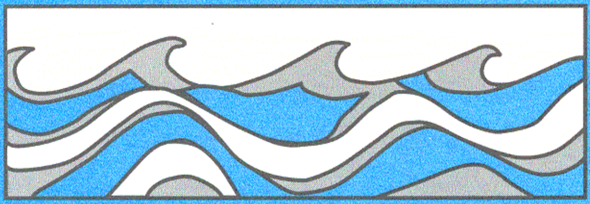
University of Washington
Department of Civil and Environmental Engineering

ADJUSTMENT OF GLOBAL GRIDDED PRECIPITATION FOR SYSTEMATIC BIAS

JENNIFER C. ADAM
and
DENNIS P. LETTENMAIER



Water Resources Series
Technical Report No.171
AUGUST 2002

Seattle, Washington
98195

Department of Civil and Environmental Engineering
University of Washington
Box 352700
Seattle, Washington 98195-2700

ADJUSTMENT OF GLOBAL GRIDDED PRECIPITATION FOR SYSTEMATIC BIAS

by

JENNIFER C. ADAM
and
DENNIS P. LETTENMAIER

Water Resources Series
Technical Report No. 171

August 2002

ABSTRACT

Systematic biases in gauge-based measurement of precipitation can be severe. Of these biases, wind-induced undercatch of solid precipitation is by far the most significant. A methodology for producing gridded mean monthly catch ratios for the adjustment of wind-induced undercatch and wetting losses is developed, suitable for application to continental or global gridded precipitation products. The adjustments for wind-induced solid precipitation were estimated using gauge type-specific regression equations from the recent World Meteorological Organization (WMO) Solid Precipitation Measurement Intercomparison. Wind-induced undercatch of liquid precipitation and wetting losses were estimated using similar methods of a previous global bias-adjustment effort. Due to the unique nature of Canada's precipitation measurement network, the Canadian adjustments were determined using more detailed information than for the rest of the domain, and are therefore expected to be more reliable. The gridded gauge adjustment products are designed to be applicable both to climatological estimates and to individual years during the 1979 through 1998 reference period, but should not be used for climate change studies. Application of the catch ratios to an existing precipitation product yielded an increase in mean annual global terrestrial precipitation of 11.2%. The results of several data set comparisons are presented.

TABLE OF CONTENTS

Page

List of Figures iii

List of Tables v

Chapter 1: Introduction 1
- 1.1 Overview 1
- 1.2 Bias in Gauge-Measured Precipitation 1
- 1.3 Global Gridded Precipitation Data Sets 3
- 1.4 Objective 4

Chapter 2: The WMO Precipitation Measurement Intercomparisons 6
- 2.1 The First International Intercomparison 6
- 2.2 The Second International Intercomparison 6
- 2.3 The Third International Intercomparison 7

Chapter 3: Analytical Methods 9
- 3.1 Overview of Bias Adjustment Method 9
- 3.2 Wind-Induced Solid Precipitation Undercatch 13
- 3.3 Wind-Induced Liquid Precipitation Undercatch 19
- 3.4 Wetting Losses 22
- 3.5 Determination of Catch Ratios for Canada 24

Chapter 4: Discussion of Errors in Bias Adjustment Methodology 30
- 4.1 Wind-Induced Solid Precipitation Undercatch 30
  - 4.1.1 Gauge Representation Errors 30
  - 4.1.2 Regression Equation Application Errors 33
  - 4.1.3 Interpolation Errors 33
  - 4.1.4 Scoring System 36
    - a) United States 38
    - b) Canada 39
    - c) Former USSR, Mongolia, and North Korea 39
    - d) Finland 40
    - e) Switzerland, Poland, Greenland, Iceland, and Romania 41
    - f) Norway and Sweden 43
    - g) Austria 43
    - h) Czech Republic and Slovakia 44
    - i) China and South Korea 45
    - j) Japan 45
- 4.2 Wind-Induced Liquid Precipitation Undercatch 46
- 4.3 Wetting Losses 47

Chapter 5: Results 49
  5.1 Catch Ratios 49
  5.2 Adjusted Gridded Precipitation 50

Chapter 6: Data Set Comparisons 53
  6.1 Comparisons to Yang et al. Catch Ratios 53
    6.1.1 Overview 53
    6.1.2 Similarities and Differences in Methods 53
    6.1.3 Method of Comparison and Results 54
      a) Greenland 56
      b) Siberia 57
      c) Alaska 57
  6.2 Global Gridded Data Set Comparisons 58
    6.2.1 Overview 58
    6.2.2 Mean Monthly Variation 61
    6.2.3 Spatial Variation 62
  6.3 Comparison of Adjusted Precipitation Data Sets over Canada 64
  6.4 Comparison of Adjusted Precipitation Data Sets over Former USSR 66

Chapter 7: Concluding Remarks 68

List of References 70

LIST OF FIGURES

Figure Number Page

3-1. Region (mapped at ½º grid resolution) in which at least half of the precipitation falls as solid precipitation during January and July. 13

3-2. Solid precipitation catch ratio (in percent) versus wind speed (at gauge height) for each of the selected countries. 14

3-3. Station locations for the 7,878 stations used from the NOAA Climate Prediction Center Summary of the Day data archive. 17

3-4. Station locations for the 6,692 stations corrected by Groisman (1998), and for the 495 stations corrected by Mekis and Hogg (1999). 25

3-5. Bi-seasonal climatological averages of the ratio of Groisman (1998b) to Mekis and Hogg (1999) for the period of 1979 through 1990. 28

4-1. Sensitivity of the catch ratio for solid precipitation undercatch (calculated using equation 2-17) to: (a) snow depth, (b) anemometer height only, and (c) gauge orifice height only. 32

4-2. Stations removed for test case in order to examine the sensitivity of the gridded catch ratios to interpolation methodology (see Table 4-1) 36

5-1. Seasonal climatologies (averaged from the monthly 1979 through 1998 climatologies for visualization purposes) of the catch ratios in percent. 50

5-2. Seasonal climatologies (in mm of precipitation per month), averaged over the period of 1979 through 1998, of the adjusted Willmott and Matsuura (2001) monthly data set. 51

5-3. Percent change in precipitation due to the application of each bias adjustment to the Willmot and Matsuura (2001) monthly precipitation data set. 52

6-1. Catch ratios inferred from Yang et al. (1998a, 1999a) and Yang and Ohata (2000) vs. our catch ratios (for wind-induced undercatch effects only) for 79 stations in Siberia, Greenland, and Alaska. 56

6-2. Bi-seasonal (summer-winter) climatologies (in mm of precipitation per month) of the five data sets used in the gridded global data set comparison. 60

6-3. Temporal variation of the five global data sets averaged over all global and Northern and Southern Hemisphere land areas. 62

6-4. Variation with latitude of Northern Hemisphere mean annual precipitation averaged over (1) all land areas, (2) North America/Greenland, and (3) Eurasia.......................64

6-5. Temporal variation of precipitation averaged over Canada. 65

6-6. Temporal variation of precipitation averaged over the Former USSR.......................67

LIST OF TABLES

Table Number Page

2-1. WMO Solid Precipitation Measurement Intercomparison regression equations associated with each national gauge (Goodison et al., 1998). 8

3-1. Parameters used when applying the WMO Solid Precipitation Measurement Intercomparison regression equations...15

3-2. Equations used to determine κ_r. 20

3-3. Average wetting losses of both the collector and the container per day. 23

3-4. Comparisons between two adjusted precipitation data sets for Canada. 27

4-1. Percent differences between the station-specific catch ratio (see Figure 4-2 for locations) and the catch ratio of the grid cell overlaying that station with respect to the station-specific value.. 35

4-2. The scoring system used to approximate the accuracy of the wind-induced solid precipitation undercatch adjustment method for each country. 37

5-1. Percent increases in precipitation annually and for each season due to the application of the bias adjustments to the Willmott et al. (2001) dataset. 52

6-1. Comparisons between our annual average catch ratios (for wind-induced undercatch effects only) and the annual average catch ratios inferred from Yang et al. (1998a and 1999a) and Yang and Ohata (2001). 55

6-2. Gridded monthly global precipitation data set specifications. 59

ACKNOWLEDGMENTS

This research was supported by NASA grant NAG5-9416 to the University of Washington. The first author would like to thank Steve Burges at the University of Washington and Bart Nijssen at the University of Arizona for sitting on her committee. Thanks are due to the members of the Land Surface Hydrology Research Group for support of all kinds, and to Serhad Atakturk and Paul English for computing support. Also, we would like to thank Dr. Pavel Groisman, Dr. David Legates, and an anonymous reviewer whose comments contributed to the significant improvement of this document. Thanks to Dr. Éva Mekis, Dr. Boris Sevruk, Dr. Carl Benson, and Dr. William Hogg for addressing specific concerns

Chapter 1: Introduction

1.1: OVERVIEW

Precipitation is a key driver of the land surface hydrological system. The production of runoff and streamflow is a complicated nonlinear process that depends on both the antecedent state (soil moisture and snow accumulation) of the system, and the intensity and spatial distribution of precipitation and snowmelt. Recent attempts to predict stream-flow for large rivers globally (e.g. Nijssen et al., 2001) have been hampered by the quality of global precipitation data sets. Furthermore, understanding the effects of climate change on the global water balance is dependant on being able to define the components of the water budget currently and in recent years. Given concerns about the effects of climate change on the global water balance, such as the potential for changes in the runoff from Arctic rivers and consequent effects on the global thermohaline circulation (e.g. Sausen et al., 1994), the provision of accurate global precipitation products is particularly important. Of particular concern are those areas (which constitute approximately ½ of the northern hemisphere land area) where snow accounts for a substantial fraction of the annual precipitation available for runoff. These areas are especially prone to poor precipitation estimates due to the large bias of gauge-measured solid precipitation.

1.2: BIAS IN GAUGE-MEASURED PRECIPITATION

Gauge measurements of precipitation are known to be inhomogeneous due to systematic and non-systematic errors. Non-systematic errors can be caused by gauge malfunction (e.g., leakage or damage), human observation errors, or by tampering (Groisman and

Legates, 1994). These errors, in some cases may be identified by consistency checks – e.g., via comparison with observations from other gauges in the vicinity. Systematic errors are more important because they lead to bias, which is not identified by data screening methods. These errors include the undercatch of precipitation due to the wind-field deformation above the gauge orifice, wetting losses due to water adhering to the surface of the gauge, evaporation of the accumulated water in the gauge between the time of precipitation and the time of observation, splashing of rain drops or blowing of snow into or out of the gauge, the treatment of trace precipitation as zero, and recording gauge techniques (Goodison et al., 1998). Observation record inhomogeneity can also be caused by changes in instrumentation (gauge type or shielding), changes in the local environment (vegetation growth or urbanization), gauge relocations, and variations in gauge design (Groisman and Legates, 1994).

The aggregate effect of all systematic biases usually is a net underestimation of precipitation. Of all the systematic biases, undercatch due to wind is generally accepted to play the largest role, in which the measurement biases for liquid precipitation tend to be relatively small (2-10% according to Sevruk, 1982; and 4-15% according to Duchon and Essenberg, 2001), but are much larger for solid precipitation (Sevruk, 1982). The magnitude of wind effects on gauge performance depends on the fall velocity of the particles (which in turn depends on the type of precipitation and therefore air temperature), and the aerodynamic properties of the gauge. Wetting losses can be significant depending on the gauge type and the number of observations per day. At synoptic stations where precipitation is measured every six hours, this loss can be as high as 15-20% of the measured precipitation (Goodison et al., 1998), but more commonly is on the order of 2-10% (Sevruk, 1982). Alternatively, recent studies have shown that average wetting losses are not as high as previously thought and that incorrect assumptions have been applied for some bias adjustment efforts (Bogdanova and Mestcherskaya, 1998; Groisman and Rankova, 2001) (see section 4.3 for details). Evaporation losses vary by gauge type and the time of year (i.e. winter losses are less than summer losses), and usually range from 0 to 4% of the measured precipitation (Sevruk, 1982). Losses due to trace precipitation are significant in some regions. In the Arctic, the combination of the arid climate and frequent low-intensity precipitation events can make the accumulation of trace precipitation significant relative to the annual total precipitation (Mekis and Hogg, 1999). For example, Benson (1982) found that traces could amount to more than 20% of the recorded annual precipitation at coastal stations on the Arctic Slope of Alaska.

1.3: GLOBAL GRIDDED PRECIPITATION DATA SETS

Data sets currently available for global hydrological simulations, and/or evaluation of the performance of global weather and climate models, generally do not account at all for gauge catch deficiencies, or at best do so in a cursory manner. Among the relatively high-resolution gauge-based global data sets, only the Legates and Willmott (1990) 1920 through 1980 monthly climatology currently incorporates corrections for systematic biases. It does so by adjusting the climatological means using correction factors derived from mean monthly meteorological data. The monthly merged gauge and satellite precipitation grids of the 2.5º Global Precipitation Climatology Project (GPCP)

(Huffman, 1997) have also been scaled by the monthly correction factors derived by Legates and Willmott (1990). An effort is in progress to develop an adjustment method for the monthly gauge-based Global Precipitation Climatology Center (GPCC) gridded precipitation product using the methods of Rubel and Hantel (1999), but the results are not yet available. Neither the recent global ½º data sets of New et al. (2000) nor Willmott and Matsuura (2001) attempt bias adjustment.

1.4: OBJECTIVE

The purpose of this study was to develop a ½º global gridded terrestrial precipitation product suitable for global modeling studies that reflects as best we could the known effects of measurement biases. The recent World Meteorological Organization (WMO) Solid Precipitation Measurement Intercomparison (Goodison et al., 1998) has produced results that demonstrate the relative biases of several national standard precipitation gauges. The regression equations developed from these results have made it possible to account for the undercatch of wind-induced solid precipitation more accurately than has been done by previous global bias-adjustment efforts. Monthly climatological adjustments are derived using these regression equations and applied to individual years during the 1979 through 1998 time-period of an existing gauge-based gridded precipitation product. As a note of caution, bias adjustment on a mean monthly basis should not be performed for climate change studies or any other type of study in which the yearly variability is of high importance (unless it is used to better understand the current climate as a baseline for determining the impacts of climate change). Legates (1995b) has shown that, because slight variations in wind speed and air temperature significantly affect precipitation measurement bias at individual stations, long-term precipitation trends cannot be separated from trends in air temperature and wind speed without first adjusting for the bias in precipitation on a month to month basis.

Chapter 2: The WMO Precipitation Measurement Intercomparisons

According to a WMO survey performed in 1987 (Sevruk and Klemm, 1989), there are more than 150,000 precipitation gauges in use in the world among which there are 50 types of national standard precipitation gauges. To check the performance of the most commonly used precipitation gauges and to develop adjustment procedures for systematic biases, the WMO has performed three international intercomparisons (Goodison et al., 1998).

2.1: THE FIRST INTERNATIONAL INTERCOMPARISON

From 1960 to 1975, the WMO performed a precipitation measurement intercomparison (Struzer, 1971). This intercomparison was designed to determine reduction coefficients relating the catch efficiency of different gauge types. Results of this intercomparison were deemed non-conclusive possibly because of the poor selection of the reference gauge in that it did not catch close to "ground truth" precipitation (Struzer, 1971).

2.2: THE SECOND INTERNATIONAL INTERCOMPARISON

From 1972 to 1976, a liquid precipitation measurement intercomparison was performed (Sevruk and Hamon, 1984). 22 countries participated in this intercomparison which was focused on rain catch differences between several different gauge types and the reference gauge. The results indicated that on average the undercatch due to wind of liquid precipitation is 3% and does not appear to exceed 20%. If wetting and evaporation losses are accounted for, this average increases to 4 to 6%. Bias adjustment procedures were developed for certain gauge types (Sevruk and Hamon , 1984).

