geosciences

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Monitoring Groundwater Change in California's Central Valley Using Sentinel-1 and GRACE Observations

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Supplementary Materials:

Figure S1. Example of interferograms after ionosphere noise correction and estimated ionosphere phase.

Figure S2. The 3-component GPS position time series at station P305.

Figure S3. Example of GRACE derived total water storage (TWS) change, groundwater anomaly, estimates of snow water equivalent, soil moisture and surface water anomaly for the entire Central Valley.

Figure S4. Mean LOS velocity map in 2006-2010 from L-band ALOS-1 ascending track 219 covering roughly the same area as Sentinel-1 data used in this study and selected velocity profile.

Figure S5. Mean LOS velocity in 2006-2010 from ALOS-1 ascending track 218 in southern San Joaquin Valley basin, south of the Sentinel-1 track used in this study. LOS subsidence time series at GPS stations LEMA and CRCN and corresponding histogram of temporal correlation between GRACE GWA and subsidence time series at these stations.

Table S1. S1 raw data list, perpendicular baseline, time separation.

Table S2. Continuous wells' IDs, longitudes, latitudes and depths

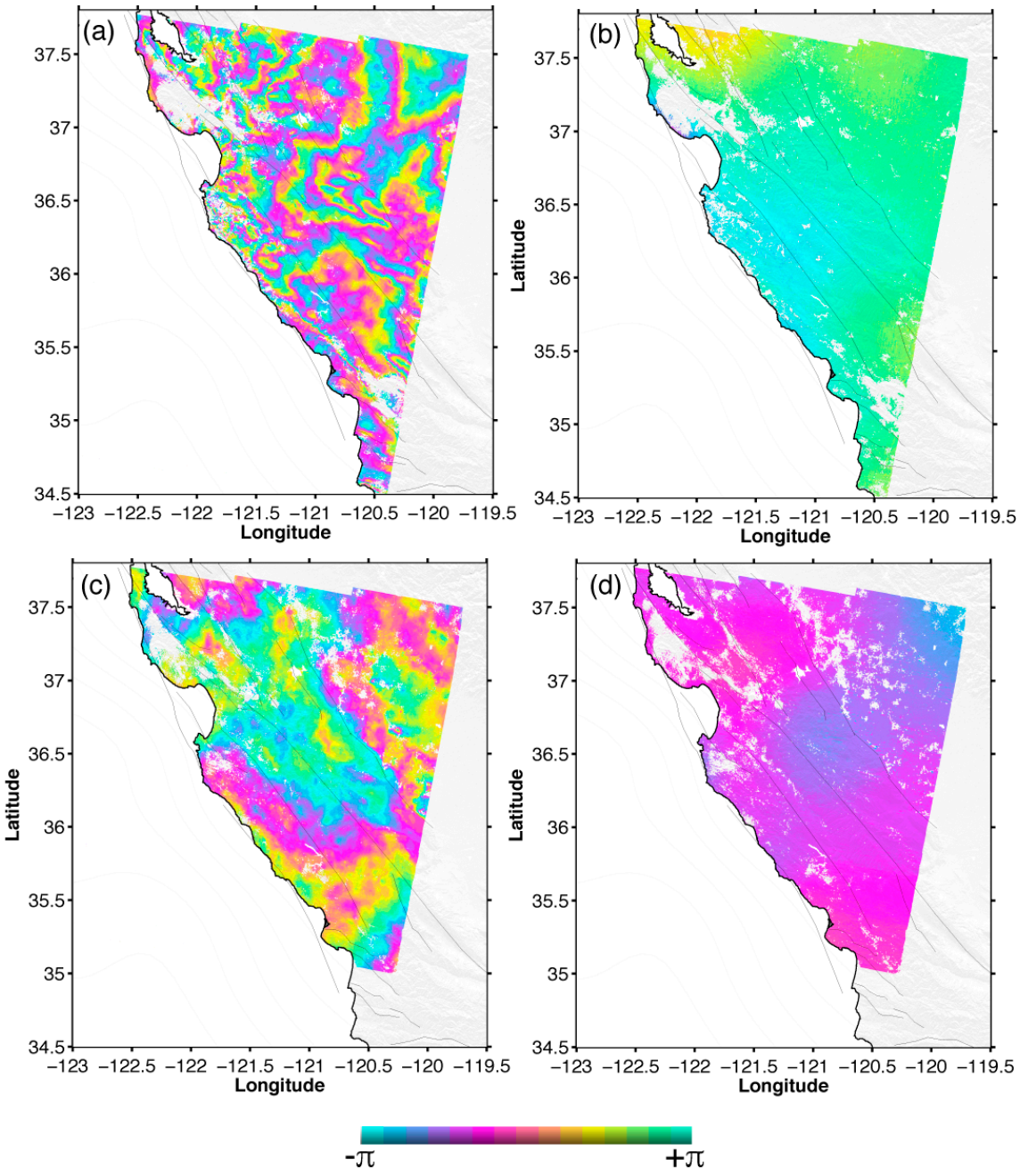

Figure 1. Example of interferograms after ionosphere noise correction and estimated ionosphere phase. The ionosphere phase is estimated through a range split spectrum technique. **a**) Interferometric pair of 20170407-20170417. **b**) Estimated ionosphere phase for the pair in a). **c**) Interferometric pair of 20160412-20105/06. **d**) Estimated ionosphere phase for the pair in c). Note one fringe in a-d represents 2π radians (corresponding to 2.7cm in LOS displacement).

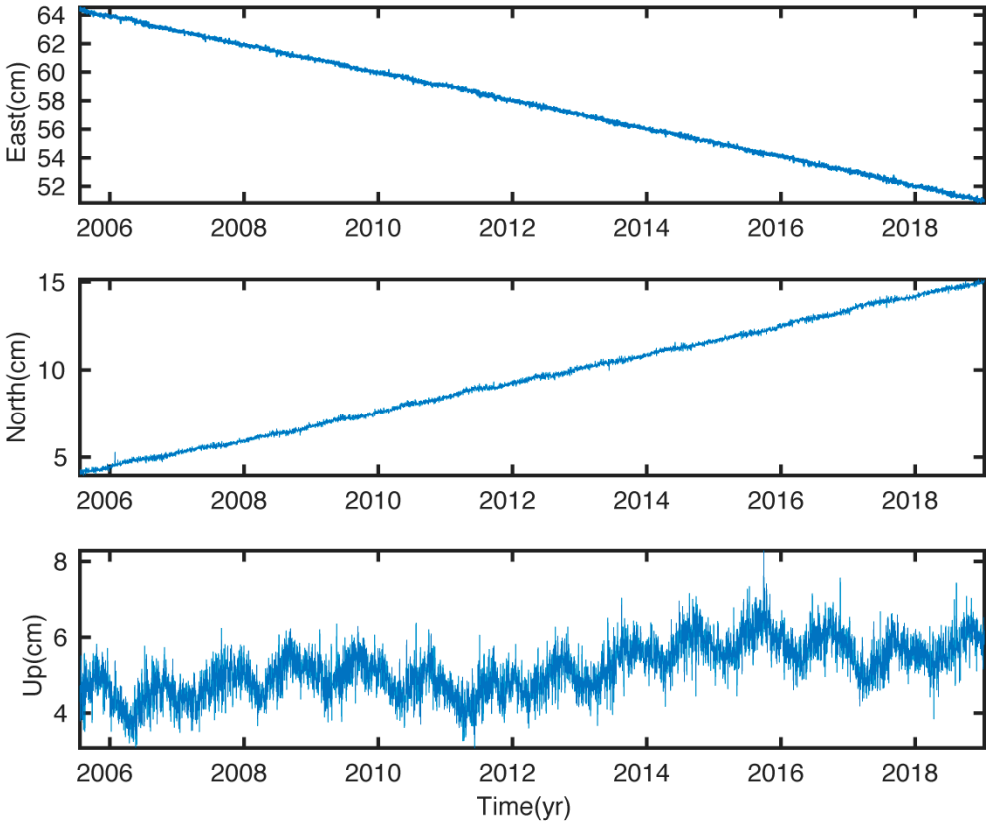

Figure 2. The 3-component GPS position time series at station P305. This station is assumed to be relatively stable and is used as the reference for the InSAR and GPS time series.

