**Supplementary Material (Figures S1-3 and Tables S1-3)**

**Figures**

**Figure S1.** Water-vapor flux vectors (kg·m−1·s−1) for summer from June to August that were vertically combined from surface to 300 hPa in 1971–2000 based on the NCEP/NCAR reanalyzed data (Kalnay et al., 1996). Locations of fossil pollen records synthesized from northern China (see Table S1 for details). EASM, ISM, and Westerlies represent the East Asian monsoon, Indian monsoon, and westerlies, respectively. Green dashed line denotes the northern boundary of modern summer monsoon modified from Chen et al. (2010).

**Figure S2.** Statistical performance of pollen-based calibration models for PANN and TANN. Performance statistics include coefficient of determination (R2), root-mean-square error of prediction (RMSEP), and maximum (Max.) bias. Scatter plots show predicted versus observed values for PANN (mm) or TANN (°C), and residuals of predicted versus observed values for PANN or TANN.

**Figure S3.** The original pollen-based stacked PANN (±232.06 mm) or TANN (±3.62 °C) reconstructions based on 22 individual reconstructions from fossil pollen records of 11 lake sediments cores in monsoonal northern China.

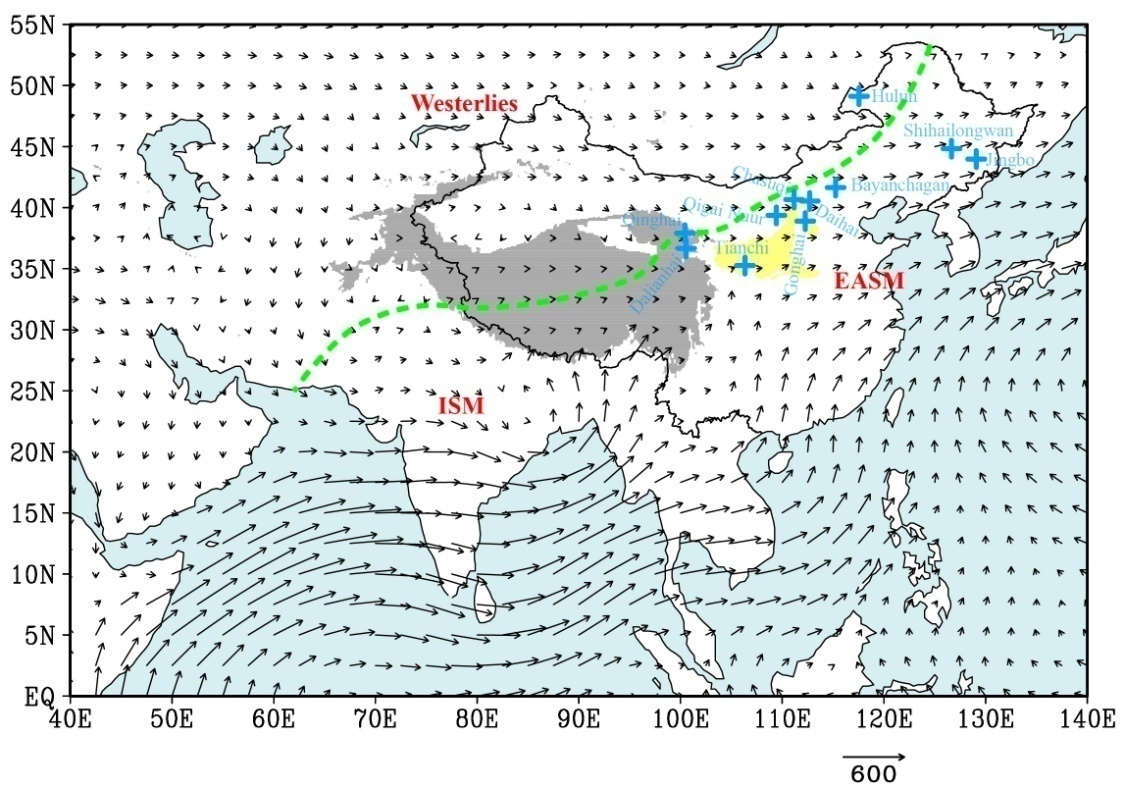
**Tables**

**Table S1.** Summary of fossil pollen records for PANN and TANN reconstructions from 11 lakes in monsoonal northern China.

