# Kigali Declaration:

## Climate science for a sustainable future for all

World Climate Research Programme
January 2024
Publication No: 01/2024

wcrp-climate.org

**Bibliographic information**

This report should be cited as:

World Climate Reserach Programme (WCRP), 2024. Kigali Declaration: Climate science for a sustainable future for all. 01/2024. WCRP Open Science Conference, 23–27 October 2023. Kigali, Rwanda. January 2024.

**About WCRP**

WCRP is co-sponsored by the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC) of UNESCO and the International Science Council (ISC), see www.wmo.int , www.ioc-unesco.org and council.science. Website: **wcrp-climate.org**

**Contact information**

All enquiries regarding this report should be directed to wcrp@wmo.int or:

World Climate Research Programme
c/o World Meteorological Organization
7 bis, Avenue de la Paix
Case Postale 2300
CH-1211 Geneva 2
Switzerland

**Cover image credit**

Image supplied by the Rwanda Convention Bureau (rcb.rw)

**Copyright notice**



**Impressum**

The Kigali Declaration was written by the following attendees of the 2023 WCRP Open Science Conference:

Detlef Stammer, Helen Cleugh, Heide Hackman, Guy Brasseur, Mercedes da Cunha Bustamante, Valérie Masson-Delmotte, Kristie Ebi, Amadou Thierno Gaye, Graeme Stephens, Neil Harris, Gabi Hegerl, Bruce Hewitson, Maria Ivanova, Laurice Jamero, Thomas Peter, Celeste Saulo, Theodore Shepherd, Steven Sherwood, Thomas Stocker, Diane Ürge-Vorsatz, Martin Visbeck.

Comments received from many members of the community, during the process, were incorporated during final drafting of the Declaration.

The Supplement to the Kigali Declaration was compiled by the conference co-chairs with the help of the Conference Theme Leads, Lisa Alexander, Pierre Friedlingstein, Bruce Hewitson, Orli Lachmy, Izidine Pinto, Regina Rodrigues, Rowan Sutton, Mouhamadou Bamba Sylla, and Cathy Vaughan. Summaries of the individual sessions were provided by their respective session chairs and rapporteurs.

# Kigali Declaration: Climate science for a sustainable future for all

## Preamble

The World Climate Research Programme (WCRP) 2023 Open Science Conference met in Kigali from October 23 to 27 2023, bringing together over 1400 participants representing scientists from diverse research communities worldwide as well as practitioners, planners, and politicians. They discussed the current state and further evolution of inclusive international climate science, and the scientifically founded actions urgently needed to mitigate against and adapt to climate change.

This declaration was prepared by conference participants. Its signatories acknowledge that because of human-induced climate change and other human impacts on the environment, the world is in a state of polycrises leading to cascading systemic risk and increasing inequality, with failure to limit global warming being one of the greatest threats to humanity.

The global climate science community, coordinated by WCRP, is a diverse community of climate science experts who stand ready to advance fundamental climate science and work with society in the co-creation of actionable knowledge that can inform and support the required transformation to a safe, just, and sustainable future for all.

The WCRP 2023 Open Science Conference was held in Africa in recognition of the disparities in the drivers and consequences of climate change around the world; persistent inequities in the global scientific community that undermine and disadvantage the knowledge contribution from communities in resource-poor nations; and a collective commitment to address both.

1. **Kigali Declaration signatories call upon the global community to urgently act now to address climate change.**

   We ask decision makers from the worlds of science, policy, industry, and civil society to:

   **Commit** to achieving a significantly increased ambition for climate mitigation and adaptation, by upholding commitments to a fair and accelerated process of phasing out fossil fuel energy systems; and by improving climate knowledge and developing climate decision support systems, at both global and regional levels. This includes sustaining healthy ecosystems, providing equitable access to clean technologies and committing to a just energy transition worldwide, while addressing the needs for development and adaptation to unavoidable climate change impacts in the Global South.

   **Implement** transformative, ethical, and equitable solutions that are timely, feasible, scalable and fit for purpose in terms of the complex risks of inevitable climate impacts and transition risks. This includes well-planned and effective nature-based solutions, technological solutions, and behavior change.

   **Pledge** to support the development of inclusive, diverse, and equitable global knowledge partnerships between science and all sectors of society - including local and indigenous knowledge communities - for accelerated and transformative action over a 10– to 20–year horizon. Responding to context-specific and demand-driven needs, and collaborative and inclusive leadership from around the world in the context of irreversible aspects of climate change, is critically important.

2. **Kigali Declaration signatories call upon the climate science community to accelerate and amplify the relevance, impact and benefit of its research for science and society, enabling transformative actions.**

   We ask the WCRP leadership, together with its partners, to:

   **Commit** to identifying and implementing timely actions to give equal visibility, voice, and access to opportunity to early career scientists, marginalized scientists, and historically disadvantaged scientific communities, in the work, leadership and global influence of WCRP.

**Expand** the disciplinary scope of climate research and collaborate effectively with the broader global sustainability science community to bring integrated knowledge to our understanding of human systems, ecosystems, and biodiversity.

**Advance** trans-disciplinarity and the effective engagement with policymakers and the broader public as partners in the co-design of research and co-creation of actionable knowledge.

**Prioritize** developing effective pathways for translating observation and model data into actionable climate information that enables informed decision-making and resilience building; facilitates community input; and addresses critical data gaps in cities and informal settlements, the oceans, and data sparse regions.

**Advocate** the principles and practices of open science and open education, and work with global science funders to support their effective adoption around the world, including in the Global South, and to raise the visibility and value of regional knowledge.

**Co-lead** with the scientific community of the Global South in setting priorities and allocating resources to foster stronger collaboration, shared and equitable leadership, and alignment with local understanding of science challenges and opportunities.

3. **Kigali Declaration signatories call upon agencies, governments, and the private sector to substantially increase their multilateral, accessible and equitable investment in the development of actionable climate information, and the implementation of climate adaptation options and loss and damage assessments founded on climate science.**

This involves:

**Mobilizing** the funding and capacity development needed to sustain fundamental and solution-oriented climate science.

**Providing** improved climate change projections (and the associated uncertainties) with context-relevant information, including for cities and human settlements. These must be complemented by the tools and data infrastructure required to make these data available and usable by all, and building the contextual knowledge and capacity so that these data are used in an informed way.

**Enhancing** long-term, sustained, high quality and accessible observations and paleoclimate reconstructions, making well-coordinated use of both remotely sensed and in situ observations to increase spatial and temporal coverage. These are required to monitor the impact of human behavior on climate, to improve climate assessments and projections, and to support climate relevant decision-making processes through exploration of a range of adaptation options, mitigation pathways, and model uncertainties.

**Establishing** improved climate information and early warning services at local and regional scales - to provide actionable information for adaptation, disaster risk and reduction strategies.

**Engaging** stakeholders, users, and sector experts to determine the climate conditions and thresholds that drive impact in human and natural systems, helping to better identify risks, assess the impact of irreversible changes, develop and deliver actionable climate information, and prioritize best adaptation options.

**Helen Cleugh and Detlef Stammer (Co-Chairs, WCRP Open Science Conference)**
18 December 2023

*Attachment:*
» *Science supplement*

**Registered participants**

1.

**Registered participants**

115. Dave Roshni, Switzerland
116. David T Divya, India
117. de Amorim Pablo Borges, Brazil
118. de Lavergne Casimir, France
119. Dehghanisanij Hossein, Iran
120. Dehondt Clément, France
121. Delfino Rafaela Jane, Philippines
122. Deman Juliette, France
123. Dengler Marcus, Germany
124. Dennis Victory, Nigeria
125. Detemmerman Valery, Switzerland
126. Dhungel Shradda, USA
127. Diakhate Moussa, Senegal
128. Diarra Doukoro, Mali
129. Díaz Leandro B., Argentina
130. Diedhiou Arona, France
131. Dieng Adji Bousso, USA
132. Dingley Beth, United Kingdom
133. Diongue-Niang Aïda, Senegal
134. Dittus Andrea, United Kingdom
135. Doherty Amy, United Kingdom
136. Donat Markus, Spain
137. Duba Tania, South Africa
138. Dube Jerit, South Africa
139. Duetsch Marina, Austria
140. Dushimimana Jean Paul, Rwanda
141. Ebi Kristie L, USA
142. Elliot Joshua, USA
143. Emami Somayeh, Iran
144. Er-Retby Houda, Morocco
145. Esteve Júlia Crespin, Spain
146. Eyring Veronika, Germany
147. Fall Cheikh Modou Noreyni, Senegal
148. Fall Papa, Senegal
149. Fan Hongdou, Germany
150. Fan Xinyang, Switzerland
151. Faranda Davide, France
152. Farmer Delphine, USA
153. Fatima Shamaila, India
154. Faye Babacar, Senegal
155. Faye Awa, Senegal
156. Felix Abdalla, Kenya
157. Fernández-Granja Juan Antonio, Spain
158. Ferster Brady, France
159. Findell Kirsten, USA
160. Fm. Asikullah, Bangladesh
161. Fosu-Amankwah Kwabena, Ghana
162. Fotso-Nguemo Thierry C., Cameroon
163. Fox-Kemper Baylor, USA
164. Frank Carly, USA
165. Frank Lydia, India/Botswana
166. Friedlingstein Pierre, United Kingdom
167. Fröb Friederike, Norway
168. G Harish, India
169. Gaol Adelina Lumban, Indonesia
170. Garbarini Eugenia, Argentina
171. Gasangwa Ivan, Rwanda
172. Gashaw Temesgen, Ethiopia
173. Gaubert Benjamin, USA
174. Gaye Amadou, Senegal
175. Gbaguidi Gouvidé Jean, Benin
176. Gbobaniyi Bode, Sweden
177. Gedara Gayathra Charuka Bandara Aldeniyagoda, Sri Lanka
178. Gensuo Jia, China
179. George Bessie Solomon, Nigeria
180. Ghomsi Franck Eitel Kemgang, Cameroon
181. Ghosh Rohit, Germany
182. Gitonga Harun M., Kenya
183. Goldenson Naomi, USA
184. Golding Nicola, United Kingdom
185. Gomez Natalya, Canada
186. Gonzales C. Kendra Gotangco, Philippines
187. Goswami Prof.Dr.Virendra Kumar, India
188. Grossi Amanda, USA
189. Gruber Nicolas, Switzerland
190. Guan Bin, USA
191. Gubssa Solomon Tesfamariam, Ethiopia
192. Gulev Sergey, Russia
193. Gulizia Carla, Argentina
194. Gutkin Nick, Belgium
195. Habib Dr. Umer, Pakistan
196. Habimana Jean Deogratias, Rwanda
197. Hackmann Heide, South Africa
198. Hakuba Maria, USA
199. Halenka Tomáš, Czech Republic
200. Hamed Raed, Lebanon
201. Hamzeh Nasim Hossein, Iran
202. Hari Manoj, India
203. Haris Farzana, India
204. Harris Neil, United Kingdom
205. Hart Melissa, Australia
206. Haruna Zaid, Ghana
207. Hassler Birgit, Germany
208. Hawkins Ed, United Kingdom
209. Hebden Sophie, United Kingdom
210. Hegerl Gabriele, United Kingdom
211. Hegglin Michaela I., Germany/United Kingdom
212. Heita Priskilla Ndelitowike, Namibia
213. Hendrizan Marfasran, Indonesia
214. Henry Leilani Raashida, USA
215. Herbert Mba Aki, Gabon
216. Hewitson Bruce, South Africa
217. Higgins Timothy B., USA
218. Hirons Linda, United Kingdom
219. Hope Pandora, Australia
220. Horvat Christopher, USA
221. Hossain Md Khalid, Australia
222. Hotor Divine Worlanyo, Ghana
223. Hu Aixue, USA
224. Hurrell James W., USA
225. Hussain Bushra, Pakistan
226. Icyitegetse Elisee, Rwanda
227. Ideki Dr Oye, Nigeria

## Registered participants

228. Idrissa Sawadogo, Burkina Faso
229. Igejongbo Toyosi, Nigeria
230. Imani Gérard, DR Congo
231. Irvine Peter, United Kingdom
232. Islam A.K.M. Saiful, Bangladesh
233. Isphording Rachael, Australia
234. Issa Awal Mohamed, France
235. Ivanova Maria, USA
236. Iyakaremye Vedaste, Rwanda
237. Jain Jagriti, India
238. Jain Shipra, United Kingdom
239. Jamero Ma. Laurice, Philippines
240. James Rachel Anne, United Kingdom
241. Jampani Mahesh, Sri Lanka
242. Jayawardena I M Shiromani P, Sri Lanka
243. Johnson Alyssa, USA
244. Johnston Peter, South Africa
245. Jong Bor-Ting, USA
246. Joshi Apurva P, India
247. Jrrar Amna, Jordan
248. Jung Chunyong, USA
249. Jury Martin, Austria
250. Kabera Telesphore, Rwanda
251. Kabir Md. Humayain, Austria
252. Kagaba Jean Bosco, Rwanda
253. Kageyama Masa, France
254. Kalele Dr. Dorcas, Kenya
255. Kalladath Nishadh, Kenya
256. Kamamba Muyaka, Zambia
257. Kamamia Brian, Malawi
258. Kaplin Beth, Rwanda
259. Karekezi Jean Pierre, Rwanda
260. Kargbo Dr Alpha, The Gambia
261. Karmakar Nirupam, India
262. Karmakar Dr. Ananya, India
263. Kashyap Rahul, India
264. Katile Mahamadou Lamine, Mali
265. Kaveri Megha, Switzerland
266. Kawamiya Michio, Japan
267. Keenan Benjamin, United Kingdom
268. Keenlyside Noel, Norway
269. Kennedy-Asser Alan, United Kingdom
270. Keppler Lydia, USA
271. KG Arunya, India
272. Khan Mohsin, USA
273. Khan Raihanul Haque, Bangladesh
274. Khapikova Polina, USA
275. Khoza Oratilwe, South Africa
276. Kim Yong-Yub, South Korea
277. Kimutai Joyce, Kenya
278. Kipkogei Oliver, Kenya
279. Klausen Jörg, Switzerland
280. Klein Cornelia, United Kingdom
281. Koketso Madimabe, South Africa
282. Koll Roxy Mathew, India
283. Kondi Akara Victoire Ghafi, Rwanda
284. Kondo Kamarou Faré, Benin
285. Kovats Sari, United Kingdom
286. Koyo Patrice, Benin
287. Kulkarni Balasaheb Govind, India
288. Kumar Pankaj, India
289. Kumar Vivek, India
290. Kumar Deepak, India
291. Kundeti Koteswararao, India
292. Lachance Janice R., USA
293. Lake Irene, Sweden
294. Lalonde Morgane, France
295. Lanet Marine, France
296. Langebroek Petra, Norway
297. Langendijk Gaby S., the Netherlands
298. Lawrence David, USA
299. Lee June-Yi, South Korea
300. Legg Sonya, USA
301. Lennard Christopher, South Africa
302. Leung L. Ruby, USA
303. Leyba Ines, Argentina
304. Lguensat Redouane, France
305. Li Chao, Germany
306. Lipscomb William, USA
307. Lique Camille, France
308. List Geneva, USA
309. Liu Chao, USA
310. Liu Yang, China
311. Liu Hailong, China
312. Lizcano Gil, Spain
313. Lomibao Keane Carlo G., Philippines
314. Lopez Pascal, Germany
315. Loutre Marie-France, Switzerland
316. Lovino Miguel A., Argentina
317. Lund Marianne, Norway
318. Luterbacher Jürg, Switzerland
319. M S Lekshmi, India
320. Macharia Kenneth, Kenya
321. Mahapatra Debasis, India
322. Maher Nicola, Australia
323. Maina Jemimah, Kenya
324. Makanjuola Oluwaseun Joshua, Nigeria
325. Makuya Vuwani, South Africa
326. Males Jamie, United Kingdom
327. Mandal Shailendra K., India
328. Manishimwe Aloysie, Rwanda
329. Mankotia Sakshi, India
330. Maraun Douglas, Austria
331. Marchant Prof Robert, United Kingdom
332. Marcheggiani Andrea, Norway
333. Marshall Shawn, Canada
334. Marti Olivier, France
335. Masson-Delmotte Valérie, France
336. Massot Alexandrine, Switzerland
337. Mastropierro Matteo, Italy
338. Masukwedza Gibbon Innnocent t., United Kingdom
339. Materia Stefano, Spain
340. Maure Genito, Mozambique

