

Supplementary Materials:

A Review of User Perceptions of Drought Indices and Indicators Used in the Diverse Climates of North America

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S-1. North American Meetings and Workshops

This section describes the meetings and workshops over the last decade that engaged North American users to assess their drought index and indicator needs.

S-1.1. Tropical Workshops

The tropical data for this analysis were obtained through user engagement at several meetings and workshops that addressed drought monitoring in tropical Pacific and Caribbean islands. These include meetings held in 2011 and 2012 in Hawaii and Guam, and in 2018 in Hawaii, that focused on drought monitoring data, tools, methodologies, and impacts in the U.S. territories Guam and American Samoa, the Commonwealth of the Northern Mariana Islands, and the free states of the Republic of Palau, the Federated States of Micronesia (FSM), and the Republic of the Marshall Islands (RMI), referred to collectively as the U.S.-Affiliated Pacific Islands (USAPI) [5]. Meetings were also held in Puerto Rico and the U.S. Virgin Islands in 2016 and 2018 that addressed drought monitoring data, tools, methodologies, and impacts in the U.S. Virgin Islands (USVI). The USAPI and USVI are included in this discussion since they are included in the geographic scope of the U.S. Drought Monitor (USDM).

At the 2011 and 2012 USAPI meetings between NOAA and University of Guam personnel, participants identified data and indicators appropriate for drought monitoring in the USAPI and established a corresponding drought monitoring methodology and process [5]. The 2018 Hawaii workshop (“Drought in the USAPI – Impacts, Resilience, and Management”) was held on 14-15 August by the USGS Pacific Islands Climate Adaptations and Science Center (CASC) in Honolulu at the East-West Center of the University of Hawaii, Manoa. The focus of the workshop was to synthesize information regarding the impacts of drought in the USAPI on various sectors across the region. The 27 participants in the 2-day workshop represented various governmental agencies and universities including the DOI, USGS, NOAA, USDA, U.S. Agency for International Development (USAID), National Drought Mitigation Center (NDMC), Guam Department of Agriculture, Guam Office of the Governor, Desert Research Institute (DRI), and the University of Hawaii, Manoa [37]. During the 2-day workshop, participants gave presentations on a variety of drought-related topics relevant to USAPI (i.e., historical droughts in USAPI, drought and wildfires in Palau and Guam, ENSO relationships to drought, drought monitoring in USAPI) as well as sector-specific drought impacts presentations (i.e., agriculture, aquatic species, ecosystems, managed natural resources, water resources, wildfire). Moreover, five interactive breakout sessions were utilized during the workshop with the aim of: 1) identifying key impacts of drought to the agricultural sector in Guam, Commonwealth of the Northern Mariana Islands, and other areas of the western Pacific; 2) identifying water supply and socioeconomic impacts of drought in USAPI; 3) identifying key impacts of drought to managed natural resources, ecosystems, and interactions with wildfire and erosion in USAPI; 4) identifying data availability and needs for drought monitoring in USAPI; and 5) developing a list of agenda topics and participants for a follow-on solutions-focused workshop. One of the key outcomes of the workshop was the

development of a series of four 2-page summary factsheets highlighting drought impacts on USAPI agriculture [38], ecosystems [39], and water resources [40] as well as drought monitoring needs and limitations [41].

The 2016 USVI meetings were held 30-31 August on St. Croix at the University of the Virgin Islands and 1 September in Río Piedras, Puerto Rico, at the International Institute of Tropical Forestry. The 2018 USVI meeting was held 30-31 May in Río Piedras, Puerto Rico, at the International Institute of Tropical Forestry. (The 2018 USVI workshop is discussed at: <https://www.usgs.gov/ecosystems/climate-adaptation-science-centers/drought-us-caribbean>. accessed on 20 August 2023) Participants at the 2016 and 2018 USVI meetings included stakeholders involved with drought monitoring, with a heavy emphasis on academia and local, territorial, and federal government entities, and USDM authors who discussed drought monitoring data and data gaps, tools, methodologies, and impacts relevant to the USVI.

Steps toward full-time drought monitoring in the USVI were taken at the 2016 meetings. For example, a positive outcome was to have a student from the University of the Virgin Islands work at USDA headquarters in Washington, DC, during the summer of 2017; one of the student's responsibilities was to create a database of Standardized Precipitation Index values for all available USVI stations. However, fledgling USVI drought-monitoring efforts were shattered by Hurricanes Irma and Maria in September 2017, as communications with key contributors were severed for weeks or months. In addition, weather data from several long-term USVI stations was lost; some observation sites were permanently shuttered. Drought experts "picked up the pieces" at the 2018 meeting in Puerto Rico, resuming monitoring efforts. Enough progress was made to add the USVI to the USDM in June 2019, with additional work (e.g. adding new manual and automated rain gauges, collecting histories of former reporting sites, and fortifying existing stations) ongoing and expected to continue.

At all of these meetings, interagency collaboration was identified as crucial for identifying potential impacts in the USAPI and USVI and differences between high and low island impacts. The results of these meetings provided the information and metrics needed to expand operational drought monitoring in the USDM from the 50 states and Puerto Rico to include the USAPI and USVI.

A 23 July 2019 workshop in Hawaii engaged users from federal agencies and Hawaiian state agencies, educational institutions and native tribes who provided user perspectives in the fields of agriculture, ranching, ecosystems, wildfires, water management, and traditional ecological knowledge. (A summary of the results of the 2019 Hawaii workshop is available at: <https://www.drought.gov/news/drought-stories-hawaii-workshop-drought-recovery>. accessed on 20 August 2023) In addition to the workshop in 2019, the Hawaii State Drought Coordinator hosts county drought committee meetings at least annually. These are usually held at the start of the dry season to discuss the current drought status following the October through April wet season, the outlook for the dry season, impact reports from stakeholders, and mitigation actions taken by federal, state, county, and private entities. Additional drought meetings are convened as needed by the county drought committee chairperson, usually in response to significant impacts during an ongoing drought.

S-1.2. High Latitude Workshops

The high latitude data for this analysis were obtained through user engagement at several meetings and workshops that addressed drought monitoring in Alaska. These include in-person workshops held in 2015 in Fairbanks, Alaska, 2019 in Juneau, Alaska, and 2020 in Anchorage, Alaska, and a series of virtual workshops held in 2021 that focused on the various regions of Alaska. One of the themes at the 1-3 May 2018 North American Drought Monitoring Forum (held in Calgary, Alberta, Canada) was drought monitoring in cold (Arctic) climates. It was determined that some of the key challenges included data availability, understanding of drought issues in northern areas, the ability to determine the impacts of drought, and a rapidly changing environment.

The 2015 Fairbanks workshop (“Ecological Drought in Alaska: The impacts of climate change on a large, diverse, remote landscape”) was held 15-16 September and organized by the Department of the Interior Climate Adaptation Science Center and their managing organization, the National Climate Change and Wildlife Science Center at the USGS. (A summary of the results of the 2015 Alaska workshop can be found here: https://ak-casc.org/wp-content/uploads/2020/11/AK_EcoDrought_Newsletter_IAN_ADACompliant.pdf. accessed on 20 August 2023) The workshop discussed issues affecting the Alaska ecosystem, including drought.

Alaska is a huge state with climates that range from the temperate rainforest in the southeast to arctic tundra in the north, and each of these regions has its own unique drought impacts and challenges. It was recognized early on that region-specific workshops would be needed for the state [42]. The 2019 Juneau workshop (“Southeast Alaska Drought Workshop: Less rain, warmer temperatures and transitioning from a 'Snow to Rain Dominant System'”) was organized by the USDA Northwest Climate Hub, National Weather Service (NWS)-Juneau, Alaska Climate Adaptation Science Center, and NDMC and was held 7-8 May [42]. The workshop engaged users from federal, state, and local agencies; Alaska Native communities; academia; and the private sector to identify drought impacts by incorporating traditional ecological knowledge as well as knowledge from a variety of fields (e.g., ecology, agriculture, climatology, hydrology, policy, utilities, community development, etc.). The workshop concluded with organizers reviewing the discussions from the first day to begin the process of developing regional metrics for the USDM [42]. This workshop addressed drought in the panhandle of Alaska, which is a temperate rainforest.

At the 2020 workshop (“NWS Alaska Region Climate Science and Services Workshop”), drought was one of several NWS climate science and services issues addressed. The workshop was held 11-13 February at the Anchorage office of the NWS Alaska Region Headquarters and organized by the NWS Alaska Region. Participants included NWS and other NOAA personnel, USGS, state and academic users, and Alaska indigenous communities. The portion of the workshop relevant to drought monitoring included a discussion of datasets, indices and indicators, and drought impacts relevant to Southcentral and southern portions of Interior Alaska, and development of draft regional metrics for the USDM for these regions in Alaska.

The 2021 virtual Alaska Drought Webinar Series was organized by the USDA Northwest Climate Hub, Alaska Center for Climate Assessments and Policy (a NOAA Climate Adaptation Partnerships/Regional Integrated Sciences and Assessments Program), NIDIS, the Department of Interior Alaska Climate Adaptation Science Center, and the Federal Reserve Bank of San Francisco and consisted of seven virtual workshops held during February and March. The 2021 Alaska Drought Webinar series meetings are described at the following two websites: (<https://www.climatehubs.usda.gov/hubs/northwest/topic/alaska-2021-drought-webinar-series>, accessed on 20 August 2023) and (<https://uaf-accap.org/research-activities/alaska-drought-webinar-series/>, accessed on 20 August 2023). The first two workshops provided an overview of Alaska climate and the USDM process, with the last five addressing drought in five regions of the state (Figure. S1):

- 16 February -- Climate review: history of climate extremes focusing on drought
- 18 February -- US Drought Monitor Process, understand the drought maps
- 23 February -- What does drought look like in Southeast Alaska?
- 2 March -- What does drought look like in Southcentral Alaska?
- 9 March -- What does drought look like in the Aleutian Islands & Southwest?
- 16 March -- What does drought look like in Interior Alaska?
- 23 March -- What does drought look like in Northwest Alaska?

Each regional workshop served as a regional listening session to learn from participants what they experienced during unusually dry times in Alaska. Speakers and participants included community members including Alaska Natives, scientists, state and

federal (USDA, NOAA, DOI) agency personnel, academics, and commercial representatives. A review on information shared during the webinar series was held virtually 29 March by the organizers to identify and consolidate the key points from the regional workshops.

