Three-dimensional Perspective Analysis of Spatio-Temporal Drought Characteristics for Developing a Drought Hazard Map

JIYOUNG YOO, BYUNG-JIN SO, HYUN-HAN KWON, **TAE-WOONG KIM**

Hanyang University(ERICA), Korea

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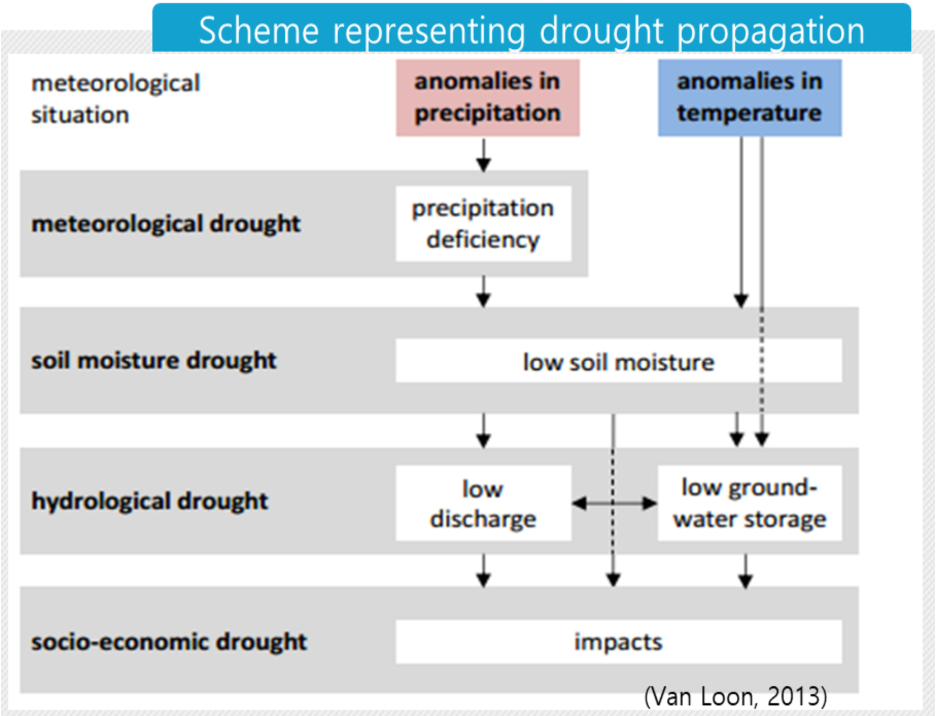
HYU 한양대학교 HANYANG UNIVERSITY

1. Introduction

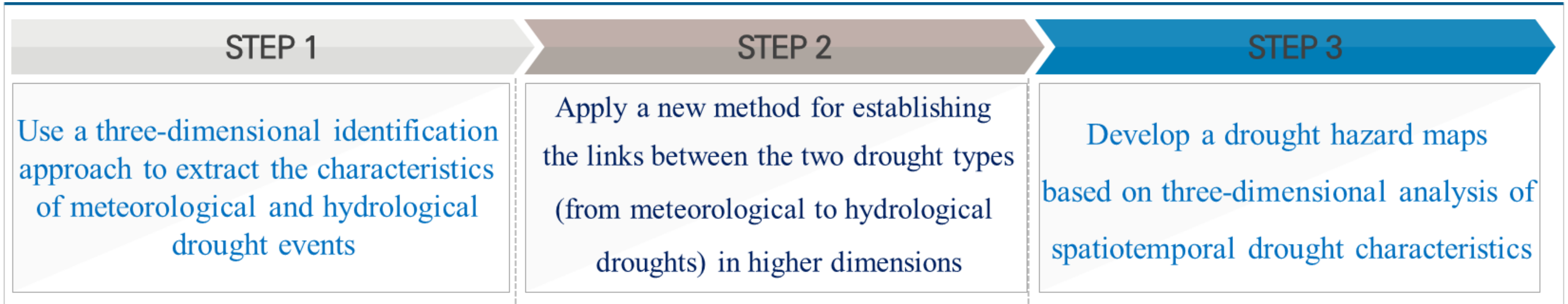
- Drought is one of the natural hazards and has widespread impacts on water supply, agriculture, energy production, ecosystem, and society (Wilhite & Glantz, 1985). From the standpoint of usable water, drought can be classified into four types: meteorological, agricultural, hydrological, and socioeconomic (Mishra & Singh, 2010).
- These four types are inherently related in that a climatic dry signal derived from the shortage of precipitation and high temperature can transfer to the hydrological cycle, resulting sequentially in soil moisture depletion, reduction in streamflow, and decline of water table (van Loon & van Lanen, 2012).

- The development of drought is rather complicated, and analysis of climate controls and catchment characteristics is essential for understanding the relationship among different drought types.
- The connection between meteorological and hydrological droughts is often analyzed in lower dimensions, for example, analyzing the time series of drought characteristics for a specific region or detecting the areal extent of drought during a given time period.



1. Introduction

- However, drought by nature is a three-dimensional phenomenon that simultaneously evolves in time and space (Haslinger & Blöschl, 2017). Andreadis et al. (2005) proposed a severity-area-duration method to track droughts through space and time along their duration, which could be recognized as a representation of drought characterization in higher dimensions.
- Lloyd-Hughes (2012) extended this three-dimensional approach to measure the similarity between individual drought structures. Several studies have applied this spatio-temporal approach for characterizing meteorological and soil moisture droughts at regional or global scales (e.g., Sheffield et al., 2009; A. Wang et al., 2011; Xu et al., 2015).
- Therefore, this study is aimed at developing drought hazard maps after assessing the relationship between meteorological and hydrological droughts from a three-dimensional perspective.



2. Data Sets and Methodology

Identification and Characterization of Droughts in Three Dimensions

STEP 1

use a three-dimensional identification approach to extract the characteristics of meteorological and hydrological drought events

- The meteorological and hydrological droughts were identified using a simple clustering algorithm proposed by Andreadis et al. (2005), in which the evolution of drought is viewed as a continuum in three dimensions (longitude, latitude, and time).
- Specifically, it contains two components, that is, spatial identification and temporal connection.

For each monthly time step (32 years × 12 months), mid-watersheds with SPI/SRI values below −1(threshold) are considered as "under drought." These mid-watersheds are further classified into different drought patches through a spatial clustering method. This algorithm is based on the principle of spatial contiguity, where the drought mid-watersheds in adjacent positions are combined into one patch.

A temporal connection is used to determine the link between drought patches in two adjacent months. Assuming there are N drought patches for the ith month and M drought patches for the i + 1th month, if the areal overlaps between any 1~N and 1~M patches exceed a minimum area threshold, then the corresponding patches should belong to one drought event.

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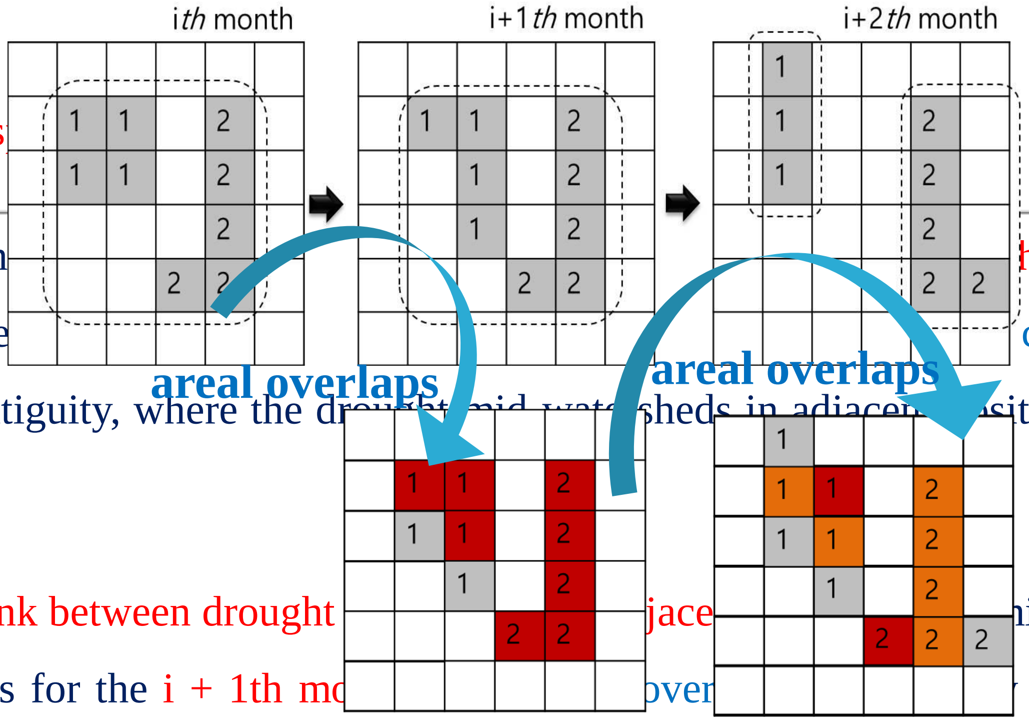

