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Californian Drought: The Processes and Factors Controlling the 2011-2016 Drought and Winter Precipitation in California

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Bachelor thesis, 15 credits, in *Physical Geography and Ecosystem Science*

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Abstract

The factors and processes controlling winter precipitation in California and the 2011-2016 California drought have been examined in a literature study. The study showed that mid-latitude cyclones are the systems that generate winter precipitation in California. The location of high- and low-pressure systems in the northeast Pacific Ocean have a huge impact on the winter precipitation as they largely determine the direction of the jet stream, which transports the moisture-holding cyclones in over the North American west coast. Baroclinic instability and warm sea surface temperatures determines the intensity of cyclones. Orographic precipitation in mountainous regions is a significant mesoscale process, through which snowpack accumulates. Furthermore, the phases of the El Niño-Southern Oscillation and the Pacific decadal oscillation generally affects Californian winter precipitation to a degree. The El Niño-Southern Oscillation probably affected the drought, but the Pacific decadal oscillation influence on the drought is unclear. Global warming and climate change surely influence the aridity in California, but the drought was probably mainly caused by natural variability.

Keywords: California, drought, winter precipitation, mid-latitude cyclones

Torka i Kalifornien: Processerna och Faktorerna som Styr Torkan 2011-2016 och Vinternederbörden i Kalifornien

Sammanfattning

Faktorerna och processerna som styr vinternederbörden i Kalifornien och torkan 2011-2016 har undersökts i en litteraturstudie. Resultaten visar främst att mellanbreddslågtryck i form av cykloner är de system som genererar vinternederbörd i Kalifornien. Hög- och lågtryckens läge i nordöstra Stilla Havet bestämmer jetströmmens gång som transporterar cyklonerna mot öster, in över den Nordamerikanska västkusten. Baroklinisk instabilitet och varma ytvatten i havet bestämmer cykloners intensitet. Orografisk nederbörd är en viktig process i delstatens bergsregioner. Genom det byggs snötäcken upp som lagrar vatten. El Niño-sydlig oscillation och Pacific decadal oscillation's faser påverkar vinternederbörden i Kalifornien till en viss grad. El Niño-sydlig oscillation påverkade troligtvis torkan, men Pacific decadal oscillation's inverkan på torkan är oklar. Den globala uppvärmningen och klimatförändringarna har troligtvis påverkat torkan, men den var sannolikt främst orsakad av naturlig variation.

Nyckelord: Kalifornien, torka, vinternederbörd, cykloner

Abbreviations

ENSO - El Niño-Southern Oscillation

GHG - Greenhouse gas

PDO - Pacific decadal oscillation

PDSI - Palmer drought severity index

S_f - Snow fraction

SOI – Southern Oscillation Index

SST - Sea surface temperature

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1 Introduction

1.1 Background

Water is a crucial factor for all living organisms on Earth. The level of water abundance for any given land surface plays a huge part in the prerequisite for life there. Droughts can therefore have a large impact on the environment. They occur in many parts of the world. California, the United States' most populous state, is currently experiencing a severe drought. The state is situated in the Western United States, and has a long coastline in the west that faces the North Pacific Ocean. The drought started in 2011/2012 (some have studied it from 2011, e.g. Seager et al. (2015), while others recognized it as starting in 2012, e.g. Yoon et al. (2015)). In April 2015, California Governor Edmund G. Brown Jr. announced that water use reductions of 25% would be implemented in the cities of California. This was the first time such restriction had been enforced in the state, which is a sign of the hydrological crisis that California is in. Still, the majority of the water use in California goes to irrigation of agricultural fields.

The Central Valley, located in the center of the state, is an important agricultural region in California where a majority of the nation's vegetable, fruit and nut productions are cultivated. However, since the valley doesn't receive the levels of precipitation that are needed for the production, it is highly dependent on irrigation collected through ground water pumping and surface water use (Bertoldi et al., 1991; Reilly et al., 2008). Wang et al. (2016) found that, since the beginning of the 2000s, drought in the Central Valley lowers the groundwater levels during the drought period and for an entire year after the drought has ended. The current drought has nevertheless increased farmers' need for irrigation. As a consequence of water deficits in the Central Valley, fields have dried up and some of the local farmers are left jobless. Ecosystems in California, such as grasslands and shrublands, as well as cattle farming are also affected by the drought (Potter 2015). Because of these negative consequences of drought, the precipitation in California is a highly valuable resource for its residents.

Precipitation in California is mostly falling during winter (Raphael and Mills, 1996; Lundquist et al. 2008). Mid-latitude cyclones are mainly responsible for the Californian winter precipitation, and much of the total precipitation in California falls over the mountains of California. Normally during winter in California, moisture holding cyclonic storms sweep in over the Californian west coast region (Raphael and Mills, 1996). They originate over the Pacific Ocean and move in over the North American continent. Hence, a portion of cyclonic storms reach California (Sheppard et al. 2002). But Californian precipitation is a complex issue, for a number of reasons. The state has a dynamic topography that varies greatly. The Central Valley is a flat region. Directly to the east of the valley lies the mountain range Sierra Nevada. The distance from the coast to the

Sierra Nevada is some hundred kilometers (Lynn et al. 2007). The snowpack that results from snowfall in the Sierra Nevada provides the Central Valley with water for the crops, especially during the spring and summer half year when the precipitation levels are low. There are also some mountain ranges along the Californian coastline. This variation in elevation is affecting the type and amount of precipitation that is falling in the state. One of the reasons for the high annual precipitation variability in California is the fact that there are relatively few storms per year that come and release precipitation over the state, and these storms, depending on their number and magnitude, can create both low and high precipitation levels in California, according to Dettinger and Cayan (2014). In their analysis, the California Delta catchment precipitation variations during much of the 20th and the beginning of the 21st century were much more determined by the variation in large storm precipitation than normal storm precipitation.

Furthermore, California is located in more than one climate zone: the northern part of the state is situated in the southern mid-latitudes and the southern part of the state is located in the subtropics. As the atmospheric circulation and the climate in general differ between the mid-latitudes and the subtropics, so does the precipitation. It is not unusual that the northern parts of California experiences more than double the amount of precipitation than south California does (Jones 2000).

Because of the importance of sufficient precipitation for California, and also because of the complexity of the Californian precipitation controls, studies on the underlying processes for the state's precipitation, and especially winter precipitation, are needed. Many of these processes originate far away from the state borders, but their impact is still of highest relevance. Therefore, this study gives an overview by gathering some of the existing knowledge of factors that may in one way or another affect winter precipitation in California. Lastly, the influence of global warming and climate change on the drought is also briefly looked into in this thesis.

1.2 Aim

This thesis aims at identifying the main meteorological processes and factors that cause the 2011-2016 California drought and control the winter precipitation in California. It also tries to determine how and to what degree these processes are influenced by global warming and climate change.

1.3 Focus

Though the current California drought is the focus of the study, previous studies that provide historical information and perspectives are included in this literature study. This was done in order to be able to relate the current drought to the long-term patterns and variations in precipitation, as well as previous drought periods.

The meteorological processes that the aim refers to are the ones that proved to be the most researched in the articles included in the literature study. Relevant climate and weather systems was looked into, specifically the ones that are prominent during the winter months or that are affecting California's winter precipitation in other ways. The meteorological processes studied were primarily synoptic scale mid-latitude cyclones, other low- and high-pressure systems and the associated winds, mesoscale orographic lifting, the global scale El-Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO), and sea surface temperature (SST) forcing.

California has the largest interannual precipitation fluctuations when looking at the contiguous United States (Shukla et al., 2015) and as mentioned earlier, the majority of it falls during the winter. According to Shukla et al. (2015), drought during December was more associated with annual drought in California than any other month, based on the period 1895-2013. Motivated by this general yearly precipitation pattern, this study focus on California's winter precipitation. Regarding the definition of the winter months, no set start and end month for the winter period was defined for this thesis (see subsection 2.2). Apart from precipitation, temperature is another climatic drought factor. According to Weiss et al. (2009), increasing air temperatures means that the atmosphere can hold more water, and also cause an increase in the evapotranspiration. Because of the increasing complexity when including temperature changes in the analysis, this study does not focus on it. Temperature is only looked on where it is linked with Californian precipitation, e.g. SSTs in the Pacific Ocean and air temperature in Californian mountains.

I do not look into the relationship between the ground water levels and the drought, and do therefore not include the human influence on the drought in terms of ground water pumping or surface water usage. The influence of anthropogenic activity was only regarded through the effects of global warming and climate change.

2 Definitions

2.1 Drought

The basic concept of drought is well-known: deficit of water. However, a clear definition of the word is harder to formulate; the term drought can seem quite vague. A reason for the hardships of grasping a specific explanation of the concept of drought is that it is mostly based on the absence of a factor, namely water. Wilhite and Glantz (1985) investigated this problem of definition. They concluded that there is no point in having a universal definition of drought. Because of the varying relationships between droughts and different parts of societies and economies, it is natural to have numerous definitions. They present specific definitions that are from meteorological, agricultural, hydrologic, and socio-economic point of views. According to Dettinger and Cayan (2014), the drought is meteorological, agricultural, hydrological, ecological, municipal, and regional.

Of these different definitions, the meteorological definition is the most commonly used (Wilhite and Glantz, 1985), and it is the most relevant for this study, as it presents meteorological theory connected to the current drought. For this thesis, drought is defined as a deficit of water caused by meteorological processes.

When I'm referring to the current drought, I mean the drought that has been ongoing from 2011 to 2016 in California. Within this 2011-2016 drought, one can identify or define shorter droughts, which has been done in many of the studies that have been looked on. All of the articles studied focus on single years or just a few of the years between 2011-2016. This thesis will thus also focus on shorter drought periods, in order to present the research in the most accurate and representative way.

2.2 Winter period

The studies reviewed define the winter period in different ways. No article was dismissed because of its definition of winter, and therefore there are variations in which months that constitute the winter period. Some articles include November in their definition, and the last month of the period varies greatly, from January to April. Seager et al. (2015) even looked at the entire winter half year, from November through April. Wang and Schubert (2014) focused on January-February because of these months' very low precipitation values in 2013. Wang et al. (2014) and Funk et al. (2014) looked at the winter months November-January, etc.

2.3 Southwestern United States and North America

Since a number of articles that focus on the southwestern United States are reviewed, the definition of that expression is highly relevant in how much of the state of California is included in that geographical region. In *Land, Sky, and People: The Southwest Defined*, Byrkit and Wilder (1992) refers to National Geographic's map *The Southwest* from 1982, in which the Mojave and Colorado Deserts in California are included in the Southwest, and the rest of California is excluded. There deserts are located in the southeastern part of California. Sheppard et al. (2002) define the Southwest in their paper mainly as the states Arizona and New Mexico, but California is mentioned in the study, as it influences the climate in these states. Seager et al. (2015) write about the southwestern North America, and seem to include the whole of California in that definition. Collins et al. (2013) mention climate predictions regarding southwestern United States and southwestern North America, but they do not define the region in any way, which probably means that at least parts of southern California is included. In Schimmelmann et al.'s (2002) article, southwestern USA implies southern California, New Mexico and Arizona. Only the southern The definition of the Southwest in this study is based on National Geographic's map *The Southwest*. Therefore, the southeastern region in California is the only part of the state that belongs to the Southwest.

3 Method

The majority of this thesis was performed through a literature study, where articles, reports and books were reviewed. ENSO and PDO data was analyzed graphically. Since the ENSO and PDO have shown to influence precipitation in California (see subsections 6.3 and 6.4), I have plotted graphs showing index data of the ENSO and PDO through past decades. The ENSO and PDO indexes were also plotted through 2011-2016 only, to be able to relate these oscillations specifically to the drought. The index data was acquired from the National Oceanic and Atmospheric Administration's National Centers for Environmental Information, and the graphs showing the indexes were made in Excel.