## Registered participants

341. Mawanda James, Uganda
342. Maybee Ben, United Kingdom
343. Mbigi Dickson, Tanzania
344. McKinley Galen A., USA
345. Meissner Katrin Juliane, Australia
346. Melnikova Irina, Japan
347. Mengis Nadine, Germany
348. Mengistu Hailemariam, Japan
349. Mengistu Michael G., South Africa
350. Mengouna Ntsengue Francois Xavier, Cameroon
351. Meroni Agostino Niyonkuru, Italy
352. Merryfield William, Canada
353. Mhondera Achieford, Zimbabwe
354. Miah Osman, Bangladesh
355. Miller Lisa, Canada
356. Mirones Óscar, Spain
357. Mlalazi Nkanyiso, South Africa
358. Mochizuki Takashi, Japan
359. Modi Aditi, India
360. Momanyi Denis, Kenya
361. Monerie Paul-Arthur, United Kingdom
362. Monfray Patrick, France
363. Montano Humberto García, Nicaragua
364. Monteiro Pedro M S, South Africa
365. Moon Suyeon, Japan
366. Moreno Luis Antonio Ladino, Mexico
367. Mori Nobuhito, Japan
368. Morrison Monica Ainhorn, USA
369. Morupisi Tlotlo Valerie, Botswana
370. Motamedi Ramin, Iran
371. Mouto Crespin, Benin
372. Msadek Rym, France
373. Msigwa Anna, Tanzania
374. Muawiya Sani, nigeria
375. Mugo Jane Wangui, Kenya
376. Mukanyandwi Valentine, Rwanda
377. Mukherji Aditi, India
378. Müller Omar Vicente, Argentina
379. Mumo Lucia, Kenya
380. Mungatia Liza, Kenya
381. Murambadoro Miriam, South Africa
382. Murmu Josna, India
383. Musyoki Phineas, Kenya
384. Muwafu Simon Peter, Germany
385. Muzuva Meshel, South Africa
386. Mwizerwa Jerome, Rwanda
387. Naicker Merishca, South Africa
388. Naish Tim, New Zealand
389. Nasir Md, USA
390. Nassar Wajahat, Pakistan
391. Navarro Juan Camilo Acosta, Italy/Colombia
392. Ndara Dr Nolusindiso, South Africa
393. Ndarana Thando, South Africa
394. Neto Francisco Osvaldo Sebastiao, Angola
395. Ngunjiri Ndirangu, Kenya
396. Nguyen Ha, Vietnam
397. Nguyen Phuong Loan, Australia
398. Nilsson Lindha, Sweden
399. Nimpa Fozong Tatiana Denise, Cameroon
400. Nitta Tomoko, Japan
401. Niyigena Bernard, Rwanda
402. Niyomwungeli Jimmy, Rwanda
403. Niyongira Paul, Rwanda
404. Nkurunziza Fabien Idrissa, Rwanda
405. Nobre Carlos Afonso, Brazil
406. Nonki Rodric Mérimé, Cameroon
407. Noor Asif Uddin Bin, Bangladesh
408. Nsabimana Olivier, Rwanda
409. Nshimiyimana Albert, Rwanda
410. Ntuli Hlengiwe, South Africa
411. Ntwali Dr Didier, Rwanda
412. Ntwari Nasson, Rwanda
413. Nzabonimpa Jean Baptiste, Rwanda
414. Nzeyimana Alexis, Rwanda
415. O'Reilly Lucas, USA
416. Octenjak Sara, Spain
417. Odoulami Romaric C., South Africa
418. Ofoegbu Chidiebere, United Kingdom
419. Ogallo Linda Ajuang, Kenya
420. Ogunniyi Jumoke Esther, Nigeria
421. Okoth Sheila, Kenya
422. Olagbegi Bosede Ruth, South Africa
423. Olaniyan Eniola, Nigeria
424. Olmo Matías, Spain
425. O'Loughlin Ryan, USA
426. Oluibukun Ajayi, Namibia
427. Omer Abubaker Omer Abbass, South Korea
428. Omrani Noureddine, Norway
429. Oo Kyaw Than, Myanmar
430. Opijah Franklin Joseph, Kenya
431. Orchard Dominic, United Kingdom
432. Orji Evelyn Ijeoma, Nigeria
433. O'Rourke Eleanor, United Kingdom
434. Osman Marisol, Argentina
435. Ospina Daniel, Sweden
436. OUARMA Issoufou, Burkina Faso
437. oumar Yassine Rachid, Chad
438. Oussou Francis, Nigeria
439. Outten Stephen, Norway
440. Ouya Melissa Achieng, Kenya
441. Ovwemuvwose Joseph, United Kingdom
442. Oyebola Adebola Elemide, Nigeria
443. Palanisamy Hindumathi, Switzerland
444. Palipana Madhushika, Sri Lanka
445. Pandey Anupam Kumar, India
446. Parra Edison Andrés Calderón, Ecuador
447. Paska Ajok, Uganda
448. Patel Ronak, USA
449. Paul Felix, Nigeria
450. Peatier Saloua, France
451. Perkins-Kirkpatrick Sarah, Australia
452. Pezzi Luciano, Brazil
453. Pfleiderer Peter, Germany
454. Phiri Austin T, Malawi

## Registered participants

455. Pinto Izidine, the Netherlands
456. Polcher Jan, France
457. Polkova Iuliia, Germany
458. Pongratz Julia, Germany
459. Pouye Ibrahima, Senegal
460. Prado Luciana Figueiredo, Brazil
461. Predragovic Milica, Portugal
462. Prempeh Nana Agyemang, Ghana
463. Purich Ariaan, Australia
464. Qazizada Mohammad Rabi, Afghanistan
465. Quail Katherine Elizabeth, Australia
466. Quirinius Katula Matovu, Uganda
467. Rabanal Valentina, Argentina
468. Raffaele Francesca, Italy
469. Rahaman Muhammad Abdur, Bangladesh
470. Rajagopal E N, India
471. Rakotoarivelo Malalaniaina Miora, Madagascar
472. Ramadas Sendhil, India
473. Rammopo Tsholanang, South Africa
474. Ranaivoson Andriamihaja; Madagascar
475. Ranasinghe Navoda, Sri Lanka
476. Randriamarolaza Luc Yannick Andreas, Madagascar
477. Rasaq Hammed Opeyemi, Algeria
478. Rasifudi Tshimangadzo, South Africa
479. Ratilla Daniel C, Philippines
480. Ratnayake Amila Sandaruwan, Sri Lanka
481. Raupach Timothy Hugh, Australia
482. Ravindran Dr Ajaya Mohan, UAE
483. Razaiarinoro Safidiniaina Jessica, Madagscar
484. Reale Marco, Italy
485. Reboita Michelle Simões, Brazil
486. Rehfeld Kira, Germany
487. Reinhardt Martin, Germany
488. Renwick James, New Zealand
489. Ribeiro Rodrigo Rudge Ramos, Brazil
490. Richardson Katy, United Kingdom
491. Rieck Jan, Canada
492. Rivera Juan A., Argentina
493. Robertson Andrew, USA
494. Rocha Maurício Rebouças, Brazil
495. Rodrigues Regina R., Brazil
496. Rogers Indea Stroeve, USA
497. Romanou Anastasia, USA
498. Rosales Daira A., Argentina
499. Rosero Diego Caicedo, Ecuador
500. Rousi Efi, Germany
501. Ruiz Juan Jose, Argentina
502. Ruscica Romina, Argentina
503. Rynearson Will, USA
504. S Sanchita, India
505. Sajjad Wasim, Pakistan
506. Salazar Alvaro, Chile
507. Salisu Adamu, Nigeria
508. Samset Bjørn H., Norway
509. Sanogo Tidiani, Mali
510. Santoso Agus, Indonesia
511. Sarkar Sahadat, India
512. Satoh Yusuke, Japan
513. Saunders Matthew, Ireland
514. Savas Dilek, France
515. Scambos Theodore, USA
516. Schmidt Luca, Germany
517. Scholze Marko, Sweden
518. Schwarzwald Kevin, USA/Austria
519. Schwinger Jörg, Norway
520. Scott Cat, United Kingdom
521. Séférian Roland, France
522. Segnon Alcade, Senegal
523. Selunkuma Ibrahim, Germany
524. Semie Addisu Gezahegn, Ethiopia
525. Sham Vera, Switzerland
526. Shampa, Bangladesh
527. Shaw Tiffany, USA
528. Shepherd Ted, United Kingdom/Germany
529. Sherwood Steven, Australia
530. Shimwa Christian, Rwanda
531. Shuralla Mohammed Essa, Ethiopia
532. Shyrokaya Anastasiya, Sweden
533. Siabi Ebenezer Kwadwo, Ghana
534. Siame Gilbert, Zambia
535. Siddiqui Md Rezwan, Bangladesh
536. Sillmann Jana, Germany
537. Simpson Isla, USA
538. Sindikubwabo Emmanuel, Rwanda
539. Singh Harvir, India
540. Singh Priyanka, India
541. Singh Dharmaveer, India
542. Singh Shrestha Mandira, Nepal
543. Sirisena Jeewanthi, Germany
544. Sloan Julia, USA
545. Smith Grant, Australia
546. Smith Doug, United Kingdom
547. Smith Lucian, United Kingdom
548. Sobolowski Stefan, Norway
549. Sodomon Agbessi Koffi, Togo
550. Solanki Ranjit, India
551. Sörensson Anna, Argentina
552. Sow El Hadji Amadou, Senegal
553. Sow Magatte, Senegal
554. Sparrow Michael, Switzerland
555. Sreejith Meenakshi, India
556. Srivastava Ankur, India
557. Stammer Detlef, Germany
558. Steiner Andrea K., Austria
559. Steynor Anna, United Kingdom
560. Stocker Thomas, Switzerland
561. Stocker Matthias, Austria
562. Stroeve Julienne, Canada
563. Suarez Moreno Roberto, Norway
564. Sukumaran Sandeep, India
565. Supratid Seree, Thailand
566. Surendran Divya, India
567. Sutton Rowan, United Kingdom

## Registered participants

568. Suzuki Kazuyoshi, Japan
569. Swaleh Mariam Maku, Kenya
570. Sylla Mouhamadou Bamba, Rwanda
571. Szopa Sophie, France
572. Tabassum Salma, Bangladesh
573. Taborga Johan Holberg Soliz, Bolivia
574. Talib Joshua, United Kingdom
575. Tambaya Iko, Nigeria
576. Tangarife-Escobar Andres, Germany
577. Tanhua Toste, Germany
578. Tanimoune Laouali Ibrahim, Niger
579. Tankala Manikyalarao, India
580. Tannor Salamatu Joana, Germany
581. Tegtmeier Susann, Canada
582. Terray Laurent, France
583. Testani Nadia, Argentina
584. Thiam Mamadou, Senegal
585. Thomalla Sandy Jane, South Africa
586. Thompson Dr Elisabeth, United Kingdom
587. Tilahun Seifu, Ghana
588. Timite Nakouana, Côte d'Ivoire
589. Tiwari Devendra Kumar, India
590. Tiwari Prakash C., India
591. Tiwari Yogesh K., India
592. Tjiputra Jerry, Norway
593. Tofa Abdullahi Ibrahim, Nigeria
594. Toluwalope Toyin Ogunro, Nigeria
595. Tomassini Melissa, Italy
596. Touma Danielle, USA
597. Traore Alou, Mali
598. Trapp Matthias, Germany
599. Tresor HIRWA, Rwanda
600. Trivedi Dr. Parul C., India
601. Tseng Wan-Ling, Taiwan
602. Tugirimana Eric Marc, Rwanda
603. Ugochukwu Kingsley Okoro, Nigeria
604. Ulbrich Uwe, Germany
605. Umukunzi Josephine, Rwanda
606. Undorf Sabine, Germany
607. Ur Rashid Irfan, Pakistan
608. Uwambajimana Dyna, Rwanda
609. Valcke Sophie, France
610. van der Wel Narelle, Switzerland
611. Vautard Robert, France
612. Verhoef Anne, United Kingdom
613. Vijitharan Dr. Sharaniya, Sri Lanka
614. Villena Cristina Ruiz, United Kingdom
615. Visbeck Martin, Germany
616. Vogel Elisabeth, Australia
617. Volodin Evgeny, Russia
618. wambui Anne, Kenya
619. Wang Aihui, China
620. Wang Shizhu, China
621. Wang Haoran, Spain
622. Wanser Kelly, USA
623. Wickramasooriya Ashvin, Sri Lanka
624. Wilfried Pokam Mba, Cameroon
625. Williams Matthew St. Michael, Jamaica
626. Wilson Shinu Sheela, India
627. Wollny Clemens, Germany
628. Yahya Otaiba Mohammed Bahar, Sudan
629. Yameogo Tatiana Stelle Kiswendsida, Burkina Faso
630. Yapo Assi Louis Martial, Côte d'Ivoire
631. Ying Wushan, Switzerland
632. Young Cora, Canada
633. Younkap Nina Duplex, Cameroon
634. Yu Jin-Yi, USA
635. Zanna Laure, USA
636. Zauisomue Erlich Honest Eerlik Irikomuni, Namibia
637. Zeng Xubin, USA
638. Zhu Feng, China
639. Ziegler Elisa, Germany
640. Zilli Marcia, United Kingdom
641. Zimmer Andrew, USA
642. Zoungrana Sombénéwendé Rasmata, Burkina Faso