2.3: THE THIRD INTERNATIONAL INTERCOMPARISON

From 1986 to 1993, a solid precipitation measurement intercomparison was performed (Goodison et al., 1998). The purpose of this intercomparison was threefold: to determine systematic bias errors in national methods of measuring solid precipitation; to derive standard methods for adjusting solid precipitation measurements; and to introduce a reference method of solid precipitation measurement for general use to calibrate any type of precipitation gauge. Participating countries were Canada, China, Croatia, Denmark, Finland, Germany, Iceland, India, Japan, Norway, Romania, the Russian Federation, Slovakia, Sweden, Switzerland, the UK, and the USA. Double Fence International Reference (DFIR) gauges were operated at 19 stations in 10 countries during the study. In an experiment performed during 1965 through 1972 at the Valdai station in Russia, Golubev (1985) found the DFIR to catch from 92 to 96% of bush gauge snowfall - that is precipitation recorded by a gauge surrounded by a bush cut up to the level of the gauge orifice over an area of approximately 100 m by 100 m. DFIR measurements were adjusted to the "true" value of the bush gauge and the catch of the various national gauges were then expressed with respect to the DFIR (Goodison et al., 1998). The work described here is the first global bias adjustment procedure that applies the results from the WMO Solid Precipitation Measurement Intercomparison. Table 2-1 is a summary of the intercomparison results for the precipitation gauges relevant to this work.

Table 2-1. WMO Solid Precipitation Measurement Intercomparison regression equations associated with each national gauge (Goodison et al., 1998). CR is catch ratio (%), w_h is daily average wind speed (m s^{-1}) at gauge height, T_{max} is maximum daily temperature (ºC), T_{min} is minimum daily temperature (ºC), and N is the number of observations used to develop the regression.

Gauge & Countries	**Equation**	**Shield**	**N**	**r^2**	**Eqn #**
Nipher Canada	Snow: $CR=100.00-0.44*w_h^2-1.98*w_h$	Nipher	241	0.40	2-1
	Mixed: $CR=97.29-3.18*w_h^2+0.58*T_{max}-0.67*T_{min}$	Nipher	177	0.38	2-2
SMHI Norway, Sweden	Snow: $CR=99.81-10.8*w_h$	Nipher	89	0.80	2-3
Tretyakov USSR, Mongolia, Finland, North Korea	Snow: $CR=103.11-8.67*w_h+0.30*T_{max}$	Tretyakov	381	0.66	2-4
	Mixed: $CR=96.99-4.46*w_h+0.88*T_{max}+0.22*T_{min}$	Tretyakov	433	0.46	2-5
	Snow: $CR=101.11-25.88*w_h+2.12*w_h^2$	None	89	0.74	2-6
IMC Romania	Not studied				
Hellmann Poland, Switzerland, Greenland, Austria	Snow: $CR=100.00+1.13*w_h^2-19.45*w_h$	None	172	0.75	2-7
	Mixed: $CR=96.63+0.41*w_h^2-9.84*w_h+5.95*T_{mean}$	None	285	0.48	2-8
	Snow: $CR=100-11.95*w_h+0.55*w_h^2$	Nipher	43	0.50	2-9
Icelandic Iceland	Not studied				
Norwegian Norway	Snow: $CR=98.18-11.27*w_h$	Yes	89	0.79	2-10
RT-1 Japan	Snow: $CR=100/(1+0.17*w_h)$	None	9		2-11
RT-3 Japan	Snow: $CR=100/(1+0.24*w_h)$	None	7		2-12
RT-4 Japan	Snow: $CR=100/(1+0.14*w_h)$	Cylindrical	23		2-13
Chinese China, South Korea	Snow: $CR=100*\exp(-0.056*w_h)$	None	38	0.56	2-14
NWS 8” USA	Snow: $CR=\exp(4.61-0.04*w_h^{1.75})$	Alter	107	0.72	2-15
	Mixed: $CR=101.04-5.62*w_h$	Alter	75	0.59	2-16
	Snow: $CR=\exp(4.61-0.16*w_h^{1.28})$	None	55	0.77	2-17
	Mixed: $CR=100.77-8.34*w_h$	None	59	0.37	2-18
Mountain Austria	Not studied				
Kostlivi Austria	Not studied				
Wild Finland	Snow: $CR=93.52-12.68*w_h$	Nipher	88	0.08	2-19
H&H-90 Finland	Snow: $CR=99.36-8.49*w_h$	Tretyakov	33	0.64	2-20
METRA 886 Czech Republic, Slovakia	Snow: $CR=100.00*\exp(-0.1046*w_h)$	None	24	0.19	2-21

Chapter 3: Analytical Methods

3.1: OVERVIEW OF BIAS ADJUSTMENT METHOD

As we note in Chapter 1, wind-related catch deficiencies are the dominant source of systematic error in gauge precipitation measurement, yet most of the widely used global precipitation data sets do not adjust for these errors. Why is this? A major reason is that wind observations needed for direct application of gauge catch adjustment formulae are rarely coincident in time and space with precipitation observations in many countries. For this reason, we quickly concluded that time-step based application of catch adjustment relationships such as the daily procedures described by Mekis and Hogg (1999), Yang et al. (1998a and 1999a), Yang (1999b), and Yang and Ohata (2001) was not feasible on a global basis. We decided instead to focus on climatological adjustments, which would allow removal or reduction of the largest errors in aggregate estimates of precipitation (a simplified approach that warrants tests against the daily time-step methods). In so doing, we accept that our emphasis is on reduction of average errors, e.g., on a monthly basis. The adjustments we develop do not deal with errors in individual precipitation events, which in some cases could be quite large, especially under conditions of anomalous wind (relative to the climatological average for the locale), or misclassification of the form (solid vs. liquid) of precipitation. These effects are likely to be largest in transitional climates or seasons, where both liquid and solid precipitation occur frequently.

The bias adjustment method used in this study is generally based upon the method summarized in Legates and Willmott (1990) and described in more detail in Legates

(1987). Legates developed mean monthly correction factors to account for the systematic biases of wind-induced undercatch, wetting losses due to moisture adhering to the internal walls of the collector during precipitation and during emptying of the gauge, and losses due to evaporation of water from the collector. The main difference between this study and that of Legates (1987) is in the determination of bias adjustment for wind-induced solid precipitation undercatch for which this study uses the results of the recent WMO Solid Precipitation Measurement Intercomparison (Goodison et al., 1998). Also, the mean monthly adjustments for wind-induced solid precipitation undercatch are derived from daily meteorological time-series rather than mean monthly meteorological values.

The general bias adjustment equation developed by Legates (1987) and based on a model proposed by Sevruk and Hamon (1984) can be used to determine bias adjusted precipitation. This equation is expressed as,

$$P_a = (1 - R)\kappa_r (P_g + \Delta P_{wr} + \Delta P_{er}) + R\kappa_s (P_g + \Delta P_{ws} + \Delta P_{es}) \qquad \text{(3-1)}$$

Where P_a is the adjusted precipitation estimate, P_g is gauge-measured precipitation, ΔP_w represents wetting losses, ΔP_e represents evaporative losses, κ is the factor that accounts for wind-induced losses, and R represents the proportion of precipitation that falls in solid form. The subscripts r and s denote the liquid and solid components of the total precipitation, respectively.

Note that in equation 3-1 the effects of trace precipitation are not included. Trace precipitation effects were ignored because the number of trace events per day generally is neither observed nor recorded in the global databases. Unlike Legates (1987), we ignored evaporation losses because they tend to be less significant than other biases (Sevruk, 1982), and because they are strongly dependent on weather conditions and site location and therefore are not amenable to averaging or interpolation (Yang et al., 1999a). Traditionally, the adjustment for wind-induced undercatch has been expressed in terms of the correction factor, κ, the ratio of "ground truth" precipitation to gauge measured precipitation. For the WMO Solid Precipitation Measurement Intercomparison, the catch ratio was chosen to represent the wind-induced undercatch of solid precipitation because it better represents the relative catch efficiency of the national gauge measurements against the adjusted reference measurements (Goodison et al., 1998). The catch ratio, *CR*, is the ratio of gauge-measured precipitation to "ground truth" precipitation and is, therefore, the inverse of the correction factor. The bias adjustment model used in this study can then be expressed as,

$$P_a = (1-R)\kappa_r(P_g + \Delta P_{wr}) + \frac{R}{CR_s}(P_g + \Delta P_{ws}) \qquad (3\text{-}2)$$

in which CR_s is the catch ratio for solid precipitation. This model was used to perform precipitation bias adjustment for all countries except Canada. Because the Canadian gauge network is unique and does not lend itself well to the model described by equation 3-2, and because superior bias-adjusted precipitation data sets exist for Canada, an alternative method was used to derive the Canadian mean monthly catch ratios. This method is described in section 3.5.

For the selected time-period of 1994 through 1998, daily values of CR_s (section 3.2), monthly values of κ_r (section 3.3), and daily values of ΔP_w (section 3.4) were determined for 7,878 worldwide stations (excluding Canada). (See section 3.2 for details relating to the selection of time-period and meteorological stations.) Daily precipitation values during this time-period were partitioned into solid and liquid amounts (also described in section 3.2) and bias-adjusted according to equation 3-2. Following completion of the daily adjustments, the adjusted and unadjusted precipitation values were summed to provide mean monthly totals, and mean monthly catch ratios were determined for each station according to the equation,

$$\overline{CR}_{all} = \frac{\overline{P}_g}{\overline{P}_a} \tag{3-3}$$

where $\overline{CR}_{all}$ is the mean monthly catch ratio that takes into account all the considered biases, $\overline{P}_g$ is the mean monthly gauge-measured precipitation, and $\overline{P}_a$ is the mean monthly bias adjusted precipitation. These monthly catch ratios were then combined with the Canadian catch ratios and gridded to a ½° resolution using the SYMAP algorithm of Shepard (1984) as implemented by Widmann and Bretherton (2000).

3.2: WIND-INDUCED SOLID PRECIPITATION UNDERCATCH

To simplify the problem, adjustment for wind-induced solid precipitation undercatch was performed only for the countries that experience at least half of their coldest month's precipitation as solid precipitation in at least half of their land areas. Figure 3-1 shows the areas of the globe that meet this criterion. 30 countries were selected: Armenia, Austria, Belarus, Canada, China, Czech Republic, Estonia, Finland, Georgia, Greenland, Iceland, Japan, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Mongolia, North Korea, Norway, Poland, Romania, Russia, Slovakia, Sweden, South Korea, Switzerland, Tajikistan, Ukraine, and USA. Figure 3-2 shows the wind speed-catch ratio relationships for each of these countries using the regression equations from the WMO Intercomparison. Table 3-1 describes the gauges that were most often used in each of these countries between the years of 1979 and 1998, the gauge that was used to determine the catch ratios, and the parameters needed to apply the catch ratio equations.

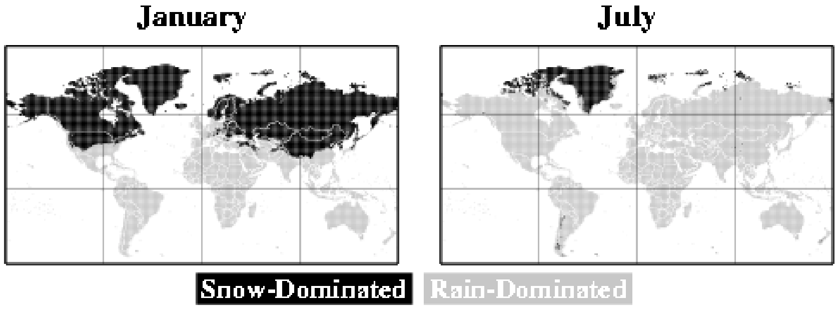


Figure 3-1. Region (mapped at ½º grid resolution) in which at least half of the precipitation falls as solid precipitation during January and July. Correction methods were developed for countries for which at least half of the land area is snow-dominated during either of these months.

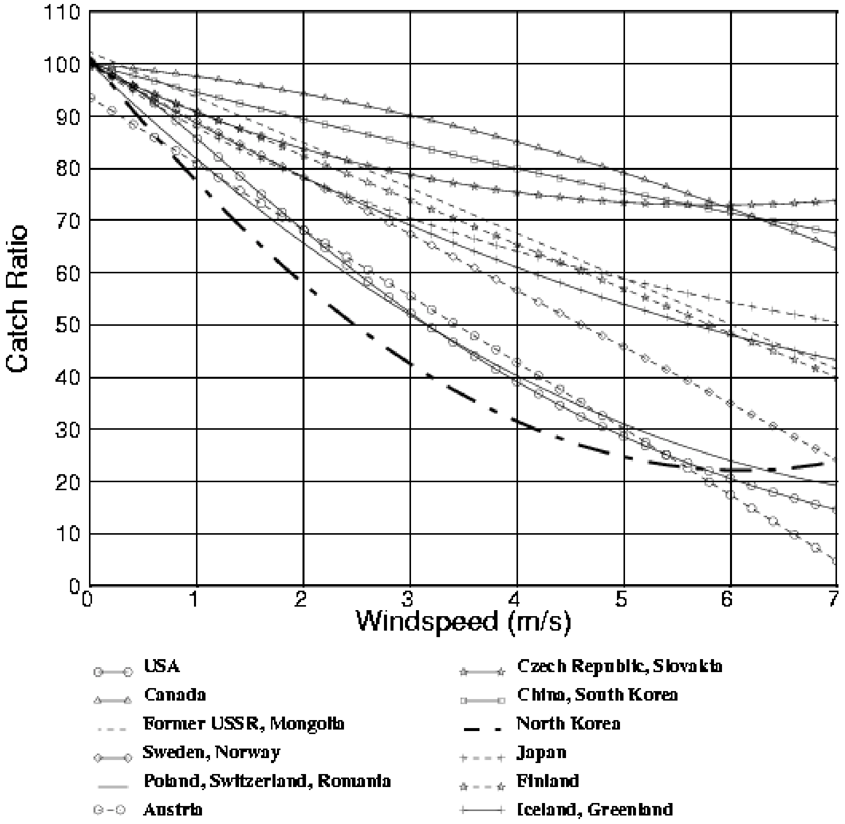


Figure 3-2. Solid precipitation catch ratio (in percent) versus wind speed (at gauge height) for each of the selected countries. Regressions were taken from the WMO Solid Precipitation Measurement Intercomparison (Goodison et al., 1998).

Table 3-1. Parameters used when applying the WMO Solid Precipitation Measurement Intercomparison (Goodison et al., 1998) regression equations.

Country	**Predominate Gauges Used**	**Gauge Corrected For**	**Height of Gauge Orifice (m)**	**Wind Speed Threshold ($m\ s^{-1}$)**	**Eqn # (Table 1)**
Former USSR	Tretyakov (sh.)	Tretyakov (sh.)	2	6.5	4
USA	NWS 8" (sh. and unsh.)	NWS 8" (unsh.)	1.1	6.5	17
China	Chinese (unsh.)	Chinese (unsh.)	0.7	6.5	14
Mongolia	Tretyakov (sh.)	Tretyakov (sh.)	2	6.5	4
Sweden	SMHI (sh.)	SMHI (sh.)	1.5	6.5	3
Greenland	Hellmann (sh.)	Hellmann (sh.)	3	6.5	9
Japan	RT-1 (unsh.), RT-3 (unsh.), RT-4 (sh.)	RT-4 (sh.)	3.5	6.5	13
Finland	Tretykov (sh.), H&H-90 (sh.), Wild (sh.)	H&H-90 (sh.)	1.5	6.5	20
Norway	Norwegian (sh.), SMHI (sh.)	SMHI (sh.)	1.5	6.5	3
Poland	Hellmann (unsh.)	Hellmann (unsh.)	1.5	6.5	7
Romania	IMC (unsh.)	Hellmann (unsh.)	1.5	6.5	7
Former Czech.	METRA 886 (unsh.)	METRA 886 (unsh.)	1	6.5	21 then 4
North Korea	Tretyakov (unsh.)	Tretyakov (unsh.)	1.5	6	4
Iceland	Icelandic (sh.)	Hellmann (sh.)	2	6.5	9
South Korea	Chinese (unsh.)	Chinese (unsh.)	0.2	6.5	14
Austria	Kostlivi (unsh.), Mountain (sh.)	Wild (sh.)	1	6	19
Switzerland	Hellmann (unsh.)	Hellmann (unsh.)	1.5	6.5	7

Countries that were partially (in land area) but not predominately dominated by coldest month solid precipitation were Afghanistan, Albania, Argentina, Azerbaijan, Bhutan, Bosnia, Bulgaria, Chile, Croatia, Denmark, France, Germany, Hungary, India, Iran, Italy, Macedonia, Nepal, New Zealand, Serbia, Slovenia, Turkey, and Uzbekistan. In order to maintain consistency, all of these partially snow dominated countries were excluded from the analysis because many of the national gauges for these countries were not studied. The correction domain should be expanded to include these countries in future versions of this data set. Before this can happen, a more comprehensive national standard precipitation gauge intercomparison should be performed.