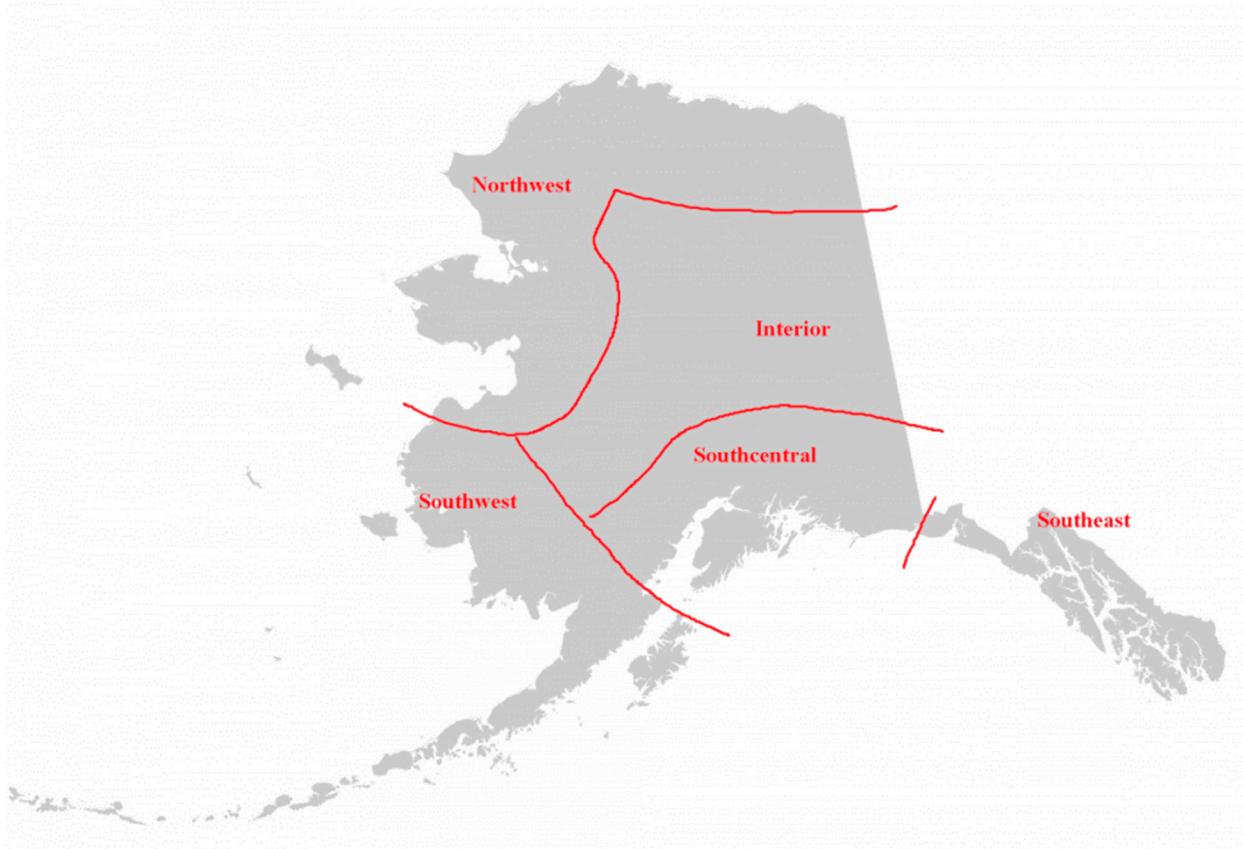


Figure S1. Map showing the Alaska regions discussed during the Alaska Drought Webinar Series 2021. Map prepared by Rick Thoman, Alaska Center for Climate Assessment and Policy, University of Alaska-Fairbanks. Used with permission.

S-1.3. The 2020 North American Drought Monitor (NADM) Forum

The NADM Virtual Forum 2020, coordinated by the National Meteorological Service (SMN) of Mexico, was held on 17-19 November 2020. It had a participation of 73 registered guests, of whom 14 were from Canada, 16 from the United States and 43 from Mexico. The main topics discussed were the scientific and administrative aspects of NADM, NADM applications in the three North American countries, the progress of the Project to Improve the Effectiveness of Early Warning Systems for Drought coordinated by the NAFTA (North American Free Trade Agreement) Commission for Environmental Cooperation (CEC), and the recent activities on Climate Services in the North American region. One of the agreements of this Forum was to elaborate drought narratives through a national summary and then emphasize regional aspects, so that users can identify drought behavior and local impacts at a more regional level.

S-2. Acronyms of Drought Indices and Indicators and Climate Subzones

This section contains tables that identify the acronyms of drought indices and indicators and acronyms of climate subzones.

Table S1. Table of Köppen climate subzones used in this paper.

Abbreviation	Description
	Tropical (A) Climates:

Af	Tropical Rainforest
Am	Tropical Monsoon
Aw	Tropical Savanna (Wet and Dry Climate)
Dry (B) Climates:	
BW	Arid (desert)
BWh	Hot Desert Climate (Tropical Desert)
BWk	Cold Desert Climate (Mid-latitude Desert)
BS	Semi-Arid
BSh	Hot Semi-Arid Climate (Tropical Steppe)
BSk	Cold Semi-Arid Climate (Mid-latitude Steppe)
Temperate (C) Climates:	
Cs	Mediterranean (dry summers)
Csa	Hot-Summer Mediterranean Climate
Csb	Warm-Summer Mediterranean Climate
Cw	Temperate with dry winters
Cwa	Warm Oceanic Climate / Humid Subtropical Climate
Cwb	Subtropical highland climate or temperate oceanic climate with dry winters
Cwc	Cool subtropical highland/Subpolar Oceanic
Cf	Humid subtropical
Cfa	Humid Subtropical Climate
Cfb	Temperate Oceanic Climate
Cfc	Subpolar Oceanic Climate
Continental (D) Climates:	
Dsa	Continental Climate - Dry Hot Summers
Dsb	Continental Climate - Dry Warm Summers
Dsc	Continental Subarctic - Cold Dry Summers
Dsd	Continental Subarctic - Dry Summers, Very Cold Winters
Dwa	Continental Hot Summers With Dry Winters
Dwb	Continental Warm Summers With Dry Winters
Dwc	Subarctic With Cool Summers And Dry Winters
Dwd	Subarctic With Cold And Dry Winters
Dfa	Humid Continental Hot Summers With Year-round Precipitation
Dfb	Humid Continental Warm Summers, Wet All Year
Dfc	Subarctic With Cool Summers And Year-round Precipitation
Dfd	Subarctic With Cold Winters And Year-round Precipitation
Polar (E) Climates:	
ET	Tundra Climate
EF	Ice Cap Climate

Table S2. List of drought indices and indicators from the *WMO Handbook of Drought Indicators and Indices* that are discussed in this paper.

Abbreviation	Description
Composite or Modeled Drought Indices:	
CDI	Combined Drought Indicator
GIDMaPS	Global Integrated Drought Monitoring and Prediction System
GLDAS	Global Land Data Assimilation System
MSDI	Multivariate Standardized Drought Index
USDM	United States Drought Monitor
Hydrological Drought Indices:	
ADI	Aggregate Dryness Index

PHDI	Palmer Hydrological Drought Index
SRSI	Standardized Reservoir Supply Index
SMRI	Standardized Snowmelt and Rain Index
SSFI	Standardized Streamflow Index
SWI	Standardized Water-level Index
SDI	Streamflow Drought Index
SWSI	Surface Water Supply Index
Meteorological Drought Indices:	
ARID	Agricultural Reference Index for Drought
AAI	Aridity Anomaly Index
AI	Aridity Index
CZI	China Z Index
CMI	Crop Moisture Index
CSDI	Crop-specific Drought Index
Deciles	Deciles
DAI	Drought Area Index
DRI	Drought Reconnaissance Index
EDI	Effective Drought Index
HTC	Hydro-thermal Coefficient of Selyaninov
KBDI	Keetch-Byram Drought Index
NDI	NOAA Drought Index
PDSI	Palmer Drought Severity Index
Palmer Z Index	Palmer Z Index
PNP	Percent of Normal Precipitation
RAI	Rainfall Anomaly Index
RDI	Reclamation Drought Index
sc-PDSI	Self-Calibrated Palmer Drought Severity Index
SAI	Standardized Anomaly Index
SPEI	Standardized Precipitation Evapotranspiration Index
SPI	Standardized Precipitation Index
WASP	Weighted Anomaly Standardized Precipitation
Remote Sensing-based Drought Indices:	
EVI	Enhanced Vegetation Index
ESI	Evaporative Stress Index
NDVI	Normalized Difference Vegetation Index
NDWI & LSWI	Normalized Difference Water Index & Land Surface Water Index
SAVI	Soil Adjusted Vegetation Index
TCI	Temperature Condition Index
VCI	Vegetation Condition Index
VegDRI	Vegetation Drought Response Index
VHI	Vegetation Health Index
WRSI	Water Requirement Satisfaction Index
Soil Moisture-based Drought Indices:	
ETDI	Evapotranspiration Deficit Index
SMA	Soil Moisture Anomaly
SMDI	Soil Moisture Deficit Index
SWS	Soil Water Storage

Table S3. List of drought indices and indicators not in the WMO *Handbook of Drought Indicators and Indices* that are discussed in this paper.

Crop Status

Groundwater Depth
Local Burn Bans
Media Reports
Precipitation Departures from Normal
Precipitation Percentiles
Precipitation Ranks
Reported Drought Impacts
Reservoir Storage
Soil Moisture
Streamflow
Temperature Departures from Normal
Temperature Ranks
Vegetation Greenness
Water Quality
Water Use (Demand)
Wildfire Locations / Reports

S-3. Discussion of CEC Study Drought Indices and Indicators by Climate Subzone

The WMO Handbook [19] grouped drought indices and indicators according to five types: composite or modeled, hydrological, meteorological, remotely-sensed, and soil moisture. The indices in the WMO Handbook were rated in the CEC survey [43] on a scale of 1 (not at all effective) to 5 (very effective) for short-term drought and for long-term drought. Indices and indicators not in the Handbook were rated without distinguishing for short-term or long-term drought. Table S2 in section S-2 lists the WMO Handbook indices, along with their abbreviations, that are discussed in the main paper and the Supplementary Material, and Table S3 lists those indices not in the WMO Handbook that are discussed here and in the paper.

The results of the ratings in each subzone were aggregated (weighted by number of respondents) by climate type and are shown in Tables S4 and S5. Of the indices in the WMO Handbook, the USDM was consistently rated as effective or very effective by more than half of the respondents in each climate type for both short-term and long-term drought (Table S4). The Standardized Precipitation Index (SPI) was rated as effective or very effective by more than half of the respondents in the A, B, C, and D climate types, and Percent of Normal Precipitation (PNP) was so rated in the A, B, and D climates. PNP was rated as effective or very effective for short-term drought in C climates, the Surface Water Supply Index (SWSI) and Vegetation Drought Response Index (VegDRI) were so rated in E climates, the Standardized Precipitation Evapotranspiration Index (SPEI) was so rated in B climates, and the Normalized Difference Vegetation Index (NDVI) was so rated in A, C, and E climates. The NOAA Drought Index (NDI), Palmer Drought Severity Index (PDSI), SPEI, and SPI were rated as effective or very effective for long-term drought in E climates.

Several drought indices and indicators not in the WMO Handbook were rated as effective or very effective by more than half of the respondents in all five climate types (Table S5). These include: crop status; precipitation percentiles and departures from normal; reported drought impacts; reservoir storage; soil moisture; streamflow; temperature departures from normal; and water use (demand). Groundwater depth was so rated for A, B, and C climates. Precipitation ranks were so rated for A, B, and D climates. Temperature ranks were so rated for A and B climates. Vegetation greenness was so rated for A, B, C, and E climates. And wildfire locations/reports were so rated for A climates. (It is noted that drought has been used as a predictor of fire activity, while the survey respondents chose wildfire locations and reports as an indicator of drought. The authors recognize this apparent conundrum and choose simply to report the survey results in this case.)

Table S4. The percent of the respondents rating each drought index and indicator (from the WMO Handbook) as effective or very effective for monitoring short-term (S-T) and long-term (L-T) drought, aggregated by climate type (A through E). Values greater than 50 are in bold italic font.