## Additional signatories

643. André Julie, France
644. António Miguel André, Angola
645. Aricò Salvatore, France
646. Bandov Prof. Goran, Croatia
647. Bekki Slimane, France
648. Bertrand Arnaud, France
649. Billen Gilles, France
650. Bopp Laurent, France
651. Boris Vanniere, France
652. Bouchet Freddy, France
653. Bourgeois Timothée, Norway
654. Brandt Peter, Germany
655. Brehmer Patrice, Senegal
656. Brenner Jean-Baptiste, France
657. Carenso Maxime, France
658. Cassou Christophe, France
659. Cavalcanti Iracema F., Brazil
660. Chenoli Sheeba, Malaysia
661. Christensen Villy, Canada
662. Clerbaux Cathy, France
663. Cohen Yann, France
664. Coll Marta, Spain
665. Counillon François, Norway
666. da Silva Sónia Cristina Pedro, Angola
667. Daae Kjersti, Norway
668. Dolman Han, the Netherlands
669. Damerell Gillian, Norway
670. Davy Richard, Norway
671. Drane Helge, Norway
672. Ducharne Agnès, France
673. Edel Léo, Norway
674. Emmanuel Harerimana, Rwanda
675. Fairhead Laurent, France
676. Fonseca Belen Rodriguez, Spain
677. Gammage Louise, South Africa
678. Ghil Michael, France
679. Giannini Alessandra, France
680. Gluckman Sir Peter, New Zealand
681. Godin-Beekmann Sophie, France
682. Gómara Íñigo, Spain
683. Goris Nadine, Norway
684. Graumlich Lisa J., USA
685. Guilyardi Eric, France
686. Gulati Prateek, France
687. Hohn David, Germany
688. Hordoir Robinson, Norway
689. Issa (Al-Mashai) Abulgasem, Libya
690. Jain varunika, India
691. Kamanzi Fidele, Rwanda
692. Ke Sai, France
693. Keckhut Philippe, France
694. Kisinga Benson, Germany
695. Kleiven Kikki (Helga) Flesche, Norway
696. Kone Kanakounou Jean Marie, Côte d'Ivoire
697. Landeira Jose M, Spain
698. Laxenaire Rémi, France
699. Lucas-Picher Philippe, Canada
700. Lynch Amanda H, USA
701. Maignan Fabienne, France
702. Maugis Pascal, France
703. Ménégoz Martin, France
704. Mignot Juliette, France
705. de Oliveira Isabelle Maria Vilela, Brazil
706. de Oliveira Mota Natanael, Brazil
707. Dietrich Laura, Norway
708. Djuidja Ursula Hillary Tumamo, Cameroon
709. Do Carmo Edson Luis Ismael, Brazil
710. do Monte Duarte João, Cabo Verde
711. Mostafa Amira Nasser, Egypt
712. Nandini-Weiss Sri Durgesh, Germany
713. Ngaira Prof Josephine, Kenya
714. Olivera-Guerra Luis-Enrique, France
715. Opler Alvin, France
716. Oudin Ludovic, France
717. Plougonven Riwal, France
718. Punnoli Dr Dhanya, India
719. Randriamasitiana Prof. Gil Dany, Madagascar
720. Ribeiro João Gabriel Martins, Brazil
721. Rivas David, Norway
722. Rodrigue Idohou, Benin
723. Saltalamacchia Francesco, Norway
724. Sanchez Rodriguez Roberto, Mexico
725. Seneviratne Sonia, Switzerland
726. Sicardi Valentina, Spain
727. Sima Adriana, France
728. Speich Sabrina, France
729. Steenbeek Jeroen, Spain
730. Steiger Nadine, France
731. Swingedouw Didier, France
732. Turbet Martin, France
733. Yuvaraj Rakesh, France
734. Zwier Maaike, Norway

# Kigali Declaration: Science Supplement

## Highlights of the Conference

The following is a summary of the main outcomes of the World Climate Research Programme's Open Science Conference that took place in Kigali between October 23 and 27 in 2023. This once-in-a-decade event was truly hybrid with around 700 delegates participating onsite at the Conference Center and an equal number joining virtually from all around the world. The Conference was instrumental in reaching audiences from the Global South (32% of the delegates were from Africa and 26% from other regions of the Global South), and at the same time had a clear eye to the future, attracting many early career scientists from around the world.

Conference participants highlighted that the increasingly rapid human-induced changes in the Earth's climate have led to profound and widespread changes in the atmosphere, ocean, cryosphere, and biosphere. Each of the last three decades has been successively hotter than those before. Global surface temperatures have already breached 1.5°C for individual months over the last year and may surpass 1.5oC for all of 2023 (Berkeley Earth estimate). This threshold will be increasingly breached – likely every second year by the 2030s.

Conference participants discussed the increasing severity of complex extremes, including compound extreme events and cascading hazards, and highlighted the gaps in our current understanding of the drivers and mechanisms of systemic changes and their impacts in different regions. They also discussed the science needed to help communities manage the complex risks arising from the inevitable climate change impacts being experienced today, and the unavoidable future impacts that are already committed, with a focus on the Global South .

Current policies and pledges are vastly insufficient to reduce greenhouse gas emissions at the pace and scale required to limit global warming well below 2°C. Instead, emissions close to today's levels in the coming decades imply exceeding 2°C by the 2050s and close to 3°C by the end of this century. The cumulative effect of $CO_2$ emissions, including the committed sea level rise, will require substantial adaptation responses.

As with other regions of the Global South, African countries face disproportionate burdens, risks and impacts arising from changes in severe weather events and patterns, including prolonged droughts, heatwaves, devastating floods and landslides, disastrous tropical cyclones, and wild/forest fires, because of climate change. Similar impacts have been observed in Latin America, the Caribbean, and the Pacific Islands, particularly in large urban centers and in coastal and small island regions where a large percentage of the population live in informal settlements. These changes have the potential to cause humanitarian crises in association with conflicts around the globe with detrimental impacts on economies, water, food security, ecosystems and biodiversity, health, education, migration, and peace. Moreover, current adaptation initiatives in the Global South are not enough to counteract the observed impacts from climate change and a considerable gap in adaptation actions continues to increase. Adaptation and mitigation decisions benefit from timely, accurate, and contextual climate information. Adequate financing, technology transfer, and capacity building can help bridge the gaps in adaptation in these regions.

Continued growth in anthropogenic greenhouse gas emissions, combined with systemic changes in land use, atmospheric aerosol content and the resulting changes in the absorption of solar radiation will further intensify climate change impacts which, if continued uninterrupted, will lead to record breaking, unprecedented events in the Earth system that will dramatically affect humans and life around the world. Any further delays to climate change mitigation and associated societal transformations will exacerbate future impacts.

Unprecedented societal and technological transformation on a global scale, for attaining net zero carbon emissions as soon as possible, is urgently required for avoiding future warming beyond 3°C. Future stabilization of temperatures will rely on reaching net-zero emission conditions, requiring new technologies, investment, rapid financial support to vulnerable nations, and commitment by all parties. Good governance and wider leadership by businesses, communities and others is essential.

The sections below summarize the main conference outcomes, starting with the main outcomes from the so-called “Dome Plenary Sessions” held in the Kigali Conference Center Dome, followed by a synthesis of all science sessions organized as Advances, Challenges and Opportunities, and finally the outcomes of each of the 40 individual science sessions.

## Dome Plenaries

2023 has been confirmed as the hottest year on record, with exceptionally high global ocean temperatures. The reasons for this year’s unprecedented spikes in temperature increases in the atmosphere and the ocean are still under investigation but, combined, they illustrate the complexity and connectivity of the climate system, and the urgent need to find sustainable solutions based on understanding of the Earth’s climate system.

In the past, there has been research and debates regarding global tipping points. While the definition of tipping points and the correct use of the phrase needs to be revisited, we have begun to realize that regional tipping points could be as detrimental as global tipping points. As a prominent example, the southern Amazon is close to a tipping point because of the combined effects of land use and climate change on the Amazon. The current Amazon drought is the worst on record – not least because deforestation depletes moisture retention after the rainy season.

A giant leap is also required by societies embarking on a new path to a sustainable world. It requires that we fundamentally reconfigure our economies, energy, food, and health systems so that they work for both people and the planet. Climate science plays a key role in empowering vulnerable nations and levelling the playing field.

Beyond problems already existing today, water security will become an increasingly real and pressing problem in the future: in 2030, 85% of the world population will live in arid regions. But the challenges of water are really: too much, too little, too polluted. The impacts of climate change on water security and availability affect communities differently, depending on their resilience and capacity. Similarly, water-related disasters affect communities differently. A new water culture is needed with education at all levels.

Extreme weather events – from flooding to compound heatwaves; droughts and wildfires – are all being increasingly experienced around the world, with human influences contributing to many observed changes. Climate change related impacts and associated losses and damages have intensified, accompanied by increasing climate anxiety; by more environmental degradation; and by disinformation and erosion of trust in science. However, these extreme weather events are happening at the same time as extreme political conflicts around the world and setting priorities depends on societal situations. There cannot be sufficient climate action without peace. However, we are not living in a time of peace, safety or security – this is the context for a discussion of what it means to deal with climate extremes in the context of climate inequity and justice. Moreover, we cannot have climate justice without social, political and economic justice and especially without human rights. The climate emergency leads to disproportionate risks and harms to those who have done the least to cause the climate crisis – especially those living in the Global South. Inequities (around climate risks) sit alongside gender, economic, and cultural inequities. There are also regional, national and within country inequities. Future climate actions need to consider equity and justice and must be addressed alongside climate change. We are far away from both. Vulnerable populations and countries have legitimate development demands and want to see themselves as part of the solution.

There is need to advance and create new science, technologies, and institutional frameworks suitable to manage climate risk and meet society’s urgent need for actionable climate information. Carbon

Dioxide Removal (CDR) is needed to achieve net zero targets, including land-based and ocean-based CDR. But CDR is not an alternative to essentially stopping all fossil fuel use. All approaches have different trade-offs and risks. For example, reforestation if inappropriately deployed could increase competition for land. A rush to sequester carbon encourages large-scale planting of trees without distinguishing between reforestation and afforestation. There is a real risk that financial incentives have the potential to drive large-scale land conversion. Solar Radiation Modification (SRM) aims to intentionally manipulate the radiation balance at the top of the Earth's atmosphere. There needs to be detailed strategies for research to inform policy about the risks and possible benefits of SRM, especially as these risks are high given current limitations in modeling the regional impacts of such manipulations. Building an effective, transdisciplinary research program that investigates the risks, benefits and impacts of climate intervention will require coordination across multiple agencies, national laboratories, and cooperative institutes – along with strong international engagement and collaboration. WCRP must be active in this research domain. It must be the "honest broker" and a respected community voice in comprehensively assessing the benefits and risks of proposed climate intervention approaches, and in synthesizing results – either leading or playing a major role in establishing a globally inclusive, transparent, and equitable scientific assessment process.

More open science, open data and citizen science is required, around the world and especially in the Global South where there is an enormous thirst for information. What is missing in general is that we are not connecting the problem to people or are misaligned to local contextual realities and lived experiences. Different users have different needs for information on weather and climate in terms of time scale and variables, depending on the sector. The common factor is the need for local and contextual information on a scale relatable to users. In other words: we need to integrate model output with the real-world changes. Climate modelling or observations for society need to generate local information for applications.

The quiet revolution of numerical weather prediction is giving way to the era of global kilometer- scale models and machine learning tools. Kilometer-scale models will improve the realism of simulations significantly and are now becoming available for wider applications. This will make a difference for generating large and unified training datasets. Existing machine learning models are already beating conventional physically based weather forecast models in deterministic scores, for some parameters but not others, and are much faster by several orders of magnitudes. However, conventional models will not be replaced by machine learning tools. The next steps will include: better models, easier to use tools, and high performance data and computing will be federated. We need to find new public/private balance and make sure that the IT industry helps with groundwork development.

Addressing climate change to pursue ambitious development goals has real value, and inequalities must be addressed as fundamental rights. Systems transitions are key in this process: energy; industrial; (land, water, ocean, ecosystem); urban infrastructure; societal choices and transitions; they all need to evolve and address decarbonization. Fundamental pillars for decarbonization are:

- Technology: this remains a challenge
- Finances: decarbonization costs significant money
- Human capacity

Global South nations are limited in financial capacity to follow conventional decarbonization pathways as they face non-climate challenges including debt, competing priorities of economic development and poverty alleviation, while seeking infrastructural transformation to leapfrog the historical pathways of the Global North.

There is progress on climate change mitigation and sustainable development. Technology costs have fallen. Solar pricing has dropped by 85% and electric batteries are also cheaper. But we continue to invest in fossil fuels. Emissions have grown in most regions but are unevenly distributed. There are options now available in every sector to halve emissions by 2030. We need to understand which options work in which region and which sector. The challenge is to scale these up in the energy and industry sectors, cities, transport and buildings, consumption patterns.

As an example, agriculture is at the frontline of the impacts of climate change, but it is also a contributor to climate change. We need to mitigate greenhouse gas emissions, but we need to do it with care so as not to penalize the most vulnerable communities who have not contributed to climate change. Unless there are immediate and deep emissions reductions across all sectors, including agri-food systems, 1.5°C is beyond our reach. But stringent mitigation to keep within 1.5°C to 2°C may lead to severe food insecurity in sub-Saharan Africa and South Asia. We must mitigate but without affecting the lives and livelihoods of all other sectors/population that are vulnerable to the impacts of climate change. A just transition should apply to the agri-food sector in parity with all other sectors. There is a need to invest in solutions that work, are proven and benefit also the most vulnerable people and the planet. The four principles of an agricultural breakthrough are:

1. Sustainable increases in agricultural productivity in low- and middle-income countries.
2. Reduced greenhouse gas emissions from the agri-food sector.
3. Improved soil, water resources and natural ecosystems.
4. Improved adaptation and resilience to climate change particularly for vulnerable producers.

There should be capacity development for inter-disciplinary research and action in the Global South that goes beyond skills transfer. We need to rethink our role as scientists and publishers, funders, individuals, and avoid helicopter research and extractive partnerships in favor of peer partnerships. Climate literacy, the limitations of local expertise and data, and the relevance of making more training opportunities/programs available (e.g. through the WCRP Academy) are all topics that require attention. Besides the need for more climate scientists, training climate negotiators and ensuring a high level of local and champion engagement is also important. Engagement necessarily entails building mutual learning relationships with stakeholders at all levels and sectors, including extension services. For this dialogue relevant information of stakeholder context is critical to develop and align evidence-based and actionable climate information that integrates local and indigenous knowledge and is delivered through climate services tailored to stakeholder cultural realities. It is essential to position climate information relevant to stakeholder's climate and non-climate stressors in ways that align to their competency and capacity to adopt useful and usable information, while also building the science community's comprehension of the heterogeneity of stakeholder lived experiences. There should equally be commensurate capacity development and contextual literacy for the Global North of the lived experience and contextual realities of undertaking climate science in the Global South, and the marked differences between these.

As we confront increasingly pressing environmental challenges, the vigor and innovation of the next generation of climate researchers are pivotal in shaping the trajectory of scientific knowledge and its application for a more sustainable future.