The daily CR_s values were based on a time-series of daily meteorological values for the period during which all of the necessary variables were available (1994 through 1998). In order to apply the WMO Intercomparison catch ratio equations (see Table 2-1), the daily values of mean precipitation, mean wind speed, maximum temperature, and minimum temperature were required. Station observations of these variables were obtained from the NOAA Climate Prediction Center Summary of the Day data archived at the National Center for Atmospheric Research. The archive period for temperature and precipitation is January 1979 through June 2001, while the archive period for wind speed is January 1994 through June 2001. The five-year period from January 1994 through December 1998 was selected for the bias adjustment analysis. The more recent years were excluded from the analysis because of the increase in the number of automated recording gauges in some countries. Because the mean monthly catch ratio values ($\overline{CR}_{all}$) are intended to be applied to the longer twenty-year period (1979 through 1998), particular attention was given to identification of changes in gauges during the twenty-year period relative to the shorter five-year period. If there was a gauge change during this period, the gauge that was most prevalent during the 1994 to 1998 period was used to create the catch ratios and a lower score (see sub-section 4.1.4) was assigned to the reliability of the adjustments for that country. The number of stations included in the global daily data set was 15,190. Stations that had no simultaneous values for all four meteorological variables on any single day and the Canadian stations were eliminated, leaving 7,878 stations (Figure 3-3). Of these stations, only 4,647 were within the domain to be adjusted for wind-induced solid precipitation undercatch. The rest of the stations were assigned a constant CR_s value of 100%. All 7,878 of the stations were analyzed for wind-induced liquid precipitation undercatch and wetting losses.

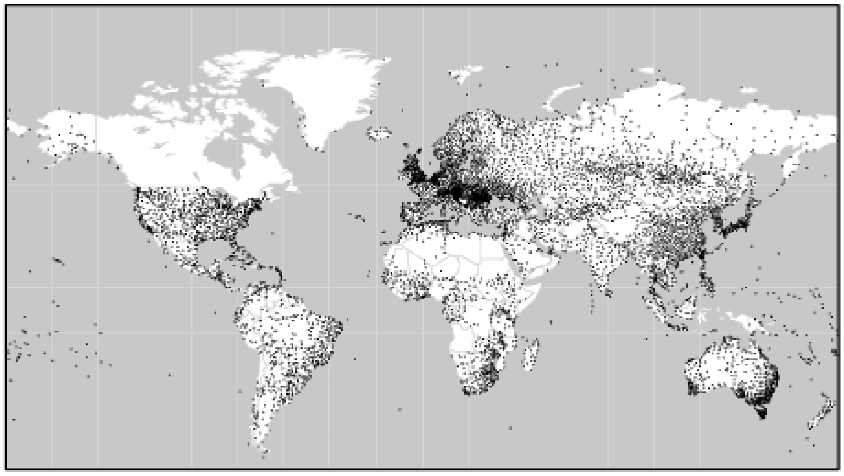


Figure 3-3. Station locations for the 7,878 stations used from the NOAA Climate Prediction Center Summary of the Day data archive. These are stations that have at least one day during the years of 1994 through 1998 in which there were coincident precipitation, maximum temperature, minimum temperature, and wind speed measurements. Note that Canadian corrections are handled separately, using methods described in section 3.5.

Precipitation was partitioned into solid and liquid as a function of the surface air temperature, using a method described in *Snow Hydrology* (US Army Corps of Engineers, 1956, pp. 54-55). All of the precipitation on a given day was assumed to be liquid if the daily minimum temperature was greater than 1.5 ºC; and if the daily maximum daily temperature was less than -0.5 ºC, all of the precipitation on that day was assumed to be solid. For daily minimum or maximum temperatures falling between the two limits, precipitation was partitioned linearly into solid and liquid.

To apply the catch ratio equations, wind speed at gauge height was required. This was estimated using similarity theory and can be expressed as,

$$w_h = \frac{\ln(h/z_0)}{\ln(H/z_0)} \cdot m \cdot w_H \qquad (3\text{-}4)$$

Where w_h is wind speed at gauge height, w_H is wind speed at anemometer height, h is the height of the gauge orifice in meters, H is the height of the anemometer in meters, z_0 is the roughness length in meters, and m is a coefficient that describes the site exposure. The universal standard anemometer height is 10 m (Goodison et al., 1998), and therefore we assumed that all of the wind speeds archived in the daily data set were measured at this height. This assumption doubtless is incorrect for some stations, but absent specific information about the stations, some assumption had to be made, and use of the nominal 10 m height seemed to be the most defensible one. The roughness lengths of 0.01 m and 0.03 m were used for the colder and warmer halves of the year, respectively (Golubev et al., 1992). The exposure coefficient was taken to be a value of one (fully exposed) due to a lack of site metadata accompanying the meteorological data. Gauge height information was taken from Sevruk and Klemm (1989), values from which were assigned to all gauges within the associated countries. Upper value threshold wind speeds were determined for each of the bias adjustment equations. The catch ratio equations are only statistically valid when they are applied using wind speeds that are within the range for which they were developed. If the gauge height wind speed exceeded the threshold wind speed, the catch ratio was calculated using the threshold wind speed. This method also decreased the chances of over-adjustment during high wind events in which snow may have been blown into the gauge (Yang et al., 1999a). For most of the countries, the wind speed threshold (at gauge height) was 6.5 m s^{-1}, following Yang et al. (1998a and 1999a), Yang (1999b), and Yang and Ohata (2001). Exceptions were made for North Korea and Austria for which the thresholds were set at 6 m s^{-1}, due to the unrealistic behavior of the regressions beyond that value (Figure 3-2).

3.3: WIND-INDUCED LIQUID PRECIPITATION UNDERCATCH

With minor variations, the method of Legates (1987) was used to determine the monthly correction coefficients, κ_r, needed for the bias adjustment for wind-induced liquid precipitation undercatch. We determined a correction coefficient for every month during the 1994 through 1998 analysis period and for the 7,878 meteorological stations described in section 3.2. Table 3-2 lists the equations that were used in the analysis. Many of the equations are dependant on μ, the transfer coefficient, which is given by,

$$\mu = \frac{p}{100} \cdot \frac{273}{T_a + 273} \cdot \frac{p}{p + 0.378 e_p} , \qquad (3\text{-}5)$$

In which p is the mean atmospheric sea-level pressure during precipitation (approximated by 100 kPa for simplification), T_a is monthly mean air temperature during precipitation in ˚C (approximated by monthly mean air temperature), and e_p is mean air humidity during precipitation (Legates, 1987). Following Legates (1987), we approximated e_p with e_a, the monthly mean vapor pressure in kPa. Legates (1987) developed a regression equation to estimate e_a as follows,

$$e_a = 0.2 \cdot \exp\left[19.0629 + 0.138952 \cdot \ln(P_g) - \frac{4798.05}{T_a + 273}\right] \qquad (3\text{-}6)$$

In which P_g is monthly gauge-measured precipitation.

Table 3-2. Equations used to determine κ_r in which μ is the transfer coefficient given by equation 3-5, w_{hp} is wind speed during precipitation at the gauge orifice, and w_p is wind speed during precipitation at the anemometer height. Equations were referenced from Legates (1987) who compiled them from various sources.

Orifice Area (cm^2)	**Shield**	**Equation**	**Eqn #**
500	Nipher	$\kappa_r = 1.0 + 0.012\ \mu^2 w_{hp}^2 \quad (w_{hp} \leq 5\ m\ s^{-1})$ $\kappa_r = 1.0 + 0.007\ \mu^2 w_{hp}^2 \quad (w_{hp} > 5\ m\ s^{-1})$	3-7 3-8
500	none	$\kappa_r = 1.0 + 0.013\ \mu^2 w_{hp}^2$	3-9
200	Tretyakov	$\kappa_r = 1.0 + 0.008\ \mu^2 w_{hp}^2$	3-10
200	none	$\kappa_r = 1.0 + 0.011\ \mu^2 w_{hp}^2$	3-11
127	none	$\kappa_r = 1.0 + 0.008\ \mu^2 w_{hp}^2$	3-12
324 (NWS 8")	none	$\kappa_r = 100/(100 - 2.12\ w_{hp})$	3-13
203 (Australian)	none	$\kappa_r = 100/(100 - 2.67\ w_{hp})$	3-14
200 (SMHI)	none	$\kappa_r = 1.0 + 0.004\ w_p^2$	3-15

It is poor to assume that the mean monthly wind speed is approximately the same as wind speed during precipitation (a parameter needed to determine κ_r). Sevruk (1982) publishes an equation developed by Bogdanova (1969) that relates monthly mean wind speed to wind speed during precipitation. This is expressed as,

$$w_p = L_r \cdot w \qquad (3\text{-}16)$$

In which w_p is wind speed during precipitation, w is the monthly mean wind speed, and L_r is an empirical coefficient which can be expressed as,

$$L_r = 1.12 + 0.295\ (0.826)^M \qquad (3\text{-}17)$$

In which M is the number of precipitation days per month at that site (Legates, 1987). The value, M, was determined for every month during the 1994 through 1998 analysis period by counting the number of days during each month in which precipitation exceeded a threshold of 1 mm at that station. Wind speed during precipitation at anemometer height, w_p, was then reduced to wind speed during precipitation at the gauge orifice, w_{hp}, using equation 3-4. The same assumptions were made as are described in section 3.2: z_0 is 0.01 m and 0.03 m for the colder and warmer halves of the year, respectively; H is 10 m; and m is 1.

Information regarding the type of national standard gauge used, whether or not a shield is used, and the height of the gauge orifice were taken from Sevruk and Klemm (1989).

This information is not known for several countries of the world and therefore was assumed. Following Legates (1987), the following suggestions were used in making these assumptions: the R.M.O. MK 1 rain gauge at 30 cm is used most frequently in British Protectorates or in countries that are or were formerly part of the British Commonwealth (Kurtyka, 1953); the R.M.O. MK 1 is the primary gauge in the Far East, Indonesia, New Guinea, Libya, and the Near Eastern Countries (Unesco, 1978); and the Hellmann gauge at 1 m is dominant in South America and Africa (Sevruk, 1982). We also assumed that the NWS 8” rain gauge is the primary gauge used in territories of the U.S. For each country, an equation from Table 3-2 was selected that best represented the geometry and shielding of the predominate gauge.

3.4: WETTING LOSSES

Wetting losses depend on the geometry and construction of the gauge, the number of measurements per day, and the frequency and form of precipitation (Sevruk, 1982). Assuming only one precipitation measurement per day, we incorporated wetting losses into the bias adjustment procedure according to equation 3-2. Wetting losses were included for every day that precipitation occurred during the 1994 through 1998 time-period. Using a variety of sources, Legates (1987) compiled wetting loss values for a number of gauge types (Table 3-3). These values tend to be uniform among gauges with similar orifice areas (Legates, 1987), and therefore national gauges not included in the list were assigned the wetting loss of the gauge with the most similar geometry. These values were reduced by one-half for solid precipitation events as suggested by Sevruk (1982) due to the fact that wetting losses during snowfall are less than those during rainfall. The former USSR countries apply wetting corrections of 0.20 mm for every liquid precipitaiton event and 0.10 mm for every solid precipitation event. These corrections are applied to each measurement prior to transmission of the data from the stations (Groisman et al., 1991). Sevruk (1982) suggests applying a wetting loss of 0.30 mm per event for the Tretyakov gauge to account for water both adhering to the sides of the collector and water remaining within the container after pour-out. Therefore, for consistency, we added a wetting correction of 0.10 mm to the daily precipitation amounts for stations within the Former USSR.

Table 3-3. Average wetting losses of both the collector and the container per day. These values were taken from Legates (1987) who compiled them from various sources. An * indicates values that were interpolated from gauges of similar construction by Legates (1987).

Gauge	$\bar{a}$ **(mm/day)**
L'Association	0.20
Australian	0.02
Chinese/Japanese	0.20*
Hellmann	0.30
Kostlivi	0.25*
Nipher	0.25
R.M.O. Mk 1	0.25
R.M.O. Mk 2	0.20
SMHI	0.30
South African	0.25*
Metra 886	0.30
Tretyakov	0.30 (0.10 applied in Former USSR countries)
NWS 8"	0.15
Wild	0.20
Ø 200cm^2	0.25

3.5: DETERMINATION OF CATCH RATIOS FOR CANADA

The Canadian gauge network is unique in that it uses two different precipitation gauges simultaneously, one to measure solid precipitation and the other to measure liquid precipitation. As of the early to mid 1970's, the Type B non-recording rain gauge was used to measure liquid precipitation at more than 2,500 Environment Canada stations (Metcalfe et al., 1996). For a subset of about 125 of these stations, the shielded Canadian Nipher gauge is used to measure fresh snowfall water equivalent; and at about 1,800 stations, a snow ruler is used to measure snow depth which is then converted to water equivalent by assuming that the density of the snow is 100 kg/m^3 (Metcalfe et al., 1996).

Two recent studies have attempted to create an adjusted precipitation archive for Canada (Groisman, 1998b; Mekis and Hogg, 1999). Both studies were more exhaustive than ours, and in particular, evaluated metadata in more detail than we did. We attempted to make use of the results of both of these studies. Groisman (1998b) completed a monthly analysis and performed adjustments on 6,692 stations located throughout Canada. Mekis and Hogg (1999), on the other hand, had access to more detailed metadata for a smaller set of 495 stations. For both studies, the station density is much higher in southern Canada than in the more remote northern regions (Figure 3-4).

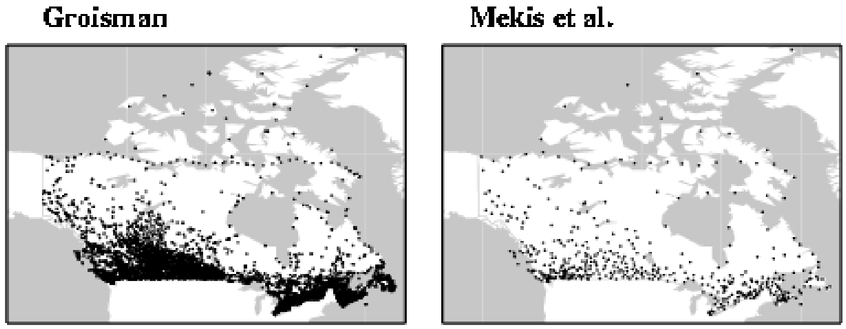


Figure 3-4. Station locations for the 6,692 stations corrected by Groisman (1998), and for the 495 stations corrected by Mekis and Hogg (1999).

