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Reanalysis Data Underestimate Significant Changes in Growing Season Weather in Kazakhstan

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Abstract
We present time series analyses of recently compiled climate station data which allowed us to assess contemporary trends in growing season weather across Kazakhstan as drivers of a significant decline in growing season normalized difference vegetation index (NDVI) recently observed by satellite remote sensing across much of Central Asia. We used a robust nonparametric time series analysis method, the seasonal Kendall trend test to analyze georeferenced time series of accumulated growing season precipitation (APPT) and accumulated growing degree-days (AGDD). Over the period 2000–2006 we found geographically extensive, statistically significant ($p < 0.05$) decreasing trends in APPT and increasing trends in AGDD. The temperature trends were especially apparent during the warm season and coincided with precipitation decreases in northwest Kazakhstan, indicating that pervasive drought conditions and higher temperature excursions were the likely drivers of NDVI declines observed in Kazakhstan over the same period. We also compared the APPT and AGDD trends at individual stations with results from trend analysis of gridded monthly precipitation data from the Global Precipitation Climatology Centre (GPCC) Full Data Reanalysis v4 and gridded daily near surface air temperature from the National Centers for Climate Prediction Reanalysis v2 (NCEP R2). We found substantial deviation between the station and the reanalysis trends, suggesting that GPCC and NCEP data substantially underestimate the geographic extent of recent drought in Kazakhstan. Although gridded climate products offer many advantages in ease of use and complete coverage, our findings for Kazakhstan should serve as a caveat against uncritical use of GPCC and NCEP reanalysis data and demonstrate the importance of compiling and standardizing daily climate data from data-sparse regions like Central Asia.

Keywords: Kazakhstan, drought, climate trends, time series analysis, GPCC precipitation data, NCEP R2 temperature data

1. Introduction

Kazakhstan's ecophysiography is largely ecotonal, ranging from forest steppe and steppe (Chibilyov 2002) into desert (Lioubimtseva 2002). Thus, it is especially vulnerable to desertification and climate change (Lioubimtseva and Henebry 2009). Over the period 1891–1990, Kazakhstan experienced a 1 °C increase in mean annual temperature, approximately twice the global rate of increase (Pilifisova *et al* 1997). By 2030, global climate models predict that temperatures in Kazakhstan will increase mostly during the spring months, with predicted springtime temperature increases ranging from a low of 2.3 °C (Geophysical Fluid Dynamics Laboratory model) to a high of 11 °C (Canadian Climate Center model; Pilifisova *et al* 1997). Kazakhstan was also subject to one of the more extreme land cover/land use change (LCLUC) events of the 20th century—Khrushchev's 'Virgin Lands' program—where more than 13 million hectares of native steppe were converted to cereal cultivation (mostly spring wheat) over a dozen years, thereby transforming Kazakhstan into supplier of nearly one-third of the Soviet Union's wheat crop (McCauley 1976, Kaser 1997). Subsequent cessation of centralized planning following collapse of the Soviet Union in 1991 resulted in substantial de-intensification of the agricultural sector in Kazakhstan, including contraction of land area in wheat cultivation, reduction of livestock herds, and sharp declines in fertilizer and pesticide use (Baydildina *et al* 2000). This LCLUC event appears to have significantly altered land surface phenology at spatial resolutions sufficient to alter atmospheric boundary-layer processes. For example, de Beurs and Henebry (2004a, 2005) found faster spring green-up and an earlier peak normalized difference vegetation index (NDVI) in wheat-growing areas of Kazakhstan following the Soviet collapse (1995–1999) relative to a pre-collapse period (1985–1988). A more recent analysis (covering the period 2000–2007) shows that Kazakhstan is one of a number of global 'hot-spots' exhibiting highly statistically significant ($p < 0.01$) declines in growing season NDVI (de Beurs *et al* 2009).

In this study, we use recently compiled climatic data from individual weather stations in Kazakhstan (NCDC 2008) to analyze contemporary precipitation and near surface air temperature trends (here over the period 2000–2006) that may be driving the recent NDVI declines observed in Kazakhstan (de Beurs *et al* 2009). In this data-sparse region, we also compare trend analysis results for precipitation and air temperature measured at stations with trend results for gridded monthly precipitation data from the Global Precipitation Climatology Centre (GPCC) Full Data Reanalysis v4 (Schneider *et al* 2008) and gridded daily near surface air temperature data from the National Centers for Climate Prediction Reanalysis v2 (NCEP R2; Kanamitsu *et al* 2002).

The significance of our contribution is twofold. First, we present a robust assessment of trends in growing season weather in Kazakhstan that are relevant to modeling vegetation dynamics: accumulated growing degree-days and accumulated precipitation. This assessment complements an earlier analysis published in Russian (Akhmadieva and Groisman 2008) of an important new dataset. Second, we compare the trends

in the station data with well known global precipitation and temperature datasets and find them lacking.