With respect to the future of climate research, two additional actions need to take place: Firstly, the climate research community needs to empower early- and mid- career researchers' leadership, particularly those from the Global South, at both the national and international levels. This involves recognizing the increasing role that younger generations play in addressing the climate change problem and its impacts, as they are poised to inhabit a warmer world with more climate-related extreme events. Secondly, it is necessary to enhance the international climate research agenda on emerging topics like Citizen science, Urban studies, extreme weather events, Artificial Intelligence/ Machine Learning techniques, climate intervention, and incorporating context with the generation of actionable climate information for solutions.

## Synthesis of Session[1] Outcomes

### Advances

With improved observations, methods of detection, and models, we are starting to see the emergence of climate change signals in relation to natural climate variability, improvements in our understanding of jets and eddies in both atmosphere and ocean, from the atmospheric jet stream in the Northern Hemisphere to the Antarctic Circumpolar Current in the Southern Ocean; and in our understanding of rapid or irreversible changes in the earth climate system ranging from land to ocean and cryosphere, and in particular, their interaction.

Novel techniques of model-data fusion are now available and in use (including Machine Learning and Artificial Intelligence) with advances in high-resolution climate modelling, understanding, adaptation and mitigation. Efforts are underway by the community to produce global datasets, reanalyses such as ERA5 in the atmosphere and other products such as those provided by Copernicus of easy access. Similar efforts spin up now for the Earth system.

Machine Learning is an important new tool whose use in developing new modeling approaches, bringing together dynamical and statistical downscaling and dealing with risk components systematically, is becoming more widespread. Major developments are underway that exploit machine learning to improve and replace parameterizations in the atmosphere and ocean. Together with other developments, they are leading to advances in research-based climate forecasting, prediction, and the development of early warning systems for climate extremes and hazards.

Advances are ongoing in higher resolution modelling to simulate convection and scale interactions with implications for both global-regional scales and local extremes. Progress is being made in representing human intervention in the land surface and water cycle in Earth system models (ESMs). Among those developments is a new African ESM that includes grassland ecosystems. There is an explosion of new techniques for paleoclimate reconstructions, which has enabled advances in our knowledge of longer-term changes in various aspects of the Earth's climate system and climate sensitivity in the last decade or two. There has been progress in understanding characteristics of, and changes in, extreme events, with increasing confidence in changes for extreme heat and drought in some regions. Advances have been made in our knowledge of changes in extreme rainfall, although gaps remain.

There have been advances in quantifying changes in the Earth Energy budget and increasing our understanding of the drivers and the importance of anthropogenic forcing for regional precipitation changes. Carbon cycle feedbacks under a changing climate are very important for understanding future Earth System responses. The interannual variability of the ocean carbon sink appears to be higher than previously thought. The Earth energy changes estimate from the ocean heat inventory is progressing rapidly towards an estimate of 0.7±0.3 Wm-2 heat uptake over the period 2005–2019, with smaller and more robust uncertainties. The heat uptake shows significant interannual variability of ±0.5 Wm-2 and a trend of 0.4±0.3 Wm-2 per decade that are both independently and consistently captured by top of atmosphere radiation measurements, in-situ ocean temperature measurements and ocean thermal expansion satellite estimates. Changes in the tropical lower tropospheric stability along with changes in tropical convective aggregation explain a substantial part of the interannual variability. Clear sky feedbacks on global climate are very robust in climate models and well understood, but questions remain about whether processes not currently represented in models could alter these feedbacks outside the model range. These questions relate to convective organization, altering humidity, and may soon be addressed by global high-resolution simulations.

1 Session numbers and details can be found on the WCRP Open Science Conference website: https://wcrp-osc2023.org/program/program-sessions.

**Challenges**

Recent global temperature changes have highlighted that a full system understanding of the climate and Earth is still missing and that especially non-linearities and feedbacks need to be included. As an example, the sudden warming of 2023 is not all explainable by forcing changes. Among the required knowledge improvements is a better understanding of internal variability, tropical-extratropical interactions, ocean-land-atmosphere interactions, eddies, jets, a more accurate localization of extremes, storms, and monsoon systems at the intraseasonal time scales. In fact, there remains a distinct lack of process understanding for monsoons, including the role of ocean and land and their interactions with the atmosphere, for which routine and field campaign measurements have been shown to have a proven benefit.

An understanding of future circulation changes in the atmosphere and ocean, and the role of internal variability and forced responses – all crucial aspect of regional climate changes, is required but currently lacking. Furthermore, a better understanding of the complex role of biosphere-atmosphere-climate interaction processes that lead to climate feedbacks under increased temperature is also required. Climate and climate risk projections remain uncertain. A probabilistic treatment of climate risks in a future climate is therefore often not possible or misleading.

We need a better understanding of the sources, fate and impacts of short-lived climate forcers, including novel Fluorine gases, secondary organic aerosols, and tropospheric ozone. Cloud-feedbacks continue to be uncertain – some of this uncertainty comes from changes in water content of high clouds, as well as phase changes. There are strong reasons to expect some climate-dependence of climate sensitivity. Causes of specific ocean warming patterns need to be unraveled in order to advance our understanding of climate feedbacks and climate sensitivity. Feedbacks in the Earth system and cascading events pose also challenges in attribution of extremes and their impacts. Properly accounting for confounding drivers remains difficult.

Understanding land use and land degradation is important because of its impact on climate through water and energy fluxes, and the significant socioeconomic consequences. Despite research efforts to evaluate land use change and its impacts on carbon, energy, and water fluxes, fundamental challenges remain, especially related to understanding the trade-offs and co-benefits of sustainable land management practices, including those related to carbon dioxide removal and sustainable agriculture. There is a growing need for more advanced models for land use and land cover change.

Large uncertainties remain also in the land carbon sink, despite important recent developments. Deforestation and land degradation, climatic extremes governing the interannual variability of the land carbon stock, carbon turnover times, and model uncertainties due to gaps in process understanding contribute towards this uncertainty.

The changing water cycle and its consequences on human water resources needs more attention. This includes reducing uncertainties and improving confidence in precipitation and evaporation projections and how the length and intensity of rain events will change. Observed trends in the water cycle can, in some regions of the world, be attributed to climate drivers, but in most cases these changes are attributed to other anthropogenic factors, such as urbanization or water abstraction. Methods are urgently needed to separate the climate and the anthropogenic signals in the observed indicators of the continental water cycle, including extremes. Research is needed to better understand the role of aerosols on extreme rainfall events.

The problem of longstanding climate model biases remains, notably in regional precipitation and teleconnection patterns. In this context there is also a need to close observational gaps and build sustainable observing systems – noting the emerging opportunities described below. At the same time, reducing model deficiencies in simulating internal variability modes at several time scales, tropical-extratropical interactions, and ocean-atmosphere-land interactions are all important. Improvements are needed in global ocean reanalysis and regional ocean modelling. An initiative like an ocean CORDEX could stimulate important advances, particularly parameterizations of air-sea flux and upper ocean processes in models. Improvements to the underlying modelling for forecasting systems are also required. Because of remaining uncertainties in climate and climate risk projections, a probabilistic treatment of climate risks in a future climate is often not possible or misleading. One needs to anticipate the unexpected, i.e., events that have previously been considered impossible or at least implausible.

There is a need for urban-resolving climate modeling approaches across scales, that accurately represents urban characteristics and processes and capture the feedback from urban areas to larger weather and climate processes. Ideally human behavior should be part of these models to help city planning in the future. There is also the need to ensure that effective tools are supported and embedded within national disease control programs. Regional collaboration in developing climate services for infectious disease control is critical. While there are advances in understanding extremes (characteristics, changes, confidence), linking these to drivers, feedbacks and compound characteristics remains a challenge.

Another gap is the effective communication of the results from operational predictive systems that can be used for decision-making. Access to advanced technology to Global South science, along with a lack of Global South data, are also outstanding challenges. Small island states need tools and protocols (and perhaps other support) to do their own attribution studies. There is need for inter- and trans-disciplinary research that connects to those stakeholders who are potentially affected. The development of regional information continues to evolve – moving closer to decision scales, but there remain challenges in the operationalization of co-production to best align with decision needs. Standards and measures to ensure robustness of climate services (and how to do this) are key requirements. Synthesizing individual learning to develop a broader base of understanding is needed, and so enable more comprehensive monitoring and evaluation.

There is a poor representation of the Global South in climate research and there remains significant inadequacies in obtaining, accessing and processing data into information and the lack of relevant observations to enable communities to optimally benefit. Capacity-poor nations continue to be disempowered by modalities of engagement with capacity-rich nations.

**Opportunities**

Among the opportunities ahead is a "three legged" approach to understand the role of atmospheric composition involving laboratory measurements, verified through in situ observations and modelling. Advances in higher resolution modelling are now possible, with the use of machine learning for improving parameterizations along with other applications (e.g. model tuning, prediction) to simulate scale interactions and implications for both global-regional scales and local extremes, as well as new large ensembles. Making methodologies transparent and reproducible, making benchmarking data available to build trust, and ensuring that documentation is accessible and available are all important steps in this context that can be approach.

There are many opportunities to improve Earth System Models, e.g. through improved representation of ecosystems and human intervention in the water cycle, as also evidenced by the advances mentioned above. Realizing the full potential of sub-seasonal to seasonal and seasonal-to-decadal predictions is within reach, including for extreme events impacts and decision support. Likewise, there are opportunities for more skillful and decision-relevant predictions from forecasts at weekly to sub-seasonal to seasonal time scales, that can be tailored in response to user needs and feedback.

There are new opportunities emerging to close observational gaps and build sustainable observing systems. As an example, new satellite missions will bring open access to global data for all, such as NASA's mission for simultaneous 5 km wind and ocean current observations. Rectifying the mismatch between data gathered in the Global North and South can be achieved through establishing and supporting strong relationships across the Global South and North - especially at the graduate level where student exchanges can be an effective way of surmounting some of these issues. Monitoring the state of the climate system in near real time and developing operational capabilities for attribution and prediction of emerging changes, are all opportunities that are within reach. Improved oceanic and land carbon estimates, deep-learning-enhanced process representations in land surface models, and satellite observational records significantly enhance our understanding of the Earth System. Despite emerging opportunities to build sustainable observing systems, there remain major gaps in the quality and amount of our historical observations in all climate components, through which data rescue and research will need to play a key role. Use of paleoreconstructs of the climate record before the instrumental era presents opportunities to better understand long time scale climate variability.

Effective Radiative Forcing trends, driven by greenhouse (GHG) concentrations and actions that have reduced aerosol levels, are driving most of the increases in the Earth's Energy changes. Significant longwave and positive shortwave cloud feedback yield a non-significant net cloud radiative effect contribution to the observed increases in the Earth's Energy Imbalance. But it implies that cloud could amplify or diminish global warming. Unexplained ocean surface warming patterns affect not only climate feedbacks but also the efficacy of different forcings and need to be better understood.

Progress is in reach for research on land use change and land-based climate solutions on local to global scales to inform effective climate adaptation strategies. The link between weather-related renewable water resources, and the way they are managed, is driven by economic considerations and processes. How water is valued (monetary or regulatory value) by society is critical. Other questions include water cycle observations, understanding and enhancing the recharge of groundwater and the combined pressures of climate change and water usage and demand.

Research and evidence play a key part of the strategy to ensure that effective climate services for health are developed, implemented, and evaluated in partnership. Accessing good quality health data remains a challenge for the development of climate services for health. New methods are being developed that can help to overcome the challenges with lack of health data, particularly in the global south. Urban climate modelling benefits health aspects but at the same time benefits from including human behavior. More research is needed to better model human processes. Urban climate modelling is essential to help plan cities, to manage risk to health and wellbeing.

Cross-cutting opportunities include the co-design of climate services for all and understanding socio-economic vulnerability to climate change. Partnerships are very important, to facilitate access to data and relevant stakeholders. There is a need for rapid extreme event attribution which will allow the communication of the role of climate change behind an extreme event at the time when people are interested. In terms of impact attribution, there is value in piloting operational attribution even if it starts out basic. Stakeholder-driven work and co-production ensure that the obtained information is actionable and can be directly used in adaptation planning.

## Summary Theme 1 Sessions: Advances in Climate Research

### S01: Climate variability on time scales from weeks to centuries and millennia

The tropical oceans play a key role in climate variability on all time scales. They generate signals that are communicated to remote parts of the world and are themselves impacted by signals propagating into the tropics. There are several deficiencies in the ability of models to represent these interactions and teleconnections and more work is needed to understand related physical mechanisms.

Examples of recent advances in understanding climate variability included: The Southern Hemisphere ENSO teleconnections get modulated by the stratospheric polar jet and its dependence on the amplitude of both phenomena. Tropical Pacific SST changes force changes in midlatitude tropospheric jet in the Southern Hemisphere. Central Pacific El Nino events can be triggered by the North Pacific Subtropical High forcing the Trade Winds in the central Pacific. Palaeoclimate observations and modelling studies indicate a weakening of ENSO amplitude during the mid-Holocene and the last interglacial. ENSO variability in the Holocene spread westward from 6000 years ago to the present day. Decreasing trends in East African Long Rains and increasing trends in the Short Rains are linked to warming over north-western Asia, related to the cool phase of the Pacific Decadal Oscillation. There has been higher interannual variability of East African Short Rains in recent decades. Intraseasonal variability of water vapour transport in central Africa can be linked to the Madden Julian and Intraseasonal Oscillations. Atmosphere and ocean processes are equally responsible for generating low frequency variability in the southern Indian Ocean

### S02: Climate predictability and prediction

There have been improvements in climate prediction and the development of early warning systems for climate extremes and hazards. However, we need more skillful, decision-relevant, and tailored predictions in response to user needs and feedback. Opportunities exist now to improve prediction by novel approaches such as climate model-data fusion.

In recent years, high demand from stakeholders and policymakers has driven unprecedented research efforts aimed at achieving operational climate predictions from seasonal-to-decadal (s2d) time scales. These demands have led to notable advances in research-based climate forecasting and understanding of underlying processes. However, operational predictability faces the problem of making results communicable for decision-making purposes, while improvements in the underlying modeling to forecasting systems are a hot spot for the scientific community with the aim of increasing prediction horizons (maintaining predictive skill with increased lead times) and reducing forecast errors. Climate system changes are responsible for variations in predictive skills. These changes must be considered in future forecast systems to account for non-stationary predictability.

Subseasonal-to-decadal climate prediction in a nonstationary climate has been recognized as a key element for the implementation of a global early warning agenda. Subseasonal-to-seasonal (S2S) predictability faces the challenge of anticipating extreme events. Understanding the processes and precursors responsible for forcing, modulating, and amplifying certain extreme events is of primary concern. Subseasonal-to-decadal (S2D) forecasting is mainly aimed at improving the predictability of phenomena including, but not limited to NAO, ENSO, PDO, AMV, and SST-forced teleconnections, making its mechanistic understanding essential. It is also important to understand the role of Interplay between the external forcings and modes of variability on S2D predictability. Reducing model deficiencies in simulating internal variability modes, tropical-extratropical interactions, and ocean-atmosphere interactions are key factors in enhancing climate prediction across time scales.