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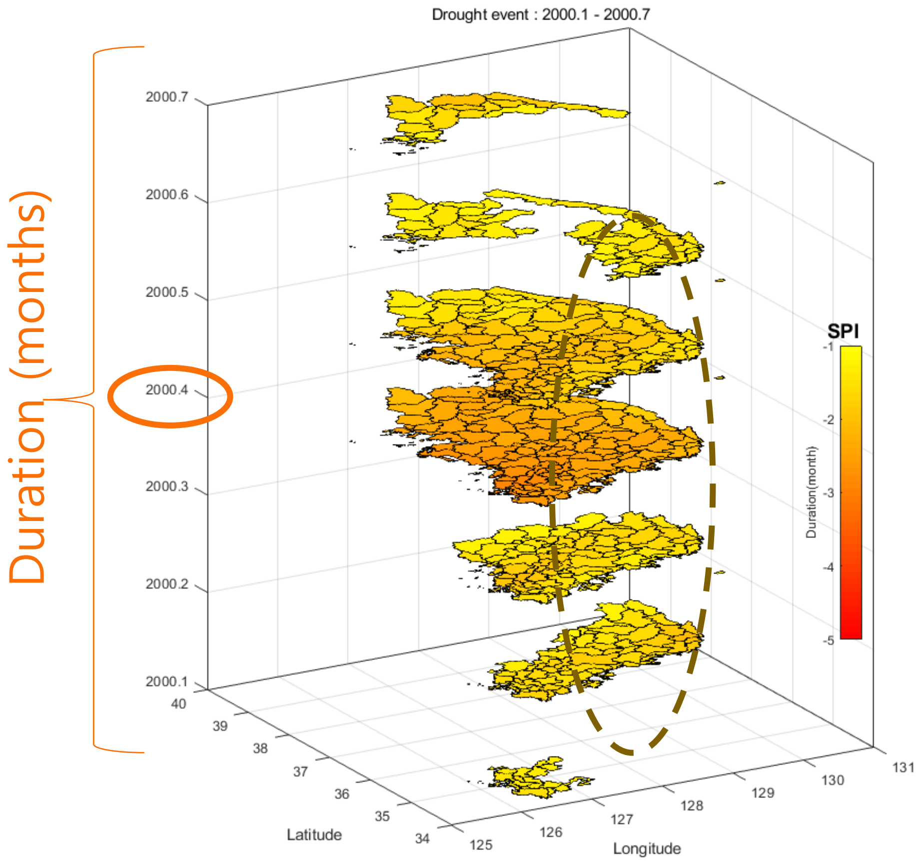
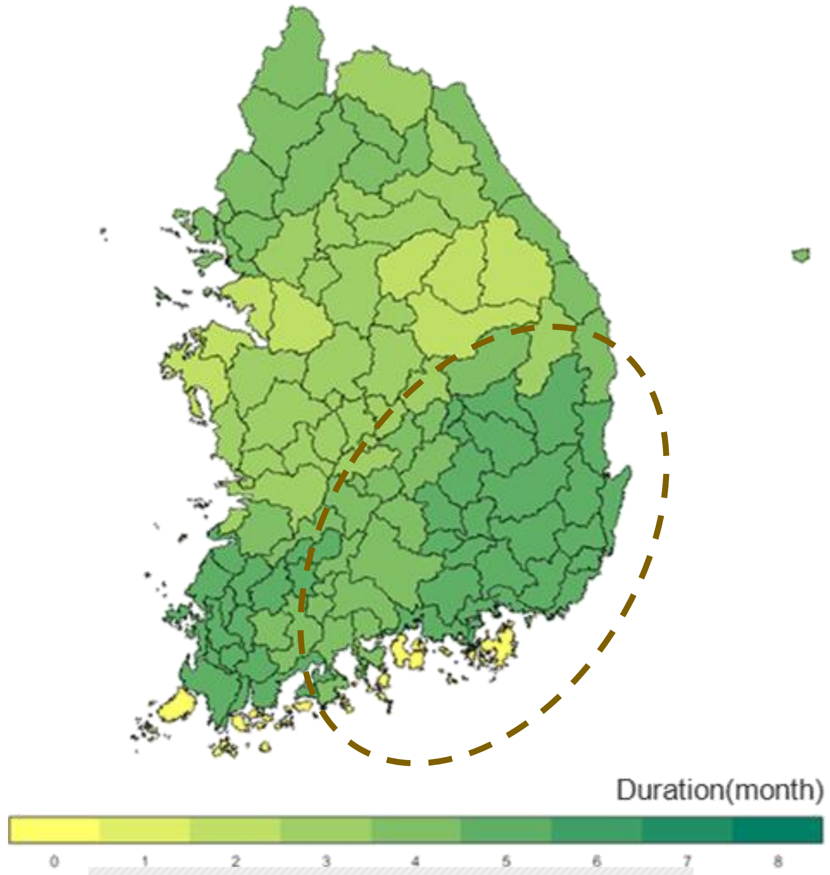
Spatio-temporal characteristics for drought event during January-July 2000