Mekis and Hogg (1999) followed the method of Metcalfe et al. (1994) and adjusted the snow ruler measurements using a mean snow density calculated from the ratio of corrected Nipher gauge measurements to snow ruler measurements during the coincident period of snow ruler and Nipher gauge measurements. The Nipher gauge measurements were corrected by applying the WMO adjustment equation for the shielded Nipher gauge by using the observed wind speed at the appropriate gauge height. Wind speed at gauge height was calculated using the similarity (logarithmic profile) approach described in section 3.2. The calculated fresh snowfall densities were used to correct the daily snow water equivalent (determined from snow ruler measurements) amounts. Fresh snowfall densities were then interpolated to stations with snow ruler measurements where no Nipher gauge measurements were taken. Groisman (1998b) used a similar method but derived monthly apparent densities by relating accumulated (snow ruler) new precipitation and (uncorrected) Nipher measurements. The monthly estimated accumulated snowfall amounts were then adjusted using a catch ratio of 0.90, which was a rough estimate of the Nipher catch deficiency over a range of climatologies (Goodison et al., 1998). Unlike the Mekis and Hogg (1999) study, their method does not utilize the WMO results, nor does it utilize wind observations directly. Both data sets make adjustments for wetting losses and wind-induced undercatch for liquid precipitation and Mekis and Hogg (1999) make an adjustment to account for trace precipitation (Table 3-4).

Table 3-4. Comparisons between two adjusted precipitation data sets for Canada. Note: Rows denoted with an * also appear in the following document: http://www.msc-smc.ec.gc.ca/ccrm/NSIDC-Compare_Groisman.doc, Éva Mekis (personal correspondence). Additional information was taken from the original papers.

	Groisman (1998b)	**Mekis and Hogg (1999)**
*Number of Stations	6,692	495 best quality stations
*Length of Data	- 1990	- 1999 (updated annually)
*Correction timestep	Monthly	Daily
Rain Correction:		
Wetting losses	+0.16 mm per measurement	+0.01 mm evaporation per measurement +0.11 mm rentention per measurement
*Number of Measurements per day	Mean value or surrounding station information is used	Varies with the type of station: Climatic stations: 2x Synoptic stations: 4x
Undercatch due to wind	Multiply by 1.02	Multiply by 1.02
*Trace correction	None	0.1 mm for each trace event. TOR (Trace Occurrence Ratio) is used to determine the number of measurements per day for the stations.
Snow correction:		
Type of data used	Snow ruler data only	Snow ruler data only
Snow ruler correction	Use climatological ratios to adjust snow ruler measurement to Nipher, then increase these values by a factor of (1/0.9) to account for average Nipher gauge undercatch.	Location specific snow density ratio is determined based on coincident snow ruler and adjusted Nipher gauge measurements following Metcalfe et al. (1994). This method makes use of the WMO Solid Precipitation Measurement Intercomparison results.
*Trace correction	None	Correction depends on type (snow or ice crystal trace) and gradually decreases towards the North. Correction also depends on measurement frequency.

We attempted to take advantage of both the more extensive station network in the Groisman data and the more accurate adjustment in the smaller Mekis and Hogg data set. For the 485 stations the two data sets have in common, mean monthly ratios of Groisman to Mekis and Hogg accumulated monthly precipitation estimates were derived for the time period 1979 through 1990. The ratios were gridded to a ½° resolution over the Canadian domain using the SYMAP algorithm of Shepard (1984) as implemented by Widmann and Bretherton (2000). As shown in Figure 3-5 (in which the bi-seasonal means were averaged from the monthly values), the gridded ratios varied both spatially and temporally. In general, the differences are largest in the coldest regions and seasons, in which the Mekis and Hogg estimates are almost always greater than the Groisman estimates.

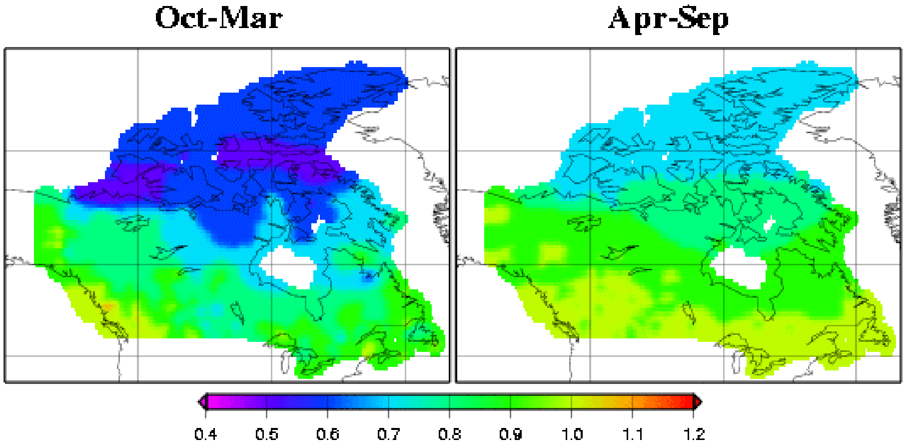


Figure 3-5. Bi-seasonal climatological averages of the ratio of Groisman (1998b) to Mekis and Hogg (1999) for the period of 1979 through 1990. The ratios were calculated and gridded from point estimates for the 485 stations the data sets had in common.

The gridded ratios were applied to the Groisman adjusted monthly station data to create an extensive network of station measurements that reflect the Mekis and Hogg adjustments. Mean monthly catch ratios were determined by dividing the original unadjusted mean monthly station data (averaged over the period 1979 through 1990) by the Mekis and Hogg adjusted Groisman mean monthly station data, averaged over the same period. Because of the unique nature of the Canadian precipitation measurement network, it was necessary to apply this alternative method in determining the Canadian "catch ratios". These ratios should not be thought of in the traditional way as representing the gauge-measured precipitation over "ground truth" precipitation, but should be thought of more as adjustment ratios, i.e. archived precipitation over "ground truth" precipitation. This is due to the fact that the majority of the solid-precipitation measurements in Canada are made using snow rulers and not a precipitation gauge.

Chapter 4: Discussion of Errors in Bias Adjustment Methodology

It is important to understand, at least on a qualitative basis, the error involved in any type of analysis, especially if there is a possibility that the results of the analysis will be used by other researchers. Because the bias adjustment for wind-induced solid precipitation undercatch is the most significant of all of the systematic biases, the bulk of this chapter is focused on this topic. However, many of the points discussed for wind-induced solid precipitation undercatch also apply to wind-induced liquid precipitation undercatch.

4.1: WIND-INDUCED SOLID PRECIPITATION UNDERCATCH

The process of applying catch ratio equations to all gauges in any given country and interpolating the ratios across the country creates many opportunities for the introduction of errors. These errors can be divided into three categories: errors involved in representing a country's gauge network with a single gauge type, errors in applying the derived regression equations, and errors in interpolating the catch ratios over a spatial domain.

4.1.1: Gauge Representation Errors

We assumed that a single prevalent type of gauge or shield is representative for a given country and that the parameters used to calculate the catch ratio are uniform across the country. Many countries use more than one type of gauge. Furthermore, in the last decade, the use of recording gauges to augment the manual gauge observations has become common (Goodison et al., 1998), although this effect is reduced somewhat by our restricted period of analysis. Shield usage is sporadic in many countries, but detailed data on which specific gauges are shielded is not uniformly available, and we relied on information published by Sevruk and Klemm (1989) to determine what type of shielding, if any, was prevalent for a given country. Also, although many countries measure wind speed at the 10 m international standard, gauge height varies in other countries (Yang et al., 1998a). Even for countries that use the 10 m standard, not all gauges conform. Similarly, the national standard height of the precipitation gauge orifice, if one exists, may not always be used for all the gauges in the network. We also made the assumption that there is zero snow depth, which (as is shown below) causes an underestimation in the catch ratio for sites that have significant snow depth.

The sensitivity of the catch ratios (for solid precipitation only) to variations in snow depth was examined for the unshielded Hellmann gauge. Increasing snow depth causes the effective gauge and anemometer heights to decrease from their standard heights of 1.5 m and 10 m, respectively. Catch ratio values determined by assuming snow depths of zero, 0.5 m, and 1 m are shown in Figure 4-1 (a). Making the assumption that there is significant snow depth causes the catch ratios to increase. This increase is not significant at lower wind speeds, but can reach up to 10% and 30% for snow depths of 0.5 m and 1 m, respectively, for higher wind speeds. The effects of the decreasing anemometer height only are shown in Figure 4-1 (b) assuming snow depths of zero, 0.5 m, and 1 m. Change in anemometer height has an insignificant effect on the catch ratio. The effects of the decreasing gauge height only are shown in Figure 4-1 (c) assuming snow depths of zero, 0.5 m, and 1 m. Change in gauge height accounts for nearly all of the change in the catch ratios when a significant snow depth is assumed.

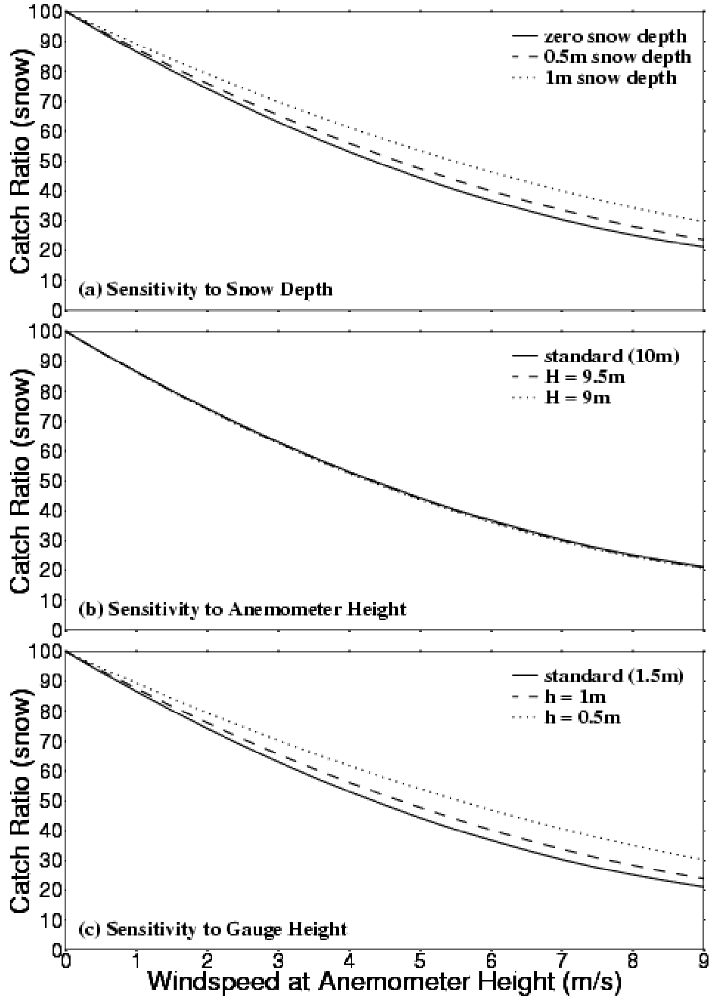


Figure 4-1. Sensitivity of the catch ratio for solid precipitation undercatch (calculated using equation 2-17) to: (a) snow depth, (b) anemometer height only, and (c) gauge orifice height only.

4.1.2: Regression Equation Application Errors

There are various sources of errors associated with the WMO Solid Precipitation Measurement Intercomparison equations used to determine the catch ratio estimates. For the more common gauges (Hellmann, Tretyakov, NWS 8”, and Nipher), catch ratio equations were derived from measurements taken at stations experiencing a wide range of environmental conditions and therefore are more readily transferable from region to region. The regression equations for many of the other gauges were derived from fewer or single sites and, therefore, the applicability of these equations is compromised. The applicability of the equations is evident in the number of observations used to derive the equations, and the accuracy of the regressions is evident in the r^2 value (see Table 2-1). Some countries did not participate in the intercomparison and therefore there were no catch ratio equations derived for these national gauges. Applying regression equations for gauges that are similar in design, material, and shielding to gauges at these stations increases the degree of error.

4.1.3: Interpolation Errors

Error is introduced in the gridding process, which in general can be expected to decrease as the number of stations within the gridded domain increases. Other factors to be considered are the uniformity of the station density across the domain, the topography of the gridded domain, and how well the selected stations used for gridding represent the entire network of stations within the domain. Meteorological stations tend to be located in valleys, and therefore interpolation of the catch ratios from valley to valley will usually result in an overestimation of the catch ratio in mountainous terrain. It is arguable that the meteorological stations used to develop the catch ratios in this study are not representative of the entire precipitation gauge network in many countries, especially the U.S. Groisman and Legates (1994) state that most of the U.S. first-order stations (stations with coincident wind speed measurements such as were required for this study) were relocated to suburban airports during the 1930's, 1940's, and 1950's. Therefore, the catch ratios are most likely underestimated for much of the U.S. and other countries for which the first-order stations are fully exposed.

In order to determine the sensitivity of the interpolated mean monthly catch ratio values (for all bias adjustments) to the station-specific values, test results were produced in which 15 selected stations were excluded from the interpolation process. These stations were chosen at random with the exception that they were required to have a nearly complete set of mean monthly catch ratios (see Figure 4-2 for station locations). The station-specific values were compared to the catch ratio of the grid cell overlaying that station and percent differences were computed for each month with respect to the station-specific value (Table 4-1). The percent differences are on average equal or less than 10% (with the exception of station 15). In general, these differences are greatest at locations where the station density is low. The cold season percent differences for the test station in Canada (station 15) are exceptionally large. In January, this site is not well represented by the surrounding sites and therefore is not adequately estimated by the interpolation of surrounding station values. One explanation for this is that there could be anomalous climate conditions at that site. We conclude that the spatial interpolation of mean monthly catch ratios produces reasonable results (within 10% error) over most of the domain, but there will be a few locations that are not adequately represented.

Table 4-1. Percent differences between the station-specific catch ratio (see Figure 4-2 for locations) and the catch ratio of the grid cell overlaying that station with respect to the station-specific value. For this test case, each station was excluded from the interpolation procedure. An * indicates stations that were included in the solid precipitation undercatch analysis (see Section 3.2).

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
1*	-1.7	2.3	6.7	-2.6	-1.2	-1.3	0.6	0.0	-0.9	-1.2	1.4	0.1	0.2
2*	6.5	11.6	7.4	6.3	4.7	-1.1	0.6	1.2	-4.0	-1.2	4.7	6.3	3.6
3*	1.2	4.8	0.0	4.6	5.0	0.4	2.2	2.9	4.3	9.5	10.3	6.3	4.3
4*	8.8	8.9	5.8	7.8	2.1	1.6	1.3	1.3	1.9	6.8	7.2	7.6	5.1
5*	4.3	-1.0	6.8	11.4	6.6	13.0	11.6	21.6	13.9	17.9	10.2	12.9	10.8
6	-1.1	-7.7	-1.5	-1.4	3.2	0.4	1.2	1.9	1.3	0.3	Nodata	-0.2	-0.3
7*	-0.5	0.0	-0.9	0.3	0.3	-0.4	0.7	1.1	0.9	-0.1	0.7	1.0	0.3
8*	-17.0	9.7	3.0	0.0	1.4	1.7	1.7	0.0	1.3	2.3	5.7	-14.0	-0.4
9	5.1	11.4	6.1	7.8	5.0	2.3	2.5	2.0	2.5	8.2	8.9	5.8	5.6
10	1.5	1.3	0.4	2.7	14.2	31.7	0.0	4.7	28.8	-0.3	2.4	1.7	7.4
11*	-3.4	-1.4	-2.9	2.1	1.9	-0.2	-0.7	3.9	4.6	9.3	-2.6	13.2	2.0
12	-0.3	1.6	0.7	0.7	1.3	1.3	1.7	-2.4	4.3	5.3	1.9	7.3	2.0
13	0.0	2.9	0.1	-0.4	1.5	0.4	0.4	-0.2	-0.6	-0.4	-0.5	1.2	0.4
14*	25.3	8.1	19.7	8.2	2.0	0.3	3.1	2.6	3.4	20.6	11.8	16.2	10.1
15*	-117.5	-11.0	-8.7	-9.0	-3.8	0.1	-0.1	-0.1	0.5	-9.0	-13.8	-16.9	-15.8

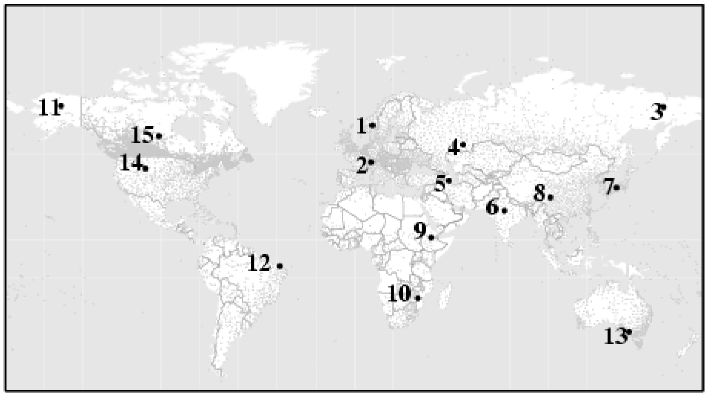


Figure 4-2. Stations removed for test case in order to examine the sensitivity of the gridded catch ratios to interpolation methodology (see Table 4-1).