The increase in the use by climate-vulnerable sectors of information from real-time subseasonal predictions and the formulation of a yearly WMO Global Annual-to-Decadal Climate Update based on operational decadal predictions are just two examples of the rapid evolution of these new sources of climate information that emerged from WCRP initiatives. The latter have illustrated the capacity of current global forecast systems to formulate predictions of the likelihood to temporarily exceed the 1.5° global warming threshold.

Communication of research-derived forecasts is of primary concern for getting useful (operational) predictions in a decision-making context beyond the purely academic framework. Decision-making relies on confidence in forecast, which in turn is based on predictive skill, underlying models, and agreement between such models. Improved modeling is therefore essential, with improved parameterization and data assimilation methods playing a pivotal role. Statistical models and machine learning methodologies must be considered with the aim of complementing and improving climate predictability from state-of-the-art dynamical models. The operational activity and the research developments in climate prediction have connected closely with climate services. Climate prediction offers information about the near future that is relevant to a large number of climate-vulnerable sectors, offering a testbed for the development of strategies for the formulation of user-oriented and increased uptake of climate information. At the same time, it can benefit from frequent user engagement to better shape the characteristics of the climate prediction systems and the identification of the most pressing research challenges. Experience has shown that this connection between climate prediction and services benefits from the participation of social and human sciences, who can help identify essential aspects such as the translation of domain information, the values of all those involved, and the context in which climate information is used.

Some of the challenges the climate prediction community is working on include the much-needed improvement of process-based forecast systems (better initialization and ensemble generation, model bias reduction and the estimation of how biases limit forecast quality, optimization of model codes, understanding of the signal-to-noise paradox, role of resolution and more realistic physics, etc.), the identification of key drivers in a changing climate and their role in understanding and estimating the limits of predictability, the need for more regularly updated climate forcings (especially aerosols but also a strategy to produce useful forecasts after explosive volcanic eruptions), the assessment of the prediction capabilities across components of the Earth system including ecosystems and biogeochemistry, the capacity to develop and include solutions based in machine learning methods (for the formulation of new predictions, post-processing, emulators of model components, use of causal inference to detect drivers, downscaling, etc.), a better understanding of the predictability and predictive capacity of regional extreme events with a special attention to compound events, an even more comprehensive use of climate observations, and an efficient connection with the climate services community to extract the relevant climate information in context from the many sources currently available.

### S03: Global and regional monsoons

After many years and generations of coupled modelling, we still face the issue of coupled Sea Surface Temperature (SST) bias which inhibits teleconnections, relevant for seasonal prediction of all regional monsoons, and for climate simulation. The ability to simulate and predict the monsoons at higher resolution is important for regional stakeholders, but also more fundamentally for the mean tropical simulation itself. There are high resolution features that, when resolved, rectify onto the mean state and even have upscale effects on tropical clouds and circulation. Intraseasonal variability in monsoon rainfall is a pervading issue across the monsoon regions. In some areas it is mature, and benefits can be gained from further enhancements to predictive systems. In other monsoon regions, the study of the role played by the intraseasonal modes, their impact on mean rainfall and the occurrence of extremes is in its infancy, and efforts are needed both to study the mechanisms involved and in sharing best practices in simulating and forecasting on subseasonal time scales.

The role of soil moisture in the monsoons appears to be little understood and hugely underexploited, potentially exerting predictive control at intraseasonal time scales, from one season to the next, and playing a role in climatic trends. The processes involved are poorly understood and greater observational understanding is also required; this problem extends to the role of land use/land cover change and irrigation practices.

Regional monsoons can be interconnected at the intraseasonal and interannual time scales, offering potential for better predictions, but also in terms of error propagation from one region to another in simulations. At the scale of climate projections, lessons can be learned from paleoclimates in terms of understanding common drivers of monsoon change and feedbacks between major regions. caution should be taken in attempting to use past climates as analogues for the future.

There is still a distinct lack of process understanding of the role of ocean and land and their interactions with the atmosphere, for which routine and field campaign measurements have been shown to have a proven benefit for improved monsoon understanding, modelling and prediction. Artificial intelligence and machine learning (AI/ML) are emerging issues that are beginning to be tested for seasonal monsoon prediction.

**S04: Storms, eddies and jets in the atmosphere and ocean**

Understanding weather phenomena that lead to extreme events should be hinged on dynamical analysis. Weather systems are embedded in jet streams that might cause non-linear processes, such as the breaking of baroclinic waves, to occur and result in the weather extremes. Current methods for identifying jet streams show a consistent decrease in jet latitude and tilt variability. This may be linked to the narrowing of the jet, as seen in all climate models. Limitations in current methods for identifying the jet might lead to uncertainty in interpreting future climate change. Furthermore, classical atmospheric dynamical theory may be used to understand changes in precipitation in climate change projections. Studies show that using the combined effect of the eddy heat and momentum fluxes may lead to more accurate location of precipitation, and therefore a reduction in uncertainty. This suggests then that eddies, like the jet streams, can shape the climate and its future. The albedo of symmetry hints at a connection between clouds and the general circulation.

**S05 and S16: Changes in the Cryosphere and their implications**

Scientific evidence is clear that due to the current trajectory of human-derived greenhouse gas emissions, the polar regions will continue warming at rates of up to 4 times the global average because of positive feedbacks, such as those related to retreating sea-ice. This amplified polar warming is driving accelerated melting from the Greenland ice sheet. The Southern Ocean has taken up much of the heat from global warming, where it will remain for centuries melting the marine margins of the Antarctic Ice Sheet. Increased and continued ocean-driven basal melting, combined with increases in surface melting in West-Antarctica, decreases the backstress from the ice shelves to the ice sheet suggesting a destabilization in the long term. New data and observations from the collaborative USA-UK-Korean Thwaites Glacier initiative highlight the complexities of bathymetry and cavity geometry on ocean circulation, heat incursions, basal melt, and grounding line stability which modelers are now using and incorporating improve the skill of their simulations. How fast Antarctic ice shelves will break-up is currently highly uncertain; it will determine when a significant acceleration in sea level rise will occur. It is likely we are close to, or already past, the tipping-point for parts of West-Antarctica leading to mass loss on century time scales. Enhanced $CO_2$ uptake by the polar oceans will continue to acidify the global ocean, with the potential for die-back of low latitude coral reefs.

The cryosphere, including the high-mountain glacier regions (e.g. Hindu Kush-Himalaya), hold 70% of the world's freshwater, and is losing snow and ice in all forms at an accelerating rate, driving global sea-level rise that will be impacting up to 2 billion people living along the world's coastlines by the end of the century, even if the 1.5oC Paris climate target is met. Sea levels will not rise evenly, as ice mass loss and redistribution cause regional variations up to ca. 30% of the global mean sea-level rise due to changes in Earth's gravitational field, axial rotation, and geoidal deformation. Local changes in sea-surface height due to ocean and atmospheric dynamics may be as much as 4 times the global mean. Moreover, coastal impacts and hazards manifest locally and local factors significantly increase risk. For example, vertical land movements (land subsidence) due to groundwater extraction, reclaimed land compaction, or tectonics will exacerbate the rate of rise significantly and the coastal hazards (e.g. flooding, groundwater inundation, erosion) reducing the time before critical adaptation thresholds are reached.

Loss of two-thirds of the world's high mountain glaciers is now likely, impacting another two billion people dependent on these ice stores for drinking, power production, agriculture, and the related ecosystems services, and through hazard related-risks from glacial outburst floods and landslides. Thawing permafrost in the Arctic has the potential for regional and widespread release of methane and carbon dioxide from soils and sediments, into the atmosphere, further enhancing global heating. Some of the polar systems such as the West Antarctic and Greenland ice sheets, mountain glaciers, and localized permafrost thaw in the Arctic feature 'tipping points' linked to global temperature thresholds close to 1.5–2oC above pre-industrial, beyond which change becomes self-sustaining, locking in large multi-generational changes and impacts even if warming were to stop or reverse after a temperature peak before 2100.

Through global atmospheric and ocean teleconnections, changes in the polar regions are being communicated to lower latitudes with dramatic consequences for climate, ecosystems and their services and society. Intense high-latitude low-pressure systems - “bomb-cyclones”, some in combination with mid-latitude blocking highs, are now bringing extreme temperatures and precipitation via atmospheric rivers to coastal and interior Antarctic and Greenland. These extremes cause unseasonal weather not only in polar regions, but also in adjacent lower latitudes impacting ecosystems and human activities. An unprecedented heat wave occurred over East Antarctica in March 2022, peaking at 39°C above climatological average - the largest temperature anomaly ever recorded globally. A local ice shelf, which was in a vulnerable state, collapsed within days, showing the potential of future heatwaves over the warmer, lower elevation West Antarctic Ice Sheet to trigger widespread surface melting and collapse of ice shelves. Winter Antarctic sea-ice extent (SIE) reached a 40 year low in 2023, following the record low annual sea-ice minimum in early 2023, due to an unseasonably warm Southern Ocean plus changed atmospheric circulation patterns bringing warm air south. These unprecedented changes were well outside the range of natural variability and coincide with new evidence from a study of ice cores that shows the emergence of an amplified surface warming pattern over Antarctica attributed to humans. Moreover, another single study suggests we are on the verge of a switch to a new reduced state in SIE, characterized by enhanced surface warming and ocean heat advection eroding ice shelves and increasing dynamic loss of the Antarctic ice sheet. Mesoscale eddies in the Southern Ocean also play a key role in affecting the dynamics of heat transport and sea ice conditions. Moreover, the profound impact of atmospheric and ocean circulation patterns on Antarctic sea ice, reveals a strong connection and atmospheric dynamics at lower latitudes modulating climate modes, such as ENSO, PDO and SAM.

Associated freshening of the Southern Ocean is affecting ecosystem-functions and loss. Direct measurements in the deep Southern Ocean suggest that a ~30% slowdown in the Antarctic overturning has occurred over the last few decades in both the Weddell and Ross Seas, linked to both meltwater and wind changes. Model projections suggest this slowdown will continue for at least the next few decades, with a collapse in the southern limb of ocean overturning circulation possible this century. Amplified Arctic warming continues to reduce, sea-ice extent dramatically and the Arctic is expected to be completely free of sea-ice, at least once between 2030–2050. Arctic warming has warmed the northwest Pacific and is attributed to increased frequency of marine heat waves. Sea ice-loss also contributes to coastal erosion, ecosystem disruption, and a loss of services, such as loss of traditional food sources and transport routes for indigenous peoples. On the other hand, an ice-free Arctic Ocean opens shipping routes and the potential for enhanced resource utilization. The high mountainous regions, such as the Andes, Alps, and Tibetan Plateau, store and release enormous amounts of freshwater into some of the most densely populated and productive agricultural regions on Earth every year. Planetary warming is changing the timing and amount of this water supply causing extremes by enhancing the impact of droughts and floods. For example, glacial lakes in high mountain Asia have increased in volume by 45% since the 1990s, creating instability in these high frozen regions that causes glacial lake outbursts and flooding, in these high frozen regions that causes glacial lake outbursts and flooding. For example, such a flood in October 2023 destroyed infrastructure and had a death toll of at least ninety people.

Actionable science is critically needed to identify safe landing pathways for the cryosphere to minimize the risks associated with cryospheric loss and enable effective anticipation of the hazards and flow-on impacts to ecosystems and society. Sustainable, equitable and just adaptation options can be implemented if they involve co-design, co-development and active engagement with decision-makers, practitioners, and communities. Investment at pace and scale in technologies for observation, evaluation and numerical modelling will support such endeavors. Priorities for future cryospheric research pathways include:

1. 1. Improve understanding of the rates and (ir)reversibility of polar ice loss and its contribution to sea level rise to sit alongside adaptive decision tools and engagement with stakeholders that can help establish signposts for decision-makers that can assist more effective development and implementation of adaptation strategies. A special focus should be given to:

    a) Understanding the delivery of heat to the Antarctic margin via ocean and atmospheric processes and how this will affect the timing of ice shelf loss and consequential rate of dynamic loss of the grounded ice sheet, including the identification of signposts and tipping points.

    b) Improved knowledge of Greenland ice mass loss and its relationship to North Atlantic regional climate variations through better understanding of atmospheric circulation changes and their links with polar amplification over the Greenland region.

2. Improve understanding of the controlling processes of sea ice variability and retreat in the Arctic and Antarctic to improve predictability, including longer-term changes in sea-ice state, in order that future heat and carbon budgets, and their consequences for the Earth System, can be better predicted, including impacts on ecosystems, human communities and cryospheric services.

3. Improve understanding of the rates and (ir)reversibility of snow and ice loss in high mountain regions, and its implications for water availability, food production, ecosystem services and related natural hazards.

4. Improve understanding of the processes of permafrost thawing in the Arctic for better predictability of spatial scale, rate and timing of irreversible methane and carbon dioxide release to the atmosphere.

**S06: Rapid and/or irreversible changes in the climate system**

Rapid, irreversible changes in the climate system manifested themselves in a hierarchy of models ranging from low-order dynamical systems to comprehensive Earth System models. For example, detailed high-resolution paleoclimatic records document abrupt, non-linear, often irreversible changes and impacts at local, regional, and global scales. Such reconstructions, along with model simulations, suggest that the Earth System has limited stability in systems comprising atmospheric and ocean circulations, hydrological regimes and statistics of extreme weather and climate events, the extent of the boreal forest and the Amazon rainforest, monsoon systems and ice masses in Greenland and Antarctica. In the public, such changes are iconically referred to as crossing of tipping points.

Hysteresis is a common feature of physical systems that comprise non-linearly coupled components with slow and fast response times, resulting in stable states that depend on their past evolution. This is well-known for the Atlantic meridional overturning circulation (AMOC). A novel finding presented in this session is that ensemble simulations using a state-of-the-art climate model under moderate greenhouse gas forcing show a few members for which the AMOC bifurcates to a significantly weaker state, while the AMOC recovers in most ensemble members when the warming is stabilized. This represents a serious challenge for the traditional approach of IPCC climate projections.

One example is the behavior of a coupled climate model close to an AMOC bifurcation, a situation that can be comprehensively analyzed using low-order dynamical system. Novel climate system behavior could arise: a small number of large decadal to centennial oscillations of the AMOC are followed by a rapid transition to one or the other stable state. This highlights the richness of dynamics that has long been suggested by dynamical systems and reduced-complexity models but are increasingly found in coupled climate models, when the parameter space is explored more systematically, or large ensembles are generated. Another example is the fate of the Amazon rainforest under global warming, which could undergo an irreversible die-back with serious consequences for regional climate and the global carbon cycle. Multiple stressors (precipitation, land use) are difficult to disentangle, but studies suggest that early warning signals can be discerned based on assumptions informed by a low-order dynamical system.

Therefore, based on the current generations of CMIP models, no confidence can be assigned to the low likelihood of irreversible changes or surprises in the climate system. This suggests that the complexity of some of the processes that may be key in tipping behavior must be better captured in climate models. While higher resolution will alleviate some of these shortcomings, a focus on process understanding is required. This would call for a systematic research program linking mathematical theory with the hierarchy of climate models, and a comprehensive assessment at the level of IPCC of this issue which could have far-reaching implications for impact studies, mitigation strategies and adaptation responses.