Three-dimensional drought event



Spatial distribution of duration

2. Data Sets and Methodology

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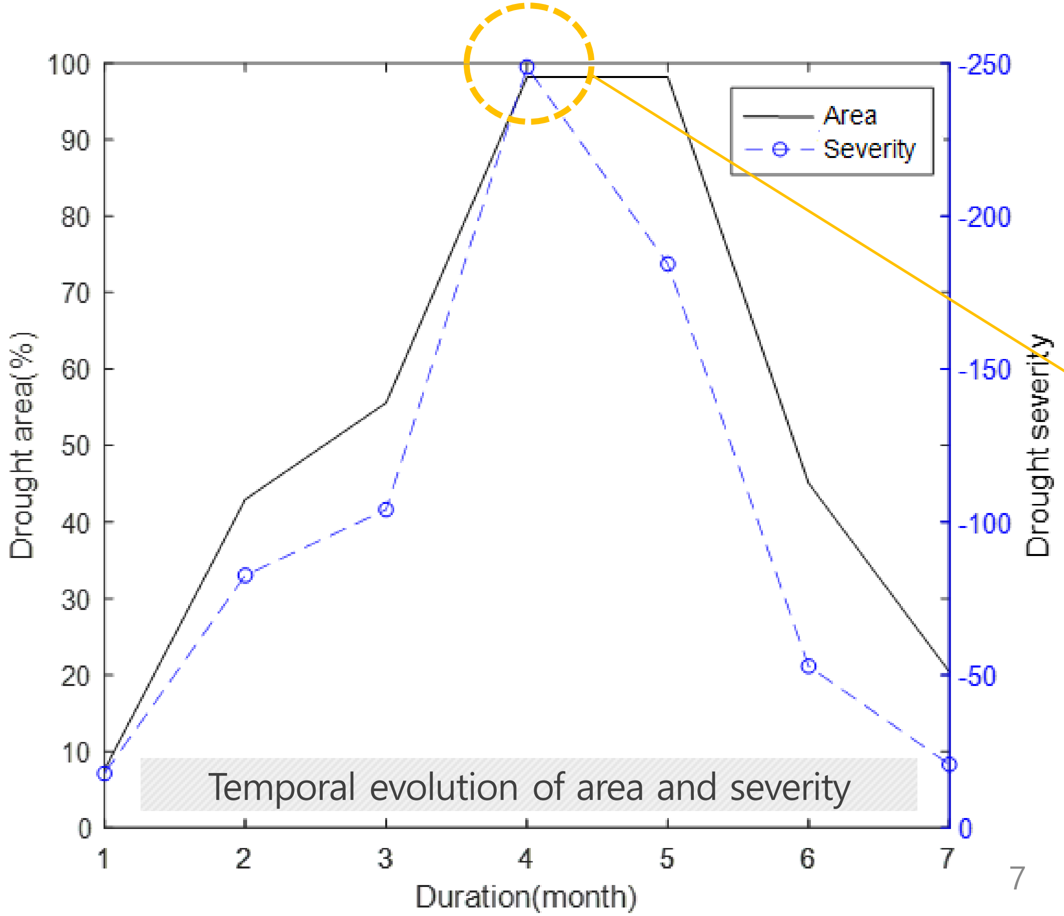
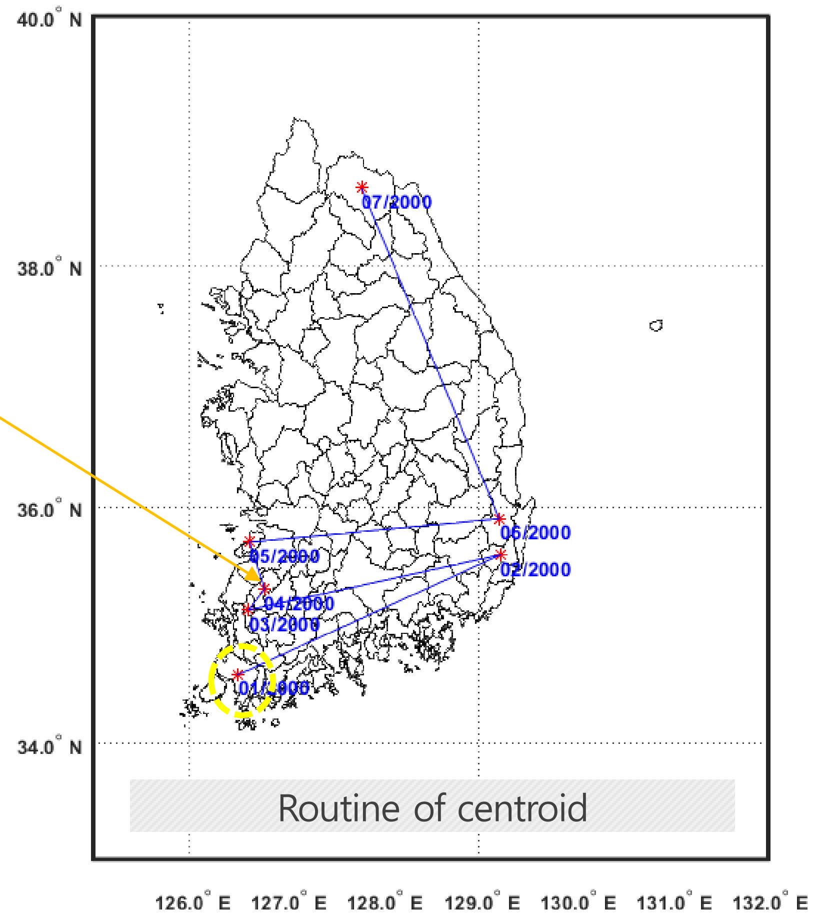


Temporal evolution of area and severity



Routine of centroid

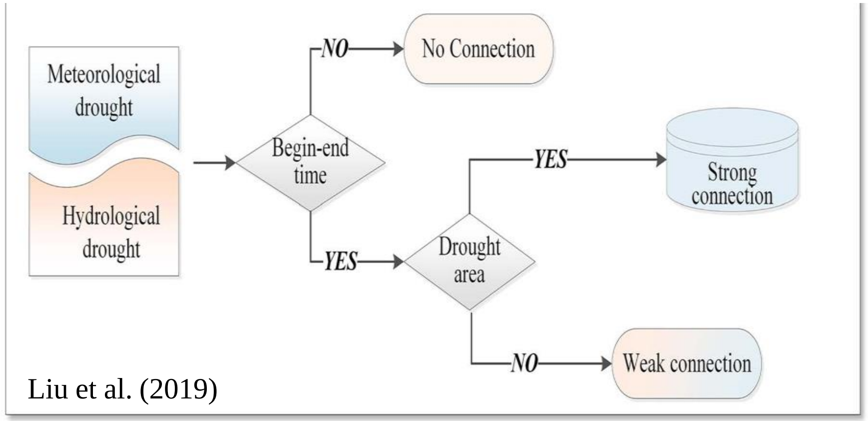
2. Data Sets and Methodology

STEP 2

Propose a new method for establishing the links between the two drought types (from meteorological to hydrological droughts) in higher dimensions

Matching Related Meteorological and Hydrological Droughts

- Meteorological and hydrological droughts are inherently connected. To understand their relationship, we applied a new method by proposed Liu et al. (2019).
- The method can automatically match related meteorological and hydrological drought events in sequence.



Liu et al. (2019)

$$\text{Overlap}_{\text{time}}\begin{cases} >0 \ \text{if} \begin{cases} MBT_i \le HBT_j \quad \text{and} \quad (MBT_i, MET_i) \cap (HBT_j, HET_j) > 0 \\ \text{or} \\ MBT_i > HBT_j \quad \text{and} \quad (MBT_i, MET_i) \cap (HBT_j, HET_j) \ge \alpha \end{cases} \\ = 0 \quad \text{if} \begin{cases} MBT_i > HBT_j \quad \text{and} \quad (MBT_i, MET_i) \cap (HBT_j, HET_j) < \alpha \\ \text{or} \\ (MBT_i, MET_i) \cap (HBT_j, HET_j) = 0 \end{cases} \end{cases}$$

where α is defined as min (DMi/3, DHj/3); MBTi and METi represent the beginning and end times of the ith meteorological drought event, respectively. Similarly, HBTj and HETj represent the beginning and end times of the jth hydrological drought event; DMi and DHj denote the drought durations of meteorological and hydrological droughts, respectively.

$$\text{Overlap}_{\text{space}}\begin{cases} >0 \quad \text{if} \quad (AM_i \cap AH_j) \ge \beta \\ =0 \quad \text{if} \quad (AM_i \cap AH_j) < \beta \end{cases}$$

where AMi and AHj represent the drought areas of meteorological and hydrological droughts, respectively. Also, β is defined threshold of overlap area.

