Examination of selected atmospheric and orographic effects on monthly precipitation of Taiwan using the ASOAdEK model

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ABSTRACT: Characterization and quantification of precipitation spatial variability are required for many studies, such as those in hydrology, ecology, forestry and agriculture. In mountainous terrains (e.g. Taiwan), interactions of moist air mass with underlying complex topography result in increased but often predictable precipitation spatial variability. When these interactions are quantitatively captured, they can contribute to precipitation mapping. In this paper, we applied a recently developed multivariate regression model [auto-searched orographic and atmospheric effects de-trended kriging (ASOAdEK) regression] to examine selected atmospheric and orographic effects: atmospheric moisture gradient (MG), terrain elevation (Z), terrain aspect and related moisture flux direction (MFD), on Taiwan mean monthly precipitation climatology, primarily based on a dense gauge network (about 110 gauges per 10 000 km²). The results indicate that (1) the regression captures over 50% of spatial variability in mean monthly precipitation over the whole Taiwan island, with improved performance when the regression is applied to sectional regions; (2) the atmospheric MG and MFD are significant factors explaining mean monthly precipitation spatial variability in Taiwan, whereas the elevation effect is not as significant; (3) when the data of sectional regions are applied in the regression, the inferred MFDs vary in a certain range, indicating slightly different climate setting between northern and southern parts of Taiwan; (4) the degree of agreement between the ASOAdEK regression-inferred MFDs and local observed prevailing winds is systemic, and can be used to explain the contrast of rainfall seasonality patterns between the northern part and the rest of Taiwan; and (5) a gauge network of 50 gauges per 10 000 km² is sufficient to capture the orographic effect on mean monthly precipitation distribution. Copyright © 2008 Royal Meteorological Society

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1. Introduction

Precipitation spatial variability is a commonly recognized phenomenon and is of interest in many disciplines, such as hydrology, ecology, forestry and agriculture (Koren *et al.*, 1999; Smith *et al.*, 2004; Xiao and Moody, 2004). Many factors and processes may contribute to precipitation spatial variability. Over mountainous terrains, precipitation spatial variability is even larger than over flat areas, mainly due to the interaction of moisture-bearing air mass and the underlying complex topography, i.e. orographic effects (Barros, 1994; Basist *et al.*, 1994). The spatial variability can be captured at a certain temporal and spatial resolution by a dense precipitation gauge network (Comrie and Broyles, 2002; Taupin, 2003) or remote sensing technique (Petty, 1995; Fulton *et al.*,

1998). Although remote sensing techniques (such as NEXRAD in the USA) provide spatial variability patterns of rainfall at the designed resolutions, gauge observations are required to correct the bias in the estimated precipitation field (Steiner *et al.*, 1999; Westrick *et al.*, 1999; Tetzlaff and Uhlenbrook, 2005; Xie *et al.*, 2006). Moreover, ground-based RADAR remote sensing techniques experience more problems in mountainous terrains, mainly due to beam blockage by complex topography (Vivekanandan *et al.*, 1999; Young *et al.*, 1999; Krajewski *et al.*, 2006).

Thus, precipitation mapping based on gauge observations is still a common approach in many cases, especially in mountainous regions and when studying climatologic aspect of the precipitation (Guan *et al.*, 2005b). Some physical processes influencing precipitation spatial variability in mountainous terrains can be used in precipitation mapping procedures (Daly *et al.*, 1994; Hutchinson, 1995; Drogue *et al.*, 2002; Guan *et al.*, 2005a). Orography may affect precipitation patterns,

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being precipitation increased with the altitude and favouring precipitation enhancement on windward slopes at the expense of relative decreases on less exposed leeward slopes. These patterns are more obvious when long-term mean precipitation is considered, and can be used to estimate spatial variability of mountain precipitation based on gauge data. A geostatistical model [auto-searched orographic and atmospheric effects de-trended kriging (ASODeK)] incorporating these physical connections was recently developed to successfully construct monthly precipitation maps for mountainous terrain in New Mexico, USA. (Guan *et al.*, 2005a).

This ASODeK model employs a multivariate linear regression (ASODeK regression hereafter) to auto-search relationships between precipitation distribution and several selected factors (atmospheric moisture gradient (MG), terrain elevation (Z), and atmospheric moisture flux direction (MFD), defined in Section 2.2), useful for precipitation mapping. In one application of the model over semiarid northern New Mexico, the regression captures on average 60% of spatial variability in mean monthly precipitation over an area of 300×150 km. The primary objective of this study is to examine the performance of the ASODeK regression in explaining spatial variability of mean monthly precipitation over the subtropical humid Taiwan island ($36\,000$ km²).