**Table S2.** AMS radiocarbon dates and calibrated ages of 11 fossil records (see Table S1 for references).

**Table S3.** Information regarding 17 Chinese historical records from the Han to Qing Dynasty including economic level, grain yield grade, grain price index, fiscal grade, agriculturalist policy territory, extreme flood years, extreme drought years, freeze disaster frequency, sand-dust event frequency, famine index, locust frequency, epidemic disaster frequency, peasant uprising frequency, number of wars, number of southward nomadic migrations, farming-pastoral boundary, and number of estimated human population.

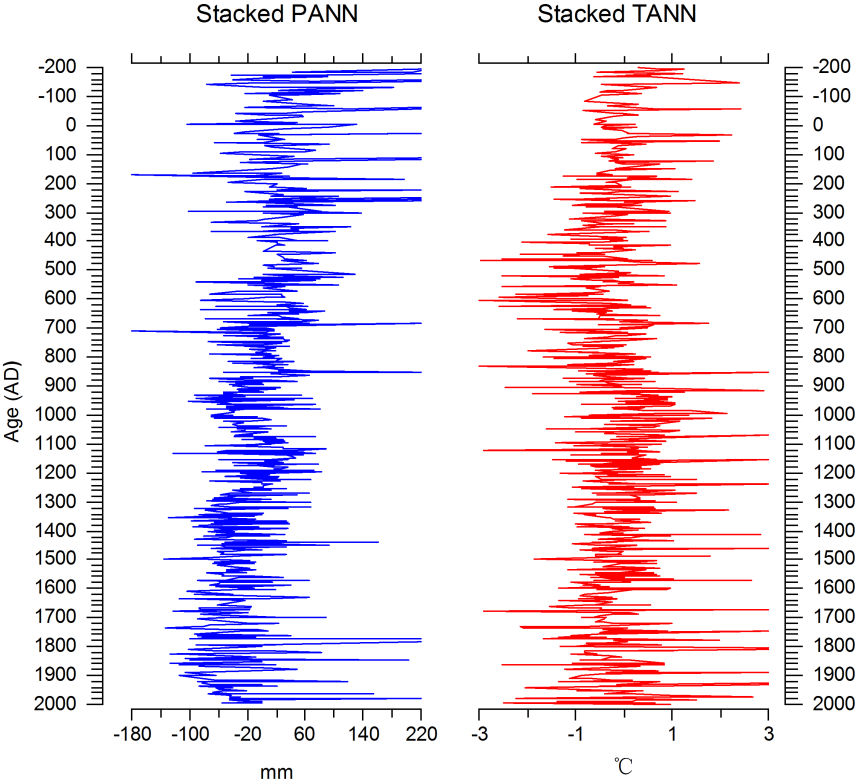
**Figure S1**

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**Figure S2**

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**Figure S3**

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**Table S1** Summary of fossil pollen records for PANN and TANN reconstructions from 11 lakes in monsoonal northern China.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Lake | Lati. | Long. | Alt. | Num. | Res. | PANN | TANN | Reference |
|  | (°) | (°) | (m) | dates | (yrs) | (E/T) | (E/T) |  |
| Bayanchagan | 41.65 | 115.21 | 1355 | 7 | 130 | E | E | Jiang et al., 2006 |
| Daihai | 40.58 | 112.67 | 1225 | 8 | 30 | E | E | Xiao et al., 2004;  Xu et al., 2010 |
| Dalianhai | 37.91 | 100.41 | 2850 | 10 | 80 | T | T | Cheng et al., 2013 |
| Gonghai | 38.90 | 112.23 | 1860 | 34 | 20 | E | E | Chen et al., 2015;  Zhang, 2015 |
| Hulun | 49.13 | 117.51 | 545 | 13 | 65 | E | E | Wen et al., 2010 |
| Jingbo | 43.98 | 129.03 | 350 | 9 | 18 | T | T | Chen et al., 2014 |
| Chasuqi | 40.67 | 111.13 | 1000 | 4 | 90 | T | T | Wang et al., 1997 |
| Qigai Nuur | 39.37 | 109.39 | 1300 | 17 | 50 | E | E | Sun and Feng, 2013 |
| Qinghai | 36.67 | 100.52 | 3200 | 6 | 70 | T | T | Liu et al., 2002;  Shen et al., 2005 |
| Sihailongwan | 44.83 | 126.60 | 833 | 40 | 55 | E | T | Stebich et al., 2015 |
| Tianchi | 35.26 | 106.31 | 2430 | 19 | 85 | E | E | Zhao et al., 2010;  Li et al., 2014 |

Lati. = latitude; Long. = Longitude; Alt. = Altitude; Num. = Number; Res. (yrs) = Resolution (years/sample); E = Earlier publications; T = This study