Index/Indicator	A		B		C		D		E	
	S-T	L-T	S-T	L-T	S-T	L-T	S-T	L-T	S-T	L-T
Composite or Modeled Drought Indices:										
CDI	16	24	5	11	3	13	5	4	0	0
GIDMaPS	22	15	11	6	16	8	9	10	0	0
GLDAS	27	32	22	26	27	32	15	27	0	0
MSDI	22	26	17	17	24	26	12	10	0	0
USDM	70	65	68	64	65	55	65	68	100	100
Hydrological Drought Indices and Indicators:										
ADI	6	19	2	8	3	13	4	4	0	0
PHDI	23	29	15	21	25	30	16	17	50	50
SRSI	19	29	16	23	15	22	9	15	0	0
SMRI	0	19	7	11	9	19	9	9	25	0
SSFI	16	16	21	18	19	20	14	14	0	0
SWI	23	16	4	4	6	9	7	7	0	0
SDI	23	23	15	15	14	13	14	13	25	25
SWSI	19	3	16	19	16	6	12	10	75	25
Meteorological Drought Indices and Indicators:										
ARID	27	6	13	2	16	3	9	5	0	0
AAI	0	0	6	6	0	8	0	0	0	0
AI	13	9	18	16	18	18	3	0	0	0
CZI	0	0	1	0	0	0	0	0	0	0
CMI	35	14	27	10	42	19	22	9	31	25
CSDI	27	15	17	7	22	13	13	5	0	0
Deciles	15	9	21	17	21	9	20	13	0	0
DAI	27	23	16	4	23	7	10	8	0	0
DRI	20	23	14	11	22	18	8	10	0	0
EDI	20	32	14	17	14	19	8	10	0	0
HTC	7	9	10	3	9	5	0	4	0	0
KBDI	30	9	16	2	25	3	14	5	0	0
NDI	20	27	16	15	22	22	12	22	19	55
PDSI	30	41	26	38	36	41	28	49	50	75
Palmer Z Index	22	3	17	3	20	3	28	14	31	0
PNP	57	53	53	59	57	49	59	57	19	25
RAI	27	18	8	16	9	21	4	10	0	0
RDI	5	6	2	2	3	3	3	4	0	0
sc-PDSI	20	20	7	12	15	16	10	15	31	50
SAI	35	15	11	9	17	20	4	0	0	0
SPEI	43	41	52	46	50	40	48	50	50	75
SPI	60	74	66	64	60	63	61	56	50	75
WASP	35	32	7	11	16	18	4	8	0	0
Remote Sensing-based Drought Indices and Indicators:										
EVI	43	18	16	2	25	6	16	13	33	33
ESI	43	18	33	18	40	12	34	19	33	17
NDVI	54	29	50	20	52	13	38	25	67	33
NDWI & LSWI	32	18	19	2	29	3	16	10	33	33
SAVI	24	18	12	2	18	3	3	4	0	0
TCI	22	35	11	12	13	18	9	10	0	0

VCI	27	26	21	8	29	8	12	14	33	33
VegDRI	30	18	44	23	44	19	28	26	67	33
VHI	22	18	23	14	24	12	17	14	33	0
WRSI	24	35	17	11	30	17	9	9	0	0
Soil Moisture-based Drought Indices and Indicators:										
ETDI	35	32	18	10	24	16	18	12	33	33
SMA	41	26	32	22	34	22	28	25	0	0
SMDI	46	15	22	8	39	20	27	14	33	33
SWS	24	26	17	13	24	19	9	10	0	0

Table S5. The percent of the respondents rating each drought indicator (not in the WMO Handbook) as effective or very effective for monitoring drought, aggregated by climate type (A through E). Values greater than 50 are in bold italic font.

Drought Index	A	B	C	D	E
Crop status	61	68	71	77	100
Groundwater depth	65	53	51	38	50
Local burn bans	35	33	30	17	17
Media reports	19	26	30	29	17
Precipitation departures from normal	64	58	60	70	67
Precipitation percentiles	68	70	55	67	83
Precipitation ranks	55	51	43	53	50
Reported drought impacts	58	75	64	72	67
Reservoir storage	71	80	78	66	67
Soil moisture	74	84	74	86	83
Streamflow	52	72	70	69	67
Temperature departures from normal	61	61	53	70	67
Temperature ranks	52	58	48	50	50
Vegetation greenness	81	65	61	50	83
Water quality	35	26	30	30	50
Water use (demand)	58	57	51	58	67
Wildfire locations / reports	54	47	43	30	17

Figure S2 summarizes the ratings for the indices in the WMO Handbook for each climate subzone. In general, the USDM is highly rated (rated as effective or very effective by more than 50% of the respondents) for both short-term and long-term drought in all of the A, B, Cf, and Dw subzones, and most of the Df subzones. The SPI is highly rated for both short-term and long-term drought in all of the A and B subzones, most of the C subzones, and several D subzones. The NDVI is highly rated for short-term drought in most A and B subzones and some C subzones. Other indices that were highly rated in several subzones for short- or long-term drought include PNP and SPEI. A slightly larger number of indices are rated highly by respondents in Cw subzones than in the other subzones.

Figure S3 summarizes the ratings for indices not in the WMO Handbook for each climate subzone. Those indices highly rated in most subzones include: crop status, reservoir storage, soil moisture, and streamflow.

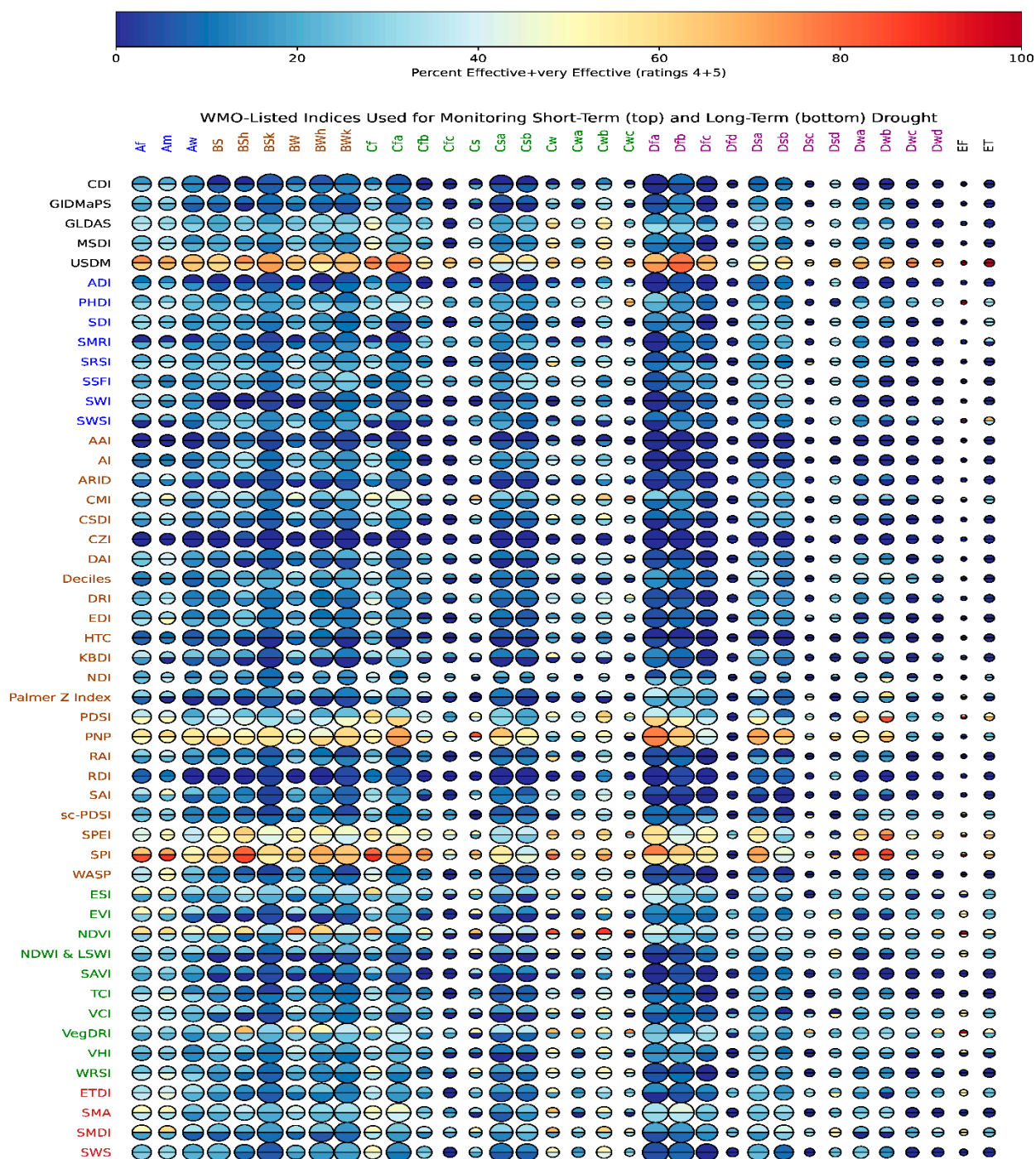


Figure S2. The percent of the respondents rating each drought index and indicator (from the WMO Handbook) as effective or very effective for monitoring short-term and long-term drought, for each climate subzone. The percentage is scaled along the color bar where the blue end extends to zero percent, the red end extends to 100%, and yellow indicates values near 50%. The top half of each circle shows the rating for short-term drought and the bottom half for long-term drought. The size of the circle is proportional to the number of respondents in the subzone.

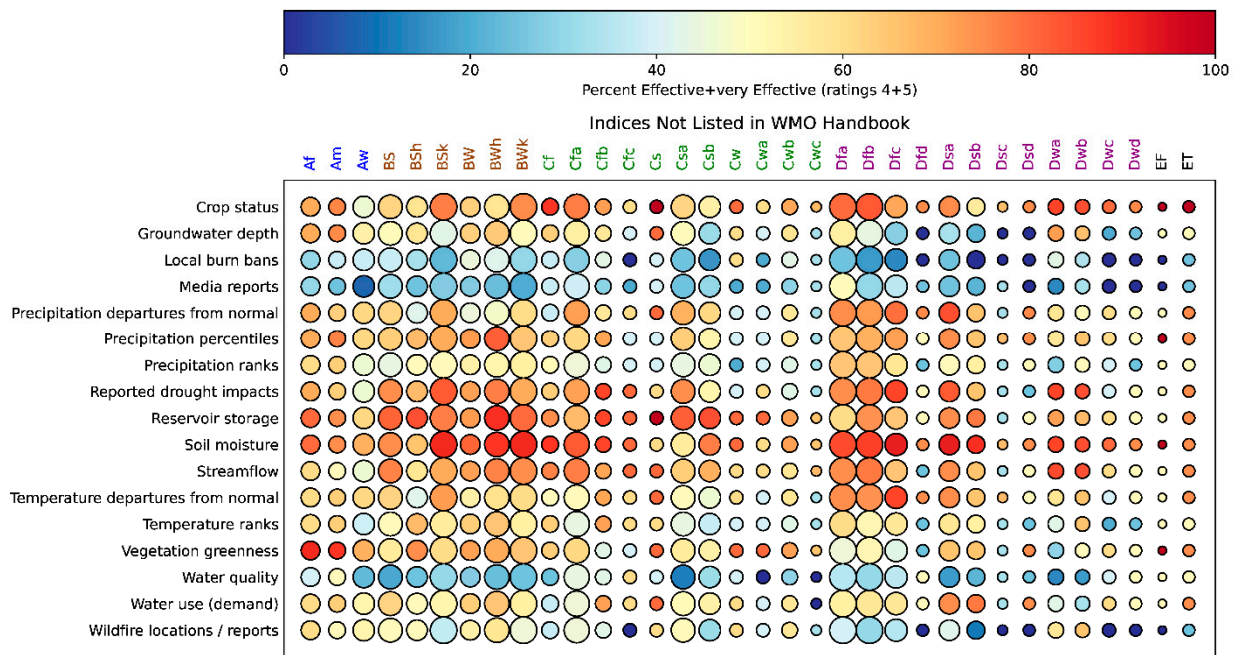


Figure S3. The percent of the respondents rating each drought index and indicator (not in the WMO Handbook) as effective or very effective for monitoring drought, for each climate subzone. The percentage is scaled along the color bar where the blue end extends to zero percent, the red end extends to 100%, and yellow indicates values near 50%. The size of the circle is proportional to the number of respondents in the subzone.

The ratings of the drought indices by subzone (Figure. S2) were generally consistent with the climate type ratings for the A climate subzones. Exceptions: some indices were rated highly in some subzones but did not reach this 50% threshold when aggregated for the climate type, while other indices that exceeded the threshold for the climate type did not reach the 50% threshold for some subzones. Examples of indices rated highly for the subzones but not the climate type include: for short-term drought, the Soil Moisture Deficit Index (SMDI) was rated highly in the Am subzone; for long-term drought, the Effective Drought Index (EDI) and PDSI were rated highly by Am respondents.