2. Methods

For the years 2000–2006, a complete record of daily precipitation and near surface air temperature is available from 243 stations out of a total of 351 synoptic stations in the Kazakhstan subset of the Global Daily Climatology Network (NCDC 2008). At each station, we aggregate daily precipitation into a running sum of accumulated precipitation (APPT), restarting at 1 January of each year. Daily average temperature is calculated as an arithmetic average of eight 3 hourly synoptic observations. We generate three separate accumulated growing degree-days (AGDD) time series using different base temperatures:

$$AGDD_t = AGDD_{t-1} + \text{maximum}\{0, (AvTemp_t - BT)\} \quad (1)$$

where t is the temporal index, AvTemp is daily average temperature, and BT is a base temperature of 0, 4, or 10 °C. A base temperature of 4 °C is typically used in modeling phenological phases of cool season crops likes wheat (Slafer and Savin 1991); whereas, a base temperature of 10 °C is commonly used to model the phenology of warm season crops like corn (Viña *et al* 2004). At each daily time step, AGDD is positively incremented if $AvTemp_t > BT$, otherwise it remains unchanged.

For subsequent trend analysis of station data, we construct time series consisting of APPT, AGDD0, AGDD4, and AGDD10 values at the 1st and 15th day of each month from March through September. Each georeferenced time series is 98 values in length (7 years × 14 dates per year).

We also analyze precipitation data from the GPCC Full Data Reanalysis v4 dataset, a gridded monthly precipitation product at 0.5° resolution (Schneider *et al* 2008). Individual APPT time series are extracted at each grid cell using APPT values from March through September (restarting each 1st January) from 2000–2007. Note that despite adding an additional year, GPCC-derived APPT time series are considerably shorter than their bi-monthly aggregated station equivalents, 56 values in each time series (8 years × 7 dates per year), given that precipitation is reported as monthly totals in GPCC data.

Lastly, we analyze near surface (2 m) air temperature data from the NCEP R2, a gridded daily near surface air temperature product at approximately 1.9° spatial resolution (Kanamitsu *et al* 2002). We calculate average daily temperature as the arithmetic average of maximum and minimum air temperature. Similar to trend analyses of surface temperature at individual stations, we construct three time series consisting of AGDD0, AGDD4, and AGDD10 values at the 1st and 15th day of each month from March through September (restarting each 1st January) from 2000–2007.

Distinguishing significant change from background variability requires either appropriate baselines for parametric analysis or robust nonparametric analysis. We adopt the latter course given the relatively short duration of time series since Kazakhstan achieved independence. Using a seasonal instead of an annual trend test increases the power of the analysis.
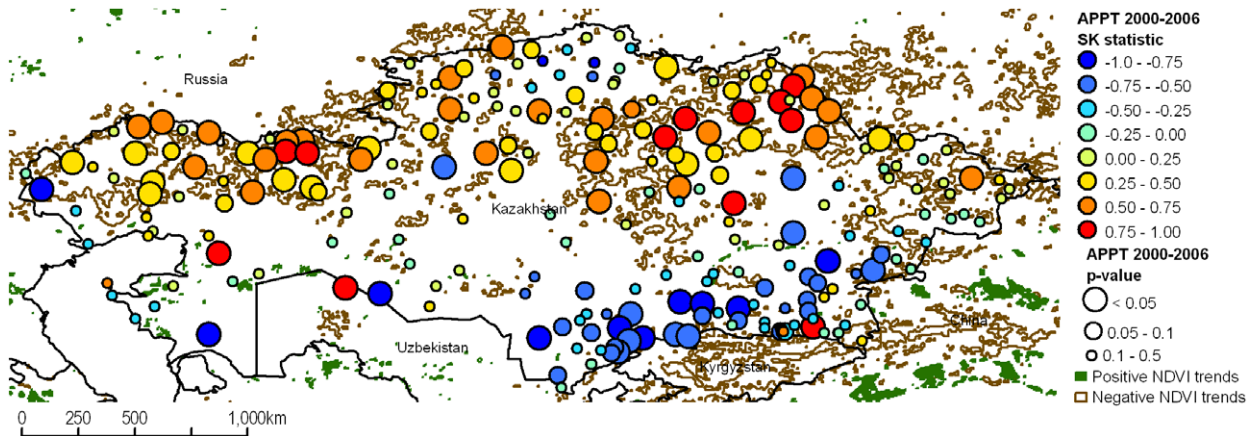
Figure 1. Normalized SK statistics and significance levels for time series analysis of APPT data from 243 weather stations in Kazakhstan 2000–2006. Symbol color indicates values of normalized SK statistics; associated significance levels represented by symbol size with circles centered on weather station locations. Polygons indicate areas with highly significant ($p < 0.01$) trends in growing season NDVI from SK analysis of 500 m resolution MODIS NBAR imagery over the period 2000–2007 (de Beurs *et al* 2009).