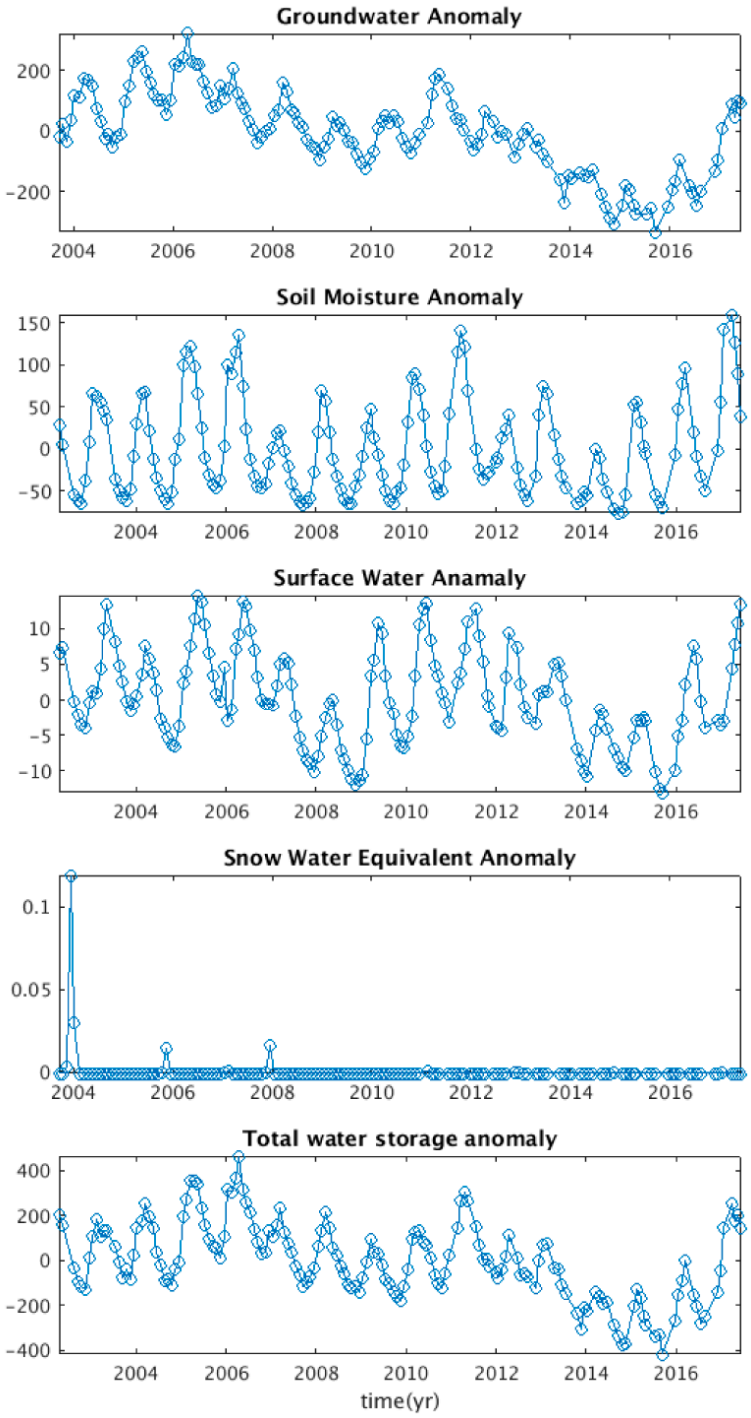

Figure 3. Example of GRACE derived total water storage (TWS) change, groundwater anomaly and estimates of snow water equivalent, soil moisture and surface water anomaly for the entire Central Valley estimated following a similar approach as described in Famiglietti et al., [2011]. The unit is mm for all plots.