There are two main reasons that we chose Taiwan for this study. (1) Because of its unique geographic location and topographic characteristics, Taiwan island provides a good setting for applications of the ASODeK auto-searching function. (2) If the atmospheric and orographic effects leading to spatial precipitation variability in Taiwan (Chen *et al.*, 2004; Wang *et al.*, 2005) are successfully captured, it will be a benefit not only for water resource management, but also for pollution assessment and sediment discharge studies (Lin and Kao, 2003; Tetzlaff and Uhlenbrook, 2005; Galewsky *et al.*, 2006; Lee *et al.*, 2006).

2. Methodology

2.1. Study area and the data

The study area, Taiwan, is a subtropical north–south-elongated island, located off the southeastern coast of mainland China in East Asia. Mean annual precipitation of the island is 2500 mm, with 3100 mm in the north and 2200 mm in the south. The north–south-oriented Central Mountain Range (CMR) stretches across the centre of the island (Figure 1). The mean elevation of CMR is about 2000 m with the peak around 4000 m. The climate is primarily controlled by the East Asian Monsoon, with northeasterly monsoon in cold seasons (October–April), and southwesterly monsoon in warm seasons (May–September) (Chen and Chen, 2003). These two predominant prevailing winds, interacting with the CMR, and a large topographic relief, provide a good setting for testing the performance of the ASODeK regression. Besides the frontal systems in winter and convective

Figure 1. Topographic map of Taiwan, distribution of 392 automatic precipitation gauges (points) and 18 conventional long-term precipitation stations (cross circles). The tunnel lines divide Taiwan into four sections (from north to south: NN, NS, SN and SS), which are applied in regression analyses. The three selected divides are located in UTM (WGS-84, zone 50) northing 2700 km (latitude 24.3845°), 2600 km (latitude 23.4825°) and 2500 km (latitude 22.5803°).

systems in summer embedded in monsoons providing precipitation to the island, the Mei-yu frontal systems in mid-May to mid-June, and tropical storms in warm seasons, also provide significant amount of precipitation to Taiwan island (Chen and Chen, 2003). Together, they compose complex climate systems in the region.

Two sets of precipitation gauge data were used in this study (Figure 1). The primary one was the Automatic Rainfall and Meteorological Telemetric System (ARMT), including about 400 gauges, with data coverage from 1993 through 2003 (Hsu, 1998; Chen *et al.*, 1999). A few gauges were excluded because they were too close to others (within 1-km pixel distance), or had data record less than 10 years, leaving 392 gauges for the data analysis in this study. The other data set was the 18 conventional precipitation stations, with data covering from 1950 through 2004. For both sets of data, mean monthly precipitation was calculated before the ASODeK regression was performed. The statistics of both data sets are included in Table I.

2.2. The ASODeK regression

The ASODeK model has two components: a multivariate regression to estimate the precipitation trend over the whole study area, and a residual (observations–regression estimates) kriging. The ASODeK precipitation map is

Table I. Statistics of mean monthly precipitation for all 392 ARMT gauges, the four sections, and the 18 long-term gauges.