4 Observations of historical droughts and patterns in California

Because reliable weather station data in the western United States have only been recorded for a little over 100 years, California's entire climate variability can probably not be identified by it (MacDonald 2007). To gain knowledge of how the Californian climate and drought has varied through the past several hundred years, tree-rings, among other thing, can be analyzed. MacDonald (2007) analyzed cores from local limber pine (*Pinus flexilis*) trees and deadwood in southern California that stretch back more than 1300 and 2000 years, respectively. Palmer drought severity index (PDSI) values (a measurement of dryness) based on the tree-ring records were estimated and plotted for the winter period January-April, from 90 AD to present. He found traces of a long-term drought ranging from the 9th century to the 14th century. In more recent time, the PDSI values showed droughts during large parts of the 17th century and during the end of the 19th century. For the 9th-14th century drought, he presents additional evidence of drought from northern parts of California like the Sierra Nevada Mountains and the Sacramento River.

MacDonald (2007) discusses the cause of the 9th - 14th century drought, based on climate models: A decrease in volcanic activity and an increase in insolation caused an increase in the SST difference between the west and east Pacific Ocean. This led to La Niña circulations (see subsection 6.3). A reconstructed PDO index has shown that a cool PDO phase (see subsection 6.4) can have existed during the 10th, 11th, and 12th centuries, which means that cool SSTs in the eastern North Pacific probably caused a high-pressure ridge that prevents wet weather from coming in over California (see subsubsection 6.1.1). An STT reconstruction from the Santa Barbara channel that show cold SST temperatures around the same period support this theory. There is thus evidence for long periods of drought that have been caused by natural variability.

Since the late 90s, California has experienced a decreasing winter precipitation (Seager et al. 2015). But 1895-2014 winter precipitation data for California show neither a decreasing nor increasing precipitation pattern; there are only shorter periods of higher and lower precipitation levels. For the more recent history, Seager et al. (2015) analyzed observational data of the 15% driest winter half years and the 15% wettest half years in California, from the period 1949/1950 to 2010/2011. The resulting maps of precipitation, SSTs, and 200-mb geopotential height anomalies of those dry and wet winters, in relation to the mean of that period, are shown in figure 1 below. The left map displays the fact that dry California winters (the driest 15%) are linked to a high-pressure ridge anomaly over the eastern North Pacific Ocean and Pacific Northwest, and a low-pressure anomaly region to the west of the high-pressure region. Furthermore, the tropical regions in the map have very low anomalies regarding both SST and geopotential height, which suggests that there are no deviating processes in those regions that affect the majority of the Californian dry winters (Seager et al. 2015), at least not for this time period. The right map however, shows that the wettest 15% California winters tend to come with a low-pressure region directly to the west of the states Washington, Oregon, and California, in addition to warm SST anomalies in the tropical eastern Pacific Ocean and throughout the US west coast, and a high-pressure region in the tropical Pacific Ocean. The warm SST anomalies and high-pressure in the tropics are El Niño-like (Seager et al. 2015).

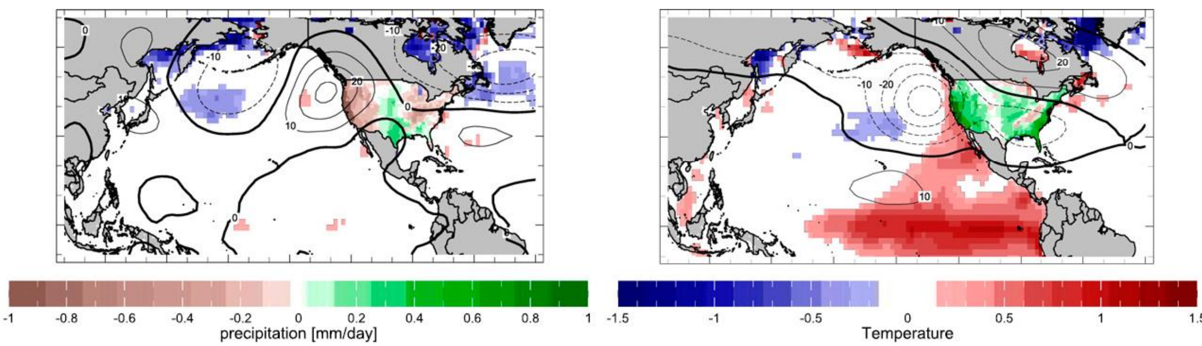

Figure 1: Averaged SST anomalies in the Pacific Ocean, the 200-mb geopotential height anomalies over the Pacific Ocean and North America, and precipitation anomalies in USA for winter half years during the period 1949/1950-2010/2011. Source: Seager et al. (2015).

Based on these results, Seager et al. (2015) argues that for this period, wet California winters can often be connected to El Niño events, whereas dry winters cannot be traced to La Niña events (see subsection 6.3). Rather, inherent atmospheric processes can be linked to the dry California winters of this period (Seager et al. 2015). For dry periods, studies have found a 15-year interval drought pattern in central and northern California that goes back further than the 20th century (e.g. Dettinger and Cayan 2014). This pattern is maintained by the current drought, which is on time with this 15-year drought interval (Dettinger and Cayan 2014).

5 Observations of the current drought in California

When it comes to temperature during the current drought, the three winters (November-April) of 2011-2014 had the warmest average three seasons observed (Seager et al.

2015). The winters of 2011/2012 and 2012/2013 were hot but not deviating in a significant way (Seager et al. 2015). The winter of 2013/2014 however, was observed as being the hottest up to that point (Seager et al. 2015). The years 2012, 2013, and the beginning of 2014 were all dry for California (Dettinger and Cayan 2014). In 2013, January and February received less precipitation than in any other year since the precipitation measurements started in 1895 (Wang and Schubert 2014). That full year came to be the year with lowest precipitation levels recorded in California (Funk et al. 2014). The winter period November–February 2013/2014 had the third lowest precipitation levels since 1895 (Funk et al. 2014). In February 2014 precipitation increased, but the drought was far from over (Dettinger and Cayan 2014).

Robeson (2015) found, based on PDSI values in central and southern California, that the year 2014 was one of the most extreme drought-years, and that the period 2012-2014 was more extreme than any other 3-year period in California since 1895. The extreme 4-year drought period 2012-2015 was estimated to be the first of its kind in terms of severity since at least 1200 years back in time (Robeson 2015). According to California Department of Water Resources, storms provided the state with some precipitation in January and March 2016, which yielded rising levels of reservoirs, and the significant snowpack in the Sierra Nevada grew larger. The 2015/2016 winter period experienced a strong El Niño event (Levine and McPhaden 2016) that brought precipitation to California. Figure 2 below shows the observed SSTs, 200-mb geopotential height, and precipitation anomalies for the winter half years 2011/2012, 2012/2013 and 2013/2014.

The three winters (2011-2014) studied by Seager et al. (2015) had all different patterns of geopotential height. 2011/2012 was a La Niña winter, with large SST differences between the east and west in the North Pacific Ocean. During it, there was a ridge that stretched over the North Pacific and North America, and a weak low to the south of the ridge in the Pacific Ocean. Seager et al. (2015) says that this type of ridge is not normally observed during La Niña winters. Notably, a large part of the ridge is located above the area of warm SST anomalies in the North Pacific Ocean, which seem contradictory to the theory that warm surface waters cause convection and thus low-pressure. During the 2012/2013 winter, a ridge existed over the Bering Sea and parts of the central North Pacific Ocean, while the tropical geopotential anomalies were much smaller. These small tropical geopotential anomalies continued for the 2013/2014 winter, and a more intense high-pressure ridge than the one during the 2012/2013 winter formed over the Bering Sea and extended south-eastward over and beyond California (Seager et al. 2015). As will be explained in the next section, such ridges are clear indicators of dry conditions in California.

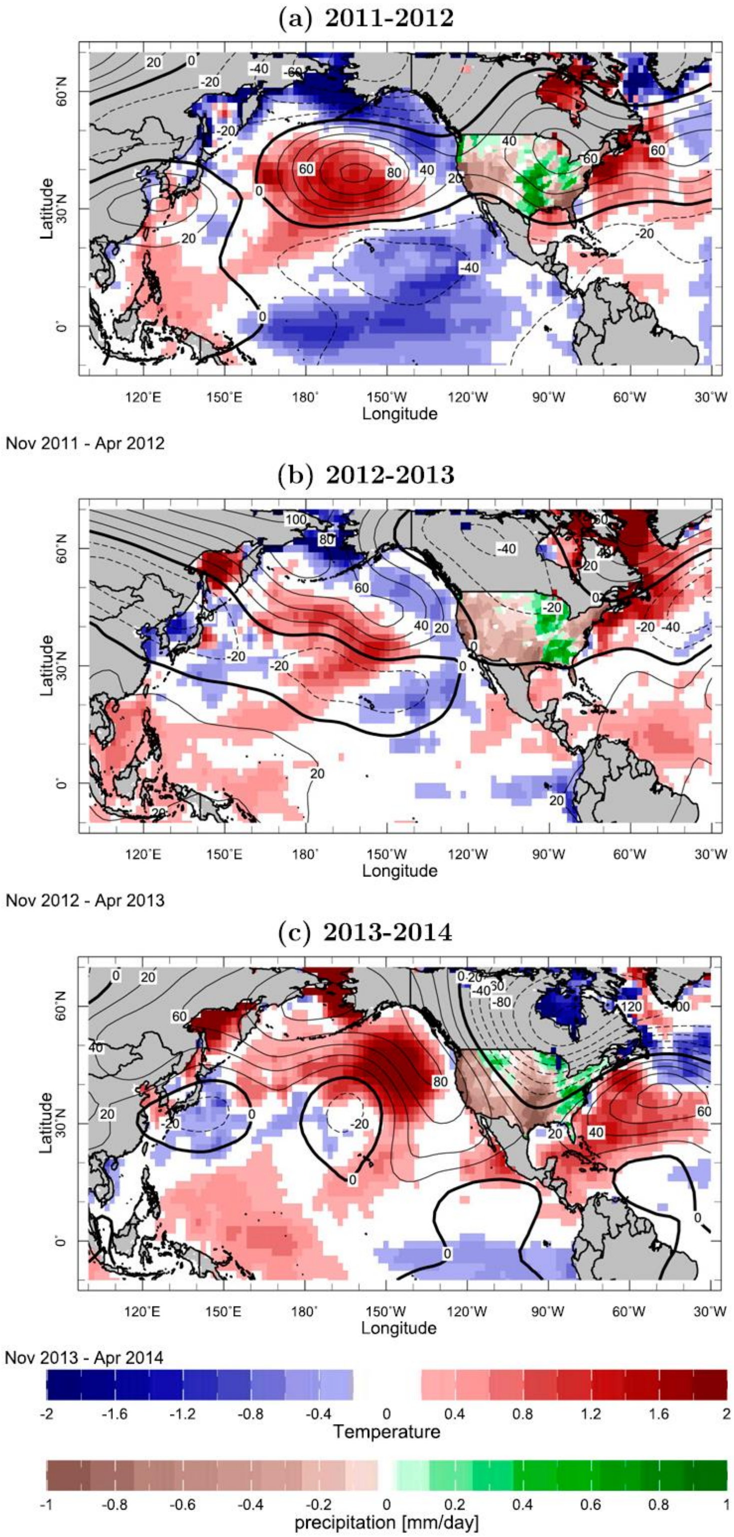

Figure 2: Average SST anomalies in the Pacific Ocean, 200-mb geopotential height anomalies over the Pacific Ocean and North America, and precipitation anomalies in USA for the winter half years 2011/2012, 2012/2013 and 2013/2014. Source: Seager et al. (2015).

