

# Index

Page numbers in *italic* denote figures. Page numbers in **bold** denote tables.

- ablation area 192, 193, 194, 195, 200  
aerosols 9, 10, 12, 16–17, 18  
albedo 1  
    Gangotri Glacier 107  
    spatiotemporal variation 139–153  
        Mago Basin 142–153  
        remote sensing 139–140, 142  
all-India summer monsoon rainfall index (AISMRI) 15  
Andes *see* Peruvian/Bolivian Andes  
APHRODITE (Asian Precipitation Highly Resolved  
    Observational Data Integration Towards  
    Evaluation of water resources) 74, 75, 76,  
    78–83, 85  
    Gangotri Glacier 101, **104**, 106, 111–112, **114**  
    Satluj River Basin study 120, 121, 123, 126,  
    129, 130, 137  
AquaMODIS 90  
    albedo variation, Mago Basin 142, 144  
avalanching 70, 175, 176, 193, 195  
AVHRR (Advanced Very High Resolution Radiometer),  
    snow-cover algorithm 89, 90  
AWiFS (Advanced Wide Field Sensor) 89, 93  
AWS (Automatic Weather Station) data  
    albedo variation 142, 146  
    Chhota Shigri Glacier 156–157  
    Gangotri Glacier 101, 104, 106, 112, **114**  
    High Mountain Asia 190  
AX010 Glacier 190, 192, 194  
  
bajada, Indus valley 24, 26, 28, 30  
Baspa Bamak glacier 56  
Baspa River valley  
    aggradation and incision 68, 69, 70–71  
    alluvial fan 52, 55, 57, 58–59, 63, 66–67, 68, 70  
    chronostratigraphy 63–66  
    depositional environment 66–68  
    geology 52, 53  
    late-Quaternary  
        climate change 52  
        land forms 52, 55  
        sedimentology 57–58, 61–63  
            aggradation and incision 68  
            role of ISM and climate change 68–71  
            Kharogla-Rakcham section 62, 63, 67  
            Kuppa 61, 65  
            Kuppa-Jareyo section 58, 59, 61, 64  
            Sangla 60, 61–63, 65  
    lithofacies 52, **54**  
    moraines 55, 56  
    morphology 55–57  
    OSL signal data 52, 53, 54, **55**, 58–59, 60, 62, 63  
    palaeolake  
        formation 67, 70  
        sediments 52, 55, 56, 58–71  
        deposition 67  
    river profile 52, 55, 56  
    river terrace sediments 52, 55, 56–57, 58–59,  
        63, 64, 65, 66, 68  
  
Beas gorge 171, 174  
Bhakra Beas Management Board (BBMB)  
    precipitation data 120, 129  
    streamflow 131–135  
‘black swans’ 9, 18–19  
Bolivian High 15  
Brahmaputra River 73, 74, 79–81, 190  
    effect of glacier retreat 3, 19  
    precipitation 74, 79–81, 82–83, 84–85  
    as water resource 189, 191, 197, 199  
  
Cartosat-1 DEM  
    Dokriani Glacier 110  
    Gangotri Glacier 102–103, **104**, 110  
Central Himalaya 1, 2  
    precipitation 74, 197  
CFSR (climate forecast system reanalysis), temperature  
    data 120, 122–123, 125, 127, 129  
Chandra Basin 37  
Chandra valley  
    glacial landforms 173  
    snow-cover algorithm 90–98  
Changri Nup Glacier 190, 195  
Chhota Shigri Glacier 156–157, 156, 190,  
    192, 194  
    surface energy balance study 157–167  
        correlation with temperature 163, **166**  
        daily and diurnal fluxes 161–163, 164, 165  
        late winter 163, 164  
        meteorological conditions 158, 160–161, **166**  
        midwinter 163, 164  
        net all-wave radiation 157  
        subsurface flux 159–160  
        turbulent fluxes 157–158  
Chitkul, Baspa River  
    landforms 57, 61, 63  
    sedimentology 62, 63, 68  
climate change 1–2, 3, 177–178  
    abrupt 7, 18–19  
    ice core records 7, 8, 9–20  
    impact on glaciers 195–197, 199  
        water resources 3, 191, 197–201, 199  
Climatic Research Unit (CRU) precipitation  
    data 74, 75  
CORDEX (COordinated Regional Climate Downscaling  
    Experiment), REMO data 101, **104**  
Coropuna ice cap (CIC) 8  
    crater core (CCC) 9, 10–14, 16, 17–18  
cryosphere 1, 2, 73  
  
dams, landslide 23, 51, 52, 67, 70, 176  
Dasuopu Glacier (DG) 8  
    summit core (DSC) 9–14, 16–17  
debris cover 192, 195, 200  
debris flow 175, 176, 177  
deglaciation 2  
    Baspa River valley 69, 70  
deglaciation discharge dividend 197, 198

