**May 22, 2015**

**Dear Editor,**

Please accept our latest revision of the manuscript, entitled “Relating Seasonal Dynamics of Enhanced Vegetation Index to the Recycling of Water in Two Endorheic River Basins in Northwest China”. The manuscript has been completely rewritten to address the reviewers’ comments. To show cause-and-effect we use a new method based on convergent cross mapping. Our point-by-point responses to the reviewers follow below. We hope you find the manuscript done to your satisfaction.

Best regards,
Charles P.-A. Bourque

**Reviewer No. 1**

**General comments**

This paper aims at analysing the role of vegetation for moisture recycling within two endorheic catchments in China. The paper addresses a research question of relevance for the audience of HESS. The authors have done substantial work to prepare relevant data for the analyses, and explain their methods in detail. However, perhaps due to the great efforts to prepare the input data, the long sections on the input data is overly comprehensive in comparison to the limited texts and figures (and perhaps thoughts) dedicated to the core issue: the link between the vegetation and the moisture recycling.

Furthermore, the authors simply take correlation for causation, and do not make any efforts to back-up the correlation with physical, logical explanations. Thus, unfortunately, key conclusions are not adequately supported by the presented analyses, results, and discussions. For example, one of the paper’s key conclusions is that about 90% of the mountain runoff returns as precipitation from low land evaporation. However, this claim merely relies on the fact that the total water volume from oasis evaporation and mountain precipitation seem to match, and is not at all backed-up by mechanisms of precipitation formation, wind patterns, or comparison to the literature.

Another insufficiently supported claim is that "vegetation growth in the oases provides a biotic trigger for the initiation of the precipitation season in the mountains", and that one month of active oasis vegetation is required to trigger the Qilian Mountains precipitation season. For publication, major revisions putting forward evidence to support the claims are necessary. (Alternatively, the authors could also consider addressing alternative research questions that their current data permit.)

**Our response:** Thank you for your comments; they are all justified. To address your concerns we have completely rewritten the manuscript, from beginning to end. To strengthen our assertions that oases EVI and evaporation are indeed causally connected to the production of precipitation in the high-mountains we conduct a convergent cross mapping (CCM) of relevant variables. As described in the manuscript, CCM is a relatively new method (2012) that allows for the examination of causation between variables. In our case, we see that the causal links are in fact bidirectional, indicating feedback between the variables. We provide explanations for why bidirectional causality is present. This feedback supports our argument that evaporation in the oases is responsible for the production of precipitation in the mountains, and ultimately the return flow to the oases.

**My general comments are as follows:**

1. The introduction can be more focused. At present, it contains much information with little direct relevance to the paper, but fails to problematise the current research frontier and fully motivate the research in question. What exactly is not solved by previous research that this present paper manage to? The literature review is also quite absent of a systematic description of water recycling mechanisms and previous moisture recycling studies (e.g., (Gimeno et al., 2012; Goessling and Reick, 2011; Lawrence and Vandecar, 2014; Tuinenburg, 2013)), which can be expected given the research question addressed here.
   **Our response:** We have rewritten the Introduction, as requested. We eliminated all non-relevant parts of the original Introduction. We added many new references and texts concerning the description of the problem.

2. The study area description is very lengthy and can be more succinct. Some information seems redundantly detailed in terms of its relevance for the scope of the study, e.g., the soil type descriptions. The authors could also consider the option to move some of the texts to an appendix.
   **Our response:** We have removed the section of soil types. We have moved some of the other material (particularly, material related to the landcover types to a new Appendix, addressing the landcover details of the manuscript). With all of the changes to this section, the study area description is now more to the point.

3. The methods section is lengthy and mainly describes the input data preparation and not the correlation and comparison analyses on the relationship between vegetation and water recycling. A suggestion is to substantially reduce the data input descriptions in favor of describing the core analyses. Data input processing descriptions could be partly removed and partly placed in for example an appendix. For increased readability and clarity, the authors could also consider adding a separate section called Data, instead of mixing data and data processing description with (currently insufficient) analyses description.
   **Our response:** We significantly reduced the methods section. We added a new sub-section related to CCM. Part of the old method sections on landcover was relegated to the new Appendix. Description of data now appears in a new Table (i.e., Table 2 of the new manuscript).

4. The results/discussion and conclusion sections are meagre. The limitations of the paper are not included, there are no comparisons between the authors' findings and that of others, and any future outlook or implications of the findings are also unfortunately missing. The authors also fail to include a discussion on the possible mechanisms that may corroborate their claim. The authors should preferably also include validation of their results or at the very least a discussion of the possibility to validate their results. For

example, what do wind data suggest? Can stable isotope measurements (e.g., Kurita, 2004; Risi et al., 2013; Yu et al., 2007) help validate the results? Are the results in line with modeling studies? Is the recycling ratio of the watershed suggested here exceptional in comparison to other similarly sized watersheds in the world?

**Our response:** We hope to have remedied this by the complete rewriting of the manuscript. We now address issues of wind direction and other pertinent subject matter. CCM validates our assertions that processes in the oases are responsible for the production of precipitation in the mountains (and vice versa). This validation coincides with statements by other researchers concerning the role of oasis vegetation in recycling of water in the region.

**Technical/specific comments**

1. The title: "...vegetation and land cover…". What's the difference between vegetation and land cover in this case?
   **Our response:** We have changed the title to "*Relating seasonal dynamics of enhanced vegetation index to the recycling of water in two endorheic river basins in northwest China*", and, therefore, eliminate the reference to "vegetation cover". In a later section of the manuscript, however, we refer to "vegetation cover types" as a subset of "landcover types".

2. P.1154, L. 7: DEM is not explained.
   **Our response:** We define DEM (digital elevation model) in Table 2, where it is first introduced.

3. P.1154, L. 22: Consider using the term "evaporation" instead of "evapotranspiration", see also Savenije (2004). "Evaporation" would also be more consistent to the authors' later use of the term "evaporated water" to refer to evapotranspiration.
   **Our response:** We now use "evaporation" instead of "actual evapotranspiration" or "evapotranspiration".

4. P. 1154, L. 22: the word "revealed" seems too strong given the evidence presented.
   **Our response:** We think with a CCM analysis and the other changes we made to the manuscript, "revealed" is now not so strong.

5. P. 1155, L. 6-8: Please reformulate the sentence "In endorheic basins,...". Difficult to understand what is meant at present.
   **Our response:** We have revised. We hope the changes will help clarify what we meant.

6. P. 1155,L. 27-28: The sentence "The role of vegetation..." says nothing more than that scientific literature has described the role of vegetation on soil moisture and runoff. Please consider writing something more meaningful, e.g., what is the role?
   **Our response:** The sentence was removed and replaced with more relevant sentences.

7. P. 1159, L. 3: There are two different references to the Penman-Monteith equation. Which of the equations is used?

**Our response:** Thank you for pointing this out. The Penman-Monteith equation is addressed in Monteith (1965); we now eliminate the reference to Penman.

8. P. 1161, L. 5: Ambivalent what is meant by "Ten landcover maps...". Perhaps the authors meant "annual land cover maps..." (one for each year) and not ten landcover maps per year? Anyway, it doesn't seem that the ten maps are the end product. If the end product actually used in the analyses is the composite landcover map, please state this more clearly and at the beginning of the paragraph for clarity.
   **Our response:** Yes, that is what we had meant. We have changed the offending text to clarify our meaning. Again, thank you for pointing this out.

9. P. 1161, Eq. 1: This equation confuses. "Majority" is not a conventional function. Are the authors for example taking the maximum or mean of the majority landcover over the years? What counts as majority? If "majority" is defined as more than 50 %, what happens if no land cover type exceed 50 %? Does one pixel contains land cover fractions of different land cover types, or only one land cover type at a time? A better explanation could be better than the confusing equation.
   **Our response:** We no longer include the equation. Hopefully, the text conveys what we mean.

10. P. 1162, L. 21: What is the rationale to have one threshold for sparse grass, one for coniferous forest, and 0.12 for the rest?
    **Our response:** The values are based on an examination of actual values and changes in EVI. In turns out that the value used for the other vegetation cover types were not so different.

11. P. 1163, L. 21: It's not clear what is meant by "the complementary method".
    **Our response:** The "complementary method" relates to a method of calculating evaporation (see Matin and Bourque, 2013b). We no longer refer to it in the manuscript.