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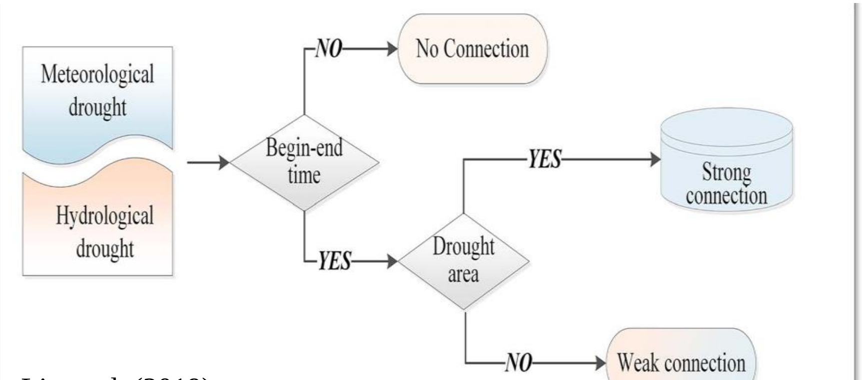
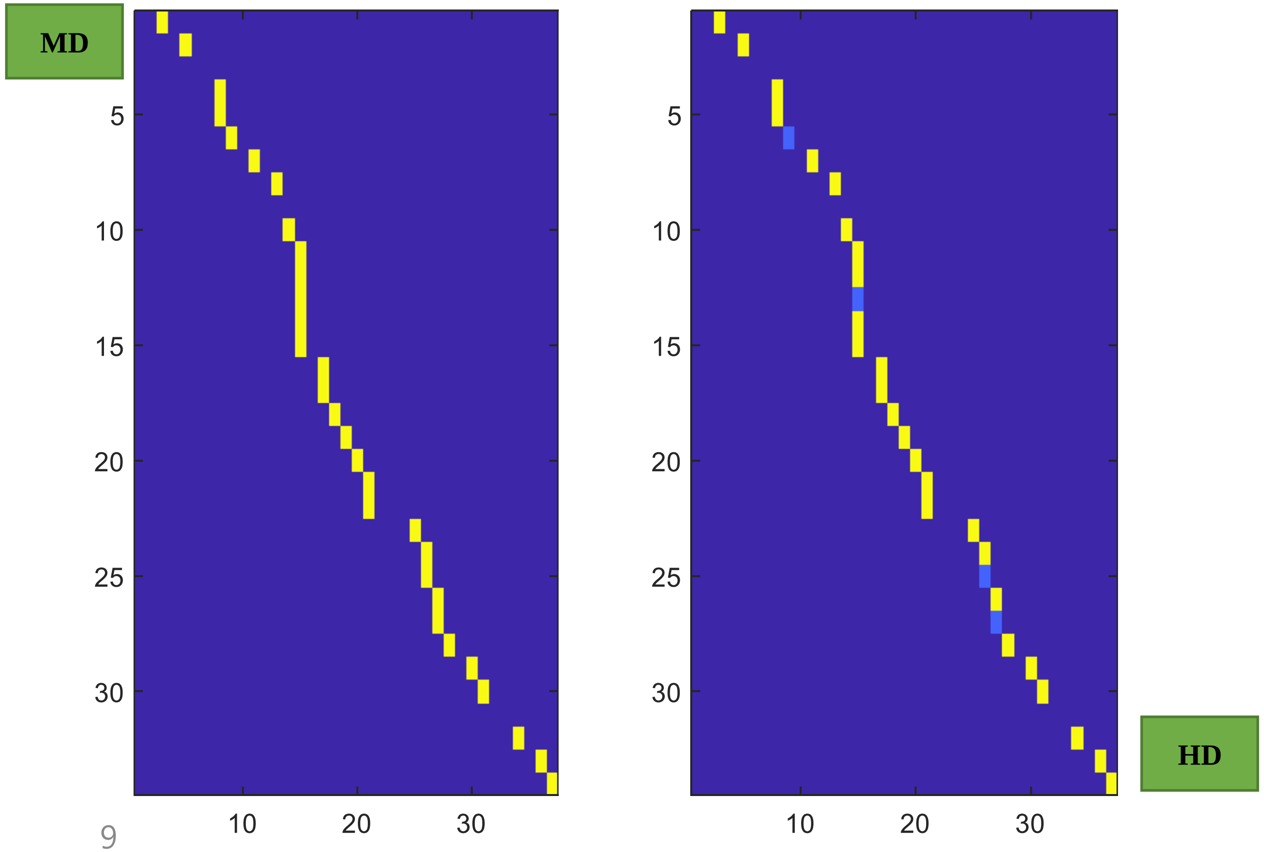


Liu et al. (2019)



3. Results

Spatiotemporal Patterns of Drought Characteristics

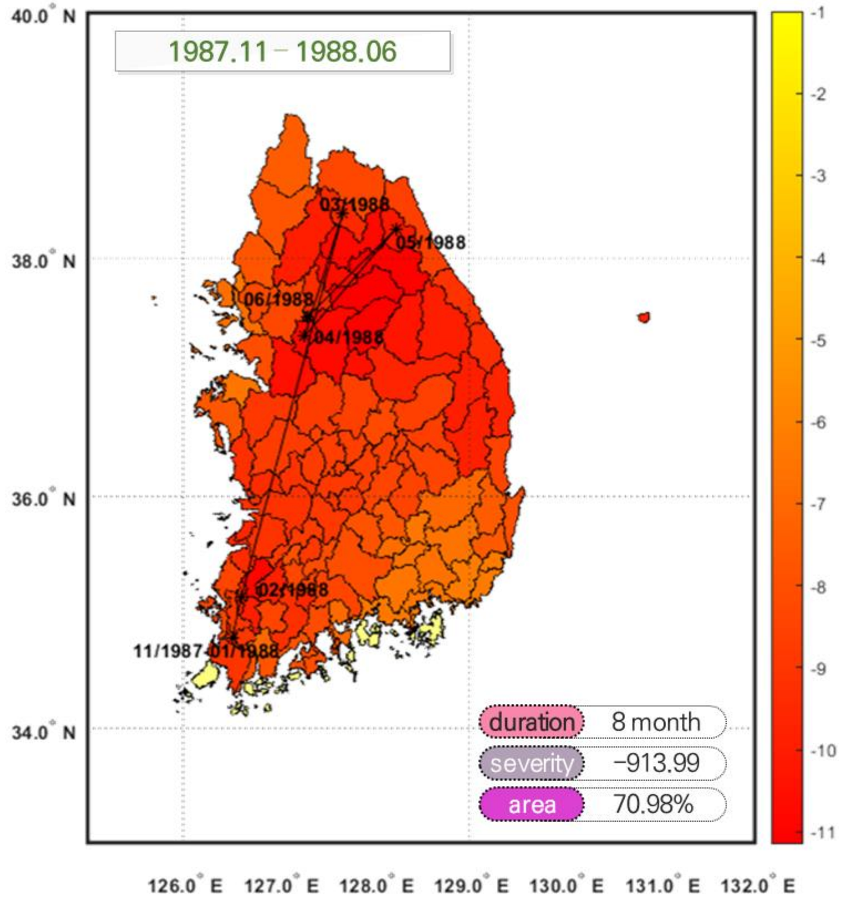
STEP 1

use a three-dimensional identification approach to extract the characteristics of meteorological and hydrological drought events

- Following the three-dimensional identification method described above, 34 meteorological and 37 hydrological drought events are recognized in South Korea

Most severe drought events ranked by severity of SPI3

No	Begin-end time	Duration (month)	Severity (-)	Area (%)
1	**1987/11-1988/6**	**8**	**913.99**	**70.98**
2	1988/8-1988/12	5	730.33	69.20
3	2000/1-2000/7	7	711.08	52.55
4	1995/11-1996/2	4	610.02	93.99
5	1983/12-1984/3	4	602.23	78.78
6	1994/7-1994/10	4	561.41	61.26
7	2008/8-2009/1	6	492.28	49.46
8	2001/4-2001/5	2	491.64	92.29
9	2014/5-2014/10	6	486.22	52.76
10	1996/8-1996/11	4	448.87	58.65



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- Following the three-dimensional identification method described above, 34 meteorological and 37 hydrological drought events are recognized in South Korea

STEP 1

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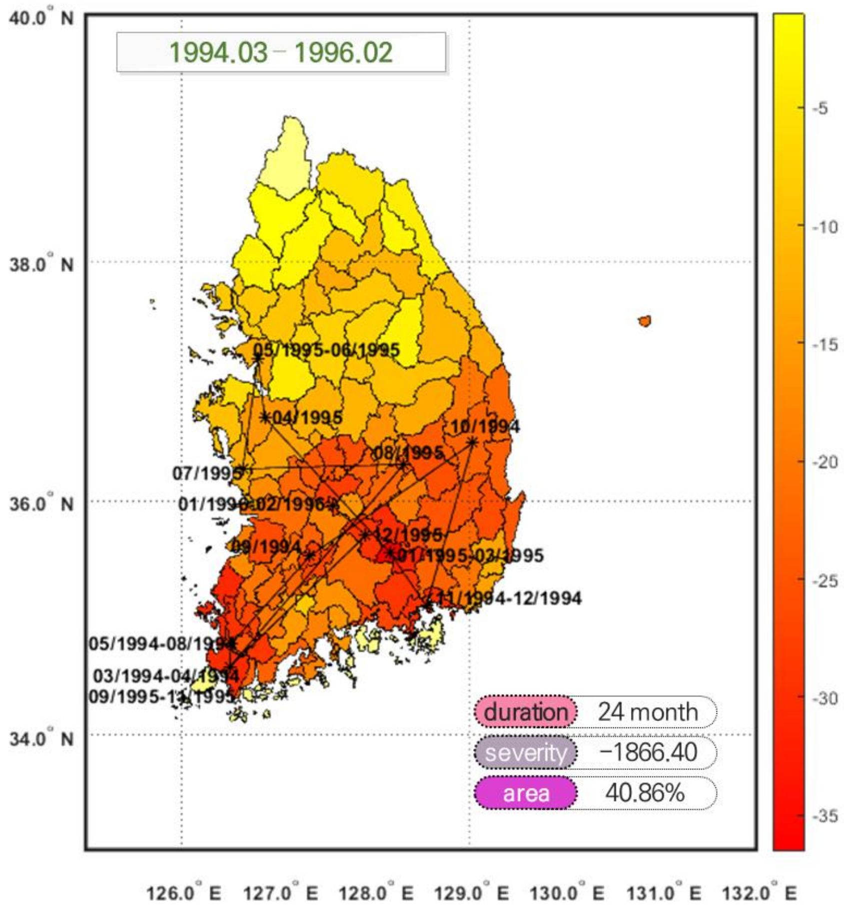
Most severe drought events ranked by severity of SRI3