**S07 and S08: Atmosphere-land and Ocean Atmosphere interactions: energy, water & carbon**

Examples from West Africa, the Tibetan Plateau, North and South America showed that important weather systems are strongly affected by spatial patterns of soil moisture. These affect the thermodynamic structure of the atmosphere which can affect cloud formation and trigger rainfall. The change can be seen in both the vertical planetary boundary layer structures, and larger scale structures such as jet streams and even hurricane tracks. When studied globally, the sensitivity of the atmosphere to an increase or decrease in soil moisture depends on the pre-existing atmospheric thermodynamic structures. The feedback mechanism of soil moisture patterns on rainfall works at different spatial and temporal scales in these different regions: from 1km-daily times scales to 100km-monthly times scales. It is important to capture both how the soil moisture changes over these different time scales and to model the atmospheric response at the right spatial resolution.

Evaporation plays a critical role in the atmosphere-system, both cooling and moistening the air, while at the same time depleting a potentially important water store. New information is available on how different ecosystems respond to the drivers of evaporation such as temperature, soil moisture and atmospheric $CO_2$ (the fertilization effect). For instance, dryland ecosystems have adapted to low rainfall and the representation of their evaporation traits in land models needs to be improved. More observations are needed in these key ecosystems to improve the models.

For longer time scales, ground water plays an important role in the water cycle. A key limitation on understanding the ground water is the lack of data on the aquifers that store the water. New information on the groundwater stores of Africa is available and should be used to improve the land-atmosphere interactions of this region.

Wildfire is a critical and natural process in ecosystem development. It also acts as a severe hazard to humans. In earth system models, the fertilization effect of an increase in $CO_2$ results in more fuel (above ground biomass) and therefore more fires. Including interactive wildfires in land models is a priority. Snow is an important store of water for humans and nature. It is important to be able to quantify the 'difficult to access' regions of the high mountains.

Continued support for the direct measurement of fine-scale atmosphere and ocean variables, for example, air-sea temperature, currents, winds, $pCO_2$, and heat fluxes. Recent fine-scale observations show an emergence of key air-sea features previously overlooked. For example, a) upper-surface temperature gradient-induced dissipation which is a key driver for air-sea fluxes, b) coupled wind-current interaction, c) ocean-induced mesoscale atmospheric features.

Parameterizations of air-sea flux and upper ocean processes in models were developed at the local scale and applied globally; however, recent measurements are showing key deviations. Moreover, recent improvements in air-sea sampling at scale has potential to improve process understanding and hence parameterization. This is a key focus area to improve both models and our ability to appreciably simulate future changes.

The observation, modeling, and prediction of precipitation as a source of the available freshwater over land or ocean remains one of the fundamental frontiers in weather and climate research. The urgency to make progress in this field becomes increasingly obvious as the availability and access to freshwater is at risk in many parts of the world, and floods have become more frequent and more severe in other parts of the world. The difficulty in making progress in the prediction of water availability arises from the fact that precipitation features (e.g., intensity, frequency, amount, duration, type, hydrometeor size and distribution, seasonality, and extremes) exhibit large temporal and spatial variability and are the product of a complex integrated system. Despite progress over the past few decades (e.g., through various existing WCRP projects), the improvement of precipitation prediction and projection skill remains a challenge due to major gaps and limitations in observing, understanding, and modeling precipitation. Therefore, WCRP has officially launched the Global Precipitation EXperiment (GPEX) in Kigali, which will take on the challenge of improving precipitation predictions around the world, including polar and high-mountain regions. It will be a cross-WCRP Lighthouse Activity centralized around the WCRP Years of Precipitation with a focus on different storm types, and associated activities before and after.

### S09: Interactions between atmospheric composition and climate, including aerosol processes

Large ensembles in fully coupled Earth system models are important in advancing our understanding of tropospheric ozone trends, especially in addressing the problem of signal-to-noise in observed trends from satellite data. Forests play a complex role in climate mitigation; their effects on Short Lived Climate Forcers illustrates the importance of adequately representing these interactions given that natural aerosol climate feedbacks are similar in magnitude to other climate feedbacks. Models must include full climate-emission-chemistry-aerosol processes. In tropical regions, aerosols are important to ice nucleation in cold clouds – more data are needed to improve the parameterizations used in models.

High-quality, long-term observations are needed to advance knowledge and understanding; there is a shortage of in situ measurements with regions in the global south being severely under-observed. Emerging priorities and opportunities included: building capacity in skills and sharing resources and equipment between the global north and south; leveraging satellite and air quality observations to constrain climate relevant processes; and updating data on Short Lived Climate Forcers for regular updates.

### S10: Lessons from paleoclimate for recent and future climate change

Benefits have been gained from a range of models (from conceptual to 10 km resolution) and records (by applying traditional to the most recent techniques) to gain knowledge and understanding of past climate and environmental changes (global and local changes). New findings showed how paleoclimate records can enlighten potential relationships between climate and human societies (e.g., over Central America). Paleoclimate information has value in model development and tuning - not only at the model evaluation stage. More use of model simulations to prepare for and guide field work in remote locations (e.g., Antarctica), or to interpret seemingly contradictory records (e.g., surface hydrological changes) is encouraged. New scenarios and processes can now be tested for the abrupt events of the last deglaciation and the Holocene, thanks to new records of ocean circulation (e.g., Indonesian throughflow).

### S11: Advances in global and regional climate modelling

Scientific research and societal needs for climate modeling are very different. Society wants information that responds to its needs, at scale, based on the best available science. Science needs agility, and creativity. For climate modeling to be responsive to societal needs, it needs to be carried out through sustainable efforts following good practices and standardized metrics, not as the byproduct of a research activity. For the research to thrive, it needs more local, regional, and international collaboration, better access to computational resources, shared data, and a robust and rich hierarchy of approaches. Focusing climate modeling on the following challenges will advance the foundational knowledge that underpins our ability to provide actionable climate information.

- Although the global picture of climate change is consistent, and well explained, thanks in part to the modelling, the emerging observational record is increasingly showing patterns of change that we can't explain. More concerted effort that targets specific questions will be needed to understand this record and the processes underpinning emerging changes. These efforts will require a hierarchy of models and engagement of the full breadth of the research community.
- Societal discourse is increasingly dominated by speculation as to the role of processes that the models don't include, or the effects of processes that models do include, but produce diverging emergent behaviors. There is an urgent need to focus research efforts on these processes which might lead to novel future climate states, to begin building story lines that would allow us to better assess the risk associated with them.
- Modeling high-impact weather events is challenging with existing global climate models. This impedes our ability to understand their controlling factors. Future efforts aiming at understanding and modeling the physics underpinning different types of high-impact weather and related events will be needed to provide confidence in our ability to assess how such events may change with warming.

Technology is at the forefront of issues related to climate modelling. Whether it be AI, advanced computing, or new computing paradigms, our climate modelling community need to learn how to make the most of technological advances which will play critical roles in addressing the above modelling challenges. Access to advanced technology is important to support climate modelling and climate science, and this is even more challenging for those working in the Global South.

In applying various technologies such as AI/ML, there is also a need for best practices including making methodology transparent and reproducible, making benchmarking data available to build trust, and providing accessible and available documentation.

As modelling is expanding to much higher resolution and including all Earth system components, there is an increasing opportunity for observation data to support understanding as well as development and evaluation of models. AI can be a useful tool in these endeavors.

### S12: Advances in climate observations and model data fusion

Along with new modeling tools, new advances in climate observations and in fusing models with data into full 'digital twins of the earth' are occurring. Predicting the next decade or two of climate change is still an initialized prediction problem: initialization of the ocean state. New observations have been revolutionizing our ability to observe the ocean as well as the rest of the climate system. New opportunities also exist to extend the data assimilation for weather prediction into climate modeling with a new model-data fusion framework. Firstly, the opportunity exists to better initialize the current coupled earth system state (including ocean, soil moisture and cryosphere) with observations to help seasonal to annual prediction. Second, a model-data fusion can be used to understand where uncertainty can be most reduced by additional data constraints, and to help design the observing system for prediction. And third, model deviations from observations can be used to help improve the models themselves and learn about key processes in the earth system. New methods for assimilation are also being developed, such as being able to emulate observations or entire models using machine learning techniques, effectively automating existing processes for assimilation which require hand-built emulation (adjoints). All these new methods will enable us to better use climate data to inform the future from months to decades ahead.

Accurate observations of the planetary climate are fundamental and critical for understanding and predicting climate change. At a fundamental level what we do not observe, we cannot understand, and what we cannot understand we cannot predict, adapt to, and mitigate. It is necessary to observe, on a sustained basis, key facets of the climate system, to monitor and understand the changing climate for numerous sectors and applications at a sufficient level of comprehensiveness.

Scientific assessments, such as those of the Intergovernmental Panel on Climate Change (IPCC), are critically dependent upon the global availability of high-quality observational data products for a broad range of Essential Climate Variables (ECVs). Observationally based products from across the atmosphere, ocean, cryosphere, biosphere and land, underpin the findings of unequivocal changes and their attribution to human activities. Evidence from proxies spanning longer periods, informs assessments as to the unusualness of these changes in a much longer-term context than can be afforded by the instrumental record. As such, improved access to and analyses of proxy records (e.g. tree rings, ice cores) are also important.

The climate observing system from satellite remote sensing and surface measurements is not as sustainable and stable as we would like it to be, but is, to a large degree, fragile and dependent on short-term science funding rather than long-term commitments. The Global Climate Observing System (GCOS) recently articulated a set of priority actions for improving the climate observing system in the 2022 GCOS implementation plan. We strongly recommend the parties of UNFCCC to act on these recommendations.

Novel techniques of model-data fusion exist that can advance high-resolution climate modelling, understanding, adaptation and mitigation. The need to close observational gaps and build sustainable observing systems was emphasized throughout the session.

## Summary Theme 2: Human Interactions with Climate

### S13: Carbon cycle

Carbon cycle feedbacks under a changing climate are very important for understanding future Earth System responses. Through the presenters' talks and the audience's input, important emerging features of the carbon cycle within the Earth System and its different components (the land, the ocean, and the atmosphere) were discussed, recent advances of our understanding and improved models and data where presented, while key remaining uncertainties and knowledge gaps were also identified. In particular, the magnitude of the trend in the ocean sink over the last two decades remains uncertain, with models and observation-based estimates providing substantially different estimates. The Southern Ocean, which is highly under sampled for carbon, plays a large role in this uncertainty. Investment in more observations and improved models is needed to obtain better estimates of ocean carbon content and its evolution over time.

Another outstanding uncertainty is the lateral transport of carbon by rivers to coastal zones, impacting our understanding of the net uptake of carbon by the land, of coastal carbon budgets and the carbon budget of the ocean. These fluxes can strongly impact territorial emission estimates and the global balance of land versus ocean carbon sinks.

Large uncertainties remain in the land carbon sink, despite important recent developments. Deforestation and land degradation, climatic extremes governing the interannual variability of the land carbon stock, carbon turnover times, and model uncertainties due to gaps in process understanding drive this uncertainty. Moreover, the behaviour of the land sink is dependent on emissions; land could become a source of carbon under strong mitigation scenarios.

Carbon cycle uncertainties can serve as a barrier for effectively applying, monitoring, reporting, and validating Carbon Dioxide Removal (CDR) options over land and sea, even though market interest and investment in CDR are emerging.

Improved in situ oceanic and land carbon observations, satellite observations, enhanced process representations in models, and the application of machine learning for both model processes and data products can significantly enhance our understanding of the Earth System and help us address some of the remaining open questions.

**S14: Global energy budget**

The Earth energy change (EEI) estimate from the ocean heat inventory is progressing rapidly towards an estimate of 0.7±0.3 Wm-2 for the period 2005–2019, with smaller and more robust uncertainties. The EEI shows significant interannual variability of ±0.5 Wm-2 and a trend of 0.4±0.3W.m-2 per decade that are both independently and consistently captured by TOA (top of atmosphere) radiation measurements, in-situ ocean temperature measurements and ocean thermal expansion satellite estimates. The EEI trend implies a planet that is accelerating its energy uptake with implications for accelerated warming.

Changes in the tropical lower tropospheric stability along with changes in tropical convective aggregation explain a substantial part of the interannual variability in EEI observed over the last 2 decades. A mean of Effective Radiative Forcing trends, driven by GHG concentrations and government actions to reduce aerosols, are driving most of the increases in the Earth's Energy Imbalance. Significant longwave and positive shortwave cloud feedback yield a non-significant net cloud radiative effect contribution to the increases in the Earth's Energy Imbalance. But it implies that cloud could amplify or diminish global warming.

We need a sustained commitment to Earth radiation and energy imbalance measurements to improve our understanding of the causes for the global energy budget changes and the EEI variations. There is a key opportunity of getting more timely forcing estimates by combining bottom-up approaches with satellite data.

**S15: Water cycle**

The dominant theme was the lack of attention from the climate research community to the changing water cycle and its consequences on human water resources. This a complex multi-disciplinary issue which should be higher on our priority list.

CMIP, and the global modelling community in general, does not dedicate enough effort to reduce the uncertainties within the projections of the impact of increasing greenhouse gases on precipitation and evaporation. Predicted changes for a warmer climate in the hydrological regimes are affected by large uncertainties. This starts with predicted trends in atmospheric humidity which do not match with the observed changes over the last few decades.

Models predict that precipitation regimes will change through the length and intensity of rain events. These results are still based on uncertain predictions and urgently need to be refined and improved to increase our confidence.

The observed trends in the water cycle can, in some regions of the world, be attributed to climate drivers; the session included examples of this for groundwater and soil moisture. But in most cases these changes are attributed to other anthropogenic factors like urbanization or water abstractions.

More generally the continental water cycle has been shown to be non-stationary. Not only does it include trends but also shifts in typical frequencies and extremes. This was illustrated with an analysis of 20 years of remote sensing products. This threatens all human water infrastructure and water distribution rules, which assume stationarity of the water cycle. To make progress in observing trends and predictions of future changes to the continental water cycle, methods need to be urgently developed to separate the climate and the anthropogenic signals in the observed indicators of the continental water cycle. Only once we can separate and attribute the causes of the changing water resources can we provide robust advice to society.

Finally, it was noted that the link between weather-related renewable water resources, and the way they are managed, is driven by economic considerations and processes. To understand how water availability changes in a warmer climate will affect human usage of the resource requires a better understanding of how water is valued (monetary or regulatory) by society.

Questions raised include: (a) which observations of the continental water cycle in Africa should be prioritized? (b) What is needed to advance our understanding of groundwater and the combined pressures of climate change and water usage and demand? (c) Which efforts could be undertaken to enhance the recharge of groundwater to increase these reserves which could be critical to living with and managing risks associated with climate change? (d) Should we consider the "water cycle" in terms of economics or environmental services and how can this help raise the awareness of the issues faced?