6 Meteorological theory and research on natural processes controlling the drought in California

This section tries to highlight and untangle the different factors and their contribution to the California precipitation and drought. In subsection 6.1 I will present weather systems on a synoptic scale, e.g. mid-latitude cyclones. Then mesoscale mechanics will be investigated in 6.2. Lastly, the global scale oscillations El-Niño Southern Oscillation and Pacific Decadal Oscillation are brought up in subsection 6.3 and 6.4 respectively. Each section contains general theory and also research that connects the theory to the drought.

6.1 Synoptic scale weather systems

The synoptic scale extends spatially from hundreds to thousands of km^2 (Ahrens 2013). High- and low-pressure regions are studied in this scale, so mid-latitude cyclones are typical synoptic scale features. Figure 3 shows how a cyclone looks like from above, with its comma cloud clearly visible. Comma clouds, named after the shape of the cloud, are synoptic scale clouds that form during the development of cyclones. In order to explain the synoptic scale mechanisms in an understandable way, a brief review of some of the planetary (global) scale patterns must also be done.

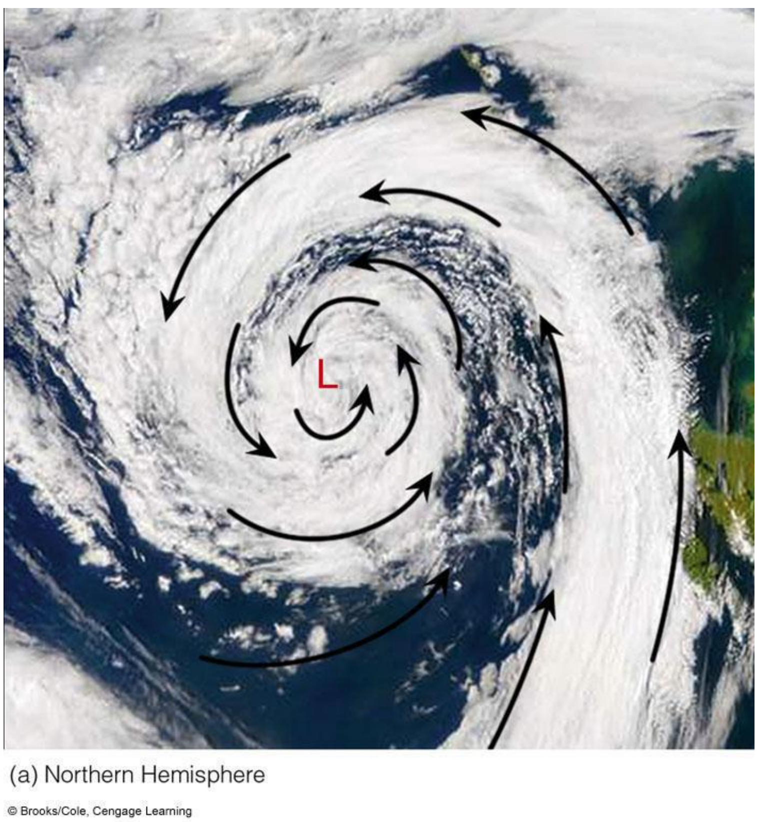

Figure 3: A satellite picture of a cyclonic low and its comma cloud. The arrows indicate the general wind direction. Source: Ahrens (2013).

6.1.1 Processes controlling the track of cyclones

Aloft in the atmosphere there are contour lines, or isobars, that form waves over both the Northern and Southern Hemispheres (Ahrens 2013). On the planetary scale, the waves create troughs and ridges due to their zonal meandering around the globe. These waves are called planetary waves, or Rossby waves. A single Rossby wave (from a trough to the next trough) can stretch over an entire continent, and they are stationary or move very slowly. Connected to Rossby waves are jet streams. Jet streams are planetary scale high-velocity flows of air aloft that partly are created due to differences in temperature between air masses in the tropopause (see figure 4), but more importantly, due to the conservation of angular momentum. These winds in the upper-level atmosphere follow the isobars quite strictly, which means that the winds also meander around the globe.

The average high- and low-pressure regions over the globe are important meteorological features that affect the movement and direction of mid-latitude cyclonic storms, which is usually toward the east or northeast. In the Pacific there are mainly two pressure systems that are relevant to California's precipitation. One of them is the subtropical Pacific high, which is a semipermanent high off the North American west coast, where upper-level air converges and creates a high surface pressure. The convergence is mainly caused by the circulation of the Hadley cell, in which descent in taking place over the subtropics. This descent is depicted in figure 4, originally in Ahrens (2013). It takes place around the same latitude as where the subtropical jet stream flows (also pictured).

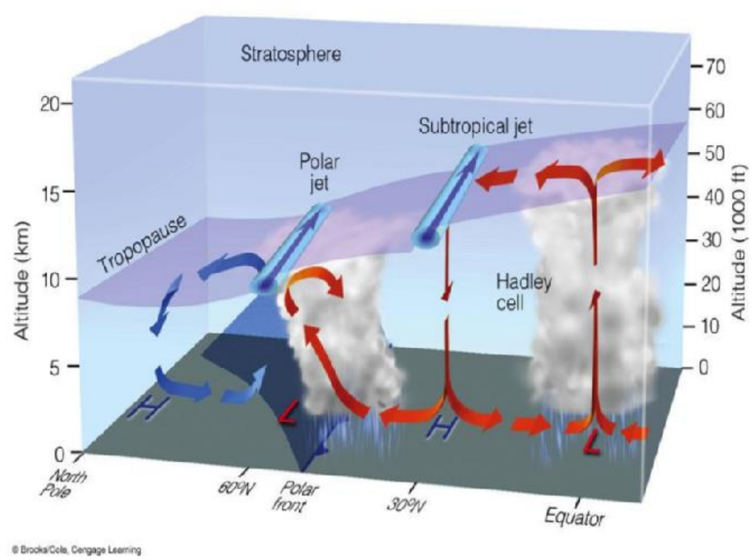

Figure 4: The general horizontal and vertical large-scale circulations in the atmosphere, from the equator to the north pole during winter. The positions and directions of the subtropical jet and the polar jet are also illustrated, as well as regions at the surface where drier and wetter conditions are found. High- and low-pressure regions are also shown. Source: Ahrens (2013).

Aloft, warm air from the equator reaches the subtropical latitudes and starts to descend when it meets colder air from the north. Because the air in the subtropics sinks, adiabatic heating (explained in subsubsection 6.2.1) occurs, which makes the air dryer and cloudless with more or less no precipitation. The stacking and descending of air causes the high-pressure. Another pressure system in the Pacific is the Aleutian low. Located above the central North Pacific Ocean and the Bering Sea, the low is a region where winter cyclones pass. The Pacific high and Aleutian low are present in figure 5 below, which was reprinted from Ahrens (2013). The figure illustrates the average global-scale surface winds and high- and low-pressure regions during January.

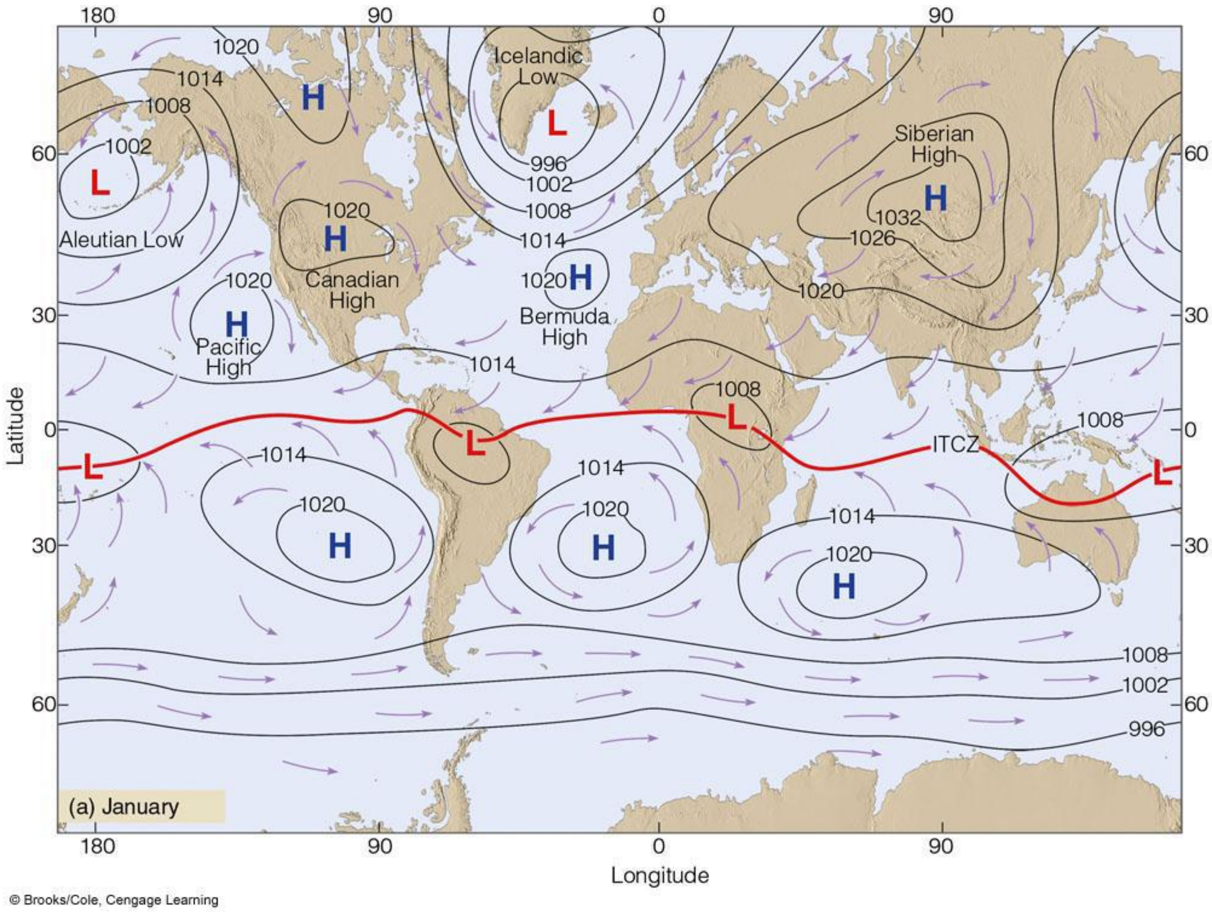

Figure 5: Average sea-level pressure and surface winds for January on a global scale. The most significant high- and low-pressures are visible and named. Source: Ahrens (2013).

As can be seen in figure 5, during winter, the Pacific high and the Aleutian low makes the surface winds between them flow eastward, toward the US west coast. The winds are called the westerlies and this is also where the subtropical jet stream flows. The Pacific high is located at a more south position during the winter than during the summer. This seasonal shift is the major reason to why California generally is dry during summer and wetter during winter. When the high is located directly to the west of California, it successfully prevents the course of the westerlies and the jet stream from going over the state, and thus inhibits precipitation.

This high-pressure have been studied in relation to drought in California. Seager et al. (2015) found that the high-pressure ridges pictured in figure 2 in section 5 that existed during the three studied winters (November-April of 2011-2014) caused the drought of these years. Wang and Schubert (2014) put 2013 precipitation data in relation to the 1980–2013 average. A resulting figure (not shown) illustrated that the low precipitation in California during January-February 2013 could be traced to low precipitation in the eastern North Pacific Ocean region, west of California. The figure also showed that during January-February, there was a region of strong positive geopotential height anomalies (i.e. a high-pressure ridge) over the eastern North Pacific Ocean. They claim that this region of positive geopotential height anomalies was the cause of the low precipitation levels, due to fewer storms coming in over California. Therefore, they concluded that the high-pressure located over the northeast Pacific Ocean lead to a decrease in the number of westerly storms moving in over California during January and February 2013, which also was said to be the cause of the low precipitation levels in California during January and February 2013 (Wang and Schubert 2014).