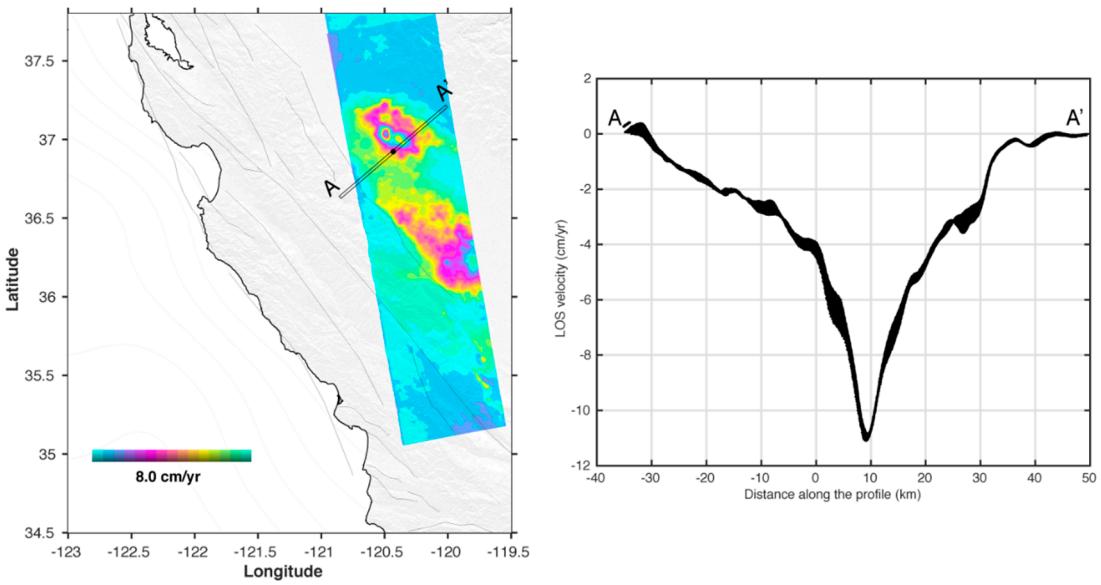

Figure 4. (**Left**) Mean LOS velocity map in 2006-2010 derived from L-band ALOS-1 ascending track 219 covering roughly the same region as Sentinel-1 in this study. The profile is the same as in Figure 7. (**Right**) ALOS-1 LOS velocity profile from the velocity map. The LOS velocity profile is used to estimate vertical subsidence profile shown in Figure 7(b).

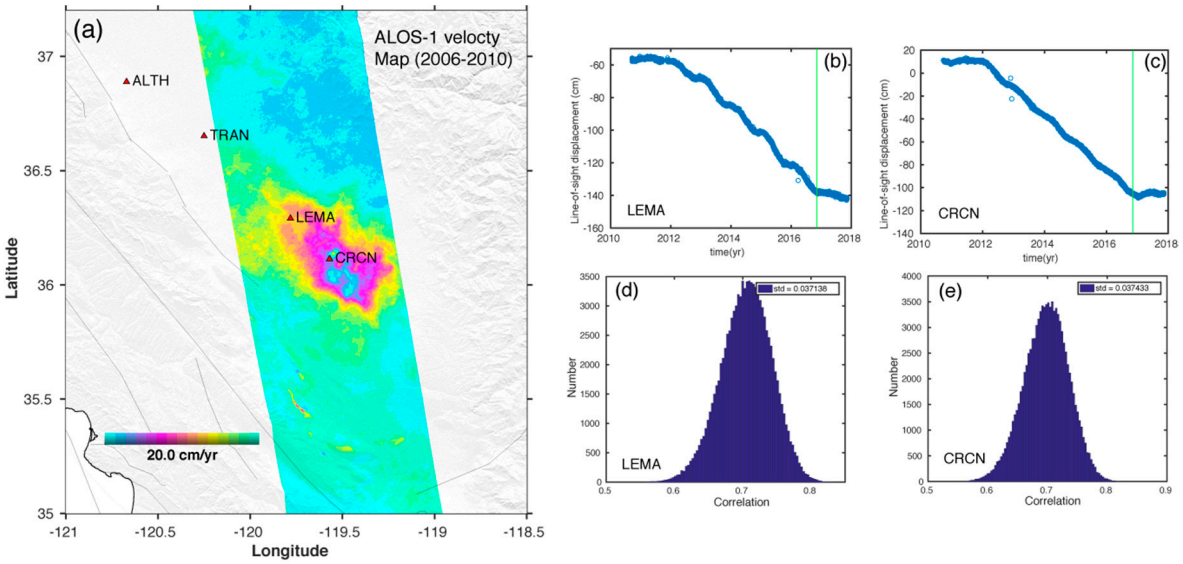

Figure 5. (**a**) Mean LOS velocity in 2006-2010 from ALOS-1 ascending track 218, south of the Sentinel-1 track 42 used in this study, in southern San Joaquin Valley basin. LOS subsidence time series at GPS stations (**b**) LEMA and (**c**) CRCN, located in the severe subsidence area during the previous drought period of 2006-2010. Histogram of temporal correlation between GRACE GWA and subsidence time series at (**d**) LEMA and (e) CRCN. Green lines in (b), (c) indicate roughly the same time as ALTH, TRAN when long term subsidence starts to slow down or cease.