Sections	Statistics	M01	M02	M03	M04	M05	M06	M07	M08	M09	M10	M11	M12
All (392)	Mean	69	101	102	133	231	341	298	361	256	180	85	70
	Max	533	610	549	508	550	808	626	818	1370	1046	835	827
	Min	6	9	9	29	29	114	7	60	38	8	0	0
	Std/mean	0.95	0.79	0.81	0.52	0.35	0.36	0.39	0.42	0.56	1.04	1.64	1.36
NN (123)	Mean	123	170	178	182	225	281	232	272	329	289	181	142
	Max	533	610	549	508	410	448	523	599	1370	1046	835	827
	Min	11	11	50	77	29	114	7	60	44	19	2	0
	Std/mean	0.63	0.47	0.53	0.36	0.28	0.25	0.38	0.40	0.55	0.81	1.11	0.95
NS (143)	Mean	49	88	85	136	231	344	286	317	193	116	43	40
	Max	277	357	309	404	550	808	626	744	626	693	453	331
	Min	7	9	13	53	61	156	32	89	38	8	0	0
	Std/mean	0.76	0.67	0.58	0.46	0.39	0.37	0.36	0.38	0.58	1.16	1.60	0.98
SN (103)	Mean	33	46	47	83	245	369	382	507	247	131	29	28
	Max	235	182	146	193	485	785	567	818	528	514	214	224
	Min	6	18	9	33	74	139	132	263	92	18	0	0
	Std/mean	0.82	0.57	0.48	0.37	0.37	0.32	0.30	0.25	0.37	0.98	1.19	1.00
SS (22)	Mean	45	43	39	67	194	526	366	472	302	195	75	51
	Max	103	101	85	154	365	695	548	664	410	392	174	115
	Min	13	13	14	29	104	379	186	295	182	61	21	15
	Std/mean	0.67	0.73	0.54	0.47	0.32	0.18	0.22	0.17	0.24	0.51	0.64	0.68
LT (18)	Mean	108	126	127	141	250	340	295	358	339	238	161	117
	Max	343	376	321	229	529	698	650	794	678	766	585	400
	Min	18	17	21	49	152	203	140	200	139	17	16	13
	Std/mean	0.92	0.79	0.66	0.40	0.39	0.38	0.44	0.40	0.45	0.95	1.14	1.09

The numbers in the section column are the number of gauges for the section, 'std' denotes the sample standard deviation.

the sum of the regression estimate map and the residual kriging map. In this study, only the regression component is used to examine Taiwan mean monthly precipitation climatology.

2.2.1. Formula and the physical basis

The original form of ASODeK regression (Guan *et al.*, 2005a) is shown in Equation (1)

$$P = b_0 + b_1X + b_2Y + b_3Z + b_4 \cos \alpha + b_5 \sin \alpha \quad (1)$$

where P is the gauge-measured precipitation (mm); X and Y are geographic coordinates (usually Universal Transverse Mercator (UTM) easting and northing in km); Z is above-sea-level terrain elevation in kilometres; α is terrain aspect, defined as the direction of the slope orientation, zero to the north, increasing clockwise and 180 to the south. Gauge observations and a topographic map of the study area are the only required input for the ASODeK regression.

The physical basis of the ASODeK regression is that part of precipitation spatial variability that is related to spatial distribution of effective atmospheric MG, Z and interaction of terrain aspect and atmospheric MFD. The MG is defined as the linear trend of apparent atmospheric moisture in the area of interest. This linear trend is auto-determined by b_1 and b_2 in Equation (1). When the same length unit is used for X and Y , the atmospheric MG can

be calculated from regressed b_1 and b_2 , in the same way that MFD is calculated from b_4 and b_5 (shown later). The MFD is defined as prevailing wind direction in which the atmospheric moisture is brought for precipitation in the area. It is not necessarily the same as the actual prevailing wind direction because in some cases non-dominant wind may bring most of the moisture for precipitation.

The assumptions embedded in Equation (1) are that (1) precipitation is linearly correlated to Z , atmospheric MG and cosine function of the difference between terrain aspect and prevailing MFD (i.e. $\cos(\alpha - \omega)$, where ω is the source direction of moisture flux (i.e. MFD), zero from the north, increasing clockwise and 180 from the south); (2) the prevailing MFD in the area of interest is uniform for a certain period (e.g. a month in this study) during which the regression is applied. With the trigonometric transformation (Guan *et al.*, 2005a), the cosine function becomes $b_4 \cos \alpha + b_5 \sin \alpha$ in Equation (1), in which MFD is not required as an input for the regression, but can be calculated from the regression results. For example, if b_4 and b_5 are both positive, $\text{MFD} = \text{atan}(b_5/b_4)$.

The linear MG is observed in the northern New Mexico, an inland area about 1200 km away from the ocean (not shown). In Taiwan island, this linear MG is only valid for May through August (Figure 2). An exponential relationship is found between monthly precipitation and the X and Y for the months of September through April. The ASODeK regression is modified for

Figure 2. Scatter plots of mean monthly gauge precipitation (top 12 panels) versus gauge UTM (WGS-84, zone 50) northing (subtracted by 2380 km), and (bottom 12 panels) versus gauge UTM easting (subtracted by 800 km), showing different relationships of the two variables between the months of September through April, and the months of May through August.

these months:

$$P = b_0 + b_1 \exp(X) + b_2 \exp(Y) + b_3 Z + b_4 \cos \alpha + b_5 \sin \alpha \quad (2)$$

all symbols are the same as in Equation (1). For simplicity in the paper, the ASODeK regression is referred to Equation (1) for the months of May through August, and Equation (2) for the months of September through April for the following regression analyses with Taiwan monthly precipitation. As it is difficult to calculate MG

from b_1 and b_2 resulted from Equation (2), no MG will be retrieved and discussed, although MG is still used to lump the b_1 and b_2 terms in the following discussion.