For B climates, examples of indices rated highly for the subzones but not the climate type include: for short-term drought, VegDRI and NDVI were so rated in the BSh and BW subzones, and NDVI was so rated in the BWh subzone; for long-term drought, SPEI was so rated for the BSh and BW subzones.

For C climates, for short-term drought, SPEI was rated highly in several subzones (Cf, Cfb, Cw, Cwa, Cwb, Cwc) as were crop or soil moisture-related indices (Crop Moisture Index [CMI], Soil Moisture Anomaly [SMA], SMDI, VegDRI) (Cs, Cw, Cwa, Cwb, Cwc) and PDSI or Palmer Hydrological Drought Index (PHDI) (Cf, Cwb, Cwc). For long-term drought, SPEI was rated highly in three subzones (Cf, Cw, Cwb), PNP was rated highly in four subzones (Cf, Cfa, Cfb, Csa), and PDSI or PHDI was so rated in four subzones (Cf, Cfa, Cwb, Cwc). The following indices and indicators not in the WMO Handbook (Figure. S3) did not rate highly in the aggregate but did for some C subzones: temperature ranks (Cf, Cfb, Cfc, Cs), wildfire locations (Cs, Cw, Cwb), water quality (Cfc), and local burn bans (Cw).

For D climates, for short-term drought, SPEI was rated highly in several subzones (Dfa, Dsa, Dwa, Dwb, Dwd) and VegDRI was rated highly in two (Dsc and Dwd). For long-term drought, SPEI and PDSI were rated highly in five subzones (Dfa, Dfb, Dsa, Dwa, Dwb) with SPEI highly rated in two others (Dfc and Dwd). The following two indices and indicators not in the WMO Handbook did not rate highly in the aggregate but did for several D subzones: temperature ranks (Dfa, Dfb, Dfc, Dsa, Dsb, Dwb) and vegetation greenness (Dfb, Dsa, Dsb, Dsd, Dwc). Two others rated highly in a few D subzones: groundwater depth (Dfa, Dwa, Dwb) and wildfire locations/reports (Dwa, Dwb).

With two subzones and a small sample size, the ratings for the E climate subzones were generally consistent with the aggregated ratings.

The respondents rated drought impacts on a scale of 1 (not important) to 5 (very important). Table S6 shows the ratings aggregated by climate type. Impacts that were rated highly (rated important or very important by more than half of the respondents) in all five climate types include: destruction of crops; increased farming costs for accessing water; increased ranching costs for animal feed and water; lower water levels in reservoirs, lakes, and ponds; and more wildfires. Other highly rated impacts across multiple climate types include a decline in income for businesses that depend on farming and ranching, and several types of environmental impacts.

The drought impacts ratings for the climate subzones were generally consistent with the aggregated ratings for the climate types, especially for those impacts above that were highly rated for multiple climate types. Reduced capacity for reservoir management was highly rated for the B climate subzones and some C subzones. Anxiety or depression about economic losses and/or health threats caused by drought were rated highly across most D subzones. Direct health problems related to limited water availability and poor water quality were rated highly in the A and E climates and several C and D subzones. The threat to public safety from increased numbers of forest and range fires was rated highly across the B climate subzones and in most dry summer C and D subzones.

Table S6. Percent of respondents rating each drought impact as important or very important, aggregated by climate type. Values greater than 50 are in bold italic font.

Impact Description	Climate Type				
	A	B	C	D	E
Economic Impacts					
Decline in income for businesses that depend on farming and ranching	55	66	50	63	67
Decline in income for businesses that service recreational activities	39	49	32	28	33
Decreased availability of water to cool nuclear power plants	10	11	15	11	33
Destruction of crops	84	87	78	83	100
Increased costs for businesses that supply water to customers	23	39	38	14	33
Increased costs for customers that normally rely on hydroelectric power	19	30	28	15	67
Increased farming costs for accessing water	65	64	57	65	100
Increased food costs	48	32	36	27	67
Increased ranching costs for animal feed and water	74	87	70	76	100
Increased transportation costs due to reduced capacity for water transportation	26	19	36	22	50
Loss of employment in the timber industry caused by wildfires destroying stands of timber	13	29	27	26	67
Reduced capacity for reservoir management	48	53	43	40	33
Environmental Impacts					
Increased disease in wild animals due to reduced food and water	19	33	23	30	50
Increased stress on and possible extinction of endangered or threatened species	26	47	39	32	67
Lack of food and drinking water for wild animals	52	60	54	34	67
Loss of wetlands	45	64	64	52	50
Loss of, or die back of forests	45	65	55	43	67
Loss or destruction of fish and wildlife habitat	42	65	59	56	100
Lower water levels in reservoirs, lakes, and ponds	58	88	83	73	100
Migration of wildlife	26	33	32	27	50

More wildfires	58	88	65	67	67
Poor soil quality	35	29	24	30	50
Wind and water erosion of soils	52	51	45	48	50
Social Impacts					
Anxiety or depression about economic losses and/or health threats caused by drought	39	36	41	56	50
Direct health problems related to limited water availability and poor water quality	74	35	48	40	83
Health problems related to increased dust	48	37	45	30	17
Human migration	16	7	5	1	0
Loss of human life	6	18	18	13	50
Reduced incomes	19	39	32	36	17
Reduced recreational activities	29	38	25	23	33
Threat to public safety from increased numbers of forest and range fires	29	70	46	49	17

S-4. User-Engagement Workshop Data by Climate Type

The data provided by user engagement at the workshops held over the past decade are grouped and discussed by climate type here.

S-4.1. Tropical (A) Climates

As noted earlier, in this study, Tropical climates include southern and coastal areas of Mexico, southern Florida, Puerto Rico and the USVI, the USAPI, and coastal areas of Hawaii. The year-round warmth results in high evaporative demand throughout the year, especially in low-latitude regions such as the USAPI, so reductions in rainfall are the primary cause of drought.

The majority of the CEC survey respondents rated PNP and SPI as effective drought indices for A climates, with NDVI effective for short-term drought. The USDM was also highly rated, but it is available for only the U.S. Other indices rated as effective include other measures of precipitation, temperature departure from normal (a proxy for evapotranspiration), condition of vegetation (Vegetation Greenness), hydrological measures of groundwater depth and reservoir storage, soil moisture condition, water use (demand), and wildfires. The majority of respondents rated drought indices, in the aggregate, as performing equally well across seasons in all three A climate subzones, but the indices perform equally well geographically only in the Af subzone.

In the USAPI, the average annual rainfall at all sites exceeds 1778 mm (70 inches), but the islands experience pronounced wet and dry seasons [36]. The extreme seasonal variations in monthly normal precipitation render PNP and SPI less useful as drought indicators than they are for other regions. Most islands are dependent on rainfall catchment systems for water supply; these are able to provide water for approximately 2 or 3 weeks with no rainfall before running out, so a tailored drought monitoring methodology was developed for the USAPI. It has been determined that a weekly minimum rainfall of 25.4 mm or 50.8 mm (1 or 2 inches, respectively), depending on the island, is needed to meet most of the water needs and stave off the development of drought [36]. Three consecutive weeks below the weekly precipitation minimum, or 2 consecutive months below the corresponding monthly minimum, is enough to initiate a drought. Once a drought has been established, SPI values, precipitation percentiles or ranks, and impacts are used to determine the drought intensity.

For large islands like Hawaii and Puerto Rico, a variety of in situ and remotely-sensed indicators can be generated. But for smaller islands like those in the USAPI [36] and USVI, data are more limited. NDVI can be used for some of the larger USAPI islands, such as Guam, Saipan, and American Samoa. But for the smaller islands, remotely-sensed soil moisture or vegetation condition is generally unavailable because the islands' areas are typically smaller than the pixel size of the satellite sensors. Soil moisture, groundwater,

and streamflow data are unavailable (USAPI) or limited (USVI) due to lack of operational observing networks. Daily and monthly precipitation observations are readily available, which makes precipitation-based indicators (precipitation totals, ranks, percentiles, and SPI) the main drought indicators for the USAPI and USVI.

The USVI have daily and monthly meteorological (precipitation) observations, limited real-time operational groundwater observations, and drought impact reports, but other data are limited or unavailable. The primary drought indicator is the SPI computed for multiple running time scales from 1 to 12 months, updated weekly. Vegetation health index products exist for the USVI, but utility is reduced by product resolution, deforestation/urbanization (except on St. John), and the small size of the three major islands. The Keetch-Byram Drought Index (KBDI), which is routinely employed by the NWS in Guam for monitoring wildfire potential, has been discussed as a monitoring tool for the USVI but has not yet been employed. The USVI have an Aw climate with a pronounced wet season (September-November) and dry season (January-April). While precipitation anomalies during the dry season can result in substantial SPI values, corresponding precipitation departures are small, so precipitation anomalies during the wet season are more likely to result in drought development, intensification, or amelioration.

Puerto Rico and the Hawaiian archipelago have large islands that have instrumented streamflow networks (HI and PR) and groundwater observations (PR), have soil moisture assessments, and whose vegetation condition can be evaluated by satellite. SPI and precipitation amount, ranks, and percentiles are readily available. The climate of the Hawaiian Islands archipelago can be split into two seasons; a cool/wet season from October through April, and a warm/dry season from May through September. Trade winds from the northeasterly through easterly directions account for 70% of days through the year. The persistence of the trades, coupled with orographic effects from the volcanic terrain, helps create frequently wet windward areas on the east-facing slopes and much drier leeward areas facing the west. The portion of the Hawaiian archipelago that consists of the eight largest islands includes a relatively dense network of rain gauges. A high density of rain gauges is needed in order to sample the strong gradients produced by the mountainous terrain across the state. However, there are fewer of the temperature, humidity, and soil moisture sites that are needed for many of the drought indices. As a result, the most representative drought indices are those which rely solely on precipitation data, such as SPI and percentile values.

The Tropical climate of southern Florida is characterized by a pronounced wet (summer) and dry (winter) season. Small precipitation anomalies during the dry season in southern Florida, as in the USVI, can result in large SPI values, which can lead to a false drought signal. Large negative precipitation anomalies during the wet season are more likely to result in drought development or intensification.

The majority of the CEC survey respondents rated hydrological and agricultural drought as very important in all three of the Tropical climate subzones, and destruction of crops and more wildfires were identified by the majority of respondents in each of the subzones as very important drought impacts. Participants at the 2019 Hawaii workshop noted hydrological and agricultural drought have the most severe consequences. Unlike in mid-latitudes, tropical agriculture is typically perennial, grown and harvested year-round. When drought damages the crops, it may take months for the plants to recover and be productive again. In Hawaii, it can take 10 years or longer for ranchers to recover from a major drought event. In the USAPI, agriculture may take 8 to 10 months to recover from drought [36]. While most large groundwater systems in Hawaii are fairly resistant to drought, water catchment users are heavily impacted by drought events. In dry forest areas, ecological drought is important, as drought contributes to stressors that can ravage native Hawaiian species.

In Mexico, tropical climate regions include the coasts from southern Sinaloa to Chiapas on the Pacific side, and from southern Tamaulipas to the Yucatan Peninsula on the Gulf of Mexico coast. The highest annual rainfall is primarily concentrated in two states, Chiapas and Tabasco, with annual accumulated rainfall greater than 4500 mm. The

Mexican Pacific coasts are drier compared to the Gulf of Mexico coast because rainfall in those regions is mostly determined by the inflow of summer tropical waves and cyclones. In contrast, the tropical climate regions of the Gulf of Mexico and the Yucatan Peninsula receive rainfall from both summer cyclones and tropical waves, as well as from frontal systems in the winter months; in other words, they receive rain almost all year round. According to surveys of drought indices and indicators used in North America, indices such as SPI and SPEI are among the most widely accepted for short and long-term drought monitoring in tropical climate regions in Mexico. Additionally, vegetation indices such as NDVI can be used mainly for drought monitoring in agriculture [48].