Furthermore, changes in measurement protocols make baseline development problematic (see NCDC 2008). Given these considerations, trend analyses are conducted using the seasonal Kendall (SK) trend test, a nonparametric method well suited to identifying monotonic trends in time series containing a strong seasonal component. Our implementation of the SK test is also corrected for serial autocorrelation, particularly important when dealing with climate data and time series of accumulated quantities. For additional details on the SK test and its use in analysis of geospatial data, see Hirsch and Slack (1984), de Beurs and Henebry (2004b, 2005), and de Beurs *et al* (2009).

The sign of the SK test statistic indicates trend direction. The magnitude of the test statistic indicates the strength of the trend; however, it cannot be interpreted as a slope. To facilitate visual comparisons, we normalize SK test statistics on the real interval $[-1, 1]$. For each layer of georeferenced SK statistics, namely, trend results for station and GPCC APPT time series, station and NCEP R2 AGDD0, AGDD4, and AGDD10 time series, we divide negative SK statistics by the most negative value in the layer (i.e., the absolute minimum) then multiply by -1 in order to maintain the correct sign of normalized SK test statistics; conversely, positive SK statistics are simply divided by the absolute maximum (most positive) value in the layer. Thus, SK statistics for each layer are normalized relative to their maximum negative trend and maximum positive trend, not with respect to the absolute difference between these values (although maximum negative trends and maximum positive trends typically had very similar absolute values). Visually, normalized SK statistics identify where, geographically, trends are largest relative to maximum values for a given layer of time series analyses. However, between different layers (say, station APPT trends versus GPCC APPT trends), normalized SK test statistics do not allow a geographic comparison of trend magnitude on an absolute scale.

3. Results

Trend analysis of APPT time series from individual weather stations over the period 2000–2006 reveals a band of statistically significant ($p < 0.05$) negative trends at stations

spanning across northern Kazakhstan (figure 1). These negatively trending stations coincide with areas in northern Kazakhstan where SK analysis of 500 m resolution MODIS NBAR imagery shows highly significant ($p < 0.01$) negative trends in growing season NDVI from 2000–2007 (de Beurs *et al* 2009). In the southern half of Kazakhstan, APPT trends are generally positive, particularly in the southeast where there is a cluster of statistically significant ($p < 0.05$) positive APPT trends among stations along the southern border with Kyrgyzstan (figure 1).

Similar analyses of APPT trends in gridded GPCC data from 2000–2007 are consistent with negatively trending station results in far western and northeast Kazakhstan, but statistically significant ($p < 0.05$) negative trends are not detected between these areas (figure 2), in contrast with station results (figure 1). In fact, GPCC data indicate three regions with statistically significant ($p < 0.05$) *positive* APPT trends in northern Kazakhstan (figure 2). In the westernmost of these areas, there is simply no evidence of increasing APPT from station data, but rather the opposite, statistically significant ($p < 0.05$) negative trends (figure 1). Within the two northernmost clusters of increasing APPT (figure 2), a number of stations exhibit positive normalized SK statistics (figure 1), but these positive trends are not significant ($p > 0.05$). While GPCC trends are positive along Kazakhstan's southern border with Kyrgyzstan (figure 2), these trends are not statistically significant ($p > 0.05$), again in contrast with station results (figure 1). North of the border area, where a cluster of significantly positive ($p < 0.05$) trends are observed in GPCC grid cells (figure 1), only a single weather station exhibits a similarly positive trend (figure 2).