For the 2013/2014 drought, Swain et al. (2014) identified a high-pressure ridge over the North Pacific Ocean off the Pacific Northwest coast. This ridge was given the name Ridiculously Resilient Ridge, because of its resistance and resilience. The ridge affected the wind patterns over the ocean: the westerly winds decreased in strength, while other zonal and meridional winds got stronger. It also caused the jet stream and mid-latitude cyclones to blow over more northern regions than California (see figure 6 below). Storms were displaced and could thus not provide the state with as much precipitation as usual during the winter period, which caused extremely low precipitation levels in California (Swain et al. 2014).

Wang et al. (2014) looked at the causes of the winter drought period of November 2013 to January 2014. During this period, California received less than a quarter of its average rainfall for that period (Wang et al. 2014). Also here an unusually high ridge over the Gulf of Alaska was proposed to be the main cause of the drought. During the same time, there was a trough over Canada and Northern USA, which formed a dipole along with the ridge. For the central and northern parts of California, the dipole was related to drying of the area. According to Dettinger and Cayan (2014), during the winter of 2013/2014, the high-pressure ridge pushed the Pacific storms over Alaska instead of over California. Research has thus shown clear evidence of the importance of the positions of the high- and low-pressure over the northeastern Pacific Ocean in determining how the subtropical jet stream, westerlies and the mid-latitude cyclones move eastward in over the North American west coast.

6.1.2 Processes controlling the intensity of cyclones

In the regions of the planetary wave troughs, i.e. where the air pressure is relatively low, instability can be created through baroclinity. A baroclinic atmosphere is where, in the upper-level regions, there is a temperature gradient in relation to the pressure. Temperature advection can occur there, i.e. cold air is flowing into warmer regions and vice versa. Such flow patterns can be generated by a shortwave that deepen a stationary longwave trough as it passes the trough. This kind of flow is associated with baroclinic instability. For a mid-latitude cyclone to develop, baroclinic instability is important. The instability of the upper-level cold and warm temperature advections in the vicinity of the trough affects the air near the surface, which often consist of a stationary front. Aloft, cold, converging air in the region of cold advection makes the air there descend, and warm, diverging air in the region of warm advection makes the air below ascend. This energy from aloft often causes the stationary front at the surface to transform into a mid-latitude wave cyclone, with the warm front moving northeast. If the divergence aloft above the forming low-pressure is greater than the convergence of air around the surface low, the cyclonic storm intensifies. The divergence of air above a low pressure system associated with a cyclone can arise due to the jet stream. In regions where the winds in the jet stream are strongest, there is convergence of air above the surface high-pressure area and divergence above the surface low-pressure area of the cyclone. Therefore, the jet stream can increase the pressure differences and intensify the cyclone.

To be able to recognize areas of convergence and divergence, vorticity is commonly studied. Vorticity is the spinning of bits of air. When air has positive (negative) vorticity, it spins cyclonically (anticyclonically) around a vertical axis. An air parcels relative vorticity is due to the curvature and shear of the flow, and its absolute vorticity is both the relative vorticity and the earth's vorticity, which is created due to the spinning of the earth. Upper-level divergence of the jet stream flow enhances the cyclonic vorticity below at the surface and causes deep ascent of air, and therefore intensifies the cyclone. Aloft in the upper troposphere, convergence is associated with a decrease in absolute vorticity and divergence is associated with an increase in vorticity, due to the curvature of isobars and its effect on the relative vorticity. Where a shortwave deepens a planetary scale trough, there is often a vorticity maximum, i.e. a region with high vorticity. When the shortwave gradually moves to the east relative to the longwave trough, the region of vorticity maximum also does.

The intensity of cyclones is largely dependent on the temperature of the ocean surface. An ocean's surface temperature is commonly called the sea surface temperature (SST). Interplay between an ocean and the atmosphere above it can cause SST variation and anomalies (Holton and Hakim, 2013). When the SSTs change, the heat flux (through latent and sensible heat) from the ocean to the atmosphere changes (Holton and Hakim, 2013). Seager et al. (2015) note that, although studies have found that SST forcing from the Pacific Ocean plays a considerable part in the precipitation variability in southwestern North America, the Californian precipitation is largely determined by internal variability in the atmosphere, and only a quarter or less of the precipitation variability is due to SSTs in the tropical Pacific. But they also argue that the observed ridges during the three 2011-2014 winters over the North Pacific Ocean was closely linked to SST anomalies there (see figure 2). So SSTs in the Pacific Ocean have a role in the current drought (see section 5 and subsections 6.3 and 6.4).

Since the 2011/2012 winter was related to a La Niña event (see section 5), and had certain SST anomalies associated with La Niña conditions, Seager et al. (2015) could conclude that SST forcing from the tropical Pacific Ocean was the cause of ridge during the 2011/2012 winter, which in turn was the cause of the drought for that winter. Also for the 2013/2014 winter, they suggested that SST-forcing contributed to the formation of the ridge and thereby the precipitation deficits in California (Seager et al. 2015). The connection was said to be heating of air over the warm SST anomalies in the western tropical Pacific. The heating affected the Rossby waves and thus the formation of the high-pressure ridge. Despite the large influence of the SST forcing on the drought, from the model analysis done by Seager et al. (2015) it was estimated that the 2011-2014 drought couldn’t only be caused by SST forcing; inherent variability in the atmosphere, as stated above, could be the major factor of the precipitation deficits. Wang and Schubert (2014) suggested that SST anomalies in the North Pacific Ocean can be linked to the drought of January-February 2013 mentioned above. However, they also point to atmospheric internal variability as being the major cause of it (Wang and Schubert 2014).

Now that a review of different processes causing the course and intensity of cyclones has been done, a summary of the processes that lead to drought can be explained: Warm SSTs in the northeast Pacific Ocean provide energy through the release of sensible and latent heat from the ocean, so that deep ascent and instability in cyclones occurs. This intensifies cyclones that move eastward over the ocean. If the Pacific high is located at a more northern region during a winter than normally, the subtropical jet stream and most of the cyclones will be steered away from their direction toward California and follow a more northern course as in figure 6. This leads to precipitation deficits in the state, and hence drought.

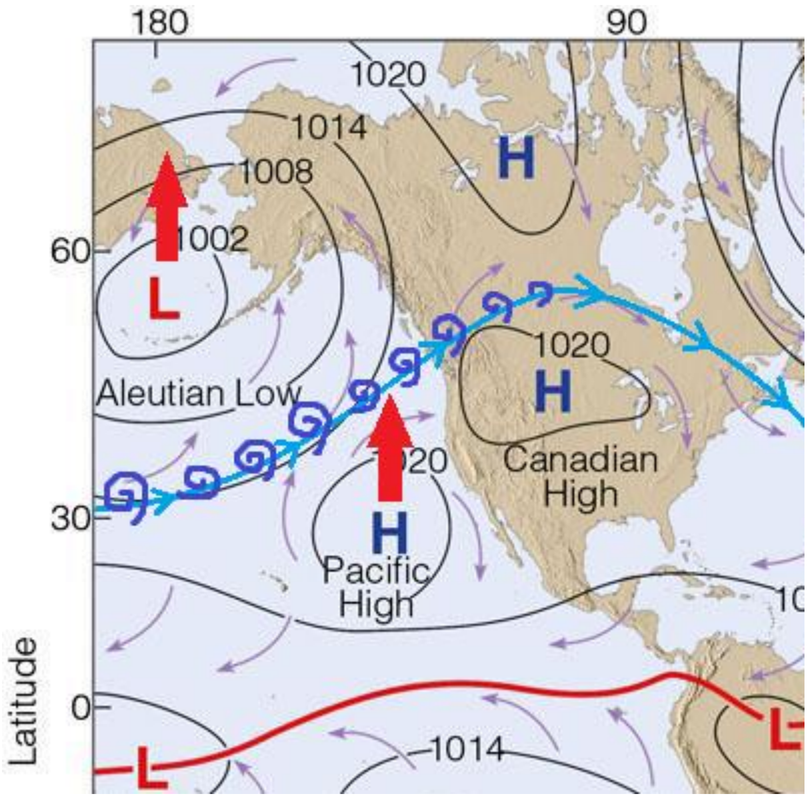

Figure 6: A cropped version of figure 5, showing how the high- and low-pressures can shift their positions (red arrows), which affects the course of the jet stream (light blue line) and hence the course of mid-latitude cyclones, here shown as comma clouds (dark blue curls).

6.2 Mesoscale weather systems

Mesoscale weather systems include winds and cloud formation that take place from some km to 100 km horizontally (Ahrens 2013). Clouds are mainly formed by four different processes: convection due to surface heating, lifting due to topography, ascent due to convergence of surface air, and lifting due to weather fronts. Lifting due to topography, or orographic lifting as it also is called, is highly relevant for cloud formation and precipitation production in California and will be explained below.

6.2.1 Orographic clouds and precipitation

Precipitation over mountainous areas is often associated with the meteorological phenomenon orographic lifting. Orographic lifting can be explained by following a hypothetical air mass, closed and separated from the surrounding air, on its way over a mountainous region. When an air mass moves towards a mountain, it has to lift in order to be able to pass over it. When the air mass lifts, its internal pressure decreases and the volume of the mass increases, which causes the water molecules within it to slow down. The vertical advection of the air mass leads thus to a decrease in the temperature inside it, according to equation 1 below:

$$w > 0 \rightarrow DT / Dt < 0 \qquad \textit{Equation 1}$$

where w is the vertical velocity and DT / Dt the temperature change.

This process is called adiabatic cooling (Holton and Hakim 2013). The cooling causes the relative humidity to increase. If the relative humidity becomes 100%, the water vapor in the air mass condensate and clouds form. These clouds are referred to as orographic clouds. In the Sierra Nevada, orographic clouds can for example have convective cumulus and stratocumulus forms, as seen in figure 7 (Lynn et al. 2007). The satellite image shows a clear cloud distribution pattern: there is more cloud development on the west side and on the peaks of the mountain range than on the east side.

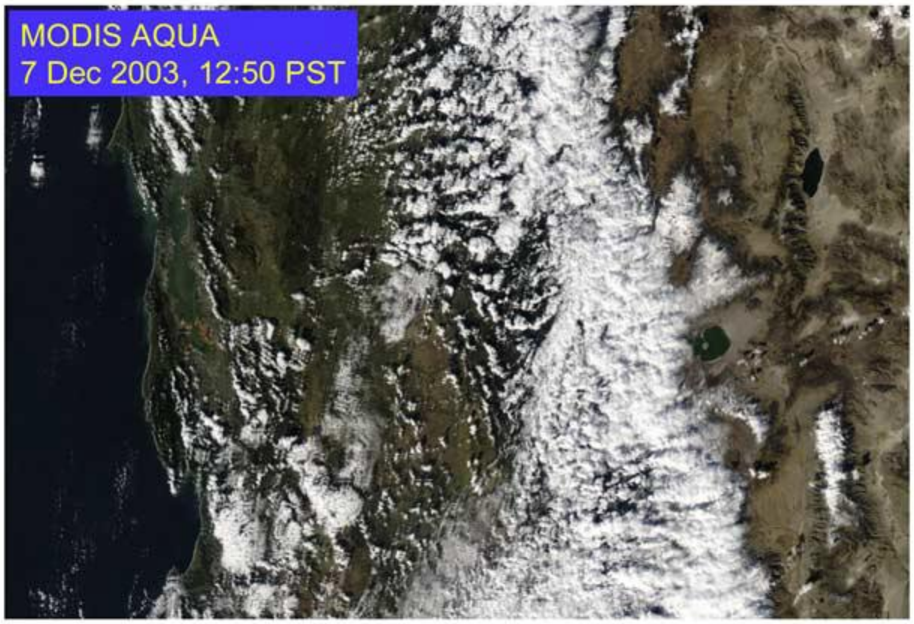

Figure 7: Orographic clouds in the form of stratocumulus (sheet-like) and convective clouds (patch-like) over the Sierra Nevada, captured by a satellite image on 7 December 2003. The rain shadow to the east of the clouds can be seen. Source: Lynn et al. (2007).