12. P. 1164, L. 1: Is "yield" the same as "runoff"? If so, please use only one term for clarity.
    **Our response:** We had intended "yield" and "runoff" to have different meanings; "yield" is the water volume after within-zone evaporation is subtracted from sum of precipitation and snowmelt within the same zone, and "runoff" is the water volume flowing downslope from the mountains. We modified the text to make that distinction clearer.

13. P. 1165, L. 7-11: The sentence starting with "Asynchrony..." is unnecessarily long and difficult to understand. Please reformulate.
    **Our response:** We have rewritten the text as suggested.

14. P. 1165, L. 7-11: It is stated that oasis-vegetation starts one month earlier than in-mountain precipitation; thus, suggesting that one month of active plan growth is required to trigger the precipitation. However, it's not clear whether the growing season is always one month ahead despite interannual variations, or if the "one month" is only an average. Please clarify. If the one month of triggering period is an important result of the paper, the authors might want to consider illustrating this result in one single figure, rather than

making the readers guess based on Fig. 3 (which isn't even referred to in Sect. 4.1) and Fig. 5.
**Our response:** The "one month" is an average; we clarify this in the manuscript.

15. P.1166, L.6-9: It's not clear whether the authors mean that the correlation between precipitation in the mountains and vegetation/evaporation in the oasis are found within each watershed individually, or if the analysis was independent of watershed borders.
**Our response:** Correlations are basin-specific.

16. A number of sentences in the results and discussion section are formulated as methods description. See for example P. 1166, L. 2-6; and P. 1166, L. 13-14.
**Our response:** We have removed them; they were not needed.

17. P. 1166, L. 25-27: "This suggests that the bulk of water originating from the mountains is eventually returned to the mountains as evaporated water." Why is it not possible that the rainfall over the mountains originates from other places than from the watershed just because the volumes happen to coincide? In the next sentence, the authors also write that this evaporated "water can travel across watershed boundaries", which should suggest that the authors also believe that precipitation in the mountains can come from elsewhere. Moisture recycling studies have shown that recycling ratios are in general low at the local scales, although higher in regions with for example strong orographic effects. Nevertheless, Fig. 5 in van der Ent et al. (2010) shows global maps of regional precipitation and evaporation recycling (i.e., recycling within 1.5 degree x 1.5 degree grid cells). In northwest China grid cells, precipitation recycling ratios are below 5 %, whereas evaporation recycling ratios can be higher. Since the authors claim that the watersheds are in principle hydrologically closed systems (with most of the evaporation returning to the mountains, and "once deposited, surface water is mostly confined to the watershed"), it seems that the authors also implicitly claim that the watershed precipitation recycling should be much higher than 5 %. Can the authors please compare and discuss their results in relation to these types of studies?
**Our response:** We rewrote the section that addresses these points. We believe that recycling ratios should be much larger than the 5% reported in van der Ent et al. (2010). We address this in the revised manuscript.

18. P. 1166, L. 26: Please specify which water flux or fluxes the word "water" refers to. Does it refer to runoff from the mountains?
**Our response:** Yes, we clarify this in the revised text.

19. P. 1167, L. 16: What is meant by "biotic trigger"? Please be more specific in explaining the mechanisms.
**Our response:** We replace the terminology with a more direct statement, "This suggests that vegetation growth in the oases, through the production of water vapour, provides an initial triggering of the precipitation season in the mountains."
20. There are a number of superfluous and unconventional abbreviations that reduce the readability of the paper. For example, NW for northwest, RS for remote sensing, LCOV

for land cover composite, and LSP for land surface phenology. They may be convenient for the authors, but cause much inconvenience for the readers.
**Our response:** We have eliminated all abbreviations in the main body of the manuscript. However, we retain some in the figure captions for convenience. Abbreviations are defined at their first usage in the figure caption.

21. Please avoid multi-letter variable names. For example, actual evaporation should preferably be written as Ea instead of AET. See HESS manuscript preparation guide: http://www.hydrology-and-earth-system-sciences.net/submission/manuscript_preparation.html.
    **Our response:** Thank you. Variable names have been simplified throughout the manuscript, as suggested.

22. Please consider making colorblind friendly figures.
    **Our response:** Because colour blindness occurs across a spectrum of intensity from monochromacy to less extreme, we are unsure of the standard to use.

23. With regard to all figures containing subplots, please add subtitles and/or legends in the figures in order to enhance readability. For example, in Fig. 3, put the watershed name to the left of the subplot rows, and add the zone name/number above each subplot column. Another example in Fig. 6: instead of writing "The first plot applies to the Shiyang River watershed and the second to the Hei River watershed." in the caption, add the watershed names to the subplot figures.
    **Our response:** We have adjusted some of the Figures, as suggested.

24. The authors show the maps for every year in Fig. 4, but do not discuss the interannual spatial variation. The differences between the years are difficult to see from the figures, and since the authors also do not consider the interannual variations important enough to discuss, Fig. 4 can perhaps be collapsed into one mean annual map.
    **Our response:** We no longer use this Figure.

**Reviewer No. 2**
The title looks novel and interesting. Moisture recycling in inland river basins may be important for understanding the local water cycle. However, while reading the text, I got disappointed. The paper is weak in its conclusion that evaporation in the oases triggers precipitation in the higher source areas. For the substantiation of this conclusion, the authors use correlation (which is not necessarily based on a causal relationship) and the timing of the vegetation growth, which in the oases predates precipitation in the mountains. But this time lag is quite normal in many places in the world. Vegetation development often predates the onset of rain. Moreover temperature depends on elevation. Vegetation will only start to develop when the temperature is above a minimum value. The temperature in the lowland is several degrees higher than in the mountains where vegetation starts later in the season. Moreover, if the authors had studied the literature on moisture recycling (e.g. Van der Ent et al., 2010 and several follow-up papers by this author) then they would have known that the atmospheric moisture source is from the West and that the length scale of recycling is in the order of several 1000 km.

**Our response:** Vast deserts in the area tell you that very little moisture from the far west or south of the study area (due to the blocking of the southeast monsoons by the Qinghai-Tibet plateau) actually reach the study area. The Introductory section of the manuscript has been rewritten to give a better account for why external atmospheric moisture is not a significant component of the water budget in the area. The Introduction introduces new references that point to that fact.

This paper could potentially be interesting to demonstrate the effect of EVI on evaporation and water yield, but then the paper should be completely re-written. An alternative title or story line might be: 'The vegetation phenology and its relationship with precipitation and evaporation in two endorheic watersheds in northwest China', or any others representing the content more properly. To support the authors' original argument, the authors would have to collect isotopic and meteorological data, such as wind directions etc. A regional moisture cycling model might also be required to draw the original conclusion. I suggest you study and refer to Van der Ent et al. (2010).
**Our response:** We used CCM to show cause-and-effect. We think this gives much more support to our conclusions.

Finally, the authors violate the important rule of using correct units. The web site of HESS on textual conventions and the correct use of physical dimensions should be followed. This same directive is used by all hydrological journals. All hydrological fluxes (precipitation, evaporation, discharge, etc.) need to be expressed in terms of fluxes: M/T, L/T or L/T. It is absolutely wrong to present a flux as a length! Although at some places in the text you do so correctly, you do it wrongly in lines 15-17 on p1165 (I guess the unit should be $m^3$/year) and in the vertical axes of Fig 6, 7, 8, 9 and 10. This must be corrected.
**Our response:** Thank you. We corrected the violations throughout the manuscripts.

Another issue, but this is a matter of taste, is the use of the term 'evapotranspiration', which although widely used, is considered bad jargon. Evaporation is the correct term, which is the physical term for the transition of liquid into vapour. For the combination of different evaporative fluxes (transpiration, interception, soils evaporation, open water evaporation) one could use the term 'total evaporation'. The addition of the term 'actual' is also redundant since evaporation from a catchment is always actual.
**Our response:** OK, we made the changes as suggested.

Finally, please don't use the abbreviation AET, which in your text can be simply replaced by the term evaporation. There is no need for this jargon abbreviation. There is also no need for the abbreviation PET. This is the potential evaporation, which can be very well symbolized by Ep. Moreover, in equations it is not allowed to use multi-letter variables, as is explained in the 'symbols' convention of HESS. So in Eq.(2) for snowmelt, I suggest to use the symbol S, and for evaporation the symbol E. In the caption of Table 3: "Evaporation (E) as a percentage of the sum of precipitation (P) and snowmelt (S)". Likewise change Figure 2 and captions of Fig.7 and 9.
**Our response:** OK, we made the appropriate changes.

