

World Meteorological Organization; Commission on Agrometeorology

Expert Team 3.1 Report on Drought

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Prepared by the following members of WMO CAgM Expert Team 3.1:

Allan Howard
Lynette Biettio
Michael Hayes
Alexander Kleschenko
Karim Quevedo Caiña
Andreja Susnik

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Introduction:

The Expert Team on Drought (Expert Team 3.1) used a review of the current literature to address five Terms of Reference requested by the management Team of the World Meteorological Organization Commission of Agrometeorology (WMO CAgM) to address priority areas in weather hazard for agriculture arising from the 16th Session of the WMO CAgM held in Antalia, Turkey in April 2014.

The Terms or Reference for the CAgM Expert Team were:

- a. *Review the definition of drought. Conduct a comprehensive review of the definitions and phases of drought e.g. onset, duration, recovery and the 'end point' of drought in all regions.*
- b. *Identify case studies and conduct a literature review of the socio-economic impacts of drought for regions or countries with successful* mitigation and preparedness programs and policies.*
- c. *Report on existing material on likely drought changes under future climate variability and change*
- d. *Conduct a literature review of the climate science to identify the main mechanisms behind drought onset and persistence in order to develop guidance material for drought preparedness.*
- e. *Report and make recommendations to CAgM on existing drought indices and potential new drought indices in consultation with the Integrated Drought Management Programme (IDMP).*

A sixth Term of Reference; engage with the GEO groups on global drought information systems, NIDIS, and other relevant groups (incl. GEOGLAM, EDO, South Pacific Drought Group), and report on changes; was not directly included in this report. However where relevant, information arising from the engagement occurrences was considered in the preparation of this report.

The main conclusions of the report are presented in the recommendations to follow. Overall the report presents areas where the WMO and other organizations can focus activities to address gaps in understanding the characteristics and behavior of drought.

Recommendations:

It is the recommendation of this report that the WMO:

For TOR a: *Review the definition of drought. Conduct a comprehensive review of the definitions and phases of drought e.g. onset, duration, recovery and the 'end point' of drought in all regions.*

1. The definition of drought should apply to broad aspects of the condition in order to account for the several expressions of drought in the hydrologic cycle, the biosphere and in society.

2. The proposed drought lifecycle be adopted and the component terms be used as the basic hydrometeorological elements of a drought.
3. The definitions of the drought lifecycle in Table A-3 be adopted to provide more precise term for studying drought.
4. Adopt the definitions for operational types of drought presented in Table A-4. These proposed types are *meteorological drought*, *hydrologic drought*, *socio-economic drought* and to use *environmental drought* in place of *agricultural drought*.
5. Take steps to more clearly separate the definition and interpretation of drought from that of aridity. This may require creating criteria (e.g. change in frequency of droughts) to clarify the separation of drought from aridity.

For TOR b: *Identify case studies and conduct a literature review of the socio-economic impacts of drought for regions or countries with successful* mitigation and preparedness programs and policies.*

6. Drought socioeconomic impact metrics must to go beyond economic cost alone and consider the hardship of the people impacted by the drought. The WMO should promote metrics that factor in all socioeconomic aspects need to be used.
7. A systematic and comprehensive way to catalogue physical and socioeconomic data regarding water scarcity and drought is needed for effective planning.
8. The WMO should promote the advantages of drought planning and highlight how measures such as improved forecasting can have significant benefits for the national economy, to help dissuade the idea that drought planning is a cost of doing business.
9. A proactive approach to drought planning offers the best chance for building effective resiliency. The WMO should continue to ongoing policy development and planning in order to continuously evaluating a nation's changing exposure and vulnerabilities.

For TOR c: *Report on existing material on likely drought changes under future climate variability and change*

10. Given that under climate change the traditional view of drought as an episodic and rare event to whose future frequency and intensity is informed by historical variability may no longer apply in some areas, the WMO CAgM and the Commission on Hydrology (CHy) should continue to work together to develop an understanding of how changes in drought characteristics will influence future drought planning and preparedness.

For TOR d: *Conduct a literature review of the climate science to identify the main mechanisms behind drought onset and persistence in order to develop guidance material for drought preparedness.*

11. Exceptional events offer unique opportunities to improve our understanding of drought processes and associated factor such as heat waves as part of a changing climate. The WMO should continue to urge the stress that data from consistent weather and climate monitoring efforts are key to understanding how extreme events will impact society in the future.
12. The relationship between heat and drought persistence has not been extensively researched. The WMO should encourage research to better understand this linkage so that more effective

prediction and management of drought persistence can help mitigate impact of droughts and heat waves on society.

For TOR e: *Report and make recommendations to CAgM on existing drought indices and potential new drought indices in consultation with the Integrated Drought Management Programme (IDMP).*

13. The Handbook of Drought Indices (WMO and GSP, 2016) contains a comprehensive review of indices used in drought identification and monitoring across the globe. The Integrated Drought Management Committee of the WMO is encouraged to continue to keep the handbook updated to include new indices as they become tested and available for operational use.
14. The WMO should encourage the research of new drought indices that will provide information on drought in finer timescales in order to better detect and predict rapid changes in drought conditions.

For TOR f: *engage with the GEO groups on global drought information systems, NIDIS, and other relevant groups (incl. GEOGLAM, EDO, South Pacific Drought Group), and report on changes.*

15. The WMO CAgM is encouraged to continue to work with the GEO groups and others involved in drought monitoring to ensure that drought information is consistent across monitoring platforms and that drought information is integrated with agricultural monitoring to develop adequate early warning systems.

A. Definition of Drought.

Key Points:

- The review of the literature reveals that the definition of drought is used in ambiguous ways and more specific terms are presented in this chapter to clarify the meaning around the use of the term *drought*.
- The literature also points out that all droughts originate from a precipitation shortage and/or a failure to meet evapotranspirative demand and that this is a temporary phenomenon. This underpins all thinking about drought definitions.
- There are four types of drought referenced extensively in the literature. These are *meteorological drought*, *agricultural drought*, *hydrologic drought*, *socio-economic drought*. A new drought type, *environmental* also called *ecosystem drought* has been proposed.
- Drought different from aridity in that drought is temporary and after some time the moisture balance returns to a long term normal conditions whereas aridity means that there is a permanent drying taking place. Under climate change these differences can be blended together in cases where droughts occur with increasing frequency or have increased duration.

Introduction

Drought is widely recognized as a creeping natural hazard (Gillette, 1950) that occurs as temporary phenomena due to the natural climatic variability. Historically droughts have been a part of the evolution of human civilization. However the potential for droughts to increase in severity, frequency and/or duration as a consequence of climate change, coupled with the increasing demand for food and water resources caused by a growing population has raised questions as to how humanity will tolerate future droughts. This in turn raises questions as to how the global society can best approach the issues of drought preparedness and response.

Traditionally, drought response has been a reactive, crisis management approach (Wilhite and Pulwarty, 2005). This approach attempts to speed the recovery process, but can be costly, untimely, poorly coordinated, and often leads to increased vulnerability to future drought events due to the reliance on government and donor assistance. One example of the potential vulnerability generated by this approach is a case where the Government of Australia drought assistance eligibility criteria states that businesses “have the capacity to repay the loan and sound prospects for a return to commercial viability within the loan term”. The statement was included in order to minimize the risk of government assistance keeping non-viable businesses going (Australian Government, Dept. of Agriculture and Water Resources, 2017). More recently a turn from lessons learned to vulnerability assessment focusing on management and risk assessment has taken place. Proactive, risk-based approaches that feature preparedness and integrated planning and management are required to increase resilience to future drought episodes (reference needed). This paradigm shift to risk-based drought management requires a balanced set of national policy and governance guidelines, proactive drought preparedness plans and activities, and institutional coping capacities to ensure coordinated and effective contingency measures for the vulnerable sectors of society (IDMP reference).

Discussions arising at the UNFCCC CoP meeting in Warsaw in 2013 and Paris in 2015 have raised the question of Loss and Damage as a pillar under climate change (reference needed). Questions have been raised as to whether we have the information to adequately assess drought as a cause of loss and damage. This requires consideration not only the drought itself, but the potential for droughts to result in increased vulnerability to other extremes, exacerbating the loss and damage caused by flooding and other subsequent events. Given the understanding that drought and other climate and weather extremes are expected to increase in frequency and severity in our future climate (reference), this question becomes especially pertinent.

The Seventeenth Session of the World Climate Congress in May-June, 2015 resolved to standardize hazard and extreme event information, including the creation of a system of assigning a unique identifier to each event so that events can be catalogued and linked to data on associated damages and losses. Within this context lies the question that is the focus of this chapter, is (are) the existing definition(s) adequate to define and catalogue drought in terms of loss and damage?

Defining Drought

Drought can be considered as a natural hazard based on the notion that precipitation deficit leads to a water shortage and subsequent negative impact on an activity, group or environmental process (Wilhite 2000, White and Walcott 2009). Their characteristics and impacts are largely controlled by the hydrologic cycle are therefore they are not independent of factors such as temperature, wind speed, humidity, runoff, groundwater, soil moisture and snow, or human factors such as land and water management. Global warming will add heat to the hydrologic cycle which could become at least as important as precipitation in some regions in determining soil moisture and streamflow deficits (Cook et al, 2014).

It is well understood in the published literature that drought is a temporary phenomenon therefore a return to longterm “normal” conditions is expected. Drought is also a relative concept whose characteristics vary not only with geo-climatic regions, but also with economy, political policies and even with time. Droughts are generally perceived in context of an average or “normal” climatic condition when in reality climate variability is such that a normal condition is really a hypothetical average of variants and therefore is seldom is experienced. Also the length of measured climatic records is often not long enough to truly capture the long term variability, and consequently the frequency and nature of drought conditions in the historical record is not well understood. Also more recent droughts are more likely to have different impacts on the hydrologic and ecological systems as a result of both increased human activity and a changing climate.

Because of the complexity of the interactions of drought with the hydrologic cycle, there is a need to specify the component(s) of the hydrologic cycle affected by the water deficit and the time period associated with the deficit. The simultaneous occurrence of a long-term deficit in deep ground-water storage and a short-term surplus of soil water in the root zone is an example of the complexity

encountered in determining what exactly what is a drought (McNab and Karl, 2016). As a result, scientists therefore have only agreed on very general definitions of a drought.

Drought studies have been suffering from the lack of consistent methods for drought analysis. Analysis has been exacerbated by the “creeping” phenomena that make detection of the onset and the end-point of a drought difficult to detect. Often these factors are determined long after the drought event has finished. A definition has been considered a necessary first step a drought analysis (Hidalgo and Talleksen, 2000) and the lack of a universally acceptable definition adds to confusion about whether or not a drought really exists and if so, its degree of severity (Wilhite et al., 2014).

A further complication to arriving at a universally acceptable definition is that the term “drought” has been a common part of human culture for centuries and has been used commonly in language for centuries to describe a wide variety of meteorological, hydrological and agricultural conditions and impacts. Vogt and Somma (2013) identified drought terms that have been related to user impact including river flow drought, groundwater drought, climatological drought, operational drought and agro-meteorological drought. Drought has also been observed according to various impacts and expressions in landscape. Marchildon et al. (2016) pointed out that some farmers in the western prairie region of Canada used rainfall measurements whereas others used crop production and yet others used the depletion of standing water bodies (lakes, reservoirs, etc), all largely based on how current conditions related to past condition, as their way of determining whether they were in a drought. While these often corresponded well to droughts based on standard scientific indices, this was not always the case. To quote from Wilhite et al. (2005) “drought ... is largely defined by the beholder and how it may affect his or her activity or enterprise”.

Wilhite et al (2014) proposed that the concept of considering all types of droughts originate from a precipitation deficiency, originally put forward by Wilhite and Glantz (1985), be the underlying concept of drought while recognizing that other factors such as high winds, high temperature and low humidity levels could exacerbate drought characteristics.

Wilhite and Glantz (1985) found over 150 definitions of drought and grouped them into four basic perspectives of drought: *meteorological*, *agricultural*, *hydrologic* and *socioeconomic*. These terms have become widely accepted and are used as standard ways of identifying droughts for operational purposes based upon regional climatic differences, crop water requirements, duration, and human interactions. They argued that because drought affects so many sectors of society there is a need for multiple categories with their own definitions. They are not universally accepted however. Russian literature distinguished atmospheric and soil droughts, and a general atmosphere-soil drought (Loginov et al., 1976; Assessment report, 2008). In a comprehensive review of the literature Dai (2011) identified *meteorological*, *agricultural*, *hydrologic* drought as the common terms but did not mention *socioeconomic* drought.

Adler (2010) proposed a fifth model, *environmental* drought, acknowledging that healthy ecosystems are resources that provide valuable services and intrinsic value. Their vitality can also be impacted by

drought and effects can be compounded by an imbalance between ecosystem needs and socioeconomic needs during times of drought.

While the need for a single definition of drought has been identified to benefit analytical needs, the need for drought planning is different. In helping governments develop drought plans by use of science based actions to address key drought issues, the High Level meeting on National Drought Policy (WMO UNCCD and FAO 2013a, 2013b) stated that emphasis should be placed on integrated approaches for drought preparedness and mitigation (Sivakumar et al, 2014). Sheffield and Wood (2011) point out that drought impacts can be felt throughout the hydrologic cycle including for example, hazards to navigation and to hydropower generation, degradation of aquifers and water quality. This supports the concept of considering drought, the term, to be used in its broadest practical sense in order to ensure planning and mitigation measures are inclusive of all related issues and stakeholders.

Recognizing that the broader definition does not necessarily suit analytical needs, a different term based on the physical criteria or indices may both address the more specific analytical needs and help reduce confusion about the intent of definition of drought. Reference to criteria for physical indices, or *drought triggers*, would be a term that could be used to reference more precise aspects of drought whereas the *drought definition* would then be linked to broader concepts of drought.

Differentiating drought from other related phenomena

Several terms, including water shortage, water scarcity, aridity and desertification have been used in association with drought and even in some cases in place of drought. Pereira et al (2002) presented this context for discerning drought, water scarcity, aridity and desertification (Table A-1).

Table A-1. The nature and causes of water scarcity in dry environments. (Pereira et al, 2002).

	Short to mid-time scale; temporary	Long Time scale or Quasi- permanent
Naturally occurring	Drought	Aridity
Man-made	Water Scarcity	Desertification

In maintaining a context for defining drought the definition of associated terms must be clarified. Table A-2 presents for several terms often associated with drought. Some terms have multiple definitions associated with them therefore publications from authoritative agencies or refereed research were used to try to narrow the range to a single, or at most two, definitions.

Droughts, being temporary phenomena, differ from aridity, which is a permanent feature. They differ from seasonal aridity, a pronounced dry season. If the seasonal aridity occurs every year it is not a deviation from “normal conditions” and therefore not a drought (Wilhite et al., 2014).

Table A-2. A set of definitions for drought and some terms which are often associated with drought

Term	Definition
Aridity	Aridity, as defined by the shortage of moisture, is essentially a climatic phenomenon that is based on average climatic conditions over a region (Agnew and Anderson 1992). A fundamental distinction exists between aridity, which is a long-term climatic phenomenon and droughts, which are a temporary phenomenon (Maliver & Missimer, 2012)
Desertification	a) Desertification is land degradation in arid, semi-arid and dry sub-humid areas resulting from climatic variations and human activities (UNCED 1994) b) the irreversible change of the land to such a state it can no longer be recovered for its original use (FAO).
Land Degradation	a) the temporary or permanent decline in the productive capacity of the land” (UN/FAO) b) “the aggregate diminution of the productive potential of the land, including its major uses (rain-fed, arable, irrigated etc.), its farming systems (e.g. smallholder subsistence) and its value as an economic resource” (FAO)
Water Scarcity	A gap between available supply and expressed demand of freshwater in a specified domain, under prevailing institutional arrangements (including both resource ‘pricing’ and retail charging arrangements) and infrastructural conditions (FAO, 2012).
Water Scarcity (Absolute)	An insufficiency of supply required to satisfy total demand after all feasible options to enhance supply and manage demand have been implemented. This situation leads to widespread restrictions on water use (FAO, 2012).
Water Scarcity (Chronic)	The level at which all freshwater resources available for use are being used. Beyond this level, water supply for use can only be made available through the use of non-conventional water resources such as agricultural drainage water, treated wastewater or desalinated water, or by managing demand (FAO, 2012).
Water Shortage	A shortage of water supply of an acceptable quality; low levels of water supply, at a given place and a given time, relative to design supply levels. The shortage may arise from climatic factors, or other causes of insufficient water resources, a lack of, or poorly maintained, infrastructure; or a range of other hydrological or hydro-geological factors (FAO, 2012).
Water Stress	The symptoms of water scarcity or shortage, e.g. widespread, frequent and serious restrictions on use, growing conflict between users and competition for water, declining standards of reliability and service, harvest failures and food insecurity (FAO, 2012).