**Table S2** AMS radiocarbon dates and calibrated ages of 11 fossil records (see Table S1 for references).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Site | Depth (cm) | Dating material | 14C age (yr BP) | Calibrated ages (2σ-range) (Cal. yr BP) |
| Bayanchagan | 0–2 | TOC | 570±50 | 520–648 |
|  | 34–36 | TOC | 3570±60 | 3693–3989 |
|  | 40–42 | TOC | 3830±70 | 4418–4074 |
|  | 46–48 | TOC | 5270±50 | 6122–5925 |
|  | 76–78 | TOC | 7040±80 | 7685–7973 |
|  | 148–150 | TOC | 9760±130 | 10,693–11,439 |
|  | 178–180 | TOC | 10,500±140 | 11,934–12,908 |
|  |  |  |  |  |
| Daihai | 160 | Organic matter | 1434±28 | 1385–1290 |
|  | 402 | Organic matter | 2688±27 | 2845–2750 |
|  | 501 | Organic matter | 3531±28 | 3885–3700 |
|  | 701 | Organic matter | 4729±32 | 5585–5325 |
|  | 901 | Organic matter | 5809±33 | 6720–6500 |
|  | 989 | Organic matter | 6593±34 | 7565–7430 |
|  | 1063 | Organic matter | 9175±34 | 10,470–10,235 |
|  | 1103 | Organic matter | 10,171±39 | 12,300–11,570 |
|  |  |  |  |  |
| Dalianhai | 3.53 | Plant remains | 1140±80 | 687 |
|  | 4.98 | Plant remains | 1955±80 | 1470 |
|  | 12.35 | Plant remains | 3587±30 | 3422 |
|  | 25.85 | Plant remains | 8817±65 | 9483 |
|  | 29.76 | Plant remains | 9860±70 | 10,720 |
|  | 30.00 | Plant remains | 10,268±53 | 11,257 |
|  | 35.43 | Plant remains | 10,620±40 | 12,022 |
|  | 39.00 | Plant remains | 11,668±83 | 13,180 |
|  | 40.00 | Plant remains | 12,464±140 | 13,937 |
|  | 40.04 | Plant remains | 12,690±72 | 14,165 |
|  |  |  |  |  |
| Gonghai | 0.46 | Plant macrofossils | 150±30 | 0–282 |
|  | 0.63 | Plant macrofossils | 368±23 | 332–498 |
|  | 1.07 | Plant macrofossils | 570±25 | 540–628 |
|  | 1.16 | Plant macrofossils | 665±34 | 565–668 |
|  | 1.99 | Plant macrofossils | 1005±40 | 804–963 |
|  | 2.49 | Plant macrofossils | 1102±30 | 968–1053 |
|  | 3.63 | Plant macrofossils | 1329±25 | 1194–1294 |
|  | 4.06 | Plant macrofossils | 2231±35 | 2159–2325 |
|  | 5.21 | Plant macrofossils | 2821±29 | 2878–2956 |
|  | 5.38 | Plant macrofossils | 3440±30 | 3640–3813 |
|  | 5.48 | Plant macrofossils | 4089±39 | 4455–4797 |
|  | 5.72 | Plant macrofossils | 4760±40 | 5470–5583 |
|  | 6.00 | Plant macrofossils | 5944±36 | 6727–6844 |
|  | 6.31 | Plant macrofossils | 6550±40 | 7427–7485 |
|  | 6.44 | Plant macrofossils | 6890±50 | 7674–7785 |
|  | 6.49 | Plant macrofossils | 7001±54 | 7765–7930 |
|  | 6.58 | Plant macrofossils | 7120±40 | 7876–7995 |
|  | 7.03 | Plant macrofossils | 8670±40 | 9550–9659 |
|  | 7.35 | Plant macrofossils | 9464±42 | 10,602–10,758 |
|  | 7.61 | Plant macrofossils | 10,020±50 | 11,360–11,690 |
|  | 7.66 | Plant macrofossils | 10,252±39 | 11,839–12,084 |
|  | 8.02 | Plant macrofossils | 10,667±83 | 12,655–12,820 |
|  | 8.54 | Plant macrofossils | 11,930±50 | 13,725–13,859 |
|  | 8.91 | Plant macrofossils | 11,490±140 | 13,203–13,477 |