**Further specific comments:**

1. The authors obviously neglected some important publications on tracing moisture origin by isotope in the Heihe River [Zhang et al., 2009; Wu et al., 2010; Zhao et al., 2011], and on topography-based landscape classification and hydrological modelling in the Heihe River [Gao et al., 2014]. I suggest the authors do refer to these relevant publications.
   **Our response:** In our Introduction, we refer to publications by Gates et al., 2008a,b; Ma et al., 2008; Ma et al., 2009; Ma et al., 2012; and Huang and Wen, 2014.

2. The authors shall use the proper and correct scientific terms. For example, in P1154, L7, it is better to change 'DEM-height values' into 'elevation'. In P1163, L1, the 'cumulative
   **Our response:** OK. We made the required changes.

3. The study area section should be separated into two sections. One is the study site section, and another is the data section.
   **Our response:** We incorporate reference to the data in a new Table 2.
4. Equation 1 and 2 use multi-letter variables. According to HESS's conventions, please use single-letter variables with subscript.
   **Our response:** OK. We made the required changes.

5. P1164, Equation (2): It is strange to put the variable k as an exponent. The k can easily be added to the subscripts: i,j,k.
   **Our response:** The equation is no longer part of the revised manuscript.

6. Section 4.3: The authors mentioned that 'Vegetation influences on precipitation'. However, it could as well be the other way around 'precipitation influences vegetation'. There may be interactions between vegetation and precipitation. But from the content of this section, I do not think the results support the authors' argument. Furthermore, in P1166, L10, the authors mentioned that 'water vapour production by the oases is responsible for the generation of precipitation in the Qilian Mountains'. This conclusion requires more supportive information, both observations and model simulation.
   **Our response:** We feel the use of CCM helps to support our conclusions.

7. In P1167, L15-17: '…vegetation growth in the oases provides a biotic trigger for the initiation of the precipitation season…". Do your results really support this conclusion? I am not convinced.
   **Our response:** All details in the manuscript from the correlation analysis, isotopic work by others, prevailing wind direction, CCM, timeseries plots, etc. are all consistent with the idea that oasis vegetation has a role in the production of precipitation in the mountains.

# Relating seasonal dynamics of enhanced vegetation index to the recycling of water in two endorheic river basins in northwest China

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## Abstract

This study associates the dynamics of enhanced vegetation index in lowland desert oases to the recycling of water in two endorheic (hydrologically-closed) river basins in Gansu Province (northwest China), along a gradient of elevation zones and landcover types. Each river basin was subdivided into four elevation zones representative of (i) oasis plains and foothills, and (ii) low-, (iii) mid-, and (iv) high-mountain elevations. Comparison of monthly vegetation phenology with precipitation and snowmelt dynamics within the same basins over a 10-year period (2000-2009) suggested that the onset of the precipitation season (cumulative % precipitation > 7-8%) in the mountains, typically in late April to early May, was triggered by the greening of vegetation and increased production of water vapour at the base of the mountains. Seasonal evolution of in-mountain precipitation correlated fairly well with the temporal variation in oasis-vegetation coverage and phenology characterised by monthly enhanced vegetation index, yielding coefficients of determination of 0.65 and 0.85 for the two basins. Convergent cross mapping of related timeseries indicated bidirectional causality (feedback) between the two variables.

Comparisons between same-zone monthly precipitation amounts and enhanced vegetation index provided weaker correlations. Start of the growing season in the oases was shown to coincide with the discharge of meltwater from the low- to mid-elevations of the Qilian Mountains (Zones 1 and 2) in mid-to-late March. Mid-seasonal development of oasis vegetation was controlled to a greater extent by the production of rain in the mountains. Comparison of water volumes associated with in-mountain production of rainfall and snowmelt with that associated with evaporation in the oases revealed that about ~90% of the water flowing downslope to the oases was eventually returned to the Qilian Mountains as water vapour generated in the lowlands.

## 1 Introduction

River basins not connected to oceans (endorheic basins; Meybeck, 2003) occupy about 13% of the total land surface of the earth (Meybeck et al., 2001) and generate about 2.3% of global runoff (Shiklomanov, 1998). Most of these basins are located in water-limited regions of the world, generally in the middle of continents remote from oceanic sources of atmospheric moisture or blocked by mountain ranges (Meybeck et al., 2001; Warner, 2004). Rivers associated with endorheic basins in northwest China are typically sourced by precipitation forming in mountains. These rivers commonly terminate in deserts as a result of strong evaporation (Li et al., 2013b). Endorheic basins are extremely sensitive to landcover and climate variability (Meybeck, 2003). Therefore, understanding the water cycle in these areas is extremely important for the long term sustainability (Pilgrim et al., 1988) of desert oases in northwest China.

The study of water recycling in the hyper-arid lowlands of northwest China has been largely centred on hydro-geochemical and isotopic analyses of precipitation and surface and subsurface water (e.g., Gates et al., 2008a; Ma et al., 2008; Ma et al., 2009; Ma et al., 2012;

Huang and Wen, 2014) and atmospheric-circulation modelling studies (e.g., Gao et al., 2004; Chu et al., 2005; Meng et al., 2009; Meng et al., 2012; Wen et al., 2012; Meng et al., 2015). In general, these studies concern coarse spatiotemporal resolutions.

Based on geologic, isotopic, and atmospheric circulation studies, aridification of northwest China has been theorised to have started about 12 Ma (mega-annum or million years) ago following (i) withdrawal of the Paratethys Sea from central Asia, resulting in loss of a major source of moisture; (ii) building of the Himalayas and southcentral Qinghai-Tibet Plateau, obstructing moisture-carrying airmasses from oceanic source-areas in the south (i.e., southeast Asian monsoon); and (iii) outward expansion of the northern fringe of the Qinghai-Tibet Plateau and subsequent growth of the Tian and Pamir Mountain ranges to the northwest of the Plateau (Kent-Corson, 2009; Zhuang et al., 2011), giving rise to the vast Taklamakan Desert (Tarim Basin, Xinjiang Province; inset in Fig. 1). Regional climate along the northern fringe of the Qinghai-Tibet Plateau, particularly along the Hexi Corridor of westcentral Gansu Province (inset, Fig. 1), is mostly controlled by the dry Central Asian airmass (Kent-Corson, 2009). Westerly airflow associated with this airmass interacts with numerous mountain ranges between the Caspian Sea to the Tian Mountains in the west of the Hexi Corridor (Warner, 2004). These interactions cause the moisture in the air to progressively lessen as the airmass continues to track eastward towards the Hexi Corridor and Qilian Mountains (Fig. 1). External contribution of moisture to the Hexi Corridor from Europe and western Asia (Warner, 2004; van der Ent et al., 2010) is anticipated to be low and of marginal importance to the localised recycling of water in westcentral Gansu.

The Hexi Corridor is renowned for its excessive dryness and large oases along the base of the Qilian Mountains, most notably the Liangzhou, Minqin, and Zhangye Oases (Fig. 1). Oases in the area provide important refugia to flora, fauna, and humans alike. Oases in northwest China occupy about 5% of the total land mass of the region, but give refuge and feed about 95% of the growing population of the area (Gao et al., 2004; Chu et al., 2005).

Direct precipitation to the oases is usually greater than to the neighbouring Badain Jaran and Tengger deserts (e.g., 120-170 vs. 40-60 kg $m^{-2}$ $yr^{-1}$; Table 1; Fig. 1). However, this amount is simply too small to support vegetation growth (Bourque and Hassan, 2009), when localised rates of potential evaporation can regularly exceed 2,000 kg $m^{-2}$ $yr^{-1}$ (Ding and Zhang, 2004; Zhang et al., 2008). A significant source of water to the oases is the generation of meltwater in the Qilian Mountains. The meltwater usually flows during the spring-to-summer warming of the mountain glaciers and previous winter's snow cover (Ji et al., 2006). Glacial meltwater currently accounts for about 22% of the total direct supply of inland river water in northwest China in general (Lu et al., 2005) and < 9% in the Hexi Corridor (Wang et al., 2009). An equally important source of water to the oases is orographic precipitation formed during the spring-fall period of each year (Zhu et al., 2004). Orographic precipitation is formed when air is forced to rise as a result of its interaction with major mountain barriers (Roe, 2005). Isotopic studies by Ma et al. (2009) confirm the importance of in-mountain production of precipitation and ice- and snow-thawed water in recharging the lowland oases of the area.