- DEM (Digital Elevation Model)  
 Dokriani glacier *110*  
 Gangotri Glacier 103, 104  
 Himalaya *170*  
 Indus Valley, Leh 24  
 Mago Basin *141*, 142  
 Samudra Tapu Glacier 91–92
- disasters  
 and Earth surface processes 169  
 and ENSO 18, 19
- Dokriani glacier 99, 101, *103*, 106, 109, *110*  
 energy balance modelling 114–115  
 mass-balance 100, 111  
 precipitation 111, 112
- drought 8–9, 13, 15, 16–17, 18, 178
- Dunde ice cap (DIC) 8
- dykes, Indus valley palaeolake sediments 26, 27
- Earth surface processes  
 and disasters 169  
 and landscape evolution 169–183  
 earthquakes 172, 175, *178*, 179  
 ‘East India Drought’ 18
- Eastern Himalaya 2  
 mass balance 196  
 precipitation 74, 197
- El Niño–Southern Oscillation (ENSO) 8, 13  
 connection with ISM *12*, 13–16, 17  
 and disasters 18, 19  
 late-eighteenth century 18
- equilibrium line altitude (ELA) 156, 192, 194, 196
- faulting, Indus valley palaeolake sediments 26, 27
- FERM (fuzzy error matrix) 94–95
- flooding 178–179, *178*, *179*  
 glacial lake outbursts 197–198, 200  
 GLOFs 179
- fluvial landforms 174–177
- Ganga River *see* Ganges River
- Ganges River 73, 74, 76–79, *190*  
 effect of glacier retreat 3, 19, 35  
 glaciers 35, 36, 77  
 thinning and melt fraction 83–84  
*see also* Gangotri Glacier  
 precipitation 74, 77–79, 82–83, 84–85  
 as water resource 189, 191, 197, *199*
- Gangju La Glacier *190*, 194
- Gangotri Glacier 76, 99–101, **101**  
 area and elevation 102–103, 104, 107–108, 109  
 DEM 103, 104, 108  
 discharge 100, **102**  
 energy balance modelling 111–115  
 ice-flow velocity 100, **102**, 103  
 length 100, **102**  
 mass-balance modelling 99, 100, 104–115  
 uncertainty analysis 107–108  
*see also* mass-balance estimation, Gangotri  
 meteorological data 101–102  
 precipitation 101  
 religious significance 100  
 retreat 100, **102**  
 runoff 99  
 source of freshwater 100  
 statistics **102**  
 thickness **102**, 103, 108, 109–110  
 volume 100, **102**, 103, 108, *109*, 111
- Garwhal 1991 and 1999 earthquakes 172, 175  
 geohazards 169, 177–180  
 mitigation 180–183  
 glacial-interglacial transition, Baspa River valley  
 68, 69, 70
- glaciation 172–174  
 cycles and stages 3, *31*, 173  
 Quaternary 2–3, 173–174
- glaciers 1, 2  
 and climate change 1, 195–197, *199*  
 impact of geomorphology 198, 200  
 impact on water resources 3, 197–201, *199*  
 debris-cover 192, 195, 200  
 ELA 192, 194, 196  
 extent/volume 35, 191–192  
 ice cores 7, 9  
 Lahaul and Spiti district 35–48  
 GPR survey 37–39  
 recessional studies 40–41  
 shape analysis 39–40  
 landforms 2–3  
 Late-Holocene-present changes 195–196  
 mass balance 192, 194, 196, 200  
 and glacier dynamics 200–201  
 mass loss 196, 197, 198  
 mass-balance modelling 99  
 Gangotri Glacier 99–115  
 retreat 3, 19, 177–178, 189, 195  
 Baspa Glacier 155  
 Gangotri Glacier 100, **102**  
 Hamtah/Parang 35–36, 40–41, 46, 47, 48  
 surface energy balance studies 155–167  
 as water resource 35, 73, 100, 189
- Global Land Ice Measurements from Space (GLIMS) 192
- GLOFs (glacial lake outburst floods) 179
- Gorkha 2015 earthquake 172, 175
- GRACE (Gravity Recovery and Climate Experiment) 196
- Great Himalaya 1, *171*
- ground penetrating radar (GPR)  
 glaciers 35, 192, 200  
 Hamtah Glacier 36, 37–39, 38, 41, 43  
 Parang Glacier 36, 37, 41, 42
- Guliya ice cap (GIC), ice cores 8, 9
- Hamtah Glacier 36–37, *190*, *194*  
 GPR survey 37–39, 38, 41, 43  
 moraine 40, 43, 47  
 recession 46, 47, 48  
 shape analysis 43–47  
 volume 48
- HAR (High Asia Refined) atmospheric dataset, Gangotri  
 Glacier 101–102, **104**, 106, 111–112, **114**
- High Mountain Asia  
 glaciers  
 and climate change 198–201  
 water resources 197–201  
 debris-cover 192, 195  
 extent and volume 191–192  
 Late Holocene-present changes 195–196  
 mass balance and ELA 192, 194  
 water resources 189–201, *190*