4.1.4: Scoring System

In order to provide a qualitative basis for comparing errors among countries, a scoring system was developed, which is summarized in Table 4-2. The scoring system was based on three variables: gauge representation, equation application, and interpolation. Although the scoring results do not provide a basis for quantitative estimation of errors in each of the approximations, it does allow for a relative assessment of accuracy among the countries included in the analysis, and gives a general idea of the likely magnitude of errors. This scoring system provides an idea of which countries for which additional information would be most worthwhile. Because the U.S. occupies the third largest land surface area of all of the countries and has the lowest score, additional station-specific information would be particularly worthwhile.

Table 4-2. The scoring system used to approximate the accuracy of the wind-induced solid precipitation undercatch adjustment method for each country.

Country	Station Density (km^2/g)	Gauge Representation (pts. out of 20)	Equation Application (pts. out of 30)	Interpolation (pts. out of 30)	Total Score (pts. out of 70)
Former USSR	13,791	20	25	0	45
Canada	1,491	20	25	15	60
USA	9,816	5	25	0	30
China	12,529	20	20	0	40
Mongolia	30,686	20	25	0	45
Sweden	1,601	15	25	20	60
Greenland	10,095	15	20	0	35
Japan	1,749	5	20	20	45
Finland	6,241	10	20	0	30
Norway	2,014	10	25	20	55
Poland	4,667	15	30	10	55
Romania	1,389	15	20	20	55
Former Czech.	2,241	10	10	20	40
North Korea	4,305	20	25	10	55
Iceland	2,711	15	10	10	35
South Korea	1,824	20	20	20	60
Austria	655	5	10	20	35
Switzerland	1,007	5	30	20	55

On a 70-point scale, 20 points were assigned on the basis of how well the specified national gauge utilized in the WMO study represented the gauge network in place over the last twenty years (see Table 3-1). 30 points were assigned for equation application depending on how well the WMO equation approximated the data that was used to derive it and whether or not the equation was derived explicitly for the national gauge specified. 5 points were deducted from this possible 30 points if there were fewer than 100 observations used to derive the equation, and an additional 5 points were deducted if the estimated r^2 did not exceed 0.7 (see Table 2-1). Finally, a maximum of 20 points was assigned according to the station density, the interpolation area over the number of stations interpolated for each country. Of these 20 points, 10 points were assigned for station densities less than 5,000 km^2 per gauge, and an additional 10 points were assigned for station densities less than 2,500 km^2 per gauge.

a) U.S.: Since the inception of the National Weather Service (NWS) in 1870, the NWS 8" non-recording gauge has been the national gauge for the U.S. It is currently used at about 7,500 locations in the U.S. and at 1,340 stations in other countries. Few of the gauges are shielded and, since 1940 when the Alter shield was introduced, the number of Alter-shielded NWS 8" gauges has decreased from 500 to approximately 200 (Karl et al., 1993). Most of the Alter-shielded gauges are used in the western U.S. (Groisman and Legates, 1994). There are also about 2,600 shielded and unshielded recording gauges in the U.S. network including the Weighing Gauge (WG), the Tipping Bucket (TP), and the Fischer and Porter (FP) which has gradually been replacing the WG as the predominate recording gauge since 1963. According to a study performed by Groisman et al. (1998a), the WG catches approximately the same annual precipitation as the NWS 8", while the TB catches about 30% less. The FP catches 95% of the annual liquid precipitation and 70 to 105% of the annual solid precipitation that the NWS 8" catches.

The catch ratios for the U.S. were determined using the regression derived for the unshielded NWS 8" gauge. Because the recording gauges tend to catch less solid precipitation than the NWS 8" gauge, applying equation 2-17 (see Table 2-1) to these recording gauges would tend to overestimate the catch ratio. Alternatively, applying equation 2-17 to the Alter-shielded 8" gauges would tend to underestimate the catch ratio. Because of this non-homogeneity, the U.S. receives only 5 points for gauge representation. The U.S. receives 25 points for equation application (there were only 55 stations used to determine the parameters and form of the equation) and 0 points for station density, yielding an overall score of 30 points.

b) Canada: When correcting the precipitation records, Mekis and Hogg (1999) utilized the intercomparison results (equations 2-1 and 2-2 in Table 2-1). Because Mekis and Hogg (1999) used only snow ruler data and related this to the corrected Nipher data, Canada receives 20 points for gauge representation. There were plenty of data points to derive the equations (241) but the r^2 was low (0.4), therefore Canada receives only 25 points for equation application. Because the Groisman (1998b) data set included 6,692 stations, the station density was adequate but the majority of stations were concentrated in the south. Therefore, Canada receives 15 points for interpolation, receiving an overall score of 60 points.

c) Former USSR, Mongolia, and North Korea: The national gauge for the former USSR countries has varied over the last century. Before 1869, the Wild gauge was used for all meteorological stations. Between the years of 1891 and 1894, the Nipher shield was implemented at many of the existing stations, and in the 1950's the national gauge changed to a shielded Tretyakov and has remained as such since (Goodison et al., 1998). The shielded Tretyakov is also the national gauge for Mongolia (of which there are 350) (Sevruk and Klemm, 1989). Previous to 1956, the national gauge in North Korea was the Chinese Standard gauge. Since then, the unshielded Tretyakov has been the national gauge (Sevruk and Klemm, 1989). Catch ratios for Mongolia and the former USSR countries were calculated using the equation for the shielded Tretyakov, and the catch ratios for North Korea were calculated using the equation for the unshielded Tretyakov. The Tretyakov gauge represents the gauge network in these three countries well (earning them 20 points each), the equations are derived specifically for those national gauges and either have a larger number of data points or a large r^2 (earning them 25 points each), and North Korea has a moderately dense station network (earning it 10 points). Therefore the overall scores for former USSR, Mongolia, and North Korea are 45, 45, and 55, respectively.

d) Finland: Finland has a diverse history of national gauges. Between 1908 and 1981, the Nipher-shielded Wild gauge was used, between 1982 and 1992, the shielded Tretyakov gauge was used, and in 1992, the H&H-90 Finnish standard bucket was introduced into operation in all manual observation stations with a Tretyakov shield (Goodison et al., 1998). The regression for the shielded H&H-90 was used to calculate the catch ratios because it was the national gauge used during the time-period of the daily data set used in the analysis (1994-1998). The intention of these catch ratios is to be able to apply them to a data set extending from 1979 through 1998. Therefore, there will be some error introduced by assuming that the catch ratios derived for the H&H-90 will also be valid for the years when the Tretyakov gauge was used. A comparison of the equations for the H&H-90 (equation 2-20 of Table 2-1) and the shielded Tretyakov (equation 2-4 of Table 2-1) shows that the error is small. The maximum difference in the catch ratios is 3.75% and occurs when there is little or no wind. Alternatively, there may be significant error incurred by the uncertainty of the extent of recording gauges in the Finnish station network. Finland receives 10 out of 20 possible points for gauge representation and 20 points for equation application, earning it a total of 30 points.

e) Switzerland, Poland, Greenland, Iceland, and Romania: One of the most widely used precipitation gauges, the Hellmann gauge is used at about 30,080 locations around the world and is the standard gauge in 30 countries (Sevruk and Klemm, 1989). This non-recording gauge, which is used to measure both rain and snow, has many versions of similar design: the German, Polish, Danish, and Hungarian. The Hellmann is currently the national gauge for Switzerland, Poland, and Greenland. There are 405 Hellmann gauges in Switzerland of which the Nipher windshield is used occasionally and mostly in the mountains. There are also approximately 60 recording gauges (Sevruk and Klemm, 1989). The regression for the unshielded Hellman was applied to compute the catch ratios for Switzerland. Because there is some usage of the shielded Hellmann in the mountains, the unshielded Hellmann cannot be considered an very good representation of the entire gauge network in Switzerland. A comparison of the equations for the unshielded Hellmann (equation 2-7 of Table 2-1) and the shielded Hellmann (equation 2-9 of Table 2-1) shows that the maximum catch ratio difference is 24% which occurs at wind speeds exceeding 6 m s^{-1}. Therefore, Switzerland scores 5 for gauge representation, 30 for equation application, and 20 for station density. The overall score is 55.

There are about 1,800 unshielded Hellmann gauges in Poland (Sevruk and Klemm, 1989). Like Switzerland, the catch ratios were determined using the regression for the unshielded Hellmann. The extent of recording gauge usage in Poland in recent years is uncertain and so Poland receives 15 points for gauge representation, 30 points for equation application, and 10 for station density. The overall score is 55.

The Nipher-shielded Hellmann gauge is the national gauge for Greenland (Yang et al., 1999a). The catch ratios were determined using the regression for the shielded Hellmann. The extent of recording gauge usage in Greenland in recent years is uncertain and so Greenland receives 15 points for gauge representation and 20 points for equation application, earning an overall score of 35.

The national gauge for Iceland is the Nipher-shielded Icelandic gauge and the national gauge for Romania is the IMC which is unshielded for solid precipitation measurement. Both of these gauges are made of the same material and of almost the same design as the Hellmann gauge (Sevruk and Klemm, 1989). Because there were no regression equations derived for the Icelandic gauge or the IMC gauge in the WMO Intercomparison, the equations derived for the shielded and unshielded Hellmann gauges were used instead. The extent of recording gauge usage in Iceland in recent years is uncertain and recording gauges comprise about 20% of the station network in Romania (Sevruk and Klemm, 1989), therefore both countries receive 15 points for gauge representation. Iceland receives 10 points for equation application and 10 points for station density, resulting in an overall score of 35. Romania receives 20 points for equation application and 20 points for station density, resulting in an overall score of 55.

f) Norway and Sweden: Previous to the 1980's, the national gauge in Norway was the Norwegian Standard gauge. Since 1982, all new gauges installed have been SMHI gauges. All gauges of either type that have been installed or moved since 1940 are equipped with Nipher shields. There are also several MI-67 gauges in use in mountainous areas. The national gauge in Sweden is also the Nipher-shielded SMHI of which there are approximately 1,000 (Sevruk and Klemm, 1989). The catch ratios for Norway and Sweden were calculated using the regression derived for the shielded SMHI. The error created by assuming that the regression equation for the SMHI applies to the Norwegian gauge is small. Equations 2-3 and 2-10 (of Table 2-1) are similar regressions, and the maximum potential difference in the catch ratios is 4.5% which occurs at wind speeds of 6 m s^{-1}. Norway receives 10 points for gauge representation, and because the extent of recording gauge usage in Sweden in recent years is uncertain, Sweden receives only 15 points for gauge representation. Both countries receive 25 points for equation application and 20 points for station density, resulting in overall scores of 55 and 60 for Norway and Sweden, respectively.

g) Austria: The two national gauges for Austria are the unshielded Kostlivi and the Nipher-shielded Mountain gauge of which there are approximately 800 of each gauge. There are also some unshielded Hellmann gauges currently in use in Austria (Sevruk and

Klemm, 1989). There were no catch ratio regressions derived for either of the Austrian national gauges, but the dimensions of the Austrian gauges are similar to that of the Finnish Wild gauge. Therefore, the catch ratios were determined using the regression for the Nipher-shielded Finnish Wild. Due to the varied gauge and shield usage, Austria receives 5 points for gauge representation. Because the Finnish Wild is made of different material than the Austrian national gauges, Austria receives 10 points for equation application. Austria receives 20 points for station density for an overall score of 35.

h) Czech Republic and Slovakia: The national gauge of the former Czechoslovakian countries is the METRA 886 non-recording gauge in which a Tretyakov shield is used in the mountains. There are also several recording gauges in the network (Sevruk and Klemm, 1989). The regressions for the METRA 886 were derived using the shielded Tretyakov as the reference gauge rather than the DFIR. Because the shielded Tretyakov also significantly under-catches solid precipitation, a second adjustment was needed to bring the METRA 886 measurements to "truth". Therefore after applying equation 2-21 (Table 2-1) for the unshielded METRA 886, a second adjustment was made using equation 2-4 (Table 2-1) for the shielded Tretyakov. Because of the varied usage of the Tretyakov shield and the presence of several recording gauges, Former Czechoslovakia receives only 10 points for gauge representation. The country receives 10 points for equation application and 10 points for station density, for an overall score of 40 points.

i) China and South Korea: The national gauge in both China and South Korea is the non-recording unshielded Chinese Standard of which there are approximately 18,000 in China and 800 in South Korea (Sevruk and Klemm, 1989). The catch ratios were determined using the regression derived for the unshielded Chinese gauge. Both countries receive 20 points for gauge representation, and 20 points for equation application. China and South Korea receive 0 and 20 points for station density for overall scores of 40 and 60 points, respectively.

j) Japan: In 1986, Japan changed from using manual gauges to recording gauges. The RT-1 is an unshielded simple tipping bucket gauge which is deployed in areas where the probability of snow is very low; therefore it is most abundant in the south. The RT-3 unshielded gauge is used in areas where there is a possibility of snow occurring and is abundant everywhere except in the very north. The RT-4 gauge is abundant everywhere and is the only gauge abundant in the very north where most of the snowfall occurs (Sevruk and Klemm, 1989; Goodison et al., 1998). This gauge is shielded with a cylindrical windshield and therefore catches significantly more solid precipitation than the other two gauges. Because it is most likely that snowfall occurring in Japan will occur in an area where the RT-4 gauge is predominant, the catch ratios were calculated using the regression for this gauge. In many cases, the RT-4 regression will be applied to RT-3 gauges, and less often to a RT-1 gauge. The maximum potential difference in catch ratio between the RT-4 and the RT-3 regressions is 13.4% and occurs at a wind speed of 6 m s^{-1}. The maximum potential difference in catch ratio between the RT-4 and the RT-1 regressions is 4.8% and also occurs at a wind speed of 6 m s^{-1}. Therefore applying the RT-4 regression to a RT-3 gauge may result in significant error. Because of this error, Japan receives only 5 points for gauge representation. It receives 20 points for equation application, and 20 points for station density, resulting in an overall score of 45 points.

4.2: WIND-INDUCED LIQUID PRECIPITATION UNDERCATCH

Many of the points mentioned in section 4.1 also apply to errors associated with the bias adjustment for wind-induced liquid precipitation undercatch, although these errors are arguably more pronounced for the liquid precipitation analysis. Gauge representation errors are more severe for the liquid precipitation analysis than for the solid precipitation analysis because it was necessary to make assumptions regarding predominant gauge type and gauge height for many of the countries not included in the analysis for solid precipitation. Application of the regression equations for the liquid precipitation analysis can be argued to be considerably less accurate than application of regression equations for the solid precipitation analysis. In a recent study by Duchon and Essenberg (2001), attempts were made to develop regression equations relating wind speed to liquid precipitation undercatch for the tipping-bucket and weighing-bucket gauges commonly used in the U.S. They argue that, because wind-induced liquid precipitation undercatch is highly storm-specific, it was impossible to develop adequate regressions. Without high-resolution wind speed measurements, rainfall rates, and drop size distributions, undercatch is inadequately estimated. Although the errors are more severe for the liquid precipitation analysis, the effects of these errors are less significant than the errors associated with the bias adjustment of solid precipitation undercatch. This is because the undercatch of solid precipitation is generally much greater than the undercatch of liquid precipitation.