Romero et al. [49] examined drought in the tropical Yucatan Peninsula of Mexico. They concluded that, in tropical regions, rainfall is far more important than temperature variation for estimating drought severity, so the study of the evolution of drought episodes resides in the rainfall regimes, although temperature can aggravate the impacts of a drought during the driest episodes. Tropical zones can experience a very marked rainfall temporality with months of scarce rainfall followed by a season of abundant rainfall. Droughts that begin in the summer rainy season (mid-summer droughts), when temperatures are at their seasonal maximum, can be short-lived (rainfall deficit lasting less than two months). The vulnerability of the areas to the heat wave depends directly on the duration of the drought episode and the retention capacity of the soil. Droughts that begin in the cooler dry season (pre-summer droughts) develop slower and last longer. In hot, humid, and sub-humid type A climates with a very marked summer rainy season, the first heavy rainfall can end a pre-summer drought. In temperate climate zones, by contrast, even the rainy season can have a precipitation deficit with respect to evaporation. In their study area, the rainy season occurs during summer but the amount of rain does not always compensate for the evaporation generated by the increase in temperatures.

S-4.2. Dry (B) Climates

The climatological community distinguishes between drought and aridity in terms of time scale. Drought is generally defined as a temporary period of below-normal water availability (short time scale) whereas aridity is related to the average climate (long time scales) and defined as a permanent state where water supply (i.e., precipitation) is not sufficient to meet evaporative water demand [46,50-56]. Dry (arid and semiarid) climates can experience drought when the water supply is below what *normally occurs for that locality*. Like Tropical climates, reductions in precipitation are an important cause of drought in Dry climates, but increases in heat-driven evaporative demand can stress the normally meager water supply, so excessive heat can also lead to drought.

Dry climates include parts of northern Mexico, much of the western U.S., and western portions of the Great Plains in the U.S. extending into parts of the southern Canadian Prairies. Similar to the semiarid U.S. High Plains, B climates in the extreme southwestern portion of the Canadian Prairies receive the majority of precipitation during the growing season of May to August when up to two-thirds of annual precipitation is received, with much of this falling in late June/early July. Drought monitoring during this period is especially critical given that there is normally just enough precipitation to sustain agriculture [57].

Much of the western U.S. experiences a dry season during the summer, with the winter half of the year being the wet season. The southwestern U.S. experiences a secondary peak of precipitation from summer monsoon rains. Spring and summer melt of mountain snowpack provides a critical water source during the summer dry season, so indicators monitoring the status of mountain snowpack are important. Many states have developed a system of reservoirs as a supplemental source of water for irrigation, urban, and commercial use.

The central plain of northern Mexico and the northwest are classified as B climates. Most of these regions are arid zones, which complicates the understanding of drought. In Mexico, the greatest number of droughts have occurred in arid and semiarid regions, where the average rainfall is less than 400 millimeters per year. The greatest impacts of

this phenomenon are reported in agriculture, as well as in cities and rural communities, since the availability of water is related to the number of inhabitants.

Agriculture and ranching are important activities in B climates [58,59], with irrigation necessary for agriculture in arid climates and common in semiarid climates [59]. This is reflected by the majority of the CEC survey respondents in each of the B climate subzones rating agricultural drought as very important and destruction of crops and wildfires as very important impacts, with the majority of respondents in most of the subzones rating hydrological drought as very important and increased ranching costs for animal feed and water, and lower water levels in reservoirs, lakes, and ponds, as very important impacts.

The majority of CEC survey respondents in most B subzones identified the typical length of a drought as being 6 or more months. This follows from the fact that water demand is normally greater than water supply in Dry climates, and once a drought begins, the climatological odds are low that enough precipitation will fall over a short time period to rapidly end the drought.

Regarding performance of the drought indicators, in the aggregate, the CEC survey response indicated that the indices and indicators did not work well across geographies and seasons in all of the B climate subzones. Three-fourths or more of the respondents said the indices did not perform equally well geographically, while half to two-thirds said they did not perform well across seasons. This reflects the seasonal variations in precipitation and evaporative demand, and indicates that there are preferred sub-regions in B climates and preferred times of the year when the indices perform best and should be used.

The CEC survey responses indicated that half or more of the respondents rated the USDM and SPI as being effective or very effective across the Dry climate subzones for both short- and long-term drought, and PNP as being effective or very effective across the Dry climate subzones for long-term drought. The SPEI and NDVI were also rated as effective for mostly short-term drought in some of the subzones. Indices and indicators that were not in the WMO Handbook, that were rated as being effective or very effective across the B climate subzones, include indicators related to crop or vegetative health (which includes soil moisture), hydrologic indicators (streamflow and reservoir levels), precipitation percentiles, temperature ranks (which some use as a proxy for potential evapotranspiration), water use (demand), and reported drought impacts.

Several states in the western U.S. have developed drought plans which identify indices and indicators that are monitored for drought development [60]. Common indicators that are monitored, assessed, or used as drought triggers by most western states include precipitation, temperature, streamflow, reservoir levels, groundwater levels, snowpack, runoff, and soil moisture [61-67]. Some states use PDSI and SWSI to monitor drought, and fuel moisture levels are used as an indicator of fire risk. In an examination of 33 state drought plans, Quiring [68] noted that reservoir levels and PDSI were used in 18 of them, followed by precipitation and streamflow (used in 16), groundwater levels (13), soil moisture (10), CMI (9), SPI and a vegetation/crop indicator (6), and snowpack (5) ([68], Figure. 4). Quiring emphasized that, for whatever drought index or indicator is used, the thresholds for defining drought should be objectively determined, by applying an appropriate probability distribution function to the data, and be location-specific.

In a Drought Research Initiative summary of the 1999-2005 Prairie drought in Canada, Hanesiak et al. [69] identified several drought indices that were used to assess the drought's characteristics. The indices included: percent of normal precipitation, precipitation departure from normal, temperature departure from normal, SPI, PDSI, the Climate Moisture Index, NDVI, crop yield (spring wheat, barley, canola, and field peas), snow cover (snow depth anomalies), snow water equivalent (SWE) anomalies, modeled soil moisture, surface streamflow, lake and pond levels, groundwater (well) levels, and GRACE satellite-based measurements of integrated total water storage (Total Storage Deficit Index). The Climate Moisture Index is an annual indicator, calculated as the difference between precipitation (P) and potential evapotranspiration (PET) over successive, 12-month periods ending on 31 July (corresponding to a "tree water year"). The Climate

Moisture Index was used to assess impacts on aspen forests in the Prairies, since forests tend to respond more slowly to moisture deficits than do most crops.

The drought indices that had the greatest acceptance for monitoring drought in arid and semiarid regions of Mexico were SPI and PNP, according to the CEC survey [43]. As in the tropical climate regions, the lack of information for calculating other indices has caused these indices based on precipitation alone to be selected as the best for short and long-term drought monitoring.

S-4.3. Temperate (C) Climates

The temperature and precipitation characteristics of C climates are favorable for agriculture [46,70]. While favorable soils and other factors are important for agricultural production, it is not a coincidence that the world's major food-producing regions (U.S. Midwest and Canadian Prairies, Brazil and Argentina, northwestern Europe, Ukraine and southern Russia, eastern China) [71] are co-located with Cfa and Cfb climates as well as Dfa and Dfb climates. In North America, Temperate climates are located in parts of central Mexico, the west coasts of the U.S. and Canada, higher elevations in Hawaii, parts of the panhandle and southern coast of Alaska, and much of the southern Plains to Southeast in the U.S.

In the CEC survey, agricultural drought was rated as very important by a significant majority of respondents in the Cf (91%), Cfa (73%), and Cfb (63%) subzones. Across all subzones, agricultural drought was rated as important or very important by the highest percentage of respondents, although hydrological, meteorological, and ecological drought were also highly rated (Figure. 2, main article). Hydrological drought was more important than agricultural drought in dry summer Temperate climates and agricultural drought was consistently rated high in Temperate climates where the growing season coincides with climatological moist conditions. This could be related to agricultural practices. In dry summer (s qualifier) Temperate climates, agriculture is typically irrigated, whereas in Temperate climates with climatologically adequate moisture during the growing season (f and w qualifiers), agriculture is typically rain-fed and drought conditions during the normally wet growing season can significantly impact crops and forage production. The typical length of a drought varied, depending on the climate subzone. In general, the majority of CEC survey respondents indicated a typical drought lasts less than 6 months in the Cf and Cw subzones and longer than 6 months in the Cs subzones, although there were exceptions [43].

Half or more of the CEC survey respondents rated lower water levels in reservoirs, lakes, and ponds as a very important impact across most of the C climate subzones. Destruction of crops and forage is an important impact in those C climate subzones (w and f) where agriculture is typically rain-fed. More wildfires have an important impact in especially dry summer Temperate climate subzones.

Regarding performance of the drought indicators, in the aggregate, the response indicated that the indices and indicators generally did not work well across geographies and seasons in most Temperate climate subzones [43]. Half or more of the CEC survey respondents rated the USDM, PNP, SPI, and SPEI highly (effective or very effective) for short-term drought across all or most of the Temperate climate subzones [43]. Several remote sensing indices (Evaporative Stress Index [ESI], NDVI, VegDRI, and Water Requirement Satisfaction Index [WRSI]) were effective or very effective for monitoring short-term drought in several climate subzones. The SPI was highly rated for monitoring long-term drought in most climate subzones, with the USDM highly rated in several subzones [43]. Several indices and indicators not included in the WMO Handbook were highly rated for monitoring drought in Temperate climates [43]. At the top of the list were crop status, soil moisture, reservoir storage, and streamflow, plus vegetation greenness, reflecting the importance of agriculture in these regions.

The Alaska Panhandle is a temperate rainforest [42]. Commercial annual agriculture is limited, there is a high dependence on natural resources from forests, and reservoirs are crucial for hydropower, so hydrological and ecological drought are of major importance

for this region. Key drought indicators are streamflow, SPI, soil moisture, and PDSI. Drought impacts include harm to wildlife, forest health, and fisheries; reduced tourism and water supply for hydropower; and reductions in the availability or suitability of subsistence foods and materials. Melting of high-elevation snowpack is an important water source, so “snow drought” results in significant impacts.

In the Hawaiian Islands, the tallest peaks on the islands of Maui and Hawaii reach just above 3 and 4 kilometers, respectively. As a result, the temperatures in the higher elevations are significantly cooler than the lower elevations and are considered to be temperate rather than tropical. These zones also straddle the typical trade wind inversion level, so the air can be quite dry compared to the humid marine layer in the lower elevations well below the inversion. Vegetation can be sparse with the treeline at about 2.4 kilometers, and there are few permanent residents in these zones. Drought can be significant at times in these temperate zones with impacts mostly affecting the agricultural sector. There are also ecological drought impacts due to the presence of several threatened or endangered species. Since these temperate areas are more sparsely occupied, there are fewer precipitation gauges to use for drought indices. While SPI, precipitation percentiles, and percent of normal values provide useful information, remotely sensed indicators such as NDVI and Vegetation Health Index (VHI) provide the best spatial coverage and are needed to fill gaps in the precipitation data coverage.

S-4.4. Continental (D) Climates

By definition, of all of the climate types, Continental (D) climates have subzones whose temperature potentially ranges from the warmest summers (qualifier a) to coldest winters (qualifier d), thus making them typically the climate zone that has the largest range of seasonal temperature variations. Continental climates are located in the U.S. from the central and northern Plains to Northeast, across parts of the Northwest, and in much of Alaska; across most of Canada south of the Arctic Circle; and in areas of higher elevation.