Naturally, there is also a chance for precipitation to occur in such clouds. According to Marwitz (1987), most of the precipitation in the Sierra Nevada is caused by deep orographic clouds. Orographic precipitation can fall over both lower- and higher-lying slopes in the Sierra Nevada (Rauber 1992), but it is mostly occurring at elevations of 1-2 km (Alpert 1986). As stated earlier, mid-latitude storms are common precipitation producers in California, so synoptic scale comma clouds yield precipitation. Inside such a comma cloud, one can detect vertical convection clouds, stratocumulus clouds, horizontal stratus clouds, as well as cirrus clouds, as the cyclone develops (Reed and Blier 1986). Reed and Blier (1986) studied the mechanisms of a comma cloud as it moved eastward from the Pacific and over California. That comma cloud produced precipitation through extensive stratus clouds and convection of air. Since surface fronts are present during cyclogenesis, clouds also form through these fronts.

The California Mountains receive much of the total precipitation falling over California (Raphael and Mills, 1996). Over the Sierra Nevada, mid-latitude cyclones often cause orographic precipitation during winter (Dettinger et al. 2004). The main reason for the storms coming during wintertime have been said to be the increasing strength of the incoming Pacific winds during that time of year (Pandey et al. 1999). The Sierra Nevada Mountains are situated in a beneficial way for precipitation to form through orographic lifting. Incoming southwesterly winds yield most of the winter precipitation there (Pandey et al. 1999). Wang and Schubert (2014) describe the general Californian winter precipitation as storms coming from the west coast and blowing over the Sierra Nevada, resulting in precipitation. The fraction of precipitation falling over mountains can however vary greatly annually and between individual storms, so there is still a considerable fraction of precipitation that falls over low-altitude regions (Dettinger et al. 2004). But between 1954 and 1999, during December-February, the orographic precipitation in central Sierra Nevada was around three times as high over high-altitudes compared to low-altitudes (Dettinger et al. 2004). Through orographic lifting, the Sierra Nevada receives and blocks winter precipitation that otherwise would have continued inland towards the Upper Colorado River Basin (Sheppard et al. 2002).

When the air has crossed the peak of the mountain and generated some precipitation during its ascending, the air mass starts to descend on the other side of the mountain, called the leeward side. When it descends the pressure on it increases, which makes the air mass decrease in volume. When the volume of the air mass decreases, the energy of the molecules in it increase and the air mass experiences an increase in temperature (equation 1 reversed). This is what is called adiabatic heating. If condensation in the air mass occurred on the windward side, it will be drier and warmer on the leeward side of the mountain than it was at the same altitude on the windward side. The mountain has thus produced a rain shadow on its leeward side. The main characteristic of rain shadow regions is their dryness (Ahrens 2013).

6.2.2 Snowpack and temperature

Due to the precipitation boost during the winters, the snowpack in the Californian Mountains mostly accumulates during the winter months. The snowpack acts as a buffer of water supply for the state, as it can stay at high altitudes for a long time. During spring and summer, melting snow from the mountains provides water for the residents (Safeeq et al. 2015). Therefore, accumulation of the snowpack during winter is a highly important resource, and it can prevent droughts from increasing in severity.

In the Sierra Nevada mountains, precipitation is equally divided between rain and snow when the air temperature is 1.5°C. Lower air temperatures than 0°C result in a significantly higher snow fraction (S_f), and temperatures higher than 3°C result in a significantly higher fraction of rain (Lundquist et al. 2008). Even if precipitation start to fall as snow, it can melt into rain as it descends though warmer air (Lundquist et al.

2008). California has been seeing a warming trend of about 1 ºC since 1895 (Seager et al. 2015). Higher temperatures in California during the winter months lead to less snowpack in the mountains (Seager et al. 2015), although a snowpack stands a 50% chance to survive when the surface temperature is as high as 3°C (Lundquist et al. 2008). Furthermore, the S_f of the precipitation is highly dependent on winter temperature, and not so dependent on variations in precipitation (Safeeq et al. 2015). For example, Safeeq et al. (2015) concluded that the S_f could be lowered by 10-15% in northern California Mountains if the winter climate warmed with another 1 ºC. The S_f dependence on winter temperature is thus clear. Over the period 1916-2003, the S_f differed as much as 40% in the low-and mid-elevations of the Sierra Nevada, and since the 1960, the decrease in S_f in the western United States has been more evident than during the preceding decades (Safeeq et al. 2015). Precipitation falling on snowpack as rain can yield different results: it can add to the existing snowpack, drain away and leave the snowpack, or add to snowmelt (Lundquist et al. 2008).

From this review it can be said that snowpack in California is a vital hydrological resource for the state. Fluctuations in air temperature determines to a large degree the precipitation type and how much snowpack that accumulates or is melted away. Some of the processes that have been explained are illustrated in figure 8, such as orographic cloud formation, orographic precipitation, accumulation of snowpack, and snowmelt.

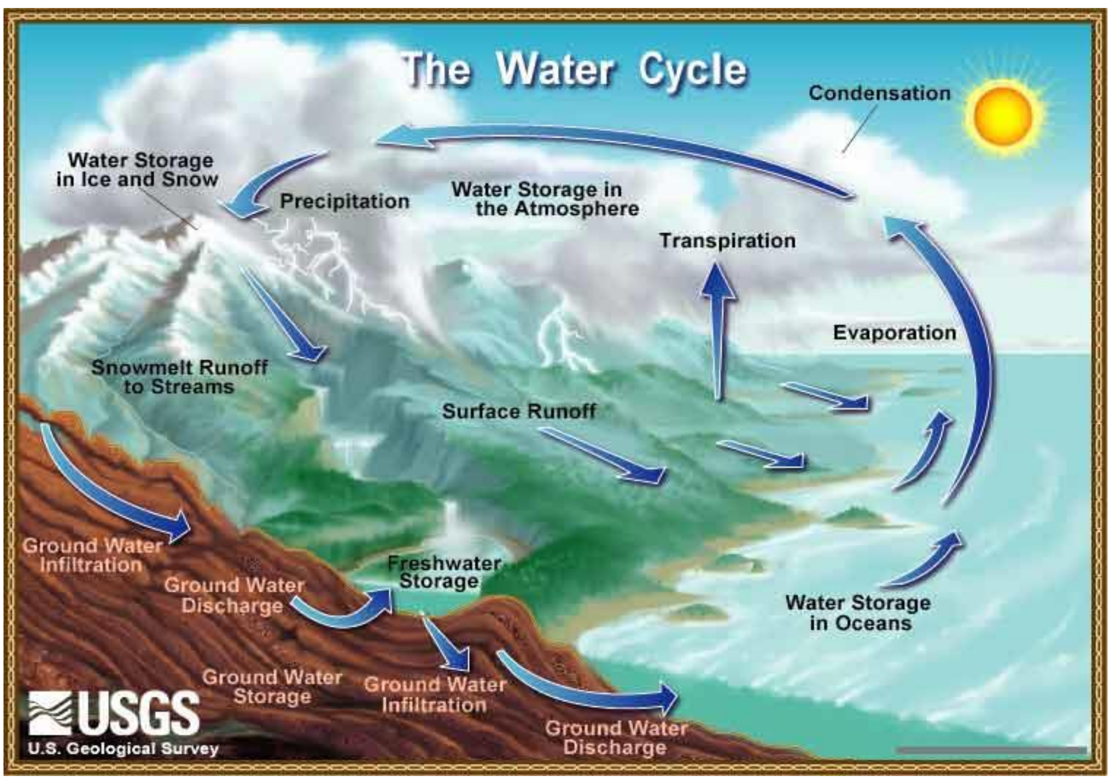

Figure 8: A diagram illustratng the water cycle, in which processes such as (orographic) precpiptation, water storage in mountain snowpack and snowmelt runoff are included . Source: U.S. Geological Survey.

6.3 El Niño-Southern Oscillation

During El Niño winters, California often experiences more mid-latitude storms than usually, due to the directional shift of the jet stream that flows south of the low pressure (Ahrens 2013). The low is illustrated in figure 5 and in figure 9 below. During La Niña winters however, a high-pressure is prevailing instead of the low over the same region, and the jet stream south of the high is generally directed to the northern US, bringing storms to the northwestern states of the US. The state of the ENSO thus affects the position of the jet stream. This is why California generally receives more precipitation during El Niño years than during La Niña years. One should have in mind that these relationships are general and not necessary valid for the drought period: (Seager et al. (2015) also found that wet winters in California often coincided with El Niño events, based on winter observations from 1949/50 to 2010/11. However, they also found that, for the same period, dry winters did not often coincide with La Niña events, but that the 2011/2012 La Niña event was the cause of the drought during that winter.

Around the equator over the Pacific Ocean, there is a large-scale tropical circulation caused by a pressure gradient across the ocean, which in turn is caused by the large gyres in the ocean and SST differences (Holton and Hakim, 2013). In the Indonesian region there is a low pressure, and in the eastern Pacific along the American west coast there is a high pressure region. This pressure difference promotes strong trade winds at the surface and westerly winds aloft. This circulation is called the Walker Circulation, which is the normal state of the atmospheric circulation over the Pacific Ocean. The surface winds cause the SSTs to be higher in the western Pacific Ocean than in the eastern. In contrast with the Walker Circulation is the El Niño-Southern Oscillation (ENSO). ENSO is a phenomenon based on the difference in pressure between the east and west part of the Pacific Ocean. When the pressure difference decreases, the wind circulation weakens and the east part of the ocean warms, generally followed by wetter than usual weather conditions over the eastern ocean basin. This state is called the El Niño. Normally during an El Niño winter, a low is formed over the North Pacific. South of this low flows the (subtropical) jet stream, which brings moist air and low-pressure storms to California. (Ahrens 2013). The low is produced because of warmer SSTs in the Eastern Pacific Ocean. The general pattern of an El Niño winter is shown by figure 9, reprinted from the NOAA.