In what will be discussed further in Sections C and D, climate change is also causing changes in the patterns of rainfall leading to a climatic shift, where in some cases such as southwestern Australia or southern Europe, a shift to longterm drying. The beginning of such shifts can be conflated with drought, as the nature of the shift may appear as an increased frequency of drought events. Drought however is

episodic with a return to 'normal', whereas the regime shift results in a new 'normal', the understanding of which becomes highly important for planning purposes.

While the terms drought and aridity have distinctive definitions, few publications (e.g. Djebou, 2017; Borcan et al., 2015; Maringo and Bernesconi 2015; Dai 2011) have examined how to distinguish between changing drought characteristics (e.g. longer duration, increased severity, greater frequency) and a transition to aridity. To avoid confusion as to what is considered drought and what is considered a climatic shift toward aridity, this study will recommend that WMO investigate indices and triggers to differentiate more clearly what would be a transition to aridity.

The relationship between drought and the landscape, the ecosystem and society are very complex as each factor interacts with the other to change the degree of vulnerability and the nature and severity of impacts. This in turn adds considerable difficulty in providing a meaningful definition to drought. Wilhite et al. (2014) identify that proposing that a drought as *a deficiency of precipitation from expected or "normal" over a season or longer period of time that results in insufficient water to meet the demands of human activities and the environment* assumes that the demands of human activity are in balance with normal water availability. Cases where human demand for water exceeds supply even years of normal precipitation could result in human induced "drought". This would be referred to as *water scarcity*.

In cases from colder regions where streamflow results from a balance between rain and snowmelt, low streamflow levels during the late summer brought on by unusually warm condition during the previous winter which skewed the balance in favor of rainfall would not qualify as a drought. In this case the net precipitation has not been in short supply but the change from snowfall to rainfall has reduced snowpacks in the headwaters causing the level of runoff to decline abnormally fast through the early summer. This phenomenon even though temporary would be referred to as a *water shortage*.

The lifecycle of drought

Questions can also be raised regarding the onset and termination of a drought. For example, how long of a period of deficient precipitation is required to generate a drought? In humid area this may be a matter of days whereas in arid and semi-arid this could be a number of weeks due to the adaptation of the ecosystem and humans to the normally-sparse precipitation in these areas. In the case of delayed monsoon seasons, the overall seasonal rainfall total may not indicate a drought however the agricultural operations in that area can be disrupted by the delay. In the case of a termination of drought conditions, how much time should be given to the period of normal precipitation patterns in order for a drought to be considered as ended? Would a short term return to normal conditions followed by another period of precipitation deficiency be considered as two droughts or one?

One approach to examining the concepts of drought event, drought onset and drought demise was presented by Mo (2011) using monthly SPI and soil moisture values and an index. The drought event was described as the period of time when the index falls below the drought threshold for a specified duration, in this case more than three months. Drought onset commences in the month when the

index falls below the drought threshold and the drought demise begins the month when the index first rises above the threshold.

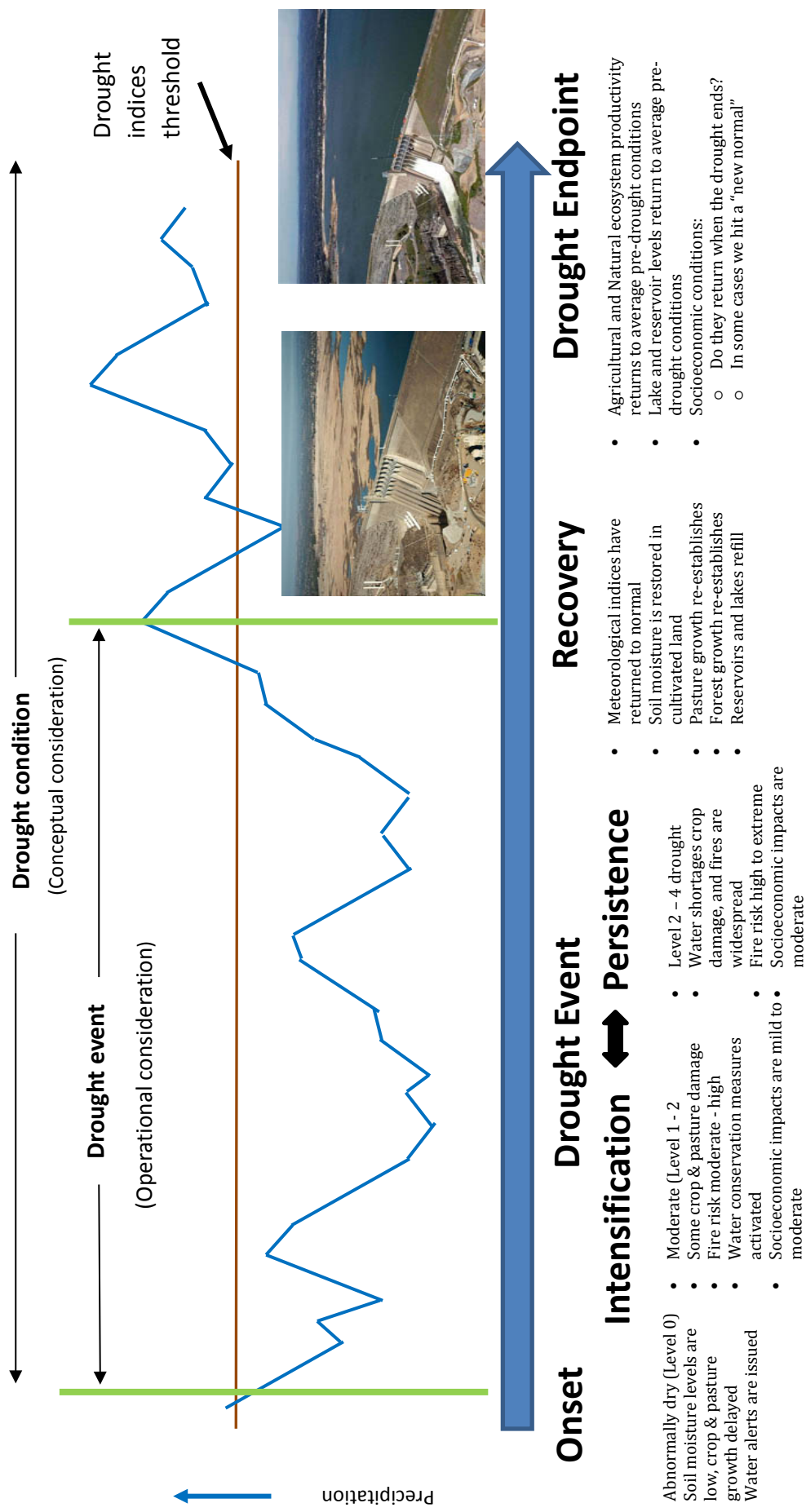
In examining a drought life-cycle, the drought event as presented by Mo (2011) would be the ultimate driver as it is the condition that creates the series of impacts that follow often long after the event itself has abated. The timing, duration, severity, location and extent of a drought event will all have some influence on the impacts and therefore influence the nature of the drought recovery. A schematic of a drought life-cycle has been prepared (Figure A-1) to illustrate the concepts. Definitions for terms relating to these aspects of drought are presented in Table A-3.

Table A-3. Recommended definitions for elements of the drought lifecycle

Drought Element	Definition
Drought Footprint	The overall period of time and geographic scale where the impact of a drought event is still evident.
Drought Trigger	The threshold where drying conditions exceed the criteria to become a drought event. The criteria are based on measurable indices that vary from region to region or even from location to location.
Drought Onset	A period of abnormally dry weather that has not persisted for sufficient duration to result in damage that would meet the criteria set for a drought in that area.
Drought Event	The meteorological conditions that result in abnormal dryness such that they meet the local or regional criteria for drought of any severity. When the period of dryness abates to the point where the local or regional criteria are no longer met, the drought event ends.
Drought Recovery	The period where meteorological conditions no longer meet the criteria of a drought event however the impacts on the ecosystem and on the social-economic, hydrological, agricultural elements of the affected area remain evident.
Drought endpoint	The period when all impacts associated with the drought have returned to the pre-drought levels.
Drought persistence	The ongoing, prolonged duration of the physical condition of drought for that region.
Drought episode	The entire drought lifecycle.
Drought classification (class)	The level of severity or intensity of a drought (e.g. D0, D1..).
Drought Impact	An observable loss or change at a specific time because of drought (WMO and GSP 2016)

The effect of high heat can influence the drought lifecycle, particularly in accelerating the onset and intensification and promoting persistence (Trenbreth, 2011). Temperature is a key driver of evapotranspiration of soil moisture, which exacerbates the impact of the low rainfall. The role of high

Figure A-1. Schematic to illustrate the stages in the lifecycle of a drought.



heat and drought is discussed in more detail in Section D. Drought persistence is not clearly defined in the literature but has been referenced in the context of assessing drought predictability (Tatli 2015; Ault et al 2014; Bonsal et al., 2010). It refers to the prolonged duration of some drought events including megadroughts that appear to have lasted up to 50 years according to paleologic records (Ault et al, 2014).

During a period of drought recovery, where adequate or normal precipitation patterns have re-established, the impacts continue to linger for some extended period as water reservoirs refill, soil moisture levels and vegetation re-establish and generally the ecosystem and society return to pre-drought conditions. The period is extremely complex as the nature of the weather patterns, the extent and intensity of land and water use, the geographic region and the nature of the land surface itself will all have a bearing on the length of recovery. Finally the metric used to determine when recovery is complete and the impacts of the drought are over also requires definition. This in itself is complex as during a drought, wildfires may have removed vegetation from the landscape leaving it vulnerable to floods, erosion and landslides. Loss of agricultural (e.g. soil erosion) or economic capacity can also result in residents of the affected area moving away. In these cases recovery from some loss and damage could take several decades or may never fully be recovered. Aridity is the term used for cases where the weather patterns never fully re-establish and Desertification is the term used when landscapes never fully recover. No term has been developed to describe conditions where society never fully recovers

Recommendations for defining drought

The concept that drought originates from a precipitation deficit is robust enough to underpin the ultimate definition or definitions of drought within the hydrologic cycle, especially when other influencing factors such as wind, temperature and humidity are considered. However continual input of heat into the hydrologic cycle from global warming will enhance moisture loss and distort the historical climate record. This will force interpretations of a deviation from “normal” to be made with more care and it will blur the line between drought and aridity. Therefore more study is needed to determine when drought transitions to aridity and how that can be adequately measured and standardized.

The four operational types of drought proposed by Wilhite and Glanz (1985), *meteorological drought*, *agricultural drought*, *hydrologic drought* and *socioeconomic drought* have been adequate for drought planning needs and for analytical needs so far, and have been adopted by the American Meteorological Society Council on September 2013 (AMS 2013). Establishment of criteria for physical indices, or drought triggers, would add precision to analysis of drought however they would vary from one location to another, making a universal trigger unadvisable at this time. The term *definition* should refer to broader concepts of drought, such as these drought types. Table A-4 presents the drought types with definitions taken for recent literature.

The term agricultural drought should be changed to a broader term. The concepts of drought impacting the agricultural and other ecosystem are similar in that they refer to the impairment of bio-productivity in the landscape and the factors that influence it, (e.g. soil moisture). Therefore the term *environmental*

drought (Adler, 2010) or *ecological drought* (Crausbay et al., 2017) could be used in place of agricultural drought as it is inclusive of both agriculture and the non-agricultural ecosystem (Table A-4).

Table A-4. Proposed operational types of drought and the associated definitions¹.

Operational Type	Definition
Drought	A deficiency of precipitation from expected or “normal” over a season or longer period of time that results in insufficient water to meet the demands of human activities and the environment ¹
Meteorological Drought	A temporary period of dryness expressed in terms of atmospheric characteristics such as a precipitation departure from some average or “normal” period ² .
Environmental or Ecological Drought	A prolonged and widespread deficit in naturally available water supplies — including changes in natural and managed hydrology — that create multiple stresses across ecosystems ³
Hydrologic Drought	A lack of water in the hydrological system, manifesting itself in abnormally low streamflow in rivers and abnormally low levels in lakes, reservoirs, and groundwater. ⁴
Socioeconomic Drought	Dryness associated directly with the supply and demand of some economic good with elements of meteorological, hydrological, and agricultural drought. It differs from the aforementioned types of drought because its occurrence depends on the time and space processes of supply and demand to identify or classify droughts. The supply of many economic goods, such as water, forage, food grains, fish, and hydroelectric power, depends on weather. ⁵

^{1,2} Wilhite et al.,(2014)

³ from the National Drought Mitigation Centre; University of Nebraska-Lincoln; <http://drought.unl.edu/DroughtBasics/TypesofDrought.aspx>

⁴ Van Loon (2015)

⁵ from the National Drought Mitigation Centre; University of Nebraska-Lincoln; <http://drought.unl.edu/DroughtBasics/TypesofDrought.aspx>

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B. Regional Case Studies: Socioeconomic Impacts of Drought and the Mitigation and Preparedness Activities to Combat Them

Key messages:

- Several case studies of droughts and socioeconomic factors have been presented in Appendix B. Some elements, mostly from the case studies have been presented in this section as examples of key messages for this study.
- Socioeconomic impact metrics must go beyond economic cost alone and consider the hardship of the people impacted by the drought. Costs can vary depending upon the degree of economic development, for example costs could be vastly higher in a highly developed country as compared to the costs in a lesser developed country. However the degree of hardship on the people and their environment is arguably higher in less developed areas. Metrics that factor in all socioeconomic aspects need to be used.
- Countries that share water systems can have a degree of social and political complexity involved that increases drought vulnerability. Commitment by all governments is a necessity in order to go forward to effectively build drought resilience.
- Even with cooperation from different countries, competing water uses and historic allocation priorities need to be addressed. In addition to strong physical science, a strong understanding of sociological behavior is needed to underpin planning.
- A systematic and comprehensive way to catalogue physical and socioeconomic data regarding water scarcity and drought is needed for effective planning.
- In some cases drought planning has resulted in measures such as improved forecasting that has significant benefits for the national economy. Drought planning should not be viewed as a cost of doing business.
- Exceptional events offer unique opportunities to improve our understanding of drought processes and associated factors such as heat waves. It is imperative that consistent weather and climate monitoring efforts are in place so that data collected during exceptional events has a historical relevance.
- A proactive approach to drought planning offers the best chance for building effective resiliency. Both the policy development process and the planning process must be viewed as ongoing, continuously evaluating the nation's changing exposure and vulnerabilities and the ways in which governments and stakeholders can work in partnership to lessen risk.

Overview

The main socioeconomic threats from droughts are related to water security and food security. Measurement of these impacts is difficult due to the changing nature of human activity and the difficulty determining meaningful economic and social metrics. Compounding these assessments are the cumulative effects of human action, past disasters, economic and political stability and the relationships with other nations and political jurisdictions.

For changes in economic impacts, Glantz et al (2007) used the changes in Gross National Product (GNP). Over the three decades spanning the 1960s, 1970s and 1980s specific droughts reduced GNP by at least one percent in countries in East Africa, Europe, North America, South America, Southeastern Asia/Australia, Southern Asia, and West Africa (World Conference on Disaster Reduction, 1994). Measures of GDP over time show that economic downturns often materialize after a drought. For example, in the year after the 1984 droughts in Sub-Saharan Africa, the GDP for Mali, Niger, and Ethiopia fell by 9 percent, 18 percent, and 7 percent, respectively. Zimbabwe's GDP declined 3 percent after the 1983 drought (Benson and Clay, 1994, referenced in Glantz et al, 2007).

Food security has been assessed from the change in world wheat prices. Perhaps as a result of the increase in global trade in recent decades, incidences of drought in any major food producing region of the world coincide with global price spikes (Figure B-1). The resultant effect on food affordability would be most threatening to countries with the weakest economies.