No	Begin-end time	Duration (month)	Severity (-)	Area (%)
1	**1994/3-1996/2**	**24**	**-1866.40**	**40.86**
2	**1987/12-1989/2**	**15**	**-1113.75**	**44.18**
3	2008/8-2009/6	11	-777.92	40.85
4	1996/8-1997/5	10	-653.57	38.97
5	2001/4-2002/4	13	-600.13	30.63
6	2000/2-2000/8	7	-431.28	34.65
7	2014/5-2014/10	6	-371.92	43.56
8	1983/12-1984/7	8	-363.37	33.00
9	1992/6-1992/9	4	-272.88	47.50
10	2009/10-2010/1	4	-259.45	41.42



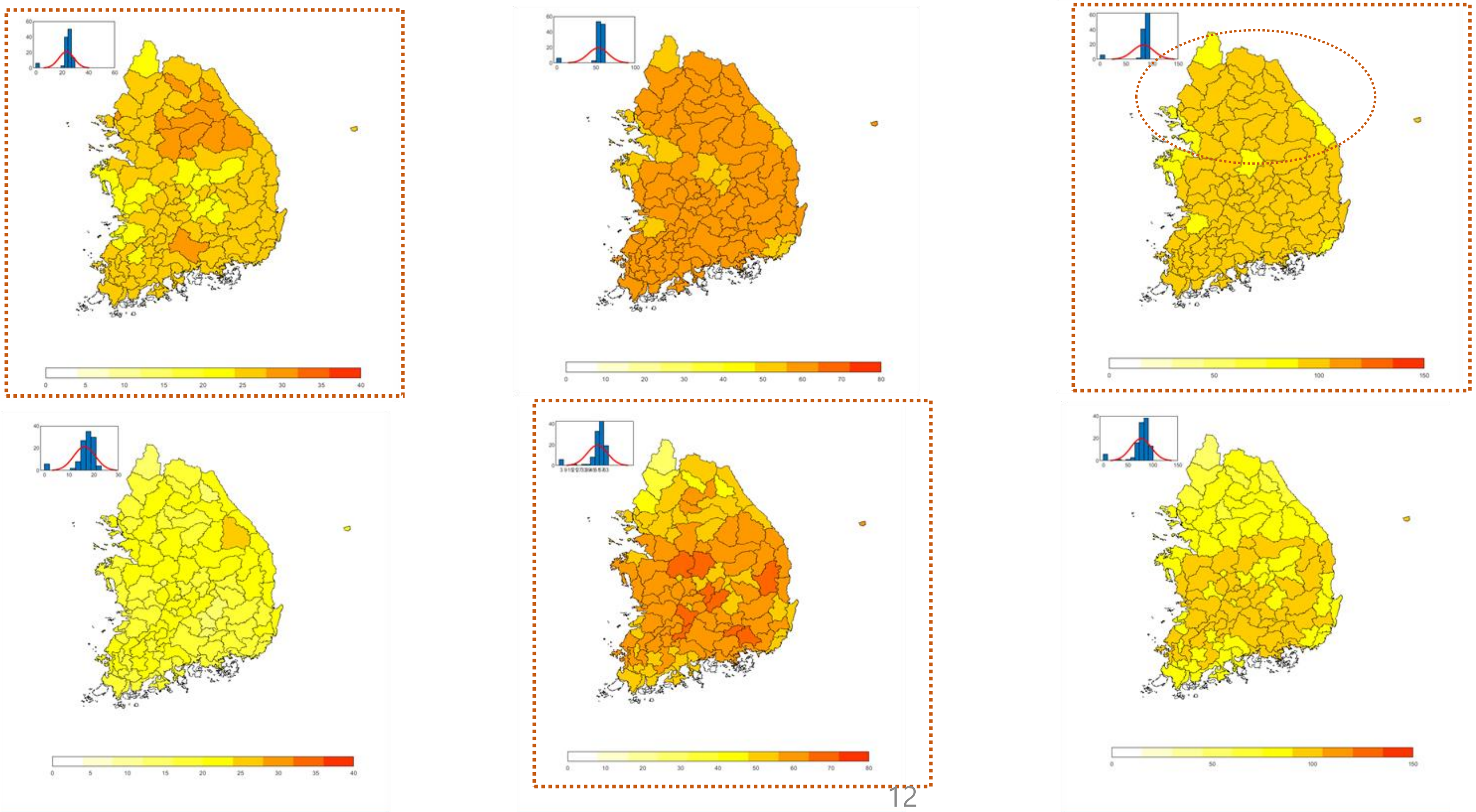
3. Results

STEP 1

use a three-dimensional identification approach to extract the characteristics of meteorological and hydrological drought events

Spatiotemporal Patterns of Drought Characteristics for SPI3 and SRI3

	Drought events	Drought duration	Drought severity
SPI3			
SRI3			



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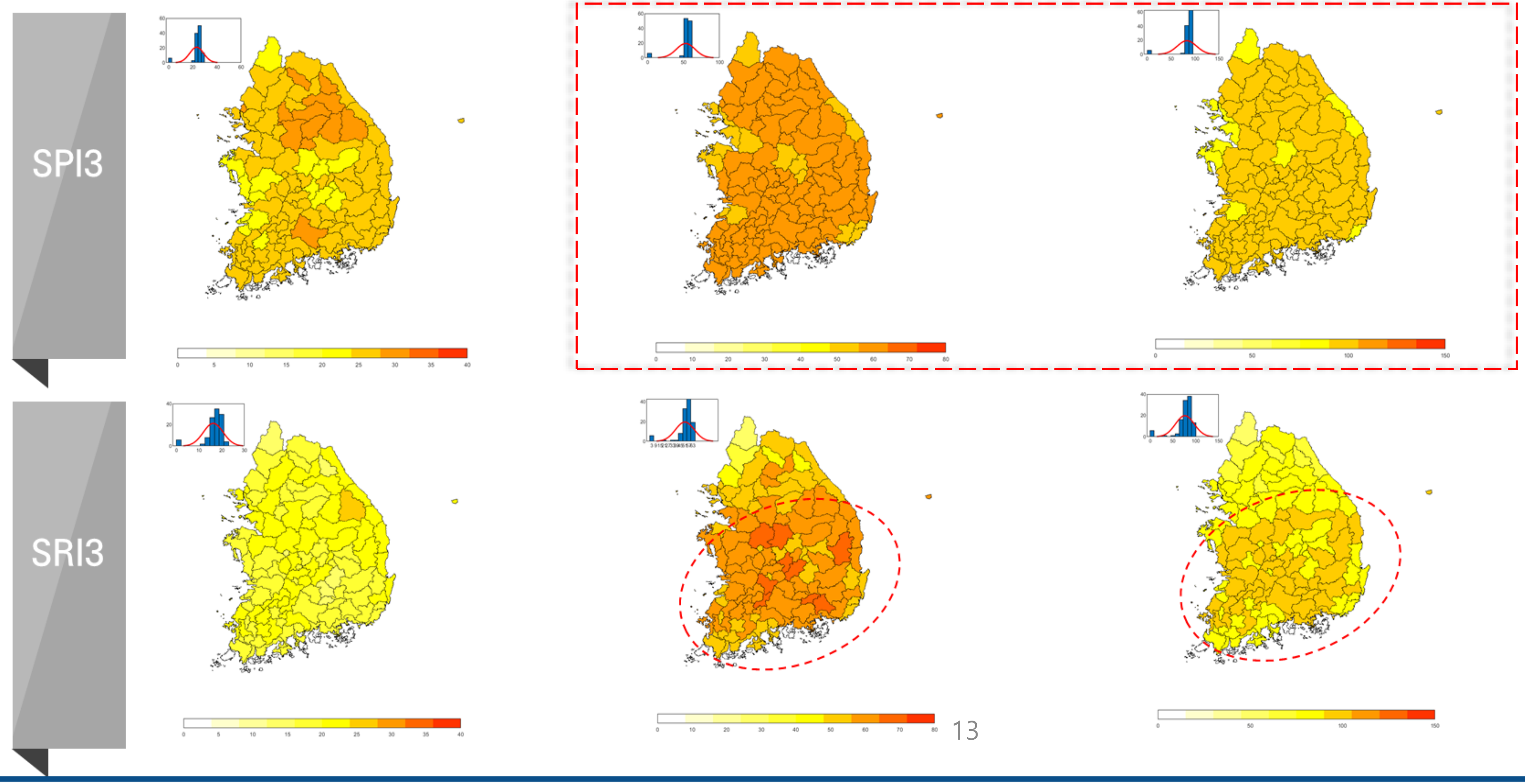
Spatiotemporal Patterns of Drought Characteristics for SPI3 and SRI3