Table S1. List of Sentinel-1 SAR scenes, time separation and perpendicular baseline with regard to the first acquisition.

Date	Dt (days)	Bperp(m)	Data IDs
20150301	0	0.00	S1A_IW_SLC__1SSV_20150301T140729_20150301T140756_004839_00605B_5ECD.zip S1A_IW_SLC__1SSV_20150301T140753_20150301T140813_004839_00605B_08DF.zip
20150325	24	-137.11	S1A_IW_SLC__1SSV_20150325T140729_20150325T140756_005189_0068C0_2D18.zip S1A_IW_SLC__1SSV_20150325T140754_20150325T140813_005189_0068C0_E316.zip
20150418	24	29.32	S1A_IW_SLC__1SSV_20150418T140730_20150418T140757_005539_00714E_D319.zip S1A_IW_SLC__1SSV_20150418T140755_20150418T140814_005539_00714E_39E7.zip
20150512	24	-39.78	S1A_IW_SLC__1SSV_20150512T140731_20150512T140758_005889_007958_BC28.zip S1A_IW_SLC__1SSV_20150512T140756_20150512T140832_005889_007958_3683.zip
20150524	12	1.19	S1A_IW_SLC__1SDV_20150524T140736_20150524T140806_006064_007D7F_71C4.zip S1A_IW_SLC__1SDV_20150524T140803_20150524T140830_006064_007D7F_F80E.zip
20150605	12	104.74	S1A_IW_SLC__1SSV_20150605T140733_20150605T140800_006239_008284_8A98.zip S1A_IW_SLC__1SSV_20150605T140758_20150605T140825_006239_008284_B2E9.zip
20150617	12	60.84	S1A_IW_SLC__1SDV_20150617T140737_20150617T140807_006414_008786_C0EA.zip S1A_IW_SLC__1SDV_20150617T140805_20150617T140832_006414_008786_ACCF.zip
20150629	12	152.15	S1A_IW_SLC__1SSV_20150629T140735_20150629T140802_006589_008C6D_9A6F.zip S1A_IW_SLC__1SSV_20150629T140759_20150629T140826_006589_008C6D_8C7E.zip
20150711	12	-74.29	S1A_IW_SLC__1SDV_20150711T140737_20150711T140807_006764_00913C_ED1B.zip S1A_IW_SLC__1SDV_20150711T140805_20150711T140832_006764_00913C_0335.zip
20150723	12	3.73	S1A_IW_SLC__1SSV_20150723T140735_20150723T140802_006939_00963C_23AE.zip S1A_IW_SLC__1SSV_20150723T140800_20150723T140827_006939_00963C_DCFC.zip
20150804	12	7.39	S1A_IW_SLC__1SDV_20150804T140739_20150804T140809_007114_009B1F_1794.zip S1A_IW_SLC__1SDV_20150804T140807_20150804T140834_007114_009B1F_4EB0.zip
20150816	12	9.35	S1A_IW_SLC__1SSV_20150816T140736_20150816T140803_007289_009FE6_77E1.zip S1A_IW_SLC__1SSV_20150816T140801_20150816T140828_007289_009FE6_D3B3.zip
20150828	12	62.80	S1A_IW_SLC__1SDV_20150828T140740_20150828T140810_007464_00A4A5_4409.zip S1A_IW_SLC__1SDV_20150828T140808_20150828T140835_007464_00A4A5_D5E4.zip
20150909	12	-12.10	S1A_IW_SLC__1SSV_20150909T140737_20150909T140804_007639_00A972_DFD3.zip S1A_IW_SLC__1SSV_20150909T140802_20150909T140829_007639_00A972_D49E.zip