As noted earlier, some of the world’s major food-producing regions (U.S. Midwest and Canadian Prairies, Ukraine and southern Russia, northern parts of eastern China) [71] are co-located with Dfa and Dfb climates. Half or more of the CEC survey respondents rated meteorological, hydrological, and agricultural drought as very important in several D climate subzones. Agricultural drought was consistently rated as the most important type of drought in the warmer a and b subzones, which is where D climate agriculture is common (U.S. Midwest and Canadian Prairies). Meteorological drought was consistently the most important type of drought in the d subzone, which is the D climate with the harshest and coldest winters. Socioeconomic drought was rated most important in the Dwc climate subzone, which subzone is typical of southeast interior Alaska. Half or more of the respondents rated destruction of crops and increased ranching costs for animal feed and water as very important impacts across most D climate subzones, indicating the importance of agricultural concerns. Concern over more wildfires was significant in just over half of the D subzones. Social (human mental and physical health) and environmental (threat to wildlife) impacts were of significant concern to those in the colder (c and d) subzones.

In the CEC survey results, the typical length of a drought varied, depending on the climate subzone. An overwhelming majority of respondents indicated a typical drought lasts less than 6 months in the Dfa and Dfb subzones, which are located primarily from the central and northern Plains and U.S. Northeast into southern Canada and coincide with primary agricultural regions. North of these areas, much of Canada is in the Dfc subzone where respondents indicated droughts typically last more than 6 months.

Regarding performance of the drought indicators, in the aggregate, the response indicated that the indices and indicators did not perform well geographically in virtually all of the D subzones. The survey response indicated that the indices did not perform equally well across seasons in most of the subzones, with the response significantly high in the Dfa (75%), Dfb (79%), Dfc (67%), and Dsa (75%) subzones.

More than half of the respondents said the indices did perform equally well across seasons in the Dsc, Dwc, Dwd, and Dfd subzones. It seems the respondents tend to think the indices and indicators don't perform well across seasons in the warmer D climate subzones but they do in the colder D climate subzones.

The CEC survey responses indicated that half or more of the respondents rated the USDM highly for short-term drought across most of the Continental climate subzones, with SPI, SPEI, and PNP so rated for about half of the subzones [43]. For long-term drought, half or more of the respondents rated the USDM highly in almost all of the subzones, while half or more of the respondents so rated SPI, SPEI, PNP, and the PDSI for about half of the subzones [43]. Several indices and indicators not included in the WMO Handbook were rated highly for monitoring drought in Continental climates [43]. At the top of the list were crop status, soil moisture, and precipitation percentiles, which were so rated by half or more of the respondents in all D climate subzones. Reservoir storage, streamflow, precipitation and temperature departures from normal, water use (demand), and vegetation greenness were so rated in most of the subzones. These indices and indicators are commonly used for monitoring agricultural and hydrological drought.

Agriculture is not a large industry in Alaska and is generally done on small-scale farms, so agricultural impacts from drought are not much of a concern in the state, but summer drought can decrease water levels in streams, hindering mobility in rural areas where rivers are a major avenue of transportation, and can increase the potential for wild-fire activity [72]. Two features complicate drought monitoring in Alaska. The first is permafrost, which acts as a boundary between surface soils and groundwater beneath the permafrost layer. During the winter, surface soils freeze, but during the summer, the surface soil layer ("active layer") thaws and will be wet even if it doesn't rain due to melting of snow and the ice in the soil (especially early in the warm season and in southern areas). The active layer can dry out later in the warm season, particularly in the interior where summer temperatures and evaporation are highest. The second complicating feature is glaciers. Low streamflow usually indicates drought, but this is regionally and seasonally dependent. During a summer warm/dry spell, melting of glacial ice will result in above-normal streamflow in glacier-fed streams, but clear-water streams (those fed by snowmelt, rainfall, and groundwater) will have below-normal streamflow after the mountain snowpack has melted. During a wet/cool spell, streamflow will be above normal in clear-water streams but below normal in glacier-fed streams.

Alaska, like most high-latitude D climates, enters a deep freeze during winter, so the drought status that develops during the warm season becomes locked in place during the cold season. The February 2020 Alaska workshop (see section S-1 for details of the user engagement workshops) identified the following drought indicators as appropriate for Southcentral and southern Interior regions of the state:

- Mountain snowpack SWE percentiles during spring (March-May).
- Wildfires during the warm season (May-August).
- Streamflow percentiles during the summer to early fall (June-October), but they should be used with other indicators (such as fish die-offs) due to complications caused by glacial melt.
- SPI and SPEI during the summer and early fall (June-September).
- Satellite-based soil moisture and vegetative health indices during the summer if they are consistent with other indicators.
- Ephemeral ponds supplied by groundwater/permafrost. Ephemeral ponds and wells are at their lowest point in March and April before springtime melt. If these ephemeral ponds dry out and don't refill in summer and fall, then that could be a drought indicator or impact (but complicated by microscale changes, e.g., ponds rapidly draining due to terminal permafrost thaw below the pond).
- If temperatures in the summer are well above normal, the Evaporative Demand Drought Index (EDDI) can be used in conjunction with SPI (high evaporative demand with low precipitation).

Ecological drought was identified at the September 2015 and February 2020 Alaska workshops as most important, with hydrological and socioeconomic drought also flagged at the 2020 workshop as important. Drought impacts that were noted during the 2020 and 2021 Alaska workshops include the following. A deep snowpack is beneficial for forests as it provides snowmelt infiltration as well as insulation against freezing air-temperatures, thus protecting tree roots (this is an issue in parts of Southeast Alaska but not a concern in the boreal forest). A lack of snow cover can have a variety of socioeconomic impacts. No snowpack in the fall can result in frozen pipes (especially on the North Slope) (if there is a cold outbreak because most infrastructure is above ground due to permafrost) and in the winter affects transportation as many Alaskans, especially those in remote villages, use snowmobiles for transportation. Reduced snowfall in the winter, as well as low precipitation during the spring and summer, can result in poor berry production (berries are an important food source for Alaskans). Low streamflow can affect fish hatcheries, habitat, and migration, resulting in salmon die-offs. (Salmon have a great cultural significance as a source of identity as well as being a source of food, a major industry, and important for tourism.) Low rivers disrupt water transportation. Low ground water recharge results in reduced water supply for some people (especially homeowners who have little water storage capacity and for whom streams or rivers are their primary water source). As lakes and ponds that are supplied by thawing permafrost dry up, waterfowl ecology and hunting would be impacted. Southern locations in Alaska, where permafrost is not present, have shallow wells for water supply; during droughts, these shallow wells can go dry.

Much of Canada lies within the D climate zone (primarily Dfb and Dfc) and, with the exception of a few agricultural regions in the south (interior British Columbia, southern Canadian Prairies, southern Ontario/Quebec, the Atlantic Provinces), the majority of this area is covered by boreal forest. It then transitions to tundra and eventually, the E climate zone. Monitoring issues are similar to those described above including the lack of stations in most of northern Canada, making drought monitoring especially difficult. In fact, the Yukon and Northwest Territories were only very recently added to the Canadian Drought Monitor and Nunavut is not yet included.

Quiring and Papakryiakou [73] noted that crop growth is highly dependent on short-term moisture conditions, and potential and actual evapotranspiration are also important variables in determining crop growth. They determined that Palmer's Z Index is a better index than the PDSI, SPI, and NDI for measuring agricultural drought in the Canadian prairies. They added that choosing the most appropriate measure of agricultural drought is particularly difficult because the answer will vary depending on the crop, the study region, and the spatial scale of the intended application.

Peña-Gallardo et al. [74] assessed the effectiveness of several drought indices for monitoring agricultural drought impacts for different crop types at the regional level in North America (specifically the agricultural regions of the U.S. which are found in the D climate zone). They found that determining the best-suited drought index for a specific crop region is particularly difficult since the response to drought varies depending on the crop's sensitivity to moisture shortage and the environmental characteristics of the study region. Their general conclusions:

- The response of the crop to drought indices shows strong seasonality.
- In general, the moisture conditions during the summer are an important determinant for barley, corn, cotton and soybean yield. Summer months correspond to heading and reproductive stages of these crop types, and in these stages, the plants would be more sensitive to water stress.
- On the contrary, winter wheat showed a higher sensitivity to drought conditions during the spring, which corresponds to the period when winter wheat is more sensitive to water availability.
- Moisture conditions during shorter timescales (1 to 3 months) were more important, except for winter wheat.

- Generally, and independently of the crop type, the SPI, SPEI and Standardized Palmer Drought Index (SPDI) showed the highest correlations with crop yield.
- The Palmer Drought Indices generally did not have statistically significant correlations with yield, regardless of the month of the year. However, among the Palmer drought indices, the Z-Index was shown to be more responsive to crop yields.
- Crops associated with high vapor pressure deficits are more sensitive to atmospheric evaporative demand, so drought indices based on both precipitation and the atmospheric evaporative demand (SPEI and SPDI) seem to better quantify drought severity in comparison to the SPI.

Three other studies published in the literature are relevant to the discussion of drought in D climates. The first, an Arctic Climate Impact Assessment [75], studied boreal forests in the D climate zones of Asia and North America and discussed the impact of drought on the dominant tree species. The study's observations:

- In Siberian forests from the southern edge of the Central Asian steppe (grassland) to the treeline in the north, especially in the southern part of this area, drought is the major factor limiting tree growth; cool wet growing seasons produce the most growth.
- In the dry regions of central Alaska and western Canada, high summer temperatures decrease the growth of white spruce when combined with drought (see also [76]).
- On drier permafrost-dominated sites in interior Alaska, the growth of black spruce decreases with increasing summer temperatures. At the upper ranges of projected warming for this century, it is not likely to survive on these sites due to drought conditions.
- Hot, dry summers stress the trees, reducing their growth reserves, which make them more susceptible to attack from pests such as spruce bark beetle and spruce budworm.

The second study, a survey article by Churakova Sidorova et al. [77], noted the importance of precipitation and permafrost-thawed water during the summer for healthy trees growing in arctic continental climate conditions like those found in Siberia (climate subzones Dwd and ET). Rising temperatures in arctic regions result in permafrost degradation and may lead to drought stress by increasing evapotranspiration and the associated atmospheric vapor pressure deficit (VPD). They emphasized that ecological drought is a concern as the enhanced VPD, as well as wildfire-induced changes in the active soil layer depth, negatively impact forest ecosystems.

In the third study, Van Loon et al. [78] analyzed hydrologic drought types in the cold climates of Austria and Norway. They defined two new drought types related to snow and ice: *snowmelt drought*, which is a deficiency in the snowmelt discharge peak in spring in snow-influenced basins, and *glaciermelt drought*, which is a deficiency in the glaciermelt discharge peak in summer in glacierised basins. They determined that *snowmelt droughts* in Norway were mainly controlled by below-average winter precipitation, while in Austria both temperature and precipitation played a role, and for *glaciermelt droughts*, the effect of below-average summer air temperature was dominant, both in Austria and Norway. They analyzed drought impact reports and found that these drought events mainly impacted hydropower production and crop yield in various countries in Europe.

S-4.5. Polar (E) Climates

In North America, Polar (E) climates are located in northern parts of Alaska, the Canadian far north, and higher elevations in the western U.S. and western Canada. More than half (60%) of the CEC survey respondents indicated a typical drought lasts more than 6 months in the ET climate subzone. Loss or destruction of fish and wildlife habitat, and destruction of crops, were the most highly rated drought impacts by most respondents in both E subzones. In Alaska's ET climates, subsistence agriculture (i.e., gathering of wild

foods such as berries and roots) and hunting of wildlife are a major part of the food resource, which accounts for the importance of these economic and environmental impacts. Regarding performance of the drought indicators, in the aggregate, the majority of the ET subzone respondents indicated that they do not perform equally well across seasons but were split 50/50 in geographical performance.