Long term mean recharge in low-lying areas north of the Qinghai-Tibet Plateau (Fig. 1) is assessed to be about 0.9-2.5 kg $m^{-2}$ $yr^{-1}$ (~1-2% of mean annual total precipitation) based on chloride mass-balance and isotopic assessments (Ma et al., 2008; Gates et al., 2008a, 2008b; Ma et al., 2009), indicating that most of the surface and shallow subsurface water generated in the mountains and flowing to the oases is eventually lost to the atmosphere as a result of evaporation. Lack of recharge of groundwater and excessive extraction of the resource for agricultural and other domestic uses has led to salinisation and desertification of the land surface in westcentral Gansu (Zong et al., 2011; Aarnoudse et al., 2012; Currell et al., 2012).

All of these studies and others available in the scientific literature (e.g., Kang et al., 1999; Gates et al., 2008a; Huo et al., 2008; Li et al., 2008; Jia et al., 2010; Ma et al., 2009; Pang et al., 2011; Zhuang et al., 2011; Ma et al., 2013) make reference to the importance of orographic rainout and the role of oasis vegetation in supporting the water cycle in the Hexi Corridor. However, none of these studies explicitly connects in-mountain production of precipitation to the seasonal evolution of oasis vegetation.

Non-geochemical assessments of regional water fluxes are complicated by the scarcity of land and climate data in arid regions of the world. In general, arid and mountainous regions of the world, including northwest China, have few to no monitoring stations. Pilgrim et al. (1988) found that the effective density of hydrometric stations in an arid region of Australia is one station per 10,000 km$^2$, compared to one station per 2,300 km$^2$ overall. Quality of data is also compromised in arid regions, due to difficulties in maintaining these stations.

Remote sensing and distributed modelling techniques are often used to supplement our understanding of eco-hydrometeorological processes at large spatial extents (e.g., hundreds of thousands km$^2$) at resolutions suitable to attending to issues of sustainable development (< 500 m). Integrating remote sensing data with distributed modelling provides us with an effective way of examining localised eco-hydrometeorological processes without resorting to a few point measurements and potentially imprecise methods of interpolation (Matin and Bourque, 2013a), except possibly in the calibration and confirmation of biophysical surfaces derived from remote sensing-based characterisations of regional fluxes.

The objective of this paper is to investigate the relative influence of oasis vegetation on water recycling and the generation of in-mountain precipitation in two large endorheic river basins in northwest China over a 10-year period (i.e., 2000-2009), based partially on a correlational and cause-and-effect examination (by way of convergent cross mapping; Sugihara et al., 2012) of relevant hydrological variables. Spatiotemporal variation in oasis-vegetation coverage and phenology is characterised by a chronological series of monthly Moderate Resolution Imaging Spectroradiometer (MODIS)-based images of enhanced vegetation index (Huete et al., 2002) and landcover-specific thresholds. Hydrological components essential to the study involve existing, independently-developed monthly surfaces of (i) evaporation and precipitation, prepared from remote sensing data (Table 2), and (ii) snowmelt and mountain return flow, generated from distributed hydrological modelling (see Matin and Bourque, 2013a and 2013b; Matin and Bourque, 2015). All surfaces were later validated against field data collected at a limited number of climate and hydrometric stations in the Hexi Corridor.

Identifying causation between relevant eco-hydrometeorological variables is an important step towards testing the idea that seasonal evolution of oases vegetation and associated production of water vapour in the lowlands are in fact implicated in the production of precipitation in the Qilian Mountains and return flow to the oases. These back and forth transfers of water (in both its gaseous and liquid state) assure the long term self-sustainability of desert oases in northwest China. Disruption in the lowland production of water vapour by affecting vegetation growth and coverage through land conversion could potentially result in irreparable damage to the self-supporting mechanisms of the oases by promoting desertification of the area (Warner, 2004; Bourque and Hassan, 2009).

## 2 Study area

The study area consists of the Shiyang and Hei River basins in westcentral Gansu Province, northwest China (Fig. 1). The Shiyang River basin is an endorheic river basin (Li et al., 2013a) located in the eastern Hexi Corridor. The Shiyang River originates from the Qilian Mountains and flows about 300-km northeastward (Gao et al., 2006) before terminating in the Minqin-lake district, bordering the Tengger and Badain Jaran deserts (Li et al., 2007; Fig. 1). The basin area is roughly 49,500 $km^2$. Elevation in the Shiyang River basin varies from 1,284-5,161 m above mean sea level (a.m.s.l.), with an average elevation of 1,871 m a.m.s.l. The Shiyang River system has eight main branches, including the Xida, Donga, Xiying, Jinta, Zamusi, Huangyang, Gulang, and Dajing Rivers (Li et al., 2013a; Wonderen et al., 2010).

The Hei River also originates from the Qilian Mountains, northwest of the headwaters of the Shiyang River network, and flows northwestward through the oases and terminates in the Badain Jaran Playa (Akiyama et al., 2007). The Hei River basin, with a land surface area of approximately 128,000 $km^2$, is the second largest endorheic river basin in northwest China (Gu et al., 2008). The Hei River basin includes the Zhangye sub-basin, with a total land area of about 31,100 $km^2$. Elevation in the Zhangye sub-basin varies from 1,287-5,045 m a.m.s.l., with an average elevation of 2,679 m a.m.s.l.

Long term average data (1950-2000) show that precipitation and potential evaporation in the deserts are approximately 80-150 kg $m^{-2}$ $yr^{-1}$ and 2,300-2,600 kg $m^{-2}$ $yr^{-1}$, based on an application of the Penman-Monteith equation (Monteith, 1965). Precipitation increases in the mountains from 300-600 kg $m^{-2}$ $yr^{-1}$, while potential evaporation decreases to about 700 kg $m^{-2}$ $yr^{-1}$ (Akiyama et al., 2007; Wang and Zhao, 2011; Zang et al., 2012). Most of the precipitation occurs during June to August. About 94% of water delivered from the mountains to lowland oases is through surface runoff. Average annual runoff in the Shiyang River is about $15.8 \times 10^8$ $m^3\ yr^{-1}$, whereas in the Hei River it is about $37.7 \times 10^8$ $m^3\ yr^{-1}$ (Kang et al., 2009).

# 3 Methods

## 3.1 Landcover types, zones, and regional sampling

Based on vegetation site preferences (Appendix), the study area was subdivided into four main elevation zones (Fig. 2a), defined by elevations: (i) < 2,500 (oasis plains and foothills; Zone 1); (ii) 2,500-3,300 (low-mountain elevations; Zone 2), (iii) 3,300-3,900 (mid-mountain elevations; Zone 3), and (iv) > 3,900 m a.m.s.l. (high-mountain elevations; Zone 4). Different landcover types in these elevation zones were then identified based on enhanced vegetation index and slope orientation (Table A1, Appendix; Fig. 1). To advance the analysis, within-zone enhanced vegetation index, evaporation, and precipitation were sampled randomly within a geographic information system (for sampling point layout, see Fig. 2a).

## 3.2 Vegetation phenology

Land surface phenology refers to the timing of different life-cycle stages of plants (Martinez and Gilabert, 2009). Seasonal changes in land surface phenology is important to understand the relationship between vegetation growth and the hydrological cycle in river basins (Martinez and Gilabert, 2009). Study of land surface phenology is also important to understand the causes of vegetation-growth-pattern changes (Fisher and Mustard, 2007; Myneni et al., 1997). Satellite-based analysis of land surface phenology addresses the development patterns in photosynthetic biomass by means of derived vegetation indices (e.g., Fig. 3a; Ahl et al., 2006) in an area that can potentially support many species. Ground-based analysis of land surface phenology, in contrast, focusses on a single plant species at a time.

Typical measures of phenology are (i) onset of greening, (ii) onset of senescence, (iii) peak development during the growing season, and (iv) length of the growing season (Hudson et al., 2010). Various methods have been adopted to assess phenology from space. Hudson et al. (2010) classified these into four groups, namely (i) threshold-, (ii) derivative-, (iii) smoothing-, and (iv) model-based methods. Among these methods, the threshold-based method is the simplest and most commonly used (Hudson et al., 2010).