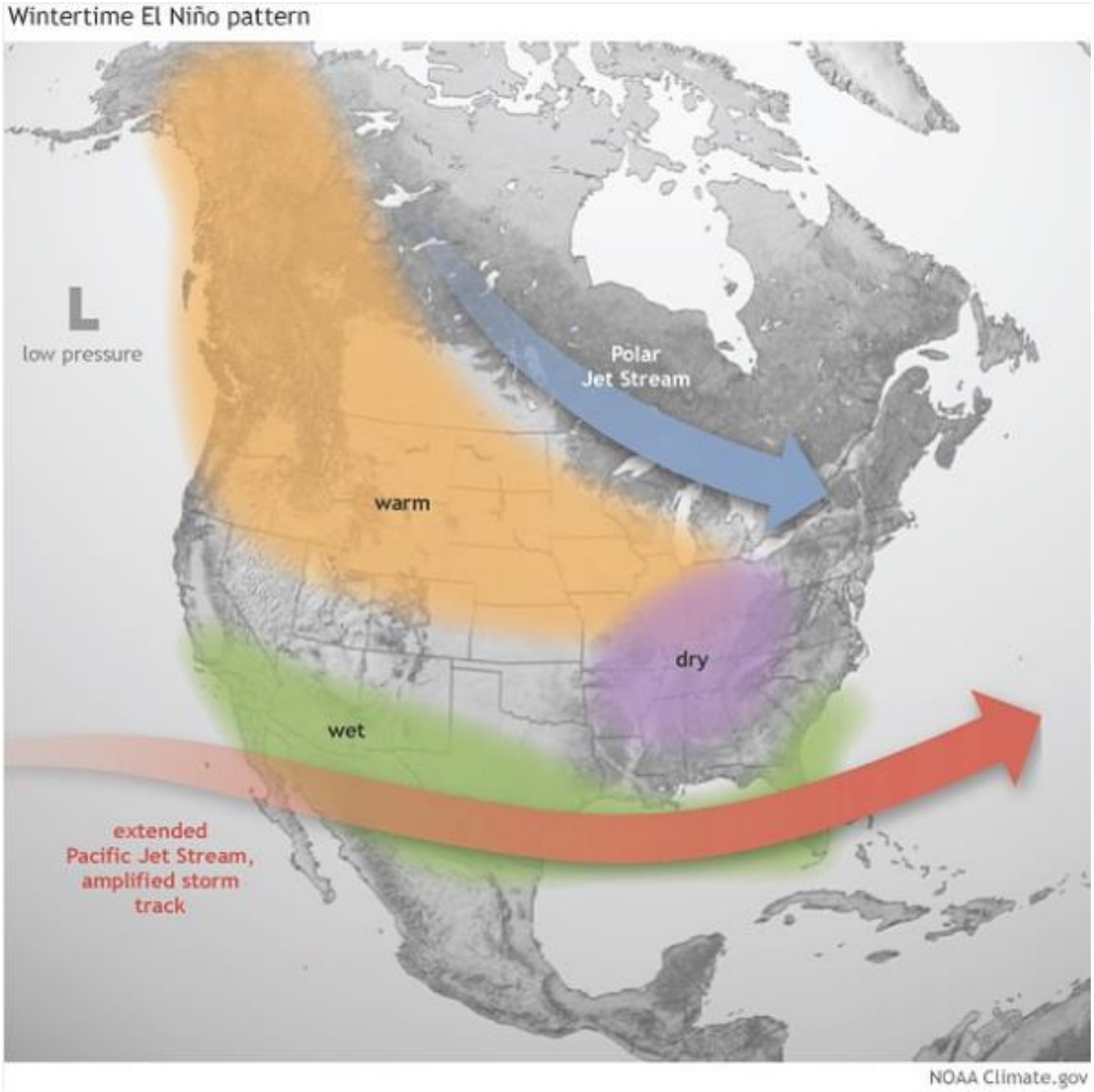

Figure 9: The low pressure over the eastern North Pacific, the course of the Pacific jet stream and the wet weather over the southern states, including California, during El Niño winters, among other things. Source: NOAA

On the other hand, when the pressure difference increases, the Walker Circulation intensifies and east-west SST differences become more pronounced. A La Niña condition is prevailing. During La Niña winters, there is a blocking high over the North Pacific. The jet stream during these conditions moves eastward south of the high-pressure area and curves around it so that the wet weather ends up over the Pacific Northwest and the northwestern states (Ahrens 2013). Northern parts of California could receive some of this wet weather.

ENSO is commonly estimated with an index called the Southern Oscillation Index (SOI), which is a monthly index that represents the phase of the ENSO. The index is computed through differences in sea level pressure measured in Darwin, northern Australia and on Tahiti in the Southern Pacific Ocean. Negative (positive) values are associated with a positive (negative) ENSO phase. In figure 10, the SOI was plotted from January 1951 to March 2016.

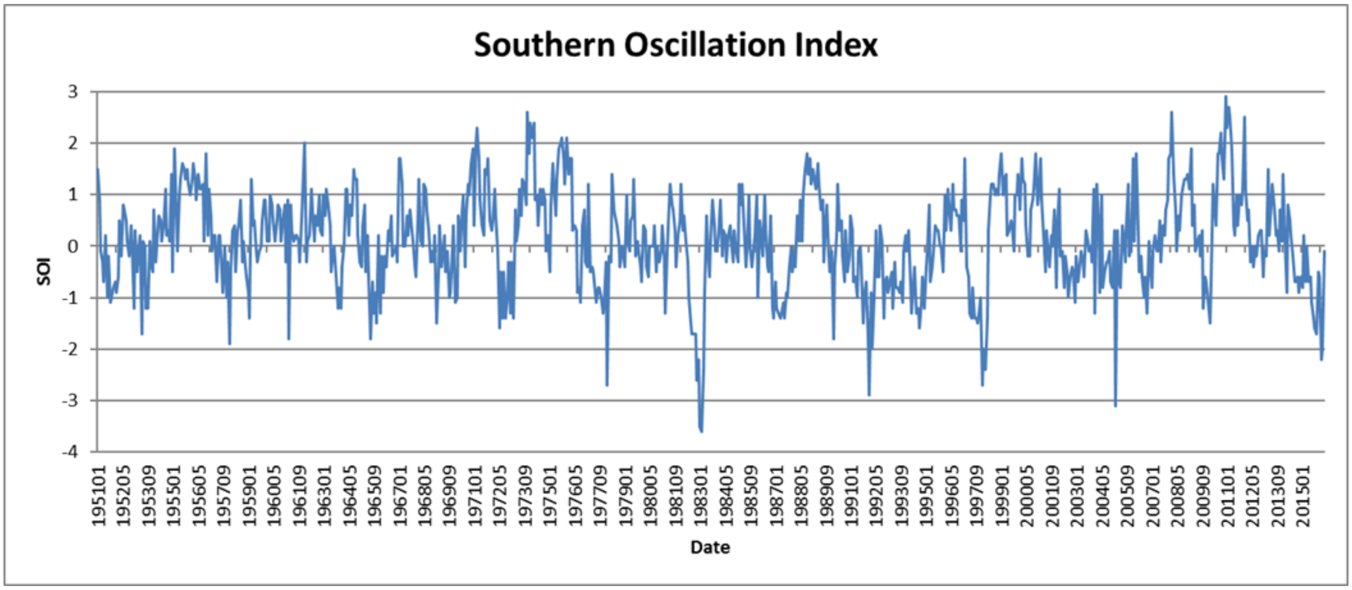

Figure 10: The Southern Oscillation Index graphed from January 1951 to March 2016. Source: The National Oceanic and Atmospheric Administration's National Centers for Environmental Information.

ENSO phases are normally a few years up to a decade long (Sheppard et al. 2002). There are many detectable positive and negative ENSO phases in figure 10. For example, there was a negative ENSO (i.e. La Niña) phase during the mid-70s, and a positive ENSO (i.e. El Niño) phase in the early 80s. Two of the largest El Niño events occurred during 1982-83 and 1997-98. Due to the El Nino event in 1997-98, California received high amounts of precipitation (Ahrens 2013). These El-Niño events can be seen as negative dips in the SOI in figure 10.

To be able to focus more on the ENSO during the current drought, a graph of the SOI from January 2011 to March 2016 was plotted, see figure 11.

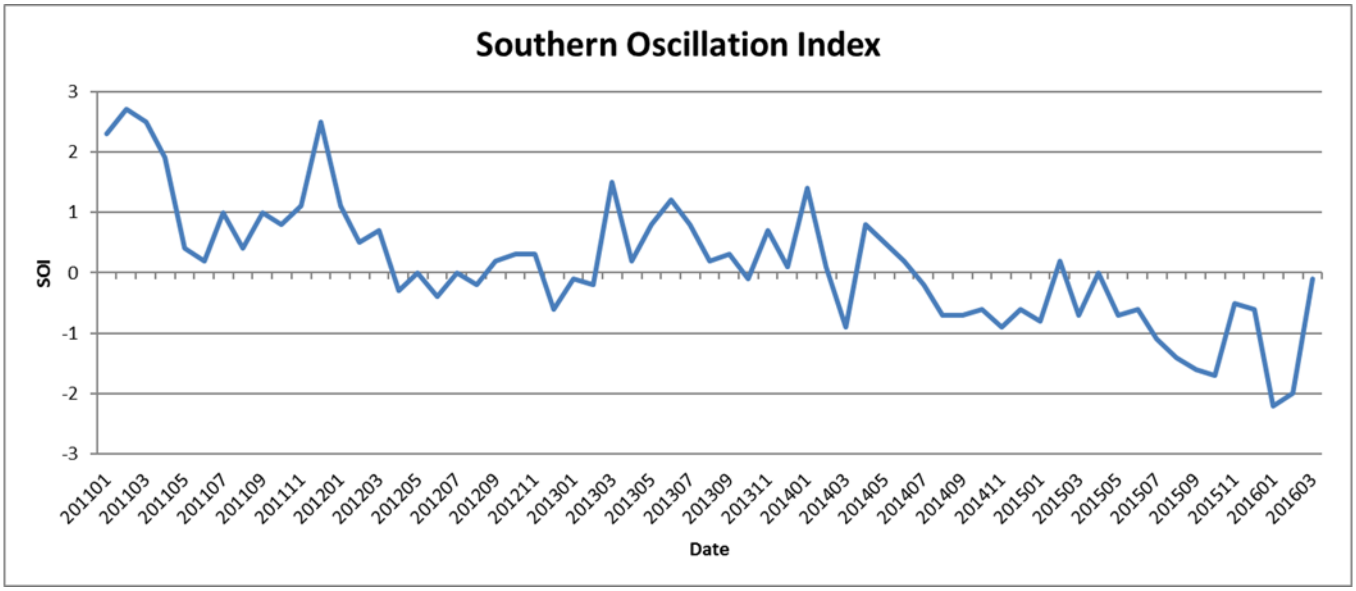

Figure 11: The Southern Oscillation Index graphed from January 2011 to March 2016. Source: The National Oceanic and Atmospheric Administration's National Centers for Environmental Information.

According to figure 11, the SOI generally had high positive index values from the start of 2011 to the beginning of 2012, which is associated with La Niña conditions. In the winter of 2011/2012, there is a La Niña peak. This corresponds to the other observations that were made of the 2011/2012 winter (see section 5). Seager et al. (2015) found that SST and geopotential height anomalies had a La Niña characteristic during the 2011/2012 winter: most of the sea off the North American west coast had negative SST anomalies, and much of the central and eastern Pacific Ocean had positive SST anomalies (Seager et al. 2015).

The middle part of the drought had neither a positive nor a negative ENSO phase, from the spring of 2012 to the summer of 2014 (see figure 11). Index values where mostly close to zero or a little larger and more or less 0 during the 2012/2013 and 2013/2014 winters. A conspicuous change in the STT in the North Pacific Ocean also occurred: The 2012/2013 winter had lower STT anomalies than the preceding winter: both the positive and negative SST anomalies in the Pacific Ocean decreased, and the former La Niña condition declined into a neutral ENSO state, which continued over the subsequent 2013/2014 winter (Seager et al. 2015). But during the 2013/2014 winter, high positive SST anomalies were observed in the eastern North Pacific Ocean and in the Gulf of Alaska (Seager et al. 2015). The analysis done by Wang et al. (2014) showed that the dipole that was over the eastern North Pacific Ocean and USA and Canada during November 2013 to January 2014 (see subsection 6.1.1) formed by the ridge and the trough could be linked to atmospheric circulations associated with an upcoming El Niño event.