The CEC survey responses for the ET subzone rated the USDM highly (effective or very effective) for both short-term and long-term drought. Of the indices and indicators not in the WMO Handbook, more than half of the respondents in the ET subzone rated the following indicators highly: groundwater depth, precipitation departures from normal, precipitation ranks, reported drought impacts, soil moisture, streamflow, vegetation greenness, and water use (demand). With subsistence agriculture important in E climates, crop (e.g., berry) status, soil moisture, and vegetation greenness are appropriate indicators to use. Vegetation greenness in tundra climates is more likely to reflect temperatures than precipitation, though other factors can be important, e.g., active layer, vegetation damage from winds during low snow winters, etc.

Drought impacts that were noted during the 2021 Northwest Alaska workshop include concerns for public health, food security/economy, and conservation. Low streamflow leads to rapid heating of the stream water and the resulting heat stress on salmon, combined with low oxidation, can result in massive die-off as well as algal blooms. Harmful algal blooms can lead to toxins accumulating in fish and shellfish resulting in a contaminated (toxic) food sources for humans and wildlife. Impacts on the ecosystem are very important as berries, salmon, and wildlife (e.g., moose) are a huge food resource in northern Alaska. While trees are rare in ET environments, tundra can burn and wildfires have a significant impact. Other impacts are similar to those experienced in the Alaska D climate zone. Indigenous knowledge is crucial, especially where instrumental data is sparse.

In Canada, the majority of the E climates are not currently monitored, so little information is available.

S-5. Review of Published Objective Research

This section contains a review of some of the existing research that has objectively evaluated the effectiveness of drought indices and indicators in specific climate zones and applications. The discussion is roughly grouped by type of indices.

S-5.1. Remotely-Sensed Indices

Anderson et al. [83] found that vegetation cover condition, as sampled by remotely sensed shortwave vegetation indices, is a relatively slow response variable, typically adjusting only after notable crop damage has already occurred. Remote sensing indices based primarily on vegetation cover condition include VegDRI. On the other hand, land surface temperature is a rapid response variable, so evapotranspiration-based indices derived from remotely-sensed land surface temperature data may be uniquely sensitive to rapidly changing conditions related to flash drought. Drought indicators based on remotely-sensed land surface temperature or evapotranspiration include the VHI and ESI. Otkin et al. [84] found the ESI to be effective in detecting rapidly-evolving agricultural drought situations (flash drought). Anderson et al. [83] note, however, that under conditions of energy-limited vegetation growth (high latitudes and elevations and during the winter/early spring), temperature and vegetation cover can be positively correlated, yielding a false drought signal in the VHI. Of the remote sensing indices, ESI shows the strongest signal (is most strongly correlated with USDM), outperforming the VHI, over much of the contiguous U.S. (CONUS), particularly in the central USA (central Corn Belt, in northern Iowa and southern Minnesota) [83]. VHI and SPI show the largest degradation in spatial consistency with other indicators during the winter months. AghaKouchak et al. [82] referenced studies that show that vegetation water indices outperform vegetation greenness indices (including the Enhanced Vegetation Index [EVI]) in high biomass ecosystems and that the Scaled Drought Condition Index (SDCI) outperformed the VHI and

NDVI over both arid (Arizona and New Mexico) and humid/subhumid (North Carolina and South Carolina) regions.

Three relatively new indices that have been developed to monitor soil moisture using orbital sensors are included in this discussion. These were not evaluated by the CEC respondents but are being used in the production of the national Drought Monitors and NADM. They include the GRACE (Gravity Recovery and Climate Experiment), SMOS (Soil Moisture and Ocean Salinity), and SPoRT products. Since GRACE has the unique ability to sense water stored at all levels (including groundwater), globally, systematically and continuously, three drought-monitoring products have been developed: surface soil moisture, root zone soil moisture, and groundwater storage [85]. Houborg et al. [85] demonstrated that incorporation of GRACE data improved soil moisture estimates, especially in the eastern CONUS. McDonough et al. [86] evaluated the soil moisture product (SPoRT-LIS) produced by the Short-term Prediction Research and Transition (SPoRT) Center and determined that the SPoRT-LIS surface soil moisture estimate is satisfactory for operational water resources management applications such as drought monitoring; Tavakol et al. [87] concluded that the SPoRT-LIS product performs best in the eastern U.S. and in the warm season. Ma et al. [88] noted that newer versions of SMOS (i.e., SMOS-IC) performed better than earlier versions (e.g., SMOS-L3), and SMOS performed well for drought monitoring in temperate and cold climate regions, but SMOS (and other satellite-based soil moisture products, such as SMAP [Soil Moisture Active Passive] and AMSR2 [Advanced Microwave Scanning Radiometer]) did not perform as well in tropical and desert regions. In summary, these three soil moisture drought indicators (GRACE, SMOS, SPoRT) show promise during the warm season. Other satellite-based soil moisture products, not discussed here, were evaluated by Beck et al. [89].

S-5.2. SPI, SPEI, and Percent of Normal Precipitation

In a study comparing drought indicators used in tropical, arid, and temperate climate zones in Africa, Naumann et al. [90] determined that, overall, dry periods measured with SPEI tend to be 1 or 2 months more persistent when compared with SPI and SMA.

Vicente-Serrano et al. [91] analyzed the sensitivity of four drought indices (PDSI, Reconnaissance Drought Index [RDI], SPEI, SPDI, where SPDI is the Standardized Palmer Drought Index developed by Ma et al. [93]) to precipitation and reference evapotranspiration inputs using global datasets. They noted that “Ma et al. (2014) argued that SPEI responds differently to temperature and precipitation variations for diverse climatic conditions, and indicated that this would challenge the spatial consistency and comparability of the SPEI.” They concluded that “the SPEI shows different sensitivity to P [precipitation] and ETo [reference evapotranspiration] as a function of the climatology. In semiarid regions the SPEI shows high contribution of ETo to drought severity. On the contrary, in humid areas, characterized by high P, drought variability is mostly determined by changes in P.”

Dai [51] noted that SPI and Deciles do not consider evapotranspiration. The importance of this was discussed by Ellis et al. [94] when they described the shortcomings of using the SPI for monitoring drought in the arid climate of the Colorado River Basin, USA: the SPI only considers one-half of the hydrologic equation, ignoring the temperature-driven climatic demand for water (potential evapotranspiration, PE). This is a critical problem in climates with an extremely warm summer season, during which evaporative loss can dominate the hydrologic budget despite significant precipitation. It is also problematic in climates characterized by months that are reliably arid, such that a single-precipitation event can dominate monthly SPI calculations. In such climates, summer precipitation is much less ‘effective’ than cooler winter season precipitation for replenishing soil moisture and water supplies. Furthermore, by not representing the loss of water to the atmosphere, the SPI cannot account for the impacts of climate change in the form of atmospheric warming.

This was also discussed by White and Walcott [95] who point out that the SPI is more suited to monitoring meteorological and hydrological droughts rather than agricultural drought. They note that, “indices based solely on rainfall data by definition take no account of other factors, in particular air (or ambient) temperature, humidity, wind speed, net radiation and evapotranspiration, deep percolation, runoff, soil type, or agricultural enterprise. Our operational experience in assessing droughts throughout Australia is that factors such as these can dramatically influence plant growth in unexpected ways and therefore need to be taken into account.” They conclude that “no one index is sufficient for assessing the effectiveness of rainfall and agricultural droughts.”

Wu et al. [96] warn that the length of record used to compute the SPI can have a significant effect on the computed values, so a consistent period of record should be used for spatial comparisons. This is basically true for all computed drought indices.

Based on a qualitative evaluation, Quiring [97] concluded that the SPI and deciles/percentiles are the most highly ranked meteorological drought indices when compared to the PDSI, Palmer Z Index, EDI, and percent of normal precipitation. He noted, however, that SPI and deciles/percentiles have difficulty with arid locations that have seasons/years that receive no precipitation; the main drawback of these indices is that they consider only precipitation (atmospheric moisture supply) and not evapotranspiration (atmospheric moisture demand). He also pointed out that percent of normal precipitation is not a robust measure of drought conditions: that is, percent normal cannot be used to compare drought conditions over space or time. For example, 50% of normal in Phoenix, Arizona [an arid climate], has a much different meaning than 50% of normal in Miami, Florida [a humid climate]. Similarly, 50% of normal precipitation in January may have a much different meaning than 50% of normal in July. This limitation with using percent normal (or departures from normal) is one of the main reasons that so many drought indices have been created.

Homdee et al. [98] determined that evapotranspiration-based indices (the SPEI and Standardized Precipitation Actual Evapotranspiration Index [SPAEl]) were better able to detect the temporal variability of droughts than the SPI in the tropical monsoon climate of northeast Thailand. They found that climatic water demand had important aspects in determining the drought conditions for this area. They point out that, if the SPI is used, “the interpretation and utilization of the SPI over the tropical monsoon region with distinct seasonal precipitation should be carefully carried out to avoid any misleading interpretations when being applied to the short timescale. Short time scales (1-3 months) may detect simply dry spells in the summer monsoon season in this region which may not cause damage to agricultural fields. Longer timescales of the SPI (> 12-month SPI) are able to broadly identify the characteristics of drought durations with the exception of their intensity level.”

Faiz et al. [99] point out that, while previous studies have documented that SPEI can be efficiently used for agricultural drought tracking, in colder regions where winter temperatures are mostly below zero and potential evapotranspiration is essentially zero, the application of SPEI is not suitable.

Vicente-Serrano et al. [92] note that precipitation and evapotranspiration-based indices, such as the sc-PDSI (Self-Calibrated PDSI) and SPEI, better reflect drought conditions than the precipitation-based SPI under global warming processes predicted by global circulation models (GCMs) because temperature is not considered in the SPI calculations but is in the sc-PDSI and SPEI computations. They further recommend that the SPEI should be used in preference to the sc-PDSI because of its simplicity, lower data requirements, and multiscalar properties.

Although the SPI is commonly acknowledged to characterize meteorological drought, the different time scales that it can be computed for allow its use to assess the effects of precipitation on different water-resource components such as soil moisture and streamflow [100]. A similar statement could be said about the utility of the multiple time scales of the SPEI.

Vicente-Serrano et al. [81] compared the performance of the SPI, SPEI, and four versions of the PDSI for monitoring drought impacts on several hydrological, agricultural, and ecological response variables (streamflow, soil moisture, forest growth, and crop yield). (The four versions of the Palmer Index are the self-calibrated version of the traditional PDSI, the Heddinghaus and Sabol modification of the PDSI [5], the PHDI, and the Palmer Z Index.) The comparative analysis was done globally using a gridded database. They concluded that the SPEI and SPI were superior to the PDSI because they are computed on multiple time scales, “but the SPEI was the drought index that best captured the responses of the assessed variables to drought in summer, the season in which more drought-related impacts are recorded and in which drought monitoring is critical.”

In the arid climate of Colorado, negative values of the SPI are more significant during the wet season than during the dry season [66].

The importance of the seasonality of precipitation was also noted by Hoell et al. [101]. They found that droughts in the northern Great Plains of the U.S., which has a distinct dry (winter) and wet (summer) season, generally last longer than in the Ohio Valley, which experiences precipitation throughout the year. Droughts in the northern Great Plains begin and end only during the warm and wet season while droughts in the Ohio Valley can begin and end during any time of year. Due to the distinct dry season in the northern Great Plains, there is a higher likelihood of longer drought persistence, as the northern Great Plains is four times more likely to experience drought lasting at least one year compared to the Ohio Valley.

In their Table 3, Yihdego et al. [15] summarized typical applications of the different time scales of the SPI. The short-term time scales (e.g., 1-month SPI) are used for evaluating soil moisture and crop stresses, while long time scales (e.g., 12-month SPI) have been tied to streamflow, reservoir, and groundwater levels. They also noted that 9-month SPI values less than -1.5 could indicate substantial impacts in agricultural areas.