Surface air temperature data from 2000–2006 show that statistically significant ($p < 0.05$) positive trends in AGDD time series from stations in northwest Kazakhstan (figure 3) generally coincide with decreasing APPT and declining NDVI (figures 1 and 2). Positive trends in AGDD time series are more pronounced at higher temperatures, with the spatial extent of positively trending stations expanding as the base temperature for AGDD calculations is increased from 0 to 4 and 10 °C,
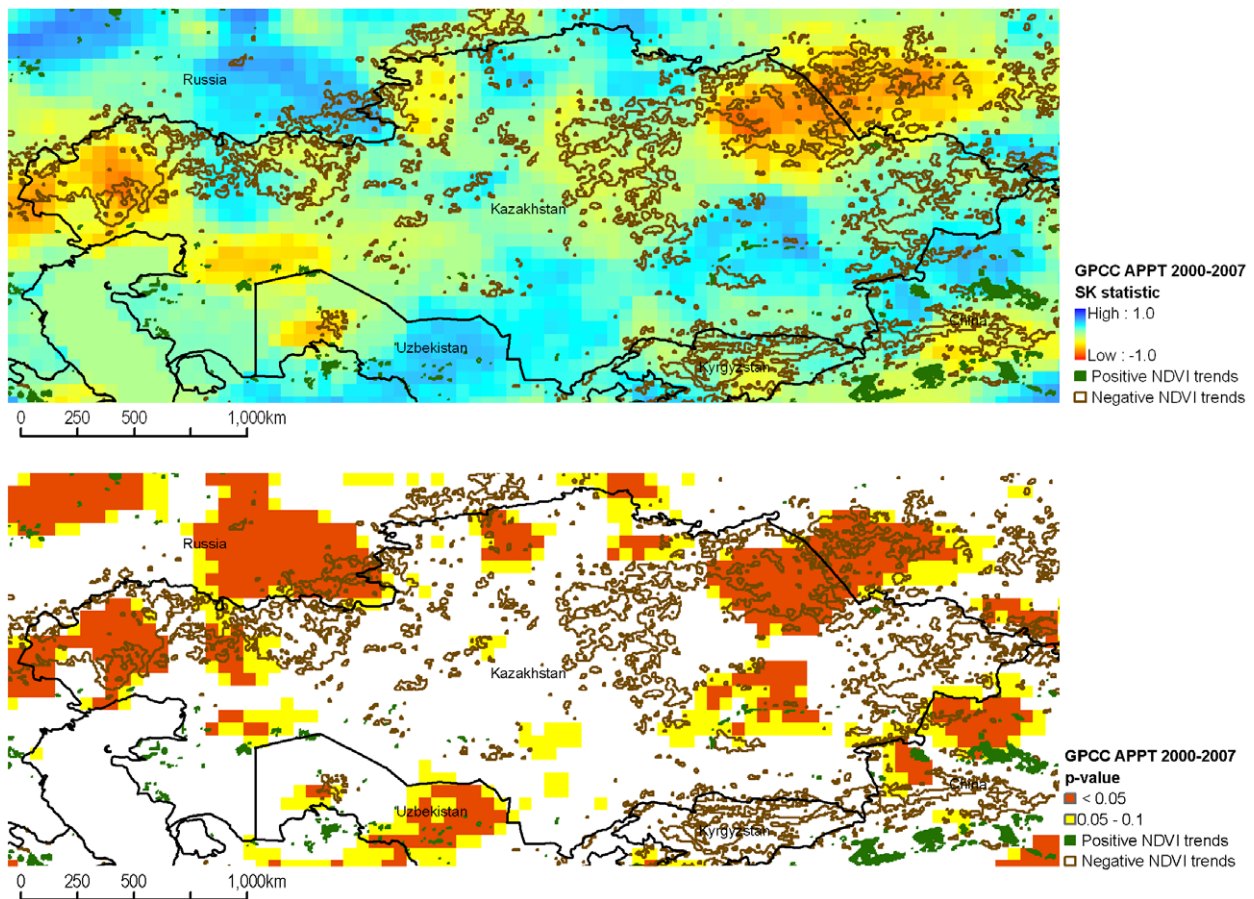
Figure 2. Normalized SK statistics and associated significance levels from time series analysis of GPCC APPT data in Kazakhstan and surrounding countries 2000–2007. Spatial resolution is 0.5°.

respectively. By contrast, a relatively small area in eastern Kazakhstan exhibits significantly negative ($p < 0.05$) AGDD0 trends, which contracts spatially as base temperatures are increased (figure 3).

Similar analyses of AGDD trends in gridded NCEP data from 2000–2007 indicate statistically significant ($p < 0.05$) increases in growing season air temperatures in far west Kazakhstan (figures 4 and 5), although positively trending NCEP grid cells are generally to the west of positively trending stations and fail to capture significant ($p < 0.05$) positive AGDD trends observed in station data from north-central Kazakhstan (figure 3). Like the station results, the geographic extent of statistically significant ($p < 0.05$) positive trends in western Kazakhstan expands with increasing base temperatures for AGDD calculations (figures 4 and 5). Unlike station results, the NCEP analysis shows statistically significant ($p < 0.05$) negative trends in AGDD0 and AGDD4 time series from far eastern Kazakhstan (figures 4 and 5); the opposite of positive trends observed in station AGDD0 and AGDD4 time series from the same region (figure 3).

4. Discussion and conclusions

Seasonal Kendall trend analyses of recent climate trends complement a recently published analysis of Kazakhstan's climate from 1990–2006 relative to a 1960–1989 baseline (Akhmadieva and Groisman 2008). Using the same station data (NCDC 2008), they found a nationwide increase in near surface air temperature of 0.8 °C between the two periods with warming concentrated geographically in northern and eastern Kazakhstan, and seasonally more pronounced in winter (+1.2 °C) and spring (+0.9 °C) than in autumn (+0.6 °C) or summer (−0.2 °C) (Akhmadieva and Groisman 2008).