- see also* Himalaya; Hindu Kush; Karakoram
- highways *see* road building
- Himachal Pradesh
- glaciers 37–48
    - Chhotra Shigri Glacier 156–167
    - snow-cover algorithm 90–98
- Himalaya 1, 2, 35, 36, 169–171, 170
- altitude 1, 2
  - Earth surface processes 169–183
    - environmental management for future 180–183
  - foothills 1
  - glaciation 172–174
  - glaciers 35–48
    - and climate change 198–201
    - debris-cover 192, 193, 195
    - ELA 192, 194
    - extent/volume 32, 36, 191–192
    - Late Holocene-present changes 196–197
    - mass balance 192, 194, 196
    - as water resource 35, 73, 189, 190, 191, 197–198
  - groundwater 12
  - human influence 176–177, 181
  - hydrological systems 174–175
  - landscape diversity 169–171
  - landscape evolution 177, 181
  - mass movement 175–176, 181
  - Pacific connection with Andes 9, 12, 13–16
  - precipitation 73–74
  - soils 176
  - topography 170
  - as water source for Asia 1, 73–74
  - weathering 176
  - see also* Central Himalaya; Eastern Himalaya, Great Himalaya; Lesser Himalaya; Western Himalaya
- Hindu Kush 1
- 2015 earthquake 172
  - extent 35, 36
  - water resources 190, 191
- Holocene
- Baspa Valley 70–71
  - Late, glacier volume changes 195–196
- Huascarán ice cap (HIC) 8
- human influence 176–177, 181
- hydrological budget 197–198, 199
- hydrological systems 174–175
- hydrosphere 73
- ice caps 8, 9
- ice cliffs 193, 195
- ice cores, low-latitude
- climate change records 2, 7, 9–20
    - late-eighteenth century 16–19
    - mid-fourteenth century 16–18, 19
  - mineral dust and major ions 10, 11, 12–16
  - $\delta^{18}\text{O}$  7, 9, 10, 11, 13–14, 15–16, 17, 18
- ice fields
- low latitude, climate records 7, 8, 9–20
  - see also* glaciers; ice caps
- India, warming 3
- India-Eurasia collision 169, 171–172
- Indian Meteorological Department (IMD), precipitation data 75, 76, 78–83, 85, 120, 121, 122, 126, 129, 137
- Indian Summer Monsoon (ISM) 8, 51, 52, 74
- Baspa River valley 68–71
  - connection with ENSO 8, 13–16, 17
- Indian Winter Monsoon 101
- Indus River 73, 74, 75–76, 190
- blockage 28–29, 31–32, 31
  - effect of glacier retreat 3, 19, 35
  - glacier elevation 35
  - OSL 24, 25, 26, 28, 29, 31–32
  - precipitation 74, 76, 77, 81, 82–83, 84–85
  - valley
    - glaciers 36–48, 76, 173
    - palaeolakes 23–32, 24, 30
      - formation 28–29, 30, 31–32
      - sediments 25, 26, 27, 28, 29
    - as water resource 189, 191, 197, 198, 199
- intensified monsoon phases (IMPs), and landslides 51, 52, 70
- Intertropical Convergence Zone (ITCZ) 8, 17–18
- IPCC (Intergovernmental Panel on Climate Change), climate modelling 177, 191, 196, 197, 200
- isotopes *see* oxygen,  $\delta^{18}\text{O}$
- Jai Prakash Dam, terrace deposits 58, 64
- Kangwure Glacier 190, 194
- Karakoram 1, 2, 171
- glaciers
    - debris-cover 195
    - extent/thickness 191–192
    - mass balance/ELA 194, 196
    - water resources 190, 191
- Karakoram Fault 26
- Karu Garang Glacier 56
- Karu Nala, sedimentology 61, 65, 67
- Kashmir 2005 earthquake 172, 175, 179
- Kedarnath, flooding 178, 179
- Kharogla, Baspa River
- landforms 56, 57, 61, 67
  - palaeolake 71
  - sedimentology 63
- Khumbu Glacier 192, 193
- Khumbu Icefall 193
- Kilimanjaro ice field (KIF)
- ice cores 8, 9
  - retreat 19
- Ladakh
- glacial stages 3, 31
  - landforms 23–32
  - palaeolakes 23–32
- Ladakh Plutonic Complex (batholith) 24, 30, 171
- Lahaul and Spiti district, glaciers 36–48
- Chhota Shigri 156–167
  - GPR survey 37–39, 41
  - recessional studies 40–41, 46, 47, 48
  - Samudra Tapu 90–91
    - snow-cover algorithm 91–98
  - shape analysis 39–40, 41–47
- Lake Titicaca 12
- water level 17
  - water source 13