Water security pertains not only to access to drinking water but also the availability of clean water and electrical power from hydroelectric facilities. Assessment of water security is complicated by conflicts from the increase of the water demand by agriculture, electricity and mining sectors, growth of population and consumption per capita. In some areas the water rights are almost entirely assigned, which creates conflicts of use in times of drought. Also many countries have few hydrological studies to account for the quality and availability of water.

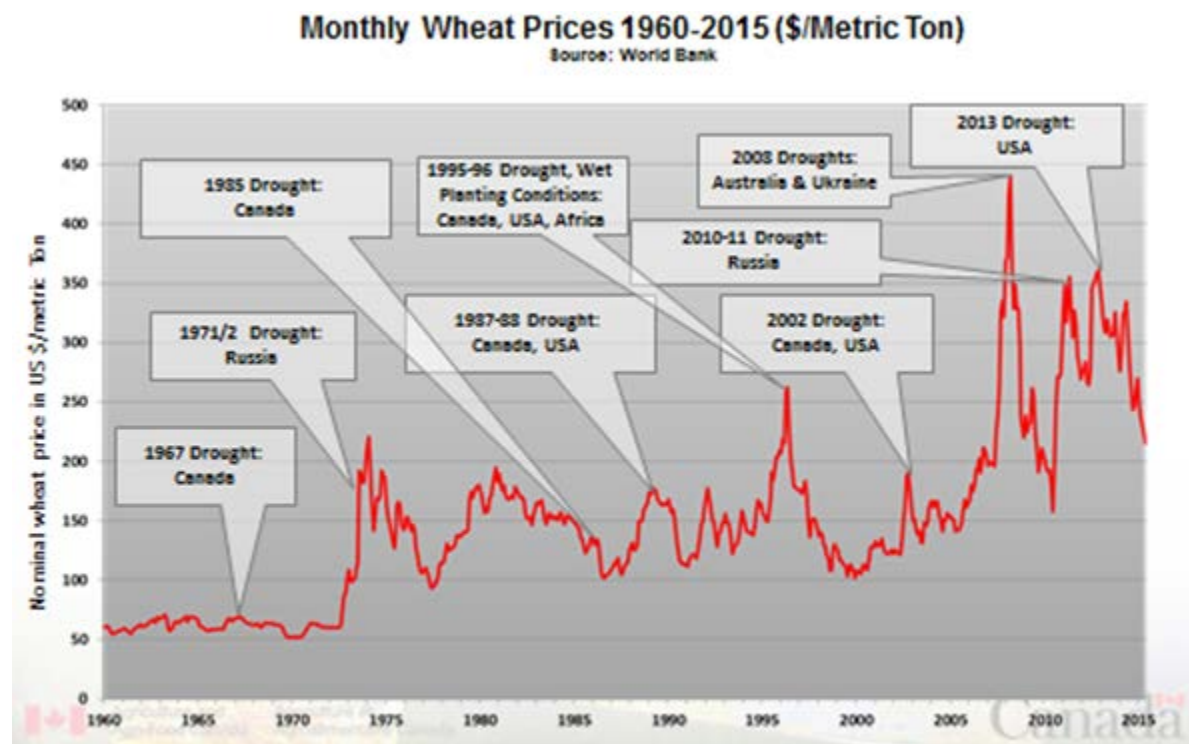


Figure B-1. The change in monthly world wheat price and the incidences of major drought events.

This section will briefly highlight examples of needs and lessons learned from recent droughts. They are intended to illustrate ways socioeconomic impacts can be better measured and mitigated. Most examples are drawn from more detailed Case Studies, which are presented in Appendix B.

In addition to the factors mentioned in the preceding paragraphs, assessment of socioeconomic impacts must take into account variability caused by several regional factors that contribute to drought vulnerability and their degree of change over time. These would include the ability of the local terrain to provide abundant resources, human action and its degree of degradation of the land and water resources, the degree of isolation of the communities, the robustness, diversity and stability of the economy and demographic factors.

Example 1: Chile

An example is based on a study by (Menza-Morales, 2010) in the O'Higgins region of Chile, where the population is heavily linked to agricultural production, with over 80% of the agricultural operations are considered small scale. The economy only has access to local markets and it is exposed to fluctuation of commodity prices. The proportion of rural population is over 60% comprised mostly of low income families resulting in a poverty rate that is higher than the regional or national average. The population is aging and undergoing rural migration.

Soza and Meza (2010) reported the impacts from the drought of 2007 and 2008, considered the worst drought by local residents. These included production losses of up to 70% in natural and improved pastures, and up to 90% in wheat crops. Livestock reported the largest economic losses. The main local impacts were: decreased water sources for a high number of producers; problems with access to drinking water; loss of production primarily in irrigated wheat and, rainfed cereals and legumes; difficulty finding water for livestock; problems feeding animals; sales at lower market prices; illness and death of livestock; and families stopped eating certain foods.

The socioeconomic impact of a drought in such as region would be expected to be considerably different than the impacts from a drought of similar severity, duration and extent in a modern agricultural community in a highly developed region such as in Europe or the United States. To address this discrepancy Meza-Mendales (2010) reported that the study produced an indicator of vulnerability to drought, the Drought Vulnerability Index (DVI) which consisted of seven sub-indices including aridity; soil water retention; irrigation security; crop diversity; farmers ability to adapt to technologies; unsatisfied basic needs; and social vulnerability linked to agriculture income.

This example demonstrates the need for socioeconomic impact metrics to go beyond economic cost and consider the hardship of the people impacted by the drought. While costs could be vastly higher in a more developed country the degree of hardship on the people and their environment is arguably higher in less developed areas.

Example 2: Islamic Republic of Iran

A second example is the Hamoun Oasis, located in the Sistan basin in eastern Iran and western Afghanistan. It was an important wetland and irrigation water source for the region, fed by the

Helmand River flowing west from Afghanistan. The river system and wetlands which have expanded to up to 4000 km² in wet periods have supported agriculture in the area for over 5000 years (UNEP 2003). During the 1970's irrigated agriculture and the population expanded significantly in the area. Dams were constructed on the Helmand River by the Afghan governments of the time to divert water upstream for their domestic use. Despite periodic droughts the region remained viable however in 1998 a drought began that became one of the most of extreme in the world at that time. By 2001 water levels the river system had dropped by 98% as water was diverted by Afghanistan, and about 99% of the wetlands had dried (UNEP 2003) (Figure B-2).

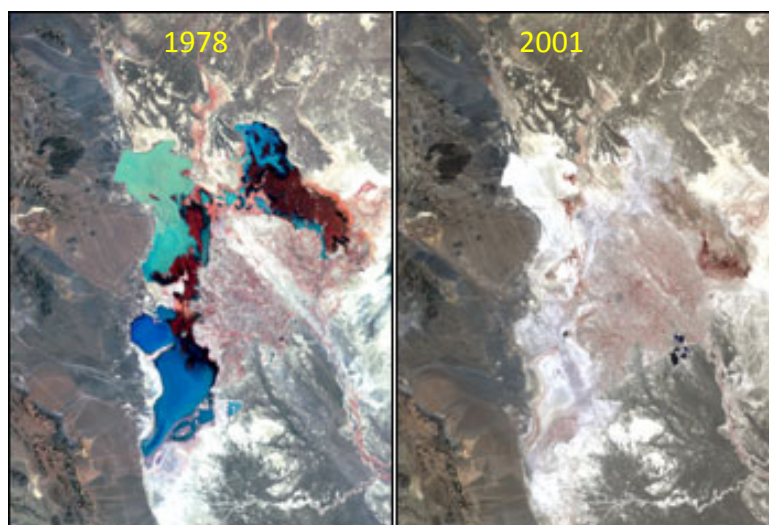


Figure B-2. Photos from the National Aeronautics and Space Administration (NASA) showing satellite views using enhanced near infra-red photography the Hamoun Oasis over a 23 year period from 1978 to 2010. Vegetative productivity is shown as red in the photographs.

Farming activities could not be sustained in the absence of irrigation water, resulting in massive depopulation. Wind erosion blew soil and salt through the area, submerging over 100 towns (Weier 2002). Political change in Afghanistan resulted in an influx of refugees into the area where with lack of food and water, problems including malnutrition and increases in diseases such as heart, respiratory, optic, cancer and even intestinal and other sicknesses among the residents of Sistan. Other negative economic and social impacts on local people of Sistan included refugee immigration, changing the living patterns and increasing social problems such as drug addiction, smuggling and dissatisfaction of people from the circumstances, increased local conflicts for water and increased water borne diseases. The UNEP (2014a) identified the major reasons for the collapse of the wetlands as:

- Reduced precipitation “apparently because of long-term climate change”;
- more water abstraction from rivers and water resources;
- mismanagement of water resources in Sistan basin;

- expansion of agricultural lands;
- Using traditional irrigation systems and low water efficiency;
- Using inappropriate cropping patterns;
- Water control in Afghanistan;
- Introduction of non-native species of aquatic plants;
- Over exploitation of pastures.

The Islamic Republic of Iran has endured heavy costs for rehabilitation and protection of the wetlands and its shared location with Afghanistan makes international bilateral cooperation essential for longterm sustainability (UNEP 2014b). This example demonstrates the degree of social and political complexity involved that both results in added drought vulnerability and is required for adaptation. Commitment by all governments is a necessity in order to go forward to rehabilitate the area and build further resilience.

Example 3: Europe

Drought occurrences have been regular and resulted in harsh impacts in Europe over past few decades over short periods (weeks or months) or longer periods spanning seasons, years or even decades (EEA, 2010; van Lanen et al., 2012). Droughts have not directly caused fatalities in Europe, but they have large socio-economic and environmental impacts affecting many sectors. Multi-faceted impacts happen in both the drier areas of southern European Union (EU) Member States, but also in countries where water availability has never before been a major concern (van Lanen et al., 2012).

So far in the 21st century Europe has endured at least eight drought or water scarcity events. These included:

- 2003; record breaking drought and heat wave covering a large part of western and central Europe (Rebetez et al., 2006; Fink et al., 2004)
- 2005; in France, Spain and Portugal (WWF, 2008, Garcia-Herrera et al., 2007),
- 2004-2006; in southern England (Marsh et al., 2007),
- 2007; in Greece, Moldova and rest of the SE Europe (Potopova, 2016; WWF, 2008; DMCSEE, 2012),
- 2011/2012; in central-eastern Europe (EDO, 2016, Zahradníček et al., 2015),
- 2012; in France, England, central and south-eastern Europe (EDO, 2016; DMCSEE, 2012).
- 2015; a large part of continental Europe was affected by a severe drought (EDO, 2015)
- 2017; severe drought in southern Europe; Italy, Spain

Little research is available regarding the link between drought severity and related impacts (Jenkins, 2012). Currently, there are many data gaps and uncertainties in the European information based on water scarcity and droughts. Information is largely incomplete, particularly for agriculture, the largest user of water, and is lacking altogether for some countries.

Past planning has emphasized expensive infrastructure (e.g. dams, modernized irrigation systems) and criticized for reducing water availability and undermining system resiliency to future droughts (Anderies et al., 2004, referenced in Perez-Blanco and Gomez, 2014; Ruttan, 2002). Drought planning has been particularly important because in recent decades, increases in water demand coupled with observed increases in drought in Europe the need for regulatory instruments to establish priorities among water uses and to define more strict controls to access of publicly provided water during droughts. These instruments are Drought Management Plans (DMPs). In addition to a regulatory function the DMPs provide drought thresholds (EC 2008). These voluntary plans have been adopted by many southern European countries, including Spain, France, Portugal and Italy (EC 2008).

In a case study of the Guadalquivir River basin in southern Spain, it was determined that if DMPs were successfully enforced, the available water would satisfy 62% of the agricultural demand during a drought (Perez-Blanco and Gomez, 2014). This was much lower than the 90% guaranteed by the older River Basin Management plans. The study also found that the ability of DMPs to meet agricultural demand was even lower, about 50% in other agricultural basins. Future ability would drop even further under climate change.

The study by Perez-Blanco and Gomez (2014) concluded that in order to avoid a sudden and disproportionate impact of droughts on agriculture and at the same time guarantee water demand for priority uses water policy needs to balance water supply and demand. Without complementary policies, DMPs may regulate water availability but not the incentives to use water. Water demand needs to be addressed as well.

They further concluded that DMPs should be considered a part of institutional change to sustainable water management and lead to a comprehensive policy that makes reduction in water availability during water scarcity and drought compatible with maintaining a sustainable agriculture sector.

The European Union and the European Environment Agency have identified the need to assemble information on a number of natural hazards, including drought (EC, 2012; EEA, 2010). In support of this request the EU FP-7 research project DROUGHTR&SPI (Fostering European Drought Research and Science-Policy Interfacing) has addressed drought identification and characterisation, drought assessment (Impacts) and drought policies to develop drought management plans at different scales (river basin, national, international) with the aim to contribute to the reduction of future Europe's vulnerability and risk to drought (Andreu et al., 2015). It demonstrates the potential of a novel database of categorized drought impact reports for Europe.

The European Union has developed and coordinated drought monitoring, information collection and dissemination and planning for the member nations through agencies such as the European Drought Observatory (EDO) and the European Drought Centre (EDC). In southeastern Europe the Drought Management Center for Southeastern Europe (DMCSEE) has a similar role.

Data is a critical requirement for planning and policy. A systematic view on drought events in Europe is available through three main web-based sources for information in Europe, hosted by the same three

main drought bodies, the European Drought Observatory (EDO), the European Drought Centre (EDC) and the Drought Management Centre for Southeastern Europe (DMCSEE).

The EDO monitors drought and publishes the current drought status for Europe at 10 day intervals. The presence of drought is based on a combined drought indicator composed of the SPI, soil moisture and vegetation conditions (Horion et al., 2012). The EDC has a drought reference database for collection and dissemination of detailed information about historical drought events in Europe and a drought impact report inventory (Spinoni et al., 2016).. The database contains descriptive information of recent major droughts in Europe including location, duration, progression, category of drought (climatological vs meteorological) and impacts. It also contains quantitative Standardized Precipitation index (SPI) drought index data. The DMCSEE was established in 2006 to coordinate and facilitate the development, assessment, and application of drought risk management tools and policies in South-Eastern Europe with the goal of improving drought preparedness and reducing drought impacts. Its work is focused on monitoring and assessing drought as well as assessing risks and vulnerability connected to drought. DMCSEE has published a drought bulletin since spring 2010 and provides several monitoring products for South-Eastern Europe (DMCSEE, 2012). DMCSEE is involved in several regional projects to enhance preparedness and mitigation action in the region including the IDMP CEE. Currently, DMCSEE is in process of preparation of Regional strategy to improve drought response in Danube region (<http://www.interreg-danube.eu/approved-projects/dridanube>).

However, despite these efforts there is no systematic, comprehensive record of drought events in Europe that contain data to support robust statistical analysis and on a multi-indicator approach.

This example illustrated the need to take a comprehensive approach to drought and water scarcity planning. There is a need to develop a database with drought information to support robust statistical analysis of drought characteristics and return periods to support planning. However even with adequate data and cooperation from different countries, competing water uses and historic allocation priorities need to be addressed. In addition to strong physical science, a strong understanding of sociological behavior is needed to underpin planning.

Example 4: The Southwest Pacific Islands

Some Island Nations in the Pacific are in the draft stage of implementing a national policy around drought management and response. Some issues with implementing a national policy in countries in the region include the diverse nature of conditions, both geographically and climatologically, with the nature and timing of impacts often differing within each country. Furthermore, it can often be difficult to obtain historical records of rainfall to enable a thorough drought risk assessment.

Risks and economic losses around drought can be managed and minimised through an operational seasonal outlook service that is fed into the decision making processes for vulnerable industries. Two excellent examples of this are found in Fiji and Samoa as summarised below from the WMO report on Climate Prediction for Small Island Nations (2016).

Fiji reports on the application of the seasonal outlook service to the sugar cane industry. The 1997-98 drought in Fiji caused a F\$104 million loss in revenue in the sugarcane industry alone. The Western sides of Viti Levu and Vanua Levu and the Yasawa were the worst hit regions, where 90% of the population received food and water rations. In September 1998 the Fiji Cabinet declared a natural disaster for the prolonged drought (Bipendra Prakash, Fiji Meteorological Service, personal communication to L Bietto).