STEP 1

use a three-dimensional identification approach to extract the characteristics of meteorological and hydrological drought events

Drought events	Drought duration	Drought severity



The drought duration and severity basically reveal a similar spatial distribution

3. Results

STEP 2

Propose a new method for establishing the links between the two drought types (from meteorological to hydrological droughts) in higher dimensions

The Links Between the Two Drought Types: How droughts are linked in higher dimension

Meteorological Drought (MD)

No	Begin time		End time		Duration (month)	Severity (-)	Area (%)
	Year	Month	Year	Month			
1	1983	12	1984	3	4	602.23	78.78
2	1985	7	1985	8	2	33.09	16.64
3	1986	3	1986	4	2	85.65	33.08
4	1987	11	1988	6	8	913.99	70.95
5	1988	8	1988	12	5	730.33	69.20
6	1989	5	1989	8	4	175.45	34.16
7	1991	8	1991	10	3	75.19	25.50
8	1992	6	1992	9	4	417.48	60.00
9	1993	4	1993	5	2	69.31	19.26
10	1993	9	1993	11	3	60.18	18.83
11	1994	3	1994	5	3	247.00	48.59
12	1994	7	1994	10	4	561.41	61.26
13	1995	1	1995	2	2	62.15	35.07
14	1995	5	1995	7	3	253.72	56.87
15	1995	11	1996	2	4	610.02	93.99
16	1996	8	1996	11	4	448.87	58.65
17	1997	3	1997	4	2	105.44	41.75
18	1997	8	1997	10	3	167.91	40.34
19	1999	1	1999	2	2	279.12	92.03
20	2000	1	2000	7	7	711.08	52.55
21	2001	4	2001	5	2	491.64	92.29
22	2001	8	2001	10	3	166.17	31.86
23	2005	6	2005	8	3	101.04	18.82
24	2005	12	2006	1	2	85.38	37.29
25	2006	2	2006	3	2	16.14	9.66
26	2006	10	2006	11	2	174.38	58.60
27	2007	1	2007	2	2	44.63	23.55
28	2007	6	2007	8	3	77.88	17.69
29	2008	8	2009	1	6	492.28	49.46
30	2009	10	2009	11	2	229.59	69.01
31	2010	12	2011	1	2	170.48	60.74
32	2012	6	2012	7	2	46.98	16.60
33	2013	7	2013	9	3	92.63	18.02
34	2014	5	2014	10	6	486.22	52.76

Hydrological Drought (SD)

No	Begin time		End time		Duration (month)	Severity (-)	Area (%)
	Year	Month	Year	Month			
1	1983	3	1983	4	2	12.77	6.03
2	1983	7	1983	9	3	105.04	25.29
3	1983	12	1984	7	8	363.37	33.00
4	1985	2	1985	4	3	22.36	4.60
5	1985	7	1985	9	3	75.24	22.13
6	1986	4	1986	6	3	96.58	30.01
7	1986	9	1986	10	2	22.24	6.42
8	1987	12	1989	2	15	1113.75	44.18
9	1989	7	1989	8	2	17.83	7.99
10	1990	9	1990	10	2	11.73	3.52
11	1991	9	1991	10	2	16.13	10.08
12	1991	12	1992	3	4	43.26	7.11
13	1992	6	1992	9	4	272.88	47.50
14	1993	9	1994	1	5	51.43	10.69
15	1994	3	1996	2	24	1866.40	40.86
16	1996	4	1996	5	2	33.84	12.67
17	1996	8	1997	5	10	653.57	38.97
18	1997	9	1997	11	3	138.29	35.99
19	1999	1	1999	4	4	108.59	14.84
20	2000	2	2000	8	7	431.28	34.65
21	2001	4	2002	4	13	600.13	30.63
22	2002	12	2003	3	4	45.47	11.49
23	2004	3	2004	4	2	12.61	3.53
24	2004	12	2005	3	4	44.92	8.86
25	2005	4	2005	8	5	50.95	6.47
26	2005	12	2006	3	4	58.52	9.20
27	2006	10	2007	3	6	224.77	27.89
28	2007	5	2007	8	4	111.75	13.67
29	2008	3	2008	7	5	180.77	27.52
30	2008	8	2009	6	11	777.92	40.85
31	2009	10	2010	1	4	259.45	41.42
32	2010	7	2010	8	2	44.22	20.18
33	2011	1	2011	2	2	66.01	22.70
34	2012	3	2012	7	5	91.95	9.61
35	2013	3	2013	6	4	42.24	4.36
36	2013	8	2013	10	3	82.41	16.78
37	2014	5	2014	10	6	371.92	43.56

- With paired meteorological and hydrological drought events, the relationship of drought transition (overlapping time and area) can be determined.

- Among the total hydrological drought events (37 in total), it was confirmed that more than 50% of the events were affected by meteorological drought.