- lakes  
 proglacial 179, 195, 200–201  
 supraglacial 42, 48, 179, 193, 195, 197  
 outburst floods 197, 200  
*see also* palaeolakes
- landforms, Ladakh 23–32
- Landsat  
 albedo variation 140  
 drainage systems 74  
 glaciers 36  
 Gangotri Glacier 100, 102, 103, **104**, 107
- Landsat Enhanced Thematic Mapper Plus 90
- landscape evolution 177, 181  
 and Earth surface processes 169–183
- landslides 175–176, 177, 178, 179  
 formation of palaeolakes 23, 51, 52, 67, 70, 176
- Langtang Glacier 190, 194, 197
- Last Glacial Maximum (LGM) 3, 70, 71, 173
- Lato, weathering 176
- Leh  
 moraine 173  
 palaeolakes 23–32, 24  
 formation 28–29, 30, 31–32  
 sediments 24, **25**, 26, 27
- Lesser Himalaya 1, 171
- linear mixture model (LMM) 90, 92–95, 97
- Lirung Glacier 190, 192
- Little Ice Age 3, 18, 195
- Mago Basin 141, 142  
 dry snow  
 albedo variation 146, 148, 151–153  
 area variation 143, 144, **150**, 151  
 slope values **144**, 146  
 firn  
 albedo variation 150, 151–153  
 area variation 147, 148, **150**, 151  
 slope values **144**, 146  
 glaciers, albedo variation 141, 146–153  
 ice  
 albedo variation 150–151, 151–153  
 area variation 149, 150, **150**, 151  
 slope values **144**, 150, 151  
 spatiotemporal albedo variation 142, 151–153  
 wet snow  
 albedo variation 148, 150, 151–153  
 area variation 145, 146, **150**, 151  
 slope values **144**, 148
- Marine Isotope Stages  
 MIS-1 68, 69, 71  
 MIS-2 68, 69, 70, 71  
 MIS-3 1, 3, 68, 69, 70, 71  
 MIS-4 32  
 MIS-5 32
- mass movement 175–176, 181  
 mass wasting *see* debris flow; landslides; mass movement
- mass-balance estimation 99–100, 192, 194, 196  
 Gangotri Glacier 100, **102**, 104–115  
 energy balance modelling 104–105, 111–115  
 ice-flow velocity method 104, 111, **114**  
 latent heat flux 106, 107, 113  
 net longwave radiation flux 105, 107, 113  
 net shortwave radiation flux 105, 107, 113  
 sensible heat flux 105–106, 107, 113  
 temperature lapse rate 106  
 and albedo parameterization 107, 112  
 uncertainty analysis 107–108
- Medieval Climate Anomaly (MCA) 17–18
- meltwater *see* snowmelt runoff
- mid-latitude westerlies 1, 170, 173
- Mid-Pliocene Warm Period 2
- Middle Miocene Climate Optimum 2
- mineral dust, ice cores 10, **11**
- mixed pixels 89
- MODIS (Moderate Resolution Imaging Spectrometer) 89, 90  
 albedo variation 140, 142  
 Mago Basin 142, 144, 146  
 SCF algorithm 90–98
- MOHITS (monsoon-influenced Himalayan-Tibetan stages) 173
- monsoon 1, 191  
 climate change 178  
 intensified monsoon phases (IMPs) 51, 52, 70  
 Satluj River Basin 120–130  
*see also* Indian Summer Monsoon; Indian Winter Monsoon; South Asian Monsoon
- moraines 3, 195  
 Baspa River valley 55, 56  
 dating 195, 196  
 Hamtah glacier 40, 40, 43, 47  
 Indus valley 28, 173  
 outburst floods 28, 197–198  
 Parang glacier 40, 40, 42, 47  
 Zaskar 173
- Naimona'nyi Glacier 8, 19, 190, 194
- NDSI (normalized difference snow index) 90, 92–94, 95, 96, 97  
 and surface albedo 140
- New Guinea ice fields (NGIF) 8
- NSIDC (National Snow and Ice Data Center) SWE (snow water equivalent) 120, 122, 124, 126, 129
- oxygen,  $\delta^{18}\text{O}$   
 in ice cores 7, 9, 10, **11**, 13–14, 15–16, 17, 18  
 Ladakh palaeolake sediments 32
- Pacific Ocean, influence on climate 8
- Pacific Ocean ENSO/monsoon connection 13–16
- palaeolakes 51–52  
 Baspa River valley 52, 55, 56, 67  
 formation 67–68, 70  
 sedimentology 56, 58–61, 62, 63, 64, 65, 67  
 Kyagar Tsp 174  
 Ladakh 23–32, 30  
 deposits 23, 24, **25**, 26, 27  
 formation 23, 28–29, 30, 31–32  
 OSL dating 24, **25**, 26, 28, 29, 31–32  
 river blockage 23, 28–29, 31–32
- Palam, palaeolake deposits **25**, 26, 28
- Parang Glacier 36, 37  
 GPR survey 37, 41, 42  
 moraine 40, 42, 47  
 recession 46, 47, 48  
 shape analysis 41–42, 44, **45**, 46–47  
 volume 48
- peak water 197