4.3: WETTING LOSSES

Perhaps the most significant source of error regarding our method of adjusting for wetting losses is the assumption that precipitation measurements for all stations in all countries occur only once per day. It is not uncommon for nations to standardize more than one measurement per day. This assumption may result in an underestimation of the wetting losses for some countries. Many previous bias adjustment efforts, such as the wetting corrections added to all precipitation events in the Former USSR countries, have added a constant wetting loss for every precipitation measurement taken. Recent studies have shown that this practice may be in error. Bogdanova and Mestcherskaya (1998) studied the effects of the changes in observational procedure in the Former USSR when most stations changed from twice-daily measurement to four measurements per day in 1966, and back to twice-daily measurements in 1986. They discovered that the increased number of measurements per day caused the wetting losses per day to remain unchanged or even to decrease to a small extent. Bogdanova and Mestcherskaya (1998) argue that this is probably due to the shortening of the time interval between measurements and that, on humid days, the containers have no time to dry out between measurements and may be used slightly wet. This study demonstrates how complex bias adjustment of wetting losses becomes if done precisely, and therefore, it is difficult to evaluate quantitatively or qualitatively the net effect of the assumption that all stations perform one measurement per day.

Chapter 5: Results

5.1: CATCH RATIOS

Figure 5-1 shows the seasonally-averaged spatial distribution of the gridded catch ratios globally. In general, the catch ratios increase from north to south with regions of lower values in high-altitude regions (such as the Alps and the Tibetan Plateau) and in regions of high wind speeds (such as the U.S. Midwest). The catch ratios vary less uniformly over North America than over other continents, primarily because of differences in solid precipitation measurement methods between Canada and the USA. Because Canada uses a snow ruler rather than a precipitation gauge to measure fresh snowfall, the catch ratios in Canada do not respond to varying climates in the same way as the catch ratios in the USA. For example, Canadian catch ratios tend to increase with altitude in the Canadian Rockies. The bias adjustment effort of Mekis and Hogg (1998), from which our Canadian adjustments were derived, include the adjustment of the Canadian snow ruler measurements by scaling the values by a more realistic snow density rather than assuming a density of 100 kg/m^3. An actual density less than the assumed density (such as with the less dense snow that often occurs in the Rocky Mountains), would create a catch ratio greater than 100% because the actual snow water equivalent is less than the archived snow water equivalent. Alternatively in the USA, the precipitation gauges tend to increase in undercatch (decrease in catch ratio) as the snow particles become lighter and are more influenced by the aerodynamics around the gauge orifice. Therefore, the differences between snowfall depth measurement in the USA and Canada account for the cold season non-uniformity of gridded catch ratios across North America.

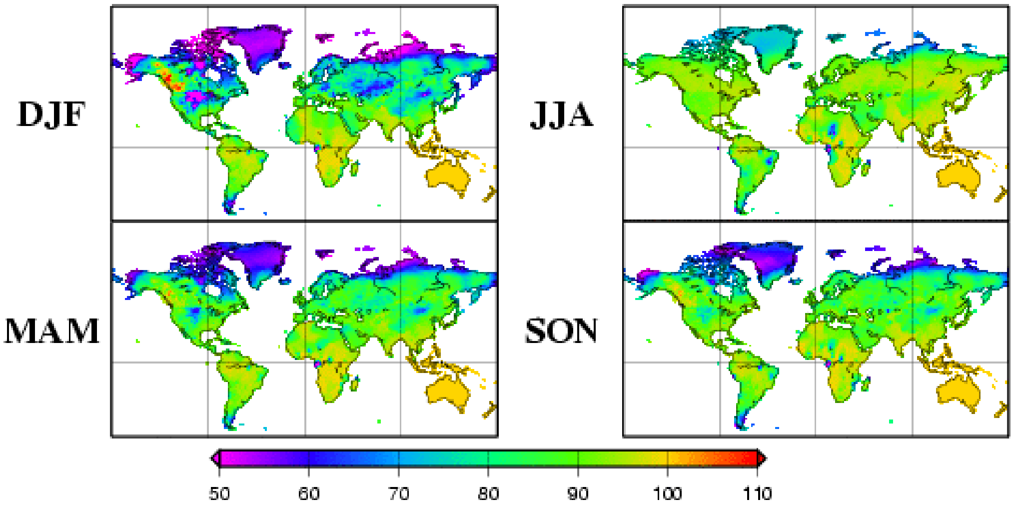


Figure 5-1. Seasonal climatologies (averaged from the monthly 1979 through 1998 climatologies for visualization purposes) of the catch ratios in percent.

5.2: ADJUSTED GRIDDED PRECIPITATION

The catch ratios were applied to twenty years of the Willmott and Matsuura (2001) precipitation data. This is a global monthly precipitation data set gridded at ½º spanning the period 1950 through 1999, which was derived from the Global Historical Climatology Network Version 2 data set (GHCN, 2002). Figure 5-2 shows the seasonal climatologies of the adjusted precipitation averaged over the period 1979 through 1998. Although discontinuities exist in the gridded catch ratios used to adjust the gridded precipitation (especially between Canada and the USA during the cold season), no discontinuities are apparent in the adjusted precipitation fields.

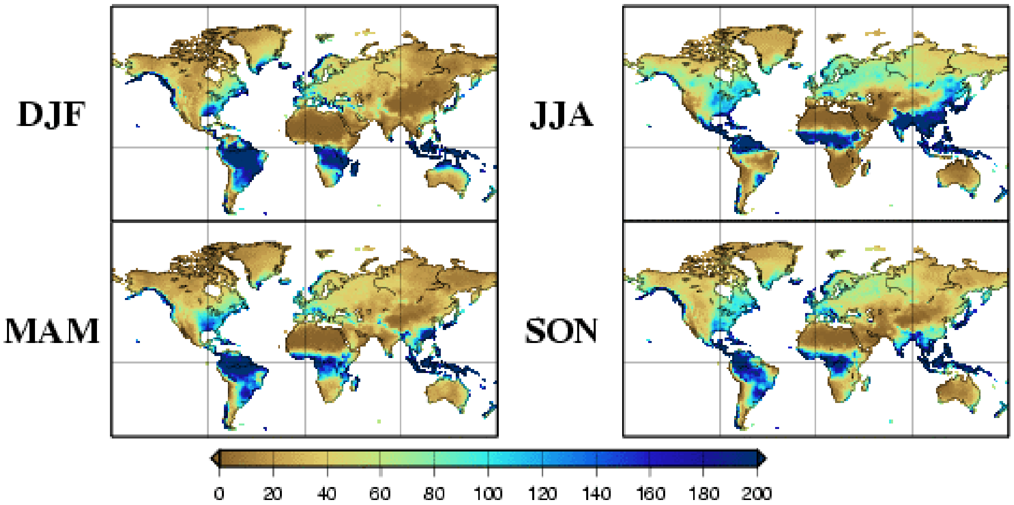


Figure 5-2. Seasonal climatologies (in mm of precipitation per month), averaged over the period of 1979 through 1998, of the adjusted Willmott and Matsuura (2001) monthly data set.

Table 5-1 shows the annual and seasonal percent increases in precipitation due to each component of the bias adjustment. The combined effect of all adjustments yields an increase in the global landmass mean annual precipitation of 11.2% over the time-period 1979 through 1998. Figure 5-3 shows the percent change in precipitation with latitude for each season due to each of the bias adjustment components. The greatest increase of over 95% occurs at approximately the 80º North latitude during the winter (DJF) of which nearly 85% of this increase us due to the bias adjustment for wind-induced solid precipitation undercatch, although it should be noted that the land area at this latitude is quite small. The bias adjustment for wind-induced liquid precipitation undercatch causes a percent increase in precipitation between 20 and 80% at latitudes between 50º and 55º South. This effect is due to the fact that the few stations used for interpolation over the southern tip of South America are associated with very high wind speeds.

Table 5-1. Percent increases in precipitation annually and for each season due to the application of the bias adjustments to the Willmott et al. (2001) data set.

Adjustment	**Annual**	**DJF**	**MAM**	**JJA**	**SON**
Wind-Induced Solid Precipitation	4.5%	8.6%	4.6%	1.0%	4.9%
Wind-Induced Liquid Precipitation	3.9%	3.7%	4.2%	3.6%	4.3%
Wetting Losses	2.8%	2.9%	2.7%	2.7%	2.9%
All Adjustments	11.2%	15.2%	11.5%	7.3%	12.1%

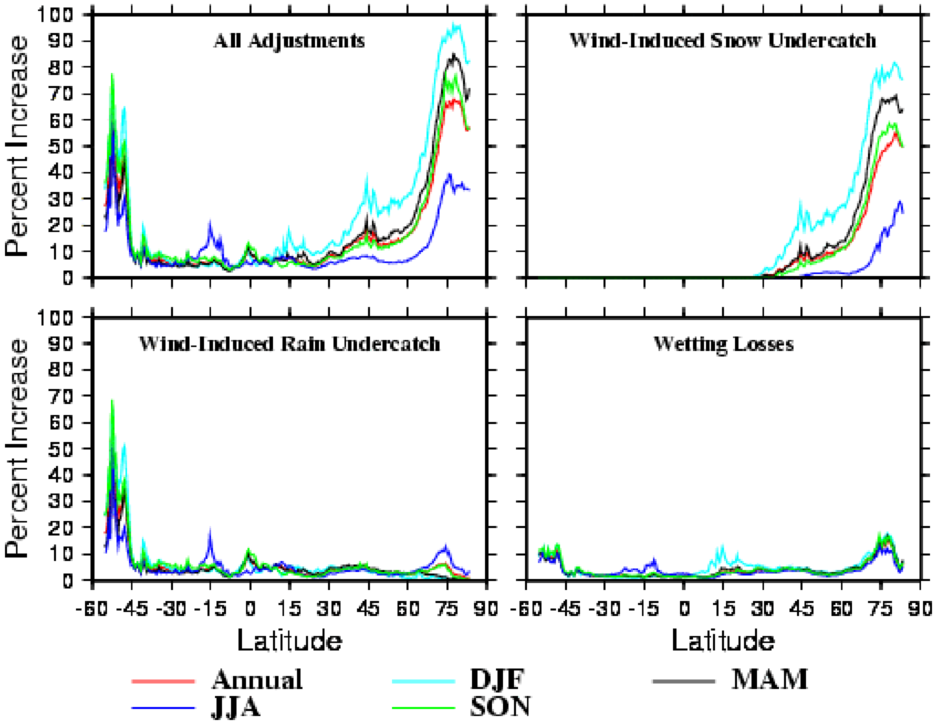


Figure 5-3. Percent change in terrestrial precipitation due to the application of each bias adjustment to the Willmot and Matsuura (2001) monthly precipitation data set.

Chapter 6: Data Set Comparisons

6.1: COMPARISONS TO YANG ET AL. CATCH RATIOS

6.1.1: Overview

Yang and others performed adjustments on the precipitation measurements from several stations in the USA (1998a and 1998b), Greenland (1999a), the Arctic Ocean (1999b), and Siberia (2001) (hereafter we refer to all of these studies by the first author, Yang). Yang made adjustments to rainfall and snowfall measurements including the systematic biases resulting from wind-induced undercatch, wetting, and the treatment of trace precipitation as zero. With regards to solid precipitation, Yang's method to adjust for wind-induced undercatch is similar to our method with the exception that Yang had access to specific station information and therefore did not need to make assumptions regarding gauge type, shielding, gauge height, and wind-sensor height. These assumptions can be tested by comparing our catch ratios (for wind-induced undercatch only - calculated for comparison purposes) to the catch ratios for wind-induced undercatch inferred from Yang's work. Although somewhat different methods were used to determine the liquid precipitation portion of the catch ratios for wind-induced undercatch, the effect this portion has on the catch ratio is small compared to the portion for solid precipitation, especially in the regions used for this comparison.

6.1.2: Similarities and Differences in Methods

The similarities between our method of estimating wind-induced precipitation undercatch and that of Yang are several: the regressions derived from the WMO Solid Precipitation Measurement Intercomparison (Goodison et al., 1998) were applied in both studies; the logarithmic wind profile approach was used to scale the wind speed to gauge height in which the same roughness parameters were used for the cold and warm seasons; the same wind speed threshold was used; adjustments were derived using a daily time-step; and precipitation was partitioned between solid and liquid using daily temperature measurements. The differences in the methods were fewer, but important: for the estimation of liquid precipitation undercatch, different regression equations were used and our adjustments were derived from monthly rather than daily meteorological data; the roughness parameters for the warm season extended from June through August rather than from April through September; the temperature thresholds used to partition the precipitation into solid and liquid were -2 and +2 ºC rather than -0.5 and +1.5 ºC; and the time-period of analyses were different from our 1994 through 1998 period.

6.1.3: Method of Comparison and Results

We determined the Yang catch ratios from their published results by dividing the total gauge-measured precipitation by the sum of the total gauge-measured precipitation and the total depth of wind-induced undercatch. These period-average catch ratios were then compared to our period-average catch ratios in two ways: by plotting Yang's catch ratios against our catch ratios for each of the regions analyzed (Figure 6-1), and by computing the percent differences between them with respect to our catch ratios. Table 6-1 lists the regions in which comparisons were made between the catch ratios, the numbers of stations in common between the two works, Yang's time-periods of analyses, and the means and standard deviations of the percent differences.

Table 6-1. Comparisons between our annual average catch ratios (for wind-induced undercatch effects only) and the annual average catch ratios inferred from Yang et al. (1998a and 1999a) and Yang and Ohata (2001).

Region	**Number of Stations Compared**	**Time-Period Analysed by Yang**	**Percent Difference Mean**	**Percent Difference St. Dev.**
Siberia	58	1986 through 1992	1.6%	4.5%
Greenland	12	1994 through 1997	2.5%	6.0%
Alaska	9 (unsh. and sh.)	both 1982 and 1983	3.5%	12.0%
Alaska	7 (unsh. only)	both 1982 and 1983	7.9%	5.8%

Our catch ratios are on average between 1.6% and 7.9% higher than Yang's with standard deviations ranging from approximately 4.5% to 12.0%. The large standard deviation for the Alaskan data is due to the inconsistent use of shields at the gauges used in our analysis. Of the nine gauges analyzed, two had Alter shields and the rest were unshielded. Excluding the shielded stations decreases the standard deviation from 12.0% to 5.8% while increasing the mean from 3.5% to 7.9%.