Aside from the mitigation of losses due to early warning of a drought, a direct economic benefit for the sugar cane industry was seen in 2015 when a forecast of seasonally drier-than-average conditions led to a halt on the replanting of sugarcane. The subsequent severe dry conditions in Fiji associated with the 2015 El Niño event would have severely impacted on any plantings, costing the industry millions of dollars in lost canes. The Fiji meteorological service provides a quarterly seasonal rainfall outlook to support production of sugar cane and to allow for better management of water and fertiliser applications among other applications. The application of seasonal forecasts has made the sugar cane industry better able to manage this natural extreme variation in the climate.

Samoa has applied seasonal forecasting to the management of the country's important hydro-electric industry. Hydropower is the biggest source of renewable energy in Samoa, with the Afulilo Dam generating around one fifth of Samoa's total energy. Originally the hydropower scheme was designed to only operate at full capacity during the wet season; however a management plan for water storage incorporating the seasonal outlook has been able to ensure a year-round supply of energy. The Afulilo Dam provides the only reservoir based hydropower in the country — with enough storage to last up to six months. El Niño events are generally associated with below average rainfall conditions in Samoa. Forecasts of an El Niño in 2015 enabled a plan to reserve water in the Dam to be implemented. Additional backups, such as maintenance on the diesel generators, were also undertaken to ensure continued electricity supply during the forecast drought. Whilst this example is not strictly focussed on agricultural applications it provides a good example of how water supplies can be conserved in the region to support agricultural and domestic needs.

The example illustrates that while comprehensive planning will ultimately build resiliency to a wide variety of drought conditions under climate change, in some areas significant benefits can be obtained from improvements in monitoring and forecasting drought.

Example 5: Russia

Historical records show that the area of Russia has been exposed to numerous heat waves and droughts. Schubert et al. (2014) identified over 30 major drought and heat wave events since 1875. These severe conditions have been associated with crop failure, famine, wildfires and loss of life however historical records do not clearly distinguish between heat waves and droughts and Schubert et al (2014) demonstrate that they are intertwined. The drought and heat wave of 2010 was so severe that researchers had to go back to AD 1092 to find a suitable analog (Schubert et al. 2014). While several studies have identified the circulation patterns leading to the drought and heat wave, and the concurrent heavy rains and flooding in Pakistan, there is currently no understanding as to what large scale factors would have played a role in making the 2010 conditions so severe (Schubert et al., 2014).

The most intense part of this drought, in terms of geographic extent and rainfall deficit, encompassed July and August 2010 and covered most of Russia's agricultural productive regions. While it did not cause a famine it was severe enough to stop Russia's grain exports¹, resulting in soaring grain prices on the global market². The losses to Russian agriculture included crop loss over an area of 13.3 million ha, equal to 17% of crop acreage in Russia and affected over 25,000 farms. Estimates of total cost of the agricultural damage ranged from 32.7 billion rubles (by the Ministry of Agriculture) to as much as 41.8 billion rubles. The number of deaths was 56,000 higher than the comparable period of 2009 (GeoRisks Research, 2015). The estimated economic loss to Russia from drought and mega heatwave, ranged from 0.7% to 1% of GDP or as much as 450 billion rubles.

From the twentieth of June to the eighteenth of August 2010 central Russia was characterized by extreme heat, referred to as a mega heat wave (Schubert et al., 2014; Miralles et al. 2015). In Moscow 20 temperature records were exceeded, including the absolute city record of +38.2 °C. Overall during the heat wave, afternoon temperatures exceeded 3 standard deviations over large areas and local

¹New York Times; Russia Crippled by Drought, Bans Grain Exports; by Andrew E. Kramer; August 5, 2010

²Washington Post; Russia bans grain exports because of fire and drought, sending prices soaring; by Ariana Eunjung Cha and Janine Zacharia; August 6, 2010

extremes exceeded 5 standard deviations (Miralles et al. 2015). While these extremes were comparable to the 2003 heat wave in Europe, the Russian heat wave extended for a longer period over a larger area (Miralles et al. 2015).

Forest fires covered vast areas of western Russia and the Ukraine and inflicted severe damage, which was aggravated by the ignition of peat bogs. Reports on the number of fires differ but all point to extreme damage:

- According to the Federal Forestry Agency of Russia, during the summer of 2010 there were more than 25,000 wildfires in the territory of Russia consuming an area of 1.1 million hectares.
- According to the Ministry of Emergency Situations (MES) of Russia, on August 20, 2010, there were 28,500 wildfires including 1146 peat fires, consuming 886,000 hectares.
- According to Munich RE, the total was 30,376 fires, including 1162 peat fires, burning 1.25 million ha and destroying 147 settlements.

Wildfires have affected the population distribution in Vladimir, Ivanovo, Penza, Tver, Rostov regions, Udmurtia, Mordovia. According to the official assessment of the Russian authorities, 2500 houses have burnt during fires in 2010 more than 3500 people were left homeless. Smog resulting from the heat and fires created health risks and compounded heat stress on citizens.

One of the worst consequences of the 2010 drought was the vulnerability Russian farmers were left with to face the ensuing drought in 2012. In a case study by Ukhova (2013), farmers reported that they had money and grain in reserve to last through the 2010 drought but by 2012 these reserves were gone. The extent of crop losses in 2012 was highly variable and was linked not only to differing climate conditions but also to adaptation techniques and to their affordability. For example farmers in the Astrakhan region had access to irrigation and while it saved their crops it drained their money. Some

farmers were either unable to pay back debts, reduced areas under cultivation in 2013 or planted no crops at all in 2013. Several farmers avoided crop insurance because of either distrust or inability to pay premiums. Other adaptation measures in different regions enabled farmers to survive financially through, for example diversification of crops or summer fallowing, however it was the medium to large farm sizes that had the land base to allow these adaptation measures to be effective. Ukhova (2013) concluded that climate change in the absence of adaptation policies is creating a food security and livelihood crisis for small farmers. The problems could be ameliorated by specific and well-designed policies.

This example is highlighted because it was combination of an exceptional event around which there was enough atmospheric and related data and documentation over a large enough scale that several studies have examined atmospheric circulation patterns, relationships between heat and drought persistence and effectiveness of some drought indices. This will be examined in more detail in Sections D and E.

Example 6: United States

Like most climates around the world, drought is a normal part of the climates in the United States as well. Figure B-3 highlights this point by illustrating that some part of the U.S. has been in severe to extreme drought according to the Palmer Drought Severity Index (PDSI) every year from 1895 to 2017. Figure B-3 also highlights the major drought events that affected the U.S. For example, during the 1930s—or the “Dust Bowl” years—the spatial extent of drought exceeded 30% of the country multiple times and almost reached 70% in 1934. The 1950s also showed an extended period of droughts for the U.S. More recently, droughts surpassed 30% coverage of the country in the late 1980s, early 2000s, and most recently in 2012. However, droughts do not necessarily have to have a large spatial extent to cause significant economic, social, and environmental impacts in the U.S. This is true for the 2011-2016 California drought and the very serious drought in the southeastern U.S. in 2007-2008.

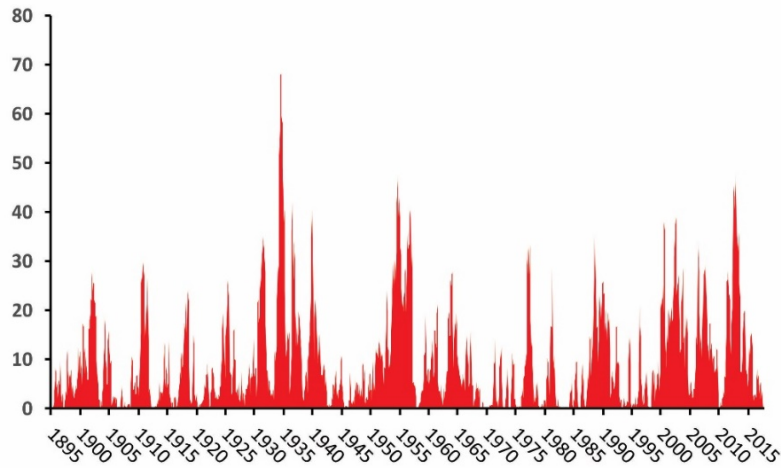
Often these serious drought events in the U.S. have provided important “windows of opportunity” for policy improvements, reforms, and improved drought risk management. For example, during the 1930s droughts, which almost stretched from coast-to-coast and coincided with a time of economic depression, dust storms were one of the iconic impacts that occurred on a regular basis during the decade. These dust storms were mainly the result of poor land management practices put in place by agricultural producers in the decades prior to the 1930s and contributed to one of the biggest lessons to come out of the Dust Bowl. The federal government created the Soil Conservation Service (SCS) to encourage agricultural producers around the country to protect their soil resources. The SCS has continued its mission, and during the 1990s changed its name to the Natural Resources Conservation Service (NRCS). The NRCS is still very active promoting the preservation of soil resources and soil health, but also rural water resources as well. The NRCS is an important legacy of the Dust Bowl drought.

Another opportunity arose out of droughts in the 1970s and 1980s. Dr. Don Wilhite, a professor at the University of Nebraska-Lincoln began investigating federal and state responses to these droughts and recognized that a more proactive drought risk management approach by officials was needed. He encouraged drought planning as a strategy to prepare for future drought events and drought mitigation

Figure B-3. Severe to Extreme drought occurrences in the United States based on the Palmer Drought Severity index.

Percent Area of the United States in Severe to Extreme Drought

January 1895–July 2017



Based on Palmer Drought Severity Index (PDSI) data from the National Centers for Environmental Information/NOAA

strategies to reduce drought risk. Many states in the U.S. have adopted this approach and the number of states in the country with some kind of drought plan went from three in the early 1980s up to 45 today. Dr. Wilhite created the National Drought Mitigation Center (NDMC) in 1995 [<http://drought.unl.edu>], and the NDMC remains very active and still has as its mission to promote drought planning and proactive drought risk management approaches to reduce societal vulnerability to drought events.

The combination of improved drought monitoring technology and an increased focus on drought risk management, as well as a need to better assess developing drought conditions, encouraged the National Oceanic and Atmospheric Administration (NOAA), the U.S. Department of Agriculture (USDA), and the NDMC to partner on the development of a new drought monitoring tool called the U.S. Drought Monitor (USDM) in 1999. The USDM is a weekly assessment of drought conditions for the U.S. [<http://droughtmonitor.unl.edu>] and because of its consistency and usability, it has gradually become an important tool for policy-makers and for communication about real-time drought conditions across the country. The product is designed to give a simple representation of drought severity and extent by showing four drought categories on a map (with a fifth “abnormally dry” category) distinguished by a ranking percentile scale and a recognizable color scheme. The product is flexible in considering multiple components of the hydrological cycle depending upon what data are available, including climate parameters, reservoir and lake levels, streamflows, groundwater levels, soil moisture, snowpack, remote sensing information, and others.

Since the USDM's humble beginnings back in 1999, the keys to its current success as a drought early warning system are the result of 1) the commitment of the original NOAA/USDA/NDMC partnership, which is a great example of the cross-agency interaction and collaboration that is necessary to monitor drought conditions, 2) its consistent availability, and 3) the involvement of a network of more than 400 local experts with knowledge specific to their region to provide feedback on the map development process each week. This engagement of local experts has helped successfully built trust in the product and assists in it being a reliable and useful tool for policy and decision makers.

The USDM success demonstrates an important lesson resulting from the coevolution in drought monitoring and risk management over the past decade. An important feedback loop has emerged where better drought management drives the need for improved drought monitoring and, in turn, improved drought monitoring encourages more effective drought management (Hayes et al. 2012). As drought plans become more specific in space and time, the need for information at higher spatial and temporal resolutions increases. Improvements in the USDM have led to shifts in national agricultural policies, inspiring additional advancements in the spatio-temporal resolution of drought monitoring to support implementation of these policies at a local scale.

Efforts to improve federal drought risk management activities in the U.S. also increased as a result of droughts in the late 1990s and early 2000s. These efforts culminated in the passage of the National Integrated Drought Information System (NIDIS) Act in 2006 [<http://drought.gov>]. Since its implementation, NIDIS has been building a suite of Regional Drought Early Warning Systems (RDEWS) across the country based roughly on either river basins or important geographic regions designed to improve the coordination and communication of drought early warning among federal, state, and local officials and organizations in that region. Pulwarty and Verdin (2013) argue that another emerging lesson for improved drought risk management is this requirement that drought monitoring systems be "people and place oriented", especially since drought impacts are often most severe at the local levels. By taking local knowledge and practices into account, this promotes an environment of mutual trust, acceptability, common understanding, and the community's sense of ownership and self-confidence in dealing with drought events. Both NIDIS and the NDMC have evolved to become entities well known for building links between community-based decision makers and early warning systems.

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C. Likely Drought Changes Under Future Climate Variability and Change

The Intergovernmental Panel on Climate Change (IPCC) has concluded that extreme events will increase with global warming. Greenhouse gas accumulation has created an energy imbalance between incoming and outgoing energy at the top of the atmosphere. Increased energy in the atmosphere under global warming is largely manifested as heat and will influence several aspects of the water cycle. Over the past 50 years, 90% of the total heat added to the climate system has been absorbed by the oceans, with the remainder going to melting sea ice, warming the land surface, and increasing atmospheric temperatures and humidity (Trenberth and Fausillo 2014). Along with influencing other extreme events, these will likely influence the frequency, severity, onset and persistence of drought however there is low confidence in a global-scale observed trend in drought or dryness due to lack of direct observations and the dependency on geographic variability and the inferred trends of drought index used (IPCC 2013). Global warming cannot be considered in isolation, however as human activities such as aerosol emissions, land use change, deforestation and water use will influence drought characteristics and impacts. Wanders and Wada (2014) found that the impact of human water use and reservoirs in non-trivial, especially in large part of Asia, the Middle East and the Mediterranean, and should be included when projecting future drought characteristics.

Quantifying the energy imbalances requires a level of accuracy not available from direct observations even with sophisticated satellite sensors but it can be estimated from models that simulate climate processes (Trenberth and Fausillo, 2014). Models have a limited capability to track processes in detail due to limited data for calibration and validation. For example soil moisture is a key variable for determining the rate of land surface warming and drying but there are many large regions where data are simply inaccessible or absent. In regions with available information, interpretation is often difficult as the measurements are highly localized and the differences in soil properties can cause great differences in the measured values even at short distances. Satellite data on soil moisture are limited to the upper few centimeters of soil, while the model data may require soil moisture data at much greater depths.

Also climate modes of variability such as the ENSO, influence climate extremes by releasing heat into the atmosphere as the ocean comes out of the El Nino phase, which can affect the monsoon circulation and atmospheric teleconnections (Trenberth and Fausillo 2012). During 2010 the sea surface temperatures were at record warm levels (Figure C-1) and the Russian drought and heat wave, the drought in Brazil, the intense Atlantic hurricane season, and the flooding in Pakistan, India, China, Columbia and Queensland, Australia, occurred following the demise of the El Nino event in May 2010. Models must be able to capture the modes of variability associated with extreme events and conclusions by Trenberth and Fausillo (2012) suggest that they are not able to do this satisfactorily. Prudhomme et al. (2014) report that significant uncertainties arise from different ways that global impact models capture the terrestrial water cycle processes. As a result the probability in predicting extremes such as drought will have margins of uncertainty that will vary with the location, the projecting timeframe, the models or the ensemble of models used and the rate of greenhouse gas emissions.

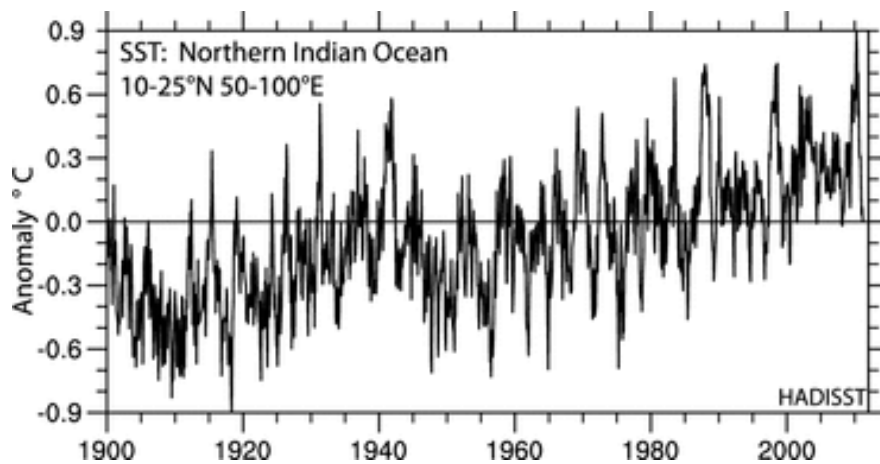


Figure C-1. Monthly anomalies in sea surface temperature (SST) for the area encompassing the Arabian Sea and Bay of Bengal. May 2010 was the highest anomaly on record (0.9°C) with a SST of 30.4°C (Trenbreth and Fausillo 2012).