- Peruvian/Bolivian Altiplano  
 ENSO events 15  
 groundwater 12–13  
 ice cores 10
- Peruvian/Bolivian Andes, Pacific connection with  
 Himalaya 9, 12, 13–16
- Phey, Indus valley sediments 24, **25**, 26, 27
- Phyang River, alluvial fan 24, **25**, 31, 32
- plate tectonics, India-Eurasia collision 169, 171–172, 181
- Pleistocene  
 Baspa palaeolakes 70, 71  
 glaciation 2
- ponds, supraglacial 193, 195, 197
- population density 177, 178
- precipitation 1, 3, 73–85  
 Baspa River 70  
 Brahmaputra River 74, 79–81  
 climatology 120–126  
 and ENSO events 8  
 Ganga River 74, 77–79  
 Indus River 74, 76, 77, 81  
 measurement 81–82  
 $\delta^{18}\text{O}$  7  
 predicted future increase 197  
 Satluj River Basin 120–126  
 annual cycle 123–126, 126, 130–135  
 correlation with discharge/temperature 126–130
- Puruogangri ice cap (PIC) 8
- Quaternary  
 Baspa River valley, sedimentology 57–58, 61–63  
 climate change, monsoon, and glaciation 51–71  
 glaciation 173–174  
 landforms 23  
 palaeolakes, Ladakh 23–32
- Quelccaya ice cap (QIC) 8  
 retreat 19  
 summit core (QSC) 9, 10–14, 16–18
- RADAN 6.6 software 38–39
- rain gauge stations 74, 76, 120, 121, 123
- RCM (Regional Climate Model), Gangotri 106
- REMO (REgional MOdel) data, Gangotri 101, **104**, 111, 113–115
- remote sensing  
 glaciers 191–192, 195, 196, 200  
 albedo 139–140  
 extent 35, 36, 73, 74  
 precipitation, Satlaj River Basin 120  
 snow cover 89, 91
- river damming *see* dams, landslide; palaeolakes, river blockage
- river flow, peak water 197
- road building 176, 177, 180
- rock-ice avalanche 193, 195
- rockfall debris 193, 195
- Sajama ice cap (SIC) 8  
 summit core (SSC) 10
- salt flats, Peruvian/Bolivian Altiplano 12, 13
- Samudra Tapu Glacier 90–91
- Sangla, Baspa River  
 landforms 56, 57  
 palaeolake 71
- sedimentology 60, 61–63, 65
- Sarchu, braided river channel 174
- satellite remote sensing *see* remote sensing
- Satluj River Basin  
 discharge 124–126  
 precipitation/temperature 126–130, 132–137  
 precipitation 120–126  
 annual cycle 126, 130–135  
 rain gauges 120, 121, 123  
 snow gauges 120, 121, 123  
 snowmelt runoff, precipitation/temperature 119–137  
 stream flow 119–120, 131–132  
 temperature 120, 121, 122–124, 125, 127  
 discharge/precipitation 126–130, 132–137