20150921	12	-44.67	S1A_IW_SLC__1SDV_20150921T140741_20150921T140811_007814_00AE0B_694A.zip S1A_IW_SLC__1SDV_20150921T140809_20150921T140836_007814_00AE0B_95B1.zip
20151003	12	-31.02	S1A_IW_SLC__1SSV_20151003T140738_20151003T140805_007989_00B2CA_D9E2.zip S1A_IW_SLC__1SSV_20151003T140803_20151003T140830_007989_00B2CA_8634.zip
20151015	12	41.06	S1A_IW_SLC__1SDV_20151015T140741_20151015T140811_008164_00B77E_5C7C.zip S1A_IW_SLC__1SDV_20151015T140809_20151015T140836_008164_00B77E_2D17.zip
20151027	12	27.49	S1A_IW_SLC__1SSV_20151027T140738_20151027T140805_008339_00BC45_9840.zip S1A_IW_SLC__1SSV_20151027T140802_20151027T140829_008339_00BC45_ACBF.zip
20151108	12	-51.93	S1A_IW_SLC__1SDV_20151108T140741_20151108T140811_008514_00C0D2_B05F.zip S1A_IW_SLC__1SDV_20151108T140809_20151108T140836_008514_00C0D2_46BB.zip
20151120	12	-26.72	S1A_IW_SLC__1SSV_20151120T140732_20151120T140759_008689_00C5C0_C157.zip S1A_IW_SLC__1SSV_20151120T140757_20151120T140824_008689_00C5C0_3A3D.zip
20151202	12	3.45	S1A_IW_SLC__1SDV_20151202T140735_20151202T140805_008864_00CAAA_7BF4.zip S1A_IW_SLC__1SDV_20151202T140803_20151202T140831_008864_00CAAA_8EC3.zip
20151214	12	81.26	S1A_IW_SLC__1SSV_20151214T140731_20151214T140758_009039_00CF82_8D56.zip S1A_IW_SLC__1SSV_20151214T140756_20151214T140824_009039_00CF82_C653.zip
20151226	12	104.62	S1A_IW_SLC__1SDV_20151226T140734_20151226T140804_009214_00D47C_EC16.zip S1A_IW_SLC__1SDV_20151226T140802_20151226T140830_009214_00D47C_2877.zip
20160107	12	24.58	S1A_IW_SLC__1SSV_20160107T140730_20160107T140757_009389_00D977_B5FE.zip S1A_IW_SLC__1SSV_20160107T140755_20160107T140823_009389_00D977_737D.zip
20160119	12	-18.23	S1A_IW_SLC__1SDV_20160119T140733_20160119T140803_009564_00DE82_D1F8.zip S1A_IW_SLC__1SDV_20160119T140801_20160119T140829_009564_00DE82_EDC9.zip
20160131	12	-38.37	S1A_IW_SLC__1SSV_20160131T140729_20160131T140756_009739_00E3A3_1A28.zip S1A_IW_SLC__1SSV_20160131T140754_20160131T140822_009739_00E3A3_282D.zip
20160212	12	-23.41	S1A_IW_SLC__1SDV_20160212T140733_20160212T140803_009914_00E8BD_328F.zip S1A_IW_SLC__1SDV_20160212T140800_20160212T140828_009914_00E8BD_5E83.zip
20160224	12	50.55	S1A_IW_SLC__1SSV_20160224T140729_20160224T140756_010089_00EDD9_4DA7.zip S1A_IW_SLC__1SSV_20160224T140754_20160224T140822_010089_00EDD9_52FD.zip
20160307	12	66.56	S1A_IW_SLC__1SDV_20160307T140733_20160307T140803_010264_00F2C9_0F10.zip S1A_IW_SLC__1SDV_20160307T140801_20160307T140828_010264_00F2C9_95CB.zip