In order to better understand the uncertainty around future greenhouse gas emissions and their potential impacts, the scientific community defined a set of four new scenarios, denoted Representative Concentration Pathways (RCPs) that were used in the IPCC Fifth Assessment Report. They are identified by their approximate total radiative forcing in year 2100 relative to 1750: 2.6 W/m² for RCP2.6, 4.5 W/m² for RCP4.5, 6.0 W/m² for RCP6.0 and 8.5 W/m² for RCP8.5 (IPCC 2013). These four RCPs represent a range of climate policies that would lead to a range of scenarios that allow climate modeling to use standardized approaches to greenhouse gas related forcing. These scenarios include:

- one mitigation scenario leading to a very low forcing level (RCP2.6),
- two stabilization scenarios (RCP4.5 and RCP6), and
- one scenario with very high greenhouse gas emissions (RCP8.5).

The RCPs are based on a combination of integrated assessment models, simple climate models, atmospheric chemistry and global carbon cycle models (IPCC 2013).

The scale of influence of interactions between land, ocean and atmospheric processes at distant locations, such as the Arctic, has the potential to impact mid-latitude areas. In a review by Sheffield and Wood (2011), a strong argument is made that under global warming the Hadley circulation will expand resulting in poleward movement of storm tracks, and reducing the precipitation in the sub-tropics. Francis & Vavrus (2012) have produced evidence that increased heat flow resulting from enhanced Arctic warming and the decrease in Arctic sea ice may cause more persistent weather patterns in the mid-latitudes. This is caused by a weakening of upper atmospheric-level west-to-east flows (jet streams), and an increased northern elongation of high pressure ridge peaks, both of which contribute to slowing

the movement of weather systems. More prolonged weather patterns increase the risk of extreme heat, cold, floods, pluvial conditions and droughts.

Climate change models project that warming of the troposphere will cause an increase in humidity (Meehl & Stocker, 2007). A higher-moisture, warmer atmosphere will have the potential for higher energy storms and weather systems with a higher risk of damaging winds and extreme precipitation events. However changing global circulation patterns are expected to lead to widespread increases in droughts (Dai 2011).

Lau and Nath (2012) have modelled summer heat waves and projected their durations to increase by 20 to 120%, with occurrences at double to quadruple the current frequency in the US and southern Canada by mid-century.

The general consensus from the Fifth Assessment of the Intergovernmental Panel on Climate Change is that on a global scale drought frequency has increased since the 1970's as a result of increasing global temperatures (IPCC 2013). There is "medium confidence" that droughts will intensify during the 21st Century in southern Europe, the Mediterranean, central Europe, central North America, Central America, Mexico, northeast Brazil and southern Africa (IPCC Special Report 2012). Drying in the Mediterranean, southern Africa and southwestern USA is likely as global temperatures increase (IPCC 2013), but it is argued by Sheffield and Wood (2011) that the magnitude of the increase in drought is likely to be overestimated when compared to modelling large scale hydrological changes over the past 60 years.

There is "medium confidence" that monsoon-related interannual rainfall variability will increase in the future. Future increase in precipitation extremes related to the monsoon is very likely in South America, Africa, East Asia, South Asia, Southeast Asia and Australia (IPCC WG1 2013).

Since climate change is giving rise to the likelihood of more drought events, the traditional view of drought as an episodic and rare event to whose future frequency and intensity is informed by historical variability may no longer apply in some areas. Climate change will result in some areas transitioning from experiencing droughts to undergoing encroaching aridity.

1. Africa

Masih et al (2014) conducted a review of drought studies in Africa and concluded that while there are an increasing number of studies on various aspects of drought, none are addressing drought at the long term or continental scale perspective.

Continental Africa has displayed a high decadal and century-scale variability that makes assessment of drought trends difficult (Masih et al., 2014). Tree ring studies of droughts from 1179 to 2002 in northwestern Africa (Tunisia, Algeria and Morocco) show a frequency of drought occurring 12 to 16 times per century prior to the 20th century, and drought occurrences were identified 19 times during the 20th century, with the latter half of the 20th century being the driest period in the past nine centuries (Touchan et al., 2008, 2011, referenced in Maseh et al, 2014). Elsewhere in Africa there was evidence

from several lake sediment studies referenced in Maseh et al, (2014) that more severe droughts had occurred prior to the 20th century, especially in western Africa and east equatorial Africa, however they concluded from the review of the literature and their analysis of droughts from 1900 to 2013 that on a continental scale there is evidence of increased aridity and severity of droughts in Africa during the past few decades.

While there is considerable uncertainty, results of simulations suggest that the frequency and intensity of droughts is likely to increase in western and southern Africa. Western Africa is expected to see the biggest increase in seasonal (4 to 6 month) droughts during the 21st century, followed by southern Africa and then eastern Africa (Sheffield and Wood 2011). Increases in frequency would be from 1.5 events in 30 years to over 4 events in 30 years for western Africa, 3 events in 30 years for southern Africa and 2.5 events in 30 years for eastern Africa, for most emission scenarios. Western and southern Africa are expected to experience similar increases in long term droughts (over 12 months) increasing from less than 0.3 events in 30 years to 1.0 events, whereas eastern Africa is not expected to experience any significant change in frequency (Sheffield and Wood 2011).

2. Asia

It was reported in Dai (2011) that east China experienced fluctuating periods of large-scale droughts during the last 500 years, with more widespread droughts during 1500–1730 and 1900 to present and fewer ones from 1730 to 1900. Severe droughts generally developed first in north China then spread or move south or southeastward. The review by Dai (2011) identified multiple studies that show drying over east China and east Australia in recent decades.

The temperature trend in Asia has steadily increased and precipitation trend in Northern Asia including northern China and Mongolia has decreased since 1955 (Son and Bae 2015). It implies the high possibility of drought threats in these regions. In addition, arid climate regions have increased toward the end of the 20th Century (Beck et al., 2006; referenced in Son and Bae 2015). This implies that Asia is experiencing both drought and aridity. In a study of Least Developed Countries (LDCs) in Asia, Miyan (2015) identified that the monsoon conditions have become erratic, contributing to drought conditions and that the current understanding of climate change in the monsoon regions remains one of the important uncertainties with respect to circulation and precipitation (Hargel et al., 2007; referenced in Miyan 2015). The study concluded that there is gap between research and knowledge generation related to drought in the Asian LDCs. This would leave them particularly vulnerable due to the balance between dense population, high food productivity, dependency upon aquatic systems and a general lack of understanding of the drought hazard.

The frequency of drought in Russia and neighboring countries increases from north to south and in the steppe zone it reaches 30 times a century or more (Kleschenko, 2000). Climate change is believed to already be affecting agricultural production in Russia. A statistical analysis of the drought and mega heat wave that the Russia experienced during the summer of 2010 has suggested that there is an 80% probability that the record heat was a result of climate change (Ramsdorf and Coumou, 2011; referenced in Trenberth and Fausillo, 2012). This however is in contrast to a study by Dole et al. (2011)

that concluded that the magnitude of the heat wave was within the range of natural variability alone. Russia's climate is expected to change more rapidly and drastically than at any time in the past 100 to 150 years, resulting in higher surface temperatures and more hazards such as droughts, floods, heat and cold waves (Safonov and Safonova 2013).

The potential impacts on Russia from climate change have been assessed in a study presented in Appendix 3. An example of the potential changes in bioclimatic potential (%) in Russia's regions for the scenario RCP8.5 from that study indicates that by the end of the 21st century the loss of productivity in the European Russia could reach 40% of current capacity (Figure C-2).

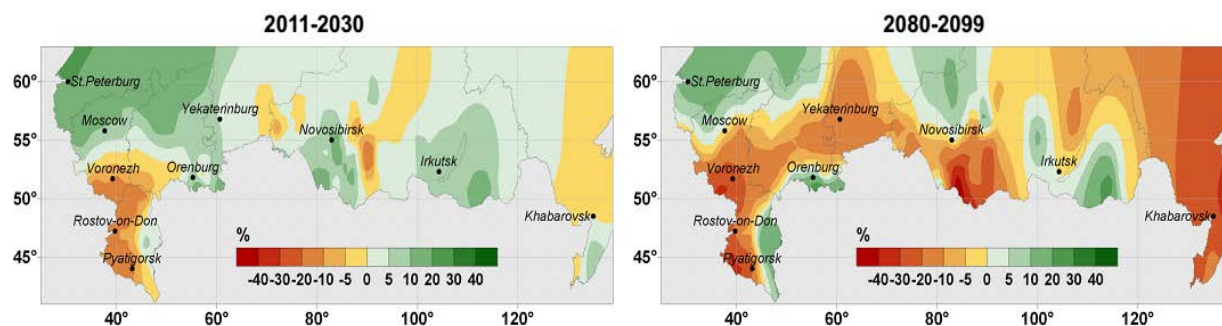


Fig.C-2. Changes in bioclimatic potential (%) in Russia's regions. GFDL CM3, RCP8.5

The study also indicates that by 2050, river flows in the Amu Darya basin, central Asia's longest river, will be 30% less than the current average. Decreasing glaciers in the headwaters will cause late summer flow to decrease drastically, adding risk to water scarcity in the region.

3. South America

Several studies predict a drying of varying degrees in the Amazonia. Cox et al. (2008) estimated the probability of a year like 2005 during which large sections of southwestern Amazonia experienced one of the most intense droughts of the last hundred years causing the river levels to fall to historic low levels, was approximately a 1-in-20-year event. It would become a 1-in-2-year event by 2025 and a 9-in-10-year event by 2060. The Amazon region would undergo changes to the rainfall regime, resulting in long dry seasons and deficient rainy seasons in the future including significant changes in the number of consecutive dry days (Fu et al., 2013; Marengo, et.al. (2009). North-east Brazil and central, eastern and southern Amazonia and central Chile may experience rainfall deficiency in the future, while the Northwest coast of Peru-Ecuador and the northern Argentina may experience rainfall excesses and extremes in a warmer future, and these changes may vary with the seasons. (Marengo, et al., 2009).

Marengo, et.al. (2010) projected climate over South America through the 21st Century showing strong warming (4–6°C), large rainfall reductions in Amazonia and Northeast Brazil (reaching up to 40%), and rainfall increases around the northern coast of Peru and Ecuador and in southeastern South America,

reaching up to 30% in northern Argentina. All changes would become more intense after 2040. The Precipitation–Evaporation (P–E) difference in the A1B downscaled scenario suggest water deficits and river runoff reductions in the eastern Amazon and São Francisco Basin in Brazil, making these regions susceptible to drier conditions and droughts in the future.

Malhi et al (2009) and da Costa et al. (2010) suggest that dry-season water stress is likely to increase evaporation in Amazonia over the 21st Century, the region tending towards a climate more appropriate to seasonal forest than tropical forests having significant implications for the future development of vegetation-atmosphere models and land use and conservation planning in the region. These seasonal forests may be resilient to seasonal drought but are likely to face intensified water stress caused by higher temperatures and to be vulnerable to fires, which are at present naturally rare in much of Amazonia (Huntingford et al., 2013).

Glacier loss and changes in the balance between rain and snow would have significant impacts in some areas where agricultural and domestic water needs are met by meltwater. More than 80% of freshwater available for downstream populations and ecosystems in the semi-arid tropics and subtropics originates in mountains (Messerli, 2001). For example, meltwater from Coropuna glacier in Peru directly supplies approximately 8,000 people with water and indirectly supports 30,000 people (Peduzzi, et al 2010). Stern (2006) estimates that a 1°C temperature increases could cause smaller glaciers to disappear, eliminating the current water supply of almost 50 million people across the Andes (UNEP, 2013). In addition, an accelerated rate of glacier melting will bring an increase of risk of hazards such as landslides, massive flood events referred to as glacial lake outburst floods and avalanches (Chevallier et al,2011; Chisolm et al, 2012) and alter ecosystems (Rabatel et al 2013). Bolivia, Ecuador, Venezuela and Colombia are also undergoing significant loss of glaciers.

In the Chilean Atacama desert, where irrigation for intense agricultural production originates with the harvesting of snowmelt, impacts of climate change are expected to result in the greatest productivity reductions in the highest value crop industries (e.g. grapes, avocado, cherries and oranges) whereas lower value crops such as wheat, oats and potato are expected to see a production benefit (Ponce et al., 2014).

4. North America

Paleoclimate studies have shown that North America, especially the Great Plains region, the southwestern US and Mexico have experienced severe, widespread droughts that lasted up to several decades (megadroughts) (Sauchyn et al. 2015; Bonsal et al. 2012; Dai 2011; Cook et al. 2007). Cook et al. (2007) presented archaeological evidence that megadroughts in the past 1000 years destabilized advanced agricultural societies. These megadroughts have been considered beyond any extreme drought conditions experienced by modern society, indicating that large areas of North America are pre-disposed to periods of extreme drought.

Heim (2017) identified 13 major drought episodes from 1900 – 2014 in the United States. Three of these were decadal droughts (July 1928 – May 1942, July 1949 – Sept 1957, and June 1998 – December

2014). The most recent of these droughts differed from the previous two as it was associated with higher temperatures and more wet conditions in some adjacent areas concurrent with dry areas.

The United States produces a National Climate Assessment (NCA) on a quasi-regular timetable. The third NCA was published in 2014 [NCA3, <http://nca2014.globalchange.gov/>] and the fourth NCA is expected in late 2017 or early 2018. Although focused on the U.S., many of the outputs and graphics in the reports provide a continental view and cover Canada and Mexico as well. Because droughts are complex to measure, changes in droughts across the continent are implied by changes in temperature, precipitation, evaporation, and soil moisture, and are influenced by seasonal variations. The NCAs also provide a look at graphics such as the changes in the maximum number of consecutive dry days, which implies more potential drought if this maximum number of days increases toward the end of this Century. Depending upon the metric, the most consistent message is that droughts will likely increase over the southwestern U.S. and northern Mexico, with less consistency in the message elsewhere.

Meanwhile, individual studies also highlight potential drought changes in the future. Cook et al (2015) used modelled near surface soil moisture to show that under the RCP8.5 scenario, significant drying is projected for the central Great Plains and for the southwest region of the US. This risk of a decadal drought increases from 40% and 60% during the 1950-2000 period for the Central Plains and the Southwest respectively to almost 100% during the 2050-2099 period for both regions. The increase in risk of a multi-decadal drought, defined by Cook et al (2015) as having a duration of 35 years or more, is even more severe increasing from less than 15% to about 80%. Slight increases in wetness are projected for the Northern Great Plains (Canada) however they caution that this could be offset by increased evaporative demand from warming. Dai (2011) also reported that large areas of the US, Mexico and southern Canada are at a higher risk of persistent severe drought in the latter half of the 21st Century.

Seager et al. (2014) projected a similar drying effect for Mexico, Arizona, New Mexico and Texas however their modelling also projects slightly wetter winter conditions and slightly drier spring for California and a shorter, sharper wet season. They attributed the record high temperatures observed during the 2011-2014 drought in California as being made more extreme by human induced climate warming.

Another study by Feng et al. (2017) focused on the central part of the continent, which will likely still be a transition zone in the future. A debate has been taking place related to future drought expectations for this region, so this study investigated modeled time series of eleven indicators that could be potential indications of drought. Because each indicator has different characteristics, interpretations of the future conditions in this central zone of the continent are quite variable. Indicators that utilize Thornthwaite evapotranspiration techniques represent the most dire expectations of the future, which Feng et al. describe as likely too pessimistic related to droughts, while the precipitation and short-term indicators represent either little change or slight drying, and probably under-predict future dryness according to Feng et al. (2017).

5. South West Pacific Region

Impacts of climate change on drought variability in the region will occur in the context of an already high baseline of regular drought occurrence. Therefore, a projected little change to a nation's time in drought of drought occurrence under climate change scenarios should not be interpreted as 'no drought' rather it should be interpreted in the context of little change to the already high occurrence of drought.