**S17: Climate feedbacks and climate sensitivity**

Clear sky feedbacks on global climate are very robust in climate models and well understood, but there are still questions about whether processes not currently represented in models could alter them outside the model range. These questions relate to convective organisation altering humidity and may be addressed by global high-resolution simulations in the near future. There are also strong reasons to expect some climate-dependence of climate sensitivity. The sudden warming of 2023 is concerning and probably not all explainable by forcing changes.

Cloud feedbacks continue to be uncertain with some uncertainty coming from changes in water content of high clouds, as well as phase changes. Unexplained ocean surface warming patterns affect not only climate feedbacks but also the efficacy of different forcings, and really need to be better understood as a community priority.

**S19: Land use and land cover change**

Land use and land degradation is important because of its impact on climate through water and energy fluxes, and the significant socioeconomic consequences (e.g., through impacts on food production, water availability, and ecosystem services). Despite research efforts to evaluate land use change and its impacts on carbon, energy, and water fluxes, fundamental challenges remain, especially related to understanding the trade-offs and co-benefits of sustainable land management practices, including those related to carbon dioxide removal (e.g., avoided deforestation, reforestation and afforestation, bioenergy carbon capture and storage) as well as sustainable agriculture (e.g., tillage practices, precision irrigation or fertilization, cover cropping etc.). As a result, the need for more advanced and accurate models for land use and land cover change is becoming even more pressing. Nonetheless, recent progress has provided a foundation for future research on land use change, from local to global scales. Research on land-based climate solutions, including how land-based carbon dioxide removal strategies will drive changes in local climate, are informing effective climate adaptation strategies through careful land management decisions.

**S20: Impacts on land and marine ecosystems**

Climate change and extremes impact various terrestrial and marine ecosystems across the globe. Impacts of changing climate are being seen in mountain biodiversity, ecosystem functioning, and local livelihood, with case studies from several African countries such as Tanzania and Kenya now available. Land degradation exist as well as social conflicts caused by climate change and overgrazing in west

Africa. Climate change, including climate extremes, are shown to affect the dynamics of terrestrial and marine ecosystems, including the role of biological pH regulation in determining responses of organisms to ocean acidification and warming, the behavior of marine mammals and marine productivity, and the urban food-energy-water nexus. There are also combined impacts of climate change and land use on biodiversity.

**S21: Impacts on food security and water availability**

Seasonal prediction information can have a skillful 8–month lead time in many places but even though this information may be available, there is a need to do a better job of managing risk with respect to agricultural production. At the climate change scale there may be missed opportunities in adaptation planning or maladaptation because $CO_2$ fertilization is not considered in many models. The impact of not including $CO_2$ fertilization may be misleading as it omits an initial increase in production through $CO_2$ fertilization before reductions due of heat/water start to dominate. This is especially the case in newer generation of climate models where the climate change signal is more pronounced and which show climate impact emergence is near with changes in major breadbasket regions, disproportionately affecting the poor. This is also reflected in reductions in stream flow and ground water recharge in Nepal.

Although it is recognized the link between the “science” of agriculture and water availability in the future and the decision space and practice is important, it lacks implementation. Examples of this are clear for Ethiopia and many parts of Africa. Scientific research and political will is needed to improve this nexus between climate, food, and water. There is also a need for not only improved modelling of agricultural production and water availability, but in parallel research into how to develop information from this data that is useful for the decision-making and policy community.

**S22: Impacts on human health and urban systems**

Climate and health: Research and evidence play a key part of the strategy to ensure that effective climate services for health are developed, implemented and evaluated in partnership, noting that WMO and WHO have a new strategy on climate services for health. There are new methods being developed that can be used to develop tools (climate services) to overcome the challenges with lack of health data, particularly in the global south. Accessing good quality health data remains a challenge for the development of climate services for health. There is a need to ensure that effective tools are supported and embedded within national disease control programs. Regional collaboration in developing climate services for infectious disease control is critical.

Urban climate: There is a need for urban-resolving climate modeling approaches across scales, that accurately represent urban characteristics and processes that can capture the feedback from urban areas to larger weather and climate processes. Urban climate modelling benefits from including human behavior and more research is needed to better model human processes. Urban climate modelling is essential to help plan cities, including to predict and manage risk to health and wellbeing, infrastructure and communities. Research is needed to better understand the role of aerosols on extreme rainfall events.

Cross-cutting: Communication is essential for the development of climate services for health and community and investment in effective communication is needed to address uncertainty, because decision makers are used to making decision under uncertainty. The development of climate services needs to consider the value of qualitative research and knowledge about behavior, as this is essential to ensure that climate services benefit all members of a community. Understanding socio-economic vulnerability to climate change is critical for adaptation planning, in both the health sector, and in urban planning and development. Methods need to be developed that engage with urban communities to use climate services within cities. Partnerships are very important and need to be developed for the co-design of climate services and to evaluate their effectiveness. Partnerships can also facilitate access to data and relevant stakeholders.

**S23: Circulation change in the climate system (atmosphere and ocean)**

Future projections of the large-scale atmospheric circulation still represent an important uncertainty in how we expect regional climate to evolve. But our understanding of the role of different drivers in atmospheric circulation change and the role of coupling between different Earth System components has improved. Some aspects of circulation change that can be attributed to anthropogenic forcing have begun to emerge in the observational record. For example, the Northern Hemisphere summer jet streams and storm tracks have exhibited a substantial weakening with likely roles for aerosol forcing and rising carbon dioxide, with a role for stratospheric ozone depletion and recovery in the Southern Hemisphere jet stream shifts. The Southern Hemisphere has also experienced considerable changes with cooling trends in the Southern Ocean and Antarctic sea ice expansion followed by a more recent subsequent decline.

The importance of tropical-extratropical teleconnections in both directions in contributing to these trends is starting to be appreciated. Furthermore, it is becoming apparent that Earth System Models are failing to capture aspects of the Southern Ocean trends and trends in the tropical Pacific, with a likely connection between the two, so work is underway to understand the origin of these issues and the implications they may have for future climate projections. In the North Atlantic, the ocean circulation has exhibited considerable variability and AMOC is expected to decline in the future with potential roles for sea ice loss and salinity and temperature feedbacks and this will likely have global implications through various teleconnections.

Overall, there are global scale teleconnections involving the atmosphere, ocean, cryosphere, and the coupling between them which will have implications for projected regional climate change and we must continue to work towards understanding these and improving their representation in Earth System Models. To better understand the cloud effects on circulation, we need global satellite cloud data at high spatiotemporal scales (e.g., several kilometers and 10 minutes). We also need to better understand the mesoscale organization of shallow and deep convections through observational data analysis (tracking of these events) and kilometer-scale modeling.

**S24: Attribution of changes**

There is a place for rapid extreme event attribution, noting the trade-off between fast and comprehensive studies. Rapid extreme attribution allows us to communicate the role of climate change behind an extreme event at the time when people are interested. In terms of impacts attribution, it would be desirable to work towards piloting operational attribution. There is also a call from small island states to receive tools and protocols (and perhaps other support) so they can do their own attribution.

While this might be basic, there is a need to start somewhere and so the focus could be how this might be rolled out on the scales where impacts occur. This is important because there are often local confounding factors that need to be addressed and this can be difficult to implement. The significant interest and opportunities regarding groups taking on operational attribution was clear. NOAA (in the USA) are developing a protocol; Copernicus C3S in Europe have an attribution center opening in 2024; University of Witwatersrand in South Africa also have a system for the African continent; and there's a center in South America also. This means that there is a great deal of exciting work happening – but as these points demonstrate, even more work is probably needed.

Extreme event attribution (EEA), determining whether there is a discernible signal of an observed extreme weather or climate event due to anthropogenic influence on the global climate, is an important tool in assessing how large-scale climate change interacts with regional/local conditions where it will be most damaging. The field of impacts attribution determines whether impacts (e.g., to human health, agriculture, infrastructural damage, or financial losses) of extreme events (e.g., heavy rainfall, droughts, heatwaves, storms) can be attributed to climate change. There are numerous challenges that should be addressed to improve the robustness of EEA assessments, particularly for certain classes of extreme events., This includes how uncertainties are addressed and reduced, and how to communicate both the results of EEA assessments and the corresponding uncertainties effectively and truthfully. Moreover, new challenges are emerging as extreme events morph towards compound and/or record shattering events. Close and coordinated collaboration between climate scientists and groups such as statisticians, climate model developers, impacts modelers, litigation experts and communication experts are imperatives to ensure substantial yet constructive developments in extreme event attribution are progressed over the next decade.

To further develop the field of EEA, the following key focus areas are suggested:

1. Sufficient model capability and capacity on demand including simulations that properly resolve extreme events and their underpinning physical mechanisms; and adequate numbers of simulations to ensure appropriate sampling.
2. Reduction in the inequity of attribution statements, particularly in lower income and more vulnerable nations, communities and cities.
3. Protocol in assessing the suitability of physical climate models for EEA.
4. Development of methodologies and best practice guides to account for compound and record shattering extremes in attribution assessments (e.g. storylines, ensemble boosting).
5. Organized and on-going engagement with impacts communities to develop protocols around impacts attribution and associated applications.
6. Significant and on-going investment in EEA communication and robust inter-disciplinary information for decision-making across local to regional scales.

**S25: Regional climate change**

Initiatives such as CORDEX have enabled strong representation of Africa with respect to available high resolution model datasets; similar systematic programmes for other Global South regions would be useful. The continued inclusion of capacity development/training in the CORDEX programme is essential.

The formation of an Africa research hub that undertakes coordinated projects that answer questions important to the Africa context; that continues the interdisciplinary approach implemented for CORDEX-Africa; and that can pursue funding opportunities is essential, given the enhanced capacities from previous efforts like CORDEX Africa. A WCRP Framework that supports this (and similar efforts in the Global South) would be useful.

Next steps planned by CORDEX for convection permitting simulations at ~1km resolution holds potential for improved understanding of tropical convection processes and improving climate services; while plans to include urban, vegetation, hydrology, sea ice (and other) model components hold potential for improved representation of processes at higher resolution. There is potential for improving model representation of extreme events through the application of Machine Learning. Obtaining “buy-in” from more nations, governments and organizations about the importance of, and potential for, Global South-North partnerships is critically important.

**S26: Mitigation scenarios including overshoot and climate intervention**

Climate intervention (CI) refers to deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change. It is being considered in the context that any additional warming will further exacerbate observed increases in the frequency and intensity of extreme weather, the melting of polar and glacial ice, and sea level rise, among other potentially catastrophic changes in the Earth system. As defined here, CI includes both large-scale carbon dioxide removal (CDR) and sequestration technologies, as well as solar radiation modification (SRM). Both types of climate intervention offer the potential to reduce climate risks, but both introduce global-scale risks.

This session explored the potential and limits of carbon dioxide removal (CDR) and solar radiation management (SRM), and the long-term Earth system impacts of temperature overshoot. Presentations discussed the potential scale of afforestation and reforestation, the complementarity of land-based and ocean-based CDR, and the potential of stratospheric aerosol injection SRM to offset some drying trends over Africa and the risk of extreme wildfire risk over most of the world.

The discussion brought to light many of socio-political factors that would constrain and shape the application of these climate intervention strategies and stressed the need for inter- and trans-disciplinary research that connects to the potentially affected stakeholders.

A lunch-time side-session brought together a panel of African researchers to further discuss and develop these themes and to discuss managing climate overshoot in Africa. The afternoon poster session attracted many presenters and provided another opportunity for a deeper, technical discussion of climate overshoot, CDR and SRM.

A consistent message from the discussions around these sessions was that while various CDR and SRM proposals have potential, neither is a substitute for emissions cuts, and both raise concerns that cannot be adequately addressed without additional research. With many critical scientific knowledge gaps and uncertainties around the potential benefits, risks and sustainable scale-up potential of CI, rigorous, transparent, and globally inclusive research is required to further understand and facilitate the comprehensive assessments that are needed to inform climate policies.

## Summary Theme 3: Co-produced Climate Services and Solutions

### S27: Hazards and Extreme events

Climate risk results from the interactions of climate-related hazards with the exposure and vulnerability of affected systems. This risk evolves with changes in hazards, adaptive capacities, and human decision making. Climatic impact-drivers, in the sense of hazards, are affecting every region of the world and every sector will be affected by changes in multiple climatic impact-drivers, including changes in extremes. The frequency and intensity of many extreme events are being affected by climate change. Climate change is increasing the probability of unprecedented extreme events and that of compounding events that require a multi-hazard, multi-risk perspective in science and decision-making and are a focus of research. We must increasingly “imagine the unimaginable” for appropriate risk preparedness and management. Changes in climate hazards, exposure and vulnerability are inherently linked to the Sustainable Development Goals (SDGs). Climate change impacts may impede reaching some SDG targets, yet many SDG achievements can reduce vulnerabilities and increase resilience.

There has been progress in understanding characteristics of, and changes in, extreme events. There is increased confidence in changes for extreme heat, and drought in some regions. Advances have been made on changes in extreme rainfall, though gaps remain. Progress has been made in developing early warning systems for extremes and impacts, but primarily on weather time scales, and it is a challenge to provide relevant, local-scale information in many vulnerable regions. It is crucial to consider connections between hazards and their changes, and impacts. Impact-based forecasts are therefore useful tools to increase the relevance of warnings for decision makers, but also face challenges around responsibility and liability. Confidence in changes in extreme events varies by event type and region, with some uncertainties owing to model disagreement or incomplete scientific understanding. Some climate tipping points are related to extremes, yet the study of threshold-breaching events requires mean state and variability information which is not always available. Some hazards, such as drought, are complex because they can affect or be detected in many variables. Collecting enough data on exposure, vulnerability, hazards, and behavioral responses is difficult, and it is challenging to reduce uncertainty on changes in hazards for which observations are sparse and there are relatively few suitable model projections, such as severe convective storms. Feedbacks in the Earth system and cascading events pose additional scientific challenges. Attribution of extremes and their impacts while properly accounting for confounding drivers remains difficult.

**S28: Regional information – Data and methods**

Artificial Intelligence (AI) allows the development of modelling approaches that go beyond the climate data and deal with the risk components systematically. This has been applied through explainable AI and causal inference for human displacement related to climate drivers.

Downscaling requires new approaches to address either the computational cost (dynamical downscaling) or the stationarity hypothesis (statistical-empirical downscaling). Machine learning approaches are helping to develop and test update methods that bring together both dynamical and statistical approaches. These methods risk requiring large training samples.

Open data sources (IRI data library, C3S CDS) are fundamental to provide traceable, reproducible and verifiable climate predictions, as WMO recommends. Public software tools that lead to feasible approaches within the time available to deliver a service are also important to generate capacity to deliver services. These elements empower remote actors to deliver the information (both in the digital format and in the form of narratives) that their regional and local users' demand.

Observational data are a challenge. Including additional data sources, especially in situ data that are not usually shared with international initiatives are particularly valuable for regional climate.

Ensemble selection methods become relevant to extract useful/skillful information and to reduce the ensemble size to perform additional processing (e.g., downscaling). Even without ensemble selection, other processing of climate data is necessary to extract the signal, such as calibration and bias adjustment in climate forecasts. However, it is important to bear in mind that one size does not fit all purposes (as the validation of the approaches often shows), and at times the data processing is not necessary or the best approach.