With the threshold-based method, a single value of vegetation index is specified as the threshold. The values of vegetation index are plotted against time of year. The time when the threshold value is passed in the upward direction is identified as the start of the growing period and when the same value is passed in the downward direction, the time is identified as the end of the growing period (Karlsen et al., 2006; e.g., Fig. 3b). Methods of selecting the threshold vary among studies. Some authors use single arbitrary thresholds, e.g., 0.17 (Fischer, 1994), 0.09 (Markon et al., 1995), and 0.099 (Lloyd, 1990), whereas some use threshold specifiers like the long term average (Karlsen et al., 2006) or % peak amplitude of vegetation indices (Jonsson and Eklundh, 2002).

In the current analysis, phenological state and regional coverage is specified by monthly MODIS-based images of enhanced vegetation index (Fig. 3a). Different thresholds were identified for each landcover type (Table A1, Appendix) to determine the onset of greening and senescence in the vegetative cover. Threshold values were generated from spatially-distributed 10-year averages of monthly mean enhanced vegetation index. Zonal averages of mean enhanced vegetation index were calculated for each landcover type for each month of the year. These values were plotted against time to generate separate time-vs.-vegetation index plots for each landcover type. The threshold values were specified at the time when mean enhanced vegetation index had maximum positive curvature when moving in the upward direction (Fig. 3b). Values generated were 0.09 for crops and sparse grass, 0.17 for coniferous forest and meadow, and 0.12 for other vegetation types.

### 3.3 Onset, cessation, and duration of the precipitation season

Most methods used in establishing the onset and cessation of the precipitation season usually aim to determine the effective planting date of crops (Adejuwon et al., 1990; Adejuwon and Odekunle, 2006; Benoit, 1977; Ilesanmi, 1972). In these methods, the onset and end of the precipitation season is equated to the onset and end of the growing season (Benoit, 1977; Odekunle et al., 2005). These methods do not help clarify the relationship between the onset of the growing and precipitation seasons, when the seasons are not entirely synchronised. Cumulative % precipitation (Ilesanmi, 1972) is the most widely used indicator of the onset and cessation of the precipitation season independent of other climatic and vegetation factors (Adejuwon et al., 1990; Adejuwon and Odekunle, 2006; Odekunle, 2006). In this method, daily % precipitation data are processed to generate five-day means. Using these means, cumulative precipitation is plotted against time of year. On these plots, the point of maximum positive curvature is defined as the onset of the precipitation season, whereas the point of maximum negative curvature is defined as the cessation of the season. Point of onset typically happens at the time when cumulative % precipitation is between 7-8%, while the typical time of cessation is when cumulation reaches about 90% (Ilesanmi, 1972). In our analysis, we apply Ilesanmi's (1972) approach to monthly data. Spatial averages of monthly precipitation calculated for the different elevation zones were used to generate cumulative % precipitation curves for each zone as a function of time of year.

### 3.4 Correlation and causality

Pearson's correlation describes the statistical co-variation between two variables (Gotelli and Ellison, 2013); it does not address matters of cause-and-effect. Correlation is employed in this study primarily to establish the strength of association between paired combinations of state variables to help form an initial description of potentially relevant eco-hydrometeorological relationships.

Recent advances in dynamic systems analysis have resulted in the development of innovative methods for identifying causality in timeseries data (Sugihara et al., 2012). One such method, convergent cross mapping, is a model-free approach that helps identify causality and direction of causality in dynamically-evolving systems. Timeseries variables are considered causally connected if both are derived from the same dynamic system. Convergent cross mapping checks for causation by measuring the extent historical registrations in one variable (i.e., timeseries one) can consistently approximate the state in a second variable (timeseries two). The method is able to provide reliable description of causality even in the presence of system feedback and confoundedness (Sugihara et al., 2012). Moreover, convergent cross mapping involves convergence, an important methodological attribute that differentiates causation from ordinary correlation (Maher and Hernandez, 2015). In general, non-causal relationships are illustrated as flat curves of predictive skill, based on calculations of Pearson's correlation between predictions and actual observations, with respect to variations in timeseries length. Causation is suggested when convergence is present and Pearson's correlation at the point of convergence is greater than zero. It is always possible to get bidirectional convergence when variables are strongly forced by an external third variable, resulting in synchrony between variables being assessed. Synchrony should be tested for convergent cross mapping to determine bidirectional pairing (Sugihara et al., 2012; Clark et al., 2014). When synchrony exists, it can sometimes be minimised by processing the “first difference” of cross-correlated variables by subtracting previous observations (at time *t-1*) from current observations (at *t*) in the original timeseries prior to performing the analysis (Granger and Newbold, 1974). In this paper, we use convergent cross mapping to assess the direction and strength of causality between (i) enhanced vegetation index and evaporation in the oases, and (ii) evaporation in the oases and production of precipitation in the high mountains, most notably in Zone 4 (Fig. 2a).

# 4 Results and Discussion

## 4.1 Vegetation development timing

Onset of greening occurs mostly in early April, except in some parts of the study area, where the growing season is slightly advanced (i.e., initiating in late March; Fig. 3). In the forest and meadow areas of the mountains, the growing season commences in May, and in some parts, in June. Early changes in vegetation development patterns (changes in monthly enhanced vegetation index) in the upper mountains of the river basins may occur as a result of localised melting of the snowpack. Vegetation growth reaches its peak in July-August and dies back in all areas of the study area in November, except in the high mountains of the Hei River basin, where vegetation senescence is observed to occur in October.

## 4.2 Oasis enhanced vegetation index development vs. evaporation

Average regional evaporation (Fig. 4) as a function of average enhanced vegetation index (Fig. 3) over the growing season (April through October) suggest that regional evaporation has strongest positive correlation with vegetation in the oases, with very high $r^2$-values when crops and dense grass were considered; i.e., 0.85, 0.83 and 0.84, 0.73 for the Shiyang and Hei River basins, respectively. Correlation with landcover types in the mountains is also present, but at a much reduced level (Table 3).

Convergent cross mapping of oases timeseries data of enhanced vegetation index with evaporation indicates feedback (bidirectional causality) between the two variables ($p$-values < 0.05; Fig. 5a and 5b), with plant-mediated evaporation providing marginally stronger control over plant growth, i.e., Pearson's correlation coefficient at the point of convergence (at the largest record length) for "B causes A" is greater than that for "A causes B", where A represents changes in enhanced vegetation index and B, changes in oasis evaporation (Fig. 5b). Fig. 5a and 5b give the results with respect to the original, unprocessed timeseries data and "first differencing" of the original data, respectively. Both are provided because convergence in Fig. 5a does not entirely guarantee bidirectional causality, because of possibility of synchrony between the two variables.

Bidirectional causality between the seasonal evolution of oasis vegetation and evaporation (transpiration) is not surprising, as the transpiration process is central to moving water-soluble nutrients vital to plant growth from the soil to the various parts of the plant (Kimmins, 1997) and in support of plant biochemical processes (~1-5% of available water). As plants produce leaf biomass, increasing leaf surface area (and, thus, enhanced vegetation index), transpirational fluxes become stronger providing that solar irradiation and soil water are not limiting factors. Elevated transpiration rates also help cool vegetation in hot environments (e.g., Fig. 2b), promoting improved growing conditions for the vegetation during the hotter part of the growing season.

### 4.3 Evaporation in the oases vs. precipitation in the high mountains

The precipitation season for the most part starts in late April to early May (Fig. 6a through 6c) and ends in September with nominal interannual variation in timing. Greatest interannual variation in cumulative % amounts is observed to occur in the lowlands (Zone 1) of both river basins, and the least in the mountains (e.g., Zones 3 and 4; Fig. 6b). Interannual variation in the lowlands is most likely associated with the convective nature of locally-generated precipitation (Zhang et al., 2010).

Pairwise correlations within individual river basins reveal that within-zone vegetation is weakly associated to precipitation generated locally (i.e., within the same zone), but precipitation in the mountains has the strongest correlation with vegetation and evaporation in the oases (Table 4). These correlations become particularly strong in the high mountains (i.e., Zone 4). This measured increase in correlative strength is expected as the monthly precipitation signal becomes stronger and more continuous with upward elevation; the impact of a variable lifting condensation level becomes less effective at higher elevations (Fig. 6d). The lifting condensation level of moistened air (i.e., the level rising air becomes saturated) defines the cloud-base height and the lowest level that precipitation can form from orographic (adiabatic) lifting. The lifting condensation level varies with relative humidity of the air prior to its vertical displacement at the base of the mountain barrier, resulting in temporal variation in the cloud-base elevation (Fig. 6d) and the portion of the mountain range affected by orographic precipitation (Bourque and Hassan, 2009).