Australia

Australia has the largest landmass of any country in the region and spans many climatic zones. The large variability in rainfall received make it difficult to assess projections of future trends — with natural variability tending to predominate the signal over much of northern Australia in the first half of this century. However, for southern parts of Australia that are dominated by mid-latitude weather systems, there is high confidence in the projection of a decline in rainfall received. Unless otherwise stated, projections for Australian drought are taken from CSIRO and Bureau of Meteorology (2015), Climate Change in Australia, Information for Australia's Natural Resource Management Regions.

Hennessy et al. (2008) showed that under a mid-range climate change projection, the frequency of meteorological drought can be expected to increase and occur over larger areas in the southwest corner of Australia as well as Victoria and Tasmania in the southeast during 2010-2040.

The time spent in drought is shown to generally increase for all parts of Australia especially for a high emission scenario (RCP8.5) Figure C-3. While there is a large uncertainty range around the projections of future drought, it should be noted that this does not imply a reduction of future risk. Risk should be assessed from the relative upper and lower future estimates with respect to the current baseline.

For southern Australia, the strong agreement amongst future climate modelling scenarios on the direction of change indicates that the area would see an increased risk of increased drought persistence regardless of the projected uncertainty. Other areas show more mixed results, though the median of the model projections does tend to be above the relevant 1986-2005 baseline for each region with the risk becoming most extreme with the highest emissions scenario.

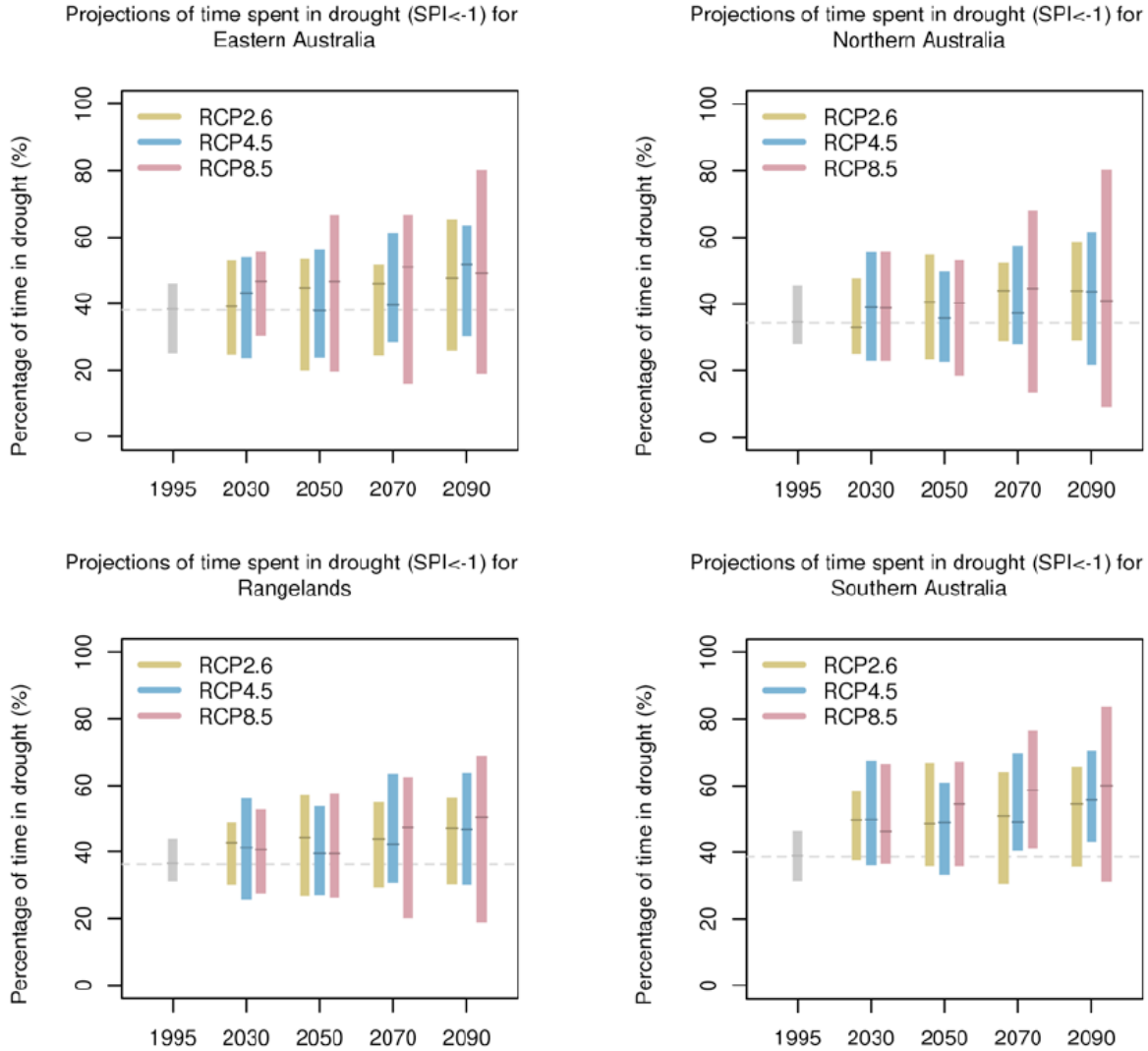


Figure C-3 Median and 10th to 90th percentile range in projected change in proportion of time spent in drought for five 20-year periods. Results are shown for natural variability (grey), rcp2.6 (green), rcp4.5 (blue) and rcp8.5 (purple) for super-clusters. Proportion of the time in drought is defined as any time the SPI is continuously (greater than or equal to 3 months) negative and reaches an intensity of -1.0 or less at some time during each event. From CSIRO and Bureau of Meteorology (2015), chapter 7.

The high degree of model agreement in Figure c-3 adds confidence to the estimates that under by the end of the 21st century Australia would be subject to median drought conditions exceeding 50% of the time regardless of emission scenarios and would range up to a possible 80% under the worst case conditions. The frequency and duration of extreme droughts will rise under all emission scenarios during the 21st century, more so than the frequency and duration of moderate or severe droughts.

Projected soil moisture typically follows the projections of rainfall, with a projected decrease in rainfall corresponding with a projected soil moisture decline over southern Australia, in part due to the projected decline in rainfall received over the region but also due to the increased evaporative demand.

Pacific Island Nations

The time spent in drought including the incidence of drought is projected to decrease for those countries that are positioned close to the equator even under very high (RCP 8.5) emission scenarios (Australian Bureau of Meteorology and CSIRO, 2014). Most countries have no projected change to the time spent in drought and no increase in the frequency of severe drought or a slight decrease in drought frequency. However, countries at the eastern edge of the South Pacific Convergence Zone such as the Northern Cook Islands are projected to have an increase in the time spent in drought under very high (RCP 8.5) emission scenarios and for a decrease in mean rainfall for the for the May-October wet season. Under low (RCP 2.6) emission scenarios the frequency and duration of drought events is predicted to remain similar to current levels.

Time spent in drought in eastern and northern New Zealand is projected to double or triple by 2040 with drought frequency also expected to increase in many regions. Downscaling of earlier projections showed a trend towards increased frequency of drought events in regions that already experience drought. In New Zealand, projected changes to rainfall are expected to lead to reduced runoff in the northeast of the South Island and the east and north of the North Island (Reisinger et al. 2014).

High-resolution climate change scenarios are the basic input for climate change impact, vulnerability and risk assessment studies at regional scales. Countries in Southeast Asia have participated in the Co-ordinated Regional climate Downscaling Experiment (CORDEX) to coordinate and report on results of global climate change projections downscaled to southeast Asian regions. Contributing to this project, Yang (2015) initially found that under 8.5 RCP scenarios, downscaled projections of rainfall for the Maritime Continent regions of Sumatra, Java, Borneo and New Guinea showed a general projected decrease in rainfall received for June to August and September to November when compared to current simulation of rainfall. This may contribute to future drought over these periods Java showed a projected decrease in rainfall received over the March to May period with the other regions showing little change to a slight increase. All regions showed little change over the December to February period.

6. Europe

Climate change in Europe is observed primarily in temperature changes since recorded observations began in the mid-19th century. The European Environmental Agency report Climate Change Impacts and Vulnerabilities (EEA 2017) identified increased temperature have led to the melting of the Greenland ice sheet, arctic seas ice, mountain glaciers and overall seasonal snow cover as well as increases in ocean heat content at depth (between 700-200 m and below 4000m) as well as sea level rise. The report also identified that modelled changes to European climate through the later stages of the 21st century would include continued warming which would be most intense at higher latitudes (Scandinavia, northeastern Europe) and be most prominent in the winter, earlier spring advancement of vegetation, increasing precipitation in high latitude regions especially during winter, and decreasing precipitation in southern regions including the Mediterranean, increased spatial and temporal variability in precipitation overall, earlier snowmelt and spring runoff events and increased risk of severe winter storms in northern,

northwestern and central Europe. Other extreme events such as heat waves, heavy precipitation events and severe spring and summer storms while expected to be more common, are difficult to predict. Most of these changes are expected to have some effect on drought frequency, severity and impacts.

There is consensus in the literature that climate change will bring about an increased risk of drought in Europe however the temporal and spatial nature of that trend is not consistent. Drought occurrences since 1950 have been generally decreasing in North-East Europe whereas the South-West experienced increasing trends during that period (Spinoni et al. 2016). While the 1950s and 1960s experienced drought hotspots in Scandinavia and Russia, the 1970s and 1980s show no outstanding spatial pattern. In Russia, heat waves associated with drought such as what occurred in 2010 have been observed as far back in time as 1875 (Schubert et al., 2014). The 1990s and 2000s were characterised by drought hotspots in the Mediterranean and the Carpathian Region however an overall increase in drought frequency has been observed (Spinoni et al. 2016). Of the 21 major droughts in Europe from 1950 to 2012, six occurred after 2000.

Modelled projections of future droughts indicate that a similar pattern between the north east and the southwest will continue, with an increasing frequency and severity of both meteorological and hydrological drought in southwestern Europe but droughts would become less severe and less frequent in northeastern Europe towards the mid to late 21st Century (EEA2, 2017; Spinoni et al., 2015; Forzieri et al 2014). Significant decreases in summer soil moisture content in the and increases in the number of heat waves and dry spells across most of the Mediterranean area, and increases in soil moisture levels north-eastern Europe are also projected (EEA 2017). Droughts affecting streamflow are expected to become more severe (Lehner et al., 2006; Feyen and Dankers, 2009), especially in the southwest (Forzieri et al 2014; Forzeri et al 2016). Current 100 year events could become as frequent as every two to five years by 2080, and these could affect some portion of the southwest annually by the end of the 21st century (Forzeri et al 2016). Teutschbein et al (2015) pointed out that in Northern Europe there is a large spatial variability among hydrologic catchments, even of similar types, and hydrological responses such as streamflow to changing climate conditions is also highly variable.

European cropland affected by drought is expected to rise by a factor of 7, from approximately 100,000 Km²/year now to over 700,000 Km²/year, with the greatest increase in Southern Europe, followed by the southern region of Central Europe (Ciscar et al., 2014).

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D. The Main Mechanisms Behind Drought Onset and Persistence in order to develop guidance material for drought preparedness.

Key messages:

- The El Niño-Southern Oscillation (ENSO) climate mode of variability is considered the most common source of droughts around the world.
- Severe droughts are mainly brought about by a combination of modes of climate variability such as the interaction of ENSO and decadal modes of variability, most commonly with the Pacific Decadal Oscillation, the North Atlantic Oscillation, the Indian Ocean Dipole,
- The relationship between heat and drought persistence has not been extensively researched however during the Russian heatwave and drought of 2010, an anomalously warm body of air several kilometers deep formed as an inversion over the drought/heat affected area promoting the continuance of clear skies and continued heating.

Drought onset can be looked at as either a deficit in precipitation caused by variability in atmospheric processes or it can result from longterm potential evapotranspiration (PET) changes brought on by changes in temperature and/or solar radiation such as those resulting from climate change.

The influence of heat on drought onset is based on foundational understanding of solar energy and warming. In brief, solar energy reaching the earth's surface is converted to longwave radiation in the form of heat. Because much of the solar energy is converted to latent heat energy, drying out the soil, soil moisture plays a critical role in buffering the land surface from temperature increases. As the moisture is driven out of the soils, more solar energy is converted to sensible heat, resulting in measurable warming of the land surface and consequently the warming of the near surface air. Warm air will maintain water in the vapor phase where it can dissipate in air movement. Increasing air temperature and decreasing humidity levels deprive incoming storms of moisture needed for cloud formation and rain. This sets up a cycle where direct exposure of land surface to daily solar radiation is increased under clear skies, resulting in further warming and desiccation of the surface, prolonging dry conditions.

There are arguments in the literature about the magnitude of the effects of increased PET on global drying. Decreasing trends in precipitation in the Mediterranean have been observed and may be linked to increasing temperatures driving PET (Briffa et al. 2009). Cook et al. (2014) using a CMIP5-driven warming and the Penman-Monteith derived PET found that globally, the increased PET would nearly triple the fractional land area that will experience drying. This however has been countered by Sheffield et al. (2012) who used observational data to determine that globally, drought has changed little over the past 60 years. While we cannot separate the influence on increased heating on current and past drought, in light of the definitions of drought proposed in Section A, discussion of the influence of longterm heating and drying should be wrapped into a discussion about encroaching aridity rather than drought. Therefore further discussion on longterm heating is considered out of scope for this study.

Changes internal to the atmosphere that result in precipitation deficits are brought about by large scale atmospheric teleconnection patterns such as Hadley and Walker circulations and Rossby waves. Forcings, or processes external to the atmosphere, may arise from anomalies in the ocean or land such as sea surface temperature (SST), soil moisture, aerosols, and greenhouse gas enrichment. Climate modes of variability include the relationship of atmospheric pressure and circulation patterns with the oceans, often producing changes in SST. They identify a chain of processes ranging from multi-year timescales over broad spatial scales, where the ocean is the main driver, to regional and local scales where seasonal and daily weather processes and landscape features are main factors. The causes of precipitation deficits both on global scales and regional-local scales and the linkage between precipitation variability, atmospheric patterns and forcing processes have been explained by Sheffield and Wood (2011) and Schubert et al. (2016). Schubert et al. (2016) concluded that decadal changes in SSTs appear to be a major causal factor in the occurrence of long term drought however they identified a number of challenges that remain in our understanding of drought. These include:

- better quantification of unforced and forced atmospheric variability as well as land–atmosphere feedbacks,
- better understanding of the physical basis for the leading modes of climate variability and their predictability, and
- quantification of the relative contributions of internal decadal SST variability and forced climate change to long-term drought.

Major mechanisms behind regional drought

Sheffield and Wood (2011) and Schubert et al. (2016) provide considerable detail in their explanations of atmospheric processes, forcings and drought formation. This section will provide a brief overview relevant to each WMO region.

In mid-latitude temperate regions, especially in North America and Europe atmospheric blocking, generally caused by persistent stationary anti-cyclones, is a frequent cause of drought (Bonsal et al., 2010; Sheffield and Wood, 2011). Oscillation of major ocean currents, such as the North American Oscillation (NAO) push the jet stream to the north (positive phase) resulting in warmer weather for the eastern US and northern Europe, and to the south (negative phase) resulting in intrusions of colder arctic air. Sheffield and Wood (2011) use modelled data to describe drought mechanisms in two locations in the US, one is the southeast and the other in the southwest. The southeast location has a high variability in moisture status but only for short durations, driven by the location of the jet stream meaning that drought can occur at any time but only for short durations. In the southwest which is located in a transition zone between temperature-dry and tropical-dry climates, the climate is much drier. Precipitation is infrequent and highly variable, and wet and dry cycles persist over much longer timescales. In these areas the Inter-Tropical Convergence Zone (ITCZ) varies in location and strength each year and can be a major influence on drought.

The correlation between precipitation variability and SST is strongest through the northern mid-latitudes, the Great Plains of North America, southwest Asia, parts of Australia, the African Sahel region

and South America, and in the tropics strong correlations have been observed in northwestern South America, Indonesia, southwestern India, Central America, southeast Asia (Schubert et al., 2016; Hoerling and Kumar, 2003; Schubert et al., 2004, Giannini et al., 2003).

The El Niño Southern Oscillation (ENSO) is one of the climate modes with widespread influence on drought and wet cycles (Figure D-1), through the spawning the El Niño and La Niña episodes which are the warm and cool phases respectively. It has been considered the most common source of episodic drought around the world (Trenberth et al., 2014). Because this mode occurs in the Indian and southern Pacific oceans, it has direct impact on India, Australia, the south Pacific nations and western South America (coastal Ecuador, Perú and northern Chile). It also has indirect effects on Africa, western South America and the northern Hemisphere.