Characteristics Analysis of Spatiotemporal Drought

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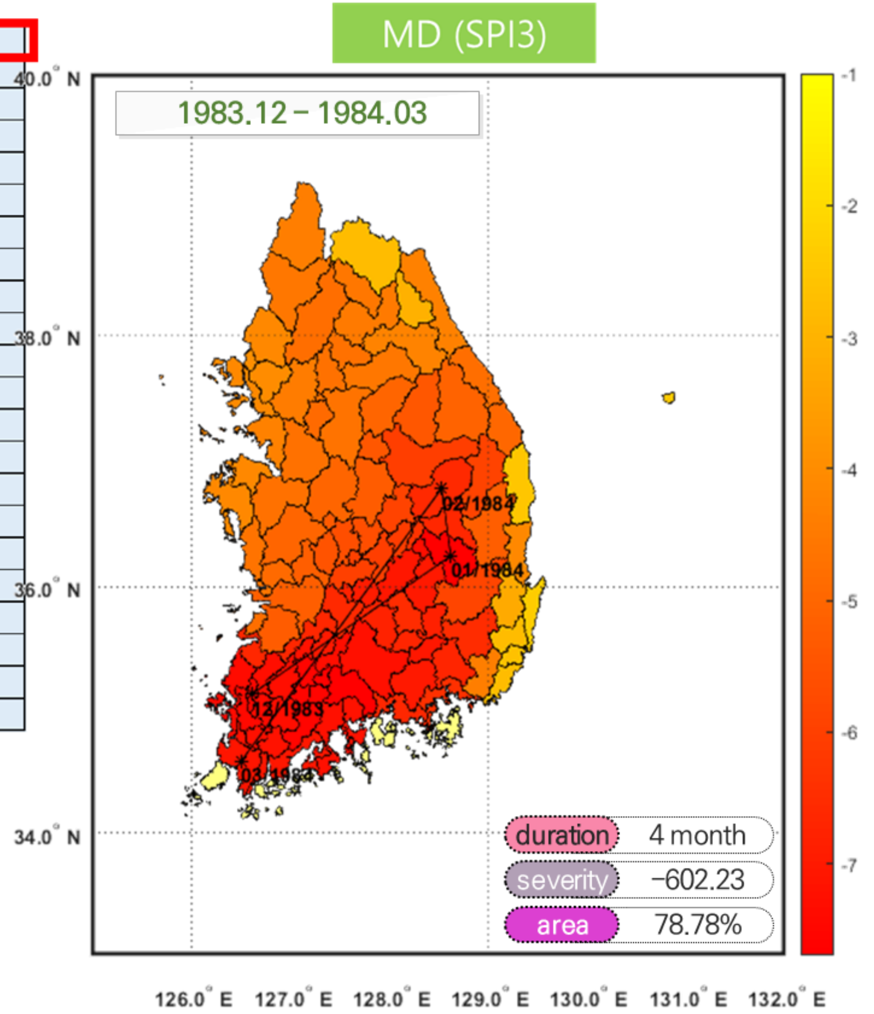
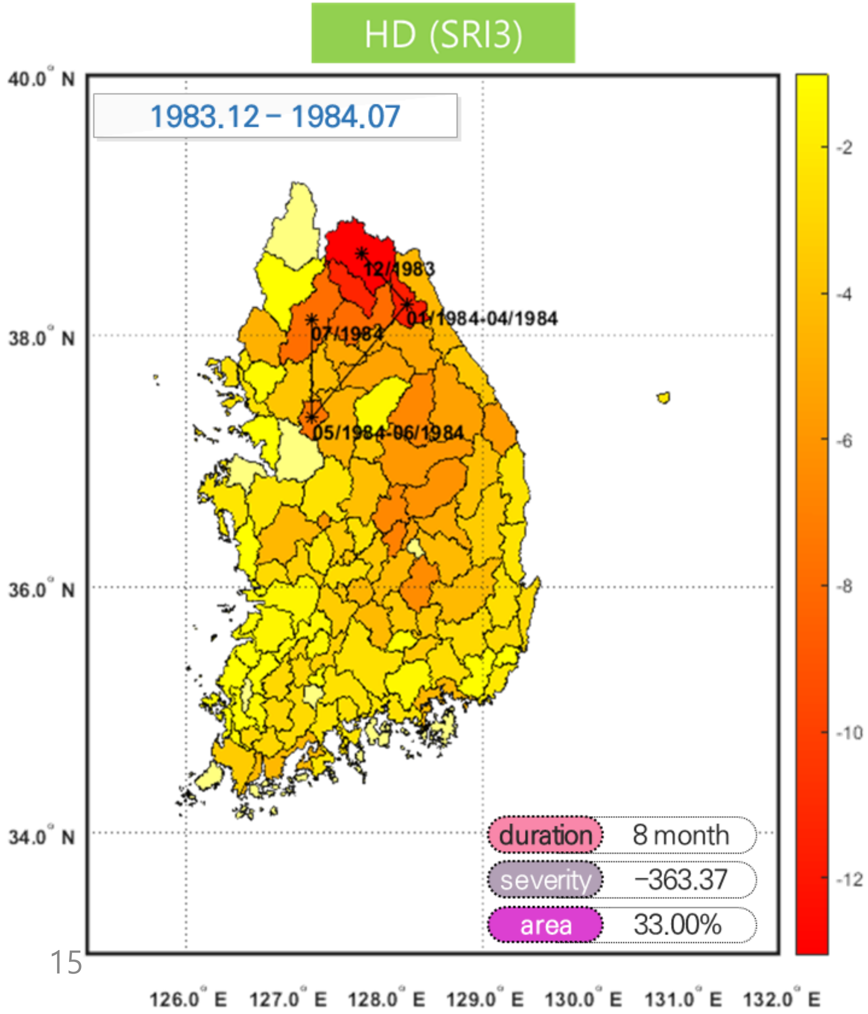
[14;15]	15
[16;17]	17
[21;22]	21





STEP 3

Develop a drought hazard maps based on three-dimensional analysis of spatiotemporal drought characteristics

3. Results

Characteristics Analysis of Spatiotemporal Drought

STEP 3

Develop a drought hazard maps based on three-dimensional analysis of spatiotemporal drought characteristics

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[16;17]	17
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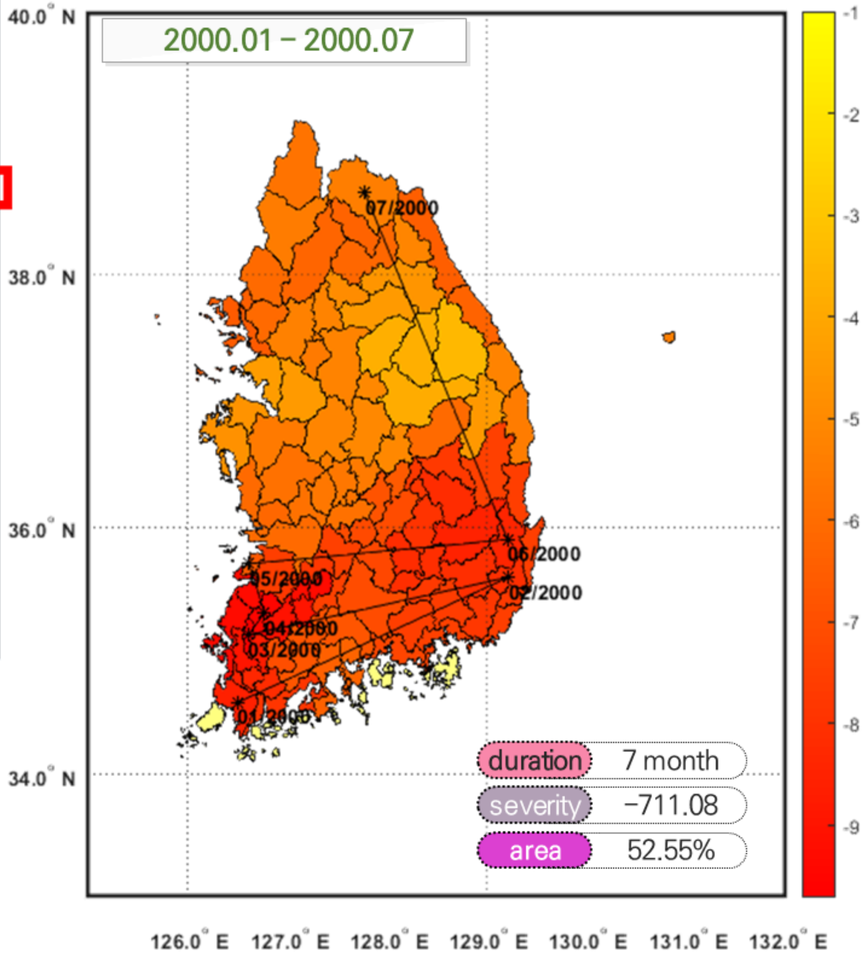
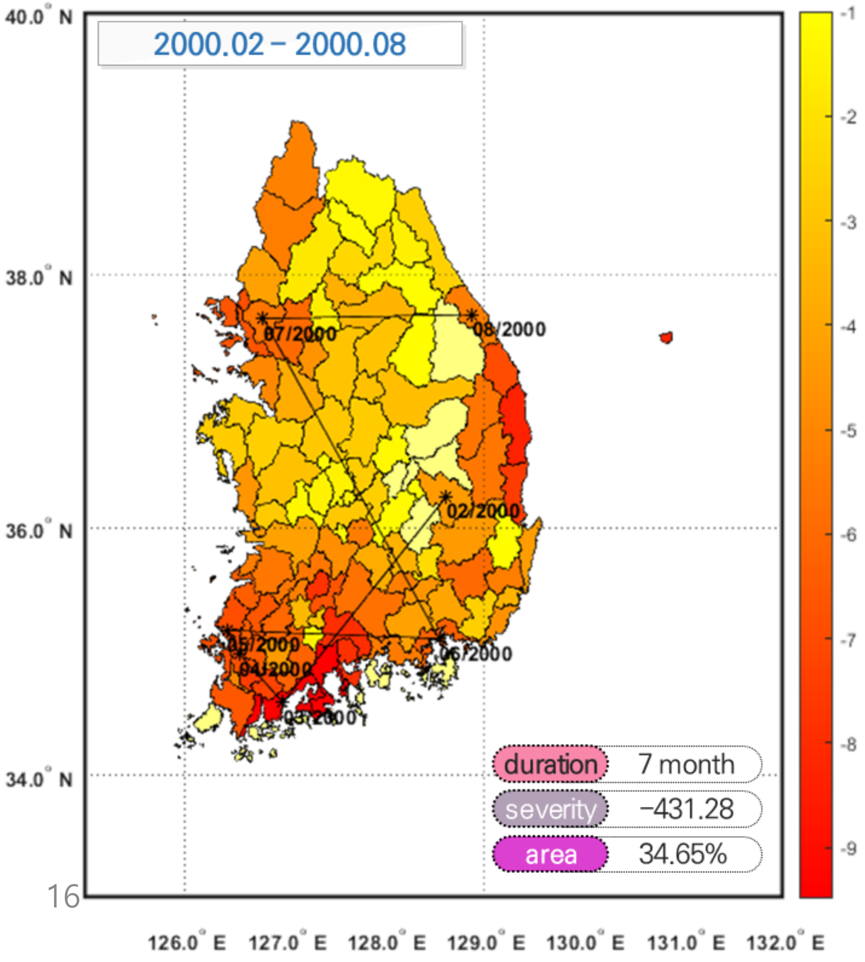
MD (SPI3)