|  | 9.42 | Plant macrofossils | 12,518±49 | 14,487–14,883 |
|  |  |  |  |  |
| Hulun | 0–1 | Organic matter | 685±21 | 0– -10 |
|  | 19–20 | Organic matter | 1335±22 | 550–610 |
|  | 34–35 | Organic matter | 1611±22 | 770–930 |
|  | 49–50 | Organic matter | 2543±22 | 1710–1870 |
|  | 59–60 | Organic matter | 3222±29 | 2480–2650 |
|  | 69–70 | Organic matter | 3630±27 | 2970–3220 |
|  | 79–80 | Organic matter | 4034±30 | 3470–3690 |
|  | 89–90 | Organic matter | 4575±31 | 4230–4430 |
|  | 101–102 | Organic matter | 5304±27 | 5290–5470 |
|  | 109–110 | Organic matter | 6338±35 | 6310–6510 |
|  | 119–120 | Organic matter | 7285±30 | 7430–7570 |
|  | 129–130 | Organic matter | 8003±38 | 8010–8200 |
|  | 149–150 | Organic matter | 9268±38 | 9480–9660 |
|  |  |  |  |  |
| Jingbo | 28.5 | Leaf fragment | Modern carbon | Modern carbon |
|  | 100 | Leaf fragment | 110±30 | 10–270 |
|  | 282 | Leaf fragment | 1150±30 | 980–1170 |
|  | 519 | Leaf fragment | 2210±30 | 2140–2330 |
|  | 700 | Leaf fragment | 2790±30 | 2800–2960 |
|  | 750 | Leaf fragment | 2830±30 | 2860–3040 |
|  | 815 | Leaf fragment | 3160±30 | 3350–3440 |
|  | 965 | Leaf fragment | 3850±30 | 4150–4410 |
|  | 1154 | Leaf fragment | 4420±30 | 6350–6540 |
|  |  |  |  |  |
| Chasuqi | 33–37 | Peat | 1650±80 | 1356–1720 |
|  | 55–60 | Peat | 2160±75 | 1989–2339 |
|  | 211–216 | Peat | 8200±80 | 9001–9406 |
|  | 258–263 | Peat | 9050±150 | 9701–10,541 |
|  |  |  |  |  |
| Qigai Nuur | 0–2 | Bulk sediment | 1950±50 | 0 |
|  | 84–85 | Bulk sediment | 2700±70 | 557–893 |
|  | 94–95 | Bulk sediment | 2780±60 | 671–906 |
|  | 124–125 | Bulk sediment | 2480±60 | 508–636 |
|  | 154–155 | Bulk sediment | 2490±40 | 505–652 |
|  | 174–175 | Bulk sediment | 3120±60 | 962–1257 |
|  | 209–210 | Bulk sediment | 3280±40 | 1178–1309 |
|  | 231–232 | Bulk sediment | 3490±60 | 1318–1536 |
|  | 261–262 | Bulk sediment | 3540±60 | 1349–1680 |
|  | 301–302 | Bulk sediment | 3760±40 | 1624–1865 |
|  | 381–382 | Bulk sediment | 6120±70 | 4455–4853 |
|  | 450–451 | Bulk sediment | 7340±60 | 6000–6293 |
|  | 501–502 | Bulk sediment | 8340±110 | 7019–7553 |
|  | 541–542 | Bulk sediment | 9320±60 | 8036–8327 |
|  | 571–572 | Bulk sediment | 9670±90 | 8349–8749 |
|  | 601–602 | Bulk sediment | 9650±50 | 8406–8586 |
|  | 631–632 | Bulk sediment | 10,170±60 | 9024–9401 |
|  |  |  |  |  |
| Qinghai | 120 | TOC | 2400±100 | 1567 |
|  | 230 | TOC | 5060±90 | 4505 |
|  | 355 | TOC | 6760±180 | 6528 |
|  | 475 | TOC | 9660±140 | 9661 |
|  | 675 | TOC | 14,820±180 | 16,540 |
|  | 745 | TOC | 15,610±90 | 17,454 |
|  |  |  |  |  |
| Sihailongwan | 45.0 | Plant remains | 525±25 | 511–624 |
|  | 47.0 | Plant remains | 335±32 | 309–478 |
|  | 77.5 | Plant remains | 1313±40 | 1173–1302 |
|  | 97.0 | Plant remains | 1784±41 | 1573–1821 |
|  | 98.0 | Plant remains | 1725±35 | 1548–1711 |
|  | 118.8 | Plant remains | 2128±42 | 1992–2304 |