Multi-year droughts that extend beyond the ENSO timescale may result from longer term climate modes of variability such as the Atlantic Multidecadal Oscillation (AMO) or the Pacific Decadal Oscillation (PDO) or the interaction between modes, global warming or random events originating from internal atmospheric variability (Schubert et al. 2016).

Droughts in the Amazonia region of South America have been a direct consequence of El Niño events, such as in 1912, 1926, 1983 and 1997-1998 (e.g. Aceituno, 1988; Uvo et al., 1998; Williams et al., 2005), however, the ENSO mode does not explain all the variability in drought. Very intense El Niño events have been associated with the extreme droughts in South America during 1925–26, 1982–83, and 1997–

El Niño and Rainfall

El Niño conditions in the tropical Pacific are known to shift rainfall patterns in many different parts of the world. Although they vary somewhat from one El Niño to the next, the strongest shifts remain fairly consistent in the regions and seasons shown on the map below.

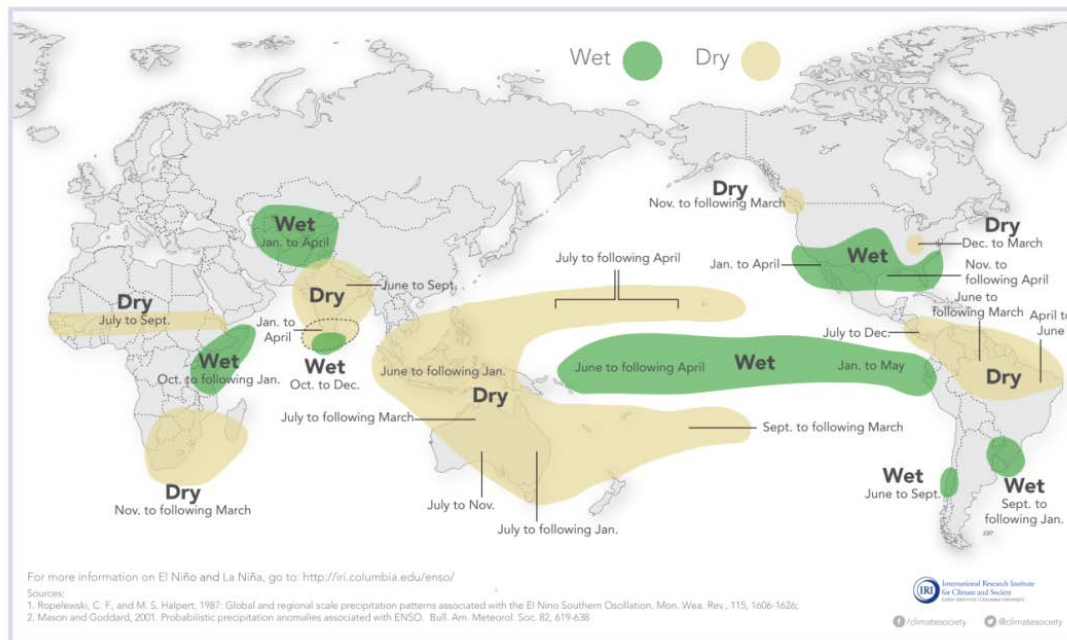


Figure D-1. Typical rainfall effects during El Niño.

Source: <https://iridl.ldeo.columbia.edu/maproom/IFRC/FIC/elniinorain.html>

98, but the last two events were also associated with intense warming in the tropical North Atlantic along with warming in the equatorial Pacific (Marengo et al, 2008). The severe South American droughts in 1964 and 2005 were not related to El Niño, indicating the active influence of Sea Surface Temperature in the Tropical Atlantic on those extremes (Marengo et al., 2008a, 2008b; Zeng et al., 2008). The 2010 extreme drought was related to the successive occurrences of an El Niño in austral summer, and a very warm tropical north Atlantic in the boreal spring and summer (Espinoza et al., 2011; Marengo et al., 2011). Garreaud et al. (2007) also confirmed that the droughts in Amazonia and northeastern Brazil have been linked to anomalously warm surface waters in the tropical North Atlantic. High-latitude forcing, such as by the Antarctic Oscillation and the North Atlantic Oscillation, appear to also play a role in climate variability over South America. (Garreaud et al, 2008).

In east Africa, ENSO accounts for the largest source of variation in seasonal rainfall but depending upon the season and location it can have opposite effects. La Nina is frequently associated with drought during the October – December period in the Horn of Africa whereas El Nino is linked to precipitation deficiencies from June – August further west (Schubert et al., 2016). In southern Africa, drought is also linked to El Nino but it is influenced by the Quasi-Biennial Oscillation (QBO) a mode of climate variability in the stratosphere that is influenced by SSTs in the neighboring Indian and south Atlantic Oceans (Sheffield and Wood, 2011). The QBO was considered strong enough to prevent a drought from the very strong El Nino of 1997-98 from impacting southern Africa (Webster et al., 1999 referenced in Sheffield and Wood 2011). In northern Africa, flow in the Nile River is influenced by El Nino which drives dry years. Recent regional droughts of 1965, 1972-73, 1893-84, 1987-88 and 1997 all correspond to El Nino events (Sheffield and Wood, 2011). The Sahel droughts are influenced by SSTs where precipitation during the June-August rainy season in the west is enhanced by colder SSTs in the eastern tropical Pacific and northern Indian Ocean and warmed SSTs in the tropical Atlantic and Gulf of Guinea (Schubert et al. 2016). Decadal variability is also considered to influence drought in the Sahel. Mohino et al. (2011) suggested the cause of the major droughts during the 1970s and 1980s was a special combination of the positive (warm) phase of the PDO, the negative (cool) phase of the AMO and the global warming trend.

There is considerable literature on the impacts of ENSO on North American weather and climate. In western Canada and the northwestern US (Pacific Northwest of North America) ENSO conditions favor warmer weather from the January-March period during warm phase (El Nino) events (reference) and droughts in the central and southern Great Plains of the US and northern Mexico have been associated with the cool phase of the ENSO cycle (La Nina) (Schubert et al., 2004; Seager et al., 2005; Schubert et al. 2016). However Schubert et al. (2004a) found that the Dust Bowl Drought of the 1930's was associated with both a cool Pacific SST and warm Atlantic SSTs. Similarly the 2006 drought in the central US and the 2007 pluvial event in the US Great Lakes region were associated with an anomalous high centered over the southwestern United States and an anomalous low is over the Great Lakes that promoted the movement of dry air from the north and blocked the entry of low-level moisture from the Gulf of Mexico (Dong et al. 2011). There is also a strong longwave linkage in the Pacific northwest with the Pacific Decadal Oscillation (PDO) where negative (positive) phases of the PDO have been associated with predominantly wet/cool (warm/dry) conditions (Mantua et al. 1997; Gurrapu et al, 2016), which creates

a greater likelihood for droughts during positive ENSO and PDO coupling. Generally SST forcing accounts for up to 40% of precipitation variance through northeastern Mexico, the southern Great Plains and the Gulf Coast areas but less than 10% of the variance in central and eastern Canada (Seager and Hoerling, 2014 referenced in Schubert et al., 2016)

Eastern parts of Australia are more likely to experience dry conditions during an El Niño event, especially during the austral winter and spring (McBride and Nicholls 1983, Wright 1988). Variability in rainfall across Australia occurs as a combination of many remote climate drivers (Risbey et al. 2009). More recently, other climate drivers and their effect on the Australian climate have been explored. Large scale climate drivers such as the Indian Ocean Dipole, which reflects a see-sawing of temperature and pressure in the tropical Indian Ocean similar to ENSO in the Pacific (Saji et al. 1999), and the Southern Annular Mode (Thompson and Wallace 2000) can all have large impacts on the variability of the Australian climate (e.g. Ashok et al. 2003, Hendon. 2007). Some of these drivers can have a compounding effect, with an El Niño event combined with the positive phase of the Indian Ocean Dipole (IOD) combining to generally result in more extensive dry conditions especially during spring over Australia than an El Niño event or IOD alone (Meyers et al. 2007).

In the tropical Pacific the main driver for most countries is the ENSO mode, but other modes such as the Indian Ocean Dipole (IOD) in the Indian Ocean and the Southern Annular Mode (SAM) in Southern Ocean latitudes can play a role in the climate variability of exposed countries in the region such as Australia (e.g. Risbey et al. 2009). An ENSO event represents a major redistribution of heat in the tropical Pacific, changing surface and subsurface temperatures and influencing atmospheric change (e.g. Philander, 1983). Countries in the region, especially those located in the Pacific Ocean experience dry conditions in conjunction with phases of ENSO and also to a lesser extent decadal oscillations in the Pacific such as the Interdecadal Pacific Oscillation (IPO) and the Pacific Decadal Oscillation (PDO).

Rainfall is also highly variable over many tropical countries in the region. As discussed rainfall variability is highly associated with ENSO events but can also vary on decadal timescales due to movements of the Interdecadal Pacific Oscillation (IPO) and the associated South Pacific Convergence Zone (SPCZ). Over the period 1981-2011, research done by PACCSAP shows that the displacement of the SPCZ south-westward during the shift to the negative IPO phase resulted in the southwest Pacific generally becoming wetter and the central Pacific becoming drier (Australian Bureau of Meteorology and CSIRO, 2014).

In Europe the mechanisms causing drought are different and even opposite for the northern and central Europe than for the south and Mediterranean areas (Schubert et al., 2016). The positive phase of NAO will push the North Atlantic jet stream further north bringing warm air to northern Europe and in its negative phase shift the jet stream south resulting in colder temperatures in that area. The reverse is true for southern Europe and the Mediterranean. Droughts in Europe are often caused by high pressure systems blocking or diverting moisture entry from the Atlantic (Sheffield and Wood 2011; Schubert et al. 2014). Droughts in northern Europe and Russia are often associated with wet conditions or to the east, suggesting a west-east atmospheric wave structure (Schubert et al., 2014). While it is unclear how the influence of the NAO and the AMO affects low frequency drought occurrences, and therefore the

predictability of drought, SSTs generally have little influence on annual precipitation variability. Drought occurrences accompanied by heat waves are not uncommon to Europe and there is evidence to suggest they date back to at least 1875 (Schubert et al., 2014).

The role of heat in drought onset and persistence

The relationship between heat and drying is well presented in the published literature (Trenberth 2011; Muller and Seneviratne 2012...). The basic principles are that over land surfaces, incoming solar radiation is largely absorbed as latent heat in the evapotranspiration of soil moisture. As the soil moisture depletes, a greater portion of the incoming energy is converted to sensible heat, warming the land surface and consequently raising the air temperatures. Water is therefore moved from the soil into the atmosphere where it can be transported by air movement. Moderate to heavy precipitation cannot be supported by evapotranspiration without convergence of air masses from storm scale circulation (Trenberth et al. 2003). Storms therefore gather atmospheric moisture from areas 10 to 25 times the size of the precipitation area, a ratio that seems to apply to storms ranging from thunderstorms to extratropical cyclones to tropical storms (Trenberth et al 2007). In the absence of changes in winds increased heating results in more moisture being transported away from divergence zones such as the subtropics and into convergence zones in the tropics and in the higher latitude storm tracks resulting in increased drying in the typically dry divergence zones and increased wetting in the typically wetter convergence zones (Trenberth 2011). Changes in winds and changes in moist static energy result in an overall shift that widens the tropics and pushes the storms tracks toward higher latitudes (Yin 2005; IPCC 2007; referenced in Trenberth 2011). Ocean currents and sea surface temperatures would have a significant effect on these processes *as discussed previously*.

On a regional scale, several studies have either correlated (Mueller and Seneviratne 2012) or associated (Hoerling et al. 2012; Trenberth and Fasullo 2012) drying with extreme heating generally as cause (drying) and effect (heating). Studies of the extreme heat waves in Russia in 2010 and Texas in 2011 showed that both of them were preceded by very dry conditions (Hoerling et al. 2012; Trenberth and Fasullo 2012). In both cases teleconnections played a major role in the onset and persistence of these droughts and heat waves. The Texas heat wave and drought were primarily a result of normal fluctuation in sea surface temperature, most notably the La Nina and to a lesser degree the warm waters of the western tropical Atlantic (Hoerling et al. 2012). The Russian drought and heat wave of June-August 2010 has been connected to severe flooding in Pakistan (Lau and Kim 2012; Trenberth and Fasullo 2012). An anomalously strong blocking pattern established over western Russia in mid-July resulted from fluctuations in air pressure systems in a wave pattern from the southeastern United States and northwest through the tropical north Atlantic and Europe during June, in particular a high pressure (anticyclone) system in the tropical north Atlantic (Trenberth and Fasullo 2012). Another wave pattern in eastern Russia linked Siberia to Asia southern and high sea surface temperature in the northern Indian Ocean. These patterns, and especially the influence of the warm water in the tropical North Atlantic and in the northern Indian Oceans were considered the main reasons for the blocking pattern re-establishing itself and intensifying the heat wave in late July (Lau and Kim 2012; Trenberth and Fasullo 2012). Among other influences in circulation patterns, the series of interconnected systems (wave train) from

Siberia to Asia included a cold front moving from Siberia to Iran and Pakistan where it mixed with the warmer moisture air to contribute to the flooding in Pakistan (Lau and Kim 2012).

The explanation of the soil moisture-temperature feedback process that includes the relationship between extreme heat and drought persistence is not as well documented. For the drought and heat wave in Russia in 2010, Lau and Kim (2012) and Miralles et al (2014) provide an explanation that the cycle of incoming solar radiation warming the land surface, in the absence of significant water evapotranspiration, resulting in reduction in clouds and precipitation which allows more downward solar radiation, resulting in more warming and desiccation of the land, causing even more reduction in cloud and precipitation and increase in atmospheric stability. The study by Miralles et al (2014) found that during the 2003 European and the 2010 Russian heat waves, the heat generated during the day was preserved overnight in an anomalous atmospheric layer up to 4 kilometres deep that was located several hundred metres above the surface. This heat was available to re-enter the atmospheric boundary layer during the next diurnal cycle, resulting in a progressive accumulation of heat over several days. This accumulation enhanced soil desiccation and led to an intensification of convection and further escalation in air temperatures. Therefore the heat waves were a result of prevailing synoptic patterns, high atmospheric demand for moisture that desiccated soils and created a strong sensible heat flux, subsequent diurnal convection that favored storage of warm air high in the atmosphere and the formation of persistent, deep, warm nocturnal layers that allowed heat to re-enter the near-surface layers, accelerating daytime heating. If any storm system was able to break through the synoptic patterns and enter these areas, it would not only be starved of moisture to generate precipitation but would be deprived of the cooling needed to condense atmospheric moisture into precipitation.

Rapid Onset (Flash) Droughts

The onset of drought in the US Great Plains in 2012 was fast and unexpected. All hydrologic conditions, such as soil moisture levels, during the spring did not indicate that the area would be vulnerable to drought. A period of anomalously high temperatures and/or, high winds and sunny skies lead to increased evapotranspiration that can result in rapid soil moisture depletion and quickly damage vegetation even in the presence of precipitation (Otkin et al., 2013). The term flash drought was used to describe the 2012 drought (NOAA Drought Task Force 2013) and their occurrence over time has since been studied (Mo and Lettenmeier 2015). Conditions change so rapidly that analysis has been based in 5 day groupings (pentads) (Mo and Lettenmeier 2015).

These types of droughts occur quickly and can happen without a significant drop in precipitation. Consequently the conventional precipitation and vegetative based drought indices cannot detect their onset, and it goes undetected by early warning systems. Typically these occur in warm seasons in the US and therefore they can have a great impact on agriculture (Otkin et al., 2013).

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E. Report and make recommendations to CAgM on existing drought indices and potential new drought indices in consultation with the Integrated Drought Management Programme (IDMP).

A review of drought indices and their use in several countries has been conducted by the World Meteorological Organization (WMO) and Global Water Partnership (GWP) (2016). The review produced a handbook that identified some of the most commonly used drought indices that are being applied operationally in drought-prone areas in order to advance monitoring, early warning and information delivery systems. These in turn support risk-based drought management policies and preparedness plans. This section of the report will discuss some most commonly used indices identified by the World Meteorological Organization (WMO) and Global Water Partnership (GWP) (2016) and also review literature about some other and new indices that may have utility in drought studies.