Convergent cross mapping of timeseries data of oasis evaporation with precipitation in the high mountains of both river basins also correctly points to bidirectional causality (feedback) between the two variables ($p$-values $< 0.05$ for all instances, except one; Fig. 5c and 5d), with the lowland production of water vapour providing the stronger control between the two variables (Fig. 5d). Rainwater generated in the high mountains eventually returns to the oases during the same growing season. This source of water is, in turn, used to promote continued vegetation growth in the oases and the production of water vapour during the growing period (see Section 4.2), intensifying the production of precipitation in the mountains. During the non-growing part of the year (i.e., November through February of the following year), in-mountain precipitation is observed to be consistently lower than the rest of the year (Fig. 6a and 6c). This is mainly due to the fact that vegetation growth (Fig. 3), evaporation (Fig. 4), and water vapour content at the base of the mountains (Fig. 6e) are their smallest and least effective during this time of year. This relationship was also observed in an earlier study examining the level of snow (as a passive tracer) and coverage in the mountains in the same area during the non-growing part of the year addressed by models and results from an analysis of remote-sensing optical (MODIS) and passive microwave (Advanced Microwave Scanning Radiometer-Earth Observing System) data (Bourque and Matin, 2012; Matin and Bourque, 2013a).

Winds associated with orographic lifting generally arise from the northwest to east-southeast sector, 61.3 and 48.1% of the time during the growing season for the Shiyang and Hei River basins, respectively (Fig. 7a). In the Hei River basin, winds from the northwest (most frequent wind direction within the northwest to east-southeast sector) actually transport water vapour to the mountains of the Shiyang River basin (Fig. 7b, lower diagram) causing precipitation levels to be slightly greater in the Shiyang River basin than in the Hei River basin (Table 3). The Hei River basin may at times receive water vapour from the Shiyang River basin, but the possibility of that occurring is significantly reduced, given that winds from the east to east-northeast sector are quite uncommon (< 5% of the time: Fig. 7a) and mountains in the Shiyang River basin may cause water vapour content of the affected air to be reduced by orographic lifting. Small oases west of Zhangye Oasis (e.g., Jinta and Jiuguan Oases) are not geographically in position for the prevailing winds of the area (i.e., northwest to north-northwest winds) to contribute significant amounts of water vapour to the upper-portion of the Hei River basin.

Asynchrony in the start of the oasis growing and in-mountain precipitation seasons (Fig. 3 and 6), suggests that the amount of water vapour sufficient to trigger the precipitation season in the Qilian Mountains requires on average at least one month of active plant growth to ensue (Fig. 8). The source of water to support initial vegetation growth in the oases is surface water generated by snowmelt in the plain and lower-mountain positions (< 3,300 m a.m.s.l.) during the March-April period of each year (Fig. 8). Meltwater production in the lower mountains of both river basins is about the same (i.e., $250 \times 10^6$ $m^3$ in the Shiyang vs. $223 \times 10^6$ $m^3$ in the Hei River basins, respectively), whereas it is substantially greater in the mid- to high-mountain portions of the Hei River basin (i.e., $299 \times 10^6$ $m^3$ in the Shiyang vs. $1{,}129 \times 10^6$ $m^3$ in the Hei River basin), as a result of differences in respective land-surface areas at high elevations, i.e., 2,979 vs. 10,328 $km^2$ for the Shiyang and Hei River basins. Delivery of this snowmelt water to the oases occurs until August, when air temperatures in the high mountains begin to decline (Fig. 8c,d).

### 4.4 Zone-specific water yield

In the oases, water vapour production by crops and grasses exceed locally-generated precipitation. Comparisons between annual cumulative water volumes associated with the sum of rainfall and snowmelt with those of evaporation for corresponding elevation zones and for the total river basin show that annual water volumes associated with evaporation (E) exceeds those of rainfall (P) + snowmelt (S) in the oases (i.e., P + S – E < 0.0), with the opposite being true in the mountains (i.e., P + S – E > 0.0). Differences in the mountains (P + S –E) tend to increase with increased elevation because of corresponding increases in rainfall and snowmelt (to a certain elevation threshold; see Matin and Bourque, 2015) and decreases in evaporation. Total water volume associated with rainfall and snowmelt collectively is about equal to that of evaporation at the river-basin level, i.e., 90% and 89% for the Shiyang and Hei River basins, respectively (Table 5). This suggests that the bulk of precipitation water originating from the mountains and returning to the oasis as surface and shallow subsurface runoff (~90%) is eventually returned to the mountains as evaporated water. Water vapour generated by the oasis can travel across the boundaries of river basins as illustrated earlier, but once deposited, surface water is mostly confined to the basin. This result and all other results in preceding sections are consistent with a hydrologically-closed system.

Recycling ratios for the study area are expected to be significantly greater that those reported in van der Ent et al.'s (2010) global moisture-recycling analysis (i.e., < 5% for northwest China, based on their Fig. 5, contrasted with potentially as high as 90%, for this study). Since regional recycling ratios are scale-dependent (van der Ent et al., 2010), these differences may not be unexpected. The grid-cell size (scale) used in the current study (250 m ×

250 m) may have allowed for the capture of detail that was effectively invisible to the global analysis, based on a 1.5$^{o}$ latitude × 1.5$^{o}$ longitude scale (van der Ent et al., 2010).

## 5 Conclusions

This paper analyses the interdependencies between different components of the hydrological cycle of the Shiyang and Hei River study basins. By correlating and cross-mapping precipitation, evaporation, and vegetation within different elevation zones of the river basins, the analysis reveals that oasis vegetation has an important role in sustaining the water cycle in both river basins. Oasis vegetation is dependent on surface water flowing to the region from mountain surface and shallow-subsurface sources. Surface runoff is generated from the precipitation falling in the adjoining mountains. Correlation analysis shows that in-mountain-generated precipitation is strongly correlated to the state of oasis vegetation ($r^2$ = 0.65 and 0.85 for the Shiyang and Hei River basin, respectively) and water vapour generated by evaporation ($r^2$ = 0.57 and 0.77). Convergent cross mapping of related timeseries revealed bidirectional causality (feedback) between paired variables. Comparisons between the onset of vegetation development and the precipitation season shows that the growing season precedes the precipitation season in the oases by on average one month. This suggests that vegetation growth in the oases, through the production of water vapour, provides an initial triggering of the precipitation season in the mountains. Onset of vegetation development in the oases is supported by the generation of snowmelt in the mountains in March through April. Analysis of annual total water volume involved at the basin-level seems to indicate that rainfall and snowmelt together, integrated across the entire river basins, accounts for about 90% of water vapour transported to the mountains, as a result of evaporation in the oases.

## Appendix A: Landcover types

Vegetation distribution in the study area (Fig. 1 of the main text) has a unique preferential association with elevation, slope, and slope direction (Jin et al., 2008). For instance, < 2,500 m a.m.s.l., the growing environment for spring wheat (prominent crop grown in the area) and dense grass is limited to the desert oases (Zhao et al., 2005; Fig. 1). North-facing slopes of the Qilian Mountains support alpine meadow at elevations between 2,500 to 3,300 m a.m.s.l. At elevations > 3,300 m a.m.s.l., deciduous shrubs represent the most dominant vegetation type. Isolated patches of conifer forests in the Qilian Mountains (mostly involving Qinghai spruce, *Picea crassifolia*) are found to grow best at elevations between 2,500 m to 3,300 m a.m.s.l. (Carpenter, 2001). Seasonal vegetation density and growth vary as a function of both vegetation type and elevation.