|  | 128.0 | Plant remains | 2450±30 | 2359–2702 |
|  | 147.0 | Plant remains | 2917±43 | 2929–3214 |
|  | 163.0 | Plant remains | 3362±51 | 3464–3719 |
|  | 165.3 | Plant remains | 3460±50 | 3587–3852 |
|  | 172.2 | Plant remains | 3655±33 | 3891–4085 |
|  | 178.5 | Plant remains | 3910±46 | 4160–4511 |
|  | 186.5 | Plant remains | 4080±35 | 4440–4809 |
|  | 194.5 | Plant remains | 4170±40 | 4577–4835 |
|  | 198.5 | Plant remains | 4375±55 | 4840–5272 |
|  | 214.1 | Plant remains | 4745±35 | 5328–5586 |
|  | 225.4 | Plant remains | 5060±40 | 5669–5911 |
|  | 237.8 | Plant remains | 5604±50 | 6299–6480 |
|  | 251.5 | Plant remains | 6030±50 | 6742–7002 |
|  | 262.5 | Plant remains | 6279±55 | 7013–7319 |
|  | 290.0 | Plant remains | 7407±76 | 8045–8374 |
|  | 306.9 | Plant remains | 7990±50 | 8649–9007 |
|  | 318.5 | Plant remains | 8520±110 | 9153–9886 |
|  | 357.0 | Plant remains | 9180±60 | 10,234–10,500 |
|  | 362.8 | Plant remains | 9059±67 | 9931–10,412 |
|  | 385.75 | Plant remains | 9650±70 | 10,767–11,202 |
|  | 386.0 | Plant remains | 9590±50 | 10,741–11,144 |
|  | 408.9 | Plant remains | 9927±63 | 11,216–11,618 |
|  | 424.3 | Plant remains | 10,243±72 | 11,650–12,362 |
|  | 451.75 | Plant remains | 10,240±80 | 11,623–12,376 |
|  | 465.6 | Plant remains | 10,930±70 | 12,815–13,000 |
|  | 466.7 | Plant remains | 10,980±150 | 12,747–13,208 |
|  | 481.0 | Plant remains | 10,818±97 | 12,657–12,956 |
|  | 565.0 | Plant remains | 12,330±80 | 14,003–14,759 |
|  | 615.2 | Plant remains | 13,290±70 | 15,384–16,170 |
|  | 662.25 | Plant remains | 13,610±140 | 15,692–16,714 |
|  | 703.0 | Plant remains | 14,800±70 | 17,655–18,491 |
|  | 834.5 | Plant remains | 15,820±80 | 18,875–19,223 |
|  | 890.2 | Plant remains | 15,350±240 | 18,009–19,034 |
|  | 1,173.50 | Plant remains | 19,430±110 | 22,657–23,572 |
|  |  |  |  |  |
| Tianchi | 162 | Plant macrofossils | 680±30 | 634–680 |
|  | 183 | Plant macrofossils | 855±35 | 688–801 |
|  | 221 | Plant macrofossils | 1080±35 | 932–1056 |
|  | 260 | Plant macrofossils | 1255±30 | 1122–1277 |
|  | 302 | Plant macrofossils | 1440±45 | 1288–1406 |
|  | 382 | Plant macrofossils | 1775±30 | 1610–1745 |
|  | 383 | Plant macrofossils | 2060±30 | 1948–2118 |
|  | 436 | Plant macrofossils | 2355±30 | 2333–2464 |
|  | 489 | Plant macrofossils | 2585±40 | 2695–2774 |
|  | 554 | Plant macrofossils | 2895±45 | 2921–3165 |
|  | 600 | Plant macrofossils | 3300±30 | 3450–3591 |
|  | 701 | Plant macrofossils | 3400±30 | 3567–3718 |
|  | 751 | Plant macrofossils | 3935±35 | 4281–4444 |
|  | 815 | Plant macrofossils | 4100±40 | 4516–4728 |
|  | 848 | Plant macrofossils | 4230±35 | 4799–4860 |
|  | 893 | Plant macrofossils | 4400±40 | 4857–5061 |
|  | 966 | Plant macrofossils | 4495±40 | 5038–5301 |
|  | 1014 | Plant macrofossils | 4820±40 | 5469–5562 |
|  | 1086 | Plant macrofossils | 5030±35 | 5707–5895 |