20160319	12	19.03	S1A_IW_SLC__1SSV_20160319T140730_20160319T140757_010439_00F7BD_B167.zip S1A_IW_SLC__1SSV_20160319T140754_20160319T140822_010439_00F7BD_43A1.zip
20160331	12	-43.69	S1A_IW_SLC__1SDV_20160331T140734_20160331T140803_010614_00FCC3_B445.zip S1A_IW_SLC__1SDV_20160331T140801_20160331T140829_010614_00FCC3_7ADB.zip
20160412	12	-48.48	S1A_IW_SLC__1SSV_20160412T140730_20160412T140757_010789_0101FE_CE65.zip S1A_IW_SLC__1SSV_20160412T140755_20160412T140823_010789_0101FE_956F.zip
20160424	12	28.03	S1A_IW_SLC__1SDV_20160424T140740_20160424T140808_010964_010756_92EC.zip S1A_IW_SLC__1SDV_20160424T140806_20160424T140833_010964_010756_3089.zip
20160506	12	35.70	S1A_IW_SLC__1SSV_20160506T140731_20160506T140758_011139_010CD3_620C.zip S1A_IW_SLC__1SSV_20160506T140756_20160506T140824_011139_010CD3_980D.zip
20160518	12	-34.85	S1A_IW_SLC__1SDV_20160518T140736_20160518T140805_011314_01127E_74F7.zip S1A_IW_SLC__1SDV_20160518T140803_20160518T140831_011314_01127E_0B90.zip
20160530	12	-12.39	S1A_IW_SLC__1SSV_20160530T140733_20160530T140800_011489_011835_92CA.zip S1A_IW_SLC__1SSV_20160530T140758_20160530T140826_011489_011835_4265.zip
20160611	12	-27.80	S1A_IW_SLC__1SDV_20160611T140737_20160611T140807_011664_011DAE_97A4.zip S1A_IW_SLC__1SDV_20160611T140805_20160611T140833_011664_011DAE_5646.zip
20160705	24	91.12	S1A_IW_SLC__1SDV_20160705T140739_20160705T140808_012014_0128CD_F687.zip S1A_IW_SLC__1SDV_20160705T140806_20160705T140834_012014_0128CD_0601.zip
20160729	24	-9.48	S1A_IW_SLC__1SDV_20160729T140740_20160729T140810_012364_013442_1E42.zip S1A_IW_SLC__1SDV_20160729T140807_20160729T140835_012364_013442_F5A2.zip
20160810	12	-64.32	S1A_IW_SLC__1SSV_20160810T140737_20160810T140804_012539_013A18_F2A6.zip S1A_IW_SLC__1SSV_20160810T140802_20160810T140830_012539_013A18_B102.zip
20160822	12	26.84	S1A_IW_SLC__1SDV_20160822T140741_20160822T140811_012714_013FEA_F1E5.zip S1A_IW_SLC__1SDV_20160822T140809_20160822T140837_012714_013FEA_50E3.zip
20160903	12	-15.77	S1A_IW_SLC__1SSV_20160903T140738_20160903T140805_012889_0145CF_F06F.zip S1A_IW_SLC__1SSV_20160903T140803_20160903T140831_012889_0145CF_2C16.zip
20160915	12	10.63	S1A_IW_SLC__1SDV_20160915T140742_20160915T140812_013064_014B65_1D6B.zip S1A_IW_SLC__1SDV_20160915T140810_20160915T140838_013064_014B65_2F77.zip
20160927	12	58.88	S1A_IW_SLC__1SSV_20160927T140746_20160927T140814_013239_015130_7B9A.zip S1A_IW_SLC__1SSV_20160927T140812_20160927T140839_013239_015130_BC31.zip
20161009	12	18.68	S1A_IW_SLC__1SDV_20161009T140742_20161009T140812_013414_0156AE_08AD.zip S1A_IW_SLC__1SDV_20161009T140810_20161009T140838_013414_0156AE_E75E.zip
20161021	12	-34.91	S1A_IW_SLC__1SSV_20161021T140746_20161021T140814_013589_015C38_9E22.zip S1A_IW_SLC__1SSV_20161021T140812_20161021T140839_013589_015C38_74B9.zip
20161102	12	62.59	S1A_IW_SLC__1SDV_20161102T140742_20161102T140812_013764_0161A0_DD4A.zip S1A_IW_SLC__1SDV_20161102T140810_20161102T140838_013764_0161A0_1883.zip