Our results concur in terms of showing recent temperature increases in northwestern Kazakhstan (figures 3–5), but also indicate that warming from 2000–2006 was concentrated toward higher temperature excursions (i.e., above a degree-day threshold of 10 °C) during the growing season. Localized cooling in eastern Kazakhstan from 2000–2006 concentrated at growing degree increments less than 4 °C also contrasts with reported warming in eastern Kazakhstan (Akhmadieva and Groisman 2008). In both cases, an examination of georeferenced AGDD trends given different base temperatures reveals localized information (both spatially and at different temperature extremes) that are obscured by statistical averaging. Akhmadieva and Groisman (2008) report a weak increase (approximately 4%) in nationwide annual precipitation from 1990–2006 relative to the 30-year baseline that was not statistically significant (as were other seasonal and geographic patterns of change) given large variability of the
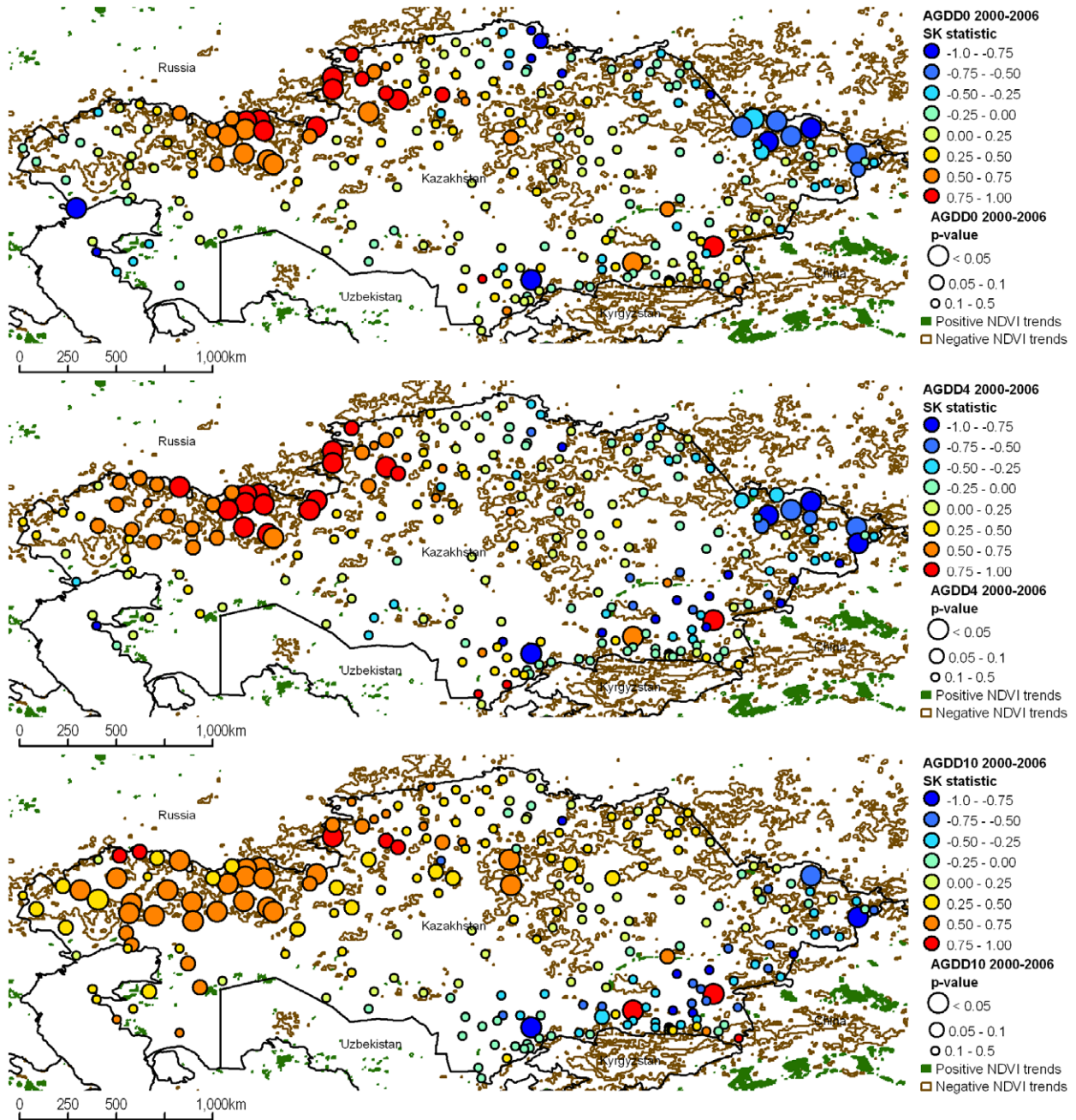
Figure 3. Normalized SK statistics and significance levels for time series analysis of AGDD0, AGDD4, and AGDD10 data from 243 weather stations in Kazakhstan 2000–2006. Symbol colors indicate values of normalized SK statistics; associated significance levels represented by symbol size with circles centered on weather station locations.

precipitation field. In contrast, the SK trend analysis identified precipitation trends over much of Kazakhstan that are opposite in sign (i.e., negative), statistically significant, and spatially coherent (figure 1).