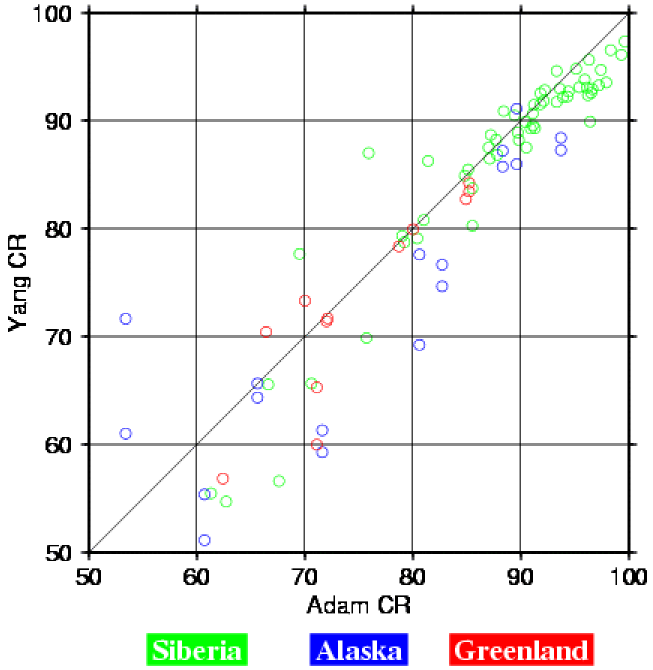


Figure 6-1. Catch ratios inferred from Yang et al. (1998a, 1999a) and Yang and Ohata (2001) vs. our catch ratios (for wind-induced undercatch effects only) for 79 stations in Siberia, Greenland, and Alaska. Note that there are two points for every station in Alaska due to the fact that Yang et al. (1998a) give results for both 1982 and 1983.

a) Greenland: Yang's Greenland gauges were all shielded and at a height of 3 m, both of which were assumed for this work. Therefore, the error in the Greenland catch ratios is most likely due either to the differences in wind-sensor height or to the use of different regression equations for liquid precipitation undercatch. Whereas we assumed the wind-sensor height to be 10 m, Yang used the actual wind-sensor heights, which ranged from 3 to 15 m. The regression equation Yang utilized for liquid precipitation undercatch would tend to estimate a larger liquid precipitation undercatch by 0 to 5% for wind speeds less than 4 m s^{-1}, which would have the effect of slightly decreasing his catch ratios for wind-induced undercatch with respect to ours. Because the mean difference in catch ratios was relatively small for Greenland (2.5%), it can be inferred that neither of these differences in approach are a large source of error on a mean monthly basis.

b) Siberia: For the Siberian gauges, Yang used all of the same parameters for gauge-type, shielding, gauge height, and wind-sensor height. As with Greenland, the regression equation Yang utilized for liquid precipitation undercatch would tend to estimate a larger liquid precipitation undercatch by 0 to 5% for wind speeds less than 4 m s^{-1}. This would explain Yang's slightly lower catch ratios between the values of 90 and 100% (the range for which the catch ratio is more affected by liquid precipitation undercatch than solid precipitation undercatch), which results in a mean difference of 1.6%.

c) Alaska: None of Yang's parameters were constant for Alaska. Some of the gauges were Alter-shielded while the majority were not, the wind-sensor heights varied from 6.4 to 16.5 m, and the gauge heights varied from 0.9 to 7.6 m. This comparison demonstrates how dramatically an incorrect assumption regarding shielding affects the standard deviation of the percent differences. Because we utilized the assumption that all of the U.S. gauges are unshielded, our catch ratios were underestimated for the two Alter-shielded gauges, and the standard deviation of the percent differences for all nine results was large (12.0%). Excluding the shielded gauges reduced the standard deviation to 5.8%, a value comparable to the standard deviations calculated for the other regions. Therefore, significant error is introduced every time the assumption that all U.S. gauges are unshielded is applied to a shielded U.S. gauge. For the stations used in the comparison, most of Yang's gauge heights were greater than our assumed 1.1 m, and most of Yang's wind sensor heights were less than our assumed 10 m. These differences appear to have the significant combined effect of causing our mean monthly catch ratios to be on average 7.9% higher than Yang's (for unshielded gauges). This effect is probably heightened by the fact that Yang's adjustments for liquid precipitation undercatch is between 0 and 5% higher than ours due to the difference in the regression equations used for this estimation.

6.2: GLOBAL GRIDDED DATA SET COMPARISONS

6.2.1: Overview

The bias-adjusted data set developed in this study were compared against four other global monthly precipitation data sets (summarized in Table 6-2). All data sets are gauge-based of which three are time-series and two are climatologies. They were all gridded using similar interpolation schemes. In addition to the Willmott and Matsuura (2001) data set, a data set developed at the University of East Anglia Climatic Research Unit (CRU) by New et al. (2000) is included. The climatological data sets are those of Legates and Willmott (1990) and GPCC (GPCC, 2002; Rudolf et al., 1994). The purpose of this comparison is, foremost, to determine the magnitude and variability of the differences between the adjusted data set developed in this study and that of Legates and Willmott (1990). Secondly, the purpose is to determine the differences between the adjusted data sets and several commonly used unadjusted data sets, which will aid in ascertaining the regions and months for which bias adjustment has the most effect on mean monthly precipitation. For more comparisons of commonly used global precipitation climatologies, see Legates (1995a).

Table 6-2. Gridded monthly global precipitation data set specifications (the data set described in this work is denoted Adjusted Willmott and Matsuura). All data sets are based on gauge observations.

Data set	Willmott and Matsuura (2001)	Adjusted Willmott and Matsuura (2001)	CRU0.5 - New et al. (2000)	Legates and Willmott (1990)	GPCC - Rudolf et al. (1994)
Data type	Time-series	Time-series	Time-series	Climatology	Climatology
Time period	1950-1999	1979-1998	1901-1998	1920-1980	1961-1990
Spatial Resolution	½°	½°	½°	½°	1°
Gauge Catch Adjustments	none	Wind-induced precipitation undercatch and wetting loss adjustments. Solid precipitation analysis applies results from Goodison et al. (1998). Other adjustments based on Legates and Willmott (1990).	none	Wind-induced precipitation undercatch, wetting, and evaporation loss adjustments. Adjustments derived from long-term monthly means.	none

For comparison purposes, monthly and seasonal climatologies were created from the time-series data sets by averaging the monthly values over the period 1979 through 1998. Although this period of averaging is different from those of the Legates and Willmott and GPCC climatologies, the comparison will still yield some degree of insight into how the data sets behave with respect to each other. All five data sets were interpolated to a common resolution and clipped to a common land mask before comparison. The bi-seasonal (summer-winter) climatologies for each of the data sets are shown in Figure 6-2.

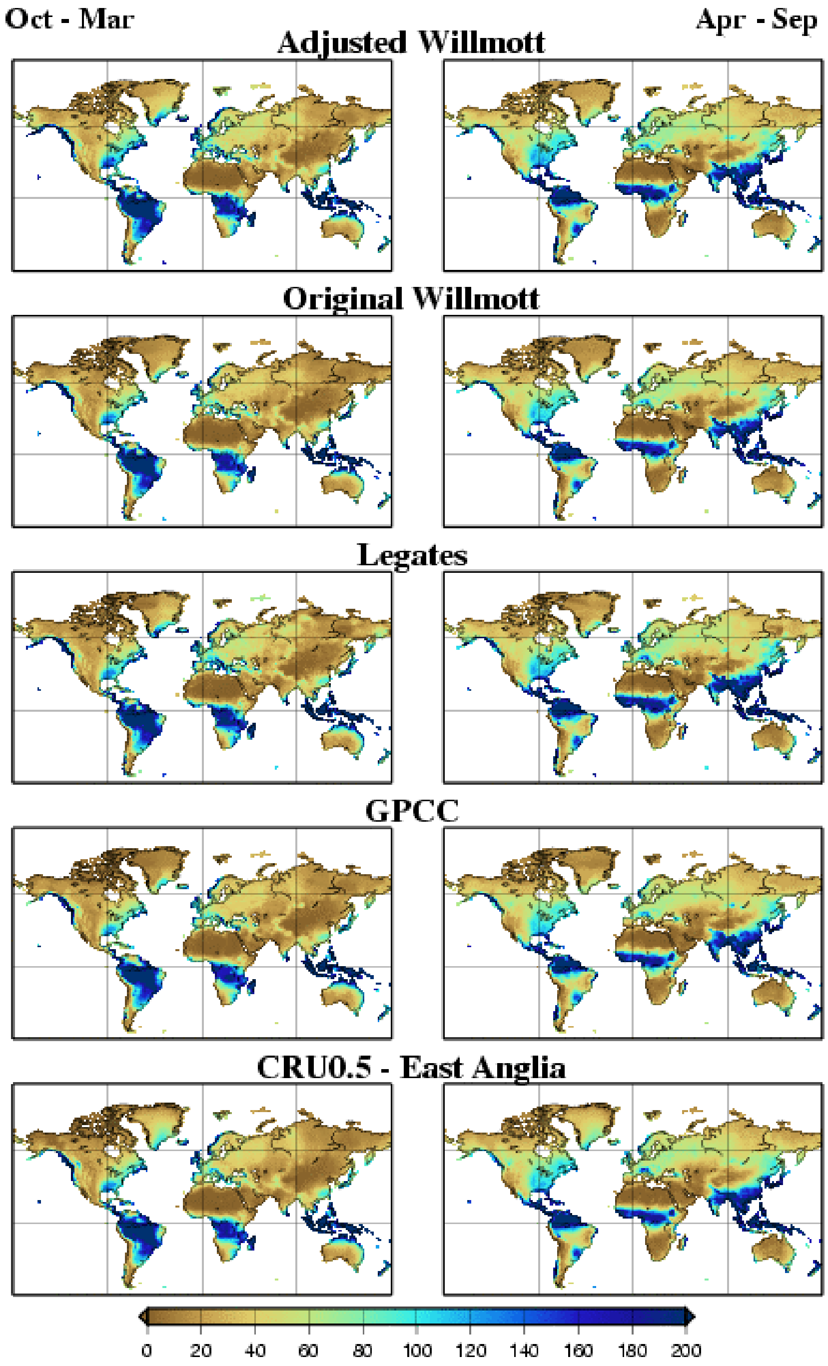


Figure 6-2. Bi-seasonal (summer-winter) climatologies (in mm of precipitation per month) of the five data sets used in the gridded global data set comparison. The averaging period for the time-series is 1979 through 1998. See Table 6-2 for details.

6.2.2: MEAN MONTHLY VARIATION

Figure 6-3 shows the mean monthly variation of precipitation averaged over all global and Northern and Southern Hemisphere land areas. For the Northern Hemisphere land areas, the Legates and Willmott data set is slightly higher than our adjusted data set during the warmer months and significantly lower during the colder months. This warm season difference is most likely due to the fact that Legates and Willmott corrected for evaporation losses while we did not. These evaporation losses are more significant during the warm season than during the cold season. The cold season difference shows that our method accounts for a greater amount of wind-induced solid precipitation undercatch than does that of Legates and Willmott. This could be because our adjustments were daily-based while Legates and Willmott was monthly-based, because our adjustments may be attenuated to airport conditions, or because of the differences in regression equations utilized by each effort. A comparison of regression equations for some common gauges shows that, for lower wind speeds (less than 3 to 5 m s^{-1}), the equations used in this study estimate the catch ratio to be as much as 4% lower than Legates and Willmott for the shielded Tretyakov, and as much as 14% lower for the shielded Hellmann. For higher wind speeds, the equations used in this study estimate the catch ratio to be as much as 9% higher than Legates and Willmott for the shielded Tretyakov, and as much as 10% higher for the shielded Hellmann. For the unshielded NWS 8", the equations in this study estimate the catch ratio to be lower than Legates and Willmott for all wind speeds, reaching a maximum difference of 140% at 6.5 m s^{-1}. Therefore, it is possible that the use of different regression equations for estimating wind-induced solid precipitation undercatch has caused the resultant catch ratios to be significantly lower for our study, resulting in a greater bias-adjustment during the Northern Hemisphere cold season. Comparison of the bias-adjusted data sets to the unadjusted data sets demonstrates that the greatest increase in global mean annual precipitation due to bias adjustment occurs during the Northern Hemisphere winter.

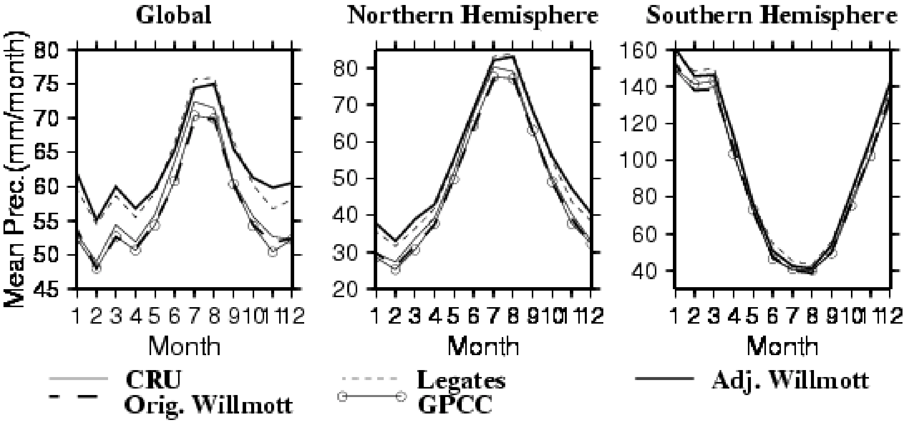


Figure 6-3. Temporal variation of the five global data sets averaged over all global and Northern and Southern Hemisphere land areas.

6.2.3: SPATIAL VARIATION

To explore how the data sets compare spatially in the Northern Hemisphere, annual mean precipitation was averaged longitudinally for three regions: all land areas, North America and Greenland, and Eurasia. These averages were then plotted against latitude for each of the data sets (Figure 6-4). Below 25˚ North in North America, our adjusted data set is approximately the same or slightly lower than Legates and Willmott but is around 10% higher than Legates and Willmott between 30 and 50˚ North. Again, this is most likely because the regression equation we used to estimate wind-induced solid precipitation undercatch of the unshielded NWS 8” gauge produces much lower catch ratios for any given wind speed than the regression equation used by Legates and Willmott. Over Canada and Greenland, our adjusted precipitation is between 5 and 10% higher than that of Legates and Willmott. Over Europe and Asia, our adjusted precipitation is significantly lower than that of Legates and Willmott between 20 and 27˚ North and between 40 and 53˚ North. One explanation for this is that our data set excludes adjustments for several countries in Europe and Asia that are only partially dominated by cold-season solid precipitation. It is possible that the inclusion of these countries into a future version of this data set may have a significant effect on the mean annual precipitation at these latitudes in Eurasia. Above 53˚ North in Eurasia, our adjusted precipitation is as much as 5 to 10% higher than that of Legates and Willmott, again possibly due to the use of different regression equations for the estimation of wind-induced solid precipitation undercatch.

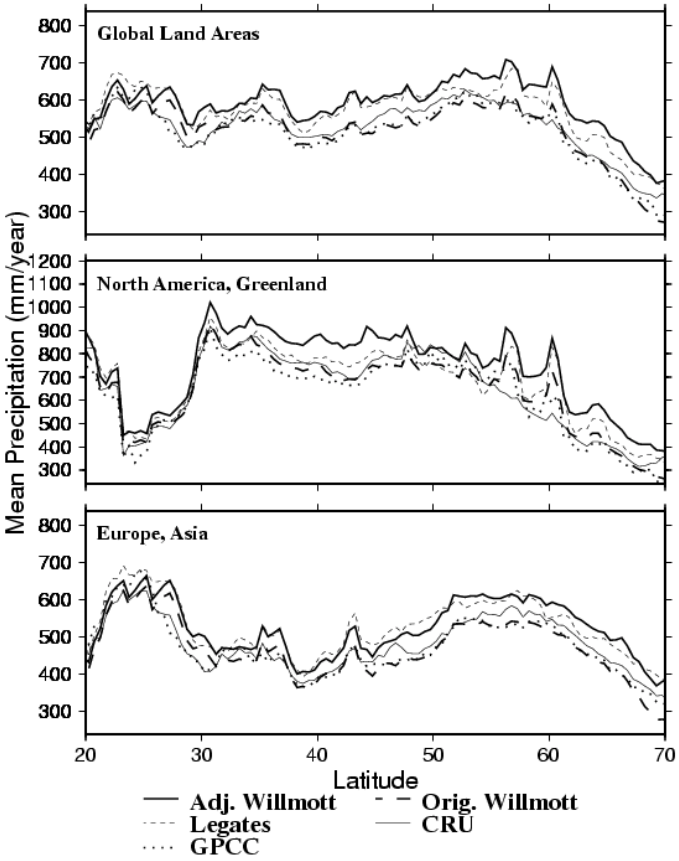


Figure 6-4. Variation with latitude of Northern Hemisphere mean annual precipitation averaged over (1) all land areas, (2) North America/Greenland, and (3) Eurasia.

