. Brecher [4] measured 1003 elevations and 471 velocities for points on the main ice stream of Byrd glacier using photogrammetric triangulation from two sets of aerial photography in Dec 1978 and Jan 1979. These data were used by Whillans et al. [5] and Van der Veen et al. [1] to conduct a force-balance measurement. The same data are used in this study also.

Bed topography of Byrd glacier was studied by the Centre for Remote Sensing of ice sheets at the University of Kansas during the 2011-12 austral summer using airborne radar sounding. Ice thickness varied from 2300 m to 500 m as seen from plots in Van der Veen et al. [1], from 3200 m to 700 m as seen from plots in Whillans et al. [5]. Maximum deformation velocity of 57 m a^{-1} was calculated by Van der Veen et al. [1] with almost all discharge being due to basal sliding with the average basal drag of 130 kPa.

Viscosity parameter $B = 600$ kPa a$^{1/3}$, corresponding to an ice temperature of -20 C was used by Van der Veen et al. [1] for calculations. The same value of viscosity parameter is used in the present study.

Agrawal [6] reported a new algorithm for calculation of ice thickness using slope and surface velocity data. The same algorithm is used in this work. This algorithm is based on the work by Adhikari and Marshall [7]. They estimated the effect of longitudinal stress gradient on effective gravitational load. In addition to the slope and surface velocity data, this algorithm requires three more parameters, i.e., average basal drag, creep coefficient and sliding length to thickness ratio.

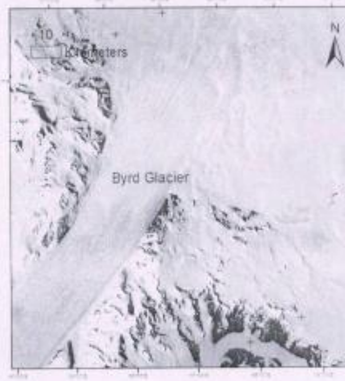

Fig. 1. Map showing the location of Byrd glacier in East Antarctica. This TIFF image of Byrd glacier is downloaded from [8]

In the present paper, a method is proposed to estimate the sliding length to thickness ratio. This ratio is important for estimating longitudinal sliding factor which is a function of slip ratio and sliding length to thickness ratio, as tabulated by Adhikari and Marshall [7]. Based on this algorithm, ice thickness is calculated corresponding to various velocity points for Byrd glacier in this work. The slope of the ice surface of Byrd glacier is less than 1 degree as seen from Brecher [4], so a constant slope of 1 degree is assumed in this work for the entire Byrd glacier. There is a requirement of a minimum threshold slope in the algorithm to reduce

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