The assumption of uniform prevailing MFD often holds for mean climate condition of a certain period of the year (e.g. for monthly precipitation) in a certain area. There may be a situation in which two or more prevailing MFDs exist. In this case, the ASODeK regression will give one bulk MFD, which has an apparent effect equivalent to the combination of multiple moisture fluxes. It should be noted that the ASODeK regression assumes that more precipitation occurs at windward slopes than

at leeward slopes. The regression would infer an MFD opposite to the actual MFD for situations in which more precipitation occurs at the leeward slope.

2.2.2. Optimal topographic windows

To conduct the ASOAdEK regression, gauge precipitation data and a digital elevation model (DEM) map of the study area are the only required input data. The DEM map is used to generate the elevation and terrain aspect. Previous studies show that the orographic effect is represented at a certain optimal DEM window (Daly *et al.*, 1994; Kyriakidis *et al.*, 2001). Often a DEM window in a range of 1–15 km is used. In this study, an optimized DEM window for terrain aspect, in a range of 1–15 km, is searched by the regression, while 1-km DEM window is fixed for elevation. Operationally, this is achieved by comparing mean absolute errors of the ASOAdEK regression estimates of the regression with all eight terrain aspects calculated from DEM windows (1, 3, 5, 7, 9, 11, 13 and 15 km).

2.2.3. Significance test

Although the ASOAdEK regression is constructed from selected relationships based on some physical precipitation processes, the actual precipitation field is often more complex than the regression can capture. It may happen that the linear relationship between precipitation and any one of the variables in Equations (1) and (2) does not hold simultaneously. This situation does not matter much in regression because the coefficients will become smaller for the terms that are not significantly linearly correlated with precipitation. However, it can be problematic if we want to retrieve some physical information (e.g. MFD) from the regression results.

We use statistical testing to evaluate the significance of a certain term in the ASOAdEK regression. For example, to test the joint significance of b_4 and b_5 terms in the ASOAdEK regression, we employ an F -test (Draper and Smith, 1998):

$$F = \left[\frac{b_4}{\text{SE}(b_4)} \right]^2 + \left[\frac{b_5}{\text{SE}(b_5)} \right]^2 \quad (3)$$

where $\text{SE}(b_i)$ is the standard error of regression coefficient b_i , the F statistic has two degrees of freedom for the numerator and $(N - 6)$ degrees of freedom for the denominator, and N is the total number of gauges. A statistically significant value of the F statistic indicates the significance of MFD effect. The retrieved MFD is then reliable, otherwise it should not be considered seriously. We apply similar F -test for assessing the significance of combined effect of X and Y terms. For elevation, a t -test is used for assessing the significance:

$$t = \frac{b_3}{\text{SE}(b_3)} \quad (4)$$

The t -test has $(N - 6)$ degrees of freedom.

2.3. Regression analyses

All ASOAdEK regressions are conducted with mean monthly precipitation derived from the ARMT observations of over 10-year records, and the conventional observations of over 50-year records. The X and Y coordinate of the gauges are obtained from the UTM (WGS-84, zone 50N) easting and northing. For the regression, the easting is subtracted by 800 km and then divided by 50 km. The northing is subtracted by 2380 km, and then divided by 100 km.

Several sets of regression analyses are designed for the ARMT gauge data: (1) all 392 gauges, (2) three ensembles of randomly selected 2/3 gauges, denoted 2/3 subsets, (3) three ensembles of randomly selected 1/2 gauges, denoted 1/2 subsets, (4) three ensembles of randomly selected 1/3 gauges, denoted 1/3 subsets, (5) all gauges between UTM northing 2700 and 2800 km, denoted NN section, (6) all gauges between UTM northing 2600 and 2700 km, denoted NS section, (7) all gauges between UTM northing 2500 and 2600 km, denoted SN section and (8) all gauges between UTM northing 2400 and 2500 km, denoted SS section.