The MODIS-based annual global landcover map currently available, as of 2012, is produced from seven spectral maps, bidirectional reflectance distribution function (BRDF) adjusted reflectance, land surface temperature ($T_s$), enhanced vegetation index, and an application of supervised classification using ground data from 1860 field sites (Friedl et al., 2010). Assessments of the product have shown that this map is not entirely realistic for zones of steep transition, particularly in mountainous areas (Liang and Gong, 2010). Improved landcover definition at regional or local scales with supervised classification usually involves much greater amounts of ground data that are normally available for most regions. Recently, decision-tree based classifications have been applied to  remote sensing data and has been shown to produce better results than other classification systems based on maximum likelihood or unsupervised clustering and labelling (Friedl and Brodley, 1997). One benefit of decision-tree based classification is that it is able to use local knowledge of vegetation characteristics together with other pertinent information, such as terrain characteristics, in its evaluation. In the current study, chronological-sequences of MODIS-based enhanced vegetation index and digital terrain information of the study area (e.g., slope orientation, elevation) are used to classify landcover with a decision-tree classifier.

One landcover map was generated for each year during the 2000-2009 period using classification thresholds summarised in Table A1. From these maps, a composite landcover map was then created based on a pixel-level assessment of the most common landcover type of the nine possible types (Table A1; Fig. 1) during the ten-year period.

**Table A1.** Landcover type definition as a function of elevation zone, enhanced vegetation index (EVI), and slope orientation.

| Zone[a] | Landcover Type | Classification Thresholds |
|---|---|---|
| **1** | Desert | Maximum growing-season EVI < 0.113 |
| | Crop | Maximum growing-season EVI > 0.27 and minimum growing-season EVI < 0.113 |
| | Dense grass | Maximum growing-season EVI > 0.27, and minimum growing season EVI > 0.113 |
| | Sparse grass and/or shrub | Maximum growing-season EVI between 0.113-0.27 and mean growing season EVI > 0.113 |
| | Bare ground | Maximum growing-season EVI between 0.113-0.27 and mean growing season EVI < 0.113 |
| **2** | Alpine meadow | Maximum growing-season EVI > 0.27 and on north-facing slopes |
| | Coniferous forest | Maximum growing-season EVI > 0.27, but not on north-facing slopes |
| | Sparse grass and/or shrub | Maximum growing season EVI between 0.113-0.27 |
| | Bare ground | Maximum growing-season EVI < 0.113 |
| **3** | Deciduous shrub | Maximum growing-season EVI > 0.27 |
| | Bare ground | Maximum growing-season EVI < 0.27 |
| **4** | Sparse shrub | Maximum growing-season EVI > 0.113 |
| | Snow and/or ice | Maximum growing-season EVI < 0.113 |

[a] Zones are classified according to elevation bands: < 2,500 m (Zone 1); 2,500-3,300 m (Zone 2); 3,300-3,900 m (Zone 3); and > 3,900 m a.m.s.l. (Zone 4).

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## Figure Captions

**Fig. 1.** The Shiyang and Hei River basins with distribution of dominant landcover classes, classified with a decision-tree classifier and categorisation thresholds summarised in Table A1 (Appendix). The inset shows the location of the study area along the northeastern flank of the Qinghai-Tibetan Plateau.

**Fig. 2.** Division of study area according to four elevation zones (a; legend) and mean July air temperature distribution (b) used in the computational fluid-flow dynamics modelling of surface wind velocity (m $s^{-1}$) and wind direction ($^{o}$ from true North, N). Open circles in (a) give the randomly-selected point-locations where enhanced vegetation index (non-dimensional), evaporation (kg $m^{-2}$ $month^{-1}$), and precipitation (kg $m^{-2}$ $month^{-1}$) were sampled.

**Fig. 3.** Ten-year average distribution of monthly enhanced vegetation index (EVI $\geq$ 0.15; non-dimensional) according to time of year (a) and spatially-averaged timeseries of monthly EVI over the course of individual years for 2000-2009 (b; shown in different colours). Letters along the x-axis of plots in (b) coincide with month, January (J) through to December (D). Vertical red lines denote the approximate month of the onset (first line) and cessation of the growing season (second line) in the Shiyang and Hei River basins, respectively.

**Fig. 4.** Ten-year average distribution of monthly evaporation (kg $m^{-2}$ $month^{-1}$) as a function of time of year.

**Fig. 5.** Predictive-skill curves (Pearson's correlation coefficients) for convergent cross mapping of enhanced vegetation index (EVI) with evaporation in the oases (a, b) and evaporation in the oases with precipitation production in Zone 4 (c, d). Plots (a) and (c) are based on

the original timeseries data, whereas plots (b) and (d) are based on the "first differencing" of the original data. Dotted lines on either side of the predictive-skill curves represent the ± standard error of estimate assessed from bootstrapping with 3000 iterations. Convergent cross mapping is based on procedures written in the R-programming language initially developed by Clark et al. (2014).

**Fig. 6.** Ten-year average distribution and timeseries of monthly precipitation (kg $m^{-2}$ $month^{-1}$) according to time of year (a, c) and spatially-averaged cumulative curves of % precipitation over the course of individual years for 2000-2009 (b). Letters along the x-axis of plots in (b) coincide with month, January (J) through to December (D). Vertical red lines denote the approximate time of the onset (first line) and cessation of the precipitation season (second line) in the Shiyang (SR Basin; i-iv) and Hei River basins (HR Basin; v-vii), respectively. Plots (i) through (iv) and (v) through (vii) represent the cumulative % precipitation in the two river basins for Zone 1 through Zone 4. Plots (d) and (e) give the monthly mean lifting condensation level (LCL) and actual water vapour content of air at the base of the Qilian Mountains (i.e., Wuwei City; Table 1) over a different 10-year period (1996-2005). Values of LCL are calculated from $(T_{dry}-T_{dew})/(\Gamma_{dry}-\Gamma_{dew}) \times 1000$ m + elevation at base of Qilian Mountains (i.e., 1534 m at Wuwei City), where $T_{dry}$ and $T_{dew}$ are the monthly surface dry-bulb and dew-point temperature (both in $^{o}$C), and $\Gamma_{dry}$ and $\Gamma_{dew}$ are the dry adiabatic and dew-point temperature lapse rates, ~10$^{o}$C per 1000 m vs. ~2$^{o}$C per 1000 m, respectively (Warner, 2004: Aguado and Burt, 2013).

**Fig. 7.** Wind direction frequency roses for Zhangye and Liangzhou Oases (a) and calculated wind velocity and direction using a computational fluid-flow dynamics model (b; Lopes,

2003) for prevailing wind directions from the northeast (upper diagrams) and northwest (lower diagram) and July peak near-surface air temperatures (Fig. 2b). Percent values in (a) represent the portion of the time during the growing season that prevailing winds are in directions (within the northwest to east-southeast sector) that will lead to the production of orographic precipitation in the Qilian Mountains.

**Fig. 8.** Ten-year mean monthly snowmelt generated within the different elevation zones (a, b) and mean monthly contribution of rainwater and snowmelt to the monthly river runoff from the Qilian Mountains (based on previous work by Matin and Bourque, 2015) and corresponding monthly enhanced vegetation index for the Shiyang (c) and Hei River basins (d) for the 2000-2009 period.

**Fig. 9.** Within-zone average monthly water yield (P + S - E) for 2000-2009. Note the scales of the y-axis for each plot are different.

**Table 1.** List of weather stations, their coordinates, elevation, and mean total annual precipitation based on measurements from 1976-2005. Stations are located within or near the Hexi Corridor (Fig. 1).

| Station ID | Station | Latitude (ºN) | Longitude (ºE) | Elevation (m a.m.s.l.) | Precipitation (kg $m^{-2}$ $yr^{-1}$) |
|---|---|---|---|---|---|
| 52323 | Mazongshan | 41.80 | 97.03 | 1770 | 70.6 |
| 52418 | Dunhuang | 40.15 | 94.68 | 1140 | 41.4 |
| 52424 | Guazhou | 40.50 | 95.92 | 1177 | 51.7 |
| 52436 | Yumen | 40.27 | 97.03 | 1527 | 66.5 |
| 52446 | Dingxin | 40.40 | 99.80 | 1158 | 54.7 |
| 52447 | Jinta | 39.82 | 98.90 | 1372 | 62.4 |
| 52533 | Suzhou | 39.77 | 98.48 | 1478 | 85.6 |
| 52546 | Gaotai | 39.37 | 99.82 | 1332 | 110.1 |
| 52557 | Linze | 39.16 | 100.16 | 1454 | 111.7 |
| **52652** | **Zhangye**[a] | **38.93** | **100.43** | **1483** | **129.8** |
| **52679** | **Wuwei** | **37.92** | **102.67** | **1534** | **170.7** |
| 52681 | Minqin | 38.63 | 103.08 | 1367 | 112.9 |

[a] Stations in bold are those found in the Zhangye and Liangzhou Oases, Fig. 1.