**S29: Regional information – Constructed for climate services**

There is the need to co-construct regional information for a variety of climate services in support of decision making. There is an increasing recognition of the urgency to bridge the gap from physical climate science to the needs of human and natural systems. There are emerging and increasing global scale to help this process. Working with decision-makers to co-construct regional information for a variety of climate services cannot be done in isolation. Sustained engagement with stakeholders is required, with both sector and regional expertise crucial. This session highlighted interdisciplinary work to co-produce useful and contextual impact- and risk-relevant information. A range of different research methods and communication techniques demonstrate that no one size fits all solutions, requiring a range of approaches to close the gap between the science and what society needs to ensure decision-making is action oriented and 'fit for purpose'. The role of 'unfancy work' is critical to process and make data useable, useful, and used.

Information is moving closer to the decision scales, requiring subsector and subregional detail. A lot of good work is happening, but urgent research is still required in key areas, such as: (a) Operationalization of climate services, (b) Improvement of scientists' understanding of decision-making landscape and deeper, sustainable capacity building efforts, (c) Quality assurance and control, database creation, availability of data, and co-production and design, (d) Minimization of data limitations and improvement of confidence, and (e) Determination of specific thresholds of climatic impact-driver response that may vary within and across sectors and regions.

**S30: Uncertainties in climate projections: plausibility, possibility and probability**

Climate and climate risk projections are uncertain. A probabilistic treatment of climate risks in a future climate is therefore often not possible or misleading. One needs to anticipate the unexpected, i.e., events that have previously been considered impossible or at least implausible.

Approaches are required that go beyond statistical hazard assessments and standard climate model ensemble projections, to enable stress testing of the affected systems. Such approaches may include the use of physical climate storylines, the UNSEEN approach, or brainstorming by the involved parties of their experience in other regions and imagining possible outcomes.

Unexpected outcomes may reveal serious limitations of current practice regarding governance, early warning systems, emergency responses and spatial planning. Complex risks may require resources simultaneously and thus overstrain the response capacities. Dynamic adaptation pathways help to adapt based on early warning signals of emerging climate trends.

Stakeholder-driven work and co-production ensure that the obtained information is actionable and can be directly used in adaptation planning. Stakeholders often want single numbers, but might accept working with uncertain outcomes, if they have a clear understanding of their sources and relevance. In the Global South resources are often missing for climate risk assessments, e.g., for observational data and research in general.

**S31 Climate knowledge co-production in a decision and policy context**

Growing climate impacts are leading to an ever-increasing demand for relevant climate knowledge and translation to inform decision and policy contexts. The climate knowledge user community has diverse needs across many different scales and cultures coupled with complexity of power relationships among societies, especially when comparing resource rich and poor nations. The science-policy interface requires transdisciplinary approaches to develop climate services through knowledge codesign, coproduction, and codelivery informing anticipatory adaptation to future challenges. To reflect these needs in the Open Science Conference Session on "Climate knowledge co-production in a decision and policy context" three Keynotes were presented on the "Transformation through Transdisciplinarity", "Co-production in Climate Services", and on "Principles for co-producing climate services: practical insights from FRACTAL". Each Keynote was accompanied by two short oral presentations on concrete case studies and local experiences with respect to the "examining participation in climate decision-making: myth and reality", the "willingness and preparedness of communities to share knowledge for climate change adaptation in Chivi, Zimbabwe", the "going to extremes in climate services: lessons and practices for managing through the new abnormal", "silver-lining in a cascading crisis: interdisciplinary knowledge production for impactful climate science in Afghanistan", and the "causal and explainable machine-learning models for hazard-induced displacement."

The discussion of the presentations and the overall topic of co-production of climate services included strong statements towards transdisciplinary knowledge sharing and joint learning, the inclusion of ethical and moral aspects and the valuation of inputs and outputs. It became clear that joint development involving natural and social science is key to the success of climate services. Academic literature is informing policies and the uptake of climate knowledge. Both, disciplinary depth and inter-/ transdisciplinary integration are needed for the co-production of climate knowledge in the decision and policy context.

**S32 and S34: Climate services**

Capacity development for climate services is key for fostering informed decision-making, empowering local institutions and communities, and thereby ensuring effective adaptation strategies. The session underscored a growing acknowledgment regarding the importance of understanding the needs and expectations of the target group and their decision contexts in the design of the training activities. It emphasized the adoption of gender responsive people-centric approaches, proactive engagement with policymakers, coordination of activities, communication of training opportunities (e.g., through a training catalogue), establishment of strategic partnerships (e.g., with boundary organizations), the need for assessing the benefits of trainings, and a commitment to ensuring the sustainability of training programs.

Climate services have been shown to have positive effects on resilience and wellbeing. However, we must make efforts towards creating tailorable standards for climate services to ensure that the service is robust int the future. Stronger efforts and needed to link learning across individual monitoring and evaluation initiatives to catalyze a synthesis learning base. Together with funding agencies, there is a need to think strategically about the sustainability of climate services initiatives as part of the continuous monitoring and evaluation process.

**S36: Observations for Decisions**

Earth observations (EO) from benthic, glider- and floater-based, ground-based, airborne, and space-based instruments are the backbone of Earth system and climate science. EO are a key pillar for WCRP research since EO provide the essential data and insights necessary to understand the complex processes and interactions within the different components (atmosphere, ocean, cryosphere, and biosphere) of the Earth system and crucial information on our changing environment under the impacts of climate change. The created knowledge in turn informs policy, adaptation strategies, and global efforts to address climate-related challenges. Observations also empower people by providing them with crucial knowledge and understanding of their situation within the context of a changing climate.

Africa faces significant challenges in terms of EO capabilities, often referred to as being "observation poor." This is due to a combination of factors, including limited financial resources, infrastructure deficits, and a lack of access to advanced technology. Many African countries struggle to establish and maintain satellite-based observation systems, weather monitoring networks, and ground-based instrumentation for environmental research. The consequences of this observation deficit are profound, as it hinders the ability to monitor and respond to critical issues like climate change, air quality, natural disasters, agricultural productivity, and water resource management in a way that is anchored in real-world data. Addressing the lack of observation in Africa is crucial for the continent's sustainable development, resilience to environmental changes, and informed decision-making for the well-being of its populations. Efforts to improve EO capacity in Africa are essential to bridge this gap and ensure data-driven decision support for various sectors, including agriculture, public health, and disaster management. The avenue of low-cost sensors and citizen science are a key opportunity (especially for the Global South) and has the potential to revolutionize various fields and applications due to their affordability, accessibility, and versatility. Importantly, instrument design, development, and deployment, data collection, particularly for long-term monitoring, and data analysis are key research activities with which a broad range of scientists can be trained and educated.

Key messages from the different presentations were:

- Historical data rescue of so far undigitized observations has great potential to improve knowledge of past precipitation events and learn about its variability and trends.
- Designing a pan-African climate observation system to deliver societal benefit through climate action reveals the strong need for co-creation and technology transfer as goals.

- Low-cost sensors for local air pollution measurements delivering new information on diurnal cycle of critical air pollutants in agricultural areas reveal potential for creating meaningful guidance for policymakers.
- Development of a pilot coastal greenhouse gas observing system in southern Africa emphasizes the complexity of coastal systems and the usefulness of low-cost sensors.
- Quantification of in situ climatological data coverage and human population dynamics across the mountains of Africa link socio-economic data to geography and flow of mountain resources.
- EO in supporting the UNFCCC Paris Agreement should be used in new, deductive approaches to make climate change salient for society and generate emotions leading to climate action.
- Ocean digital twins incorporating a broad range of ocean-related observations could become a key resource to inform adaptation planning with respect to regional sea-level rise.

**S37: Regional attribution**

A challenge in attributing extreme events is the presence of further factors that confound human influences. Examples shown were as diverse as water or land management, and water demand by invasive species. For reliable local/small regional attribution it is vital to address all relevant factors. This is why impact studies generally require a knowledgeable regional perspective in the team addressing it. Climate models are not always able to reliably simulate extremes. This emerged in the attempts to link to landslides, where the issue was caused by the scales involved, but possibly also sampling, and in variance of extremes in CMIP models (my talk) which impede reliable use of analogues to determine implications of past extremes for adaptation.

There is an urgent need for more representation of the global south in attribution research and applications, both in terms of events analyzed and teams analyzing it. Many speakers stressed this. Despite perceptions in the climate community or improvement in this area, analysis of extreme events in the research community (represented by BAMS supplement) is still very uneven and unequal in terms of i) who is involved in the studies, ii) what regions' extremes are analyzed, and iii) what factors are considered. There is little evidence of any trends towards more even representation. Providing information on attribution is useful even in cases where it is scientifically a straightforward, thermodynamic response.

Operationalizing extreme event attribution: Climate services such as C3S are interested in operationalizing extreme event attribution, building on their preexisting climate monitoring activities leveraging a range of methodologies including reanalysis + forecasts, seasonal forecasts and hindcast evaluation amongst others.

**S38: Connecting regional impacts and climate information**

An interconnectedness of climate challenges exists across various regions, showing a common strength of regional coordination, community engagement, holistic approaches, and data accessibility. To fill the identified gaps, there is a need for improved data management, long-term resilience planning, and a focus on the unique challenges faced by indigenous communities. The common perspectives and solutions point towards enhanced collaboration, data sharing, and a holistic approach to addressing climate change impacts in a rapidly changing world.

Common Strengths: a) Resilience through Regional Coordination: Multiple presentations emphasized the importance of regional coordination and collaboration to enhance climate resilience. A discussion on the Indian Ocean observation system highlighted the need for regeneration and resilience through complementarity and redundancy. The necessity for integrated water resource management in transboundary river basins to address both climate and socio-political challenges was underlined.

b) Community Engagement: The significance of community-level climate information in East Africa was discussed. The importance of recognizing local priorities was stressed, enhancing community capacity for resilience, and utilizing participatory scenario planning to integrate indigenous knowledge into modern forecasting practices. c) Holistic Approaches: Rising water levels in Uganda highlight the value of a holistic approach to flood management, including defined roles for various institutions, regional cooperation, and the enforcement of existing laws. d) Data Accessibility: Accurate weather data for precision agriculture in Rwanda are needed, emphasizing the importance of overcoming data limitations through sensor support to aid farmer decision-makers.

Identified Gaps: a) Data and Service Gaps: Significant data gaps exist caused by the COVID-19 pandemic in the Indian Ocean observation system, which affected the monitoring and prediction of societally relevant impacts, indicating the need for improved data management and servicing. b) Drought Resilience: Drought impacts in southwest Mali highlighted the consequences of climate change on livestock production. While responses like crop residual storage and bushfire control are known, there remains a gap in addressing the long-term resilience of pastoral communities in drought-prone regions. Indigenous c) Community Impacts: Climate change's adverse effects on indigenous agricultural revenue identify the negative impact of teak on fertile land. Addressing the livelihood challenges of indigenous communities requires further exploration.

Common Perspectives and Solutions: a) Enhanced Data Availability: Improving data availability and management is a shared priority. This can be achieved through the deployment of sensors, regional collaboration, and data sharing. b) Community Engagement and Indigenous Knowledge: The value of involving local communities and integrating indigenous knowledge into climate adaptation strategies was highlighted. Combining traditional knowledge with modern forecasting practices can enhance resilience. c) Transboundary Collaboration: The importance of hydro-diplomacy and integrated water resource management exist in transboundary river basins. Collaborative efforts among countries are essential for managing shared resources and addressing climate-related challenges.

**S39: Institutions and frameworks**

The world is becoming less optimal for humans, and we need to rapidly enhance our ability to deal with climate information in a decision/ policy context. In this process we should explore new approaches and make new mistakes. An unprecedented amount of climate data is now available to users but neither the capacity nor the capability often exists among communities to deal with this information. Having hammers, saws and drills are key capacities you need to have if you want to build a wooden structure, but they are not useful if you don't know how to use them.

Several international activities are supporting the capability effort by making more data available easily accessible and usable. A further push exists to operationalize other data streams via WIPPS (e.g. storm surges predictions, climate projections), methodologies (e.g. attribution) or interface (e.g. IPCC Climate Atlas via Copernicus). Much more effort is required to support communities in extracting the relevant information and account for it in existing decision processes. The ongoing effort towards a National Framework for Climate Services in some nations are examples of where there is interest in building national capability and capacities.

**S40: Lessons from failures**

Failure is hard to talk about and easily disguised by choice of metrics, yet the nature of the long-term legacy is a key indicator of the real value of any action. Failure may often have more profound value than a success by introducing necessary course corrections or encouraging objective assessment of alternative avenues.

The legacy of the engagement between the resource rich and resource poor nations (typically referred to as Global North and Global South) is troublesome, and disproportionately weak in Africa with a consequence that resource poor partners are dis-empowered in many contexts. Resource rich nations need to move beyond treating the issues as one of mere inequity that can be ameliorated simply by increasing the numerical participation from the south and recognize that the need is additionally to share the power of convening and engage in co-leading to empower and engage with the intellectual expertise in resource poor nations.

Awareness of the lived experience of individuals in resource poor-nations is, on its own, an inadequate driver of effective modalities of engagement. This awareness needs to be converted into a deeper comprehension of the lived realities of the context to enable structuring actions aligned to the realities of the situational needs and that have efficacy in empowering the resource poor partner. Comprehension comes through “deep listening” that recognizes research is personal and can understand the threefold nature of the lived experience in terms of feelings of the individual, the values at play, and the structural parameters that characterize the situational context.

Changing the efficacy of the engagement between the global north and global south necessitates a release of a measure of control by the north and to share authority to facilitate equitable convening of the agendas that begins right at the design phase of any action and continues through to implementation. A cost-benefit framing encourages the use of quantitative de-personalizing metrics, while a “rights” based framing elevates the value of individuals and lived experience.

Building resilience has multiple modalities and needs to be aligned with the community’s risk exposure. Lower accuracy and lower resolution models and error diagnosis serve crucial evidential roles in scientific research and should not be quickly discounted. Society is not homogeneous, and such assumptions about a community can deeply undermine the efficacy of a well-intended action, a trap that risk communicators often fall into.

Mass dissemination and communication methods about weather and climate risk alerts makes assumptions about the homogeneity of the community and can lead to unintended and negative consequences. How the public perceive and receive research and scientifically based information on climate hazard can result in the public responding in a way that can cause harm. Risk communication methods should be informed by local customs and practices. The target community can build a culture of risk sensitivity and imagination, and this can be effectively linked to risk reduction actions, but first one must understand the communities. Unaccounted for relational dynamics of multi-scalar governance can undermine adaptation.

The intersectional realities of a context are often poorly understood, of major importance to achieving success in adaptation actions, and often skirted by the agencies and actors engaged in a decoupled manner from the realities of the context. The consequences of actions initiated without comprehension of the context cause at best ineffective adaptation and wasted resources, and at worst cause harm to the individual and the lived experience of a community, including leaving a more degraded state at the end of the action.