The experiments of (2)–(4) are to examine how the performance of ASOAdEK regression degrades with decreasing gauge density. For each ensemble, the randomly selected subset data are used for calibrating the regression coefficients, the rest of ARMT gauge data is regarded as the hold-out sample set for cross-validating the regression estimates. With this series of experiments, we also examine how the regression-inferred MFDs shift with decreasing gauge density. For each gauge density, we randomly generate three subsets, and run regressions for each of the 12 months. The resulted subset monthly MFDs are then compared with the MFDs inferred from the regression with all 392 gauges included. Thus, there are 36 trials for examining the gauge-density effect on model-inferred MFDs.

The experiments of (5)–(8) aim to test how the regression performance varies at different parts of Taiwan. As it is difficult to exactly locate the boundaries, the section boundaries are prescribed to reflect different climate characteristics between the northern and southern parts of Taiwan reported in the literature (Yen and Chen, 2000; Hsu and Chen, 2002). Nonetheless, the four sections should be enough to capture the trend of rainfall climatology from the north to the south of Taiwan. The statistics of mean monthly precipitation of the four sections are included in Table I.

3. Results

3.1. Significance of the ASOAdEK regression

The ASOAdEK regressions of 12 mean monthly precipitation data based on all 392 ARMT gauges are summarized in Table II. Overall, the regression explains about 60% of precipitation spatial variability during cold-season months (October through April), and about 40%

Table II. The ASODeK regression results of monthly precipitation with all 392 gauges.

Month	Window ^a (km)	b_0	b_1	b_2	b_3	b_4	b_5	SSR (mm ²)	SSE (mm ²)	Adjusted R^2	MAE (mm)	MAE/ mean (%)	Inferred MFD ^b
1	7	9.72	2.85	1.16	11.95	15.21	11.39	1007 612	625 258	0.61	24.5	35.8	37
2	5	13.65	2.21	2.52	27.72	10.19	9.54	15 82 472	871 594	0.64	30.5	30.2	43
3	1	12.89	-0.31	3.61	41.59	-1.12	10.17	15 21 071	11 45 085	0.57	31.8	31.0	96 (50)
4	7	55.70	0.22	2.33	51.88	16.05	2.15	10 78 133	785 553	0.57	30.0	22.5	8
5	15	146.03	53.47	-26.85	41.43	-6.46	-56.84	620 987	19 46 727	0.23	52.6	22.6	264
6	13	371.87	93.15	-112.06	34.65	24.60	-115.52	25 45 115	31 51 960	0.44	69.3	20.3	282
7	15	454.23	24.75	-90.91	21.79	35.95	-45.35	19 03 344	33 39 974	0.36	73.6	24.6	308
8	15	603.94	63.61	-154.97	24.83	46.36	-48.24	40 01 812	48 94 364	0.44	88.6	24.5	314
9	3	165.89	12.02	-2.19	-1.40	-3.66	-7.08	33 92 555	45 81 361	0.42	77.7	30.3	243 (215)
10	5	67.74	17.63	-3.44	7.69	15.05	48.31	11 02 52 277	33 18 488	0.75	58.4	32.6	73
11	5	-24.67	13.25	-1.55	-14.31	19.81	4.82	53 06 728	21 94 673	0.70	44.6	53.0	14
12	13	-16.79	5.72	0.99	3.98	-2.41	1.12	19 88 201	15 83 113	0.55	35.0	49.9	155 (34)

Months 1–4 and 9–12: $P = b_0 + b_1X + b_2Y + b_3Z + b_4 \cos \alpha + b_5 \sin \alpha$, months 5–8: $P = b_0 + b_1 \exp(X) + b_2 \exp(Y) + b_3Z + b_4 \cos \alpha + b_5 \sin \alpha$. SSR, regression sum of square; SSE, error sum of square; adjusted R^2 , adjusted coefficient of multiple determination; MAE, Mean absolute error, which is the sum of absolute difference of the regression estimate and the observation of each gauge divided by the gauge number.

^a The DEM window size for calculating terrain aspects inferred from the optimal ASODeK regression of the month.

^b The regression-inferred moisture flux direction, in degree clockwise from north, with 3 months of significance level below 99.99% replaced by those (in the brackets) derived from the subsets.