Contemporary negative precipitation trends across much of northern Kazakhstan (figures 1 and 2) and positive temperature trends in northwest Kazakhstan (figure 3) suggest that negative NDVI trends observed across northern Kazakhstan in recently released MODIS Collection 5 NBAR imagery (de Beurs *et al* 2009) cannot be attributed solely to legacy effects of agricultural de-intensification following

the Soviet collapse (de Beurs and Henebry 2004a, 2005). Significant negative NDVI trends in northern Kazakhstan reflect the effects of a regional drought that was sufficiently severe and extended to be detectable in a relatively short time series (8 growing seasons) of satellite observations (de Beurs *et al* 2009).

Importantly, recently compiled station data from Kazakhstan (NCDC 2008) conflict with gridded global reanalysis products—GPCC (Schneider *et al* 2008) and NCEP R2 (Kanamitsu *et al* 2002)—which suggests that these widely used global products do not accurately portray contemporary
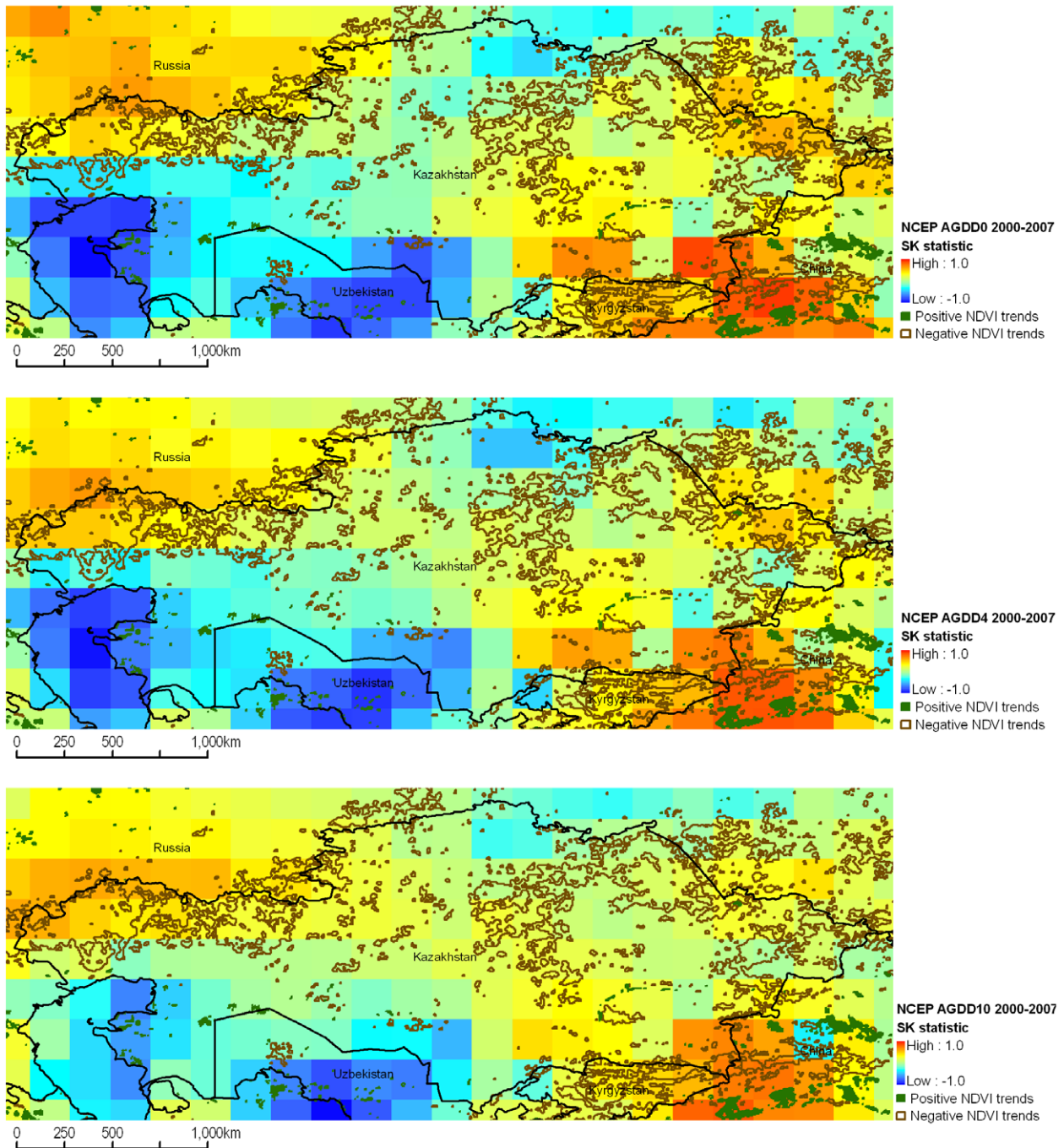
Figure 4. Normalized SK statistics from time series analysis of NCEP R2 AGDD0, AGDD4, and AGDD10 data in Kazakhstan and surrounding countries 2000–2007. Spatial resolution is approximately 1.9°.

trends in precipitation and near surface air temperature across a substantial portion of Kazakhstan. In northern Kazakhstan, GPCC and NCEP R2 products substantially underestimate the geographic extent of recent drought and temperature increases. In southern Kazakhstan, GPCC based analyses of APPT trends generally agree in sign with station based trends (largely positive), but statistically significant ($p < 0.05$) results from the two datasets rarely coincide spatially. In far eastern Kazakhstan, negative AGDD0 and AGDD4 trends found in the NCEP R2 data are inconsistent with positive AGDD trends evident at individual weather stations.