6.3: COMPARISON OF ADJUSTED PRECIPITATION DATA SETS OVER CANADA

Our adjusted precipitation data set was also compared to adjusted data sets for Canada. As described in Section 4, Mekis and Hogg (1999) and Groisman (1998b) made corrections to Canadian station data for systematic biases. Recall that both data sets were utilized to develop our catch ratios; Mekis and Hogg for the more realistic catch ratio values and Groisman for the denser station network. One purpose of this particular comparison is to determine the extent to which we were able to capture the Mekis and Hogg adjustments on a mean monthly basis. For comparison purposes, climatologies were created for the period 1979 through 1990, and the grids were interpolated to a common resolution and land mask. Figure 6-5 shows the variation of spatially-averaged mean monthly precipitation for each data set. Our adjusted data set is nearly equivalent to that of Mekis and Hogg on a mean monthly basis for seven months (October through June), during which months our data is as much as 5% greater than that of Mekis and Hogg. Our method was able to capture the approximate values of the more detailed Mekis and Hogg adjustments on a mean monthly basis during the cold season, but somehow introduced bias during the late summer and fall. This comparison also shows that the bias adjustment effort of Groisman had little effect on cold season precipitation but a much greater effect on warm season precipitation on a mean monthly basis.

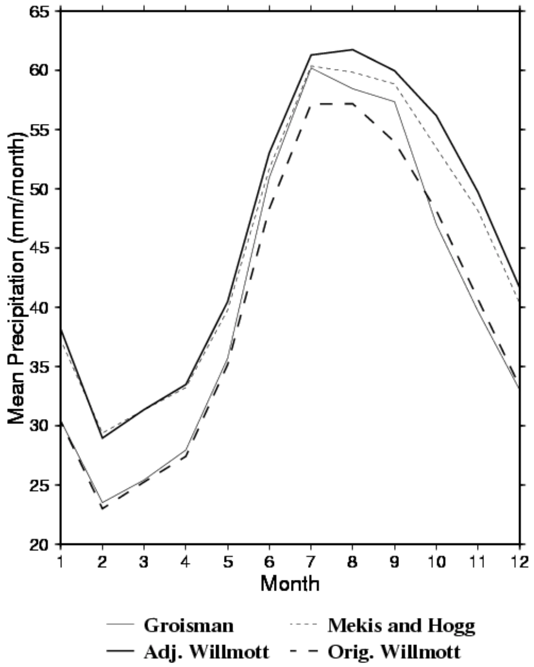


Figure 6-5. Temporal variation of precipitation averaged over Canada.

6.4: COMPARISON OF ADJUSTED PRECIPITATION DATA SETS OVER FORMER USSR

Groisman et al. (1991) corrected precipitation data for 622 Former USSR stations on a monthly basis for the period 1891 to 1993 (NSIDC, 1998). Their procedure consisted of homogenizing the data (for gauge type changes, station relocations, changing degrees of exposure, and varying sampling periods); adjusting for wetting losses; and adjusting the data for wind-induced precipitation undercatch (Groisman et al., 1991). The adjustments for wind-induced undercatch were performed by scaling the measured precipitation by mean monthly values specific for each site which are published in the *Reference Book on the Climate of the USSR (1966 – 1969).* Figure 6-6 shows the variation of spatially-averaged mean monthly precipitation for the Groisman et al. (1991) data set, the Willmott and Matsuura (2001) data set, and our adjusted precipitation data set. The Groisman et al. cold season averages are as much as 10% greater than those of our adjusted precipitation data set, whereas the Groisman et al. warm season averages are as much as 5% lower than those of our adjusted precipitation data set.

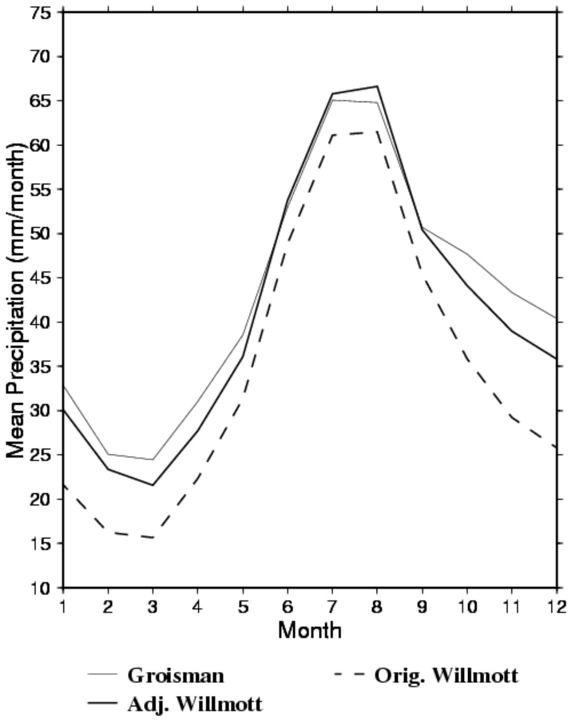


Figure 6-6. Temporal variation of precipitation averaged over the Former USSR.

Chapter 7: Summary

The adjusted precipitation data set described herein may offer an improvement over current global products that are either unadjusted for precipitation catch deficiencies or that use methods that predate the most recent WMO Intercomparison (Goodison et al., 1998). This bias adjustment effort (for wind-induced undercatch and wetting losses) increases the mean annual global landmass precipitation by 11.2%. Comparisons of our adjusted data with other precipitation time series or climatologies revealed the following key items:

- Yang et al.'s (1998a and 1999a) and Yang and Ohata's (2001) mean annual catch ratios (ranging from 50 to 100%) were on average between 1.6 and 7.9% lower than our station-specific mean annual catch ratios (for wind-induced undercatch only) for each region. This difference is due partly to the use of different regression equations for the liquid portion of the wind-induced undercatch adjustment, and partly to the fact that we made assumptions regarding gauge type, gauge height, and wind-sensor height while Yang had access to that station-specific information. On a climatological basis, our corrections capture the most significant aspects of Yang's results, recognizing that the studies on which their results are based are more encompassing and detailed.

- Our adjusted data set shows less warm season precipitation than the Legates and Willmott (1990) adjusted precipitation climatology, most likely because we did not adjust for evaporation losses. Conversely, our data set shows significantly more Northern Hemisphere cold season precipitation than that of Legates and Willmott (1990) due to the different methods used for the estimation of wind-induced solid precipitation undercatch. This difference becomes more pronounced towards the North with the exception that the differences are highest over the U.S. because of the use of very different regression equations for the unshielded NWS 8" gauge. Our estimates show less precipitation than Legates and Willmott (1990) in some areas of Eurasia possibly because countries that are not snow-dominated during the coldest month were excluded from our analysis for wind-induced solid precipitation undercatch.

Development of high quality gridded global precipitation data sets suitable for large-scale modeling is an incremental process. We believe that the adjustment procedure, and accompanying adjusted data set is a next step in a progression. Its major desirable feature is that it is closely tied to the results of the most recent WMO precipitation measurement intercomparison (Goodison et al., 1998). Nonetheless, further improvements can be made in various ways. For instance, if metadata on individual stations were available globally, many of the site-specific assumptions could be discarded and replaced with definitive information, e.g., for gauge type, shielding, gauge height, wind-sensor height, and degree of exposure; and adjustments for wetting losses may become more precise. However, such an approach would entail a large investment of effort to assemble metadata not currently available in any central archive (or, in many cases, even in digital form).

LIST OF REFERENCES

Benson, C.S., *Reassessment of winter precipitation on Alaska's Arctic Alope and measurement on the flux of wind blown snow*, Geophysical Institute of Alaska, Fairbanks, Alaska, 26 pp, 1982.

Bogdanova, E.G., A computation method of wind speed averages during rainfall (in Russian). *Trans. Voyeykov Main Heophys. Observ., 244*, 48-55, 1969.

Bogdanova, E.G. and A.V. Mestcherskaya, Influence of moistening losses on the homogeneity of annual precipitation time series, *Russian Meteorology and Hydrology, 11*, 88-99, 1998.

Duchon, E.D. and G.R. Essenberg, Comparative rainfall observations from pit and aboveground rain gauges with and without wind shields, *Wat. Res. Res., 37* (12), 3253-3263, 2001.

GHCN, 2002: The Global Historical Climatology Network. http://www5.ncdc.noaa.gov/ol/climate/research/ghcn/ghcn.html

Golubev, V.S., On the problem of actual precipitation measurement at the observation site, *Proceedings of the International Workshop on the Correction of Precipitation Measurements*, *WMO/TD-104*, 61-64, World Meteorol. Organ., Geneva, 1985.

Golubev, V.S., P.Y. Groisman, and R.G. Quayle, An evaluation of the United States standard 8-in. nonrecording raingauge at the Valdai polygon, Russia, *J. Atmos. Oceanic Technol.*, *9*, 624-629, 1992.

Goodison, B.E, P.Y.T. Louie, and D. Yang, WMO solid precipitation intercomparison, final report, *WMO/TD-872*, 212 pp, World Meteorol. Organ., Geneva, 1998.

GPCC, 2002: The Global Precipitation Climatology Centre. http://www.dwd.de/research/gpcc

Groisman, P.Y., V.V. Koknaeva, T.A. Belokrylova, and T.R. Karl, Overcoming biases of precipitation measurement: a history of the USSR experience, *Bull. Am. Meteorol. Soc., 72*(11), 1725-1732, 1991.

Groisman, P.Y., and D.R. Legates, The accuracy of United States precipitation data, *Bull. Am. Meterol. Soc*., *75*(2), 215-227, 1994.

Groisman, P.Y., E.L. Peck, and R.G. Quayle, Intercomparison of recording and standard nonrecording U.S. Gauges*, J. Atmos. Oceanic Technol*., *16*, 602-609, 1998a.

Groisman, P.Y., National Climatic Data Center Data Documentation for TD-9816, Canadian Monthly Precipitation, 21 pp, *Natl. Clim. Data Cent*., Asheville, N.C., 1998b.

Groisman, P.Y., E.Y. Rankova, Precipitation trends over the Russian permafrost-free zone removing the artifacts of pre-processing, *Int. J. of Clim., 21*, 657-678, 2001.

Huffman, G.J., The Global Precipitation Climatology Project monthly mean precipitation data set. *WMO/TD-808*, World Meteorol. Organ., 37 pp, Geneva, 1997.

Karl T.R., R.G. Quayle, and P.Y. Groisman, Detecting climate variations and change: New challenges for observing and data management systems, *J. Clim., 6* , 1481-1494, 1993.

Kurtyka, J.C., *Precipitation Measurements Study, Report of Investigation No. 20*, Department of Registration and Education and State Water Survey Division, Urbana, IL, 163 pp, 1953.

Legates, D.R., A climatology of global precipitation, *Publ. Climatol., 40*(1), 86 pp, 1987.

Legates, D.R. and C.J. Willmott, Mean seasonal and spatial variability in gauge-corrected, global precipitation, *Int. J. of Clim*., *10*, 111-127, 1990.

Legates, D.R., Global and terrestrial precipitation: a comparative assessment of existing climatologies, *Int. J. of Clim., 15,* 237-258, 1995a.

Legates, D.R., Precipitation measurement biases and climate change detection, Proceedings, *Sixth Symposium on Global Change Studies*, American Meteorological Society, Dallas, TX, 168-173, 1995b.

Mekis, E., and W.D. Hogg, Rehabilitation and analysis of Canadian daily precipitation time series, *Atm. Ocean*, *37*(1), 53-85, 1999.

Metcalfe, J.R., S. Ishida, and B.E. Goodison, A corrected precipitation archive for the Northwest Territories, Environment Canada - Mackenzie Basin Impact Study, Interim Report #2, 110-117, *Proceedings of the Sixth Biennial AES/DIAND Meeting on Northern Climate*, Atmos. Environ. Serv., Yellowknife, NWT, Canada, 1994.

Metcalfe, J.R., B. Routledge, and K. Devine, Rainfall measurement in Canada: changing observational methods and archive adjustment procedures. *J. Clim*., *10*, 92-101, 1996.

National Snow and Ice Data Center, Adjusted monthly precipitation, snowfall and rainfall for Canada (1874-1990). Digital data available from nsidc@nsidc.org. Boulder, Colorado. EOSDIS NSIDC Distributed Active Archive Center, University of Colorado at Boulder, 2000.

National Snow and Ice Data Center, Former Soviet Union precipitation archive (1891-1993). Digital data available from nsidc@nsidc.org. Boulder, Colorado: NSIDC NSIDC Distributed Active Archive Center, University of Colorado at Boulder, 1998.

New, M.G., M. Hulme, and P.D. Jones, Representing twentieth-century space-time climate variability. Part II: development of 1961-90 monthly grids of terrestrial surface climate. *J. Clim*., *12*, 829-856, 2000.

Nijssen, B., G. O'Donnell, D.P. Lettenmaier, D. Lohmann, and E.F. Wood, Predicting the discharge of global rivers, *J. Clim*., *14*(15), 3307-3323, 2001.

Reference Book on the Climate of the USSR, 1966-1969: Issues 1-34, Part 4, Sect. 2, Gidrometeoizdat (in Russian).

Rubel, F. and M. Hantel, Correction of daily rain gauge measurements in the Baltic Sea drainage basin. *Nordic Hydr*., *30*, 191-208, 1999.

Rudolf, B., H. Hauschild, W. Rueth and U. Schneider, Terrestrial precipitation analysis: operational method and required density of point measurements, *Global Precipitations and Climate Change* (Ed. M. Desbois, F. Desalmond), 1994.

Sausen, R., S. Schubert, and L.Dumenil, A model of river runoff calculated from a global atmosphere general circulation model, *J. of Hydr*., *155*, 337-352, 1994.

Sevruk, B., Methods of correction for systematic error in point precipitation measurement for operational use. Operational Hydrology Rep. 21 Publ. *589*, 91 pp, 1982.

Sevruk, B. and W.R. Hamon, International comparison of national precipitation gauges with a reference pit gauge. WMO Instrument and Observing Methods Report No. 17, 111pp, World Meteorol. Organ., Geneva, 1984.

Sevruk B. and St. Klemm, Types of standard precipitation gauges. In: B. Sevruk (Ed.) Precipitation measurement. Swiss Federal Institute of Technology, Zurich, 227-232, 1989.

Shepard, D.S., Computer mapping: The SYMAP interpolation algorithm, Spatial Statistics and Models, edited by G.L. Gaile and C.J. Willmott, pp. 133-145, D. Reidel, Norwell, Mass, 1984.

Struzer, L.R., Practicability analysis of rain gauge international comparison test results (in Russian). *Trans. Voyeykov Main Geophys. Observ.*, *260*, p. 77-94, 1971.

US Army Corps of Engineers, Snow Hydrology: Summary Report of the Snow Investigations. North Pacific Division, Portland, OR, 437p, 1956.

UNESCO, *World Water Balance and Water Resources of the Earth,* UNESCO Series Studies and Reports in Hydrology, No. 25, Leningrad, 663 pp, 1978.

Widmann, M. and C.S. Bretherton, Validation of mesoscale precipitation in the NCEP reanalysis using a new grid-cell data set for the northwestern United States, *J. Clim.*, *13*, 1936-1950, 2000.

Willmott, C.J. and K. Matsuura, Terrestrial air temperature and precipitation: monthly and annual time series (1950 - 1999) (Version 1.02). Center for Climatic Research, University of Delaware, Newark, 2001.

Yang. D., B.E. Goodison, C.B. Benson, and S. Ishida, Adjustment of daily precipitation at 10 climate stations in Alaska: Application of WMO Intercomparison results, *Water Resour. Res.*, *34*(2), 241-256, 1998a.

Yang, D., B.E. Goodison, J.R. Metcalfe, V.S. Golubev, R. Bates, T. Pangburn, and C.L. Hanson, Accuracy of NWS 8-inch standard non-recording precipitation gauge: results of WMO intercomparison, *J. Atmos. Oceanic Technol., 15*(1), 54-68, 1998b.

Yang, D., S. Ishida, B.E. Goodison, and T. Gunther, Bias correction of daily precipitation measurements for Greenland, *J. Geophys. Res.*, *105*(D6), 6171-6182, 1999a.

Yang, D, An improved precipitation climatology for the Arctic Ocean, *Geophys. Res. Lett., 26(*11), 1625-1628, 1999b.

Yang, D., T. Ohata, A bias-corrected Siberian regional precipitation climatology, *J. Hydrometeor*., *2*(3), 122-139, 2001.