Figure 3. Significance level ($1 - p$ value of t or F testing) of selected variables (elevation, moisture flux direction, and moisture gradient) in explaining spatial variability of mean monthly precipitation in Taiwan (1993–2003). The three panels on the left are for regression analyses of all 392 gauge observations (all), and of three randomly selected subsets of 2/3, 1/2 and 1/3 gauges, each having three realizations. The three panels on the right are the results of regression analyses of all gauge observations, of four sections (NN, NS, SN and SS) defined in Figure 1, and of 18 long-term observations (1950–2004).

during warm-season months (May through September). The performance is low for May, in which only 23% of spatial variability is explained by the regression. The mean absolute errors are around or below 30% of mean monthly precipitation for most months. For the 18 long-term conventional gauges, the regression explains about 80% of spatial variability in precipitation during cold months, and 70% during warm months (Figure 4(a)). Overall, this result is better than a more complex regression application with Taiwan precipitation (Basist *et al.*, 1994) in which 61% spatial variability of long-term mean annual precipitation is explained, given that regression performance is often better for annual precipitation than monthly precipitation (Daly *et al.*, 1994).

The significance tests for all regressions are summarized in Figure 3. Among the three factors (MG, Z and MFD) examined in the ASODeK regression, MG (not necessarily linear) is the most significant, and Z is the least significant, with MFD in-between (Figure 3). Among the 12 months, the significance of elevation tends to be larger in the first several months than the rest of the year. For the regression with all 392 ARMT gauges, the MFD is not significant in explaining spatial variability of September and December mean monthly precipitation, slightly significant for March with a p -value of 0.003. However, it is significant for the 2 months (September and December) when some subsets/sections of gauges are considered in the regression. Thus, in the later discussion, MFDs retrieved from subset regressions of good significance are used for September, December and March (Table II). Although the density of 18 long-term conventional gauges is only 5 gauges per 10 000 km², the regression works fairly well in explaining their own spatial variability (Figure 4(a) and (b)). When the gauge density is reduced to 1/3 of the current ARMT network density (110 gauges per 10 000 km²), the significance of MG and MFD in the regression decreases (Figure 3). The degraded performance of the ASODeK regression for the 1/3 ARMT subsets is evident from the increasing root mean square error (RMSE) of the cross-validation of regression estimates (Figure 4(c)).

In comparison of four sections, the ASODeK regression captures more precipitation spatial variability in the southern sections (SS and SN) than the northern sections (NN and NS) (Figure 4(a) and (b)). If evaluated with regression mean absolute error, the ASODeK performance for each of the four sections is better than that for the entire island. Among the four sections, the performance generally decreases from south to north.

3.2. Regression-inferred MFDs

The regression-inferred mean monthly MFDs from all 392 gauges and four sections are summarized in Figure 5(a). Overall, the MFDs are northeasterly for the cold-season months, and westerly (from southwesterly to northwesterly) for the warm-season months, with March, April and September in transition. The southern sections tend to have more easterly MFDs, and the northern

Figure 4. Summary of adjusted coefficients of multiple determinations (a), relative mean absolute errors (ratio of mean absolute error over mean) (b) of the ASODeK regressions for six sets of gauge observations shown in Figure 3, and relative root mean square errors (c) of cross-validation for 2/3 subsets (with the 1/3 observations as holdout samples for crossvalidation), 1/2 subsets (with 1/2 observations as holdout samples) and 1/3 subsets (with 2/3 observations as holdout samples).

sections have more northerly MFDs in the cold-season months. In the warm-season months, the southern-section MFDs shift to southwesterly, and northern-section MFDs shift to northwesterly.

How do these ASODeK-regression-inferred monthly MFDs compare with the observed prevailing wind directions? We plot the inferred monthly MFDs of NN section together with the observed first three most frequent prevailing winds of the month at Keelung, a city at the northern tip of Taiwan (Figure 5(b)). Similar plots for the inferred monthly MFDs of SN and NS sections are shown together with the observed most frequent prevailing winds at Penghu, a small island to the west of Taiwan (Figure 5(c)). And the plots of regression-inferred MFDs of SS section are shown with the most frequent prevailing

Figure 5. ASOADeK regression-inferred mean monthly moisture flux direction (MFD) for all 392 gauge observations (with March, September and December values replaced with results from significant subset regressions) and four subregions (a), and comparisons of selected subregion MFDs to its nearby observed prevailing winds for NN (b) with wind climatology observed at Keelung (25.135 N, 121.732 E), for SN and NS (c) with wind climatology observed at Penghu (25.629 N, 122.071 E), and for SS (d) with wind climatology observed at Lanyu (22.039 N, 121.551 E). The three prevailing wind directions are the three most frequent directions (ordered by the symbol size) from histogram analyses using a 30° bin. The insignificantly inferred MFDs are plotted in grey.