The result that SK statistics of GPCC time series are generally negative but not significant across northern and central Kazakhstan (like corresponding APPT time series at individual weather stations), may be due to the shorter duration of observations (56 values for monthly GPCC versus 98 values for semi-monthly station data; see section 2). Thus, the GPCC based time series may simply not be long enough to reveal signals that are statistically significant.

Globally, the total number of weather stations used to generate the GPCC Full Data Reanalysis v4 falls off sharply from more than 30 000 stations in 2000 to fewer than 10 000
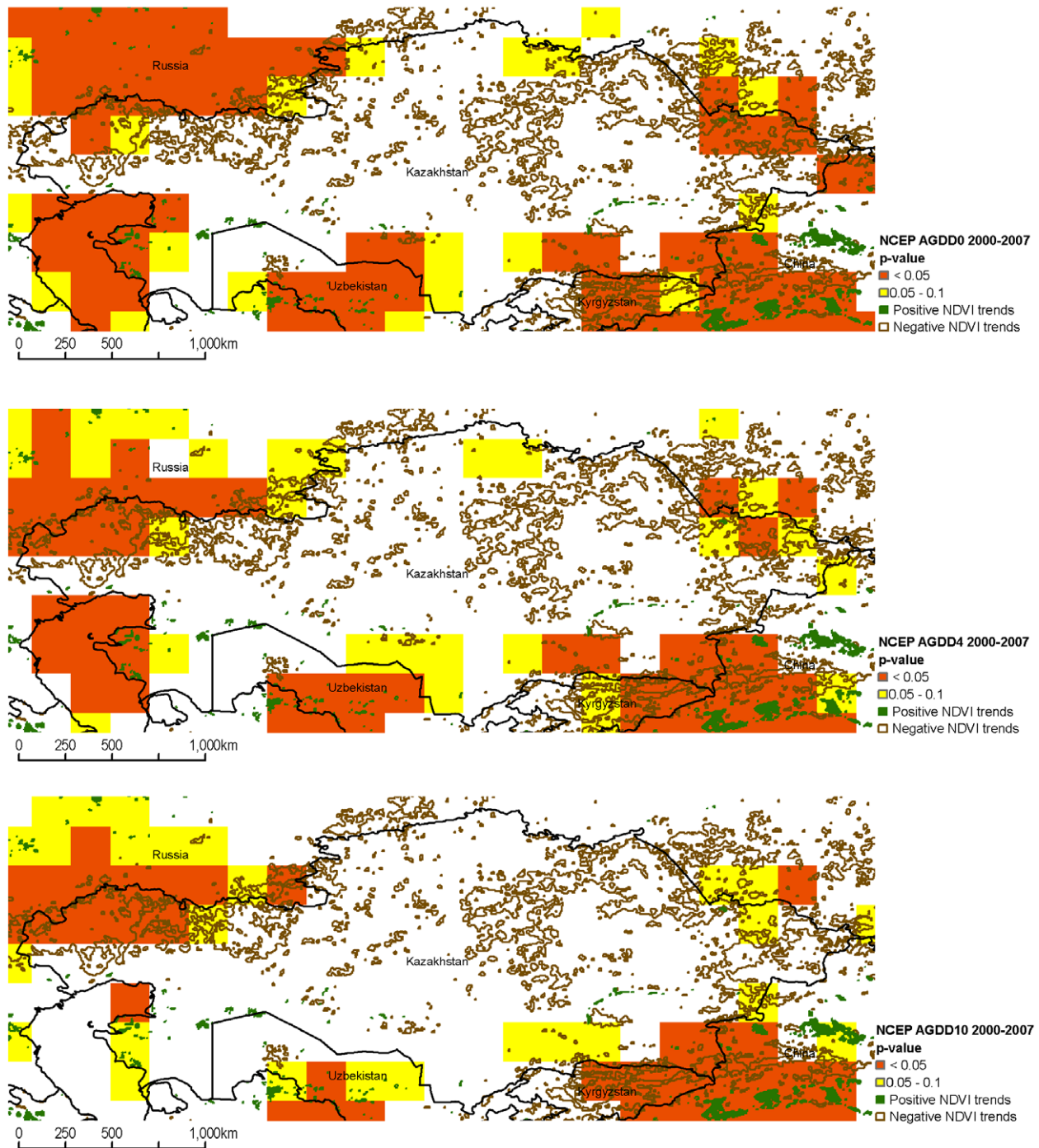
Figure 5. Significance levels corresponding to normalized SK statistics in figure 4. Spatial resolution is approximately 1.9°.

stations in 2007 due to time lags in incorporating more recent data (Schneider *et al* 2008). Within Kazakhstan proper, only 52 weather stations were used to interpolate the 2000 GPCC product (figure 6), while data from 63 stations was incorporated in 2007 (albeit with fewer stations from surrounding countries, Uzbekistan in particular). This limitation emphasizes the importance of compiling and standardizing daily climate data from data-sparse regions like Central Asia.