TOC = Total organic carbon

**Table S3** Information of17 Chinese historical records from the Han to Qing Dynasty including economic level, grain yield grade, grain price index, fiscal grade, agriculturalist policy territory, extreme flood years, extreme drought years, freeze disaster frequency, sand-dust event frequency, famine index, locust frequency, epidemic disaster frequency, peasant uprising frequency, number of wars, number of southward nomadic migration, farming-pastoral boundary, and number of estimated human population.

|  |  |  |
| --- | --- | --- |
| Index | Abre. | Reference |
| Economic level | ED | Wei et al., 2015 |
| Grain yield grade | GY | Su et al., 2014 |
| Grain price index | GPI | Ge et al., 2014 |
| Fiscal grade | FG | Wei et al., 2014 |
| Agriculturalist policy territory | AT | Zhang et al., 2014 |
| Extreme flood years | EF | Hao et al., 2010 |
| Extreme drought years | ED | Hao et al., 2010 |
| Freeze disaster frequency | FD | Cai, 2009 |
| Sand-dust event frequency | SD | ` et al, 1984 |
| Famine index | FI | Fang et al., 2015 |
| Locust frequency | LF | Li et al., 2010 |
| Epidemic disaster frequency | EPD | Gong, 2003 |
| Peasant uprising frequency | PUF | Fang et al., 2015 |
| Number of wars | NW | Ge et al., 2014 |
| N. of southward nomadic migrations | SNW | Pei and Zhang, 2014 |
| Farming-pastoral boundary | FPB | Zhang et al., 2014 |
| N. of estimated human population | HP | Li et al., 2009 |

Abre. = Abbreviation; N. = Number

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