Generally in the assessment of the existence, severity and/or extent of drought, one index is not used alone nor is it applied to a wide variety of geographically dispersed drought situations. A series of indices are typically used in order to capture the creeping nature of drought in the context of a spatially and temporally variable climate (Wilhite 2011). Indices are data driven therefore the availability of data in a temporally and spatially consistent pattern over several years is required to effectively identify the variability in the data record that can identify drought.

E.1 Precipitation based indices

The SPI and SPEI

The Standardized Precipitation Index (McKee et al., 1993) was developed as a statistically robust method that can be applied over multiple time scales to assess precipitation variability, both deficits and surpluses. The index required only precipitation data is based on the period of record for as few as one observation station. The methodology normalizes the historical distribution of precipitation then standard statistics can be used to describe the deviation, either positive (wet) or negative (dry). The longer the period of record, the more robust the assessment becomes. Time periods are user defined and tend to range from one to sixty months, depending upon the nature of the variability the user wants to assess.

A meeting of 54 international drought experts at the University of Nebraska in Lincoln Nebraska in December 2009 reviewed the drought indices currently in use and approved the “Lincoln Declaration on Drought Indices”. The declaration recommended that the Standardized Precipitation Index (SPI) be used by all National Meteorological and Hydrological Services (NMHSs) around the world to characterize meteorological droughts, in addition to other drought indices that were in use in their service.

The Standard Precipitation and Evapotranspiration Index (SPEI) was developed to better represent the soil water balance by combining an evapotranspiration factor into the simple calculations and flexible timescales offered by the SPI (Vincente-Serrano et al., 2010). The inclusion of a term for evapotranspiration, particularly when evapotranspiration is calculated using the Penman Monteith

equation, has resulted in the SPEI being slightly superior to the SPI when correlated to droughts (McEvoy et al., 2012; Vicente-Serrano et al., 2012; Kingston et al., 2014).

Care needs to be taken in interpreting these multi-scalar indices for drought impacts. The SPI has limited application over a range of climatic conditions, primarily due to the focus of the index is entirely on precipitation without consideration of other meteorological or hydrologic variables, and the focus on the historical precipitation distribution. Figure E-1 shows how the SPI would apply different areas with vastly different precipitation distributions in Canada (Howard et al., 2012). The median precipitation ranges from 350 mm/yr to about 1800 mm/yr generally from west to east. An SPI of -3, an extreme drought, would represent an annual total of less than 250 mm/yr on the Canadian Prairies to almost 1250 mm/yr on the Atlantic coast. While an SPI of -3 represents an extreme deviation with considerable local impacts, the absolute difference in total rainfall means the impacts on environmental or agricultural activities would differ considerably from the Prairies to the Atlantic coast. Interpretation of SPI for drought impacts should be limited to regional analysis where climatic conditions are similar. The SPEI was not tested however due to the similar methodologies, the same caution would apply.

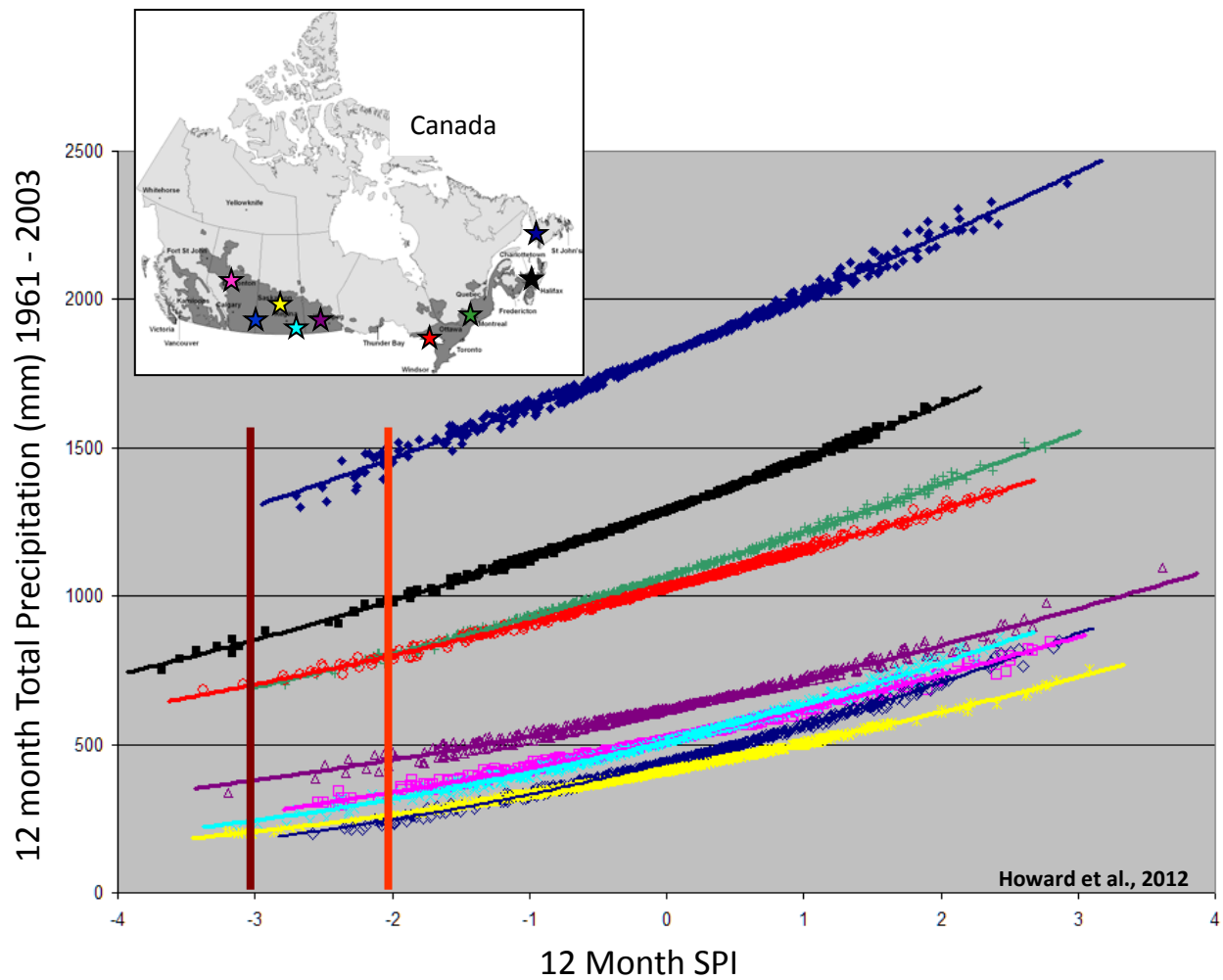


Figure E-1. Regional variation of precipitation associated with the SPI at meteorological monitoring stations across Canada.

The PDSI

The Palmer Drought Severity Index (PDSI) (Palmer 1965) has been used to quantify long-term changes in aridity over global land in the 20th and 21st century (Dai 2011; Sheffield and Wood 2008), and in tree-ring based reconstructions of paleo drought (Cook et al., 2004; Sauchyn and Skinner 2001). The PDSI values have been used to determine drought conditions in forested landscapes (Kim et al. 2013) and have been significantly correlated with warm season streamflow and soil moisture levels in many parts of the world and can be used in low and mid latitudes and a drought index (Dai 2011).

Its initial limitations were that the empirical constants used to characterize climate were averaged values from a few locations representing a small range of climate variability, limiting spatial comparison of the index (Wells et al. 2004) and a recommendation that it not be used to compare conditions at different locations (Guttman, 1998). The range of drought was also limited by use of 30 year climate records, which were found to not capture the full range of climate variability. It also did not identify contributions from snowmelt, and while it has a memory component built into to represent antecedent conditions, it is purely mathematical and is not sensitive to changing biophysical processes. Some studies have successfully coupled soil moisture models with the PDSI to refine soils moisture estimates from snowmelt (Akinremi et al. 1996). Advances in computing technology made it possible to improve the performance of the PDSI by dynamically replacing the averaged constants with values based on the characteristics of the local climate. Wells et al. (2004) presented a self-calibrated PDSI (SC-PDSI) that automatically calibrated the index by replacing the constants with dynamically calculated values for any location, adjusting the sensitivity of the index, and enabling it to better capture extreme wet and dry events. Improvement to the evapotranspiration component of the PDSI has also been made by using the Penman-Monteith model instead of the original Thornthwaite model (Dai 2011). It is now a commonly used reliable index referenced in many recent research publications.

Comparisons between the SPEI and SC-PDSI with historic droughts in China have shown that the SC-PDSI was better correlated with SPEI and with historical records for droughts of medium and long duration (9 to 19 months) and therefore can be used to monitor changes in streamflow and groundwater levels (Zhao et al., 2015). However the study concluded that it was insensitive to short duration droughts and to drought recovery phases whereas the SPEI was more suitable to monitoring short, medium or long term droughts due to the flexible timescale.

E.2 Evaporative Demand Indices

The Evaporative Stress Index (ESI)

The launch of the Moderate Resolution Imaging Spectroradiometer (MODIS) opened the door to the potential for monitoring both vegetative photosynthetic activity and land surface temperature that allow the determination of moisture fluxes over the canopy and ultimately moisture stress over areas large enough for operational drought monitoring. The Evaporative Stress Index (ESI) was developed using changes in land surface temperature to estimate actual evapotranspiration (ET) and then determine anomalies in the ratio of ET to evaporative demand, also referred to as potential evapotranspiration (E_0) (Anderson et al., 2007 a,b). The ESI has been found to be well-suited to detect

rapid onset droughts (flash droughts) because it is sensitive to rapid decreases in ET that precede drought onset (Otkin et al. 2013), drought intensification (Otkin et al., 2014) and useful early warning capabilities at sub-season timescales in the United States (Otkin et al., 2014; 2015). The ESI also correlated well, spatially and temporally, to short-term (up to 6 months) precipitation-based indices (SPI and PDSI) and with the U.S. Drought Monitor for the 2000 – 2009 growing seasons, without requiring any precipitation data (Anderson et al., 2011). The ESI also provided some unique information on where moisture stress was being alleviated by active water management (e.g. irrigation) or natural processes decoupled from precipitation (e.g. shallow water tables) during the 2000 -2009 growing seasons (Anderson et al, 2011). Then ESI has also correlated well to corn, soybean and cotton yields from 2003 to 2013 in most areas of Brazil (Anderson et al., 2016). It is however not effective under cloudy conditions because of its dependence on optical satellite data. The index is currently in operational use as one of a suite of indices for assessing drought in the U.S.

The Evaporative Demand Drought Index (EDDI)

The Evaporative Demand Drought Index (EDDI) can serve as a detector of both rapidly evolving (flash) droughts and sustained droughts. It has been shown to have significant promise as a primary indicator of drought and early warning of drought stress relative to current operational drought indicators, such as the US Drought Monitor (USDM) (Hobbins et al., 2016).

The EDDI is based on the behavior of evaporative demand (E_0). During period of precipitation decline E_0 will increase as soil moisture depletes (ET decreases) and land surface temperature increases. It will also increase under heat or high wind conditions even if ET increases and precipitation is not significantly declining, such as in the case of some flash droughts. Therefore the anomalies in E_0 relative to a climatic median can be used to detect drying/dry (E_0 becomes positive) or wetting/wet (E_0 becomes negative) conditions. EDDI relies on input from the North American Land Data Assimilation System (NLDAS-2) dataset, a modeled data layer of the continental US, northern Mexico and southern Canada at a 1/8 degree resolution containing several meteorological variables reanalyzed from observation station, remote sensing and simulation data.

Evaporative demand can be a sensitive indicator of water stress and EDDI can operate at multiple timescales ranging from weekly several months, offering the potential to be both an early warning indicator of emerging drought and a tracked of existing drought conditions. EDDI uses a similar classification scheme as the USDM to identify the frequency of occurrence of drought severity levels, so it can be easily compared to and used with the USDM. The EDDI has advantages over the ESI in that it is not dependent upon clear sky conditions and it is effective in areas where moisture levels and ET are not dependent upon precipitation, such as irrigated areas and areas subjected to high water tables (Hobbins et al., 2016). EDDI is slated to be operationalized at the NOAA National Water Center by May 2019.

Both the ESI and the EDDI are not directly dependent on observation station data and as a consequence they can be used in data sparse areas. Further validation of these indices is ongoing to better understand their applicability to a range of climate conditions internationally.

E.3 River system based

In Spain in the Segura River system, irrigation accounts for a very high proportion (over 80%) of the water demand. Water released from reservoirs was found to be closely linked to demands and considered a good method for assessing water deficits (Sivakumar et al., 2011). A basin specific indicator that represented water deficit was developed based on a time series relationship between runoff and water released from reservoirs that spanned over 60 years of monitoring in the basin. From the indicator a monthly index could be developed that, supported by SPI data, enabled an assessment of four levels of drought severity.

E.4 Some Examples of Uses of Drought Indices in Operational Monitoring

In the Southwest Pacific Region, drought is largely monitored using rainfall based indices across the countries in the region, with the longer nature of rainfall records most able to provide a historical context for recent drought occurrence. The two most commonly used rainfall indices are rainfall deciles (e.g. Gibbs and Maher 1967) and the Standardized Precipitation Index (SPI) (McKee et al. 1993). Rainfall indices such as the SPI and Deciles have the benefit of being able to monitor extremely wet periods as well as extremely dry, which is important in the region. Furthermore, observations of rainfall have the benefit of being easier to communicate and able to be analysed more easily on facilities within the country. No large computing resources or fast internet connections are needed, which can be an operational issue for some countries in the region. Analysis periods are chosen that historically have impacted on resources.

Drought is often defined in terms of impacts not necessarily just rainfall deficits (e.g. Wilhite, 2007). In some cases indices that report more directly to the impacts of low rainfall such as soil moisture or vegetation indices are used. Some countries in the region, such as New Zealand, are moving to more impact-based information to support the rainfall analysis, such as days of soil moisture deficit and depth of potential evapotranspiration deficit in New Zealand's case (WMO and GWP, 2016). Rainfall deciles have a long history of use over Australia. They have been used in the monthly Drought Statement since the mid-1960's. The Australian Bureau of Meteorology has recently included commentary on modelled soil moisture as part of its monthly Drought Statement (www.bom.gov.au/climate/drought/).

When determining the periods of analysis in countries in the region a history of droughts in the country is examined and a drought trigger is used based on historical rainfall records. A variety of relevant timescales of SPI and Deciles are used across the region. For countries in the region with a tropical regime, shorter timescales are able to capture short- and medium-term moisture conditions and provides a 'within' wet or dry season estimation of rainfall. A 3-month index may be useful for monitoring soil moisture levels associated with shallow rooted crops and for monitoring small streams and small rain water tanks. A 6-month averaging period can indicate seasonal to medium-term trends in rainfall and is likely to be relevant for medium-sized fruit trees, and common deeper rooted crops across the region like mature sugar cane and Kava and also for monitoring small rivers. The 12-month percentile method is usually tied to mature trees, river flows, reservoir levels, and shallow or household wells. For ground-water on atolls longer 24-, 36-month or longer indices are ideal as the residence times of these fresh water lenses are large.

Canada, the United States and Mexico collaborate to produce the monthly North American Drought Monitor (NADM). The NADM is based upon the United States Drought Monitor (USDM) and uses a convergence of evidence approach to identification of drought conditions. Due to the complexity of drought conditions, no single index is used and the blend of indices varies from one country to another depending upon data, the season and climate variability. In all cases, the determination of conditions is verified on the ground. Expert judgement is used to ensure that drought areas are consistent near and across international borders. Drought conditions are expressed in terms of:

- severity, a five point scale of Abnormally Dry (D0) Moderate (D1), Severe (D2), Extreme (D3) and Exceptional (D4); and
- persistence, areas of short term (less than 6 months) and areas of long term (greater than 6 months) are delineated and superimposed on the severity polygons on the map.

Indices used in the NADM include various combinations of the PDSI and SPI (over 1, 2, 3, 6, 12 and 24 month periods), satellite based vegetative indices and modelled soil moisture. While the NADM provides a broad scale view of drought across the three countries plus the Hawaiian Islands and Puerto Rico, no drought conditions are identified for the Canadian Arctic as yet. The broad areas with sparse observation stations, and reduced levels of vegetation due to perennially dry and cold conditions, require a stronger means for validation of the impacts of conventional indices under dry polar conditions.

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