An El Niño event occurred, but not until the winter of 2015/2016. After a short increase in the spring of 2014, the index values had a general decrease and reached a low in January 2016. The 2014/2015 winter had, according to figure 11, weak negative values, and the expected El Niño winter turned out to be very small or even non-existent (Levine and McPhaden 2016). The 2015/2016 winter on the other hand, had strong negative SOI values, especially for January and February 2016. The 2015/2016 winter thus experienced a strong El Niño winter, which is also established in research, e.g. by Levine and McPhaden (2016). From the analysis above, one can say that the observed ocean-atmosphere changes between the winters that Seager et al. (2015) studied and also the overall notion of the ENSO phases thorough the drought matches the change of the SOI through the drought quite well. The idea that El Niño periods have become more common than La Niña periods during the last decades (Trenberth & Hoar 1997; Sheppard et al. 2002) could mean that California winters generally got wetter than they would have if the phases were more equally balanced.

In summary, a La Niña event caused the drought of the 2011/2012 winter, while the 2012/2013, 2013/2014 and 2014/2015 winters where not caused by either ENSO phases. A strong El Niño event brought precipitation to California during the winter of 2015/2016. The El Niño may continue onto the next winter season, which could increase the chance of moist weather during the winter of 2016/2017.

6.4 Pacific Decadal Oscillation

The Pacific Decadal Oscillation (PDO) is an interdecadal oscillation (Sheppard et al. 2002), based on the mid-latitudinal ocean and atmosphere climate over the North Pacific Ocean (Mantua et al. 1997). The winter months November-March are said to be period when the mechanisms of the PDO are the most relevant (Sheppard et al. 2002). As with the ENSO, there is a positive phase and a negative phase, which depend on the SSTs in the region (Mantua et al. 1997). When there is a positive PDO phase, the STTs in the central North Pacific Ocean have cool anomalies, while the SSTs in the eastern Pacific Ocean are warmer than normally. There is also an increase in the number of westerly storms that blow in over California. This is due to the increase of the Aleutian low, which is located over the northernmost part of the Pacific (see figure 5), or over the Gulf of Alaska. During a negative PDO phase, the eastern part of the Pacific Ocean is relatively cool and the west-to-central North Pacific is relatively warm, which can cause high-pressure anomalies. The phases of the PDO and ENSO can thus bring similar effects.

Like with the ENSO, there is an index for the PDO, which is computed through observed and estimated SSTs in the North Pacific Ocean. The variation of the index through time is plotted in figure 12 below, from 1895 to 2016. As expected, the positive and negative phases generally have a longer time span than the ENSO phases. Mantua et al. (1997) identified a positive PDO phase between 1925 and 1947, a negative phase from 1947 to

1977, and a positive phase that started in 1977. When looking at figure 12, this positive phase ended by the end of the 90s. Since then, it seems like the PDO has mainly been in a negative phase, especially from the mid-00s to the mid-10s.

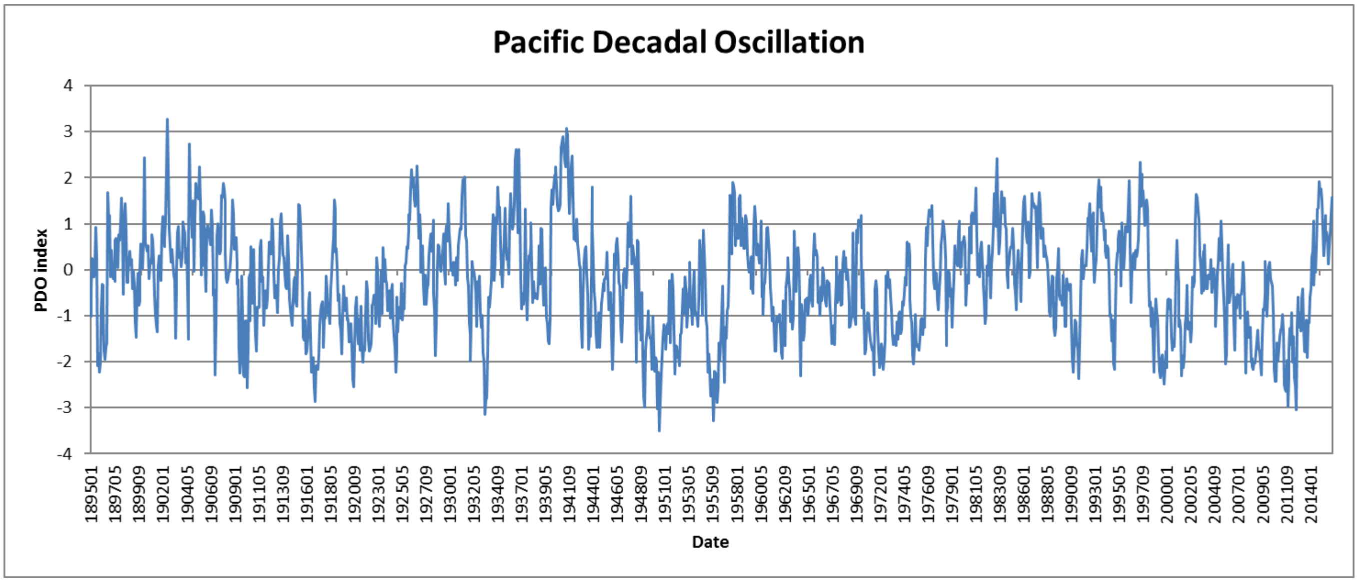

Figure 12: The Pacific Decadal Oscillation Index plotted from January 1895 to March 2016. Source: The National Oceanic and Atmospheric Administration's National Centers for Environmental Information.

Mantua et al. (1997) claim that the PDO and ENSO are connected, and that both could affect each other. A figure (not shown) of correlations in their study said that the SOI and the PDO had a correlation coefficient of -0.35 for the period 1900-1992. This means that positive PDO phases quite often come with positive ENSO phases, and the same for their negative counterparts. They also claim that there is a positive correlation between the PDO and the winter precipitation levels in parts of North America, but California is not specifically mentioned. Furthermore, California coastal SSTs are said to be related with the PDO (Mantua et al. 1997). Sheppard et al. (2002) also say that the PDO is connected to the ENSO in a positive way, that the PDO can increase or decrease the effects of El Nino and La Niña phases, depending on the current phases of the PDO and ENSO. For example, a positive PDO phase can amplify the effects of a positive (El Niño) ENSO phase.

As with the SOI, a graph of the PDO index was made spanning from January 2011 to March 2016, see figure 13 below. In contrast to the SOI during this period, the PDO index experiences a general increase. Between 2011 and 2013, there are exclusively negative index values. From 2014 to 2016, there are mostly positive index values. Looking back on figure 12 at the long-term pattern, it seems like this increase could be an indication of the start of a positive phase of the PDO. When comparing figure 11 and 13, the downward trend of the ENSO and the upward trend of PDO are probably related to each other. This could be a confirmation of the positive correlation that Sheppard et al.

(2002) mentioned. As El Niño (positive phase) values are show in negative numbers in the SOI, both the SOI and PDO index show a general trend from negative ENSO and PDO phases towards positive.

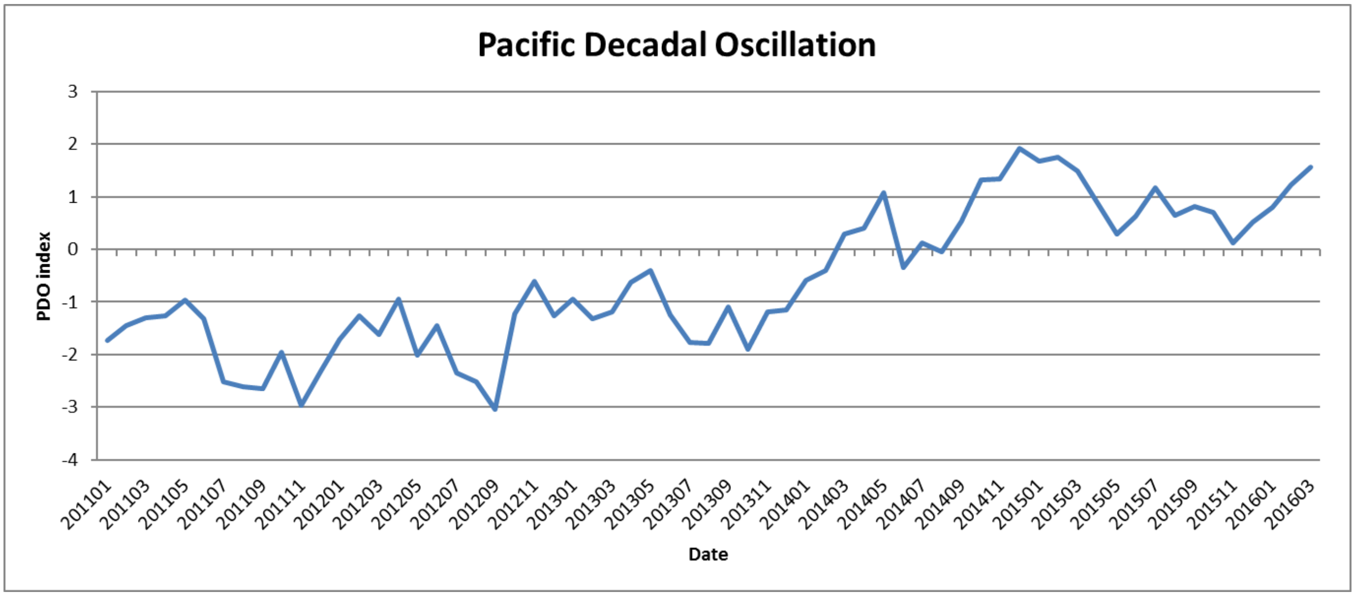

Figure 13: The Pacific Decadal Oscillation Index plotted from January 2011 to March 2016. Source: The National Oceanic and Atmospheric Administration's National Centers for Environmental Information.

Contradictory to the other studies reviewed, Dettinger and Cayan (2014) concluded that the PDO and ENSO are not in any way related with the precipitation levels in the California Delta catchment: El Niño events and positive phases of the PDO are as likely to produce dry conditions as wet conditions there. The studied drought recurring pattern of a 15-years interval supports this non-relation, by the fact that neither the PDO or ENSO has such time interval; the PDO has a larger time interval than 15 years, and ENSO has a shorter one (Dettinger and Cayan 2014).

To summarize it: The PDO's influence on the drought and on precipitation in California by itself is quite unclear. But the fact that the ENSO and PDO has shown similar phase shifts (from a negative towards a positive phase) during the drought indicates that it somehow affects the precipitation in California, at least together with the ENSO. Motivated by Sheppard et al.'s (2002) claim that the ENSO and the PDO are positively connected, the PDO can have strengthened the La Niña phase during the start of the drought and the El Niño phase during the latter part of the drought. But a definitive conclusion of the relationship between the PDO and the drought cannot be drawn.

7 The influence of global warming and climate change on the drought

Climate change and global warming are meteorological concepts that are under much research. Their influence on and relationship with the California drought has also been studied. Here some research on the California drought related to global warming and climate change are reviewed.

Funk et al. (2014) researched whether observed global warming and its heating of SSTs in the Pacific Ocean had any effect on the ENSO-neutral 2012/2013 and 2013/2014 droughts in California. The SSTs showed an increase in the North Pacific Ocean during the last century, but a significant effect of it on the two droughts was not found, based on model simulations. Therefore, global warming could not be linked to the droughts (Funk et al. 2014). Seager et al. (2015) claim that the increase in temperature of 1 ºC since 1895 in California can partly be explained by the increase in greenhouse gas (GHG) emissions. But the warming trend over the 20th century is more importantly an effect of internal natural variability, namely a general decrease in the sea level pressure over the eastern North Pacific Ocean (Johnstone and Mantua 2014). Swain et al. (2014), found that the type of North Pacific high-pressure named the Ridiculously Resilient Ridge observed during the 2013/2014 drought (see subsubsection 6.1.1) was more likely to occur with global warming than without it.