Figure 6. ASOADeK regression-inferred moisture flux directions of various gauge subsets deviated from those of all 392 gauges (March, September and December values are replaced with most significant subset-inferred MFDs), for ensembles of three 2/3-subsets (72 gauges per 10 000 km²), of three 1/2-subsets (54 gauges per 10 000 km²) and of three 1/3-subsets (36 gauges per 10 000 km²). A few non-significant inferred subset MFDs are not included.

winds observed at Lanyu, a small island to the southeast of Taiwan (Figure 5(d)). For the NN section, the MFDs of the cold-season months are in good agreement with the observed prevailing winds, while those of warm-season months are different from the observed prevailing winds. The results of the SS section are opposite. The inferred MFDs of the SS section are generally consistent with the observed prevailing winds for the warm-season months, and deviated from the observations for the cold-season months. The degree of consistency between the inferred MFDs and the observed prevailing winds for NS and SN sections are in-between of NN and SS sections, but closer to that of SS.

The sensitivity of inferred MFDs to the gauge density is summarized in Figure 6, in which the difference (or shift) of subset MFDs from those of all ARMT gauge set is plotted. The inferred MFDs from three ensembles of 2/3 subsets are similar to those inferred from all ARMT gauges. The three 1/2 subset ensembles infer MFDs slightly deviated but within acceptable ranges, with only three of 36 monthly MFDs with a shift exceeding 45°. When the gauge network is made sparse to 36 gauges per 10 000 km², the ASOADeK-regression-inferred MFDs become unreliable. This is consistent with increasing RMSE of crossvalidation of the ASOADeK regression at this gauge density (Figure 4(c)).

4. Discussion

The ASOAdEK regression-inferred MFDs are generally consistent with the overall climate setting in Taiwan, i.e. northeasterly in the cold-season months, and westerly (southwesterly) in the warm-season months. The results of the four sections suggest that monthly MFDs are not uniform over the whole Taiwan. In the cold-season months, the moisture flux generally comes from the north, with northeasterly MFDs in the northern Taiwan, and easterly in the southern sections (Figure 5(a)). In winter, there are two responsible processes: orographic lifting in the windward side of the northern terrain and the frontal system. The former confines most of winter rain in the NN section, while the latter can bring rain to the southern SN and even SS sections. In the warm-season months, the atmospheric moisture generally comes from the south, with southerly to southwesterly MFDs in the southern sections, and northwesterly for the northern part of Taiwan (Figure 5(a)). The southwesterly for the southern-section MFDs is reasonable because of the prevailing southwesterly monsoon in the summer. The northwesterly for the northern section may be due to the prevailing winds associated with the typhoons passing through or nearby Taiwan, if it is dominated by typhoon events in summer. Another possibility is the effect of the Mei-yu frontal systems, which usually bring northwesterly behind them, if this occurs in Mei-yu season. The inferred MFDs from the 11-year data records can be the lump effects of both mechanisms. Since climate setting varies slightly between sections, application of the ASOAdEK regression over a sectional area will give better regression estimates than over the entire island (Figure 4(b)).

The contrast of the ASOAdEK-regression results between the warm- and cold-season months, and between the northern section and southern sections, merits further discussion. In September through April, the atmospheric moisture distribution decays exponentially from the north to the south, and from the east to the west, while in June through August, the atmospheric MG is in opposite direction and decays linearly from the south to the north, and from the west to the east. This suggests that the warm-season climate system is more effective in transmitting atmospheric moisture inland for precipitation in Taiwan, whereas the cold-season climate system is less efficient. The efficiency in the warm months is probably related to the two efficient moisture-carrying climatic processes: Mei-yu and typhoon in the season.