HD (SRI3)



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Characteristics Analysis of Spatiotemporal Drought

STEP 3

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1	3
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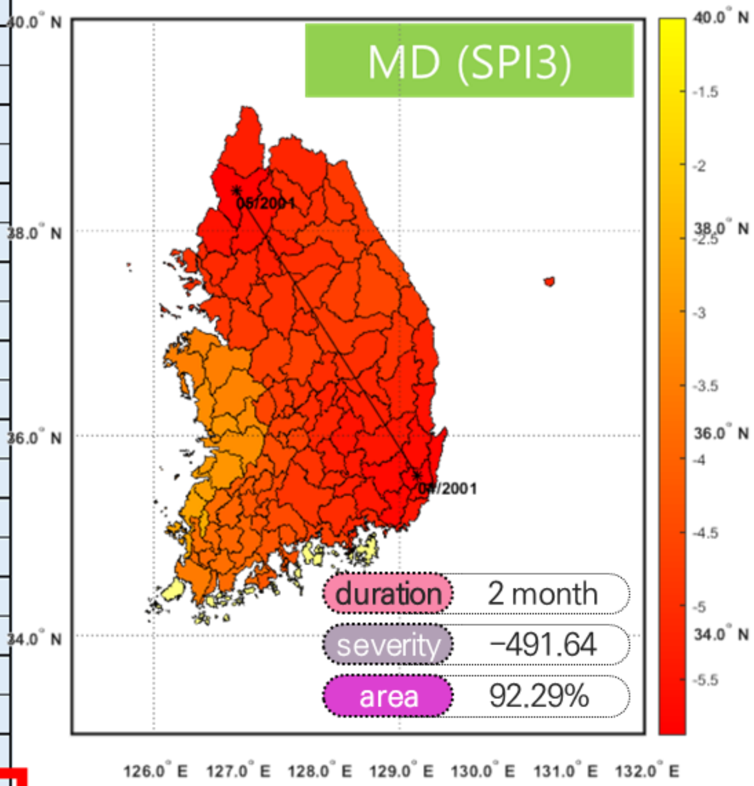
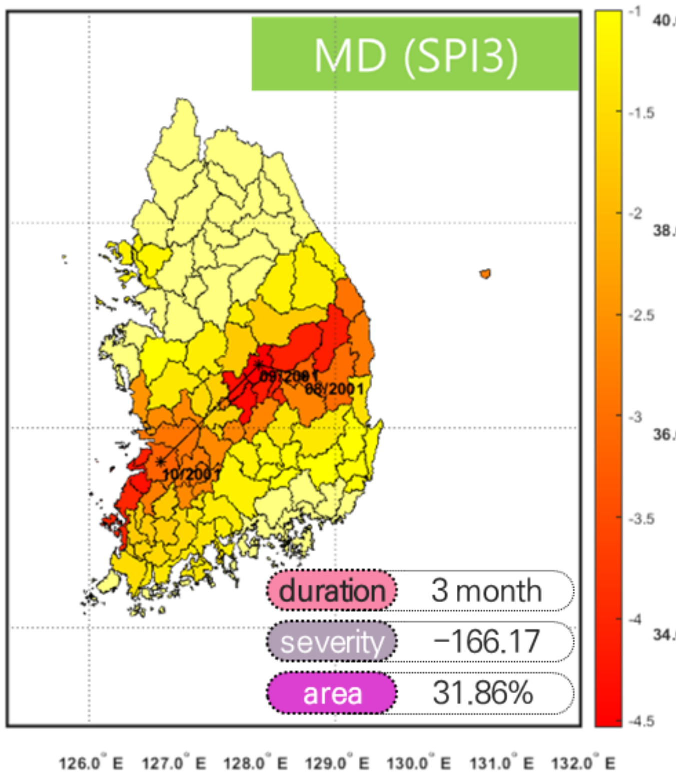
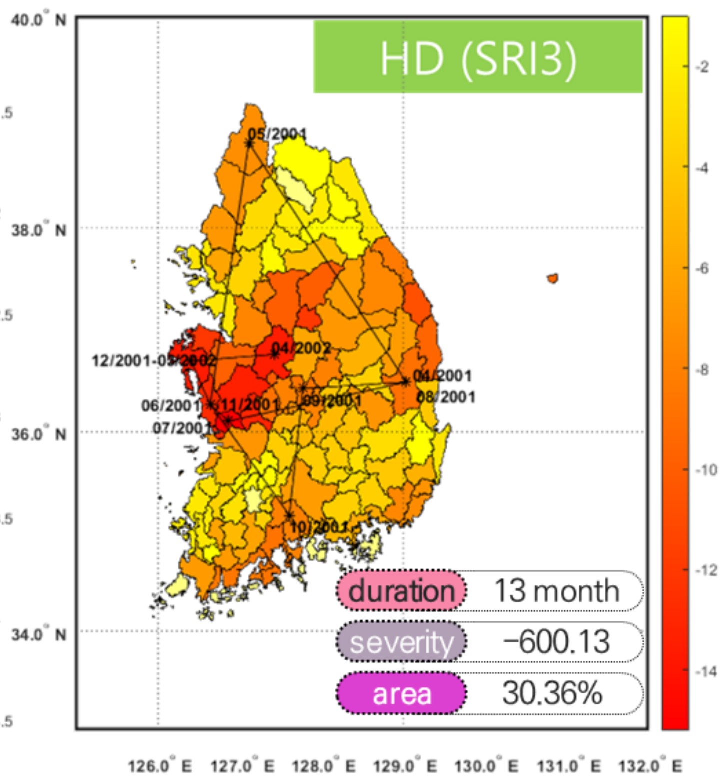


2001.04 – 2001.05



2001.08 – 2001.10



2001.04 – 2002.04

4. Discussion and Conclusions

- In this study, a new approach for linking meteorological and hydrological droughts is applied to developing drought monitoring maps in three-dimension perspective. This approach is two type of drought characteristics including duration, severity, and area are considered for constructing connections.
- The process of linking meteorological and hydrological droughts involves several thresholds: SPI and SRI-based on threshold (- 1.0), two parameters for judging the temporal and spatial overlaps between meteorological and hydrological droughts.
- As a successive investigation on the drought propagation process, this study attempts to explicitly establish the relationship between these meteorological and hydrological droughts over space-time dimensions by incorporating the characteristic of drought area.
- The results of this study can be used as a tool to monitor the transition phenomenon from meteorological drought to hydrological drought in order to determine the potential drought risk.
- However, this study was limited to understanding the mechanism of drought transmission by analyzing the impact of weather conditions on hydrologic drought occurrence. Also, other factors such as catchment control and human interventions are not included, which may limit the application of derived conclusions to other regions.
- Therefore, future works involving the effects of catchment control and human interference are highly desirable and the spatial scale will be downscaled to space-time drought analysis.

Thank you!

Question?

→ E-mail: 7924pooh@hanyang.ac.kr

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