Wang and Schubert (2014) focused on the precipitation average of January and February 2013. The periods 1871–1970 and 1980–2013 were compared to look at differences between a period less affected by global warming (1871-1970) and a period most likely more affected by it (1980-2013), and because oscillations didn't affect the comparison to a large degree. The comparison showed a decrease in the strength of the Pacific jet stream and the westerlies. They speculate that this could lead to fewer moisture-transporting storms moving in over California. On the other hand, an estimated increase in the likelihood of wetter air masses over the Pacific Ocean west of California due to global warming would mean an expected increase in the moisture received by California. Because these two changes in processes seem to cancel out one another, the study could not find a wetting or drying trend between the periods 1871–1970 and 1980–2013 (Wang and Schubert 2014). Hence, they did not find it probable that global warming affected the drought during early 2013 and other similar dry spells in a significant way.

Williams et al. (2015) utilized four different global warming scenarios, and found that global warming contributed considerably to the drought during the years 2012-2014, and increases the probability of droughts in California. They estimated that global warming could explain 8-27% of the drought during 2012-2014, and 5-18% of the drought during 2014. Still, natural variability was said to be the main control of the drought during both periods.

Seager et al. (2015) found that the 2011-2014 drought was not primarily caused by climate change, but by natural variability. Similarly, Cheng et al. (2016) drew results that indicated that climate change did not cause the drought's effect on ecosystems and agriculture in California considerably. On the other hand, Wang et al. (2014) states that GHG emissions (CO_2, CH_4, NO_2 and CFCs) contributed to the intensity of the unusually strong ridge over the Gulf of Alaska during the winter of 2013/2014. They also claim that an increase in the GHG emissions increased the link between the dipole and the atmosphere circulations found during a year preceding an El Niño event (see subsubsection 6.1.1). To summarize the findings of these studies, the influence of global warming and climate change on the drought seems to be relatively small in relation to natural variability.

8 Projections on future precipitation in California and the development of the drought

The California drought has arguably not ended, and when it does, future droughts will undoubtedly come. Projections on how the precipitation in California and how the drought may develop are therefore highly valuable. Seager et al. (2015) pointed out that the current low levels of winter precipitation are not representative concerning the future Californian precipitation levels. The models utilized estimated that the major effect climate change has in relation to the drought is through the long-term warming of the atmosphere, i.e. global warming, which will decrease the S_f and increase the rainfall fraction (also see subsubsection 6.2.2), and also increase the evapotranspirational demand of the air above land. Analysis of the models further suggested that future winter precipitation in California will increase due to a strengthening of the westerlies as well as a lowering of the sea level pressure in the North Pacific Ocean, brought on by climate change (Seager et al. 2015).

Models project that the Hadley cell will widen by end of this century, which will make the tropics extend latitudinaly, so that the subtropics move further away from the equator (see figure 4; Collins et al. 2013). Because of the descending air in the subtropics, southwestern USA will likely see a decrease of precipitation in the future. This shift in descending air can be connected to the seasonal shifting of the Pacific high that is explained in subsubsection 6.1.1. The RCP8.5 future scenario suggests that for the end of the 21st century, higher surface temperatures and the widening of the Hadley cell will increase the drying of the soil in the southwestern US. For this scenario, southwestern US is likely to experience a precipitation decline. An increase in the duration of dry spells is also expected in the region. Because of a decline in winter precipitation the southwestern US will be subject to drying, according to numerous projections (Collins et al. 2013).

Generally, for the mid-latitudes and subtropics, the precipitation levels are declining (Meehl et al. 2007). The drought risk in the mid-latitude regions increases with global warming, according to model projections. Collins et al. (2013) say that global warming will very likely increase the occurrence and intensity of the precipitation extremes in many mid-latitude regions, although precipitation events would be fewer (Meehl et al., 2007). When looking at the RCP8.5 scenario for the end of the 21st century, the subtropical regions will probably have a decrease in precipitation from now to then, while the mid-latitudes will receive both less and more precipitation, depending on region (Collins et al, 2013).

Collins et al, (2013) mention that projections of models indicate that the southwestern North America will experience extensive drought in the latter part of this century. Research have found that the natural variability is much more dominant here than the influence of anthropogenic activity on the precipitation decreases in the southwestern North America. However, increases in GHGs is said to be the cause of the projected future subtropical shift toward the poles mentioned earlier. This movement of the subtropics would intensify the drying of the southwestern North America. Moreover, GHG emissions make it harder for such drying to end, as the molecules stay intact in the atmosphere for a long time.

Schimmelmann et al. (2002) present a flooding pattern in southern California, based on flood deposited sediment layers found in the Santa Barbara Basin. These layers stretch back 2000 year in time. These layers suggested that, at least for the last 2000 years, flooding in southern California has occurred in intervals of about 200 years, with only three exceptions where flooding doesn’t seem to have taken place. They discuss whether this pattern will continue, and if it does, southern California could experience flooding some time during the current century. This could mitigate the drought in this region, at least for a shorter period.

9 Discussion

This thesis aimed at identifying the main meteorological processes and factors that cause the current California drought and control the winter precipitation in California, and tried to determine how and to what degree these processes are influenced by global warming and climate change.

Since many of the factors brought up in this literature study are closely linked to one another, I find that it is not possible to look at their importance entirely separately. As have been proved by the sections 4-8, the relationships between different factors and their individual significance is quite a complex issue, including global warming and climate change. Although there are many factors and processes that may contribute to California’s winter precipitation and to the drought specifically, there are some processes that undoubtedly play a crucial role: The mid-latitude cyclones bring the highly important moisture from the Ocean to the continent. These storms must be steered in the right direction, which the westerlies and the upper-level jet stream help with. There is clear evidence that high- and low-pressure regions off the California coast are affecting the pathways of the westerlies and the jet stream, which in turn affects California's winter climate. For the cyclones to develop and intensify, SSTs in the Pacific Ocean need to have a favorable pattern. When the cyclones have reached California, the state's mountains amplify the precipitation through orographic uplifting and orographic precipitation. The air temperature in the mountains affects the S_f of the winter precipitation, and the S_f in turn influences the snow pack there and how much water storage in the mountains that are available as melting runoff during the dry spring and summer. Because of this, I regard precipitation events and water availability in California as a results of a chain of events, starting with the ocean-atmosphere interaction and ending with an air mass over California reaching a relative humidity of 100%, resulting in rain or snowfall.

For the more uncertain factors, the ENSO phases surely affect the jet stream and thus the direction of cyclones. It seems like the change in the ENSO during the drought followed California's hydroclimate quite well for the period: the first part of the drought was connected to a La Niña event, the middle part of the drought was ENSO-neutral, and the late part of the drought was connected to an El Niño winter. The contribution of the PDO is more uncertain than ENSO's. Moreover, the PDO index for 2011-2016 in figure 13 could lead to misinterpretations, as the PDO is based on multi-decadal variations and not variations of a few years. One important point that Mantua et al. (1997) makes is that it is extremely hard to determine the present state of the PDO, because of its multi-decadal pattern: relatively short positive (negative) phases occasionally occur during longer negative (positive) phases. It may thus be difficult to say which state the PDO has been in during the drought, and therefore also how it may have affected the drought. Still, the positive trends of ENSO and PDO during the drought (see figure 11 and 13) could indicate the start of a wet period for California and a possible the end of the drought, or a decrease in its severity.

The main reason for dry winters could be explained by looking at the summer conditions, when the Pacific high is generally located to the west of California, compared to a more south position during winter (see figure 6). Dry versus wet winters could therefore be compared with general summer versus winter conditions. Figure 1 shows very clearly that, historically, a high-pressure off the coast causes dry winters and that a low-pressure off the coast leads to wet winters for California. The same figure suggests that SST forcing in more prominent for wet winters than for dry winters. Unlike the average SSTs for the dry winters in figure 1, the 2011/2012, 2012/2013 and 2013/2014 dry winters had quite strong SST anomalies. This suggest that these dry winters are not common dry winters, that the processes acted differently for these winters.

Natural variability is quite an abstract factor that nevertheless needs to be considered. Since research (e.g. MacDonald 2007) has found evidence that droughts have been a reoccurring natural phenomenon in California for several hundred years, without the possibility of substantial anthropogenic influence through global warming or climate change, it is not feasible to exclude the idea that a part of the current California drought is controlled by inherent natural variation. Internal natural variability is actually a major cause, according to the reviewed research: Historically, atmospheric circulation anomalies and the decrease in sea level pressure in the eastern North Pacific Ocean, from 1900 to 2012, is said to be caused mainly by natural variation (Johnstone and Mantua 2014). Seager et al (2015) highlight research that show that SST forcing generally only explains up to 25% of how precipitation in California varies between years. They therefore indicate that random variations in the atmosphere is of high significance. As stated before, natural variability was the cause of the drought during the years 2011-2014 rather than climate change (Seager et al. 2015). Moreover, natural variability was the major cause of the drought from 2012 to 2014, according to Williams et al. (2015). Summarizing these findings, internal natural variability of processes seems to be the major cause of the drought and of California's hydroclimate in general.

As mentioned earlier, the precipitation in California has showed neither an upward or downward trend since 1895. It can thus be hard, at present, to determine if the current precipitation deficits are going to break the long-term pattern, or if it is merely a brief period of lower precipitation levels that will end soon. The warming trend of 1 ºC over the past century could affect the amount of snowpack in the Californian Mountains. Global warming together with natural variability could in the future cause more precipitation to fall as rain and therefore decrease the mountain snowpack. A general decrease in snowpack leads to less runoff from the mountains in the summer. This would mean that California would face dryer condition and less water availability. If the subtropical zone extends more to the north, as is suggested by Collins et al. (2013), the Pacific high would naturally also be displaced, as it is dependent on the Hadley cell (see subsubsection 6.1.1). This could affect the course of the jet stream, the westerlies and cyclones, and result in fewer cyclones for California. However, the RCP8.5 is the worst case scenario of the climate trajectories, and many of the climate projections in section 8 are based of it. The projections in section 8 can therefore seem quite extreme.

The difference between the reviewed articles in which drought years and winter months that were studied, and therefore different usage of meteorological data, inevitably leads to incoherencies for this thesis. This may not have affected the outcome significantly, but it is still a fact to regard. The start of the drought is not very clear; some say it begun in 2011, others say 2012. Processes described affecting the Southwest should not be of as high importance as the ones focusing solely on California, as the southwestern studies are only valid for the most southern part of the state.

10 Conclusions

Through this thesis the following conclusions can be drawn:

- California has been experiencing a drought during the past few years.
- Historically, dry winters have often been associated with a ridge in the northeastern Pacific Ocean, while wet winters have often been associated with a low-pressure around the same region. The shifts of the high- and low-pressures over the northeastern Pacific Ocean largely determines the number of mid-latitude cyclonic storms that are steered in over California, as the pressure systems control the direction of the planetary jet stream, with which the cyclonic storms flow. The development of such cyclones is fueled by baroclinic instability and warm sea surface temperatures that enhance the ascent of air in the cyclones.
- Orographic lifting causes much of the valuable precipitation in California. The air temperature affects the precipitation type and snowpack in the mountains, and hence the buffer storage and runoff of water from the mountains.
- Negative (2011/2012) and positive (2015/2016) ENSO phases probably influenced the drought. The role of the Pacific decadal oscillation in relation to the drought seems to be uncertain, although it has shifted similarly to the El Niño-Southern Oscillation during the drought.
- Some studies see global warming and climate change as a considerable factor for how processes act. Still, natural variability seems to be the main control of processes related to the drought. There is evidence of historical droughts that have been caused by natural variability. Further research on the influence of natural variability versus global warming and climate change would bring more clarity to why the processes act the way they do.

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