Climatologically, Mei-yu in Taiwan occurs from mid-May to mid-June. Quasi-stationary fronts with active meso-scale convection are embedded in a large-scale convergent zone in subtropical East Asia. The southwesterly from the Indochina Peninsula and the South China Sea brings abundant moisture to the convergent zone to maintain the frontal systems and active convection. Since Taiwan is situated in front of or in the frontal zone, heavy rainfalls occur in Mei-yu season every year and often result in severe flooding and landslide. Total rainfall amount in Mei-yu season is only second to the typhoon

season, which starts in July. The second-half of the summer is strongly affected by land-falling typhoons, which occur 2–3 times on average but contribute more than 40% of total summer rainfall. The high moisture-carrying capacity of the two climatic processes, together with the prevailing southwest monsoon, homogenizes monthly precipitation (averaged over a long period) over the entire Taiwan for the warm-season months, indicated from the low coefficient of variation for May through August (Table I). This leads to less spatial variability (compared with the cold-season months) that can be captured by the ASOAdEK regression (Figure 4(a)), although the orographic effects are still significant (Figure 3) (Chen *et al.*, 2007).

The role of the local prevailing winds in transmitting atmospheric moisture for precipitation is indicated from the degree of agreement between the ASOAdEK-regression-inferred MFDs and actual prevailing winds. In the NN section, the prevailing winds bring atmospheric moisture for precipitation for the cold-season months, but not for the warm-season months. This explains that the cold-season months have more precipitation than the warm-season months in the very north of the NN section, such as rainfall climatology at Keelung (Figure 3 in Yen and Chen, 2000). Because of the less efficient moisture-transiting processes in the cold months, this winter precipitation dominant climate pattern is limited to very north of the Taiwan island (part of the NN section in this study) (Figure 3 in Yen and Chen, 2000). For other sections (SS, SN and NS), the prevailing winds bring in atmospheric moisture for precipitation in the warm-season months, but not in the cold-season months. Thus, the summer precipitation dominates in these areas (Figure 3 in Yen and Chen, 2000). That summer precipitation dominant climate pattern occurs in most parts of Taiwan is apparently related to more efficient moisture-carrying capacity of the summer climatic processes.

5. Conclusions

In this study, the ASOAdEK regressions were applied to examine mean monthly precipitation over a humid subtropical region, Taiwan. For mean monthly precipitation obtained from 11-year ARMT gauge network, the results suggest that the regressions capture about 40% spatial variability for the warm months (May through September), and over 60% for the cold months (October through April). For 18 sites with available mean monthly precipitation calculated from 50-year observations, the regressions explain 80% spatial variability for the cold months, and 70% for the warm months. This performance is better than some previously published regression performance in this area. The ASOAdEK regression performance for the dense gauge network improves when it is applied to the sectional regions. The improvement is bigger for the southern part than for the northern part of Taiwan.

Among the three factors considered in the ASOAdEK regressions, the results indicate that the atmospheric MG

and MFD are significant factors explaining mean monthly precipitation spatial variability in Taiwan, while the elevation effect is not as significant. The MG follows exponential functions of UTM easting and northing for the cold months, but linear functions for the warm months, suggesting different moisture-carrying capacity of the climate systems between the two seasons. The linear decay of the atmospheric moisture over Taiwan in the warm month is likely to be attributed to the dominance of the prevailing southwesterly, which transports moisture from south to north and is often enhanced during the Mei-yu frontal events and after the passage of typhoons through Taiwan.

The regression results infer northeasterly MFDs in the cold months, and westerly MFDs in the warm months, in general agreement with the climate settings of Taiwan. When the data of sectional regions are applied in the regression, the inferred MFDs vary in a certain range. The degree of agreement between the ASODeK regression-inferred MFDs and locally observed prevailing winds is systemic, and can be used to explain the contrast of rainfall seasonality patterns between the northern part and the rest of Taiwan.

The ASODeK regression results indicate that a gauge network of 54 stations per 10 000 km² is enough to capture mean climate settings of the island. Since these results were based on randomly selected gauge subsets, which could have clusters of gauges, the actually needed number of gauges can even be smaller. Also, the number of years during which monthly precipitation was calculated affects the conclusion of an appropriate gauge density given above. In this study, the ARMT network had data record of about 10 years. If the data record were longer, the required number of gauges could be smaller. This conclusion is drawn while studying mean climatologic aspects of Taiwan precipitation. We do not intend to suggest a reduction of current ARMT network density since the high-density gauge network is necessary and very useful for meteorological and hydrological studies, especially for flooding risk monitoring and assessment. Nonetheless, our results will provide some guidance for developing and maintaining a gauge network for monitoring long-term climatology.

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