Station data can be difficult to use over large areas due to missing data and measurement inconsistencies. Thus,

both the remote sensing and climate modeling communities have an affinity for gridded climate products. However, the quality of the patterns of change and variability captured in gridded products must be evaluated by the end-user with respect to the particular questions under investigation. Here we show significant discrepancies between trends apparent in the gridded data and those found at individual weather stations. Although gridded products offer the allure of complete coverage, our findings in Kazakhstan should serve as a caveat against uncritical use of GPCC and NCEP reanalysis data.
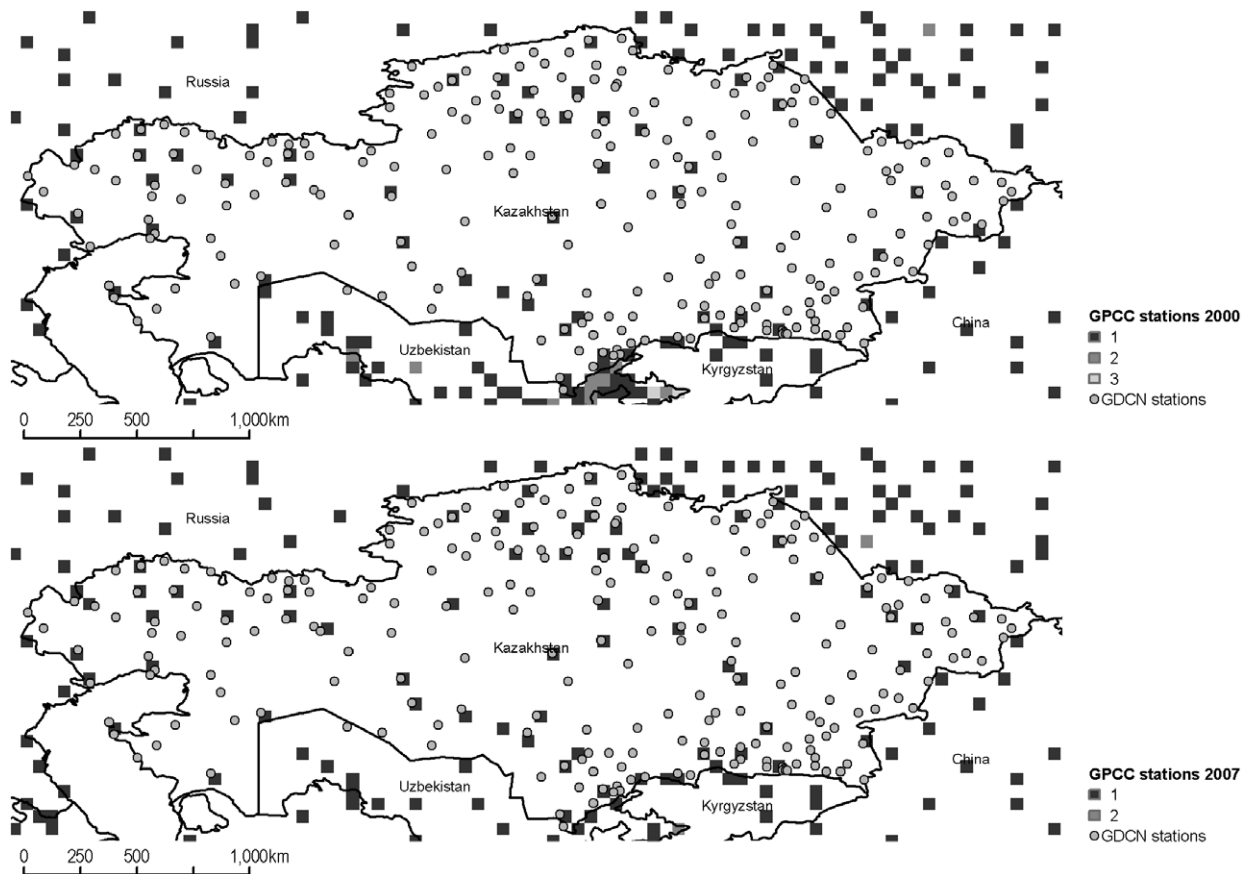
Figure 6. Locations of weather stations in Kazakhstan and surrounding countries used to generate the GPCC monthly precipitation product in 2000 and 2007 compared with locations of 243 stations from the Kazakhstan subset of the Global Daily Climatology Network (GDCN) with complete daily records of precipitation and near surface air temperature over the period 2000–2006. Numerical values indicate number of stations per 0.5° GPCC grid cell.

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