20161114	12	59.14	S1A_IW_SLC__1SSV_20161114T140746_20161114T140814_013939_01671F_D9CE.zip S1A_IW_SLC__1SSV_20161114T140812_20161114T140839_013939_01671F_98C0.zip
20161126	12	56.14	S1A_IW_SLC__1SDV_20161126T140742_20161126T140812_014114_016C6F_7029.zip S1A_IW_SLC__1SDV_20161126T140810_20161126T140838_014114_016C6F_548D.zip
20161208	12	2.57	S1A_IW_SLC__1SSV_20161208T140745_20161208T140813_014289_0171FB_B359.zip S1A_IW_SLC__1SSV_20161208T140811_20161208T140838_014289_0171FB_2CD3.zip
20161220	12	29.30	S1A_IW_SLC__1SDV_20161220T140741_20161220T140811_014464_017775_9B94.zip S1A_IW_SLC__1SDV_20161220T140809_20161220T140837_014464_017775_00D5.zip
20170101	12	117.37	S1A_IW_SLC__1SSV_20170101T140743_20170101T140810_014639_017CDB_8051.zip S1A_IW_SLC__1SSV_20170101T140808_20170101T140836_014639_017CDB_D23B.zip
20170113	12	124.34	S1A_IW_SLC__1SDV_20170113T140735_20170113T140802_014814_01822C_BE80.zip S1A_IW_SLC__1SDV_20170113T140800_20170113T140826_014814_01822C_F2EB.zip
20170119	6	-49.96	S1B_IW_SLC__1SDV_20170119T140706_20170119T140733_003918_006BFF_D888.zip S1B_IW_SLC__1SDV_20170119T140731_20170119T140808_003918_006BFF_8F85.zip
20170125	6	78.21	S1A_IW_SLC__1SSV_20170125T140743_20170125T140811_014989_01879A_5605.zip S1A_IW_SLC__1SSV_20170125T140809_20170125T140835_014989_01879A_C795.zip
20170206	12	49.66	S1A_IW_SLC__1SDV_20170206T140739_20170206T140809_015164_018CFA_37BB.zip S1A_IW_SLC__1SDV_20170206T140806_20170206T140834_015164_018CFA_0953.zip
20170218	12	-30.72	S1A_IW_SLC__1SDV_20170218T140742_20170218T140810_015339_019272_1533.zip S1A_IW_SLC__1SDV_20170218T140808_20170218T140835_015339_019272_BC42.zip
20170302	12	-65.96	S1A_IW_SLC__1SDV_20170302T140742_20170302T140809_015514_0197C3_36EC.zip S1A_IW_SLC__1SDV_20170302T140807_20170302T140836_015514_0197C3_43F2.zip
20170326	24	82.52	S1A_IW_SLC__1SDV_20170326T140743_20170326T140811_015864_01A243_0379.zip S1A_IW_SLC__1SDV_20170326T140808_20170326T140836_015864_01A243_77B2.zip
20170407	12	32.64	S1A_IW_SLC__1SDV_20170407T140743_20170407T140810_016039_01A77A_1FA9.zip S1A_IW_SLC__1SDV_20170407T140808_20170407T140837_016039_01A77A_3A54.zip
20170419	12	-8.63	S1A_IW_SLC__1SDV_20170419T140744_20170419T140812_016214_01ACDC_D405.zip S1A_IW_SLC__1SDV_20170419T140809_20170419T140837_016214_01ACDC_CBF8.zip

20170501	12	2.75	S1A_IW_SLC__1SDV_20170501T140744_20170501T140812_016389_01B229_79F5.zip S1A_IW_SLC__1SDV_20170501T140810_20170501T140838_016389_01B229_D3A7.zip
20170513	12	66.84	S1A_IW_SLC__1SDV_20170513T140745_20170513T140813_016564_01B775_092E.zip S1A_IW_SLC__1SDV_20170513T140811_20170513T140839_016564_01B775_C38E.zip

Table 2. Continuous wells in the study region.

Well ID	Longitude(°)	Latitude(°)	Depth (m)
12S12E16H005M	-120.6554	36.8903	219.46
13S15E31J006M	-120.3732	36.7552	152.4
14S13E11D006M	-120.5315	36.7326	413.92
14S15E05J001M	-120.3517	36.7397	70.1
18S16E33A001M	-120.2299	36.3266	326.14
20S18E06D001M	-120.0652	36.2263	306.93