- sea-level rise 19, 73
- sea-surface temperature (SST) 7–8, 13–15, 17, 18
- shape analysis  
 Hamtah Glacier 43–47  
 Parang Glacier 41–42, 44, **45**, 46–47
- Shaune Garang Glacier 190, 192
- Sheti valley, weathering 176
- Shey, Indus valley palaeolake deposits 24, **25**, 26–28, 29
- snout monitoring 36, 109
- snow, accumulation rate 9, 13
- snow gauges, Satluj River Basin 120, 121, 123
- snow water equivalent (SWE) 151  
*see also* NSIDC SWE data
- snow-cover fraction (SCF), operational algorithm 90, 92–98
- snow-cover mapping 89–98  
 algorithms 90  
 sub-pixel 89–90
- snowfall 1, 3
- snowline 3, 192  
*see also* equilibrium line altitude
- SNOWMAP algorithm 90
- snowmelt runoff  
 Ganges River 77  
 and river flow 197–198, 198, 199  
 Satluj River Basin, impact of temperature 119–137
- soils 176
- South Asian Monsoon (SAM) 170, 173, 174  
 history 1–2, 3
- South East Asian Monsoon (SEAM) 16
- Southern Oscillation Index (SOI) 15
- speleothem  $\delta^{18}\text{O}$  records 16–17, 18
- Spiti Range, Parang Glacier 36–48
- Spiti Valley, palaeolake deposits 23  
*see also* Lahaul and Spiti district
- Spituk group sediments 24, **25**, 26, 28, 31
- Spituk palaeolake 28, 29, 31, 32
- surface energy balance (SEB) studies 155, 200  
 Chhota Shigri Glacier 157–167  
 Gangotri Glacier 111–115
- SURFRAD (Surface Radiation Budget Network), albedo variation 140
- SWHTS (semi-arid western Himalayan-Tibetan stages) 173
- talus 176, 177
- terraces, river, indication of climate change 52
- TerraMODIS 90, 91, 95  
 albedo variation 140  
 Mago Basin 142, 144

- 'Third Pole' 1, 7, 19  
Tibetan Plateau 1  
TIN (Triangulated Irregular Network) 103  
TRMM (Tropical Rainfall Measuring Mission) satellite  
  data 74, 75, 76, 78–85  
  Gangotri Glacier 101, 104, 106, 111–112, **114**  
uplift, tectonic, and monsoon development 1–2  
water resources 189–201  
  impact of climate change 191, 197–201  
  role of glaciers 3, 19, 35, 189, 191  
'water towers of Asia' 73, 189  
water vapour flux 7  
weathering 176  
westerly winds 1, 170, 173  
Western Himalaya 1, 2  
  precipitation 74  
Yala Glacier *194*  
Zaskar *171, 173*  
Zaskar River 24, 30, *174*  
Zhadang Glacier 197  
Zinchan group sediments **25**, 26, 27, 28  
Zinchan palaeolake 28–29, 32