**Table 2.** Input variables and their image-data sources relevant to the generation of evaporation, precipitation, and snowmelt surfaces addressed in this study, including their spatiotemporal resolutions (columns 3 and 4) before and after spatial enhancement. Bracketed values are not given in cases where there is no spatial enhancement or temporal aggregation used (modified after Matin and Bourque, 2013a).

| **Variables** | **Product generation or source** | **Spatial**<br>Original<br>(after processing) | **Temporal**<br>Original<br>(after processing) |
|---|---|---|---|
| Normalised difference vegetation index (NDVI)[a]<br>Enhanced vegetation index (EVI)[a,b] | MODIS vegetation indices (Huete et al., 2002; Huete et al., 1997; Wan et al., 2004). | 250 m | 16 day<br>(1 month) |
| Land surface temperature ($T_s$)[a,b] | MODIS land surface temperature (MOD11A2; Wan et al., 2004); monthly averages were produced by weighted averaging of 8-day composites. The original 1000-m resolution was enhanced to 250 m using MODIS EVI (at 250-m resolution) as primary predictor; processing steps are outlined in section 3.2.1 (steps 1-6; in Matin and Bourque, 2013a). | 1,000 m<br>(250 m) | 8 day<br>(1 month) |
| Land surface emissivity ($\varepsilon_s$)[a] | MODIS land surface emissivity was derived by averaging MODIS-bands 31 and 32 emissivities (Petitcolin and Vermote, 2002). | 1,000 m | 8 day<br>(1 month) |
| Land surface albedo ($A_s$)[a] | MODIS products combined with BRDF-albedo products (MCD43B3; Davidson and Wang, 2005). | 1,000 m | 16<br>(1 month) |
| Surface dry-bulb air temperature ($T_{dry}$)[a,b]<br>Surface dew-point temperature ($T_{dew}$)[a,b] | MODIS atmospheric profile data (MOD07; Seeman et al., 2006); near surface air temperature are extracted at the pressure level closest to the ground-surface described by the region's digital elevation model (DEM). Daily data were averaged to generate monthly averages. Original $T_{dry}$-images were digitally enhanced to 250 m by relating their values to enhanced $T_s$ images; 5000-m resolution images of MODIS-$T_{dew}$ were enhanced to 250 m by relating to MODIS-EVI (250 m) and enhanced $T_s$. Both $T_{dry}$ and $T_{dew}$ were calibrated and validated against independent climate-station data (Matin and Bourque, 2013a). | 5,000 m<br>(250 m) | 1 day<br>(1 month) |
| Surface relative humidity[b] | Relative humidity (250-m resolution) was calculated as the ratio of actual vapour pressure to saturated vapour pressure calculated from monthly $T_{dry}$ and $T_{dew}$ (Bourque and Hassan, 2009), both at 250-m resolution. | 250 m | 1 month |
| Total precipitable water[b] | MODIS near infrared daily total precipitable water product (MOD05; Gao and Kaufman, 2003; Kaufman and Gao, 1992); monthly values were generated by averaging daily values. | 1,000 m | 1 day<br>(1 month) |
| Elevation[a,b] | Shuttle Radar Topographic Mission (SRTM) DEM; gap-filled version (v. 4) obtained from the Consortium of Spatial Data and Information (CGIAR-CSI, 2008; Reuter et al., 2007). | 90 m | n/a[c] |

| | | | |
|---|---|---|---|
| Net radiation and soil heat flux (i.e., $R_n$-G)[a] | Calculated from estimated incoming solar radiation obtained with the Solar Analyst tool in ArcGIS and SRTM DEM-elevation data, and remote sensing-based $A_s$, $T_{dry}$, and $T_s$ images in estimating outgoing and incoming reflected shortwave and longwave radiation surfaces for $R_n$ and a NDVI-based correction of incident solar radiation for the ground heat flux (G; see Matin and Bourque, 2013b). | 250 m | n/a |

[a] Variables used in the calculation of evaporation; [b] variables used in the digital enhancement of TRMM-precipitation data (Matin and Bourque, 2013a); [c] n/a=not applicable.

**Table 3.** Regression fits (y=mx+b; m=slope and b=y-intercept) and their associated coefficients of determination ($r^2$) for comparisons between basin-level monthly evaporation over a 10-year period (2000-2009) as a function of same-month enhanced vegetation index for different vegetated-cover types (subset of landcover types in Table A1 and Fig. 1). Vegetated-cover types are ordered according to their position in the basins (Fig. 1), starting with vegetation types in Zone 1 (< 2,500 m a.m.s.l.).

| **Landcover Type** | **Shiyang River Basin** | | | **Hei River Basin** | | |
|---|---|---|---|---|---|---|
| | **m** | **b** | **$r^2$** | **m** | **b** | **$r^2$** |
| Crops | 175.87 | -6.92 | 0.85 | 157.47 | -3.5 | 0.84 |
| Dense grass in oases | 175.84 | -8.32 | 0.83 | 170.06 | -7.78 | 0.73 |
| Sparse grass and/or shrubs | 218.23 | -2.97 | 0.54 | 214.39 | -1.1 | 0.49 |
| Alpine meadow | 83.80 | 16.18 | 0.32 | 90.57 | 12.82 | 0.41 |
| Coniferous forest | 74.77 | 22.58 | 0.27 | 97.46 | 15.57 | 0.39 |
| Deciduous shrubs | 46.26 | 23.81 | 0.12 | 79.21 | 16.56 | 0.42 |

**Table 4.** Coefficients of determination ($r^2$) for comparisons between zone-specific precipitation (zones associated with column 1) with same-month, same-zone, or oasis enhanced vegetation index (EVI) and evaporation (E; zones associated with row 1) for the Shiyang and Hei River basins, respectively. Cells associated with comparisons that were not addressed in the analysis, are marked with "-". Values of $r^2$ that are in bold are derived for comparisons between zone-specific precipitation with same-month, same-zone EVI and E; values not in bold, are for comparisons between zone-specific precipitation with same-month oasis EVI and E.

| **Elevation Zone**[a] | | **1** | | **2** | | **3** | | **4** | |
|---|---|---|---|---|---|---|---|---|---|
| | **River Basin** | **EVI** | **E** | **EVI** | **E** | **EVI** | **E** | **EVI** | **E** |
| **1** | Shiyang River | **0.44** | **0.41** | - | - | - | - | - | - |
| | Hei River | **0.51** | **0.39** | - | - | - | - | - | - |
| **2** | Shiyang River | 0.54 | 0.52 | **0.61** | **0.34** | - | - | - | - |
| | Hei River | 0.68 | 0.56 | **0.62** | **0.34** | - | - | - | - |
| **3** | Shiyang River | 0.61 | 0.55 | - | - | **0.52** | **0.20** | - | - |
| | Hei River | 0.78 | 0.68 | - | - | **0.69** | **0.43** | - | - |
| **4** | Shiyang River | 0.65 | 0.57 | - | - | - | - | **0.44** | **0.18** |
| | Hei River | 0.85 | 0.77 | - | - | - | - | **0.75** | **0.47** |

[a] Zones are classified according to elevation bands: < 2,500 m (Zone 1); 2,500-3,300 m (Zone 2); 3,300-3,900 m (Zone 3); and > 3,900 m a.m.s.l. (Zone 4);

**Table 5.** Evaporation as a % of the sum of precipitation (P) and snowmelt volumes (S) for individual elevation zones and mountain area within the Shiyang and Hei River basins, and for the entire river basin, respectively.

| **Elevation Zone**[a] | **Evaporation (%)** | |
|---|---|---|
| | **Shiyang River Basin** | **Hei River Basin** |
| **1** | 136 | 210 |
| **2** | 88 | 100 |
| **3** | 58 | 81 |
| **4** | 35 | 62 |
| **Entire Mountain Area** | 72 | 81 |
| **Entire River Basin** | 90 | 89 |

[a] Zones are classified according to elevation bands, i.e., < 2,500 m (Zone 1); 2,500-3,300 m (Zone 2); 3,300-3,900 m (Zone 3); and > 3,900 m a.m.s.l. (Zone 4).