Stefanidis et al. [17] analyzed SPEI data from a Mediterranean oak forest. They determined that, at shorter time scales (3 and 6 months), the SPEI was more sensitive and more efficient for identifying more frequent short-length drought events, while longer time scales (12 and 24 months) were more effective at detecting longer-lasting drought episodes.

Chen et al. [102] analyzed SPEI data for the temperate steppe region of China. Their results indicate an overall trend of worsening drought over the period 1960-2020, and that drought characteristics differed from the relatively humid meadow steppe to the semi-humid and arid zones.

Chong et al. [103] compared SPI and SPEI data for two states in Malaysia. Since the country is located near the equator and experiences minor fluctuations in climatological temperature, they found little difference between the SPI and SPEI, but they recommend that the SPEI be used when temperature rises become evident. They analyzed the SPI data using wavelet transforms to assess the spatiotemporal variation of drought.

Stagge et al. [16] analyzed four impact types, spanning agriculture, energy and industry, public water supply, and freshwater ecosystems, across five European countries using the SPI and SPEI. Europe is predominantly a C climate type. Their conclusions:

- Agricultural impacts are explained by 2- to 12-month anomalies, though anomalies greater than 3 months are likely related to agricultural management practices. Seasonality is important for agricultural drought.
- Energy and industrial impacts, typically related to hydropower and energy cooling water, respond slower (6–12 months).
- Public water supply and freshwater ecosystem impacts are explained by a more complex combination of short (1- to 3-month) and seasonal (6- to 12-month) anomalies.

S-5.3. Multi-Index Comparisons

Keyantash and Dracup [21] evaluated 14 drought indices for their two test regions in Oregon (in climate subzones Csa and Csb) according to 6 criteria. They found that Rainfall

Deciles and the SPI were the best drought indices for monitoring meteorological drought, Total Water Deficit was best for hydrological drought, and Computed Soil Moisture was best for agricultural drought. Other conclusions:

- The precipitation anomaly, which is the difference between the observation and a long-term climatological mean, “is not especially informative, since the importance of the anomaly depends on climate; a monthly deficit of 1 cm is substantially more significant for a desert ecosystem compared to a montane forest.”
- Minor amounts of precipitation during periods in which little or no precipitation is routine (e.g., summer along the USA West Coast) can trigger the termination of a drought, even though the absolute quantity of precipitation is trivial and does not terminate the water deficit. Therefore, climates with highly seasonal precipitation may not be well suited to rainfall deciles when used by themselves to indicate drought termination (or drought initiation). Precipitation percentiles suffer from the same weakness.
- The Drought Area Index (DAI) was developed specifically for the monsoon (Am) climate of India, but has been calibrated for other regions of the world, including the Dfa climate of Nebraska. Keyantash and Dracup [21] note that it requires only precipitation data, thus it addresses only the water supply side of the drought equation.
- Since the SWSI explicitly accounts for snowpack and its delayed runoff, Keyantash and Dracup [21] conclude that it is a suitable measure of hydrological drought for regions, such as the mountainous western U.S., where snow contributes significantly to the annual streamflow, and show that it is a consistent measure of hydrological drought conditions for their test regions in Oregon.
- Issues affecting the universal applicability of the PDSI are reviewed in Heim [5] and other papers referenced therein, including its treatment of all precipitation as rainfall (whereas snowfall may not be immediately available as water in the month it fell), using only temperature to estimate evapotranspiration, and methods of calibration. Some of these issues have been addressed by the Alberta modification of the PDSI [115], the self-calibrated PDSI [117], and computation of evapotranspiration using the Penman-Monteith method [51]. Dai [51] noted that the PDSI and PHDI do not work well over mountainous and snow-covered areas, but PDSI can be used as a drought index over the low and middle latitudes.
- The Palmer Z Index is preferable for quantifying agricultural drought than the more commonly used CMI because it responds quickly to changes in soil moisture values.

Wang et al. [104] evaluated the suitability of six drought indices in naturally growing, transitional vegetation zones in Inner Mongolia. The study area covered a 2400-km-long aridity gradient from forests to deserts. The six drought indices considered included the SPI, SPEI, MI (relative moisture index), Pa (precipitation anomaly percentage), K (Sielianow coefficient), and scPDSI. These indices were correlated against NDVI which was used to represent vegetation occurrence and health. Their conclusions:

- On an annual timescale, SPI and SPEI performed well in grasslands (steppes), with the SPI the most appropriate index in assessing drought in steppes and deserts.
- On a seasonal timescale, all of the drought indices performed best in summer and worst in the spring and fall in all vegetation zones, due to low temperatures, not available soil water, limiting vegetation growth during these seasons. The scPDSI displayed the greatest sensitivity during the summer, but not during the other seasons. On a monthly timescale, scPDSI demonstrated the greatest sensitivity to the various vegetation zones (i.e., forests, steppes, and deserts) in June and July. Further analysis indicated that summer

drought had a lag-effect on vegetation growth, which varied from one to 6 months according to the specific vegetation cover.

- The mixed response of drought indices to NDVI and the lag-effect in transitional vegetation on annual, seasonal, and monthly timescales were ascribed to differences in drought index definition and the dominant plant species within the transitional cover.
- The scPDSI, because it incorporates a soil water storage component, was regarded as the better measure of monthly drought across vegetation zones compared to the SPI, SPEI, Pa, and MI, which don't have a soil water storage component.
- All six of the drought indices performed weaker in forests across all time-scales because forests, located near mountain ranges, receive additional water from snowmelt, improving overall growing conditions for forests downslope. The deep roots of trees can access water from deep in the ground and large quantities of carbohydrates and nutrients stored in the roots can cause forests to be less vulnerable to severe, prolonged meteorological drought. In forests, water is normally not a limiting factor.

Other conclusions by Wang et al. [104]:

- At the annual time scale, SPI is the most appropriate to assess drought in steppes and deserts, followed by SPEI and Pa.

At the seasonal time scale, the scPDSI-index gave the best results for typical steppes, desert steppes, and deserts during the summer, followed by SPEI; SPI and SPEI were most appropriate for meadow steppes. None of the six drought indices considered were appropriate for forests.

Wanders et al. [22] examined how 14 drought indicators characterized drought in all 5 climate zones across the world. They found that, overall, the effects of hydroclimate and of properties of the groundwater system are more profound than changes in soil type. Their specific conclusions include:

- A challenge for all hydrological drought indicators using streamflow is to cope with no streamflow for part of the year. This readily leads to a very poor performance.
- In B climates, the SPI has trouble with fitting a gamma distribution through the low number of months with precipitation. In BW climates, where water is (almost) never available, soil moisture and hydrological drought indicators should not be used; in these regions, very deep groundwater storage is possible.
- In EF climates, all precipitation is accumulated as snow which will melt only when temperatures are above 0°C, which is very rare. Soil moisture is also heavily affected by the frozen soils in these climates. These locations (mostly situated at the poles and in Greenland) give rise to difficulties for all indicators, except for those which focus only on precipitation. So, streamflow and soil moisture drought indicators face difficulties in EF climates, where streamflow is (almost) absent due to average monthly temperatures which are always below 0°C.

Droughts in soil moisture are more likely to occur in sandy soils than in loamy soils, for a fixed threshold.

In their global analysis of four drought indices (PDSI, RDI, SPEI, SPDI), Figure 9 of Vicente-Serrano et al. [91] showed that the highest correlations of SPEI and RDI with precipitation occurred in Mexico, the CONUS, and western and southern Canada. The highest correlations with reference evapotranspiration occurred from northern Mexico to the western CONUS and across western Canada. The lowest correlations with both precipitation and reference evapotranspiration occurred over parts of Alaska and northern and eastern Canada (boreal regions of North America). Low correlations with reference evapotranspiration also occurred in equatorial regions.

In a study to quantify the time taken for drought to evolve from precipitation deficits to deficits in soil moisture or streamflow, Gevaert et al. [105] determined that drought propagation is strongly related to climate type. They concluded that 1) droughts propagate slower in dry and continental climates and quicker in tropical climates, and 2) winter season drought propagation tends to be slower than in the summer, especially in tropical savanna and continental climates.

S-6. The Köppen Climate Classification System

The five major Köppen climate types (A, B, C, D, and E) are defined mathematically [46] and described below:

- Tropical climates are warm year-round (long-term average monthly mean temperature of the coldest month is at least 18°C [64.4°F]), with precipitation falling as rain. The year-round warmth results in high evaporative demand throughout the year, especially in low-latitude regions such as the USAPI. Reductions in rainfall, therefore, are the primary cause of drought.
- Dry climates are characterized by long-term average annual precipitation (P ; water supply) that is less than the long-term average annual potential evapotranspiration (PET; atmospheric water demand), with Köppen's mathematical threshold based on formulae relating P to long-term average annual temperature (T).
- Temperate (C) climates lie in the temperature range between Tropical and Continental climates and are defined mathematically as having the long-term average temperature of the warmest month $> 10^{\circ}\text{C}$ (50°F) and the long-term average temperature of the coldest month between 0°C and 18°C (between 32°F and 64.4°F).
- Continental (D) climates are defined mathematically by Köppen as having the long-term average temperature of the warmest month $> 10^{\circ}\text{C}$ (50°F) and the long-term average temperature of the coldest month $\leq 0^{\circ}\text{C}$ (32°F), which thus makes them typically the climate zone that has the largest range of seasonal temperature variations.
- Polar (E) climates are the cold climates of the world, typically located at or near the North and South Poles and defined mathematically as having the long-term average temperature of the warmest month $< 10^{\circ}\text{C}$ (50°F).

The five Köppen climate types are divided into subzones designated by secondary and tertiary letters (descriptive names associated with each subzone are listed in Table S1 in section S-2):

- Tropical (A) climates are subdivided into three types, depending on seasonal variations in rainfall: Af, Am, and Aw. Af climates are Tropical Rainforest climates with wet conditions year-round. Am climates are Tropical Monsoon climates with seasonally excessive rainfall. Aw climates are Tropical Savanna climates with a pronounced dry season (usually winter).
- Dry (B) climates are subdivided into four types based on magnitude of dryness and the long-term average annual temperature. BS (semiarid or steppe) climates have P below the threshold but more than half the threshold amount, while BW (arid or desert) climates have P below half the threshold amount. T is used to further classify the subzones into h (hot or tropical) climates ($T \geq 18^{\circ}\text{C}$) and k (cool or cold, mid-latitude) climates ($T < 18^{\circ}\text{C}$). BSh are tropical steppe climates, BSk are mid-latitude steppe climates, BW h are tropical desert climates, and BW k are mid-latitude desert climates.
- Temperate (C) and Continental (D) climate subzones are defined by seasonal variations in precipitation and extremes in temperature and have the following qualifiers: s (dry summers), w (dry winters), f (moist all seasons), a (long hot summer), b (warm summer), and c (short cool summer). Continental climates have an additional qualifier of d (average temperature of the coldest month $< -38^{\circ}\text{C}$ [-36.4°F]). The fully-qualified Temperate subzones are: Cfa,

Cfb, Cfc, Cwa, Cwb, Cwc, Csa, and Csb, and the fully-qualified Continental subzones are: Dfa, Dfb, Dfc, Dfd, Dwa, Dwb, Dwc, Dwd, Dsa, Dsb, Dsc, and Dsd. The CEC survey also included Cs, Cw, and Cf subzones.

- There are two Polar (E) climate subzones defined by temperature: ET (Tundra with very short summers), where the long-term average temperature of the warmest month is between 0°C (32°F) and 10°C; and EF (Ice Cap, perpetual ice and snow), where the long-term average temperature of the warmest month is 0°C or below. With temperatures so low year-round, the air is not able to hold much moisture and total precipitation amounts are typically low compared to most other climate zones, so there are no precipitation-based subzones for Polar climates.